ELECTRIFICATION OF DHL'S BENELUX MIDDLE-MILE TRANSPORTATION PROCESS

MASTER THESIS INDUSTRIAL ENGINEERING AND MANAGEMENT

Stan Smit | May, 2025

DHL eCommerce

DHL | UNIVERSITY OF TWENTE.

ELECTRIFICATION OF DHL'S BENELUX MIDDLE-MILE TRANSPORTATION PROCESS

Raalte, May 2025

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Document information

Number of pages including appendices and references: 97
Number of pages excluding appendices and references: 70
Number of appendices: 11

Management Summary

In 2015, the European Union, including The Netherlands, signed the Paris Climate Agreement to limit global temperature rise to below 2°C, committing to reducing emissions by at least 55% by 2030 and achieving zero emissions by 2050. DHL Group, currently emitting 40 million MT CO_2, must eliminate its emissions by 2050. While DHL has made progress in electrifying last-mile delivery in the Netherlands, transitioning to electric trucks for the middle mile faces challenges due to the limited driving range of electric trucks, which requires frequent (re)charging. Continuous truck operations during the day further complicate charging availability, potentially making existing routes infeasible to drive.

Additionally, many hubs are operating near their contracted grid capacity, and as the Dutch grid faces net congestion, it is difficult to increase the energy capacity at hubs for implementing charging facilities. Consequently, DHL needs to determine how, when, and where to charge electric trucks within its middle mile process to facilitate a successful integration. DHL plans to start by integrating the first electric trucks this year, leading to the main research question addressing both short-term and long-term challenges, including simultaneous demand of eTrucks for the same charging station as the electric fleet grows.

? | How to evaluate the suitability of the DHL middle mile network for electrification and how to optimize the integration of electric trucks in this transportation network?

Research method

To address the central research question, two tools were developed: an Evaluation Method (EM) and a Generic Solution Method (GSM). The EM specifically assesses the feasibility of electrifying DHL BeNeLux routes by analysing key parameters such as a truck's usable battery capacity, charging power, and arrival State of Charge (SoC) threshold. It calculates the percentage of routes that can be electrified, while having the main assumption that trucks always have immediate access to charging stations upon arrival at hubs that have a charger. This method also provides detailed insights into the reasons behind each route's feasibility or infeasibility, allowing for informed recommendations on suitable specifications for eTrucks and charging stations.

The GSM, on the other hand, utilizes data similar to DHL's route data and aims to improve the feasibility percentage for different transportation network sizes. It considers various scenarios upon a truck's arrival at a hub, including instances where no other trucks are demanding charging or when the number of arriving trucks demanding a charger exceeds the number of available charging stations. In such cases, priority is given to the truck with the most critical SoC. If a truck cannot be prioritized, but needs to charge, it can either wait for a charger to become available or detour to a nearby hub where a charging station is available for the truck upon arrival. The GSM optimizes these options, considering the costs associated with waiting and detouring to determine the best choice for each truck in each route. Penalty costs for not meeting Time Windows later in the route sequence due to delay caused by waiting or detouring are also considered in the trade-off.

Results

From a data analysis of the contracted grid capacities at DHL's hubs, it was determined that currently only six hubs have sufficient capacity in their energy contracts to support the installation of 1 to 3 charging stations. Additionally, the analysis conducted using the EM indicates that for DHL's middle-mile operations, electric trucks with a minimum battery capacity of 600 kWh are suitable. This capacity aligns well with the typical distances driven within the DHL BeNeLux network, where routes often range between 300 and 500 kilometers, providing an adequate driving range of approximately 500 kilometers.

The results from the analyses conducted with both the EM and GSM, clearly demonstrate that increasing the battery capacity from 400 kWh to 600 kWh significantly enhances the percentage of routes that are feasible to drive with an electric truck. For example, in the EM, the percentage of feasible routes is almost doubled from 27.84% with a 400 kWh truck to 53.69% with a 600 kWh truck. Similarly, in the results for

the GSM for the large problem size, the feasibility percentage increases from 28.25% to 68%. Furthermore, the findings in the research indicate that increasing the charging power to higher values than 150 kW do not significantly improve the feasibility percentage compared to enlarging the usable battery capacity of the truck. While higher charging power can reduce charging times, the primary factor of route feasibility lies in the usable battery capacity. This highlights the importance of focusing on improving battery capacity as a more effective strategy for increasing the number of electrically feasible routes within DHL's middle-mile operations.

Summarized Output for trucks:	**400 kWh (EM)**	**600 kWh (EM)**	**400 kWh (GSM large problem)**	**600 kWh (GSM large problem)**
Number of routes evaluated	352	352	400	400
Corresponding driving range	~ 300 km	~ 500 km	~ 300 km	~ 500 km
Number of feasible vs infeasible routes	98 vs 254	189 vs 163	113 vs 287	272 vs 128
Percentage of feasible routes	27.84%	53.69%	28.25%	68.00%

As DHL plans to begin integrating electric trucks into its middle mile network before the end of this year, the EM is slightly changed such that it can determine the optimal hubs which should be homebase to the first DHL electric trucks. This analysis identified **H, I, B** as optimal location due to their sufficient grid capacities and substantial own fleet sizes, allowing for the electrification of existing routes without major adjustment.

The GSM addressed the challenges of multiple trucks simultaneously demanding the same charging station. To tackle this issue, the GSM tested four charger assignment prioritization policies: First Come First Serve (FCFS), Last Come First Serve (LCFS), Random and Priority. The Priority policy consistently outperformed the others, achieving better feasibility percentages by 2% in small problem sizes, 3-4% in medium sizes, and 8-10% in larger problem sizes. This improvement highlights the significance of charging policies in larger problem sizes, where the presence of more trucks leads to increased overlap of service times of different trucks at the same location. Additionally, the GSM improved the feasibility percentage by offering trucks two options. If a charger was not immediately assigned upon arrival, trucks could either detour to the nearest available hub with an open charging station or wait at their current location until a charger became available. By employing a cost trade-off that considered delays from waiting or detouring and the potential penalty costs for exceeding time windows, the GSM could identify the optimal solution for each truck in each problem size, day, and distribution of charging station over the network. However, despite these improvements, the GSM was limited in its ability to handle multiple infeasible segments within a single route sequence. It was designed to manage only the first infeasible segment it encountered in a sequence; any additional infeasible segments were not addressed. As a result, the GSM could not achieve 100% feasibility across most cased, due to this limitation in the GSM itself.

Key recommendations

Based on the results and conclusion from the research, the key recommendations are listed below:

- Invest in trucks having at least a battery capacity of 600 kWh, as these trucks have a driving range aligning well with the typical distances driven in the DHL middle-mile network.
- Focus on implementing 150 kW charging stations, as this level meets the greatest part of the operational needs without incurring unnecessary higher costs incurred for higher capacity chargers.
- In the DHL middle-mile network, start the transition to electric trucks at the Region Hubs in **H, I**, and **B**. Importantly, ensure that at least two hubs are equipped with a charger such that not only routes that are feasible on a single charge can be electrically driven.
- In the future, implement the priority charger assignment policy to enhance route feasibility, especially important for scenarios where multiple trucks arrive simultaneously at charging stations.
- If a truck is connected to a charging station but cannot achieve the required SoC to reach the next location within the scheduled (un)loading time or break time, extend the recharge duration at the current location, such that unnecessary detours are avoided.

Preface

Dear reader,

You are about to read the master thesis titled *'Electrification of DHL's BeNeLux middle mile transportation process.'* This research was conducted at DHL eCommerce, specifically at the headquarters in Utrecht and the Region Hub in Hengelo. It serves as the final assignment for my master's in industrial engineering and management at the University of Twente.

My journey within DHL eCommerce began in 2020 when I took on the role of a delivery driver at one of DHL's City Hubs. This hands-on job allowed me to gain valuable experience in the last-mile operations of DHL, giving me an advantage as I was already familiar with the organisation. However, stepping into the headquarters in Utrecht and focusing on middle-mile operations enabled me to discover even more layers of the company.

During my time as a delivery driver, I witnessed firsthand the pros and cons of the transition from diesel vans to electric vehicles. One notable experience was helping a colleague who had to switch vans due to insufficient range to complete his delivery tasks. This experience enlarged my understanding of the concerns that truck drivers face during this transition. As a result of my own practical experiences, I am grateful to have played a part in the initial steps toward integrating electric trucks into the middle-mile network of DHL eCommerce. This involvement has given me a sense of purpose and fulfillment, knowing that my work can truly make a first impact in this transition.

In January 2025, a consortium, named EnerLogix was established, bringing together the University of Twente and TU Eindhoven with six major logistics service providers, including DHL. Each of these logistics companies operates distinct networks and faces unique challenges in electrifying their operations. The primary objective of this project is to foster mutual learning among the participants, facilitating the exchange of knowledge and best practices. As part of this initiative, master's students from both universities will engage with the six companies to tackle specific challenges related to electrification in transportation. My project, which started in October 2024, positions me as the first student who contributes in this way to the consortium. Hopefully, lots of other students will follow, who will undoubtedly provide the consortium with more and more valuable insights.

Finally, I would like to thank several individuals who have played a significant role in my research journey. First, I want to thank , the owner of City Hub Raalte, for getting me in touch with the DHL headquarters. I am also grateful to Renz Bassant for his dedicated guidance and support throughout the process. Special thanks go to Wim Tekkelenburg, Supervisor of Operations at Region Hub Hengelo, for our brainstorming sessions and for arranging an electric demo truck on two occasions. The latter enabled me to gain some real-life insights, which are included in this report. Undoubtedly, I also thank my supervisor from the University of Twente, Martijn Mes, for his help and patience Throughout the process, he consistently challenged me to bring this thesis to a higher level. Additionally, I would like to sincerely thank Stephan Meisel for kindly taking on the role of second supervisor.

Now, all that is left is to wish you an enjoyable time reading this research!

Stan Smit

Raalte, May 2025

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List of Abbreviations

AC	Alternating Current
B2B	Business To Business
B2C	Business To Customer
BEV	Battery Electric Vehicle
BNL	BeNeLux
C	Customer (in GSM)
CH	Central Hub
CO_2	Carbon dioxide
DC	Direct Current (charging)
DC	Distribution Centre (in GSM)
DHL	Adrian Dalsey, Larry Hillblom, and Robert Lynn
DP	Deutsche Post
EM	Evaluation Method
EV	Electric Vehicle
EVRP	Electric Vehicle Routing Problems
FCEV	Fuel Cell Electric Vehicle
FCFS	First-Come, First-Served
GSM	Generic Solution Method
HVO100	100% Hydrotreated Vegetable Oil
ILP	Integer Linear Programming
kVa	Kilo-Voltampere
kW	Kilowatt
kWh	Kilowatt-hour
LB	Lower Bound
LCFS	Last-Come, First-Served
LNS	Large Neighbourhood Search
OEM	Original Equipment Manufacturer
MT	Megaton (mass unity)
PUD	Pick-Up and Delivery
RH	Region Hub
RL	Reachable Location
RQ	Research question
TSP	Travelling Salesman Problem
TW	Time Windows
VRP	Vehicle Routing Problem
UB	Upper Bound

1 Introduction

This chapter introduces the reasons for executing the research as well as its design. Section 1.1 provides the organization's background. After that, Section 1.2 defines the problem and the motivation for the research, while 1.3 addresses the research design. In the final subsection of this chapter, a conclusion is provided.

1.1 About DHL and DHL E-Commerce[1]

Back in 1969, Adrian Dalsey, Larry Hillblom, and Robert Lynn founded DHL, which initially focused on delivering documents between American cities of San Fransico and Honolulu. Through the years, the company expanded its operations worldwide, becoming one of the leaders in express shipping industry. DHL Group, which is a global logistics and supply chain company that specializes in international shipping, courier services, and transportation, operates in more than 220 countries worldwide. The organization has an international network of hubs, warehouses, and delivery centres which allows the company to offer international shipping solutions.

Actually, DHL Group exists of two brands, namely DHL and Deutsche Post. The latter is the largest postal service provider in Europe and the market leader in the German mail market. Next to that, DHL offers a comprehensive range of parcel, express, freight transport and supply chain management services, as well as e-commerce logistics solutions. In fact, as mentioned earlier, DHL Group exists of five divisions, which are outlined and briefly explained below.

Figure 1) Overview of the five divisions of DHL

EXPRESS	Time-sensitive transport of urgent documents and goods, primarily as time-definite international shipments.
GLOBAL FORWARDING, FREIGHT	International freight forwarding services for air, ocean and overland, offering both standardized transportation and multimodal, sector-specific solutions, together with customized industrial projects and customs services.
SUPPLY CHAIN	Customized logistics services and supply chain solutions built on globally standardized modules such as warehousing, transport and value-added services.
E-COMMERCE	Domestic parcel transportation services in selected countries across Europe, the USA and Asia. Deferred cross-border are also available to, from, and within Europe, as well as to from the United States
POST & PARCEL GERMANY	Transporting, sorting, and delivering documents and goods in Germany and export to the rest of the world.

The next two subsection provide background on DHL's eCommerce division in the BeNeLux. Subsection 1.1.1 describes the organizational structure, while Subsection 1.1.2 illustrates the journey of a parcel through the DHL eCommerce network.

[1] For clarity and readability, please note that throughout the rest of this thesis, the term "DHL" specifically refers to DHL eCommerce BeNeLux. In case any other DHL division is being referenced, this will explicitly be mentioned.

1.1.1 About DHL eCommerce

As this Master Thesis is written on behalf of DHL eCommerce Benelux, the Benelux (BNL) part of this division is explained in more detail than the other divisions. Globally, DHL has as core businesses the domestic parcel transport in Europe, the United States and in multiple countries in Asia, and the deferred cross-border services within and between both the United States and Europe, and especially the different domestic networks in Europe.

DHL provides deferred domestic parcel delivery services via both their own as partner networks, while serving Business-to-Customer (B2C) as well as Business-to-Business (B2B) customers across all sectors. In order to meet expectations for speed, reliability, price, and sustainability, 28.500 vehicles and 42.000 employees are involved.

Below, Figure 2 presents some key insights into DHL's transportation network. Currently, the BNL network of DHL consist of four Central Hubs and twenty Region Hubs, with a fifth Central Hub being under construction in Zwolle. Additionally, the Dutch network includes 132 last-mile City Hubs. The main distinction between Central and Region Hubs lies in their function: Central Hubs operate continuously to sort parcels, while Region Hubs serve as transhipment points for goods. Within this network, especially Region Hubs supply parcels to the City Hubs, which are strategically located near the parcels' final destinations, which allows DHL to maintain short and efficient delivery routes.

As shown in Figure 2, the network in Belgium and Luxembourg only consists of Region Hubs, with no last-mile City Hubs or ServicePoints being present. This is because DHL has outsourced its last-mile operations to Bpost in these countries, resulting in the absence of city hubs and service points.

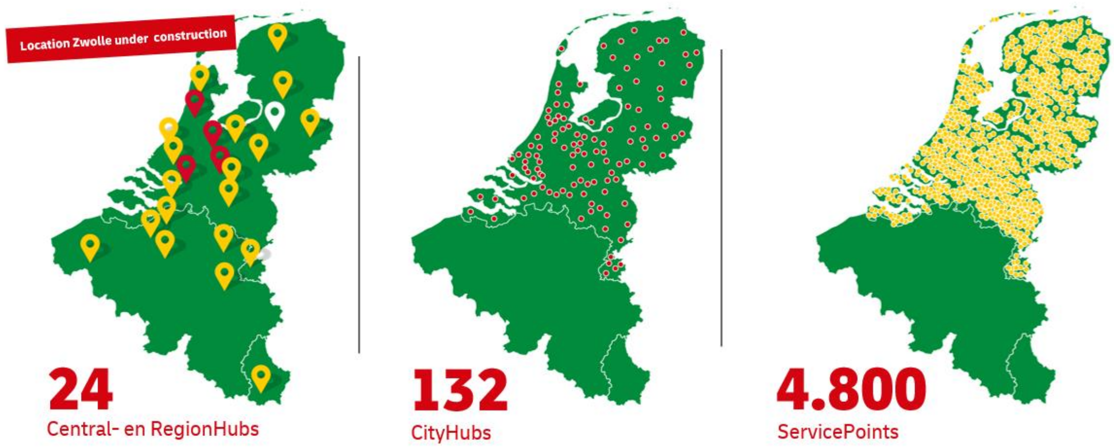

Figure 2) Overview of all DHL hubs in the BeNeLux

1.1.2 Journey of a parcel through DHL's network

The diagram in Figure 3 provides a general outline of a parcel's journey through DHL's network before it reaches a ServicePoint or its final destination. As visible, the line haul is used to transport goods from central or region hubs to City Hubs or other Region Hubs. Large order quantities, for example for B2B, are transported via the line haul directly to the delivery address using a box truck or trailer, while smaller orders, such as for B2C, are commonly transported to the final destination via one of the City Hubs. From there, delivery drivers in vans take those parcels to a ServicePoint or final address.

Figure 3) Journey of a parcel through DHL's transportation network

1.2 Problem description

This section explores the challenges and motivations for decarbonization of DHL's middle mile process. Subsection 1.2.1. discusses the research motivation, emphasizing the global pressure and EU obligations driving the need to reduce emissions. Subsection 1.2.2 presents the problem statement, while Subsection 1.2.3 delves deeper into the net congestion problem, which makes the decarbonization process more complex.

1.2.1 Research motivation

The global pressure to eliminate carbon emissions is increasing. Back in 2015, the European Union (EU), on behalf of the Netherlands as well, signed the Paris Climate Agreement. This agreement has a goal to limit global average temperature to well less than 2° Celsius, with a clear aim of staying at 1.5° Celsius (UNFCCC, 2016).This agreement outlines various commitments that have been established between EU members states, in order to achieve the goals, set in the Paris Climate Agreement. Those states have agreed that by 2030, the EU must reduce emissions by at least 55%. Further, by 2050, the EU aims to be climate-neutral, meaning that net greenhouse gas emissions have to be equal to zero.

The above mentioned forces organizations to adapt their business operations accordingly. As a result, the logistic sector finds itself at a crossroads in the transition towards more sustainable processes. As a member of the EU, the Netherlands is also bounded by the Paris Climate agreement, requiring all sectors to contribute to emissions reduction. Consequently, DHL must invest in making its processes more sustainable to remain operational and competitive in the future. According to the Dutch Climate Agreement's chapter on mobility, the logistics sector has until 2030 to achieve a 30% reduction in CO2 emissions. Subsequently, the goal is to eliminate carbon emissions, by establishing zero-emission as the norm, by 2050 (TNO, 2019). Currently, electrification of transport is seen as one of the workable routes towards decarbonization.

In recent years, DHL has already made significant progress, electrifying the greatest part of the own last-mile fleet (excluding service partners) (Bassant, 2024). However, the electrification of the middle mile transport sees significant challenges. One of the main obstacles is that the Dutch electricity grid is already operating near its capacity. Upgrading capacity contracts for each hub is difficult, and expanding the capacity of the Dutch electricity net is expected to be a long-lasting process (Pató, 2024). As a result, there merely exists possibilities to expand contracted grid capacities soon.

DHL prefers electric trucks over other alternatives to decarbonize their middle mile process, primarily because there is currently no hydrogen infrastructure in the Netherlands, making hydrogen-powered trucks difficult to implement. In contrast, a charging infrastructure for electric trucks already exists. Besides, according to Nijenhuis (2025), electric trucks emit significantly less CO_2 over their entire lifespan compared to diesel trucks, despite having higher emissions during production. This is because eTrucks are much more energy-efficient while driving and rely on electricity, which often has a lower CO_2 emission per kWh than burning diesel. As an example, he describes that a diesel truck consumers 25 liters per 100 km and emits about 81.4 kg of CO_2, while an eTruck using 121.5 kWh per 100 km emits only 24.4 kg of CO_2 in the Netherlands. In countries with a cleaner energy mix, such as France (only 2.1 kg CO_2 per 100 km), the difference is even greater. Although producing an eTruck (72,500 kg CO_2) results in more emissions than a diesel truck (27,500 kg CO_2), this gap is closed after just tens of thousands of kilometers. Over the lifetime of a truck, total emissions from an eTruck are lower, especially as electricity continues to become greener.

Given that a great part of the last mile fleet is already electric, and that real estate operations require a part of the available energy, hubs are consuming already a large portion of their contracted grid supply. The figure below provides a rough indication of the impact on energy consumption when electric box trucks (yellow) and electric trucks are incorporated to DHL's operations. Note that this situation varies across hubs, since not all hubs have the same quantity of energy available.

Figure 4) Energy consumption versus contracted grid capacities for adding different EVs

Additionally, future electricity market prices are expected to fluctuate even further depending on time and location, which will complicate energy management even more. At the moment, there is a lack of existing integrated solutions for energy and logistics planning. Several uncertainties make it difficult to validate and implement such solutions, for example:

- The uncertain future development of electric truck technology and its market adoption
- The complex and uncertain dynamics of daily energy management and logistics planning
- The large investments required (investment costs versus operational costs)

For the above-mentioned reasons, and to remain operative, competitive, and especially sustainable, on the way to 2050, DHL is seeking efficient energy management solutions that can deal with network congestion. Further, DHL opts to gradually increment the number of eTrucks within its middle mile network, starting with at least **XX** eTrucks at the end of 2025.

1.2.2 Core problem and action problem

As mentioned in the previous subsection, the core problem follows from the goal of achieving zero net-emissions by 2050. From this EU goal, which is discussed in more detail in the previous subsection, the core problem for this research can be derived. Despite DHL's ongoing investments in greening their processes, DHL Group currently emits 40 million MT CO_2 globally (DHL Group, n.d.). Within this total, DHL eCommerce BNL contributes **XX** of CO_2 emissions. In 2021, this number stood at **XX**, with a target to reduce it to **XX** by 2030, and to achieve full decarbonization by 2050. Therefore, the core problem, specific to this research, can be defined as:

DHL eCommerce BNL currently emits **XX** Carbon, which must be eliminated by 2050 due to climate change goals. In 2030, this must be reduced by 30% to **XX**.

The previous subsection addressed challenges associated with implementing electric trucks in DHL's operations. If these problems are combined, the action problem can be defined as:

Currently, there is a lack of information on how, when and where electric trucks can be charged within DHL's transportation network

1.2.2 Problem identification

To understand the problem, it is important to find the different underlying (core) problem(s) in the problem context. For this, a problem cluster is created, which visualizes the connections between the different problems in the context. In this cluster, both the core and action problem from previous subsections are incorporated.

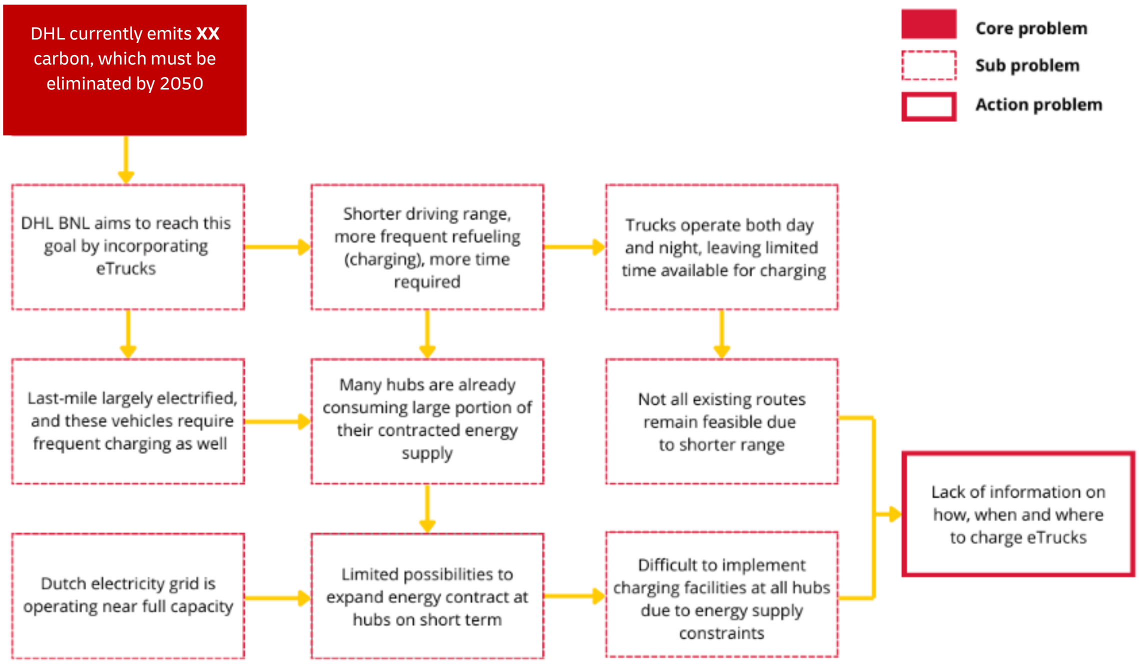

Figure 5) Problem cluster

In Figure 5, the core problem identified is that DHL currently emits **XX** of carbon annually, which must be eliminated by 2050 to meet climate change targets. As mentioned before, research focuses on exploring the implementation of electric trucks in DHL's middle mile operations to help meeting these targets. However, the shift to electric trucks introduces multiple new challenges. The first subproblem arises from the limited driving range of electric trucks and the need for more frequent charging than a diesel truck that can be refuelled easily. Next to this, charging an electric truck typically takes more time than refuelling a diesel truck . Additionally, as trucks operate continuously both during day and night, the time available for charging is limited. Consequently, existing routes may no longer be feasible due to the range limitations of electric trucks.

A related subproblem is that DHL's last mile delivery process has already seen significant developments in electrification, with electric vans requiring charging as well. This creates additional demand on hubs' daily energy consumption. Note that the latter only holds for Region Hubs that have a City Hub inhouse. Many hubs are already using a large portion of their contracted grid supplies, and with the Dutch electricity grid operating near full capacity, which is explained in more detail in next subsection, there are limited possibilities to increase grid capacity in the short term. This situation complicates integrating charging facilities at all hubs due to these energy supply constraints.

Finally, the combination of these subproblems leads to the action problem, which is the current lack of information on how, when, and where to charge electric trucks within DHL's middle mile operations. Addressing this is important to ensure the successful integration of electric trucks into the company's logistics network, while meeting both operational and environmental goals.

1.2.3 Net congestion

In the Netherlands, companies' energy usage is capped by energy contracts, which specify the maximum amount of energy a company can consume at a given location. This system is described in more detail in Section 2.4. Ideally, a DHL hub would be able to draw as much energy as possible. However, due to the nature of energy contract, this is not feasible, as they determine the maximum energy amount a consumer is allowed to draw from the grid.

At the moment, the Dutch electricity grid is operating near full capacity. In the Figure 6 on the right, this is visualized by the red and orange colours. This network congestion leaves limited possibilities for expanding energy contracts in the coming years. This is a result of the rapidly growing demand for electricity, which in turn is a consequence of the energy transition which is currently going on. To address this, Dutch grid operators are making significant investment to expand the grid. For this, the annual expenses are expected to be €8 billion, starting in 2025. During this transition, the government is committed to ensure that sufficient space is available for these expansions. Additionally, it aims to speed up the approval process for grid expansion projects to accelerate the overall progress (Rijksoverheid, 2024).

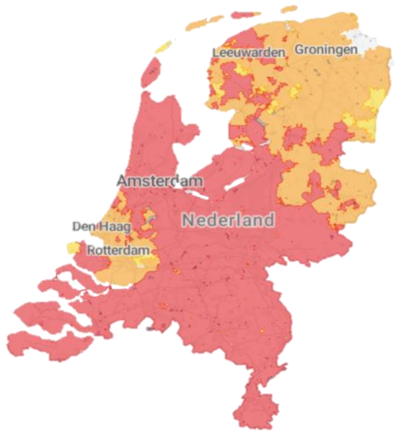

Figure 6) Dutch grid faces congestion

This phenomenon has as impact on this thesis that it ensures that reaching a decarbonized middle mile process becomes a way more difficult, especially for the first coming years, as on the short term no sufficient grid upgrades are expected. Therefore, it is not possible to just install charging stations at hubs and easily start the transition to an electrified middle mile transportation network.

1.3 Research design

This section presents the research design. Subsection 1.3.1 outlines the research objectives, followed by the research question and approach in Subsection 1.3.2. Finally, Subsection 1.3.3 defines the scope of the research.

1.3.1 Research objectives

As described earlier, this research specifically focuses on DHL's middle mile transportation process, in which electrification of trucks is seen as most feasible option. This research aims to assess the feasibility of integrating electric truck into DHL's operations by analyzing current battery technologies, charging speeds, and operational requirements. The first objective is to evaluate the extent to which DHL can electrify its middle mile fleet within a year, identifying specific routes and hubs that would be suitable for to start the transition to an electric driven middle mile network, while accounting for current grid capacities at hubs. Consequently, the research objective is formulated as follows:

Provide an evaluation method which evaluates the feasibility of electrifying current DHL middle mile routes and provide recommendations on which routes and hubs are suitable for electric truck implementation.

However, in a real-world scenario, trucks arrive simultaneously at locations. The second objective focuses on developing recommendations for optimizing charging allocations, particularly in scenarios where multiple electric trucks may arrive simultaneously at hubs. This includes examining the implication of limited charging infrastructure and the impact of simultaneous truck arrivals.

Provide a comprehensive method outlining decisions for electric trucks on where to charge in the network, including solutions for managing simultaneous demand for the same charging stations and maximize route feasibility

1.3.2 Research questions & approach

From the objective provided in previous subsection, the main research question can be derived. This research question includes both goals, as for the integration of electric trucks both short term and long term goals have to be considered. Below, the main research question is presented:

How to evaluate the suitability of the DHL middle mile network for electrification and how to optimize the integration of electric trucks in this transportation network?

Below, the research questions, including the sub research question, relevant to this research are presented. First, it is necessary to map the current situation. In this way, a baseline is created on which the rest of the thesis can be further expanded.

Chapter 2 | Current Situation and process analysis

RQ 1 **What is the current situation at DHL regarding the middle mile process, and what data regarding electrification is currently available?**

- (1.1) How is the transportation network currently designed?
- (1.2) What does the middle mile fleet (including transportation partners) look like at the moment?
- (1.3) To what extent are charging facilities for electric vehicles currently available at all Central and Region Hubs?
- (1.4) How much energy is currently contracted per hub and what is the current connection power per hub?
- (1.5) What do the routes in the BNL network currently look like?
- (1.6) Which electric trucks are currently available on the Dutch market?
- (1.7) What is currently possible with an electric truck within DHL's network?

In order to answer this research question and its sub questions, (DHL) data has to be obtained and analysed. Further, a test pilot will be done at the Region Hub in Hengelo with an electric truck, in order to gather real life data of allocating electric trucks on both PUD routes and night routes. This will be explained more in depth in Section 2.7.

Chapter 3 | Literature review

RQ 2 **What does literature tell us regarding implementing electric vehicles in transportation problems?**

- (2.1) Which factors influence the implementation of electric trucks in a transportation network?
- (2.2) In what way the net congestion problem can be solved and what measures can be taken to enlarge energy capacity or to effectively use the available capacity?
- (2.3) What kind of (electric) vehicle routings problems, similar to DHL's, do currently exist?

For the second research question, literature will be consulted, with a focus on factors that impact the driving range of an electric truck, as well as challenged that are commonly encountered during the integration of electric trucks in a transportation network. Throughout this chapter, relevant studies are reviewed, which highlight the challenges identified and propose solutions to address these issues.

Chapter 4 | Solution Method

RQ 3 **How could models be used and developed to evaluate whether a route can be electrified and how to maximize the number of routes that can be electrified in a transportation network?**

- (3.1) Which data and parameters that are available are associated with electrifying routes?
- (3.2) In which way a model can be used to evaluates the feasibility of electrifying current BNL routes?
- (3.3) Which hubs and which routes are the most interesting to electrify on the short term (within a year)?
- (3.4) What optimizations can be done to maximize the number of routes that can be electrified?
- (3.5) How does an optimization model for maximizing the number of routes that can be electrified look like?

To address this third research question, findings from literature and practice will be integrated with quantitative modelling, data analysis, and evaluation and optimization techniques to create both an EM that evaluates DHL routes and a General Solution Method (GSM), which is able to manage trucks that demand for a charging station at the same time at a hub. The EM will be used and slightly modified to gain understanding in which type of trucks and which type of charging stations are suitable for DHL's BNL network. Beside this, the EM will be used to determine which hubs should be qualified for the first implementation of electric trucks and charging stations.

To solve the formulated problem for the GSM, algorithms or heuristics identified from the literature will be considered. A comparison of potential solving techniques will be conducted, after which the best-fit algorithm or heuristic will be used, depending on the complexity of the problem, the size of the data set, and computational feasibility.

Chapter 5 | Results

RQ 4 **What performance can be expected of the implementation of electric trucks in DHL's middle mile network?**

- (4.1) What is possible within current borders of energy capacity management at the hubs?
- (4.2) What current routes remain possible to drive with electric trucks, and which do not?
- (4.3) What is the effect of charging power and battery capacity on feasibility of routes?
- (4.4) What is the effect of maximizing the feasibility of routes?

To evaluate the performance expected from the implementation of electric trucks in DHL's middle mile network, a systemic approach will be adopted. In this approach, a quantitative data analysis with practical insights derived from the developed model and real-world operations will be integrated.

Chapter 6 | Implementation

RQ 5 **How to implement electric trucks in DHL's middle mile operations?**

- (5.1) How does the route to the integration of the first electric truck look like?
- (5.2) How to use the delivered method to increase the number of electric trucks in the network step-by-step?

To deal with the ultimate research question, an advice will be created to address the implementation of electric trucks in DHL's middle-mile operations. For this, a structured and phased approach will be taken in order to ensure that the transition to electric trucks is effective, sustainable, and aligned with DHL's operational and tactical objectives.

1.3.3 Research scope

To comply with 2050 sustainability goals, DHL is exploring multiple decarbonization options, including using renewable energy, solar panels, heat pumps, and external battery storage for its real estate. DHL has also invested heavily in electrifying its last-mile process. However, this research focuses specifically on DHL's middle mile transport, as outlined below.

- Middle Mile Process Only

The analysis will exclusively cover DHL's middle mile transport operation, which means that the first- and last-mile processes are excluded. This is since the last mile is already electrified for the greatest part. Next to that, focusing on the middle mile only ensures a broad enough research field.

- DHL BeNeLux Transportation Network

Geographically, the focus is on all movements between all Central, Region and City Hubs is limited to the Benelux. Transportation movements to locations outside the BNL are excluded, as well as movements to other parties within the Benelux.

- Battery Electric Vehicles

In the long term, DHLS sees Battery Electric Vehicles (BEVs) as the most realistic solution for fully eliminating carbon emissions from its fleet. While there are various alternatives, such as Hybrid Electric

Vehicles (HEVs) and Hydrogenated Vegetable Oil (HVO100), this study is focused on BEVs only. HEVs can reduce emissions, but they still rely on fossil fuels, which conflicts with DHL's commitment to achieving net zero emissions by 2050. Additionally, hybrid electric trucks are merely available. Further, HVO100 can be considered as an interim solution, but since the focus is on decarbonizing, BEVs is a much more practical choice. Additionally, Fuel Cell Electric Vehicles (FCEVs) offer a zero-emission alternative. However, the lack of green hydrogen, high costs, inefficiencies, and the lack of supporting infrastructure in The Netherlands, make them less practical than BEVs. The relatively short distances in the Netherlands, and the density of DHL's logistics network, further support the viability of BEVs as a solution. Given the strategic focus on decarbonization and the available research time, this study will exclusively concentrate on the integration of BEVs into the middle-mile logistics process.

- Contracted Grid Capacity & Net Congestion

In this research, the effects of contracted grid capacity, particularly the limited possibilities to expand energy contracts due to network congestion in the energy grid, will be research. Solutions will focus on the alternatives to expand the energy capacity.

- Impact on Routes

Further, the study will explore how electrification impacts transportation routes and logistics planning, especially in terms of vehicle range, charging time, charging infrastructure, and scheduling constraints.

- Sub-Contractors

Since a great part of the movements between the different Central hubs and Region hubs is outsourced to sub-contractors, these partners play a crucial role in the middle-mile transport network. Therefore, these subcontractors need to be considered as well in the route to full electrification of the middle mile transportation process of DHL. In the Generic Solution Method, discussed in Chapter 4, a homogenous fleet of trucks is considered, such that there does not exist any difference between own trucks and subcontractor trucks.

- Short & Long Term (Operational vs Tactical)

This research will address both the operational and tactical aspects of the electrification of a logistics network. Specifically, for the DHL middle-mile network only the short term will be handled, as DHL just want to know how, and at which hubs in its network, the first electric trucks can be implemented. To provide a more tactical view on the problem, another model will be used to explore the difficulties of electrifying a complete fleet in a transportation network. For this model, no difference between own trucks and sub-contractor trucks is made, such a homogeneous fleet is considered.

1.4 Conclusion

This first chapter has introduced DHL's organization structure and its goal to decarbonize their processes, and specific to this thesis, the need to decarbonize the middle mile transportation process. It turned out that the complexity of reducing CO_2 emissions is significantly increased by the existence of net congestion in the Netherlands, which causes challenges in accommodating charging stations at hubs.

The action problem for this research is the current lack of comprehensive information regarding when, where and how to charge eTrucks effectively within DHL's network. To tackle this, two primary research objectives have been established.

The first research objective involves assessing the feasibility of integrating electric trucks into DHL BNL specific routes by analyzing current battery technologies, charging speeds, and operational requirements. This includes evaluating the extent to which DHL can electrify its middle mile fleet, identifying specific routes and hubs that would be suitable for initiating the transition to an electric-driven middle mile network, while accounting for current grid capacities at hubs.

The second objective focuses on developing recommendations for optimizing charging allocations in real-world scenarios where multiple electric trucks could need the same charging station simultaneously at hubs. In such cases, only one truck can charge. As a results, this objective involves the creation of a method which examines the implications of limited charging infrastructure at hubs.

2 Current process and data description

To create a solid foundation for the research, this chapter provides an overview of DHL's current operations and their progress toward electrification of their processes. Section 2.1 outlines the current design of DHL's transportation network, followed by section 2.2, which discusses the status of decarbonizing the Dutch fleet. Section 2.3 describes the current presence of charging facilities at DHL hubs, while Section 2.4 focuses on the available electric infrastructure at middle-mile hubs in the DHL network. Section 2.5 presents the current design of BNL routes, and Section 2.6 examines the electric trucks currently available on the Dutch market. Section 2.7 highlights a pilot project conducted at the Region Hub in Hengelo and its relevance to this thesis. Finally, Section 2.8 summarizes the key insights of this chapter. Below, the research question guiding this chapter is repeated for clarity.

What is the current situation at DHL regarding the middle mile process, and what data regarding electrification is currently available?

2.1 Current design of DHL's transportation network

As given in Figure 2 in Section 1.1, the transportation network of DHL exists of four Central Hubs and twenty Region Hubs within the BeNeLux, together with 132 City Hubs and 4.500 Service Points in The Netherlands. Below, the function of each kind of hub or point is briefly addressed.

In DHL's logistics network, Central Hubs only focus on sorting operations, while Region Hubs manage both sorting and the arrival and departure of cargo to and from customers. Region hubs also transport goods to City Hubs, which are located close to the final destinations. City Hubs play a crucial role in handling the last-mile delivery of small goods. From these hubs, these good are distributed directly to customers or to service points, where customers can pick up their parcels. This system ensures that deliveries are efficiently managed from larger hubs to the final delivery points, optimizing the flow of goods across different regions.

Subsection 2.1.1 explains the processes at Central Hubs, Subsection 2.1.2 covers those at Region Hubs, and Subsection 2.1.3 focuses on the processes at City Hubs.

2.1.1 Processes around Central Hubs

In 2019, DHL opened the largest sorting center in the Netherlands, located in Zaltbommel. This facility serves as a key Central Hub, processing both domestic and international shipments, which are then distributed to all other Region Hubs and City Hubs across the country. The hub is equipped with a double cross belt sorter, which has a total length of 910 meters and featuring 2.600 parcel positions. This sorting system can handle up to 40.000 parcels per hour, which allows a daily capacity of 500.000 parcels. Its primary function is to streamline sorting operations and facilitate parcel distribution over the other hubs. On daily basis, approximately eight hundred trucks depart from only Zaltbommel (LogistiekProfs, 2018).

2.1.2 Processes around Region Hubs

As this research is scoped on the middle mile process, it is essential to outline the working of the processes at the Region Hubs as well as the transportation movements between these hubs. Each Region Hub can be used for inbound sorting, outbound sorting, or both. For example, the Region Hub in Hengelo handles both. At night, trucks from other Region Hubs arrive in Hengelo to deliver goods destinated for the surrounding area. Once all trucks have arrived and their cargo is unloaded, the inbound sorting process begins. After sorting, drivers distribute the goods to various locations across the 'Twente' and 'Achterhoek' regions.

After completing delivery activities, drivers start picking up goods from different locations throughout the region. Once all drivers have returned to the Hengelo hub with their collected goods, the outbound sorting process begins. The goods are then sorted by destinated regions. During the night, these shipments are transported to other region hubs, which completes the daily cycle of this process. Below, this process is visualized in Figure 7. The combination of distributing and picking up goods across the region is called the Pick-up and Delivery process (PUD).

In contrast to the Region Hub in Hengelo, some other hubs are only used for inbound or outbound sorting. If a hub is used only for inbound sorting, it supplies the surrounding area, but the outbound sorting is handled by a different hub. Similarly, a hub might focus exclusively on outbound sorting, with inbound sorting managed elsewhere.

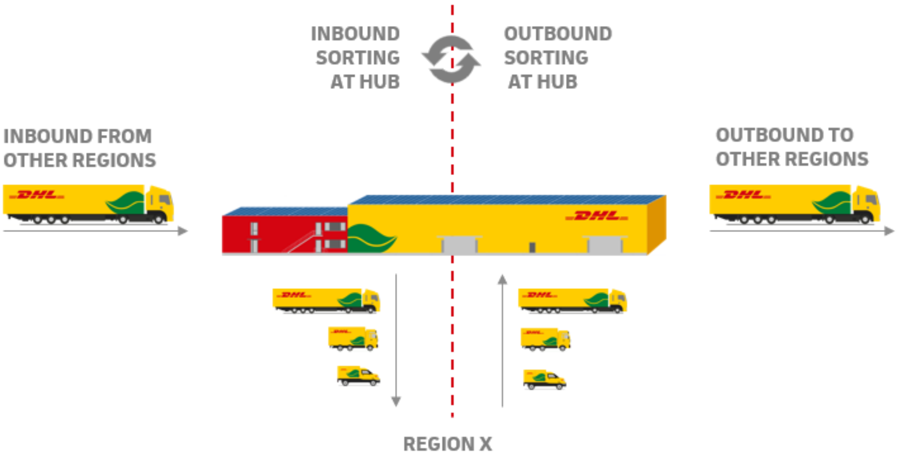

Figure 7) Visualization of inbound and outbound sorting at hubs

2.1.3 Processes around City Hubs

In the hub structure of DHL, City Hubs serve as the final sorting and departure point in the "region x" segment of Figure 7. Each day, these hubs receive goods from Central Hubs or Regional Hubs via trucks or box trucks, with each City Hub being located close to the final delivery destinations. This proximity enables DHL to maintain high standards for sustainability and delivery performance.

Typically, goods arrive at City Hubs in two waves: early morning and afternoon. This schedule supports a workflow with both day and evening shift. At some hubs, a third wave allows same-day delivery, further enhancing service responsiveness. The process includes a middle-mile operation, which covers the transportation of goods both inbound from Region Hubs to City Hubs and outbound back to the Region Hubs. This middle-mile structure ensures efficient movement of goods, optimizing both the time and environmental impact of deliveries.

2.2 Current status of decarbonizing the complete Dutch DHL fleet

DHL's transportations movements in the first mile, middle mile, and last mile are carried out using both its own fleet of vehicles and subcontractors. While DHL has made significant progress in electrifying its own fleet, as detailed in Subsection 2.2.1, this does not automatically extend to sub-contractor vehicles. Further information on this aspect is provided in Subsection 2.2.2.

2.2.1 Electrification of own fleet

In recent years, DHL has made significant investments to reduce its carbon emissions, focusing on decarbonizing its real estate, and particularly its last-mile fleet. Currently, the last-mile fleet exists of **XX** electric vehicles (vans), which accounts for **XX**% of the total fleet. This makes DHL's e-fleet the largest in the Netherlands. This fleet is further supplemented by a smaller number of vehicles running on HVO biofuel, which is made of renewable sources, such as vegetable oils, animal fats, and waste oils. Using this biofuel instead of conventional fuel accounts for a CO_2 reduction of 90%. (DHL Group, 2024).

In addition to the **XX** electric vans, DHL has invested in **XX** electric box trucks, which are divided over **XX** Region Hubs. The allocation of these trucks is based on the high available energy capacity at these hubs compared to others, as explained in more detail in Section 2.4.

For middle-mile transport, which involves long-haul deliveries, all trucks currently run on diesel, while being in a transition to HVO100. This is viewed as an interim solution for decarbonizing this segment of the supply chain (DHL eCommerce, 2024). These transport operations are managed by both DHL-owned trucks as those of subcontractors. Currently, DHL has **XX** trucks under own management. In Appendix C this is outlined. As the fleet does not include any electric trailer trucks yet, this is not added to the table.

In the figure below, the current status as well as the actions taken to reach DHL eCommerce BNL goals – described in Subsection 1.2.1 - are indicated. Although the green line does not actually touch the x-axis, the green line is meant to indicate that between 2040 and 2050 all carbon emissions are removed and thus the actual emissions quantity equals zero. In 2025, this quantity is equal to **XX**, while it was equal to **XX** kT in 2021.

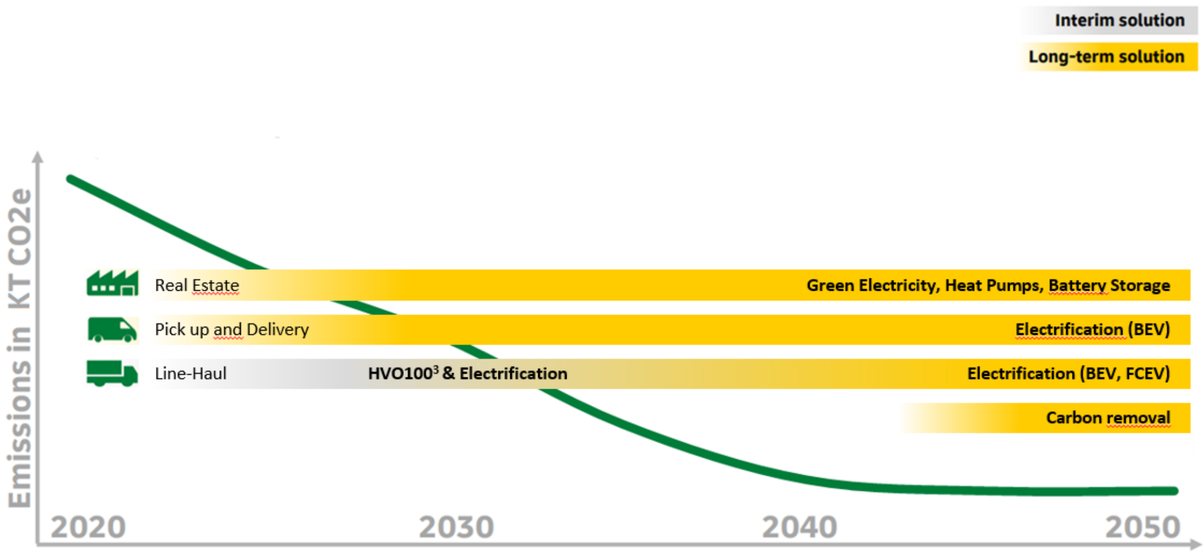

Figure 8) Current State of Electrification and Roadmap to 2050

2.2.2 Sub-contractors

As mentioned, in DHL's middle mile operations, transportation movements are handled both by its own fleet and by sub-contractors. The routes operated by these sub-contractors can vary significantly in complexity. For instance, a sub-contractor may be assigned a single-leg route, where they pick up cargo from a Region Hub and deliver it directly to a designated destination. After completing the delivery, the subcontractor leaves the DHL system, continuing performing activities for other companies during that day. Currently, no data is available on the electrification status of sub-contractors, as DHL works with a wide range of sub-contractors spread all over the BeNeLux.

However, subcontractors often work for multiple clients within the same day. In some cases, a subcontractor may complete a series of legs for DHL, then switch to performing deliveries for other companies, before returning to a DHL hub to manage new legs again. This flexible arrangement means that a subcontractor's schedule is not fully dedicated to DHL, as visualized below. This makes it difficult to mention the exact number of trucks operating exclusively for DHL at any given point in time.

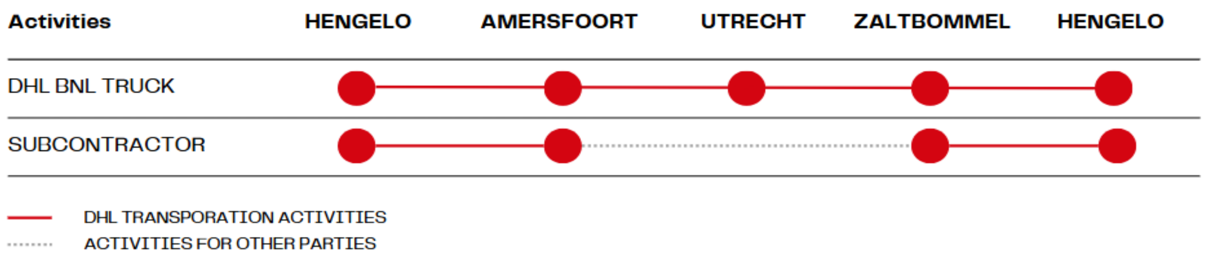

Figure 9) Route of a DHL Truck versus Route of a Sub-Contractor Truck

2.3 Current charging facilities at hubs

As discussed in the previous section, the middle-mile fleet currently includes **XX** electric box trucks. To remain operational, these trucks require access to appropriate charging facilities.

Currently, three types of charging stations are available at the designated hubs for both electric box trucks and electric vans. For the electric box trucks there are Direct Current (DC) stations capable of delivering up to 150 kilowatt (kW) per hour, as well as Alternating Current (AC) stations that can provide up to 43 kW per hour. Each electric van has access to a smaller AC station with a charging capacity of up to 11 kW per hour. This lower capacity is sufficient for vans, as they require less energy to fully charge their batteries. Currently, Region Hub Hengelo is the only hub equipped with a 150 kW DC charging station.

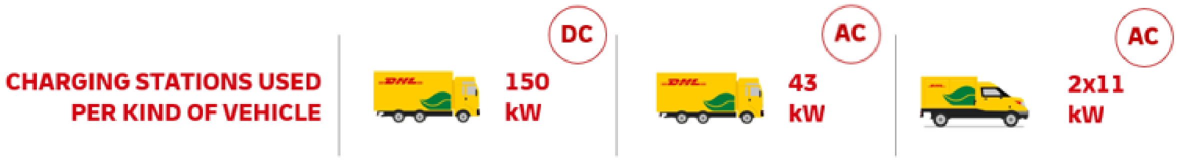

Figure 10) Available types of charging stations in DHL's network

The difference in charging speeds between Direct Current (DC) and Alternate Current (AC) stations comes from the nature of EV battery storage, which requires DC energy. While electric vehicles can be charged at AC stations, this requires the vehicles internal converter to transform AC into DC, allowing the battery to store the energy. This conversion process takes additional time compared to DC charging, where energy is stored directly in the battery, resulting in faster charging times (Saraswahti, 2024).

Typically, each DC station is equipped with two charging connections, allowing it to charge two vehicles simultaneously. When two vehicles are connected, the available energy can be split evenly, providing each vehicle with 75 kW per hour. However, DHL has access to smart technology that enables flexible energy distribution, allowing the station to allocate power unevenly based on the battery levels of the connected vehicles. This adaptive charging capability optimizes energy use, prioritizing vehicles that require faster charging.

Compared to the DC 150 kW charging station, the 2x11 kW charging station delivers a maximum of 11 kW per hour to each vehicle. If only one vehicle is connected to this station, it will still receive a maximum charging power of 11 kW, as the station's capacity is divided across the two 11 kW outputs. This limitation is primarily due to the cable specifications for buses, which are designed to manage a maximum of 11 kW. However, if a thicker cable is used, as is the case for eTrucks, the charging station could provide up to 22 kW to a single vehicle.

2.4 Current electric infrastructure at each hub in middle-mile network

Each hub must be connected to the electricity grid to access power and remain their sorting and delivery processes operational. This requires specific infrastructure, including electricity cables and a grid connection, measured in kilovolt ampere (kVa). Next to that, there is a difference between the amount of energy a hub uses, can use, and is allowed to obtain from the grid. Below, some key terms are defined to clarify these differences:

- Contracted Grid Capacity (kWh): maximum energy capacity a hub is authorized to draw from the grid, as agreed for a contract period with the energy provider.
- Used Energy Capacity (kW): actual amount of energy used by the hub during operations.
- Grid connection (kVA): physical infrastructure which links the hub to the electricity grid, determining the potential power supply.

It is important to highlight that the grid connection quantity is measured in kVA, while the other amounts are measured in kilowatt-hour (kWh) This distinction arises from the difference between apparent power and real power in electrical systems. In electricity theory, apparent power is measured in kVA. This measures the total electrical power supplied by the grid, regardless of how much of that power is actually used. For that reason, grid connections are measured in kVA, as in that way the total capacity available for the hub is defined. Next to this, the real power is measured in kW, which represents the actual power that is used to perform operations, such as, in case of this specific research, charging an electric vehicle. Therefore, the energy consumed by each hub is measured in kW (IEEA, 2010).

2.4.1 Contracted Grid Capacities at Hubs

Below, Figure 11 gives an overview of the current grid capacity (kWh) and the peak energy usages (kW) for each Dutch Central or Region Hub. As can be seen, most of the hubs consume the greatest part of their contracted grid capacity. Note that the hubs **B**, **H**, **I**, **N**, **O**, **P**, still have room left. Therefore, these hubs are potentially having the possibility to equip with a DC charging station.

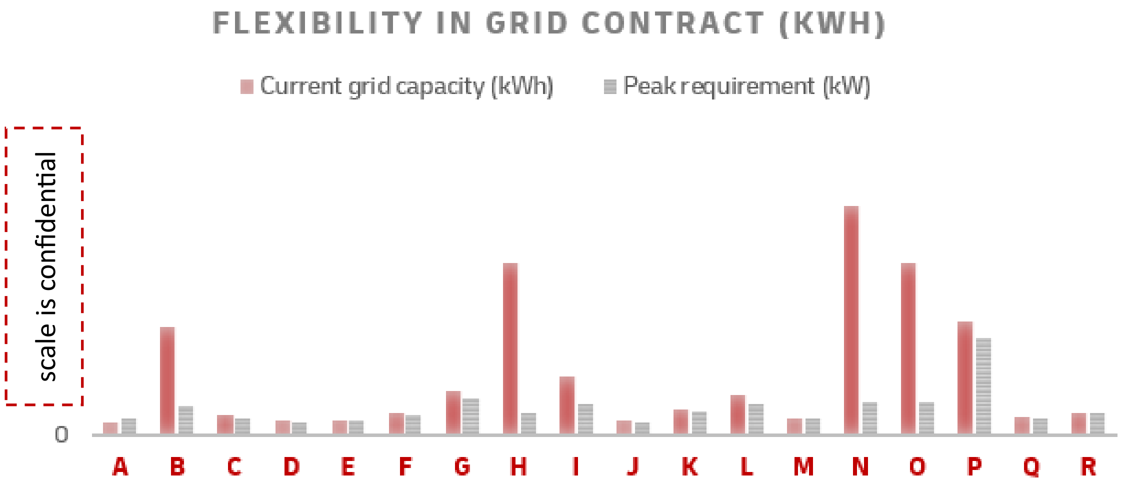

Figure 11) Contracted grid capacity versus peak requirements for Central and Region Hubs

2.4.2 Impact of grid connections on energy usage

As mentioned, grid connections are measured in kVA. To determine the maximum power in kW that can be transmitted through a connection, one can multiply the connection capacity by 0.8. This factor serves as a crucial consideration when deciding which DC charging stations to utilize. For DC charging of 150 kW, a connection of 175 kVA typically suffices. For higher DC charging rates, a bigger connection is necessary.

According to rates provided by Stedin, a Dutch grid operator, the construction costs for connections up to 175 kVA are approximately €6.800. For connections ranging from 175 kVA to 1000 kVA, the additional construction costs start at €20.000. Connections exceeding 1.000 kVA incur construction costs around €45.000, while those above 1.750 kVA can exceed €250.000. Additionally, there is periodic connection fee, which is around €126.000 for connections up to 175 kVA. However, for connections above 175 kVA, this fee can surpass one million euros (Stedin, 2025).

Further, according to rough indications given by Kempower (2025), a company which provide charging solutions, the costs for charging above 150 kW doubles the costs €40.000 to €80.000. This all together indicates that there is a substantial increase in costs associated with implementing DC charging above 150 kW. Consequently, determining the required charging power at hubs becomes a critical decision that must be carefully considered.

2.5 Current design of BNL routes

To provide a clearer understanding of the typical distances covered in the middle-mile network of DHL, an analysis was conducted using a histogram to visualize the distribution of route distances. This histogram categorizes the distances into predefined bins of 50 kilometers, allowing for an effective representation of the frequency and range of distances driven across 352 routes in the network. Later on, these same 352 routes are also used for an analysis on the feasibility of drive these routes with an electric truck instead of a diesel truck.

The figure below shows that over 50% of all routes fall within the 300 to 500 km range, indicating that these distances are typical for the BNL network. Additionally, it is important to highlight that there are no routes exceeding 700 kilometers. This information is crucial for assessing the feasibility of electrifying routes, as the driving range of electric truck plays an important role in determining the viability of implementing electric vehicles on specific routes.

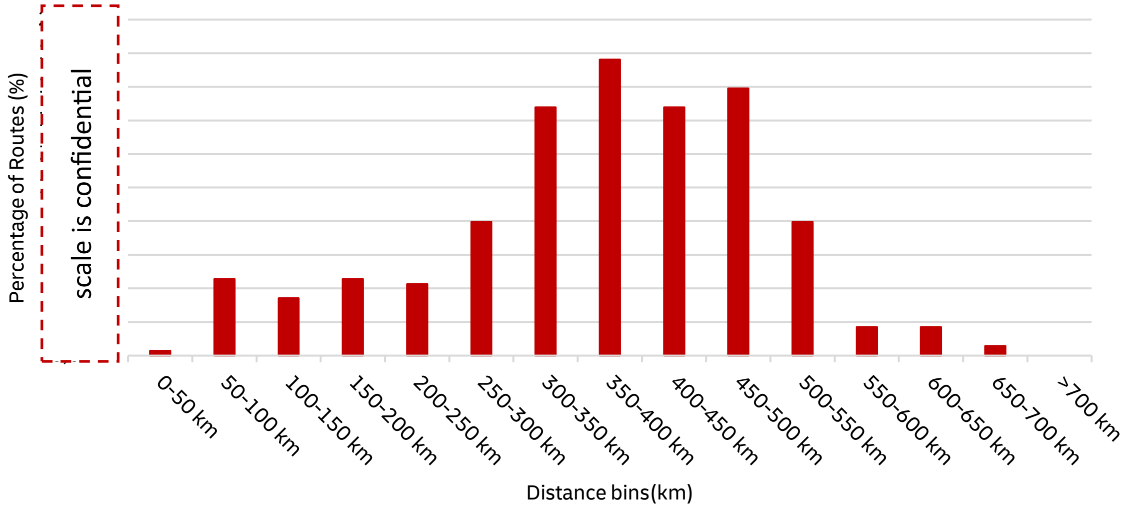

Figure 12) Overview of route distances in DHL BNL network

2.6 Current electric trucks on the Dutch Market

In the current landscape of the trucking industry, manufacturers are developing electric trucks to anticipate on the transition to zero emissions, which is driven by increasing customer demand for the electrification of their operations. This research focuses on three notable electric truck options from different suppliers: Renault, Volvo, and Mercedes.

The Renault truck has been used in an eTruck pilot, which aimed to assess the practical applications and benefits of electric trucks in real-world scenarios. This pilot, discussed in Section 2.7, provides valuable insight into the performance and efficiency of electric trucks in DHL's network.

While other manufacturers, such as DAF, also offer electric trucks, this research focuses on these three suppliers due to their availability and relevance to the research objectives. Both demo models of the Renault and Volvo trucks were temporary accessible from a regional truck rent company, allowing for direct comparison and evaluation. Further, the Mercedes eActros, is considered because of its 600 kWh battery capacity, accounting for a driving range of 500 kilometer. By comparing this higher range with the lower ranges of the Volvo FH Electric and the Renault e-Tech T, it is opted to draw meaningful conclusion about the suitability of each truck for various operational scenarios. This approach will enable a well-informed recommendation regarding which truck to implement in DHL BNL's logistics operations.

The results of this comparison, including insights from the Evaluation Method and the Generic Solution Method, will be discussed in Chapter 5. This analysis will ultimately facilitate a decision on the most appropriate electric truck, which can be integrated in the DHL network. In the three following subsections, the specifications for each of the above mentioned trucks are introduced.

2.6.1 Renault e-Tech T

Renault developed the Renault e-Tech T, which is a truck available with a flexible battery configuration, offering between 4 to 6 battery packs. This allows for a total battery capacity ranging from 360 to 540 kWh. Out of the total battery capacity, the usable energy ranges from 330 to 490 kWh. This distinction is important as it indicates the amount of energy that can be effectively used for driving. The truck is designed to provide a driving range of approximately 300 kilometers on a full charge. The Renault e-Tech T supports fast charging at rates of up to 250 kW, which provides an extended range up to 500 km.

Figure 13) Specifications Renault e-Tech T

2.6.2 Volvo FH Electric

Volvo Trucks developed the Volvo FH Electric, which is a truck that has similar specifications to the Renault e-Tech T. This truck also has a driving range up to 300 kilometres, which also can be extended to 500 km if the truck is charged. The Volvo FH Electric supports both AC and DC fast charging. With DC fast charging, the truck can charge at rates of up to 250 kW, allowing for rapid replenishment of the battery.

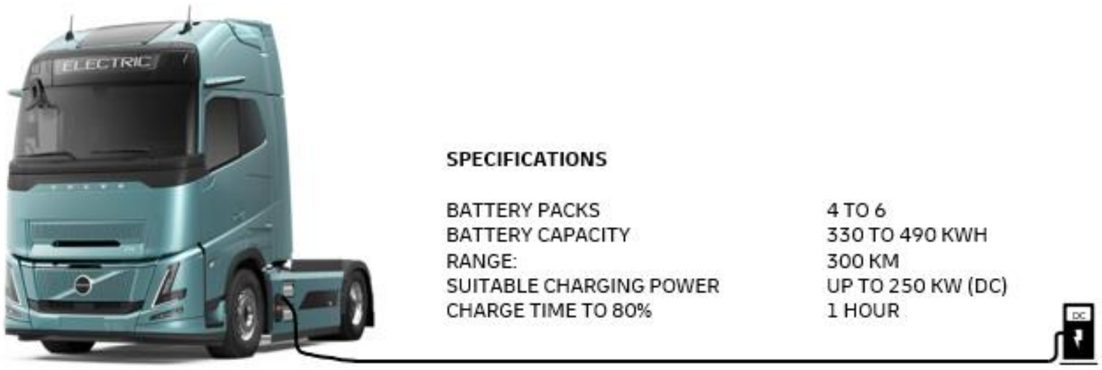

Figure 14) Specification Volvo FH Electric

2.6.3 Mercedes eActros 600

The Mercedes eActros 600 is an advanced electric truck designed for sustainable freight transport, featuring a robust electric powertrain. With a substantial battery capacity of up to 600 kWh, it offers a range of up to 500 kilometers. The truck supports fast charging at a maximum power of 1 Megawatt, which ensures that the truck can be recharged from 20% to 80% within 30 minutes.

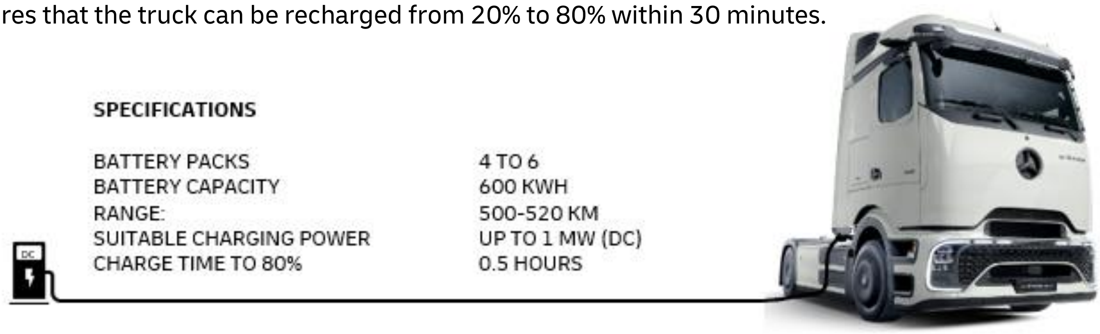

Figure 15) Specifications Mercedes eActros 600

2.7 Pilot with Renault e-Tech T

In November 2024, the Region Hub in Hengelo utilized a Renault e-Tech T pilot truck for one week. This truck, from which the specifications are presented in the previous subsection, was deployed specifically within the Pick-Up and Delivery process, as detailed in Subsection 2.1.2. The decision to use the truck in the PUD process rather than the BNL process was influenced by the fact that BNL routes are typically operated during nighttime hours. Additionally, the Hengelo hub is currently the only DHL location with a DC charging station, which means that the truck cannot be recharged at intermediate stops at other DHL hubs. Additionally, DHL's safety policy prohibits drives from stopping at highway rest areas during night operations. Key insights from this pilot and possible implications for the BNL network are discussed below, with a complete analysis being **not available due to confidentiality.**

For the above mentioned reasons, this pilot was limited to the PUD process, which is operating during daytime hours. In this process, the truck was deployed on four different routes of varying distances. It was observed that the truck easily manages the distances within the PUD network, which has a maximum route length of **XX** kilometer. Initially, DHL expected a worst-case scenario in which trucks always have to be fully recharged from an energy level close to 0% to 100% upon returning to the hub. However, it became evident that not all of the battery's energy is consumed during operations. This realization leads to shorter recharging times to reach full capacity, enabling the truck to be prepared for its next route more quickly.

Another significant insight is that while the 400 kWh truck can easily navigate the routes within the PUD delivery network, it faces challenges on more demanding routes, such as a route to a certain location in the area **(confidential)**, which has a total distance of 250 kilometers and results in the truck returning with a SoC of only 27%. This practical observation indicates that the truck will require frequent recharging when operating in the BNL network, where over 60% of the routes exceed 300 kilometers (as shown in the figure in Section 2.5). This finding complicates the integration of trucks with only 400 kWh usable battery capacity within the BNL network, characterized by the longer distance, and is particularly relevant to thesis, as it underscores the challenges of electrifying logistics in a high-distance area.

Additionally, a key insight is that the charging station at the Region Hub in Hengelo is situated far from the loading docks. This prevents the truck from charging while at the dock, necessitating multiple coupling and decoupling of the trailer, which results in significant downtime and wasted recharging time. This observation highlights the need for dock charging to become standard practice, as typical stops at hubs in the BNL network last between 15 and 45 minutes, providing a small window for recharging.

2.8 Conclusion

DHL has made significant progress in electrifying their processes, with the greatest part of its last-mile fleet now electrified. The deployment of **XX** box trucks in the PUD network across **XX** different hubs represent a notable advancement. However, challenges for electrifying the middle mile network persist due to net congestion, which complicates the installation of new charging stations at DHL hubs. Among the Central and Region Hubs in the Netherlands, only hubs **B**, **H**, **I**, **N**, **O**, **P** do have space in their current grid capacity to be accommodated with charging stations. Additionally, a charging power of 150 kW for DC charging represents an important costs boundary, as infrastructure beyond this level incurs significantly higher expenses. Thus, exploring the feasibility of routes with this charging power is important.

Insights from the pilot using the Renault e-Tech T indicated that while the 400 kWh truck effectively managed PUD routes, it is expected to struggle in the BNL network, where distances often exceed 300 kilometers. Routes like HEN31 to **a confidential location in the area** demonstrated the need for more frequent recharging. Further, charging at the loading dock should become standard practice to maximize recharging time.

3 Literature review

This chapter addresses the second set of research questions by exploring the use of an optimization model to assess the impact of electrifying hub-to-hub movements in the DHL network. Section 3.1 discusses key factors influencing the integration of electric trucks. Section 3.2 presents relevant theory on vehicle routing and its relation to electrification. Section 3.3 reviews algorithms and heuristics for solving such routing problems. Finally, Section 3.4 concludes with insights from the literature applicable to this research. The corresponding research question is restated below.

What does literature tell us regarding implementing electric vehicles in transportation networks?

3.1 Factors impacting implementation of electric trucks in a transportation network

This section explores the key factors that influence the implementation and performance of electric trucks in a transportation network. Subsection 3.1.1 examines current battery technology and its limitations. Subsection 3.1.2 looks at how the battery's State of Charge (SoC) affects long-term battery degradation. Subsection 3.1.3 discusses the role of driving behavior in energy consumption. Subsection 3.1.4 considers the impact of varying load conditions on range. Subsection 3.1.5 highlights the influence of temperature on the energy usage. Lastly, Subsection 3.1.6 addresses the importance and challenges of charging infrastructure availability and placement.

3.1.1 Battery technology

In an electric vehicle, the power system differs from that of a diesel vehicle. Instead of a fuel tank supplying diesel to a motor, an electric vehicle relies on a battery pack and an electric motor to drive the wheels. The vehicle's range is determined by the battery size, measured in kilowatt-hours (kWh), which represents its capacity. However, manufacturers often lack clarity about these capacities.

In battery management literature, a distinction is made between nominal and usable battery capacity. Nominal capacity refers to the total energy a battery can theoretically holds, while usable capacity is the energy available for driving. This difference is crucial, as fully depleting a battery can damage the battery and reduce its lifespan. To prevent complete discharge and overcharging, EV manufacturers incorporate safety margins. Of course, the larger the battery size, the higher the range of the vehicle (Voelcker, 2021) Currently, nominal battery capacities for electric trucks, produced by different Original Equipment Manufacturers (OEM), between 200 kWh and 700 kWh. This accounts for driving ranges up to 500 kilometers (IO-Dynamics, 2024).

3.1.2 Impact of State of Charge on battery degradation

According to Argue (2025), the SoC of significantly impacts the degradation of EV batteries. SoC represents the amount of energy an EV battery holds in relation to its total capacity, with 100% indicating a fully charged battery and 0% indicating a completely discharged one. The article emphasizes that maintaining the SoC between 20% and 80% is optimal for minimizing battery stress and extending battery life. Regularly charging to full capacity or allowing the SoC to drop below 20% can accelerate battery degradation.

Additionally, vehicle manufacturers implement charging buffers to protect battery health. This results in a difference between net and usable battery capacity, meaning that batteries are designed in such a way that their full capacity never can be used during driving (Jenkins, 2017). These buffers restrict the amount of battery capacity that can be utilized, preventing the battery from frequently reaching its maximum or minimum levels. Consequently, this practice helps slowing down battery degradation and extending the overall lifespan of the battery.

3.1.3 Driving Behaviour

According to Donkers et al. (2020), driving style actually has a significant influence on the energy consumption of EVs. In this paper, three driving styles were modeled, namely: eco-driving, normal driving, and aggressing driving. All styles are characterized by the driving speed, acceleration and deceleration, lateral acceleration, and regenerative braking efficiency. The study highlights the impact of driving styles and desired speeds on the energy consumptions of EVs. Aggressive drivers consume significantly more energy, with a relative difference of up to 17% at high speeds (130 km/h) due to increased aerodynamic drag. On the other hand, at extremely low speeds, eco-drivers use about 5% more energy because of longer travel times and the higher energy demands of the climate control system. The combination of higher acceleration from aggressive driving leads to a 25-30% increase in energy consumption during acceleration, regardless of speed. Additionally, larger speed oscillations negatively affect energy consumption, with aggressive drivers experiencing a 22% increase in energy suage from oscillations of about 0.2 m/s^2, while eco-drivers see minimal impact, underscoring the efficiency benefits of cruise control for non-eco drivers. In this sense, adopting eco-driving techniques and utilizing cruise control can enhance the efficiency of EVs, which leads to reduced energy consumption and an improved overall performance.

3.1.4 Load conditions

Cieslik et al. (2023) address that, in current literature, there exists a gap in understanding how load weight impacts the energy consumption of electric vehicles under real-world conditions, particularly in urban, suburban, and highway driving. The study conducted provided insights into the usability of electric delivery vans under varying load conditions. The electric vehicle assessed was a cargo van-type structure with a gross vehicle weight of 3055 kg. During the test, the van followed a pre-defined route, with the same driver operating the vehicle throughout the process. The cargo load was systematically varied between empty and full to assess its impact on performance. Key findings include that the maximum range of light-duty vehicle in actual traffic conditions deviates from the manufacturers declared range, which was 330 kilometers, with reductions of 15% for unloaded trips and 22% for fully loaded trips. The addition of 850 kg of load significantly reduces the range, with the most significant decrease (nearly 14%) observed on urban routes due to higher energy consumption during acceleration. The figure below presents the effect of cargo weight on estimated range on different road types.

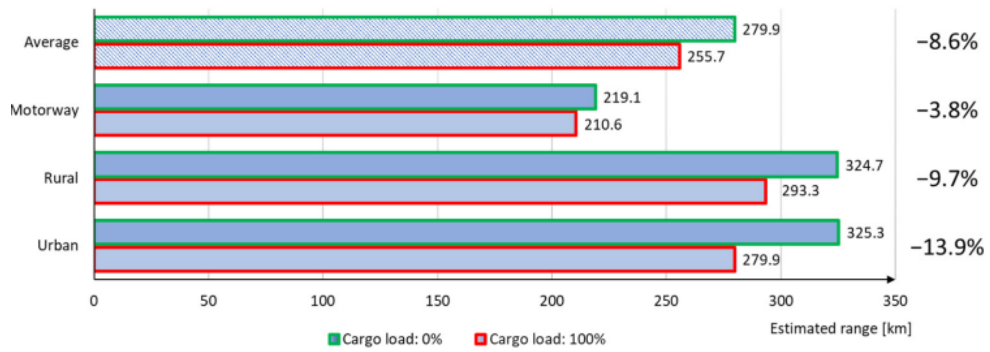

Figure 16) Effect of cargo weight on estimated range on different road types (*Cieslik et al. (2023)*)

3.1.5 Environmental Conditions

Al-Wreikat et. Al (2022) evaluated the impact of ambient temperature and trip characteristics, such as driving distance and average vehicle speed, on the energy consumption of an electric car during road tests. The results showed that the electric car's specific energy consumption increases if the ambient temperature decreases. Further, the paper shows that the relationship between the ambient temperature and the energy usage follows a non-linear u-shape trend. In this, it is observed that the energy usage decreases from cold weather conditions until the minimum at 21 °C is reached. Note that this information was only available for electric cars, and not specific for electric trucks.

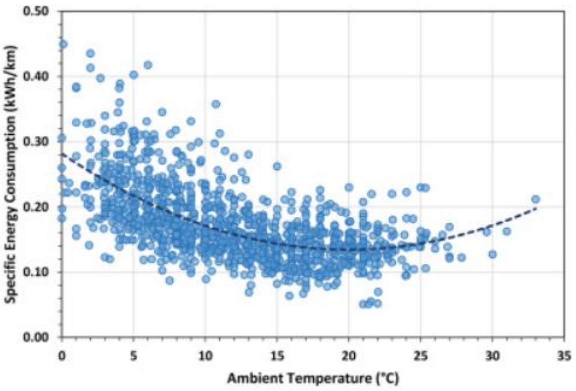

Figure 17) Impact of ambient temperatures on energy consumption of EVs (*Al-Wreikat et. Al (2022)*)

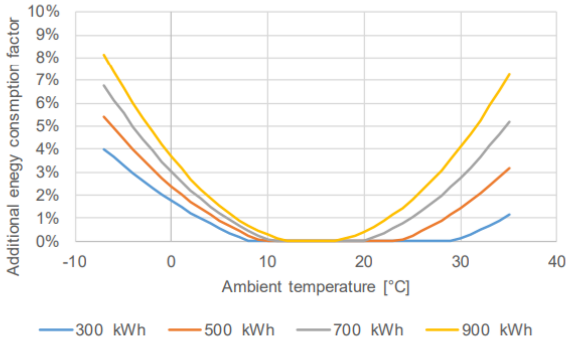

Figure 18) Impact of ambient temperature on energy consumption *(ICCT, 2021)*

Further, effects of the ambient temperature on energy consumption of electric trucks have been modeled by the Internation Council on Clean Transportation (ICCT, 2021), which assessed the additional energy requirements for trucks equipped with various battery sizes under different temperature conditions. Ambient conditions can have a significant impact on the energy consumption of electric trucks. At lower temperatures, energy consumption increases due to heightened air resistance from greater air density and decreases battery efficiency. Additionally, using cabin heating or air conditioning contributes to energy consumption that varies with temperature (TNO, 2022). Similar as the graph in Figure 17, obtained from Al-Wreikat et al. (2022), the diagram in Figure 18 illustrates a U-shaped curve, indicating that energy consumption is most efficient at temperatures between 15 and 20 degrees Celsius. Energy consumption increases when ambient temperatures fall below or rise above this optimal temperature range.

3.1.6 Charging infrastructure

In the context of EV charging, particularly for electric trucks, the charging speed is generally determined by the truck's charging capabilities rather than the power output of the charging station. This dynamic is crucial for understanding the interaction between the EV and charging stations during charging. For example, if an electric truck is designed to handle a maximum charging power of 250 kW, the charging speed will be constrained by this rate, regardless of whether the truck is plugged into a higher-powered charging station, such as a 300 or 350 kW charger. This occurs because the truck's onboard charging systems can only process the power it is designed to accept (Milence, 2022).

Conversely, if the truck is connected to a charger with a lower power specification, the vehicle will be restricted to charging at a rate that matches the maximum output of the charger, even if the truck itself could potentially manage higher charging powers.

3.2 Challenges faced during integration of electric trucks in logistic networks

Integrating electric trucks into logistics networks present a promising solution for reducing carbon emissions and improving sustainability in freight transportation. However, this transition introduces several challenges that must be addressed to ensure a successful integration. In this section, literature is explored on these challenges and how these can be managed. Subsection 3.2.1 focuses on grid capacity constraints, highlighting the limitations of local electricity networks in supporting widespread electric vehicle charging. Subsection 3.2.2 discusses the scarcity of charging stations and examines how this scarcity affects routing, scheduling and overall network reliability.

3.2.1 Grid Capacity Constraints

The electrification of heave-duty vehicles introduces significant demands on existing power grids, as high-power charging stations are essential for electric trucking operations. These types of stations require substantial electrify, which often exceeds the capacity of current grid infrastructure. For instance, a study in which the Texas (United States) power grid was simulated revealed that in case just 11% of all heavy-duty vehicles would charge simultaneously, this could lead to notable voltage violations, which compromises grid stability (El Helou, 2022). To address these challenges, El Helou (2022) proposes some strategies, including the enhancement of grid capacity through investments in transmission and distribution systems which can accommodate increased loads from electric truck charging.

To clarify the issue of high energy demand, Squires (2025) gives the example of charging a semitruck in just a few hours to a full charge, a single charging connector must provide at least 350 kW of power. Charging multiple heavy-duty trucks simultaneously could require a charging station location to having a peak of over 20 megawatts (MW) of power. Next to this, the National Renewable Energy Laboratory's Chief engineer for EV charging and grid integration emphasizes this by giving the example of plugging in 100 Tesla Model Y's and charging them at the same time. This would ask for the same amount of electricity that is needed to fast-charge four or five electric trucks.

In an article of TNO, a TNO-expert explains that net congestion can be compared to 'traffic jams' on the electricity grid: "We experience this when the demand on the network exceeds its capacity. This can be due to either an oversupply or excessive demand at certain times. Due to the energy transition, both demand and supply of electricity are increasing, which makes that capacity of the electricity grid increasingly insufficient during peak times (TNO, 2024).

TNO (2024) describes grid reinforcement as the most obvious solution when it comes to net congestion. However, this is a time consuming process requiring significant investments, as materials and space have become scarcer and more expensive. Additionally, there is a shortage of workers to carry out these tasks. Therefore, grid operators and governments are collaborating in the National Action Plan for Grid Congestion to speed up permits and construction, better utilize infrastructure, and encourage flexible electricity usage.

3.2.2 Scarcity of charging stations

The limited grid capacity has as result that the availability of charging infrastructure for electric trucks adoption poses a significant barrier. In contrast to passenger electric vehicles, electric trucks always require high-power charging stations. Next to this, this in combination with the fact that trucks are bigger than passenger vehicles, the establishment of suitable charging stations is complex and costly.

In an article of The Times, two relevant persons provide their view on this problem. Saul Resnick, the UK CEO of DHL Supply Chain emphasizes that the biggest limitation is not just the supply of electric trucks, but actually the infrastructure to charge these vehicles. Matt Finch, UK Policy manager at the non-profit organization Transport Environment, adds that the lack of charging stations for trucks is a "chicken and egg problem," because service stations are unwilling to install them until the point in time there are truck to use them. Here, another problem rises for service stations, as truck chargers generally demand more electricity than these stations can draw from the grid (Cooke, 2024).

3.3 Optimization Techniques in the deployment of electric trucks and charging stations

The integration of electric trucks into logistics networks, together with the establishment of charging stations, can be presented as a complex optimization problem. Operations Research techniques are more and more applied to address these types of challenges, particularly in optimizing deployment strategies while considering net congestion constraints.

A central challenge in deploying electric trucks lies in solving the Vehicle Routing Problem (VRP), a well-established optimization problem in logistics. Originally this problem is introduced by Dantzig and Ramser (1959) as the Truck Dispatching Problem, which generalizes the Traveling Salesman Problem (TSP). The VRP focuses on optimizing routes for vehicles to service a set of customers. The original focus was on optimizing routes for a single vehicle delivering gasoline, but Clarke and Wright (1964) expanded this to multiple vehicles, leading to more complex logistics scenarios. Lenstra and Kan (1981) proved the VRP to be NP-hard, making exact algorithms impractical for larger instances, which prompted the development of various solution methods and problem variants.

While initially developed for conventional fuel-based vehicles, its relevance extends directly to electric trucks, as they must also navigate route planning, customer demands, and time windows. However, electrification introduces additional constraint such as limited capacity, charging station availability, and charging times, which significantly complicate traditional VRP formulations. These additional constraints have led to the emergence of specialized variants like the Electric Vehicle Routing Problem.

Researchers have adapted the VRP to real-life cases, resulting in numerous variants that incorporate specific constraints. A key variant is the Capacitated VRP (CVRP), which addresses the limited cargo capacity of vehicles, which is crucial for real-world applications like DHL's middle mile operations. It ensures that customer demands do not exceed vehicle capacity while routes are optimized from a central depot (Rojas-Cuevas, 2018). Another key variant is the VRP with Time Windows, which involves servicing customers within specified time intervals, again adding complexity to the routing generation process (Solomon, 1991). Further, the VRP with Simultaneous Delivery and Pick-Up (VRPSDP) can be mentioned as a key variant to this research as well, since in the middle mile process of DHL trucks often perform both delivery and pick-up activities at the hubs. The VRPSDP recognizes the need for vehicles to perform both activities at the same location (Min, 1989).

3.3.1 Vehicle Routing Problem

With a shift towards zero-net emissions, DHL opts to integrates electric vehicles into its middle mile operations. Due to the limited range, and lacking charging infrastructure, this integration asks for a re-evaluation of traditional VRP models, leading to new formulations of the VRP. Erdogan and Miller-Hooks (2012) proposed the Green VRP (GVRP). This model addresses challenges related to alternative fuel vehicles, including driving range and refuelling infrastructure. It optimizes routes while considering fuel consumption and refuelling needs.

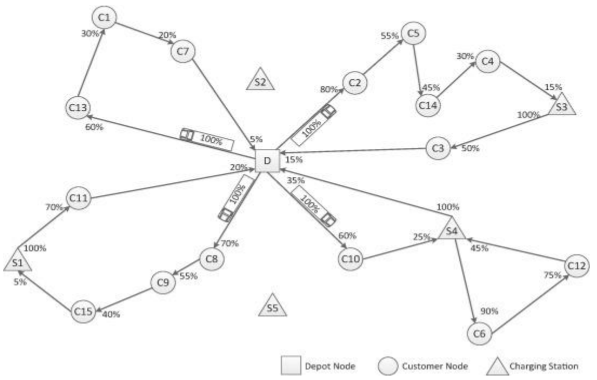

Figure 19) Visualization of Electric Vehicle Routing problem

Building on the GVRP, the Electric VRP (EVRP) recognizes the unique constraints of electric vehicles, such as the need to recharge at charging stations during routes. In literature, the Electric Vehicle Routing Problem (EVRP) can be viewed as a variant to the GVRP. Kucukoglu et al (2021) define the EVRP as a problem in which the aim is to find the best route plan for electric vehicles, where a given cost function is minimized, while satisfying multiple constraints. According to this paper, in literature the most common assumptions for the EVRP are that trucks start and finish their routes at the depot node, and that each customer node is to be serviced by exactly one electric vehicle. Further, an EV can visit a charging station, from which the location and traveling distance to any other node is known, for recharging operations between any two customers. More than one EV can visit the same charging station. The battery level of an EV must always range between 0 and its battery capacity, while a vehicle's battery is always fully charged when visiting a charging station.

As mentioned, the EVRP is an extension of the well-known VRP. As the VRP is classified as NP-hard, it follows that the EVRP, being a generalization of the VRP, can also be regarded as NP-hard (Desaulniers et al., 2016). Kucukoglu et al. (2021) discuss various studies that present exact algorithms and heuristics for solving EVRPs. Given the NP-hard nature of the problem, there are merely studies describing exact approaches for solving EVRPs. For instance, Desaulniers et al. (2016) introduced an exact branch-price-and-cut algorithm, which is able to solve four variants of the VRP: (i) at most one recharge per route with a full charging policy, (ii) at most one recharge per route with a partial charging policy, (iii) multiple recharges per route with a full charging policy, and (iv) multiple recharges per route with a partial charging policy.

Decompositions and reformulation of mixed-integer programs are classic techniques used to create better relaxations and reduce symmetry. These methods typically involve adding variables (columns) and/or constraints (cutting planes) to the model as needed. When the linear relaxation at each node of a branch-and-bound tree is solved using column generation, this approach is called branch-and-price. Additionally, just like in the regular branch-and-bound method, cutting planes can be added to strengthen the relaxations, which has a result the branch-price-and-cut method (Desrosiers, 2010). Next to such exact methods, Kucukoglu et al. (2021) provide an overview of the meta-heuristic algorithms used in the reviewed papers. The analysis reveals that (Adaptive) Large Neighbourhood Search and (Adaptive) Variable Neighbourhood Search are frequently used. Furthermore, Tabu Search (TS), Adaptive Tabu Search (ATS), and Granular Tabu Search (GTS) are also often used.

3.3.2 Implementation of electric trucks and charging stations in diverse types of networks

Below, three studies on three different networks are considered, namely: Europe, a remote low-traffic flow region and a densely populated high-traffic region.

Europe

Shoman et al (2023) introduce an innovative trip chain approach to estimate the charging infrastructure demand for long-haul electric trucks in Europe by 2030. The methodology leverages publicly available origin-destination data to simulate truck travel distances, stop location, duration, and energy requirements, while considering truck driving regulations. The findings indicate that charging areas must have significantly more overnight (CCS, 50-100 kW) chargers compared to megawatt (MCS, 0.7-1.2 MW) chargers, with an estimated requirement of approximately 40000 CCS and 9000 MCS chargers across Europe. Each charging area is expected to host an average of 8 CCS and 2 MCS chargers servicing about 2 and 11 battery electric trucks on daily basis, respectively.

The study acknowledges several assumptions that may influence the accuracy of the results, such as electric truck energy consumption rates, and travel patterns, as well as the flexibility in EU regulations regarding break times. The research highlights the urgent need for substantial investment in charging infrastructure, particular in central European Countries like Germany and Belgium, which are critical for European long-haul transport. The results emphasize the importance of planning for a robust charging network to meet future electrification targets. Overall, the study provides essential insights for the effective deployment of charging infrastructure for long-haul electric trucks in Europe.

Remote low-traffic region

Alonso-Villar et al (2025) presented a novel methodology for planning fast-charging infrastructure for long-haul battery electric truck in low-traffic flow regions, particularly focusing on Iceland's Reykjavik-Westfjords freight routes. The approach combines a vehicle energy consumption model, a non-linear charging optimization framework, and a queueing model to effectively design a fast-charging station network. The methodology simulates truck travel distances, stop locations, duration, and energy requirements using real driving data and considered adverse climate conditions, ensuring that the charging network is optimized for realistic scenarios.

Findings reveal that larger battery capacities and higher charging rates significantly reduce additional routing times for electric trucks. Specifically, trucks with a 540 kWh battery using 500 kW chargers experience minimal extra routing time, averaging 25 minutes, while those with a 360 kWh battery and 350 kW charging rates face longer delays, averaging 83 minutes. The study estimates that to support a fully battery-electric heavy-duty vehicle fleet on Reykjavík-Westfjords route, a well-planned fast-charging infrastructure is essential, with specific locations and charging durations identified for optimal performance.

The study of Alonso-Villar et al (2025) shows the importance of tailored fast-charging infrastructure development in remote and challenging environments to facilitate the electrification of freight transport. It highlights that the proposed methodology provides a comprehensive framework for planning charging networks, ensuring alignment with realistic range limitations, driver rest regulations, and safety margins. The results can be valuable for fleet operators, as they offer insights into optimal station design and routing times necessary for effective truck electrification.

Populated high-traffic region
Zähringer et al (2024) developed an algorithm for optimal dynamic charging strategies for long-haul electric trucks using a dynamic programming approach. The algorithm is designed to minimize time loss during charging stops while considering real-world charging behaviors and mandatory rest regulations. The study includes three case studies to evaluate the impact of various charging infrastructure properties on battery electric trucks operations and time efficiency.

In one of the studies, the research examines the influence of different charging network properties on time loss for electric trucks. Four scenarios with varying infrastructure characteristics are analyzed, focusing on charging point density, and charging power. The results indicate that as the density of charging points increases, the average time loss decreases significantly. In a scenario with a density of two charging points per 100 kilometer and a mix of charging powers, not time loss is expected under optimal conditions. On the other hand, in a scenario with low density, time loss is present, demonstrating the key role of charging infrastructure density in supporting efficient long-haul operations. The findings emphasize that a 50 kilometer average distance between charging stations, with charging powers between 700 kW and 1 MW and at least 75% availability, is necessary to keep time losses comparable to diesel trucks.

3.3 Conclusion

This literature study provides several insights which can be used for the solution methodology of this thesis. As discussed in Subsection 3.1.1, battery health deteriorates significantly when the SoC drops below 20%. To enlarge battery lifespan, the model should therefore enforce a minimum SoC threshold, ensuring trucks do not discharge below this limit.

Moreover, as outlined in Section 3.3, the success of electric truck integration depends also on the availability and performance of charging infrastructure. This includes both the location of charging stations within the network and their power ratings, which determine charging speed. The research methods must account for whether a truck can reach a charging station in time, how long it takes to recharge, and whether station capacity is sufficient to meet charging demand. In addition, the model should incorporate constraints found in advanced EVRP variant that better reflects DHL's operational realities.

Since electric vehicle routing problems are considered to be NP-hard, exact optimization methods become computationally infeasible at scale. To ensure the model remains efficient and practical for large network instances, heuristic or hybrid solution approaches should be employed. Finally, a scenario-based analysis is recommended to explore the impact of varying assumptions, such as grid limitations, infrastructure availability, and vehicle specifications.

4 Solution methods: Evaluation and Optimization

As introduced in Section 1.3, DHL would like to know which of their current BNL routes are suitable to drive with an electric truck, while considering the existing boundaries caused by grid capacities and net congestion. In Section 4.1, an Evaluation Method (EM) was developed to assess the feasibility of each route based on a fixed set of input parameters and assumptions. In this method, the main assumption is that a charging station is always available whenever a truck arrives at a hub with a charging station, meaning it does not account for simultaneous demand for the same charger by multiple trucks.

To address this limitation and provide a more forward-looking perspective, the Generic Solution Method (GSM) introduced in Section 4.2 incorporates the dynamic management of charging infrastructure, including conflicts arising when multiple trucks require access to the same charger. While both methods output the percentage of feasible routes, the GSM actively optimizes this percentage under more realistic operational constraints.

In both methods, the limited availability of charging stations, caused by net congestion, plays a significant role in determining route feasibility. For clarity, the research question addressed in this chapter is repeated below.

> How could models be used and developed to evaluate whether a route can be electrified and how to maximize the number of routes that can be electrified?

4.1 Evaluation of DHL routes

To evaluate BNL routes, data from DHL's OPC (Operations, Planning & Control) tool is used. This tool provides detailed information for each segment of a route. In a composed MS Excel file, each row corresponds to a route segment and includes the following data in the columns: route ID, homebase of the truck, origin and destination of each segment, distance between these locations, time for loading/unloading activities, break time, whether the hub is an intermediate destination or the homebase, and the carrier assigned to the route, which indicates whether the route is operated by DHL or a subcontractor. The typicality of the route distances is explained and visualized in Section 2.5.

Subsection 4.1.1 explains the working of the route evaluation method, supported by a corresponding flowchart that illustrates the step-by-step decision process. Following this, subsection 4.1.2 outlines the underlying assumptions of the approach, while subsection 4.1.3 outlines the input parameters required for applying the evaluation approach.

4.1.1 Working of Evaluation Method

The data mentioned above is loaded into the evaluation method that assesses the feasibility of operating the routes with an electric truck. After evaluation, the method outputs an Excel File that includes the total number of feasible routes, the total number of infeasible routes and the percentage of feasible routes over the total number of evaluated routes. Additionally, a detailed worksheet is added for each route, providing information on required energy, SoC updates, availability of chargers at destinations, and the feasibility of electrifying the route.

To evaluate the feasibility of electrifying a specific route, a flowchart outlines the systematic decision-making process. This algorithm considers the SoC of the truck's battery and the availability of charging infrastructure at the visited hubs. The evaluation begins at the truck's starting hub. The first step is to check whether the truck's initial battery SoC is above a defined threshold, denoted as SOC_{min}. If the initial SoC is below this threshold, the route is immediately classified as infeasible. If the SoC meets the threshold, the evaluation proceeds.

For each subsequent hub in the route sequence, the projected SoC upon arrival must remain above SOC_{min}. If the expected SoC at any hub falls below this threshold, the route is considered infeasible to ensure there is no risk of having insufficient battery capacity. If the SoC is sufficient, the evaluation continues. The next step checks whether the destination hub has sufficient grid capacity to support a DC charging station. If sufficient grid capacity is unavailable, charging at this hub is not possible, which may result in a route being unworkable.

Next, the process determines whether the current hub is the truck's homebase. If it is not, the evaluation loops back to assess the feasibility of reaching the next hub in the route sequence with adequate SoC. This iterative process continues for each leg of the route. If the hub is identified as the truck's homebase, a final check ensures that the projected SoC upon arrival is at or above SOC_{min}. If this condition is satisfied, the route is classified as feasible. If not, it is marked as infeasible.

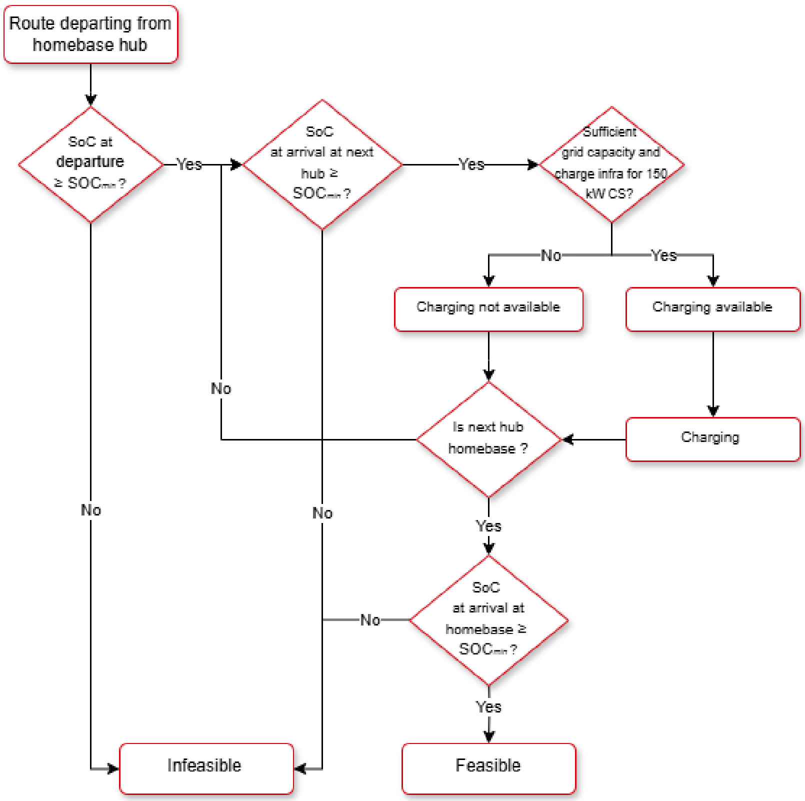

Figure 20) Flow Chart for working of Evaluation Method

4.1.2 Assumptions

Given that electrifying truck transportation is still in its initial stages at DHL, and that this EM has to check the electrical feasibility of each route separately, certain assumptions have been made for the operation of this model:

- Charging stations are assumed to be always available at hubs with sufficient grid capacity.
- Each station is assumed to be a singular DC charging station consistently delivering a specified energy amount (in kW).
- Charging occurs directly at the dock, eliminating the need for additional on-site movements, such as (de)coupling the trailer, which would not be optimal, as explained in Section 2.7.
- Charging time is set to a specified percentage of the service or break time at the hub, ensuring time for connecting to the charger and driving to the charging dock is accounted for.
- The average energy usage calculated with is set to 1.25 kWh:km which aligns with findings from pilots and literature.

4.1.3 EM Input Parameters

To execute the evaluation, the following parameters must first be specified:

- Usable Energy Capacity of the eTruck: the total energy capacity available for use by the eTruck
- Energy Usage per kilometer: The amount of energy consumed by the eTruck for each km traveled.
- Charging power of the charging station: The power output of the charging station, measured in kW.
- Minimum SoC at Arrival: The minimum battery charge level required when the truck arrives at the hub.

Additionally, it is possible to manually add charging hubs to the list of charging locations. By default, the charging locations are retrieved from a Microsoft Excel file, which indicates whether charging electric vehicles will be feasible at those hubs within one year based on the contracted power capacity. For sensitivity analysis purposes, the option to manually add hubs has been included, allowing for flexibility in evaluating different scenarios.

4.1.4 Selecting at which hubs to charge

As discussed in Chapter 2, certain hubs have sufficient space in their energy contract to support charging infrastructure. These hubs are **B**, **H**, **I**, **N**, **O**, **P**. Using the route EM, an expanded model identifies the most strategic charging locations within DHL's network. The goal is to determine the optimal combination of hubs for charging electric trucks, prioritizing the highest number of feasible DHL routes, and in the case of a tie, prioritizing sub-contractor routes.

The selection process is initialized by evaluating all combinations of two hubs. After this, the combination of charging hubs which results in the highest number of feasible DHL routes is selected. In case of a tie (multiple combinations yielding the same number of feasible DHL routes), the combination with the highest number of feasible sub-contractor routes is selected. In subsequent steps, one additional hub is gradually added to the combination. For each step, all additions of a single hub to the current combination are evaluated. The new combination that maximizes the number of feasible DHL routes is selected. Again, if there are multiple combinations with the same number of feasible DHL routes, the combination with the highest number of feasible sub-contractor routes is chosen.

By following this iterative process, the model ensures that the selected hubs provide the most efficient charging infrastructure for electric trucks. Additionally, the feasibility of sub-contractor routes is also taken into consideration, ensuring a comprehensive and effective charging network. Next to identifying the most strategical charging locations in DHL's network, this approach also provides the actual DHL routes that are most interesting to electrify on short term. For each optimal combination of hubs, with the number of hubs ranging between 2 and 20, the feasible DHL routes are provided as well. In appendix I, the pseudo code for this algorithm is outlined.

4.2 Generic Solution Method: optimal implementation of EVs in VRP

The EM described in the previous section calculates the percentage of feasible DHL BNL routes relative to the total number of routes assessed. In this analysis, specific to DHL's network, it is assumed that charging stations are only available at some of the hubs due to net congestion problem. Additionally, it is assumed that these stations are always available and not occupied by other trucks upon their arrival.

However, this assumption may not reflect future real-world conditions, since due to the network congestion problem it may occur that less charging stations are available at a hub than electric trucks possibly could arrive in the same time interval at a hub. If that occurs, a decision has to be made on which truck is assigned the charging station. In DHL's nightly transportation operations, trucks continuously arrive and depart from various hubs within designated time windows. To address this, a GSM is developed, applicable to both DHL's processes and those of other transportation companies.

In Subsection 4.2.1 the model is described, while Subsection 4.2.2 highlights the related requirements. Further, Subsection 4.2.3 outlines the different assumptions that are made regarding this model.

4.2.1 Model description

The Generic Solution Method handles a problem, based on DHL's night process transportation model, that can be described as a Capacitated Homogeneous Electric Vehicle Pickup and Delivery Problem with Time Windows. Let $H = DC \cup C$ represent the set of all hubs in the network, where DC is the set of Distribution Centers and C is the set of customer locations. These two types of locations serve distinct roles in the model. DCs function as homebases for trucks, meaning trucks start and end their routes at these locations. Customer locations are purely visited nodes, meaning trucks can perform pickups or delivery there but cannot start or end their routes at these sites.

A fleet of electric trucks is represented by the set K. Each truck $k \in K$ starts its route from a hub in the set DC and is assigned to perform a set of predefined pickup and delivery stops, which consists of pickup and delivery activities related to specific orders. The assignment of orders to trucks and the corresponding stop sequence is treated as input to the model and is not optimized as part of the problem. This assumption simplifies the problem and allows the model to focus on the operational feasibility of executing these routes with electric trucks. However, the model can adapt the route by inserting additional stops at charging hubs when necessary. These recharging stops are not tied to customer orders and are flexibly added to ensure trucks can complete their assigned sequence. The original customer-related stop sequence is respected, but the model decides where and when to insert charging activities in the route sequence.

For each pair of hubs (i, j), a distance d_{ij}, a travel time t_{ij}, and an energy requirement e_{ij} is defined for travelling the arc. Note that a homogeneous fleet is considered, such that energy requirements are equal for all vehicles. Each truck has a maximum capacity N, and the transportation costs are defined by a constant cost per unit distance c_{ij}.

The operational constraints include time windows for delivery and pickup activities at each hub, defined by minimum start time a_i and maximums start times b_i. Each truck k has a defined work time limit before taking a break, denoted as W, and a maximum shift time, denoted as S.

Further, charging station availability is a critical aspect of the model, with each hub i having a number of charging stations c_i, being a nonnegative integer. Each charging station at hub i is considered to have a charging power P_i. In this model, a fixed charging power is considered for each charging station at each hub. However, in the model this is a parameter that can be adjusted for each hub specifically. This helps to easily adjust the model according to another network design, which keeps the model generic. Further, the model ensures that trucks can only start their route with a full battery charge and establishes constraints on the SoC throughout their journey.

The objective of this problem is to maximize the percentage of routes that are feasible to electrify within a given problem size. A problem size, which will be addressed in more detail later, exists of a specified number of trucks, each starting its route at one of the Distribution Centers (DC). From there, a route is generated along Customers (C) and other DCs. For each problem size, routes are generated for a pre-specified number of days, such that there are routes generated for multiple days.

The objective is to maximize the feasibility percentage, while minimizing the total costs associated with waiting times for charging at hubs, transportation distances, and detour actions to other hubs for recharging. The model aims to efficiently select a smart charging decision for each truck k, while it has two options if a charging station is not directly available for the truck: let truck k wait for a charging station to become available against waiting costs, or detour to a charging station at another hub, against additional transportation costs. Note that if a route is infeasible to electrify due to not meeting arrival thresholds, this does not mean that the complete problem is infeasible. In this context, the feasibility percentage refers to the share of routes that are feasible to complete with an electric truck, relative to the total number of input routes.

4.2.2 Requirements

The solution to the problem must meet several requirements. These requirements, organized by categories, are specified below, and will be included as constraints in the model formulation.

Traffic requirements:

- Each truck must start its route at a DC.
- Each truck must return to exactly the same DC from which it started
- If a truck enters an immediate hub, it must leave that hub as well, ensuring no dead ends.
- Each hub must be visited according to a visiting frequency matrix.

Time requirements:

- Trucks must arrive at each hub within specified minimum and maximum start times for delivery and/or pick-up activities.
- For each route, the sum of the total driving time and activity durations at hubs cannot exceed the maximum shift time.
- Each truck must meet the service time windows.
- Charging time at a hub is limited to the maximum of break time and the total loading and unloading time, as these two overlap each other.
- Charging time is thus also limited to the difference between a truck's arrival time and departure time at a hub.

Loading/Unloading requirements:

- The total load assigned to a truck cannot exceed its capacity
- If demand exceeds a single truck's capacity, multiple trucks or multiple trips must be used to fulfill the demand.
- The total transported goods across all trucks must meet the demand for each route segment.

Battery and Energy requirements:

- The SoC at arrival at a hub must account for recharged energy and energy consumed during travel.
- The SoC upon arrival at any hub must meet a minimum threshold to qualify the route segment as feasible for electrification.
- The SoC arrival threshold is set to 20%. In this way, unforeseen circumstances can be managed, and this helps prevent battery degradation, as often discharging the battery below this level can accelerate the degradation process, as discussed in Section 3.1 of the literature review.
- A truck's battery cannot be charged beyond its maximum capacity.
- The number of trucks simultaneously charging at a hub at time t cannot exceed the number of available charging stations.

Charging requirement:

- In case less truck than charging stations available arrive simultaneously, all trucks start charging.
- Trucks must either wait for a charger to become available or take a detour to another charging hub.

4.2.3 Assumptions

To formulate the electric truck routing problem as described in Section 4.2.1, several assumptions have been made. These assumptions, which are important for effective modelling, are outlined below. Note that these assumptions are quantified in the sections on experimental settings in Chapter 5.

- All trucks in the fleet are considered to be homogeneous, such that each truck has exactly the same specifications. Each truck is assumed to have the same fixed usable battery capacity and a fixed energy usage rate in kWh per kilometer.
- All demand is considered to be deterministic, meaning it is assumed to remain constant over time.
- The average driving speed for the eTrucks is assumed to be constant.

- Break time is assumed to overlap with the service time, such that the potential charging time is the maximum of the break time and the service time. This means that the start time of a break is equal to the start time of service at a hub.
- eTrucks will charge at their designated loading docks. This eliminates the need for (de)coupling the truck and driving to a separate charging station located elsewhere at the hub site, as is currently practiced at the Region Hub Hengelo (described in Section 2.7).
- In case an eTruck is not assigned a charging station at any location, then the truck is unloaded/loaded at a dock without a charger, meaning that the unloading/loading activities are performed without the truck being recharged during this service time.
- Charging at public stations along highways is not included in this model. Only charging at designated hubs is permitted. This is due to the fact that companies often restrict truck drivers from remaining stationary on highways overnight, due to safety reason. This policy is considered in this model.
- The charging time is considered to be a fraction (in %) of the total service time at a hub. This accounts for the fact that the truck's arrival time does not coincide with the start of the charging process, as the truck must first drive to its assigned dock and connect to the charging station. Next to this, this percentage also accounts for not obtaining full charging power directly after start charging.
- The charging power is considered to be constant for the complete actual charging duration.
- All trucks begin their routes with a full charge.
- If a truck detours to another location for an intermediate recharge or waits at its current location for a station becoming available, it will recharge the amount of energy necessary to reach the next destination in its route sequence.

4.3 Generic Solution Method: Mathematical formulation

After consulting literature, the model described by Dondo et al. (2004) fits as a good starting point of the model considered in this research. Dondo et al. (2004) defined a formulation for the Pick-up and Delivery Problem with Time Windows, where they seek to minimize the sum of the total travel costs for a homogenous fleet of vehicles. In case a vehicle cannot meet the required time windows for pickups or deliveries, this leads to additional penalty costs. In the network considered in the model for this research, these requirements are the same. However, this research differs from the model considered in Dondo et al. (2004) since there a heterogeneous fleet of electric trucks is considered instead of a homogeneous fleet of trucks. Therefore, new requirements have to be introduced.

Subsection 4.3.1 covers the sets and parameters, while Subsection 4.3.2 discusses the various variables. Subsection 4.3.3 focuses on the objective, and subsection 4.3.4 addresses the constraints. Note that this model is constructed as a descriptive and heuristic framework designed to reflect operational realities of a middle-mile network. Rather than aiming for algorithmic optimization, it supports high-level planning and scenario analysis, especially regarding feasible route electrification under real-world constraints.

4.3.1 Sets and parameters

The problem for the GSM has the following sets and parameters:

Sets		
H	Sets of all Hubs in the network	$H = DC \cup C$
DC	Set of Distribution Centers	
C	Set of Customers	
K	Set of trucks	$k \in K$
Parameters		
h_{ik}	Binary parameter indicating whether hub i is homebase to truck k	
g	Grid size	
d_{ij}	Distance between hub i and hub j	
t_{ij}	Travel time needed to drive from hub i to hub j	
q_{ij}	Number of pallets to be transported from hub i to hub j	
N	Truck capacity	
c	Constant costs per unit distance driven between hub i and hub j	

p_w	Penalty costs for waiting before charging can start at hub i
p_{TW}	Penalty costs for violating the upper bound of a time window (arriving too late)
s_k	Start time of shift for truck k
W	Work time limit before taking break, Constant (4 hours)
S	Maximum shift time, Constant (8 hours)
v	Average velocity for each truck
$bt_{i,k}$	Break duration at hub i for truck k
$lt_{i,k}$	Loading duration at hub i for truck k
$ut_{i,k}$	Unloading duration at hub i for truck k
a_i	Minimum start time for delivery and/or pick-up activities at hub i
b_i	Maximum start time for delivery and/or pick-up activities at hub j
$ct_{i,k}$	Charging time at hub i for truck k
cs_i	Number of charging stations at hub i
$e_{i,j}$	Energy required to travel between hub i and hub j
γ	Energy usage in kWh per unit distance
SOC_{min}	SoC threshold for being able to arrive at a hub (20%)
B	Battery capacity for each truck
P_i	Power of charging station in kWh at hub i

4.3.2 Variables

The decision variables of the model are outlined below. Notably, there is one binary decision variable that determines whether truck k travels a route segment between hub i and hub j. Additionally, three continuous decision variables are utilized to monitor the following: the arrival times at hubs for each truck k, the waiting time for a truck k for a charging station to become available at the hub, and the SoC of truck k during its route.

$x_{i,j,k}$	1 if truck k departs from hub i and arrives at hub j, 0 otherwise
$y_{i,k,t}$	1 if truck k charges at hub i at time t, 0 otherwise
$z_{i,k}$	1 if truck k detours to another hub looking for charger
$SOC_{i,k}$	Variable representing the SoC of truck k during departure from hub i
$SOC_{j,k}$	Variable representing the SoC of truck k at arrival at hub j
$w_{i,k}$	Variable representing the waiting time of truck k at hub i before a charging station becomes available
$\tau_{i,k}$	Variable representing the arrival time of truck k at hub i
$\sigma_{i,k}$	Variable representing the departure time of truck k from hub i

4.3.3 Objective

The objective of the model is to maximize the number of feasible routes, while considering the associated costs, including costs for actions, such as waiting or detouring, which make an infeasible route segment feasible. Each route consists of multiple segments, and for a complete route to be considered feasible, every individual segment must also be feasible. If even one segment in the route sequence is infeasible, then the entire route is classified as infeasible.

Note that this model adopts a descriptive, heuristic approach rather than a prescriptive optimization framework. Its purpose is to reflect realistic operational decisions and constraints in a middle-mile context, allowing for practical scenario evaluation rather than mathematically optimizing a transportation problem.

Initial costs are incurred based on the driving distance covered by the truck. The model calculates the driving costs per unit distance, which reflects the operations expenses associated with moving the truck from location i to location j.

If a truck needs to detour to reach a charging station at an alternative hub, costs are incurred based on the additional distance traveled during the detour. In the model, detouring distance and waiting time are treated equally in terms of costs, as for both situation the delay is measured in minutes. Note that the additional recharging time is also incurred for the same unit costs, as this also ensures for extra delay time.

When a truck arrives at a hub and must wait for a charging station to become available, costs are incurred for the duration of the wait. This includes the time spent waiting for access to the charger, as well as the time required for recharging the truck to the necessary SoC The model accounts for these waiting costs to ensure that all potential delays are factored into the overall cost assessment.

If due to a delay a truck arrives later than the upper bound of its scheduled time window at the next destination, it incurs high penalty costs for violating the time window. These penalties are significant because they reflect the operational impact of delayed deliveries, which for example can affect customer satisfaction and service reliability. The model calculates these costs based on the duration of the delay and applies a penalty rate per minute to quantify the financial implications of late arrivals.

Further, another cost component is the one for enlarging the search space for detouring if a truck cannot charge at its current location and has a too small SoC to reach another location, while still meeting the arrival threshold of 20%. This cost component is explained in more detail in Subsection 4.4.3.

4.3.4 Constraints

The constraints for the initial plan and determination of route feasibility, in accordance with the assumptions and requirements defined in the previous two subsections, are outlined, and explained below.

Flow constraints

$$\sum_{j \in H} x_{i,j,k} = \sum_{j \in H} x_{j,i,k} \leq h_{i,k} \qquad \forall i \in DC, \forall k \in K \qquad (4.2)$$

$$\sum_{j \in H, j \neq i} x_{i,j,k} = \sum_{j \in H, j \neq i} x_{j,i,k} \qquad \forall i \in H, \forall k \in K \qquad (4.3)$$

Constraint (4.2) ensures that each truck begins and ends its route at exactly the same DC. Further, constraint (4.3) maintains a balanced flow at each hub, which ensures that if a truck arrives at an intermediate destination, it must also depart from that location after servicing.

Time Constraints

$$\sigma_{i,k} = \tau_{i,k} + \max\,(bt_{i,k}; ut_{i,k} + lt_{i,k}) \qquad (4.4)$$

$$\tau_{j,k} = \sigma_{i,k} + t_{i,j} x_{i,j,k} \qquad (4.5)$$

$$a_i \leq \tau_{i,k} \leq b_i \qquad \forall i \in H, \forall k \in K \qquad (4.6)$$

$$\sum_{(i,j) \in H} t_{i,j} x_{i,j,k} + \sum_{i \in H} (bt_{i,k} + lt_{i,k} + ut_{i,k}) \leq S \qquad \forall k \in K \qquad (4.7)$$

Constraint (4.4) establishes that the arrival time at hub is determined by the travel time and the duration of activities performed at the previous hub. Constraint (4.5) calculates the actual travel time, while (4.6) specifies the time windows for the start time of servicing at each hub. To ensure operational efficiency, constraint (4.7) limits the working time to not exceed the maximum shift duration.

Charging Time Constraints

$$ct_{i,k} \leq \max\big(bt_{i,k}, lt_{i,k} + ut_{i,k}\big) \qquad i \in H, k \in K \qquad (4.8)$$

$$ct_{i,k} \leq \sigma_{i,k} - \tau_{i,k} \qquad i \in H, k \in K \qquad (4.9)$$

$$ct_{i,k} \leq \frac{(100\% - SOC_{i,k}) * B}{100\% * P_i} \qquad (4.10)$$

Above, constraints regarding the charging time at a hub are presented. Constraint (4.8) ensures that the charging time does not exceed the maximum break duration and service duration at a hub. Since these two durations can overlap, the truck remains stationary at the dock for the longest time of these two. Further, constraint (4.9) ensures that the charging time must not exceed the difference between a truck's departure time and arrival time at a hub. Next, constraint (4.10) ensures that if the truck is charged to full capacity, the charging time does not exceed the time required to achieve this level of charge, preventing any overcharging.

Battery and Energy Constraints

$$SOC_{j,k} = SOC_{i,k} + y_{i,k}\left(\frac{(\alpha_i \lambda_{i,k})}{B} * 100\%\right) - \left(\frac{(e_{i,j} x_{i,j,k})}{B} * 100\%\right) \qquad \forall i,j \in H, \; k \in K \qquad (4.11)$$

$$SOC_{i,k} \geq 100\% * h_{i,k} \qquad i \in DC, k \in K \qquad (4.12)$$

$$SOC_{j,k} \geq SOC_{min} \qquad \forall j \in H, k \in K \qquad (4.13)$$

$$SOC_{i,k} + y_{i,k,t}\left(\frac{ct_{i,k} * P_i}{B} * 100\%\right) \leq 100\% \qquad \forall i \in H, k \in K \qquad (4.14)$$

$$\sum_{k \in K} x_{i,j,k}\, y_{j,k,t} \leq c_j \qquad \forall i,j \in H \qquad (4.15)$$

Next, constraint (4.11) calculates the SoC upon arrival at a hub, considering the SoC from the previous hub, the energy recharged at the that hub, and the energy consumed during the recently traveled route segment. To ensure that each truck always starts its route with a full charged, constraint (4.12) is added to the formulation. Further, (4.13) and (4.14) calculate the recharging and consuming rate, respectively. A threshold that must be met is set by (4.15), such that a route segment is only considered to be feasible if the SoC of the eTruck meets that threshold. Constraint (4.14) ensures that this same SoC can never exceed 100%, such that the truck's battery can never be charged beyond its maximum capacity. As last, constraint (4.15) sets an availability limit for charging stations at each hub: no more trucks can be charged at a hub than it is equipped with charging stations. In this constraint, for each timestep t which in this model is each minute of the day, the model sets a binary value for $y_{j,k,t}$, which states whether truck k charges at hub j at time t.

4.4 Generic Solution Method: Solution Methodology

Upon the arrival of an eTruck at a hub, multiple decisions must be made regarding its recharging needs. These decisions depend on the availability of charging stations and the number of eTrucks arriving at the hub in the same time interval. Two key decisions need to be addressed: first, how to assign simultaneously arriving eTrucks to the available charging stations, and second, what to do with the eTrucks that cannot be assigned to a charging station at the hub they currently visit.

The decision which eTruck to assign a charging station is based on the type of charging required, which can be opportunity charging or priority charging. Once this assignment is made, any eTruck that cannot be allocated to an available charging station has two options: they can either wait for a station to become free at the current location or proceed to another hub where they can recharge. The model operates based on four distinct scenarios that an eTruck may encounter, as illustrated in the flow chart below. This figure is included in Appendix E, where it is shown in a larger size for better readability.

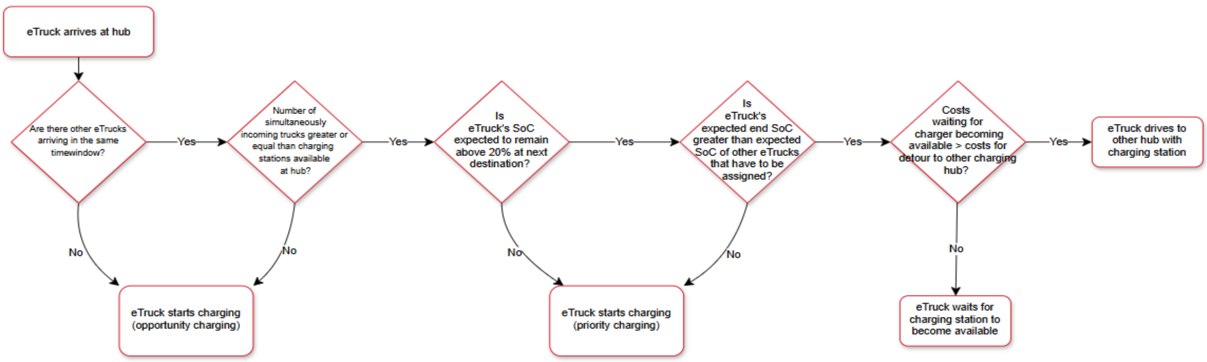

Figure 21) Flow chart visualizing charging prioritization

4.4.1 Arrival scenarios

Upon arrival at a hub, a truck can face five scenarios based on the number of stations the hub is equipped with, and the number of stations that are occupied upon arrival. Below, these five scenarios are defined:

Scenario I – Opportunity Charging with no other incoming trucks

If a truck arrives at a hub and no other truck is expected to arrive within the service duration of this truck, the truck will always charge. This situation represents opportunity charging, where the truck can recharge without any concern for limited resources, since no other vehicles will be asking for charging stations. Thus, if an eTruck arrives, and no other trucks are expected soon, it will be able to recharge at the hub regardless of its battery level or time of arrival. This helps to increase the probability of remaining the SoC above the arrival threshold for later segments in the same route. Additionally, this helps to decrease the amount of energy that has to be charged to the truck, to make it available for the subsequent route it is going to drive.

Scenario II – Multiple Trucks arrive simultaneously: more charging stations available than number of incoming trucks

If multiple trucks are scheduled to arrive at the same hub in a specific time window, but this number is lower than the number of charging stations at this hub, then all trucks will be assigned a charging station. This is still considered opportunity charging, as there are enough stations to accommodate all truck, which means no prioritization rules have to be applied. So, for example, if five eTrucks arrive in the same time window, and the hub has eight charging stations, all five trucks will be able to charge without any issue. This is due to the fact that the truck demand does not exceed the station availability. For this scenario, the same logic as for Scenario I holds.

Scenario III – More trucks arrive simultaneously than charging stations available

In the event that during a specific time interval more trucks are scheduled to arrive at a hub, than there are available charging stations, priority charging will be enforced. This means that only a number of trucks equal to the available charging station are assigned a charger. Trucks can be prioritized based on factors such as their arrival times or battery levels. Subsection 4.4.2 outlines various rules for managing this scenario.

Scenario IV – eTruck does not get a charging station assigned directly upon arrival

If a truck is not assigned a charger at a hub, but it actually needs a recharge to reach the next destination, the method considers two options: it either lets the truck wait for a charging station to become available or it lets take the truck a detour to another hub for recharging. Further details on this process are outlined in Subsection 4.4.3.

Scenario V – eTruck arrives at a hub without charging station

Another scenario is that an eTruck has a scheduled arrival at a hub in its route sequence which is not equipped with a charging station. In this case, charging is logically not available, which means that for these kind of hubs opportunity and priority rules do not have to be applied.

Below, the different scenarios are summarized.

Table 1) Summarization of arrival scenarios eTrucks in GSM

Charger available at hub?	More simultaneous arriving trucks than charging stations available at a hub?	Is truck prioritized?	Type of charging	Corresponding scenario(s)
True	False	False	Opportunity charging	I, II
True	True	True	Priority charging	III
False	True	False	No charging station avaialble	IV
False	False	False	No charging station available	V

4.4.2 Charging strategy: Which truck to give priority in case of congestion?

As discussed in the previous subsection regarding Scenario III, a truck may encounter a situation upon arrival where the number of arriving trucks exceeds the available charging stations. Note that in the remainder of this thesis, “simultaneous arrival” refers to the situation in which multiple trucks arrive at a location while having overlapping service intervals. In this case, a decision must be made regarding which trucks will receive priority for charging. The following options, drawn from queuing theory, are outlined:

First-Come, First-Served (FCFS): This method prioritizes trucks based on their arrival time. The truck with the earliest arrival time is the first to receive a charging station, and subsequent trucks are selected in the order of their arrival. This approach is straightforward and promotes fairness, as it treats all trucks equally based on their arrival sequence.
Last-Come, First-Served (LCFS): In contrast to FCFS, this method prioritizes the truck with the latest arrival time. This approach may be useful in situation where newer arrivals have urgent operational needs or are at a higher risk of running out of charge.

Random selection: In this approach, trucks are selected randomly from the queue to receive access to a charging station. Although this method seems arbitrary, it can help eliminate biases and ensure that all trucks have an equal opportunity to be served. In this case, each truck has the same probability of being selected, which can be calculated by dividing one by the total number of trucks requesting charging.

Prioritized selection: The priority charging logic follows two main rules. First, trucks that are unable to reach their next destination due to SoC is expected to drop below 20%, will be given the highest priority. Note that next decision is given. This ensures that trucks that are critically low on power and cannot complete their journey without charging are taken care of first.

After addressing the trucks with the lowest SOC, the next priority is determined by the expected SoC at the end of a truck’s route. Trucks that are expected to have the lowest remaining SoC at the end of their journey will be prioritized next, ensuring that they are charged before their SoC becomes critical. For example, if six trucks arrive at a hub with only five charging stations, priority will be given to the truck(s) that cannot complete their next trip due to a SoC below 20%. Then, for the remaining stations, trucks will be prioritized based on their expected SoC at the end of the route.

The options outlined above are illustrated below in a scenario where three trucks have overlapping service windows, as they are all arriving and departing in each other time intervals. In the visualized scenario, there is only one charging station available, meaning that only truck can be selected for recharging at any given time.

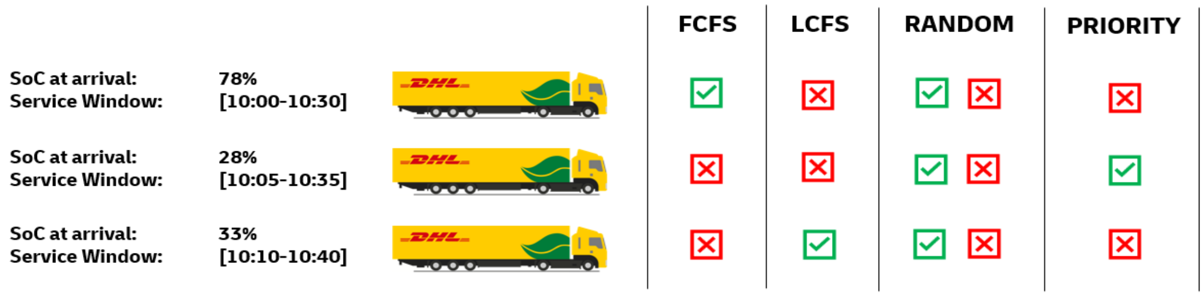

Figure 22) Four charging assignment policies

4.4.3 Managing infeasible trips

When an eTruck is not assigned a charger at a hub due to priority rules, as discussed in previous section, but requires one to reach its next destination, a trade-off must be made regarding its subsequent actions. If the truck proceeds without charging, it will be unable to complete the journey to the next scheduled stop. In such situations, the truck faces to options: it can either wait for a charger to become available at its current location or detour to an alternative site that has a charging station.

$$\text{trade off} \ = \begin{cases} \text{wait for charger becoming available at current location} \\ \text{detour to an alternative location with charging station} \end{cases}$$

The trade-off between waiting and detouring is applied only to route segments that are not feasible, meaning that the truck cannot continue its journey due to not having a charging station assigned at the current hub directly upon its arrival at that hub. This trade-off scenario is only relevant when the current hub is equipped with a charging station. If the location is not equipped with any charging stations, a truck can never charge here and has to perform charging activities elsewhere. If the hub has charging stations available but none are assigned to the truck, the method must decide whether the truck waits for a charger or detours to an alternative location. Note that if the truck has enough SoC to reach its next destination, the trade-off is not made, and the truck just drives to the next destination.
In cases where the truck is at a hub that does not have any charging stations at all, waiting is not an option, and the truck must detour to the nearest hub that does have a charger, after it has finished its unloading/loading activities at the current location. The decision-making process is thus focused on finding the best balance between the waiting for a charger and the detour distance to another hub with available charging stations.

Waiting time
The determination of the waiting time for an available charging station depends on several factors, including the number of charging stations available, the departure times of trucks with higher priority, and the truck's own arrival time relative to the charging queue. To determine this waiting time, the method first identifies all trucks that are currently charging and have priority over the waiting truck. Among them, it finds the earliest departure time and calculates the waiting time as the difference between this departure time and the arrival time of the waiting truck.

For example, imagine a hub is only equipped with two chargers, while three trucks arrive in each other service intervals, such that these have overlap. Below, this is visualized in Figure 23. If Truck 2 requires a recharge to reach its next destination, but Trucks 1 and 3 have higher priority and are already assigned to a charging station, regardless of the chosen charger assignment policy, the method determines that Truck 2 has the option to wait until a charger becomes available. If the trade-off results in the truck choosing this option, the truck's waiting time for a charging station equals the difference between its own arrival time and the earliest departure time of one of the trucks that is currently being recharged, which obviously is Truck 1.

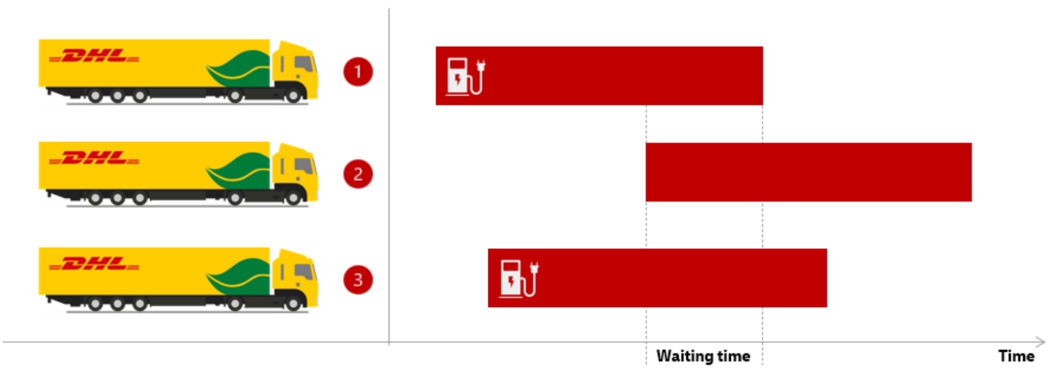

Figure 23) Visualization of 'waiting time' for a charging station becoming available

Detour
For the detour option, the hub to visit for recharging must be identified. This decision-making process begin with evaluating the current SoC of the and the distance it can still travel while meeting the arrival threshold at the next destination. This is calculated using the following formula:

$$\text{Remaining travel range (km)} = \frac{(\text{Current SoC} - \text{Arrival Threshold}) * \text{Usable Battery Capacity}}{\text{Average energy usage}}$$

For each infeasible trip of each truck, the method utilizes the distance matrix to assess the distances from the current location to all potential charging locations. If the distance to a hub with an available charging station upon arrival there is less than the remaining acceptable travel range of the eTruck, that location is considered reachable and is subsequently included in the search space for the truck. It is important to note that the size of the search space is influenced by two factors, including the current SoC of the truck and the overall complexity of the problem instance. This is illustrated in the visualization below, where the blue circle represents the remaining travel range of an eTruck with a 35% SoC, while the orange circle indicates the range for an eTruck with only 25% SoC.

Furthermore, the distinction between smaller and larger problem instances is significant. In instances with a greater number of Distribution Centers and Customers equipped with charging station, all within the same grid size, the likelihood of proximity to a charging station increases. This means that as the problem instance expands, the accessibility of charging stations becomes more evident. Obviously, any charging locations that fall outside the designated circle for a specific truck are unreachable by that truck and, consequently, are not included in the search space for that particular vehicle. As a result, these locations are never selected as alternative charging location in the search process. It is important to note that while Euclidean search spaces are utilized within a theoretical framework, actual distances in real-world scenarios are not Euclidean. Nevertheless, the concept of a search space remains relevant, as it is defined by the remaining travel distance.

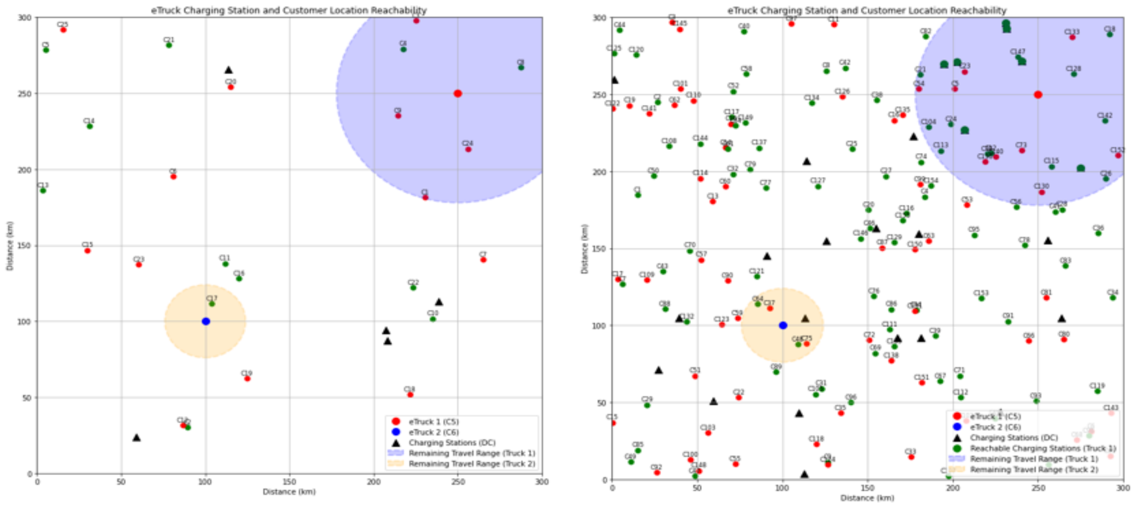

Figure 24) Search space of trucks with different SoC's

In some cases, it occurs that the SoC at the current location of the truck is close to 20%, which ensures the remaining travel range to be approaching zero. In cases where the current location is not equipped with chargers and detouring is the only option, the GSM enlarges the search space by reducing the arrival threshold to 10%, which increases the search space. This allows the GSM to find a charging location for trucks being in such a situation, while having a small remaining travel rang. As this situation is normally not allowed, this deduction comes with high penalty costs, which are discussed in Section 5.3.

Once the search space is defined, the GSM efficiently identifies the best charging location within that space. This location minimizes the total distance, which is the sum of the distance from the current position to the charging location and from the charging location to the next scheduled destination. As illustrated below, this approach ensures that integrating a charging stop at an alternative location ensures in the shortest possible detour. In the example provided below, the shortest route is presented by the solid arrows, which indicate a shorter distance compared to the dashed alternative.

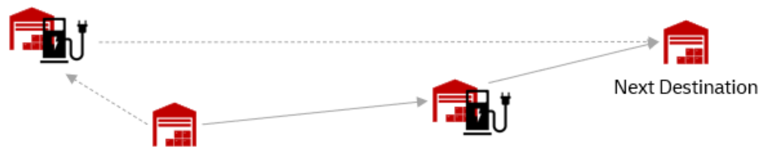

Figure 25) Logic of selecting best alternative charging location

Waiting versus detouring
After the GSM calculated the waiting times and the detouring distances (and related travel times) the trade-off can be established. Note that the trade-off only is done for an infeasible route segment under the condition that at the current location a charging station is available. If this this not the case, then the truck always searches for an alternative charging location. In the GSM, this is forced by setting the waiting costs to a big number (10^6) such that this option is never chosen in the trade-off.
Within finding the best new charging location within the search space, one particular situation can occur. In the event that a truck is currently charging at a location, but the recharge duration is not sufficient for recharging enough energy to be able to reach the next destination, this segment is still considered as infeasible. Then, the GSM sets the waiting time to a high number such that this option is never chosen, as this is not possible as the truck is currently assigned a charger at the current location. However, in the search for the new charging location, it can occur that the current location still has a charging station available for the additional needed recharge duration. In that occasion, the truck chooses the current hub as detour hub as it has the lowest detour distance, which equals logically zero. Therefore, the delay costs are a way lower than for other locations in the same search space.

In case the truck has both the option to wait or detour to perform a recharging moment, the truck is charged for the duration that ensures the truck has sufficient charge to reach its next destination. This duration can be determined based on the state of charge at the start of charging, and the energy requirement for the remaining travel distance to the next scheduled destination. With the charging power, this duration can be calculated as follows:

$$\text{Recharge duration (minutes)} = \frac{\text{energy requirement for trip} - \text{current battery level} - \text{arrival threshold}}{\text{Charging power}} * 60$$

When considering whether to wait or detour, the recharge duration must be added to the waiting time on both occasions. The truck’s total down time will not only include the time spent waiting for a charger, but also the actual time it spends recharging to the required state of charge. However, if there is still overlap between the initial schedules unloading/loading times and recharging time, this overlap may be subtracted from the total waiting time, as these times were initially scheduled. The formula below gives the waiting costs for a truck. Note that the times are in minutes.

$$\text{Waiting costs for truck k} = (\text{Waiting Time} + \text{Recharge Time} - \text{(Un)Loading Time}) * \text{Cost per minute waited}$$

In case a truck detours, the costs are given by the formula given below. Note that if a truck detours to an alternative location, the truck does not perform unloading/loading activities at that hub. Therefore, in this situation this duration is set to 0, ensuring no reduction in the overall time the truck is not driving. Therefore, the (un)loading time can be removed from the formula.

$$\text{Detour costs for truck k} = (\text{Detour Travel Time} + \text{Recharge Time} - \text{(Un)Loading Time}) * \text{Cost per minute detoured}$$
$$\text{Detour costs for truck k} = (\text{Detour Travel Time} + \text{Recharge Time}) * \text{Cost per minute detoured}$$

Additionally, the time required for the truck to wait, or detour could affect truck’s arrival time at the next scheduled destination, which actually is not allowed. Therefore, such occasions lead to a late arrival penalty if the truck misses its scheduled window. Therefore:

$$\text{Late arrival penalty costs} = \text{Late arrival Time} * \text{Penalty per minute of delay}$$
$$\text{Late Arrival Time} = \text{Arrival Time} - \text{Upper bound arrival time window}$$

Decision-making process
The GSM will compare the total cost for both waiting and detouring and eventual late arrival penalty costs, due to late arrivals at a later moment in the route sequence. The optimal decision minimizes the total delay costs, which could include any combination of waiting costs or detours costs and penalties for late arrivals. In this way, it is ensured that the truck follows the most efficient and cost-effective path while visiting all nodes in the scheduled route.

$$\text{Total delay costs for waiting} = \text{Waiting Costs} + \text{Late Arrival Penalty Costs}$$
$$\text{Total delay costs for detouring} = \text{Detour Costs} + \text{Late Arrival Penalty Costs}$$

Subsequent to this, the GSM chooses the option which has the lowest total delay costs. In case the truck waits at a location for a charger becoming available, then the truck additional waiting time and recharging time are added, which has impact on the arrival times at next locations. In this case, the route sequence is not modified. However, if the truck detours to another location, this location is added to the route sequence in the middle of the locations for the segment which was initially infeasible. Then, the GSM updates the feasibility status of this segment to true, which ensures the complete route to be feasible.

As summarized output of the GSM, the total feasibility percentage of the initial plan is given including the total costs, which is then just the sum of the transportation costs, which are a result of just driving between locations. Next to this, the GSM outputs the feasibility percentage of the new plan and its costs, which also include the total delay costs for waiting and detouring.

4.6 Generic Solution Method: Implementation of Local Search

As DHL is currently in the situation that there is not one electric truck integrated in the middle-mile process yet, the order in which to make actually infeasible routes feasible. Suppose a logistics provider only has a specific budget available for improving the number of feasible routes for electrification. Then, it is crucial to identify a configuration of trucks that maximizes the feasibility percentage while keeping the total delay costs, incurred by implementing an option from the trade-off between detouring or waiting, below the budget limit. However, it is important to note that detouring or waiting at certain location along the route may not always lead to the overall feasibility of the complete route, which means that some improvements are ineffective if they are applied.

To optimize the configuration of trucks and ensure that the applied improvements (detouring or waiting) lead to the highest possible increase in feasibility percentage, a combination of a swap method and simulated annealing is employed.

In each iteration, the algorithm performs a swap in the status for improvement application status for truck currently following infeasible routes. If a truck's status is set to true, it indicates that the truck will wait or detour at a selected point in its route, such its route structure is adjusted in order to improve the feasibility status. Conversely, if the status is false, the truck just is scheduled to drive its original route, which may result in an infeasible outcome.

Simulated annealing is then applied to explore the solution space and identify the best configuration of trucks for which the improvements are applied, ensuring that the total additional delay costs remain within the budget cap. This method allows for the systematic adjustment of the improvement application status to maximize the feasibility percentage while having budget constraints.

Swap Method
The swap method is a local search technique used to explore different configurations of solutions. In this context, it involves exchanging the improvement application status between two trucks. By swapping these statuses, the algorithm evaluates the impact of applying or not applying the improvement for each

truck on the overall feasibility of the routes. This method allows for the exploration of different combinations of improvements, providing insights into which configurations yield better feasibility outcomes.

Simulated Annealing

Simulated annealing is a probabilistic optimization technique, which is designed to help escape local optima during the optimization process. The method begins by generating an initial solution at a specified starting temperature. From this initial solution, a modification is made to create a neighbouring solution. If this solution is better than the current solution, it is always accepted. However, if the neighbouring solution is worse, it may still be accepted on a probability that decreases as the quality of the solution declines and as the temperature decreases. The temperature is gradually reduced according to a cooling constant (α), with the goal of decreasing the likelihood of accepting inferior solution over time.

For this process, the initial temperature is set to 1000, such a greater exploration of the solution space is allowed, which enables the algorithm to accept poorer solutions that can help to escape local optima. This setting is essential when starting from an arbitrary solution, as it encourages a broader search. Further, the final temperature is set to 1, which ensures that, as the algorithm converges, it becomes more selective. This ensure that improvements are favoured over random exploration. This cooling schedule is important for balancing exploration and exploitation.

The probability measure for accepting to replace the current solution with the neighbour solution is defined by the following equation :

$$P = \exp\left(\frac{-\Delta E}{KT}\right)$$

Where ΔE indicates the difference between the best objective and the objective of the current neighbourhood. K is the Boltzmann constant, and T is the control parameter at a given iteration, or in other words the temperature. A typical value for the Boltzmann constant K is 1, which is also used. This probability measure allows for a selection of a solution that is not improving the current solution, which helps the algorithm to escape from local optimums (Gogna, 2013).

Further the cooling rate is set to 0.95, which determines the pace in which the temperature decreases over the iterations. In this case, the temperature is multiplied by 0.95 after each iteration, leading to a gradual decrease. This setting ensures for a balance between exploration and converge, allowing the algorithm to adaptively refine its search as it approaches the final solution.

In this study, the stopping criterion is set to a maximum of 10 iterations without improvement. This prevents the algorithm from running indefinitely and ensures it converges to a solution in a reasonable timeframe. If no improvement is observed for 10 consecutive iterations, the search is terminated.

In appendix J, pseudocode is added to explain the working of the combination of the swap method and simulated annealing.

4.7 Conclusion

As the research question for this chapter focuses on how to develop a method for evaluating the electrification potential of routes, an evaluation method has been created to assess the feasibility of electrifying DHL's middle mile routes. This method incorporates key input parameters, such as truck specifications, including usable battery capacity and average energy usage per kilometer. Using data obtained from DHL's OPC tool, the EM checks for each route segment if it meets the arrival threshold, such it is feasible for electrification or not. The output includes detailed assessments for each route, enabling an understanding of why a route is classified as feasible or infeasible, along with a summarized overview of the total number of feasible and infeasible routes.

To address the challenge of multiple trucks simultaneously demanding a charging station at any location, the GSM is introduced. The primary objective of the GSM is to maximize the percentage of feasible routes while minimizing associated delay costs, which include driving costs, waiting costs, detouring costs, threshold lowering costs, costs incurred due to extra recharge time, and penalty costs for time window violations. These costs are crucial as they directly influence the operational efficiency of electrifying routes.

A key feature of the GSM is its ability to manage the trade-off between waiting for a charging station to become available and detouring to an alternative location for recharging. When a truck, which needs a recharge, arrives at a hub and cannot immediately access a charger, it faces the decision to either wait at the current location or detour to another hub with a charging station available at the moment it arrives there. This trade-off is evaluated based on which option results in lower overall costs, including costs for waiting times, additional travel distances, and potential time window violations. By systematically assessing these options, the GSM minimizes the costs for each truck that is in such a situation.

The experimental setup for the GSM involves three problem sizes, reflecting varying numbers of locations (DCs and customers) and trucks within the network. Each experiment simulates multiple scenarios over a specified number of days, allowing for a comprehensive evaluation of how different charger assignment policies and the wait/detour options affect the feasibility of electrifying routes.

To identify the optimal configuration of trucks within a defined budget limit, the GSM uses a combination of the Swap method and Simulated Annealing. The Swap method facilitates the exploration of different configurations by exchanging the improvement application status between trucks, enabling the method to assess the impact of applying or not applying specific improvements (waiting or detouring) on overall route feasibility. Simulated Annealing enhances this process by providing a probabilistic approach to escape local optima, systematically exploring the solution space to find the best configuration that maximizes feasibility while keeping total delay costs within budget constraints. Together, these techniques ensure that the GSM effectively identifies the most cost-efficient configuration for integrating electric trucks into a transportation network.

5 Results

In the previous chapter, both the Evaluation Method and the Generic Solution Method were introduced. Section 5.1 outlines the experimental setup used for both methods. Section 5.2 presents the results and provides an analysis of how varying input parameters affect the feasibility of electrifying routes. Similarly, Section 5.3 present the results for the Generic Solution Method. Section 5.4 describes the validation of both methods by comparing their outputs to real-world pilot data. Finally, Section 5.5. summarizes the key conclusions drawn from the analyses of both methods. Below, the research question addresses in this chapter is presented again:

? What performance can be expected of the implementation of electric trucks in DHL's middle mile network?

5.1 Experimental Settings EM

In this section, the set-up parameters and input data for the Evaluation Method are presented. A dataset comprising 352 BNL routes was used for this evaluation. These routes vary in terms of distance, homebase hubs, and the sequence of hubs visited. In section 2.5, the distribution of distance of these 352 routes is presented in a histogram with different distances, and it was shown that over 50% of the routes have distances between 300 and 500 kilometers.

The default input parameters settings applied in the initial evaluation are as follows:

Usable battery capacity:	500 kW
Charging power:	150 kWh
Energy usage:	1.25 kWh:km
SoC arrival threshold:	20%
Charging locations:	**B**, **H**, **I**, **N**, **O**, **P**

Although the electric trucks described in Section 2.6 typically have usable battery capacities of 400 kWh and 600 kWh, a default capacity of 500 kWh is used here to provide a balanced baseline for analysis. In the following subsection, a sensitivity analysis is conducted to examine how variations in the above input parameters affect route feasibility.

The charging power is set to 150 kW based on insights from Section 2.4, where it was shown that construction costs and costs for maintaining charging station significantly increase when the charging power is higher than 150 kW. By selecting 150 kW as default input parameter, the EM uses this as baseline parameter, such that the effect of using higher power can be measured.

The SoC arrival threshold is set at 20%, as discharging batteries below this level is known to accelerate battery degradation and reduce long-term battery health. This threshold ensures that the evaluation aligns with best practices in battery management.

The six charging location listed above are based on the analysis in Subsection 2.4.1, which identified hubs with sufficient remaining grid contract capacity. These locations are considered feasible for short-term deployment of charging infrastructure, making them a realistic and practical choice for this evaluation.

5.2 Results of Evaluation Method

In this section, the results of loading the route data into the evaluation method are presented. Using the intermediate input parameters as presented in Subsection 5.1.1, the EM determined that 142 out of the 352 routes are feasible for operation by an eTruck, resulting in **40.34%** of all routes being feasible. Alongside a summary, the method provides a detailed overview for each route. Below, the summary output of the evaluation method is presented:

Table 2) Summary Output Evaluation Method

Evaluation Model Summarized Output	
Number of routes evaluated	352
Usable battery capacity and corresponding driving range	500 kWh (400 km)
Number of feasible routes	142
Number of infeasible routes	210
Percentage of feasible routes	40.34%

Subsection 5.2.1 provides detailed examples of the output generated by the EM, illustrating how it assesses route feasibility. Subsection 5.2. through 5.2.5 present the results of sensitivity analyses, showing how changes in input parameters affect feasibility scores. In Subsection 5.2.6, the EM is aligned with real-world specifications of electric truck to relate its practical applicability. Finally, Subsections 5.2.7 and 5.2.8 use the EM to identify which hubs in the network are most suitable for the installation of charging stations.

5.2.1 Detailed examples of output of Evaluation Method

As previously mentioned, the EM offers comprehensive overviews for each route separately, allowing for a thorough analysis of the feasibility of each route. As an example, below, the outputs for four distinct routes are analyzed, all facing a different scenario during the route. Due to confidentiality, route names are fictive according to the letters presented in Figure 11 in Section 2.4.1.

ROUTE I16	Route feasible to drive on one charge
ROUTE I53	Route feasible due to recharging moments at intermediate hub(s)
ROUTE P52	Route infeasible due to lack of charging stations at intermediate hubs
ROUTE P13	Route infeasible despite having recharging moments at intermediate hub(s)

ROUTE I16: Route feasible to drive on one charge

ROUTE I16 is a route that starts from the Region Hub **I**, which serves as the truck's homebase. It is one of the few routes that can be completed on a single charge for a truck with a battery capacity of 500 kWh. The route starts in **I**, proceeding to **[LOCATION]**, and then visiting hubs **[LOCATION]** and **[LOCATION]**, before returning to **I**, which is the homebase. Notably, there are no charging opportunities along this route, meaning that no intermediate charging can be scheduled. The truck is calculated to return to its homebase with a SoC of 21.25%, which meets the required threshold, thus confirming the route's feasibility.

Table 3) Detailed evaluation Output for ROUTE I16

RouteID	Origin	Destination	Distance	Energy Required for this Part	Departure Energy Level	Arrival Energy Level	Energy Recharged	Departure SoC (%)	Arrival SoC (%)	Charger at destination	DestinationType	Feasible	Unloading/Loading Time	Break Time	Total Idle Time	Recharging Time (minutes)	Carrier
				confidential				100	95,5	FALSE	Intermediate hub	TRUE	26	0	26	24	DHL
								95,5	57,25	FALSE	Intermediate hub	TRUE	26	60	60	24	DHL
								57,25	57	FALSE	Intermediate hub	TRUE	20	0	20	24	DHL
								57	21,25	TRUE	Homebase	TRUE	0	0	0	0	DHL

ROUTE I53: Route feasible due to recharging moments at intermediate hub(s)

The following details relate to route **I53**, which starts from **I** and visits the hubs in **[LOCATION]**, **[LOCATION]**, and **[LOCATION]**. As noted, charging is available at the second intermediate destination **[LOCATION]**, allowing the method to schedule recharging here. Here, the recharging time is calculated as max {unloading/loading time, break time} multiplied by 0.8, as explained in Chapter 4. Upon returning to **I**, the truck is calculated to arrive with a SoC of 22.25%, which is slightly above the required arrival threshold. According to the EM, without the 48 minute recharge in **[LOCATION]**, which contributes an additional 24% to the SoC, the method gives as output that the truck would not have been able to return to its homebase in **I**.

Table 4) Detailed evaluation output for ROUTE I53

RouteID	Origin	Destination	Distance	Energy Required for this Part	Departure Energy Level	Arrival Energy Level	Energy Recharged	Departure SoC (%)	Arrival SoC (%)	Charger at destination	DestinationType	Feasible	Unloading/Loading Time	Break Time	Total Idle Time	Recharging Time (minutes)	Carrier
confidential								100	50,5	FALSE	Intermediate hub	TRUE	46	0	46	0	DHL
								50,5	47	TRUE	Intermediate hub	TRUE	46	60	60	48	DHL
								71	49,5	FALSE	Intermediate hub	TRUE	39	0	39	48	DHL
								49,5	22,25	TRUE	Homebase	TRUE	0	0	0	0	DHL

ROUTE P52: Route infeasible due to lack of charging stations at intermediate hubs

Below, output details for route P52, starting at Region Hub **P**, are presented. As visible, there are no charging stations available at intermediate destinations. The route is calculated to be feasible up to arrival in **[LOCATION]**. The critical issue arises in the final leg of the journey from **[LOCATION]** back to **P**, where the truck requires 197.44 kWh. However, with only 256.31 kWh available, the SoC is expected to drop to a level of 11.77% upon arrival. This level is insufficient for allowing the completion of the trip to be feasible, which means that the absence of charging stations at the intermediate hubs ensure that the truck is not expected to make it back to its homebase.

Table 5) Detailed evaluation output for ROUTE P52.

RouteID	Origin	Destination	Distance	Energy Required for this Part	Departure Energy Level	Arrival Energy Level	Energy Recharged	Departure SoC (%)	Arrival SoC (%)	Charger at destination	DestinationType	Feasible	Unloading/Loading Time	Break Time	Total Idle Time	Recharging Time (minutes)	Carrier
confidential								100	86,8	FALSE	Intermediate hub	TRUE	14	0	14	0	DHL
								86,8	66,63	FALSE	Intermediate hub	TRUE	14	30	30	0	DHL
								66,63	51,26	FALSE	Intermediate hub	TRUE	14	30	30	0	DHL
								51,26	11,77	TRUE	Homebase	FALSE	0	0	0	0	DHL

ROUTE P13: Route infeasible despite having recharging moments at intermediate hub(s)

Below, the output details for route P13 are presented. There are four intermediate hubs in the route sequence, where recharging is available at the third intermediate destination **[LOCATION]**. P13 is classified as infeasible despite having the possibility to recharge at an intermediate location. The energy demands of the route exceeds the vehicle's capacity to recover sufficient charge, ultimately leading to an inadequate SoC to reach the next location, including the homebase.

Table 6) Detailed evaluation output for ROUTE P13

RouteID	Origin	Destination	Distance	Energy Required for this Part	Departure Energy Level	Arrival Energy Level	Energy Recharged	Departure SoC (%)	Arrival SoC (%)	Charger at destination	DestinationType	Feasible	Unloading/Loading Time	Break Time	Total Idle Time	Recharging Time (minutes)	Carrier
confidential								100	81,13	FALSE	Intermediate hub	TRUE	26	30	30	20,8	DHL
								81,13	52,4	FALSE	Intermediate hub	TRUE	26	0	26	20,8	DHL
								52,4	43,48	TRUE	Intermediate hub	TRUE	26	30	30	24	DHL
								55,48	9,93	FALSE	Intermediate hub	FALSE	26	0	26	24	DHL
								9,93	3,13	TRUE	Homebase	FALSE	0	0	0	24	DHL

To summarize, the EM demonstrates the importance of strategically placed charging hubs in ensuring the feasibility of eTruck routes. The detailed analysis of Route **I53** highlights how intermediate charging can significantly impact the ability of an eTruck to complete its route. By ensuring that charging infrastructure is available at key locations, DHL can optimize the use of electric trucks and increase the number of feasible routes within its network.

5.2.2 Impact of battery capacity on percentage of feasible routes

Multiple eTruck manufacturers, such as Mercedes, Volvo, and Renault, are introducing various eTrucks with differing usable battery capacities and driving ranges to the market. To make an informed decision on which manufacturer and truck type to choose, it is important to study the impact of battery capacity on the percentage of feasible routes in the DHL network.

The battery capacity of an eTruck significantly affects the percentage of feasible routes it can cover. With a 400 kWh usable battery capacity, the feasibility percentage is 27.84%. Increasing this capacity to 500 kWh raises the feasibility percentage to 40.34%, and further increasing it to 600 kWh boosts the feasibility percentage to 53.69%.

The action range of the truck, calculated using the energy usage per km (1.25 kWh per km), plays a crucial role in determining route feasibility. For example, a truck with a 400 kWh battery capacity has an action range of 300 km, while a 500 kWh battery extends this range to 400 km, and a 600 kWh battery extends it to 500 km. In the pilot project, the Renault eTruck, with a 400 kWh battery capacity, was used. Another option is the Mercedes e-Actros 600, which offers a 600 kWh battery capacity. Volvo, DHL's current OEM for trucks, offers an eTruck with around 500 kWh battery capacity. These variations in battery capacity, and thus in route feasibility, should be considered. The next chapter will provide conclusions and recommendations.

5.2.3 Impact of energy usage on percentage of feasible routes

To understand the impact of energy usage on the feasibility percentage over all routes, the EM was run with multiple energy usage values ranging from 1.00 to 1.50 kWh per kilometer. According to expectations and as noted int the literature review, the energy usage of an eTruck is currently estimated at 1.25 kWh per km. However, there is a lack of information on how factors such as ambient temperature, driving style, and added payload affect the energy of an eTruck. Based on information provided in the literature review, it is known that these factors can cause the energy usage to be higher or lower than the estimated value.

To explore the impact of varying energy values on the percentage of feasible BNL routes, the EM was run over three battery capacities simultaneously. For each capacity, the EM calculated the feasibility percentages for energy usages ranging between 1.00 and 1.50, in steps of 0.01, which means that the method performed 150 iterations. In the figure below, the impact of varying energy usage on the feasibility of routes in the DHL network is illustrated. Logically, as the energy usage increases, the percentage of feasible routes decreases. This is because higher energy consumption reduces the effective range of the eTruck, making it more challenging to complete routes without recharging.

Furthermore, it is important to note the significant differences between the lines representing different energy capacities. At an energy usage of 1.25 kWh per km, the difference in the percentage of feasible routes between a capacity of 400 kWh and 500 kWh is 9%, while the difference between 500 kWh and 600 kWh is even greater at 11%. This highlights the substantial impact that increased capacity can have on route feasibility.

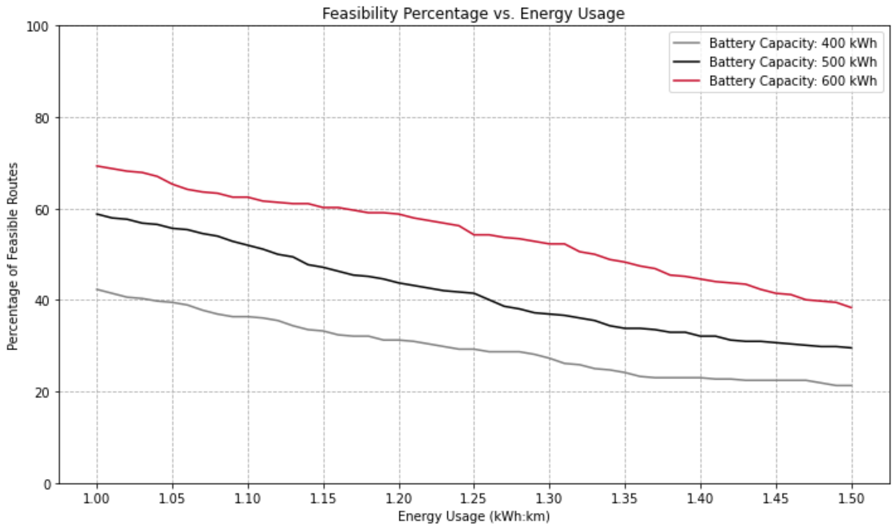

Figure 26) Feasibility percentages for different energy usages

5.2.4 Impact of charging power on percentage of feasibility of electrifying routes

To assess the impact of different types of charging stations used in the network, the EM was executing using four types of DC charging stations with powers of 150 kW, 300 kW, 400 kW and even 1000 kW. Including 1000 kW charging stations, also known as megawatt (MW) charging, is considered as it represents a potential future development. The analysis was conducted for eTruck with battery capacities of 400 kW, 500 kW, and 600 kW, allowing for a comparison of the differences between these truck types.

Below, the figures for each type of eTruck are provided. For the 400 kWh truck, the most significant improvement in feasibility percentage occurs when upgrading from a 150 kW charging station to a 300 kW charging station, resulting in an increase of 7.7%. Beyond this point, the feasibility percentages show minimal improvement with further increases in charging power. For the other types of trucks, the differences between the impacts of distinct types of chargers are even more minimal. Similar to the 400 kWh eTruck, the 600 kWh eTruck does not show any improvement when upgrading from a 400 kW to a 1000 kW charging station.

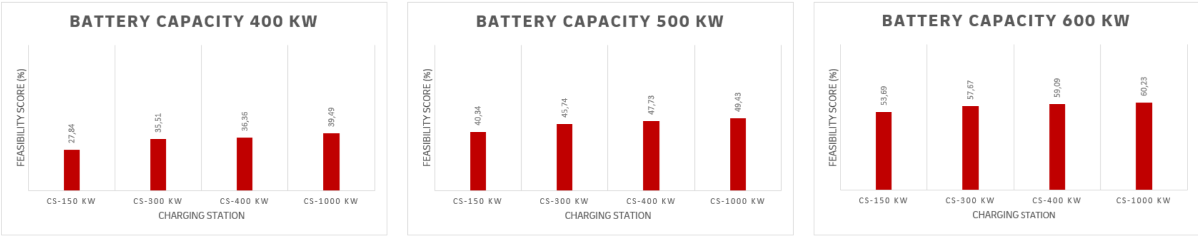

Figure 27) Impact of upgrading charging power on feasibility percentage.

5.2.5 Impact of modifying the State of Charge arrival threshold

By default, the SoC threshold that an eTruck must maintain upon arriving at any hub is set to 20% in this EM. This threshold acts as a safety buffer to manage risks and ensure that the eTruck has enough capacity to manage unforeseen circumstances, such as detours, and still reach the hub. In this sense, this threshold is a strategic decision that can be adjusted by management based on their risk tolerance. However, as mentioned in the literature review, in Section 3.1, driving with a SoC lower than 20% also ensures battery degradation, which ensures a decrease of the usable battery capacity after a certain period.
However, since driving with a SoC smaller than 20% is still possible, just as **Company XX** does (see Section 4.1), insights into how the percentage of feasible routes changes with different SoC threshold can be interesting. An analysis is conducted with threshold ranging from 1% to 40%. Note that in this analysis, the other default settings still apply. Thus, the calculations are done with an energy usage of 1.25 kWh per kilometer, charging stations providing 150 kW and a battery capacity of 500 kWh.

The results of this analysis are visualized in the figure below. For instance, for an eTruck with a 500 kWh battery capacity, if DHL decides to take on more risk by lowering the threshold to 10%, the feasibility percentage would increase from 43.47% to 51.99%, representing an increase of 8.52%. On the other hand, if DHL opts to be less risk-tolerant and raises the threshold to 30% instead of 20%, the feasibility percentage would decrease to 36.36%, which is a decrease of 7.11%.

This analysis provides valuable insights into how varying the SoC threshold impacts the feasibility of routes, helping DHL make informed decisions about the balance between risk and operational efficiency.

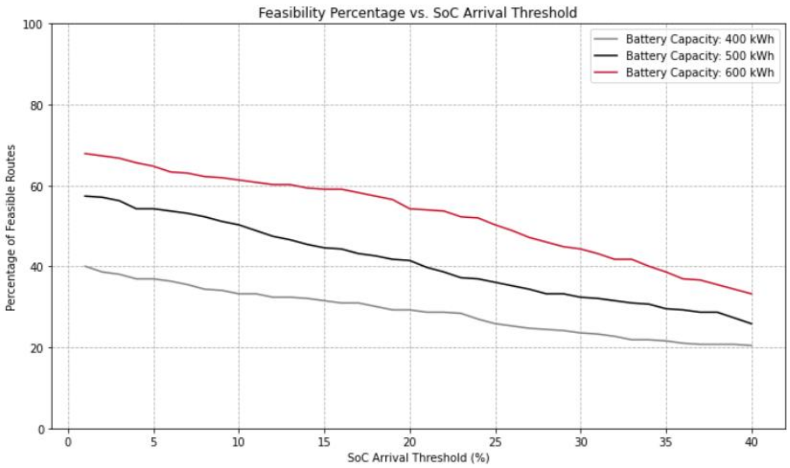

Figure 28) Impact arrival threshold on feasibility percentage

5.2.6 Aligning the Evaluation Method with reality

To provide insight into the performance of real-world trucks discussed in Chapter 2 and Section 5.1, the EM was executed using the usable battery capacities of three electric trucks: the Volvo FH Electric, the Renault e-Tech T, and the Mercedes eActros 600. Notably, both the Volvo and Renault Trucks have identical usable battery capacities, resulting in the same inputs and outputs for the EM. Below are the detailed results of this analysis.

Renault e-Tech T and Volvo FH Electric
Both the Renault e-Tech T, utilized during the pilot project outlined in Section 2.8, and the Volvo FH Electric, used in another pilot in February 2025, feature a usable battery capacity of 400 kWh. This capacity translates to an approximate driving range of 300 kilometers. When the EM was run for these trucks, the output below was generated, including a feasibility percentage of **27.84%**.

Table 7) Evaluation Method Output for Renault e-Tech T and Volvo FH Electric

Evaluation Model Summarized Output	
Number of routes evaluated	352
Usable battery capacity and corresponding driving range	400 kWh (320 km)
Number of feasible routes	98
Number of infeasible routes	254
Percentage of feasible routes	27.84%

This feasibility percentage is notably low and is primarily caused by the limited range of these trucks. Given that the average distances driven in the BNL network are around 500 kilometers, the 300 kilometer range falls short, making it challenging for these vehicles to complete longer routes without recharging. The lack of charging infrastructure at intermediate destinations further worsens this issue, limiting the operational viability of these trucks for longer hauls.

Mercedes eActros600
In contrast, the Mercedes eActros 600 offers a higher usable battery capacity of 600 kWh. Utilizing this enhanced capacity as an input parameter for the EM yields significantly different results, including a feasibility percentage of **53.69%**.

Table 8) Evaluation Method Output for Mercedes eActros 600

Evaluation Model Summarized Output	
Number of routes evaluated	352
Usable battery capacity and corresponding driving range	600 kWh (480 km)
Number of feasible routes	189
Number of infeasible routes	163
Percentage of feasible routes	53.69%

This represents a substantial improvement in feasibility, effectively doubling the percentage compared to the Renault e-Tech T and Volvo FH Electric. The increased battery capacity allows the Mercedes eActros to support a greater driving range, making it more suitable for longer routes typical in the BNL network. The higher feasibility percentage indicates that this truck can perform more effectively within the constraint of current lacking charging infrastructure, making it a more viable option.

5.2.7 Most strategic hubs in the network on the short term
In the DHL hub network, hubs are widely distributed across the BeNeLux region. The frequency of visits to different hubs by DHL-operated routes and sub-contractor routes varies significantly from hub to hub (see Appendix C). Additionally, the strategic importance of a hub as a location for charging stations is influenced by its position in the network and whether it has its own DHL fleet, and if so, especially its size.

As presented in Section 2.4, the hubs **B**, **H**, **I**, **N**, **O**, **P**, have space in their energy contracts, making them prime candidates for the initial rollout of charging stations in the DHL network. Therefore, the selection process, as explained in Section 4.2, is conducted for these six locations.

The primary criterion in this selection process is to identify the combination of hubs that results in the highest number of feasible DHL routes. This prioritization is based on the fact that locations with their own fleet are easier to electrify. In the event of a tie between multiple combinations, the combination with the highest number of feasible sub-contractor routes is chosen.

In line with the result that implementing a 600 kWh truck is the most optimal option, the selection process is conducted with this usable battery capacity. Further, the input parameters are the same as used in the EM. Specifically, recharging occurs via a DC charging station delivering 150 kW, and the energy usage is set to 1.25 kWh per km, while the arrival threshold is again set to 20%. hubs **B**, **H**, **I**, **N**, **O**, **P**

Applying these parameters, the selection process first chooses the combination of **H** and **I**. Subsequently, **N**, **B**, **P**, and **O** are gradually added to the combination. This final combination results in 19 DHL routes becoming feasible and 170 sub-contractor routes becoming feasible, with the percentage of feasible routes over the total number of evaluated routes equaling 53.69%. A more detailed analysis of each step in the selection process is provided in Appendix G **(confidential)**.

Table 9 Output for selection process of which hubs to equip with charging stations first

Combination	Total Routes Evaluated	Number of Feasible Routes	Number of Infeasible Routes	Percentage of Feasible Routes	Added Hub	DHL Feasible Routes	SubCo Feasible Routes
H, I [location names confidential]	352	156	196	44,32	I	Confidential	
H, I, N	352	164	188	46,59	N		
H, I, N, P	352	174	178	49,43	P		
H, I, N, P, O	352	183	169	51,99	O		
H, I, N, P, O, B	352	189	163	53,69	B		

In the DHL network, Central Hubs do not have their own fleet and are only visited by routes operated by both DHL and sub-contractors. Therefore, selecting these hubs depends solely on the number of visits. Although these hubs have the highest number of visits, the percentage of visits by DHL-operated routes is low compared to other hubs. Consequently, other hubs such as **H**, **I** and **N** are selected earlier. These hubs have a high number of own trucks, making them more strategic locations for charging stations.

B is chosen last because the majority of visits at this hub are conducted by sub-contractors. Additionally, the own fleet at **B** consist of only three trucks, making it a less attractive location for early electrification compared to other hubs with an own fleet, such as **H**, **I** and **N**.

This adding process leads to the nineteen DHL routes becoming feasible. To verify the feasibility of these routes, the detailed evaluation output is available for these routes in Appendix G **(confidential)**. As visible in the overview below, in the first combination of hubs being equipped with charging stations leads to ten routes becoming feasible. Lots of these routes can be done on a single charge, which means an intermediate recharging moment is not necessarily.

However, for example, the above does not hold for route **I92**, which has a distance of 453 kilometer, and finishes its route with 22,96%, which is nearly above the arrival threshold of 20%. Due to the fact that the truck can recharge at another Region Hub in its route sequence, it is able to return to **I** with enough charge.

Table 10) Overview of feasible routes per charging combination.

Route ID	Route overview	Hubs with charging station	Total Distance	SoC upon return at homebase
H51	3 intermediate stops	H, I	328	31,60%
H70	3 intermediate stops	H, I	56	92,98%
H73	3 intermediate stops	H, I	361	24,80%
H77	5 intermediate stops	H, I	298	48,02%
H95	4 intermediate stops	H, I	362	48,53%
I15	4 intermediate stops	H, I	412	24,17%
I16	4 intermediate stops	H, I	315	34,38%
I53	3 intermediate stops	H, I	407	35,21%
I54	2 intermediate stops	H, I	320	48,67%
I92	3 intermediate stops	H, I	453	22,96%
I73	3 intermediate stops	H, I, N	405	26,62%
N31	3 intermediate stops	H, I, N	331	41,12%
N51	4 intermediate stops	H, I, N	330	41,25%
N52	3 intermediate stops	H, I, N	353	26,48%
N45	3 intermediate stops	H, I, N, B	444	26,23%
N95	3 intermediate stops	H, I, N, B	405	25,66%
N64	4 intermediate stops	H, I, N, B, P	399	34,16%
N68	4 intermediate stops	H, I, N, B, P	419	47,33%
N92	4 intermediate stops	H, I, N, B, P, O	463	20,87%

5.2.8 Most strategic hubs in the network with a view in the long term

In the short term, it is not realistic to assume that grid congestion will not be a limiting factor for equipping more hubs with charging stations. However, in the long term, the grid congestion problem is expected to be resolved through improvements in the grid infrastructure. Once this infrastructure is upgraded, it could potentially become feasible to install charging stations at more, or even each, Central or Region hub(s) in the network.

Given this future scenario, it is important to identify which additional hubs would become strategically important for charging infrastructure. To address this, the selection process used in the previous section is now applied to all Central Hubs and Region Hubs in the network. In this analysis, the hubs identified as potential charging locations in the short term, and thus used in the previous subsection, are prioritized over the remaining hubs. This prioritization assumes that these hubs will already have charging stations by the time the other hubs are selected.

Table 11) Selection process results without net congestion limitations

Combination	Added Hub	Total Routes Evaluated	Number of Feasible Routes	Number of Infeasible Routes	Percentage of Feasible Routes	DHL Feasible Routes	SubCo Feasible Routes
Confidential		352	145	207	41,19	Confidential	
		352	156	196	44,32		
		352	164	188	46,59		
		352	174	178	49,43		
		352	183	169	51,99		
		352	189	163	53,69		
		352	206	146	58,52		
		352	219	133	62,22		
		352	229	123	65,06		
		352	239	113	67,9		
		352	249	103	70,74		
		352	260	92	73,86		
		352	269	83	76,42		
		352	277	75	78,69		
		352	284	68	80,68		
		352	290	62	82,39		
		352	300	52	85,23		
		352	308	44	87,5		
		352	310	42	88,07		
		352	310	42	88,07		

The table above shows that the first hubs added to the network are **K** and **G**. This can be logically explained by several factors. Firstly, both hubs have a relatively high number of own trucks, which increases the feasibility of more routes operated by DHL. Additionally, **K** has the fourth highest number of visits, while **G** has the second highest number of visits according to the provided data, surpassing even the central hub in **O**. Another key factor is the strategic location of **G** and **K**. Both hubs are located in the middle of the transportation network, reducing the distances to locations near the border of the network, such as for example **T**. This makes them strategically positioned between the northern and southern parts of the network, enhancing their overall importance. On the other hand, the three locations **Q**, **R**, **S**, also located in the middle of the network, are selected late in the process. This is likely because none of these locations have their own fleet, and particularly **Q** and **R** have a very low number of visits by DHL-operated routes. Additionally, it is noteworthy that the key performance indicators do not show any significant increase after the addition of **R** following **Q**. This is due to the fact that the distance between these two locations is less than one kilometer, making the energy usage difference negligible.

Further, note that that in case at all hubs charging is available, only 88.07% of the routes are feasible. These infeasible routes are typically routes in which the truck commutes between two widely separated locations, such as the example provided below. Table 12 gives an overview of route I52, which is a commuting route between **I** and **T**. The one-way distance between both hubs is 304 kilometers. Although the truck is able to reach **T**, this does not hold for the return to **I**. This is due to the fact that the truck is recharged to a SoC of 56,67%, while the first route segment already consumed 63,33% SoC. Only if the truck would have been able to charge for a longer period, or with a higher charging power in the same period, the route would have been able to become feasible.

Table 12) Detailed output for route I52.

RouteID	Origin	Destination	Distance	Energy Required for	Departure Energy Level	Arrival Energy Level	Energy Recharged	Departure SoC (%)	Arrival SoC (%)	Charger at destination	Destination Type	Feasible	Unloading/ Loading	Break Time	Total Idle Time	Recharging Time (minutes)	Carrier
Confidential								100	36,67	TRUE	Intermediate	TRUE	46	60	60	48	DHL
								56,67	0	TRUE	Homebase	FALSE	0	0	0	48	DHL

In summary, the selection process prioritizes hubs with high visit numbers, strategic locations compared to other locations, and a considerable number of own trucks, which explains the order in which the hubs are added to the set of locations with charging stations.

5.3 Set-up of experiments: GSM

In this section, the experimental settings for the GSM are outlined. In Subsection 5.3.1, the settings for the different network/problem sizes are explained, while in Subsection 5.3.2 the route specific settings are explained. Next, Subsection 5.3.3 outlines the truck specifications, while Subsection 5.3.4 explains the set-up of charging station availability in the networks.

5.3.1 Set-up of transportation network sizes

The GSM is designed to be adaptable for various transportation networks of different sizes in terms of number of Distribution Centres, Customers and Trucks. The setup of the transportation network involves several key components, which are discussed below. As input for the GSM, routes are generated for a different number of DCs, Customers, Trucks and the duration in days for which routes are generated.

The operational area is organized within a 300x300 kilometer grid, which accurately reflects the typical travel distances encountered in the BNL network of DHL. This grid structure ensures that the method simulates realistic travel conditions, which enhances the relevance of the results. Importantly, the GSM is designed with flexibility in mind, which allows users to adjust parameters such to accommodate both smaller and larger geographical areas. This adaptability ensures the method remains generic and applicable across a wider range of logistical scenarios, which enables the exploration of various problem sizes.

Random coordinates are assigned to each DC and Customer location within the grid layout, with triangles representing DCs and circles denoting customers. The difference between the terms of these two kinds of locations exists in the fact that DCs serve as homebases to trucks, and Customer locations are only visited by trucks and thus do not serve as homebase to any trucks within the fleet.

For each defined network size, routes are generated over a specified number of days, with each truck assigned a new, randomly generated route for each day. This approach guarantees a wide variety of route distances and arrival times, allowing for a comprehensive analysis of the system's performance under differing conditions. The distances of these routes typically range from 300 to 700 kilometer, with most falling within the 300-500 kilometer range, which aligns with real-world operations such as DHL's BNL network.

To evaluate the performance of the GSM, and its improvements, under different conditions, three network scenarios are considered: small, medium, and large. These scenarios differ primarily in the density of locations in the same grid size, which ensures variety in complexity. The overall objective of having three different scenarios in terms of problem size is to assess how the number of trucks, charging stations, location density impacts the performance, particularly in terms of percentage of feasible routes that can be electrified and in terms of costs incurred to improve the percentage of feasible routes. Below, the three set-ups for each problem size is outlined.

Table 13) Problem sizes for GSM

Problem Size:	**Small**	**Medium**	**Large**
Number of DCs	5	10	25
Number of Customers	25	100	150
Number of Trucks	50	150	400
Number of Days	10	10	10

5.3.2 Set-up of route data

As explained in the previous subsection, the GSM is run for different problem sizes, while routes being generated for each truck for 10 different days (or iterations), with a different route being generated for each truck every day and having a different starting time between 07:00 and 08:00. This randomness introduces variability into the GSM, ensuring that the performance is evaluated across a wide variety of conditions, including different route distances, arrival times, and charger availability.

To calculate the distances between locations, and to provide route distances, the random generated coordinates are used to create a distance matrix. This distance matrix specifies the distances for each arc from hub i to hub j. In this matrix, the distances are calculated as the Euclidean distance between both hubs using the following equation:

$$d_{ij} = \sqrt{\left(X_j - X_i\right)^2 + \left(Y_j - Y_i\right)^2}, \tag{4.15}$$

where d_{ij} is the Euclidean distance between hub i and hub j, and (X_i, Y_i) are the coordinates of hub i and $\left(X_j, Y_j\right)$ are the coordinates of hub j.

Based on this distance, the values for the travel time t_{ij}, the energy requirement e_{ij}, and the transportation costs c_{ij} can be calculated. All these values are also extracted to an input file in the form of a matrix, such that the GSM easily reads the values. The travel time t_{ij} can be calculated using the distance d_{ij} and the average speed v of the truck. Then, the travel time t_{ij} is calculated by:

$$t_{ij} = \frac{d_{ij}}{v}, \tag{4.16}$$

Next, the transportation costs c_{ij} are calculated by multiplying the distance d_{ij} by the constant costs per unit distance driven between hub i and hub j, which is denoted by c. This cost is considered constant, meaning it remains the same regardless of the specific route taken. Transportation costs c_{ij} can be calculated using:

$$c_{ij} = d_{ij} * c, \tag{4.17}$$

Furthermore, the energy requirement can be determined using again the distance d_{ij} between hub i and hub j. Multiplying this distance by the average energy usage per unit distance (γ) gives the energy requirement for a route segment, which is again added to an energy requirement matrix:

$$e_{ij} = d_{ij} * \gamma, \tag{4.17}$$

Additionally, binary parameter h_{ik} indicates whether hub i is homebase to truck k. This parameter is necessary to ensure that a truck returns to the starting hub after completing its route. Since a truck can only have one homebase, this binary parameter only equals 1 for only one hub i. Therefore, the tool considers a homebase matrix, where for each truck k the sum over all hubs for this parameter equals 1:

$$\sum_{i \in DC} h_{ik} = 1 \quad , \quad \forall k \in K, \tag{4.18}$$

The assignment of trucks to a homebase occurs randomly, ensuring a random distribution over all hubs. This reflects real-world scenarios like DHL's, where trucks are not evenly divided among all hubs.

Furthermore, the start times for each truck, denoted as s_k, are determined by defining a specific time interval within which the truck is scheduled to begin its route. The tool then automatically generates a random starting time within this interval. This randomization creates a realistic scenario, reflect the real-world situation where trucks do not all start their routes simultaneously. Additionally, this helps to increase the variability of arrival times of trucks at locations. Further, service times are influenced by the volume of goods being transported and the necessary activities (unloading/loading) at the hub. To simulate variability in service times, the following probabilities are applied:

- ✓ Service time of 20 minutes with a probability of 0.3
- ✓ Service time of 45 minutes with a probability of 0.7 (noting that 45 minutes is more typical)

5.3.3 Set-up of truck specifications and charging station availability in the network

In the experiments, trucks are considered to have a usable battery capacity of 600 kWh, as in the evaluation method it is found that trucks with at least this usable battery capacity are best suitable for transportation network sizes considered in this research. From earlier conclusions, the energy usage of the truck is again set to 1.25 kWh per kilometer. Further, the driving speed of trucks is set to 85 km/h, which in accordance with findings by Shoman et al. (2023).

In section 4.3, the parameter cs_i is introduced, which represents the number of charging station at hub i. For the experiments, the charging power for each station is set to 150 kW, as aligned with the finding from the EM in previous subsection. Further, to incorporate the variety in the availability of charging stations within the network, the experimental setup includes five distinct scenarios, each with a different probability distribution for the number of charging stations at each hub. These scenarios are designed to reflect varying levels of charging stations across the locations in the network, ranging from no availability to full availability of charging stations.

For each problem size, five different setups for the number of charging stations at each hub are generated. The key parameter for these setups is the non-zero probability, denoted as $\mathrm{P}(\mathrm{X} \neq 0)$, which represents the probability that a hub has at least one charging station. In other words, the non-zero probability defines how likely it is that a location will have charging stations, ensuring some hubs are more likely to have charging stations than others. In this way, it is possible to mimic the strictness of 'net-congestion' in the network. The probability determines the density and availability of charging stations across the hubs in the network, which directly impacts the feasibility of electrifying truck routes.

For these experiments, an upper limit in the number of charging stations is set to five. In this way, the problem that not all simultaneous arriving trucks can charge still comes up in the larger problem size. For the strict, moderate, and relaxed scenarios, the number of charging stations at each hub is drawn randomly, ensuring that the distribution aligns with the set probability.

The five predefined scenarios are as follows:
1) **Never**: In this scenario, no charging stations are available at any hub, other than the homebases. The latter is due to the fact that a truck needs a charging station to be able to drive its next route. However, intermediate recharging at these hubs is still not allowed for experimental testing. The probability $\mathrm{P}(\mathrm{X} \neq 0) =$ 0.0, meaning that all hubs have 0 charging stations. This represents a situation where no charging infrastructure exists within the network, which means truck will only be able to drive routes that are feasible on a single charge.
2) **Strict:** Here, there is a small chance of having charging stations at a hub. The probability $\mathrm{P}(\mathrm{X} \neq 0) =$ 0.3, means that for 30% of the locations, at least one, and at most five charging station(s) are available. This scenario simulates a network with limited charging locations.
3) **Moderate:** In this case, the probability is higher with $\mathrm{P}(\mathrm{X} \neq 0) = 0.7$, meaning that 70% of the hubs are likely to have charging stations. This scenario represents a moderately developed charging infrastructure, where most hubs are equipped with chargers.
4) **Relaxed:** The probability is set to $\mathrm{P}(\mathrm{X} \neq 0) =$ 1.0, which means that at least one charging stations is available at every hub. This scenario represents a situation where the network is fully equipped with charging stations. This does not directly mean that a truck has always access to recharging points at every hub, since there may be overlapping arrivals of other trucks.
5) **Charging Always Available:** In this scenario, each truck has always access to a charging station upon arrival at any of the locations. Specifically, the number of charging stations at each hub is set to 1000, ensuring that charging is always available and there is no limitation on capacity. Of course, this not a realistic scenario yet, but it allows for analysis on the performance of the GSm under the condition that charging is always available.

5.3.3 Set-up of costs for experiments

As discussed in Subsection 4.4.3, for infeasible segments a trade-off can be applied for infeasible segments to determine the best option for a truck at any given moment in its route sequence. The trade-off options are presented again below for clarity:

$$\text{trade off} = \begin{cases} \text{wait for charger becoming available at current location} \\ \text{detour to an alternative location with charging station} \end{cases}$$

In the GSM, the costs are established based on the values provided in the table below. It is important to note that the cost per minute for detouring and waiting are equal. This is because it actually does not matter whether the truck waits at its current location for a charging station or detours to another location to charge, both options results in a delay. The objective is to select the option that minimizes this delay time for each specific truck.

Furthermore, the penalty for arriving late at any location incurs a cost of 20 units per minute. This penalty discourages options that result in arrival times exceeding the upper bound of the service time window, making such options less attractive.

Table 14) Costs settings for GSM

Type of costs	Value
Cost per minute detour	5
Cost per minute waiting	5
Penalty costs per minute arriving late an any location	20
Penalty costs for lowering threshold to 10% to increase the search space	10000
Fixed costs for waiting at a location that is not equipped with charging stations	10^6

In cases where a truck cannot charge at its current location and must seek another charging location, but its SoC is too close to the arrival threshold of 20%, it may struggle to find another charging location while still meeting the threshold requirement. To address this, the method allows for a reduction of the threshold to 10%. However, since arriving at a hub with an SoC below 20% is considered to be unacceptable, due to reasons provided earlier in this report, this threshold reduction incurs significantly higher cost compared to other options. Consequently, this option is only considered if no more attractive alternatives are available. Further, observe that the fixed costs for waiting at a location that is not equipped with charging stations is set to 10^6, such that this option is always outperformed by detouring.

With these costs settings, the different problem sizes are run for the different distribution sets of charging stations in the networks, while the charger assignment is set to the Priority policy. The latter is done due to the fact that this policy always outperforms the other charger assignment policies.

5.4 Results of Generic Solution Method

In this section, the results of the GSM are presented and analysed. As discussed in Section 4.5, three problem sizes, each for an instance of ten days, with varying numbers of DCs, customers and trucks are explored. The impact of charging station availability within the network is examined for these instances.

In the first subsection, 5.3.1, a baseline measurement is conducted to determine how many routes in each instance are feasible for electrification without the need for recharging. Subsequent subsections then explore different quantities of charging stations assigned to each location. In Section 5.3.2, different heuristics are applied for assigning chargers to trucks in the event of simultaneous arrivals. Section 5.3.3 discusses the impact of incorporating metaheuristics for detouring.

Below, Table 15, again, provides the sizes of the four problem instances. Further, note that all calculations are performed with an eTruck having a usable battery capacity of 600 kWh and an average energy usage of 1.25 kWh:km. Further, the arrival threshold of 20% is applied as well. And, as mentioned in Chapter 4, the charging power is assumed to be constantly equal to 150 kW for each charging station.

Table 15) Problem sizes and instances for Generic Solution Method

Problem Size:	Small	Medium	Large
Number of DCs	5	10	25
Number of Customers	25	100	150
Number of Trucks	50	150	400
Number of Days	10	10	10

5.4.1 Baseline measurement: No intermediate recharging moments

To reflect the current real-world scenario where net congestion significantly limits the availability of charging stations at hubs, the feasibility of electrifying routes is first examined under the condition that no charging stations are available along the route. It is important to note that the homebases of the trucks are designated as charging locations, as a truck cannot depart without being fully charged at its homebase prior to departure. In this analysis, it is assumed that trucks always depart with a full charge. However, in case a truck arrives at another DC, which is not its homebase, it is for this analysis not allowed to charge there, such that the feasibility of routes on a single charge is evaluated.

Since charging is not considered in this first analysis, simultaneous arrivals at charging stations are not relevant, and therefore charging search logic for detouring are not yet applied. Similar to the EM used in the previous section, the generic method in this case simply checks whether routes are feasible for electrification without intermediate recharging or charging strategies. This exploration serves as a baseline measurement, indicating how much routes in the instance are feasible without the need for intermediate recharging.

Table 16) Baseline Measurement Results GSM: Feasibility percentages without recharging

Problem Size	Lower Bound	Upper Bound	Mean	Median	Standard Deviation
Small	16,00%	26,00%	22,20%	23,00%	3,33%
Medium	2,00%	22,67%	8,47%	6,34%	6,53%
Large	1,50%	15,25%	6,86%	5,50%	4.87%

In the results, with a summary of the key statistical results for each problem size, it is observed that the feasibility percentage decrease as the problem size increases. Due to the unavailability of charging stations, this factor is not yet from impact on this increase. The decrease in feasibility is more likely due to the random nature of route generation in the GSM. In contrast to the small instance, in the medium and large instance, the network is more complex, with more trucks visiting more DCs and customers, spread across the same 300x300 kilometer grid. Also, a denser network results in more variety in route generation, as there are simply more locations that can be added to a route sequence. This increases the likelihood that more routes will exceed the truck's maximum range, making them infeasible. Therefore, the feasibility percentages for increasing network sizes are lower than for a small size.

5.4.2 Upper Bound measurement: Intermediate recharging always available

Below in Table 17, the statistical results for the different problem sizes are given in the situation that charging is always available at each location for each truck. Observe that feasibility does not reach 100% for any case, even when charging is always available. This is primarily due to certain route segments exceeding the truck's battery range, preventing the truck from reaching its next destination, even if the truck is recharging at the location, it current is. The latter is due to the fact that trucks are recharging for the duration of unloading/loading activities, which may be a too short time to recharge the truck to the level that is needed to reach the next level.

Table 17) UB Measurement: Results for GSM if intermediate recharging is always available

Problem Size	Lower Bound	Upper Bound	Mean	Median	Std Deviation
Small	64,00%	78,00%	69,80%	70,00%	4,66%
Medium	50,67%	72,67%	62,80%	62,34%	7,94%
Large	45,50%	74,00%	62,75%	64,00%	9,02%

A clear example of such an occurrence can be observed in the large problem instance, where Truck 2 follows the route sequence DC5 → C6 → C49 → DC5 on Day 1. While the truck successfully reaches C49, it is only able to recharge 120 kWh at this location. However, this amount is insufficient for the truck to complete its journey back to DC5 while maintain a SoC above the required arrival threshold of 20%.

This scenario mirrors the challenged faced by the DHL Route **I52**, which operates as a pendle route between DHL locations in **I** and **T**. As explained in Section 5.2.8, even with available charging, the truck cannot fully replenish the energy needed to complete the return leg, resulting in an infeasible route. This highlights the limitation that, even under optimal charging availability with charging stations of 150 kWh and 600 kWh trucks, certain route segments remain infeasible due to insufficient charging durations or excessive energy requirements.

Table 18) Example of infeasible route sequence: Truck 2 in large problem size

Truck	Route Segment	Distance	Capacity at Origin	Capacity at Destination	Recharge d Energy	SoC at Origin	Soc at Destination
2	1	186	600	367	98	100%	61%
2	2	242	465	162	120	77%	27%
2	3	202	282	29	98	47%	5%

5.4.3 Impact of charger assignment policies: Variety in charger availability in the network

When charging stations are present in the network, the variation in the number of available stations can affect the number of feasible routes. Additionally, the method used to assign charging stations to trucks – especially when demand at a hub exceeds the number of chargers available – also influences the feasibility score. In Section 4.4.2, this issue is already introduced and discussed, presenting four assignment policies: FCFS, LCFS, Random, and Priority. That section also introduced the distribution of charging stations across the locations in the network. In this section, both factors are combined in order to draw conclusion about how increasing the number of charging stations, together with a chosen truck assignment method, impacts the overall feasibility.

Note that in this analysis, trucks that arrive at a hub with a charging station available and no other simultaneous truck arrivals occur, the truck always takes the opportunity to recharge, no matter the current SoC of the truck.

Below, an analysis of the feasibility of electrifying truck routes under different charging assignment policies over a ten-day period. For each day, unique routes are generated for individual trucks, and feasibility scores were assessed based on the probability that a given location was equipped with at least one and up to five charging stations.

The results reveal that the priority policy consistently outperforms the other policies across all problem sizes, achieving the highest feasibility percentages. This difference becomes clearer as the problem size increases, suggesting that this policy is especially effective in bigger problem sizes where multiple trucks arrive simultaneously at a location more often. As more trucks arrive at charging locations at overlapping times, the choice of charging assignment policy becomes increasingly critical regarding the overall feasibility of electrification. In the small size, the priority policy outscores the other policies with around 2% in the small size, while in the medium size this is 3-4%. In the large size, the difference indeed becomes clearer with a difference ranging between 8-10%.

By optimizing charger assignments, the priority policy improves overall feasibility of routes in a way that other policies do not. In contrast, the FCFS and LCFS policies tend to yield similar results, typically differing by only 2-3 percentage points in feasibility scores across almost every scenario. This difference is likely due to the fact that both policies assign charging stations based solely on arrival order, rather than applying a sophisticated strategy based on the specific needs per truck. Due to that, it can occur that a truck that actually does not need to recharge is prioritized over a truck that needs to recharge.

The random policy, although generally in the same feasibility range as FCFS, most often provides the worst outcomes. This is expected since Random lacks any structured decision-making mechanism and assigns charger arbitrarily, which increase the likelihood of inefficient charger utilization. Therefore, sometimes it performs better than FCFS or LCFS, but more often worse, as can be observed in the results in Appendix I. This highlights the importance of a more structured assignment approach, particularly as network size increases, only more.

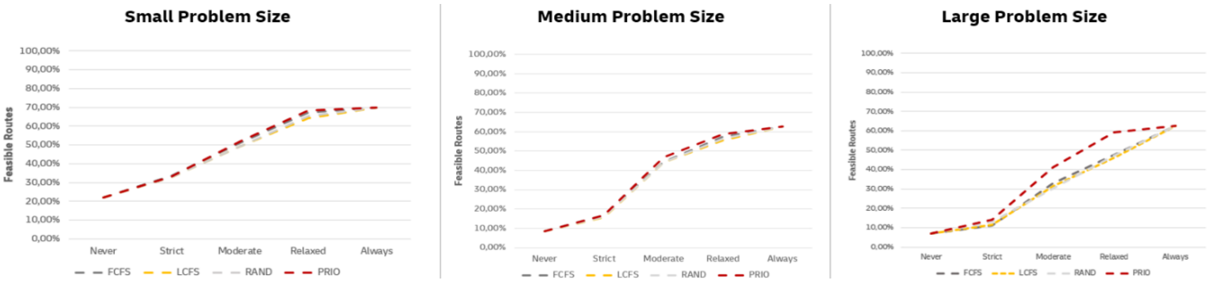

Figure 29) Feasibility percentages for different charging assignment policies

In scenarios where charging is consistently available upon arrival at any location, all policies result in the same feasibility percentage. This consistent availability of charging eliminates congestion at charging stations, which makes charger assignment policies unnecessary. However, the Priority policy reaches this upper limit more quickly than other approaches, which demonstrates its effectiveness in enhancing the feasibility percentage earlier in the process. This highlights the adaptability of priority policies in both congested conditions and unrestricted availability of charging stations in the network.

It is important to note that, despite this availability, not all routes are yet feasible for electrification. Some routes contain segments with distances that exceed the SoC available to the truck at the start of the segment. For instance, Truck 2 in a large network, as discussed in Subsection 5.2.8, and DHL route **I53**, outlined in Subsection 5.2.8, describe this issue. In such situations, alternative strategies must be applied, which will be addressed in the following section.

5.4.4 Improving the feasibility percentage: Waiting or Detouring

Again, the GSM is applied across various combinations of problem sizes, charging station distribution, and days (or iterations). As observed in the results presented on the following page, achieving 100% feasibility is often not realized. This limitation arises because the code only manages the first infeasible segment of the route, after which it successfully makes this segment feasible. However, if additional infeasible segments exist later in the route – such as those resulting from the absence of a charging station at a subsequent location – the overall route remains classified as infeasible.

This issue is further explored in later examples within this subsection. The results indicate that the issue of not achieving 100% feasibility decreases when a more relaxed charging distribution is used. This can be logically explained by the fact that increasing the number of charging stations within the network provides more charging opportunities along a truck's route. For instance, consider a route consisting of four segments where the third and fourth segments are infeasible. In this scenario, the GSM can only address the first segment. If there is no charging station at the destination of the third segment, the route will still be marked as infeasible, because the fourth segment remains infeasible. Conversely, with a more relaxed charging station distribution, the likelihood of having a charger available at this location increases. Consequently, the probability that the truck can charge at this location – and thereby making the final segment feasible – also increases. This issue is also addressed in the limitations of this research.

Table 19) Statistical summary of feasibility percentages and costs over 10 days in the small problem size

Results Small Priority					
Day	**Never**	**Strict**	**Moderate**	**Relaxed**	**Always**
LB	16,00%	26,00%	44,00%	62,00%	64,00%
UB	26,00%	38,00%	60,00%	76,00%	78,00%
Mean	22,20%	33,20%	52,00%	68,20%	69,80%
Median	23,00%	33,00%	53,00%	68,00%	70,00%
StDev	3,33%	4,02%	5,08%	4,94%	4,66%

Results Small size					
Day	**Never**	**Strict**	**Moderate**	**Relaxed**	**Always**
LB	16,00%	56,00%	72,00%	82,00%	100,00%
UB	26,00%	82,00%	96,00%	100,00%	100,00%
Mean	22,20%	74,60%	86,60%	94,40%	100,00%
Median	23,00%	77,00%	87,00%	95,00%	100,00%
StDev	3,33%	7,55%	6,33%	4,97%	0,00%

Costs Small size					
Day	**Never**	**Strict**	**Moderate**	**Relaxed**	**Always**
LB	0,00	3,35E+05	2,39E+05	1,90E+05	1,54E+05
UB	0,00	1,40E+06	3,34E+05	2,47E+05	1,97E+05
Mean	0,00	5,73E+05	2,76E+05	2,24E+05	1,78E+05
Median	0,00	3,78E+05	2,71E+05	2,28E+05	1,78E+05
StDev	0,00	4,21E+05	2,80E+04	2,01E+04	1,28E+04

Table 20) Statistical summary of feasibility percentages and costs over 10 days in the medium problem size

Results Medium Priority					
Day	Never	Strict	Moderate	Relaxed	Always
LB	2,00%	5,33%	32,00%	44,00%	50,67%
UB	22,67%	38,00%	62,67%	70,00%	72,67%
Mean	8,47%	16,80%	46,74%	58,67%	62,80%
Median	6,34%	13,67%	47,71%	58,67%	62,34%
StDev	6,53%	9,97%	9,50%	8,73%	7,94%

Results Medium with Detouring/Waiting					
Day	Never	Strict	Moderate	Relaxed	Always
LB	2,00%	36,67%	61,33%	75,33%	95,33%
UB	22,67%	88,00%	95,33%	97,33%	100,00%
Mean	8,47%	60,40%	83,73%	90,22%	98,30%
Median	6,34%	63,67%	86,00%	92,00%	98,67%
StDev	6,53%	16,94%	9,51%	6,64%	1,50%

Costs Medium size with Detouring/Waiting					
Day	Never	Strict	Moderate	Relaxed	Always
LB	0,00	9,01E+05	6,44E+05	5,89E+05	4,59E+05
UB	0,00	2,56E+06	1,07E+06	9,56E+05	7,53E+05
Mean	0,00	1,50E+06	8,90E+05	7,73E+05	6,19E+05
Median	0,00	1,34E+06	9,08E+05	7,93E+05	6,25E+05
StDev	0,00	5,31E+05	1,38E+05	1,14E+05	8,95E+04

Table 21) Statistical summary of feasibility percentages and costs over 10 days in the large problem size

Results Priority					
Day	Never	Strict	Moderate	Relaxed	Always
LB	1,50%	4,75%	24,00%	39,25%	45,50%
UB	15,25%	25,00%	51,75%	70,00%	74,00%
AVG	6,86%	14,20%	41,15%	59,36%	62,75%
Median	5,50%	12,13%	41,25%	57,50%	64,00%
St Dev	4,87%	6,94%	10,28%	9,39%	9,02%

Results Large with Detouring/Waiting					
Day	Never	Strict	Moderate	Relaxed	Always
LB	1,50%	27,00%	59,00%	74,25%	96,50%
UB	15,25%	74,00%	87,00%	94,25%	98,75%
AVG	6,86%	51,39%	77,50%	86,55%	97,75%
Median	5,50%	49,50%	77,75%	87,00%	97,63%
St Dev	4,87%	16,83%	9,16%	7,29%	0,66%

Costs Large szie with Detouring/Waiting					
Day	Never	Strict	Moderate	Relaxed	Always
LB	0,00	2,87E+06	2,07E+06	1,70E+06	1,37E+06
UB	0,00	5,02E+06	3,01E+06	2,60E+06	2,12E+06
Mean	0,00	3,49E+06	2,39E+06	2,05E+06	1,64E+06
Median	0,00	3,41E+06	2,45E+06	2,06E+06	1,64E+06
StDev	0,00	6,36E+05	3,06E+05	3,15E+05	2,66E+05

The results presented in the tables consist of the statistical values (over a ten day period) for the feasibility percentages for electrifying the routes across three different network sizes: small, medium, and large. The percentage represent the success rates of the combination of the earlier introduced charger priority assignment policy in combination with the method applying a trade-off between waiting and detouring for each route's first infeasible segment. It can be observed that for all network sizes, the feasibility percentages often do not reach 100%. This is due to the GSM's limitation, which is explained on the previous page, leading to lower overall feasibility percentages.

However, it is shown that the addition of a trade-off for each truck significantly improves the feasibility percentages for each truck. These improvements suggest that allowing for detours or waiting for charging stations to become available enables trucks to access charging infrastructure more effectively, thereby facilitating a greater number of routes that can be electrified. As a result, the flexibility introduced by this trade-off is important for maximizing the utilization of available charging stations and ensuring that electric trucks can complete their journeys.

Additionally, it can be observed that the costs associated with delays decrease as the charging station distribution relaxes. This trend is logical, as a higher density of charging stations provides more options in the search space for finding suitable detours, as well as waiting . Furthermore, with more charging stations, trucks may not need to detour at all. They can extend their recharge duration at their current location where they are charging, which makes the additional distance for a detour equal to zero. This avoids unnecessary costs. The costs in the table include the initial driving expenses per unit distance and the costs incurred due to the trade-off for trucks that arrive at location with charger but are not prioritized for charging .

It is also important to note that costs are significantly higher for each charging station setting as the problem size increases. This increase in costs is a direct result of the larger number of trucks that require a trade-off between detouring or waiting. As the network size grows, the complexity of managing multiple trucks increases, leading to higher operational costs associated with delays and the need for strategic decision regarding charging station utilization.

The most relaxed charging station distribution, as well as the column in which charging is always available upon arrival at any location, logically shows the highest feasibility percentages across all size, indicating that the more charging stations in the network, the higher the chance is of achieving feasible routes. This is visualized by the figure below. For example, initially the truck cannot make it to location 3 due to the fact that the segment between 2 and 3 is infeasible. The GSM solved this issue by detouring via location 4, where a charger is available. In a strict charging distribution, there is no charging station at location 3, which ensures the truck cannot recharge there, which makes the segment between location 3 and the homebase, indicated by a triangle, infeasible. However, in the moderate charging station distribution, there is also a charging station available at location 3, which ensures the truck can recharge there for the duration of unloading/loading activities, making the final route segment feasible.

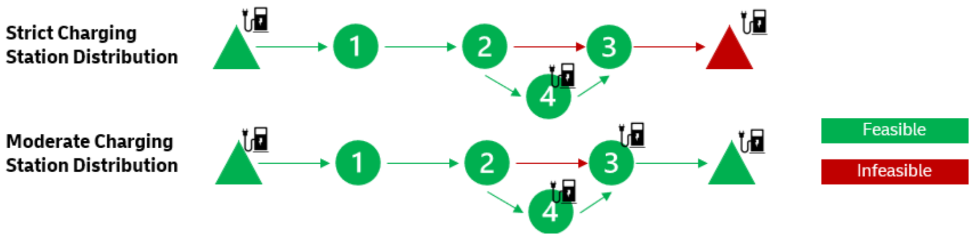

Figure 30) Example of route having different feasibility across different charging policies

Examples of improved routes: A detour (without arrival threshold deduction)

In the small problem size on day 1, with a strict charging station distribution, Truck 38 drives the route sequence DC2 → C15 → C21 → DC2, which has total route distance of 532,78 kilometer. At location C21, the truck has a remaining SoC of 40.78%, which means it has only a remaining travel range of 99.74 kilometer, which is not sufficient to reach its homebase. This remaining travel range can be used to find a location which has a charging station. Therefore, the range of the green circle, visualizing this remaining travel range, equals exactly 99.74 kilometer. As can be seen, there are nine possible locations (including the current location; C21) to detour to. However, from those locations, only four locations have a charger available at the moment truck 38 potentially arrives there, namely: DC3, C5, C18, and C20. Below, Table 22 lists reachable locations (RL), its costs and its effects for the driving schedule of Truck 38.

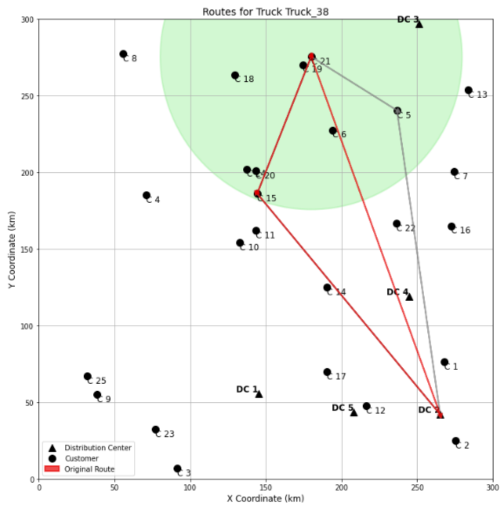

Figure 31) Detour visualization (threshold = 20%)

Table 22) Reachable locations for Truck 28 from C23 in small problem size on Day 1

RL	Distance from current location	Distance to next destination	Combined Distance	Arrival Time at RL	Recharge Duration	Arrival Time at Next destination	TW UB Next Destination	Total Delay Costs
DC3	74.54	255.07	329.61	14:54	2.26	20:02	15:00	7688.05
C5	66.66	200.43	267.09	14:48	1.81	18:50	15:00	5935.45
C18	51.64	259.84	311.84	14:38	2.30	19:51	15:00	7377.40
C20	83.15	200.29	283.44	15:00	1.80	19:01	15:00	6237.2

As can be observed from the table above, detouring to C5 to charge there provides the cheapest Total Delay Costs. Therefore, this location is marked as best alternative charging location. As the current considered location (C21) does not have any charging stations, the Total Delay Costs for charging at this location are set to 10^6, such that this option is not chosen. In the cost comparison, the GSM observes that detouring is thus a cheaper option, and therefore adds C5 to the adjusted route sequence, which makes the route feasible.

Examples of improved routes: A detour (with arrival threshold deduction)

In the same problem size (small) , on day 1, and with a strict charging station distribution, Truck 21 follows the route from DC4 to C5, then to C6, and back to DC4. According to the initial plan, the truck arrives at C19 with a SoC of 23.30%. This level is insufficient to return to its homebase, as it does not meet the required arrival threshold of 20%. However, as the current SoC is close to the threshold, there is only one location available within the search space. Unfortunately, upon eventual arrival at this location, Truck 21 would not be assigned a charging station, as it is not equipped with one. Given that no other feasible solutions exist within the initial search space, the method expands the search space by allowing the truck to arrive at its charging location with a minimum SoC of 10%. Consequently, the truck detours to C18, where it recharges enough to ensure that the segment leading back to DC4 becomes feasible. As illustrated in Figure 32, the grey lines of the new route detour through a location that lies outside the original green circle but remains within the newly defined remaining travel range associated with the threshold adjustment. At C18, the truck recharges sufficiently to achieve the required SoC of 20% for its return to the homebase. This threshold adjustment incurs a penalty of 10000 units, resulting in total delay costs of 15112 units, which is indeed 10000 units higher than in the previous example.

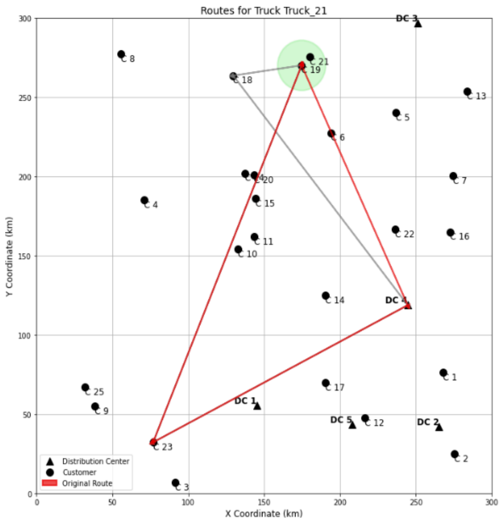

Figure 32) Detour visualization (threshold = 10%)

Examples of improved routes: Enlarging the recharge duration at the current location

In certain scenarios, a truck may be assigned a charger at its current locations but still fails to charge enough to reach its next destination. This occurs because only the maximum of the unloading/loading time and break time is considered for recharging. Consequently, the truck departs for the next location according to the initial plan, but it may not have a high enough SoC to reach that destination, necessitating an additional recharge.

In this particular case, the truck is at a location with a charging station, leading the method to recognize this as a detour to a charging point, even though the detour distance is effectively zero. The method then checks whether at least one charging station is available for the required additional recharge duration. If a station is free, this option is considered in the search for the best alternative charging station. Since there is no waiting time at the current location, the costs associated with this option are set to 10^6 again, which discourages the GSM from selecting it.

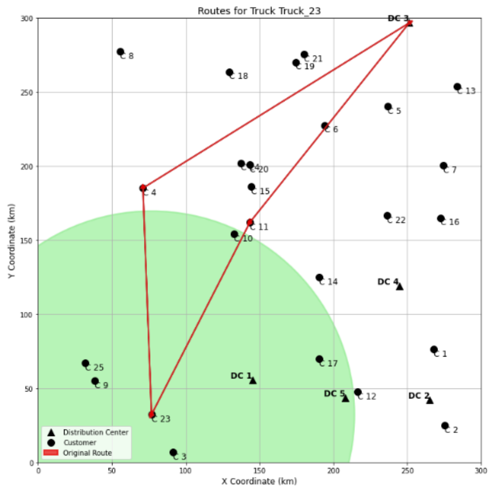

Figure 33) Visualization of enlarging recharge

This situation occurs for Truck 23, in the small problem size and strict charging distribution on Day 1. The truck travels from DC3 to C11, then to C23, but is unable to reach C4. The table below lists all charging locations within the truck's search space. Observe that the reachable location C23, where the truck currently is, offers the lowest Total Delay Costs, making it the preferred choice for the "detour" option.

As these costs are lower than the waiting option, Truck 23 extends its recharge period at c23 to ensure it can successfully reach C4. Upon arrival at C4, the truck has an SoC of 48.74%. After an opportunity recharge at C4, Truck 23 continues its journey back to the homebase, where it arrives with a final SoC of 36.55%, which makes this initial infeasible route thus feasible.

Table 23) Overview of reachable locations

RL	Distance from current location	Distance to next destination	Combined Distance	Arrival Time at RL	Recharge Duration	Arrival Time at Next destination	TW UB Next Destination	Total Delay Costs
DC1	72.24	149.24	221.48	16:07	1.24	17:52	15:00	4574.40
DC5	131.64	197.2	328.84	17:13	1.64	19:32	15:00	7084.20
C10	134.07	68.93	203.00	16:11	0.57	16:59	15:00	3395.00
C17	119.54	165.78	285.32	16:49	1.38	18:46	15:00	5946.60
C23	0	153.08	153.08	15:18	1.28	17:06	15:00	3285.40

Examples of improved routes: Waiting at the current station for a charging station becoming free
When multiple trucks are present at a location with overlapping service intervals and there are fewer chargers available than needed, prioritization rule come into play. If unprioritized trucks require a recharge, a trade-off must be made between waiting for a charger or detouring to another location, similar to previous examples.

In the small problem size, with strict charging distribution on Day 1, Truck 38 follows the route sequence DC2 → C13 → DC3 → DC2. Due to the large distance between DC3 and DC2, the truck cannot complete this segment without meeting the required arrival threshold of 20%. Upon arriving at DC3, Truck 38 has a SoC of 44.54%, which is insufficient to reach the next destination. However, this location has only one charging station, and Truck 38 is prioritized for charging based on the priority rules. Table 24 below summarizes this:

Table 24) Overlapping trucks

Truck	Service Interval	Meets threshold at next destination?	Current SoC	Expected SoC at end of route	Charger assignment
4	10:56 - 11:14	No	46.43%	0%	False
38	10:34 - 11:04	No	55.74%	0%	False

The potential waiting time for Truck 38 is calculated as the difference between the end recharge time of Truck 4 and the arrival time of Truck 38, which results in 40 minutes. Along with a necessary recharge duration of 1 hour and 14 minutes, this results in Truck 38 arriving 22 minutes late at its next destination, incurring a total delay cost of 983 units.

In comparison, detouring to the best alternative charging location, C20, would incur a significantly higher costs of 5147.75 units. Consequently, the GSM selects the waiting option, which ensures that both the route segment and the overall journey becomes completely feasible for Truck 38. Observe that in the figure on the right no grey lines are added, as there is no detour.

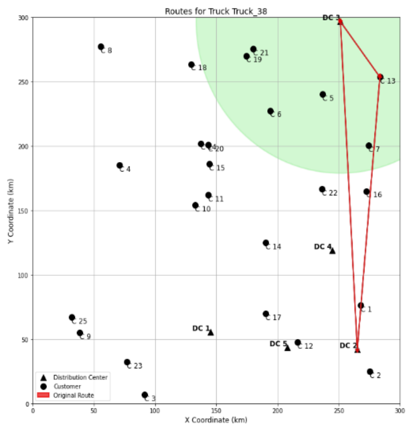

Figure 34) Visualization of waiting

Example of unimproved route: Waiting or Detouring does not make the route feasible

In the same problem instance as discussed in previous examples, Truck 18 follows a route from DC1 to C13, then to C9, and back to DC1. Due to the high distance to C13 from both DC1 and C9, the truck faces a high energy requirement for both route segments. Consequently, it cannot reach C17 from C13 without exceeding the arrival threshold. To address this, the GSM opts for a detour via C5, where the truck can recharge sufficiently to continue to C17. However, the segment between C9 and DC1 remains infeasible, as the truck cannot recharge at C9. As a result, the updated schedule indicates that the truck will arrive back at its homebase, DC1, with a SoC of only 17.19%, which is below the required threshold, resulting in the complete route being infeasible for electrification.

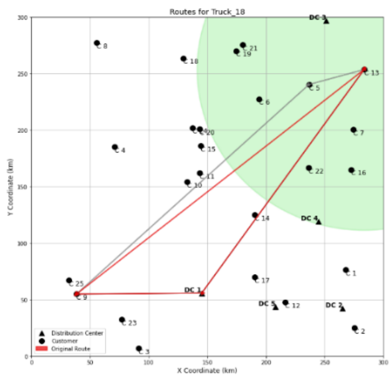

Figure 35) Visualization of infeasible detour

A good solution to this problem would involve recharging an additional 5.00% SoC at DC4, allowing the truck to complete the final segment to DC5. However, this is a limitation in the GSM, which is mentioned earlier in this subsection and is also discussed in Section 6.3 of this report.

However, this infeasibility is exactly the type of infeasible route which is mentioned in Figure 35. If the charging station distribution is set to moderate, C9 does have a charging station available for Truck 18 at the moment it arrives there. In that situation the truck recharges there for the entire duration of the unloading/loading activity or break time, which ensures that the truck can make it back to its homebase. The above mentioned difference is shown in both tables below.

Table 25) Route of Truck 18 infeasible in strict charging policy

Origin	Destination	Distance (km)	Charger at Destination	Recharge duration at destination	SoC at departure	SoC at arrival	Feasible
DC1	C13	241.63	True	0.65	100.00	49.66	True
C13	C9	315.64	False	1.14	49.66	0	False
C9	DC1	106.71	True	0	0	0	False

Table 26) Route of Truck 18 feasible in moderate charging policy

Origin	Destination	Distance (km)	Charger at Destination	Recharge duration at destination	SoC at departure	SoC at arrival	Feasible
DC1	C13	241.63	True	0.65	100.00	49.66	True
C13	C13	0	True	1.14	65.91	65.91	True
C13	C9	315.64	True	1.14	94.41	28.65	True
C9	DC1	106.71	True	0	57.15	34.92	True

5.4.5 Local Search Implementation

In this analysis, a local search strategy is employed to identify the highest feasibility percentage for electrifying truck routes within the constraints of a specified budget. This approach is relevant for companies, just like DHL, which initially will have a limited budget available as they start their journey toward decarbonizing operations. The objective is to maximize the feasibility of electrifying routes, while adhering to a budget cap. The methodology searches for the best configuration in terms of routes to be electrified by iteratively adjusting configurations (true = electrify, false = not electrify), while staying within the budget.

Below, the results for the small problem size are presented for charging policies ‘strict’, ‘moderate’ and ‘relaxed’. There is no need to present the results for policies where charging is never available or always available, as in these situations the configuration of routes that are selected to electrify will always be the same. For this result, a budget cap of 50000 is set, which means that this amount can be used for waiting or detouring decisions. By swapping constantly swapping the configuration status, which is true or false, the method opts to search for the highest feasibility percentage while keeping the budget cap in mind.

Table 27) Feasibility percentages with budget caps

	Strict			Moderate			Relaxed		
Daynr	Initial result without detour/wait	Initial result with detour/wait	Result with cost boundary	Initial result without detour/wait	Initial result with detour/wait	Result with cost boundary	Initial result without detour/wait	Initial result with detour/wait	Result with cost boundary
1	32,00%	76,00%	46,00%	50,00%	86,00%	68,00%	62,00%	92,00%	84,00%
2	38,00%	82,00%	57,99%	84,00%	96,00%	84,00%	76,00%	100,00%	84,00%
3	38,00%	80,00%	56,00%	54,00%	92,00%	82,00%	76,00%	98,00%	88,00%
4	26,00%	56,00%	42,00%	46,00%	72,00%	62,00%	68,00%	82,00%	80,00%
5	34,00%	78,00%	54,00%	48,00%	84,00%	66,00%	62,00%	96,00%	86,00%
6	32,00%	80,00%	50,00%	60,00%	88,00%	76,00%	70,00%	96,00%	94,00%
7	30,00%	70,00%	60,00%	44,00%	86,00%	66,00%	64,00%	98,00%	92,00%
8	38,00%	72,00%	50,00%	58,00%	88,00%	82,00%	68,00%	94,00%	94,00%
9	34,00%	78,00%	46,00%	52,00%	84,00%	74,00%	68,00%	94,00%	88,00%
10	30,00%	74,00%	48,00%	54,00%	90,00%	76,00%	68,00%	94,00%	88,00%

The analysis above compared three levels of charging infrastructure availability, which are already discussed in Subsection 5.3.3. Across 10 operational days, the results clearly illustrate the benefits of better charging infrastructure and optimized decision-making:

Under the strict policy, the initial feasibility without any detour or wait is low, often between 26% and 38%. While feasibility improves significantly when detours and waiting are allowed (e.g., up to 82%), the budget-constrained local search still manages to improve feasibility to an average of around 51%.

Under the moderate policy, initial feasibility is already higher, ranging from 44% to 84%. When unlimited costs are allowed, feasibility reaches as high as 96%. Importantly, the local search approach consistently achieves cost-constrained feasibility values in the 60–84% range, significantly closer to the ideal.

Finally, under the relaxed policy, initial feasibility begins high, between 62% and 76%, and can reach up to 100% without cost constraints. Impressively, the budget-bound local search method achieves feasibility levels averaging around 88%, demonstrating that better access to charging reduces the cost of achieving higher levels of electrification.

Overall, the findings show that charging infrastructure quality has a direct impact on the cost-efficiency of electrification. Even with limited budgets, selecting the right routes can yield significant gains. Further, companies can prioritize routes for electrification based on a balance of feasibility and costs, especially in early stage decarbonization.

5.5 Validation GSM and EM

The validation of the EM and the GSM is important for ensuring their effectiveness in predicting the feasibility of deploying an electric truck on all routes. Subsection 5.5.1 outlines the validation of the input data and working of the EM with an actual real-world electric truck, which drove one of DHL's BNL routes. Subsection 5.5.2 describes the evaluation of the GSM with the EM.

5.5.1 Validation of input data

To compare the performance of the EM against real-world data, a practical test was once conducted again. In February 2025, a demo Volvo FH Electric is used to assess one of the BNL routes that is evaluated by the EM as well. The specifications of this truck can be read in Subsection 2.6.2. As the truck was only available for two days for DHL, the truck is used to simulate a BNL route. Although these routes typically are driven during the night, this particular simulation took place during the day. This decision was made because there are currently no charging options available at any of the visited hubs, and DHL prohibits charging along the highway during the night for safety reasons.

The selected route, HEN16, departs from Region Hub Hengelo, travels via three intermediate destinations back to Hengelo. This route covers a total distance of **XX** kilometers. For this route, the usable battery capacity of the Volvo of 400 kWh is used as input parameter in the EM, together with an average energy usage of 1.25 kWh per kilometer.

Table 28) Output of Evaluation Method for Route HEN16.

RouteID	Origin	Destination	Distance	Energy Required for this Part	Departure Energy Level	Arrival Energy Level	Energy Recharged	Departure SoC (%)	Arrival SoC (%)	Charger at destination	Destination Type	Feasible
Confidential								100	94,23	FALSE	Intermediate hub	TRUE
								94,23	45,19	FALSE	Intermediate hub	TRUE
								45,19	44,87	FALSE	Intermediate hub	TRUE
								44,87	0	TRUE	Homebase	FALSE

According to the output of the EM for route HEN16, presented in Table 28, the final route segment from is marked as infeasible. This is due to the fact that the predicted SoC at arrival in Hengelo falls below 20%, and even reaches 0%. Consequently, the method suggests that the eTruck would be unable to return to Hengelo.

In practice, the truck departed from Hengelo with a SoC of 98% and arrived at **location 1** with a SoC of 88%. Subsequently, it reached **location 2** with a SoC of exactly 45%. On the return journey to Hengelo, the truck recharged at a charging station along the highway, arriving there with a SoC of 33%. After a 45-minute charging session, the truck resumed its return to Hengelo with a SoC of 63%. Ultimately, it reached Hengelo with a SoC of 18%, which corresponds to an actual usage of 45% SoC, aligning with the expectations provided by the output of the EM. Below, a visualization of the route is presented.

Confidential

Figure 36) Visualization of Route HEN16

For the above mentioned route, the evaluation successfully provided accurate expectations regarding its feasibility for each route segment. The predicted SoC demonstrated a slight margin of error, indicating that the method's forecasts were generally reliable. However, it cannot yet be concluded that this outcome validates the effectiveness of the EM in its entirety.

To establish a more comprehensive validation, it is crucial to conduct further testing across a variety of routes utilizing real electric trucks. If more routes had been tested with an eTruck, preferably with each route being evaluated multiple times, it would have been possible to validate the method effectively. By analyzing multiple routes and their respective performances, the method's accuracy, and reliability in predicting charges and feasibilities can be better assessed. This will be discussed as well in Chapter 6.

5.5.2 Validation of outcomes of both methods

To validate the GSM against the EM for DHL, the objective is to determine whether both methods show consistent behaviour under identical conditions. For this validation, the large problem size is utilized, as it most accurately reflects the operational characteristics of the DHL BeNeLux network. A series of test is conducted using various input settings for the large problem size on Day 1, focusing on the different combinations of usable battery capacity and charging power. The following configurations are assessed:

- Usable Battery Capacity (kWh): Truck with capacities of 400, 600, and 800 kWh are evaluated
- Charging Power (kW): Charging powers of 150 kW, 300 kW, and 1000 kW are tested.

For each combination, the feasibility score, which indicates the percentage of routes that can be completed successfully, as well as the total costs associated with each configuration, will be analysed. This validation approach is relevant as it systematically examines the impact of varying battery capacities and charging powers on route feasibility, providing an understanding of both methods their performances. By using realistic scenario that reflect the network of DHL, the validation ensures that the findings are applicable and meaningful. Additionally, comparing the results from both methods under the same conditions helps to identify the reliability of the GSM.

Table 29) Feasibility scores for GSM from different settings for battery capacity and charging power

Usable battery capacity (kWh)	Charging power (kW)			
	150	300	400	1000
400	28.25%	34.25%	36.00%	36.5%
600	68.00%	71.75%	72.25%	72.25%
800	95.00%	95.50%	95.50%	95.50%

From the results presented in Table 29 above, it is clear that the feasibility percentage shows a steeper increase when a higher usable battery capacity is used at the same charging power, compared to the variations in feasibility observed when different usable battery capacities are compared at the same charging power. This trend highlights once again the relationship between battery capacity and route feasibility, suggesting that increasing the battery capacity has a substantial impact on the truck's ability to complete routes successfully.

These observations align with the patterns identified in the EM discussed earlier in Section 5.2. The consistency between the findings from both the GSM and Em reinforces the validity of this relationship and emphasizes the importance of considering battery capacity as a key variable rather than the charging power.

5.6 Conclusions

This section presents key conclusions based on the analyses conducted in the previous sections. Subsection 5.6.1 highlights the conclusions derived from the Evaluation Method, while Subsection 5.6.2 discusses the conclusions drawn from the Generic Solution Method.

5.6.1 Conclusions Evaluation Method

Trucks equipped with higher battery capacities, such as the 600 kWh offered by for example Mercedes, are significantly more advantageous for the BNL network, which faces numerous limitations in charging infrastructure. The increased battery capacity allows for a range that aligns more closely with the average distances of 300 to 500 kilometers typically driven within this network. This alignment is crucial for operational efficiency, as it reduces the frequency of necessary recharges, thereby enhancing overall productivity.

The above conclusions are strengthened by the observation in differences between feasibility percentage for the Renault e-Tech T and Volvo FH Electric of 27.84%, compared to the 53.69% for the Mercedes eActros 600. This highlights the necessity for investment in higher capacity electric trucks only more. The doubling of the feasibility percentage with the Mercedes eActros 600 clearly indicates that this model is better suited for the demands of the BNL network. Therefore, a key conclusion is that investing in trucks with higher battery capacity is a strategic move that can enhance operational effectiveness.

Moreover, the evaluation of different types of DC charging stations in the network reveals critical insights into the relationship between charging power and battery capacity for electric trucks in DHL's BNL network. The analysis included four charging station types, with powers of 150 kW, 300 kW, 400 kW and 1000 kW, and was conducted using usable battery capacities of 400, 500 and 600 kWh. For the 400 kWh eTruck, a notable improvement in feasibility percentage was observed, when upgrading from a 150 kW charging station to a 300 kW station, resulting in a 7.7% increase in feasibility. However, subsequent upgrades to higher charging power yielded minimal improvements in feasibility. This trend continued for other truck types, where the differences in feasibility percentages between various charging powers became increasingly negligible.

These findings suggest that while investing in higher charging power can provide some small benefits, the impact is significantly less compared to investing in eTrucks with larger battery capacities. The declining returns associated with increased charging power highlight the importance of prioritizing battery capacity enhancements over charging power enhancements. Therefore, strategic investments in DHL's middle mile network should focus on trucks with a higher battery capacity rather than solely upgrading charging infrastructure, as this approach is likely to yield more substantial improvements in overall performance and efficiency within the logistics network.

Further, the analysis indicated that if charging at 150 kW is consistently available at all hubs, and eTrucks are equipped with a battery capacity of 600 kWh, then 88.07% of DHL BNL's routes are feasible to electrify. The remaining 11.93% of routes are classified as infeasible due to having extremely long distances between two hubs, which do not allow sufficient time to recharge the truck to the necessary level for reaching the next destination. In such cases, increasing the charging power beyond 150 kW, or driving with an eTruck with a battery capacity even higher than 600 kWh, could enhance route feasibility and enable successful operations. Another way to manage this problem is the same way as is done in the GSM: let the truck search for the closest hub with a charging station available at the moment it arrives there. Then, the truck can recharge to the capacity desired to let the truck remains its tour to its next destination.

To conclude, it can be stated that if DHL wants to start with implementing eTrucks by the end of 2025, the Region Hubs in **H**, **I**, **B** are the most suitable to start with. This is due to the combination of facts including these hubs still have space in their contracted grid capacity, having an own fleet, and the most DHL routes becoming feasible.

5.6.2 Conclusions Generic Solution Method

The GSM has been executed for three problem instances: small, medium, large. For each of these instances, a baseline measurement was established, which means that intermediate recharging was not permitted. In this measurement, the feasibility percentages for route electrification were notably low (with a mean of 6,86% for the large problem size versus 22.20% for the small problem size). This indicates the significance of the existence of charging infrastructure in the logistics network, as well as the challenge of electrifying routes under current real-world constraints arising due to net congestion.

Even when charging stations are consistently available for each truck at any location, feasibility does not reach 100% due to limitations such as insufficient charging time during unloading and loading operations or break time. This highlights the importance of not just availability of charging stations, but also the fact that electrifying routes without adjusting the locations a truck visits do not go without significance delays in case 150 kWh chargers and 600 kWh trucks are used in a network with a grid size of 300 square kilometers.

Further, the analysis of charger assignment policies revealed that the priority policy consistently outperforms other methods (FCFS, LCFS and Random) in terms of feasibility percentages. This effect is more pronounced in larger problem size, where the need for efficient charger assignment thus becomes more critical. This can be explained due to the fact that in a larger problem size more trucks operate in the network, which increases the likelihood of trucks having overlap in their service windows at locations.

Certain route segments, and thus complete routes, remain infeasible regardless of charging availably due to the segment exceeding the truck's battery range in front of the route segment. This highlights the necessity for alternative strategies to address infeasible segments, such as waiting for a charger becoming available at the location where the truck currently is or to detour to another location where the truck performs a recharge moment.

Further, the validation of the GSM against the EM revealed consistent behaviour under identical conditions, reinforcing the relationship between battery capacity and route feasibility. Higher usable battery capacities significantly improved the percentage of feasible routes, rather than higher charging powers. This corresponds with the trend observed in the results of the EM.

The local search strategy is shown to be a method for incrementally improving electrification feasibility while having a budget cap. By continually testing route configurations and assessing cost impacts, the method prioritizes electrifying those routes that give the most feasibility within the set budget constraint. This mirrors real-world decision logistics companies must make in starting to electrify their routes.

6 Conclusions and Recommendations

In this final chapter, conclusions and recommendations for DHL taking the first steps in electrification of the middle mile transport are provided. In Section 6.1, a conclusion to the main research question is given, encompassing both conclusions specific to DHL operations and the General Solving Method. Following this, Section 6.2 outlines recommendations for DHL. Section 6.3 discusses the limitations of this research, and finally, Section 6.4 highlights areas for further investigation. In this section, an answer to the main research question is given, which is:

> How to optimize the integration of electric trucks in
> The middle mile network of DHL eCommerce BNL?

6.1 Conclusions

To reach the goal of being decarbonized by 2050, DHL plans to implement its first electric trucks in the BNL network by the end of this year, although facing restrictions due to net congestion. In this research, DHL BNL routes are evaluated, assuming that charging is accessible at a predefined set of hubs. By the end of this year, DHL intends to begin operating a limited number of BNL routes using electric trucks.

An answer on the question where and how to integrate electric trucks and charging stations in the BNL network is formulated in subsection 6.1.1, while subsection 6.1.2 presents conclusions from the GSM that considers the challenge of electric trucks arriving simultaneously at hubs where the number of available charging stations is insufficient for all trucks to charge.

6.1.1 Conclusion integration of Electric Trucks in the DHL middle-mile network on the short term

In the short term, the integration of electric trucks into the DHL middle-mile network can be initialized at six hubs, namely: **B**, **H**, **I**, **N**, **O**, **P**. These hubs have sufficient contracted grid capacities to accommodate one to three charging stations at each of these hubs. Based on the EM's results, it is concluded that **H**, **I**, **B** are the most optimal choices for initiating this transition. Besides the fact that these hubs have the required grid capacities, these hubs also have substantial fleet sizes, allowing for the electrification of DHL's own routes, without directly having the need to completely adjust route structures.

Therefore, the recommendation is to start operating electric trucks at these three hubs by the end of the year, ensuring these locations are equipped with the right charging infrastructure. It is advisable to install chargers at a minimum of two hubs to enable truck to drive routes that are not feasible on a single charge. For example, the route **I53**, which has Region Hub **I** as its homebase, cannot be completed on a single charge but becomes feasible if the truck can recharge at location **H**, which is on its route. For other routes, that according to the EM are interesting to electrify in an early stage of the transition can be read from Table 10 on page 48.

Regarding the specifications of the trucks, both the EM and GSM indicate that a truck should have a usable battery capacity of at least 600 kWh, corresponding to a driving range of approximately 500 kilometers. This range aligns well with the typical distances covered in the DHL BeNeLux network. Should an option for a truck with even a higher usable battery capacity become available on the market, it would be even more advantageous from an operational perspective, as this makes electrification easier, although it would likely come at higher costs.

The analysis also showed that a 600 kWh truck can effectively operate within the network, even with a relatively limited number of 150 kW charging stations. This configuration allows for a substantial portion of routes to be feasible for electrification. Furthermore, both insights gain from both EM and GSM indicate that charging capacities above 150 kW are not necessary, as they do not significantly increase the feasibility percentages. This is attributed to the hub-to-hub structure of the routes, with in an ideal scenario having a charger always available at each hub.

6.1.2 Conclusion on integration of electric trucks in a more advanced situation

The integration of electric trucks into the DHL middle-mile network is at an early stage, with none of the middle-mile routes currently being electrified. However, this research, utilizing the GSM, has explored the future challenges of electric truck usage, particularly concerning potential challenges such as simultaneous demand for charging stations from multiple trucks.

The analysis revealed significant insights into the feasibility of electrifying routes under varying conditions. In the GSM, the baseline measurement showed that without any intermediate recharging, the feasibility percentages differed for the three different problem sizes, with the small size having a mean feasibility of 22.20%, while medium and large had a mean feasibility of 8.47% and 6.86%, respectively. This coincides with an insight from the EM that there is always a number of routes feasible on a single charge within a logistics network. On the other hand, when charging stations are consistently available at each location, the upper bound measurements showed improved feasibility percentages, yet 100% feasibility was still not achieved. This observation is consistent with insights from the EM, as certain route segments may require more energy than can be recharged during unloading, loading, or break times, ensuring them becoming infeasible.

In the experiments, three scenarios were explored where the distribution of charging stations across the network followed different policies: strict (low probability of having one to five chargers), moderate (medium probability), and relaxed (high probability). The impact of charger assignment policies was significant. The priority policy consistently outperformed other strategies (FCFS, LCFS and Random), particularly in larger problem sizes where the likelihood of multiple trucks arriving simultaneously is higher. This is logical, as larger problem sizes involve more trucks, increasing the chances of simultaneous arrivals. This insight shows the importance of effective charger assignment strategies for improving route feasibility, especially as the problem size increases.

Additionally, the exploration of waiting versus detouring strategies yielded valuable insights for improving the feasibility of electrifying truck routes. The analysis of trade-off between waiting for a charger and detouring to an alternative location revealed that if trucks are currently recharging but do not have enough charging time to reach the next destination, the method always chooses to let the truck stay at the current location when searching for an alternative charging option. This choice minimizes additional driving costs and delays, as the distance to the charging location is zero, thereby helpings to keep penalties for failing to meet time windows at subsequent locations as low as possible.

Further, when considering budget cap constraints, the method can identify the best configuration of routes that maximizes the feasibility percentage within the available budget. This aspect is important for companies willing to electrify their transportation process, while operating under financial limitations. This allows for strategic selection of routes to electrify such that costs are considered, and a highest feasibility percentage is reached.

In summary, while the integration of electric trucks offers promising opportunities for DHL's middle mile operations, several challenges remain, which do not directly come up when only a small number of electric trucks are integrated. This is due to the fact that charger demand is low in this case. However, as DHL aims to be decarbonized by 2050 and wants to achieve 100% electrification of its middle mile routes in the future, it will need to improve the contracted grid capacities of hubs, such that more charging stations can be placed in the network. Then, it will need to implement optimized charger assignment policies, and establish effective strategies for managing route feasibility, including extending recharge duration, detouring, or waiting for chargers to become available after a truck has arrived at a location.

6.2 Recommendations

As discussed, this section gives a summation of recommendations, based on the findings and conclusions from this research. In this section, the recommendations are listed in three different subsections, categorized by the Evaluation Method, the Generic Solution Method and the pilots with the Renault e-Tech T and the Volvo FH Electric.

6.2.1 Recommendations based on Evaluation Method

Based on results gained from the EM, the following recommendations are made:

- Invest in trucks having a usable battery capacity of at least 600 kWh

Trucks with a usable battery capacity of 400 kWh, such as the Renault e-Tech T and the Volvo FH Electric, are sufficient for the PUD process. However, these trucks are not interesting for deployment in the night operations, compared with other types of trucks. Invest in trucks, which have a usable battery capacity of at least 600 kWh, such as for example the Mercedes eActros 600. This usable battery capacity provides a driving range of 500 kilometers, which aligns well with the typical distances travelled within the DHL BNL network.

- Invest in higher battery capacities rather than higher charging powers

Focus on investing in trucks with higher battery capacities rather than upgrading charging stations to higher power levels. Increasing the capacity of charging stations does not significantly enhance the percentage of electrically feasible routes within the BNL network.

- Use charging stations with a power of 150 kW

Invest in DC charging stations with a power of 150 kW. As noted above, increasing the power of the charging station above 150 kW does not yield significant benefits and comes with substantial additional costs.

- Increase recharge time in different ways

Implement charging at loading and unloading docks as a standard practice. This approach enhances charging efficiency, as this ensures optimal use of the potential charging time. Explore the possibilities to use break time as charge time, as this can enhance the potential charging time.

- Start electrification of middle mile process in **H**, **I** and **B**

The routes that present an interesting opportunity for electrification are those departing from the hubs in **H**, **I** and **B** (in order of significance). These hubs are more advantageous for electrification compared to Central Hubs **P** and **O**, as they have their own fleet, while the latter two do not.

The routes, driven by a DHL truck, which are feasible for electrification, utilizing trucks with a usable battery capacity of 600 kWh, include the following: **H51**, **H99**, **H73**, **H77**, **H95**, **I15**, **I16**, **I53**, **I54**, and **I92**. Note that in this case charging is only available in **H**, **I** and **B**. While no feasible routes currently depart from **B**, this hub remains a valuable option due to its frequent visitation by trucks operating on the above mentioned routes.

Given the previous recommendation, the initial implementation of charging station should prioritize **H**, followed by **I**, and then **B**. It is important to select at least two hubs for charging station installation ensure such that routes with intermediate recharging are also feasible. Although **B** comes after **N**, the Region Hub in **N** is currently under construction, which makes it difficult to start the electrification process there.

6.2.2 Recommendations based on Generic Solution Method

Based on results, and examples, gained from the GSM, the following recommendations are made:

- Drive routes with trucks with a minimum usable battery capacity of 600 kWh

Similar to the recommendations gained from the results of the EM, the GSM results suggest that routes should be driven using trucks with a minimum usable battery capacity of 600 kWh. This capacity ensures an adequate driving range that aligns with the typical distances covered in the analysed networks. In contrast, utilizing a truck with only 400 kWh of battery capacity significantly worsens the feasibility percentage, making this option impractical

- Use the priority charger assignment policy

To enhance feasibility of electrifying truck routes within the logistics network, it is recommended to adopt and implement the priority charger assignment policy as the standard approach for assigning charging stations to trucks in case multiple trucks simultaneously demand the same charging station at any location.

- Enlarge recharge duration at current location if needed and possible

If a truck is connected to a charging station but the scheduled break time or unloading/loading duration is insufficient to achieve the required SoC for reaching the next destination, it is advisable to extend the recharge duration at the current location instead of opting for a detour to another charging station. Since the truck is already at the current location, this approach minimizes costs and avoids any additional travel distance, delay times and delay costs, associated with a detour. By prioritizing this option, the truck can effectively reach the necessary SoC without incurring extra time or distance, which minimizes the costs for making a specific truck's route segments feasible. Therefore, extending the recharge time at the present location is the most cost-effective and practical solution to ensure the truck can continue its journey.

6.2.3 Recommendations based on pilots Renault e-Tech T & Volvo FH Electric

From a more practical perspective, some recommendations from experiences gained during the pilots with the Renault e-Tech T and the Volvo FH Electric are outlined below:

- Intermediate returns should be used to recharge the truck

If a truck returns to the Region Hub during the PUD process to unload goods, this time should be utilized to recharge the truck. During the day, there is more energy capacity available for this purpose. Additionally, this helps to reduce the required charging time between the PUD and BNL processes, as the truck returns with a higher SoC. This approach also helps to flatten the peak energy demand during both processes.

- Charging at the dock should be standard practice

Ensure charging at the dock becomes the norm, which eliminates the need for truck drivers to perform additional tasks on-site, such as uncoupling and coupling trailers. Not only does dock charging save driver a significant amount of extra work but is also maximizes the effective use of potential charging time.

6.3 Limitations

During executing the research several limitations have been encountered that may impact the comprehensiveness and applicability of the findings. Below, these limitations are outlined:

- Lack of sufficient real-live data regarding the performance of eTruck within DHL network

There was a lack of comprehensive data regarding the performance of eTrucks within the DHL network. Some data has been obtained from pilot programs involving two demo eTrucks. However, the limited availability of these trucks for DHL hindered the collection of sufficient real-life data to draw solid conclusions.

- Input data for EM was limited

The input data for the EM was constrained by the availability of route data, which was only available for one single day. It was not possible to extract a file from the OPC tool with data on multiple weeks, or even years. Break times and (un)loading times are dependent on volumes, which fluctuate, meaning that these times can differ for another day. For that reason, on another day there can be less potential charging time, which in extreme scenarios possibly could result in a route becoming infeasible.

- No option to track detailed real-life data

During the pilots, there was no option to track data regarding critical factors such as payload, wind direction, temperature, and other environmental conditions. This made it more difficult to declare the causes of fluctuations in energy consumption.

- GSM not able to manage multiple infeasible segments in one single route sequence

The GSM often fails to achieve 100% feasibility due to multiple infeasible segments in truck routes, as it can only address the first segment. This issue is mainly a problem in a strict charging station distribution, while a more relaxed distribution improves feasibility by increasing available charging opportunities along the route.

6.4 Further research

In this section subjects for further research are discussed.

- Validation of GSM and EM with real electric trucks

Although the GSM showed the same behaviour as the EM, validation of the method with real world is important to ensure its accuracy and reliability in predicting the feasibility of electrifying routes. As discussed in previous section, the lack of having an eTruck available for a longer time, hindered the possibility to carefully validate the EM. To validate the methods carefully, multiple routes should be tested multiple times using real eTrucks to gather comprehensive data on energy usages and charging requirements. If data is collected, then statistical analysis could be performed to assess the performance against the collected data, which then identifies areas of potential improvement.

- Improving the GSM such it is able to manage multiple infeasible segments in one route sequence

Another factor that could be studied in the future is solving the issue of the method not being able to handle multiple infeasible segments. In that way, also for stricter charging station distribution over the network, the costs associated with making all routes feasible can be studied.

- Charging solution at loading docks

Another key area of exploration could be the implementation of charging solutions at loading docks. It is essential to ensure that the charging infrastructure is designed to prevent damage to both the trucks and the charging units. Truck drivers often need to reverse their vehicles into parking spots, which is a movement that involves complex turning movements and limited visibility. The presence of objects around parking areas at loading docks increases the probability of collisions, which can lead to damage to both the trucks and the charging equipment. To address these challenges, innovative charging solutions should be considered. For example, systems that deploy charging equipment from above, or from under the ground, can eliminate the need for drivers to navigate around ground-level obstacles.

- Impact of electrification of trucks on internal logistics

Further, the implementation of electric truck charging stations at loading docks will significantly impact the internal logistics of hubs, especially during the initial years when the number of available chargers may be limited. In such scenarios, trucks with various routes may need to share the same dock at different times, leading to several logistical challenges. For example, the current internal logistic systems in hubs are optimized to minimize the distance that forklifts and other material handling equipment must travel. However, the need to accommodate trucks, with different routes, at the same charging dock at different points in time, may initiate the need for a redesign of material handling equipment routes. These vehicles may need to take alternative routes within the building, which rises a new optimization challenge.

- Impact of electrification on interaction between DHL PUD and BNL process

In this research, the interaction between the PUD process and BNL process is not significantly studied, as the primary focus is especially on the electrical feasibility of the BNL routes. However, as explained in the problem statement, each truck is deployed in both the PUD process and the BNL process, which means it is only idle between both processes. Given that the truck consumes energy during both processes, it is essential to recharge them to ensure they are available for the next process. This problem is slightly mentioned in Section 2.8, where the pilot involving the Renault e-Truck is discussed. From this pilot, it is learned that it was possible to completely recharge the truck, after being deployed in the PUD process, to a full charge such that it becomes available again for the BNL process. However, there remains a lack of real data on other routes. Specifically, this problem can be further explored in future research, as it actually is important for operations.

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Appendices

Appendix A – Location List

Confidential

Appendix B – Energy information per Central Hub and Region Hub

Confidential

Appendix C – Overview of Own Fleet and Number of Visits

Number of own trucks and number of visits per hub

Confidential

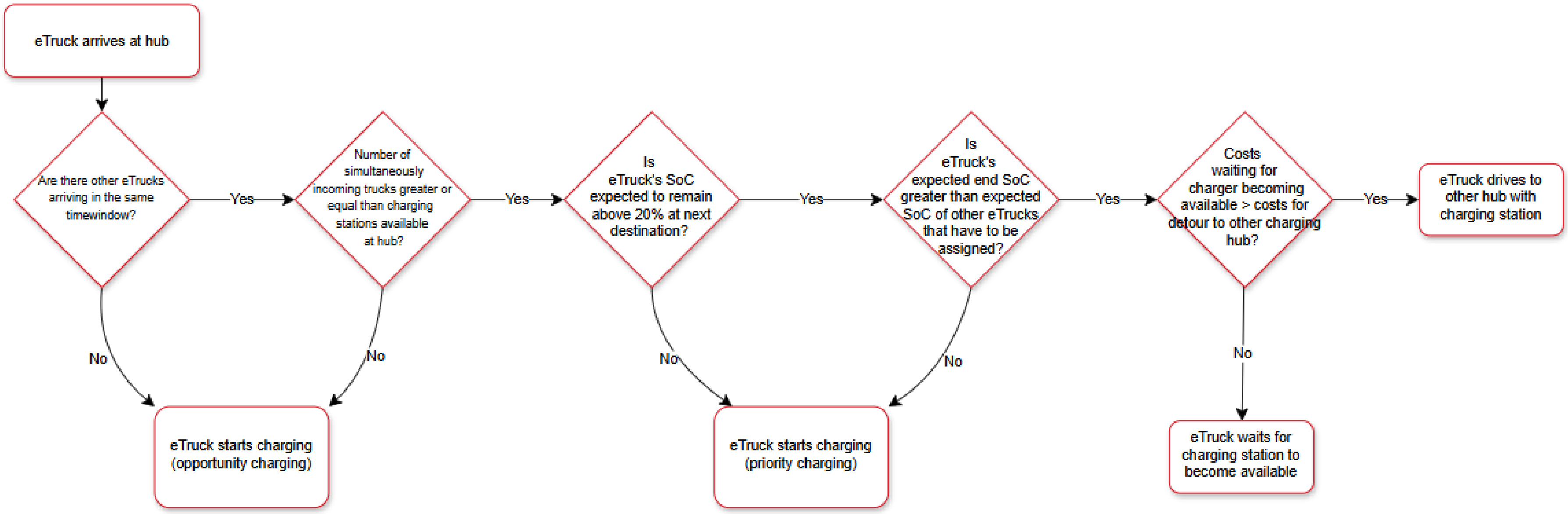
Number of (e-)Box trucks and Trailer Trucks per hub

Confidential

Appendix D - Tests with Renault e-Truck in DHL's network

Confidential

Appendix E – Flow chart arrival process at hub for an electric truck



Appendix F – Detailed Route Output feasible routes

Confidential

Appendix G – Selection process Hubs

Confidential

Appendix H – Feasibility percentage for all different charging policies and problem sizes

Problem size small

Results First Come First Serve

Day	Never	Strict	Moderate	Relaxed	Always
1	24,00%	32,00%	48,00%	62,00%	64,00%
2	24,00%	38,00%	52,00%	74,00%	78,00%
3	22,00%	38,00%	54,00%	74,00%	76,00%
4	16,00%	28,00%	46,00%	68,00%	70,00%
5	22,00%	34,00%	48,00%	64,00%	66,00%
6	24,00%	34,00%	58,00%	66,00%	72,00%
7	26,00%	30,00%	44,00%	64,00%	64,00%
8	20,00%	38,00%	58,00%	68,00%	68,00%
9	26,00%	32,00%	50,00%	66,00%	70,00%
10	18,00%	30,00%	52,00%	68,00%	70,00%
LB	16,00%	28,00%	44,00%	62,00%	64,00%
UB	26,00%	38,00%	58,00%	74,00%	78,00%
Mean	22,20%	33,40%	51,00%	67,40%	69,80%
Median	23,00%	33,00%	51,00%	67,00%	70,00%
StDev	3,33%	3,66%	4,74%	4,01%	4,66%

Results Last Come First Serve

Day	Never	Strict	Moderate	Relaxed	Always
1	24,00%	32,00%	50,00%	60,00%	64,00%
2	24,00%	38,00%	50,00%	70,00%	78,00%
3	22,00%	40,00%	50,00%	68,00%	76,00%
4	16,00%	26,00%	42,00%	64,00%	70,00%
5	22,00%	32,00%	46,00%	62,00%	66,00%
6	24,00%	30,00%	54,00%	62,00%	72,00%
7	26,00%	30,00%	42,00%	64,00%	64,00%
8	20,00%	38,00%	58,00%	68,00%	68,00%
9	26,00%	34,00%	52,00%	62,00%	70,00%
10	18,00%	30,00%	48,00%	62,00%	70,00%
LB	16,00%	26,00%	42,00%	60,00%	64,00%
UB	26,00%	40,00%	58,00%	70,00%	78,00%
AVG	22,20%	33,00%	49,20%	64,20%	69,80%
Median	23,00%	32,00%	50,00%	63,00%	70,00%
StDev	3,33%	4,45%	5,01%	3,33%	4,66%

Results Random

Day	Never	Strict	Moderate	Relaxed	Always
1	24,00%	32,00%	50,00%	60,00%	64,00%
2	24,00%	38,00%	50,00%	70,00%	78,00%
3	22,00%	36,00%	48,00%	72,00%	76,00%
4	16,00%	26,00%	42,00%	68,00%	70,00%
5	22,00%	34,00%	44,00%	64,00%	66,00%
6	24,00%	32,00%	54,00%	64,00%	72,00%
7	26,00%	30,00%	44,00%	64,00%	64,00%
8	20,00%	38,00%	58,00%	68,00%	68,00%
9	26,00%	32,00%	50,00%	60,00%	70,00%
10	18,00%	30,00%	52,00%	64,00%	70,00%
LB	16,00%	26,00%	42,00%	60,00%	64,00%
UB	26,00%	38,00%	58,00%	72,00%	78,00%
AVG	22,20%	32,80%	49,20%	65,40%	69,80%
Median	23,00%	32,00%	50,00%	64,00%	70,00%
StDev	3,33%	3,79%	4,92%	4,01%	4,66%

Results Priority

Day	Never	Strict	Moderate	Relaxed	Always
1	24,00%	32,00%	50,00%	62,00%	64,00%
2	24,00%	38,00%	54,00%	76,00%	78,00%
3	22,00%	38,00%	54,00%	76,00%	76,00%
4	16,00%	26,00%	46,00%	68,00%	70,00%
5	22,00%	34,00%	48,00%	62,00%	66,00%
6	24,00%	32,00%	60,00%	70,00%	72,00%
7	26,00%	30,00%	44,00%	64,00%	64,00%
8	20,00%	38,00%	58,00%	68,00%	68,00%
9	26,00%	34,00%	52,00%	68,00%	70,00%
10	18,00%	30,00%	54,00%	68,00%	70,00%
LB	16,00%	26,00%	44,00%	62,00%	64,00%
UB	26,00%	38,00%	60,00%	76,00%	78,00%
AVG	22,20%	33,20%	52,00%	68,20%	69,80%
Median	23,00%	33,00%	53,00%	68,00%	70,00%
StDev	3,33%	4,02%	5,08%	4,94%	4,66%

Problem size medium

Results First Come First Serve

Day	Never	Strict	Moderate	Relaxed	Always
1	10,00%	22,00%	50,67%	64,67%	72,67%
2	6,00%	13,33%	46,00%	58,67%	64,67%
3	2,00%	6,00%	29,33%	45,33%	50,67%
4	22,67%	36,00%	62,00%	70,00%	72,67%
5	3,33%	7,33%	32,00%	48,00%	56,00%
6	6,67%	14,00%	46,00%	54,67%	60,00%
7	5,33%	13,33%	40,00%	56,67%	59,33%
8	14,67%	24,67%	51,33%	64,67%	70,00%
9	2,00%	8,67%	37,33%	46,00%	54,00%
10	12,00%	21,33%	48,67%	64,67%	68,00%
LB	2,00%	6,00%	29,33%	45,33%	50,67%
UB	22,67%	36,00%	62,00%	70,00%	72,67%
Mean	8,47%	16,67%	44,33%	57,34%	62,80%
Median	6,34%	13,67%	46,00%	57,67%	62,34%
St Dev	6,53%	9,32%	9,84%	8,76%	7,94%

Results Last Come First Serve

Day	Never	Strict	Moderate	Relaxed	Always
1	10,00%	20,67%	54,00%	64,00%	72,67%
2	6,00%	13,33%	44,00%	55,33%	64,67%
3	2,00%	4,67%	28,67%	43,33%	50,67%
4	22,67%	35,33%	62,00%	68,67%	72,67%
5	3,33%	6,67%	32,67%	46,00%	56,00%
6	6,67%	12,67%	45,33%	54,00%	60,00%
7	5,33%	12,67%	41,33%	56,00%	59,33%
8	14,67%	22,00%	49,33%	62,37%	70,00%
9	2,00%	8,00%	35,33%	44,67%	54,00%
10	12,00%	20,00%	48,00%	61,33%	68,00%
LB	2,00%	4,67%	28,67%	43,33%	50,67%
UB	22,67%	35,33%	62,00%	68,67%	72,67%
Mean	8,47%	15,60%	44,07%	55,57%	62,80%
Median	6,34%	13,00%	44,67%	55,67%	62,34%
St Dev	6,53%	9,16%	10,09%	8,72%	7,94%

Results Random					
Day	Never	Strict	Moderate	Relaxed	Always
1	10,00%	22,00%	52,67%	63,33%	72,67%
2	6,00%	12,67%	44,67%	57,33%	64,67%
3	2,00%	4,67%	28,00%	42,67%	50,67%
4	22,67%	36,00%	63,33%	69,33%	72,67%
5	3,33%	6,67%	32,67%	47,33%	56,00%
6	6,67%	13,33%	45,33%	55,33%	60,00%
7	5,33%	12,67%	41,33%	56,67%	59,33%
8	14,67%	22,00%	52,00%	64,67%	70,00%
9	2,00%	8,67%	34,67%	45,33%	54,00%
10	12,00%	22,00%	48,00%	62,00%	68,00%
LB	2,00%	4,67%	28,00%	42,67%	50,67%
UB	22,67%	36,00%	63,33%	69,33%	72,67%
Mean	8,47%	16,07%	44,27%	56,40%	62,80%
Median	6,34%	13,00%	45,00%	57,00%	62,34%
St Dev	6,53%	9,47%	10,59%	8,88%	7,94%

Results Priority					
Day	Never	Strict	Moderate	Relaxed	Always
1	10,00%	22,00%	54,00%	66,00%	72,67%
2	6,00%	14,00%	49,33%	59,33%	64,67%
3	2,00%	5,33%	32,00%	44,00%	50,67%
4	22,67%	38,00%	62,67%	70,00%	72,67%
5	3,33%	7,33%	34,00%	49,33%	56,00%
6	6,67%	13,33%	46,09%	56,00%	60,00%
7	5,33%	12,67%	42,67%	58,00%	59,33%
8	14,67%	25,33%	54,00%	66,00%	70,00%
9	2,00%	8,67%	41,33%	50,67%	54,00%
10	12,00%	21,33%	51,33%	67,33%	68,00%
LB	2,00%	5,33%	32,00%	44,00%	50,67%
UB	22,67%	38,00%	62,67%	70,00%	72,67%
Mean	8,47%	16,80%	46,74%	58,67%	62,80%
Median	6,34%	13,67%	47,71%	58,67%	62,34%
St Dev	6,53%	9,97%	9,50%	8,73%	7,94%

Problem size large

Results First Come First Serve					
Day	Never	Strict	Moderate	Relaxed	Always
1	11,00%	16.75%	42,00%	59,75%	74,00%
2	3,25%	9,25%	28,25%	44,00%	63,75%
3	5,50%	9.00%	29,50%	43,25%	61,00%
4	1,75%	12,36%	18,00%	30,00%	45,50%
5	15,25%	22,75%	45,75%	57,25%	68,75%
6	5,75%	11,25%	34.75%	48.5%	64,25%
7	5,50%	9,50%	32,75%	47.5%	61,25%
8	1,50%	4,00%	16,75%	32,75%	49,75%
9	12,25%	18,00%	39,25%	57,25%	69,50%
10	10.50%	18,75%	42,50%	56,00%	69,75%
LB	1,50%	4,00%	16,75%	30,00%	45,50%
UB	15,25%	22,75%	45,75%	59,75%	74,00%
AVG	6,86%	13,23%	32,75%	47,53%	62,75%
Median	5,50%	11,81%	32,75%	50,00%	64,00%
St Dev	4,87%	6,14%	10,58%	11,75%	9,02%

Results Last Come First Serve					
Day	Never	Strict	Moderate	Relaxed	Always
1	11,00%	15,50%	41,50%	58,75%	74,00%
2	3,25%	9,50%	27,50%	42,00%	63,75%
3	5,50%	7,75%	28,75%	42,25%	61,00%
4	1,75%	3,75%	15,50%	28,00%	45,50%
5	15,25%	20,75%	42,75%	55,75%	68,75%
6	5,75%	10,75%	30,00%	43,75%	64,25%
7	5,50%	7,75%	29,00%	45,00%	61,25%
8	1,50%	4,00%	16,00%	31,75%	49,75%
9	12,25%	18,00%	41,25%	57,50%	69,50%
10	10.50%	17,50%	41,75%	57,25%	69,75%
LB	1,50%	3,75%	15,50%	28,00%	45,50%
UB	15,25%	20,75%	42,75%	58,75%	74,00%
AVG	6,86%	11,53%	31,40%	46,20%	62,75%
Median	5,50%	10,13%	29,50%	44,38%	64,00%
St Dev	4,87%	6,04%	10,30%	10,95%	9,02%

Results Random					
Day	Never	Strict	Moderate	Relaxed	Always
1	11,00%	14,75%	41,25%	61,00%	74,00%
2	3,25%	9,75%	28,75%	44,50%	63,75%
3	5,50%	8,25%	30,50%	41,75%	61,00%
4	1,75%	4,25%	16,00%	29,75%	45,50%
5	15,25%	22,25%	45,75%	58,25%	68,75%
6	5,75%	19,25%	33,25%	46,25%	64,25%
7	5,50%	8,75%	29,25%	45,75%	61,25%
8	1,50%	4,25%	17,50%	31,00%	49,75%
9	12,25%	18,75%	18,50%	57,75%	69,50%
10	10.50%	18,25%	42,75%	57,00%	69,75%
LB	1,50%	4,25%	16,00%	29,75%	45,50%
UB	15,25%	22,25%	45,75%	61,00%	74,00%
AVG	6,86%	12,85%	30,35%	47,30%	62,75%
Median	5,50%	12,25%	29,88%	46,00%	64,00%
St Dev	4,87%	6,60%	10,72%	11,19%	9,02%

Results Priority					
Day	Never	Strict	Moderate	Relaxed	Always
1	11,00%	19,75%	51,75%	70,00%	74,00%
2	3,25%	11,50%	37,75%	56,25%	63,75%
3	5,50%	11,50%	38,25%	55,00%	61,00%
4	1,75%	4,75%	24,00%	39,25%	45,50%
5	15,25%	25,00%	50,50%	64,75%	68,75%
6	5,75%	12,75%	41,75%	57,50%	64,25%
7	5,50%	11,00%	40,75%	57,25%	61,25%
8	1,50%	4,75%	25,25%	42.50%	49,75%
9	12,25%	21,00%	51,00%	67,75%	69,50%
10	10.50%	20,00%	50,50%	66,50%	69,75%
LB	1,50%	4,75%	24,00%	39,25%	45,50%
UB	15,25%	25,00%	51,75%	70,00%	74,00%
AVG	6,86%	14,20%	41,15%	59,36%	62,75%
Median	5,50%	12,13%	41,25%	57,50%	64,00%
St Dev	4,87%	6,94%	10,28%	9,39%	9,02%

Appendix I – Feasibility percentage for all charging policies and problem sizes including trade-off

Results Small Priority

Day	Never	Strict	Moderate	Relaxed	Always
1	24,00%	32,00%	50,00%	62,00%	64,00%
2	24,00%	38,00%	54,00%	76,00%	78,00%
3	22,00%	38,00%	54,00%	76,00%	76,00%
4	16,00%	26,00%	46,00%	68,00%	70,00%
5	22,00%	34,00%	48,00%	62,00%	66,00%
6	24,00%	32,00%	60,00%	70,00%	72,00%
7	26,00%	30,00%	44,00%	64,00%	64,00%
8	20,00%	38,00%	58,00%	68,00%	68,00%
9	26,00%	34,00%	52,00%	68,00%	70,00%
10	18,00%	30,00%	54,00%	68,00%	70,00%
LB	16,00%	26,00%	44,00%	62,00%	64,00%
UB	26,00%	38,00%	60,00%	76,00%	78,00%
Mean	22,20%	33,20%	52,00%	68,20%	69,80%
Median	23,00%	33,00%	53,00%	68,00%	70,00%
StDev	3,33%	4,02%	5,08%	4,94%	4,66%

Results Small size with Detouring/Waiting

Day	Never	Strict	Moderate	Relaxed	Always
1	24,00%	76,00%	86,00%	92,00%	100,00%
2	24,00%	82,00%	96,00%	100,00%	100,00%
3	22,00%	80,00%	92,00%	98,00%	100,00%
4	16,00%	56,00%	72,00%	82,00%	100,00%
5	22,00%	78,00%	84,00%	96,00%	100,00%
6	24,00%	80,00%	88,00%	96,00%	100,00%
7	26,00%	70,00%	86,00%	98,00%	100,00%
8	20,00%	72,00%	88,00%	94,00%	100,00%
9	26,00%	78,00%	84,00%	94,00%	100,00%
10	18,00%	74,00%	90,00%	94,00%	100,00%
LB	16,00%	56,00%	72,00%	82,00%	100,00%
UB	26,00%	82,00%	96,00%	100,00%	100,00%
Mean	22,20%	74,60%	86,60%	94,40%	100,00%
Median	23,00%	77,00%	87,00%	95,00%	100,00%
StDev	3,33%	7,55%	6,33%	4,97%	0,00%

Costs Small size with Detouring/Waiting

Day	Never	Strict	Moderate	Relaxed	Always
1	0,00	4,08E+05	2,91E+05	2,46E+05	1,89E+05
2	0,00	3,35E+05	2,39E+05	1,90E+05	1,54E+05
3	0,00	3,54E+05	2,51E+05	1,93E+05	1,61E+05
4	0,00	1,40E+06	3,34E+05	2,47E+05	1,97E+05
5	0,00	3,63E+05	2,81E+05	2,40E+05	1,81E+05
6	0,00	3,55E+05	2,73E+05	2,19E+05	1,75E+05
7	0,00	1,34E+06	3,03E+05	2,34E+05	1,90E+05
8	0,00	3,69E+05	2,52E+05	2,19E+05	1,79E+05
9	0,00	4,16E+05	2,64E+05	2,24E+05	1,75E+05
10	0,00	3,88E+05	2,70E+05	2,33E+05	1,76E+05
LB	0,00	3,35E+05	2,39E+05	1,90E+05	1,54E+05
UB	0,00	1,40E+06	3,34E+05	2,47E+05	1,97E+05
Mean	0,00	5,73E+05	2,76E+05	2,24E+05	1,78E+05
Median	0,00	3,78E+05	2,71E+05	2,28E+05	1,78E+05
StDev	0,00	4,21E+05	2,80E+04	2,01E+04	1,28E+04

Results Medium Priority

Day	Never	Strict	Moderate	Relaxed	Always
1	10,00%	22,00%	54,00%	66,00%	72,67%
2	6,00%	14,00%	49,33%	59,33%	64,67%
3	2,00%	5,33%	32,00%	44,00%	50,67%
4	22,67%	38,00%	62,67%	70,00%	72,67%
5	3,33%	7,33%	34,00%	49,33%	56,00%
6	6,67%	13,33%	46,09%	56,00%	60,00%
7	5,33%	12,67%	42,67%	58,00%	59,33%
8	14,67%	25,33%	54,00%	66,00%	70,00%
9	2,00%	8,67%	41,33%	50,67%	54,00%
10	12,00%	21,33%	51,33%	67,33%	68,00%
LB	2,00%	5,33%	32,00%	44,00%	50,67%
UB	22,67%	38,00%	62,67%	70,00%	72,67%
Mean	8,47%	16,80%	46,74%	58,67%	62,80%
Median	6,34%	13,67%	47,71%	58,67%	62,34%
StDev	6,53%	9,97%	9,50%	8,73%	7,94%

Results Medium with Detouring/Waiting

Day	Never	Strict	Moderate	Relaxed	Always
1	10,00%	72,00%	89,33%	92,00%	98,67%
2	6,00%	46,00%	80,67%	88,00%	97,33%
3	2,00%	36,67%	61,33%	75,33%	97,33%
4	22,67%	88,00%	95,33%	97,33%	99,33%
5	3,33%	39,33%	77,33%	88,00%	98,67%
6	6,67%	60,00%	85,33%	88,00%	98,00%
7	5,33%	67,33%	86,67%	95,33%	98,67%
8	14,67%	72,00%	90,00%	96,00%	100,00%
9	2,00%	49,33%	81,33%	92,00%	100,00%
10	12,00%	73,33%	90,00%	95,33%	95,33%
LB	2,00%	36,67%	61,33%	75,33%	95,33%
UB	22,67%	88,00%	95,33%	97,33%	100,00%
Mean	8,47%	60,40%	83,73%	90,22%	98,30%
Median	6,34%	63,67%	86,00%	92,00%	98,67%
StDev	6,53%	16,94%	9,51%	6,64%	1,50%

Costs Medium size with Detouring/Waiting

Day	Never	Strict	Moderate	Relaxed	Always
1	0,00	1,22E+06	7,85E+05	6,93E+05	5,44E+05
2	0,00	2,35E+06	9,13E+05	8,18E+05	6,28E+05
3	0,00	2,56E+06	1,07E+06	9,56E+05	7,53E+05
4	0,00	9,01E+05	6,44E+05	5,89E+05	4,59E+05
5	0,00	1,46E+06	1,07E+06	8,83E+05	7,10E+05
6	0,00	1,32E+06	9,04E+05	7,99E+05	6,22E+05
7	0,00	1,37E+06	9,55E+05	7,87E+05	5,99E+05
8	0,00	1,19E+06	7,85E+05	6,74E+05	5,28E+05
9	0,00	1,41E+06	9,85E+05	8,64E+05	6,77E+05
10	0,00	1,19E+06	7,91E+05	6,70E+05	6,70E+05
LB	0,00	9,01E+05	6,44E+05	5,89E+05	458779,80
UB	0,00	2,56E+06	1,07E+06	9,56E+05	752902,00
Mean	0,00	1,50E+06	8,90E+05	7,73E+05	618901,59
Median	0,00	1,34E+06	9,08E+05	7,93E+05	624598,40
StDev	0,00	5,31E+05	1,38E+05	1,14E+05	89529,94

Results Priority

Day	Never	Strict	Moderate	Relaxed	Always
1	11,00%	19,75%	51,75%	70,00%	74,00%
2	3,25%	11,50%	37,75%	56,25%	63,75%
3	5,50%	11,50%	38,25%	55,00%	61,00%
4	1,75%	4,75%	24,00%	39,25%	45,50%
5	15,25%	25,00%	50,50%	64,75%	68,75%
6	5,75%	12,75%	41,75%	57,50%	64,25%
7	5,50%	11,00%	40,75%	57,25%	61,25%
8	1,50%	4,75%	25,25%	42,50%	49,75%
9	12,25%	21,00%	51,00%	67,75%	69,50%
10	10,50%	20,00%	50,50%	66,50%	69,75%
LB	1,50%	4,75%	24,00%	39,25%	45,50%
UB	15,25%	25,00%	51,75%	70,00%	74,00%
AVG	6,86%	14,20%	41,15%	59,36%	62,75%
Median	5,50%	12,13%	41,25%	57,50%	64,00%
St Dev	4,87%	6,94%	10,28%	9,39%	9,02%

Results Large with Detouring/Waiting

Day	Never	Strict	Moderate	Relaxed	Always
1	11,00%	68,00%	87,00%	94,00%	98,75%
2	3,25%	45,25%	71,50%	84,25%	97,50%
3	5,50%	47,50%	72,25%	83,50%	97,25%
4	1,75%	28,75%	59,00%	74,25%	97,50%
5	15,25%	74,00%	85,50%	92,25%	97,75%
6	5,75%	53,50%	78,25%	88,25%	98,50%
7	5,50%	49,50%	77,25%	85,75%	97,50%
8	1,50%	27,00%	71,50%	75,75%	96,50%
9	12,25%	69,00%	87,00%	93,25%	98,25%
10	10,50%	67,5%	85,75%	94,25%	98,00%
LB	1,50%	27,00%	59,00%	74,25%	96,50%
UB	15,25%	74,00%	87,00%	94,25%	98,75%
AVG	6,86%	51,39%	77,50%	86,55%	97,75%
Median	5,50%	49,50%	77,75%	87,00%	97,63%
St Dev	4,87%	16,83%	9,16%	7,29%	0,66%

Costs Large szie with Detouring/Waiting

Day	Never	Strict	Moderate	Relaxed	Always
1	0,00	3,01E+06	2,07E+06	1,70E+06	1,37E+06
2	0,00	3,56E+06	2,54E+06	2,10E+06	1,67E+06
3	0,00	3,52E+06	2,54E+06	2,14E+06	1,71E+06
4	0,00	5,02E+06	3,01E+06	2,60E+06	2,12E+06
5	0,00	2,87E+06	2,08E+06	1,79E+06	1,39E+06
6	0,00	3,29E+06	2,37E+06	2,02E+06	1,62E+06
7	0,00	3,68E+06	2,52E+06	2,13E+06	1,70E+06
8	0,00	3,91E+06	2,54E+06	2,51E+06	2,03E+06
9	0,00	3,05E+06	2,10E+06	1,76E+06	1,41E+06
10	0,00	3,00E+06	2,09E+06	1,76E+06	1,41E+06
LB	0,00	2,87E+06	2,07E+06	1,70E+06	1372498,90
UB	0,00	5,02E+06	3,01E+06	2,60E+06	2121938,15
Mean	0,00	3,49E+06	2,39E+06	2,05E+06	1643389,79
Median	0,00	3,41E+06	2,45E+06	2,06E+06	1644967,40
StDev	0,00	6,36E+05	3,06E+05	3,15E+05	266176,22

Appendix J – Pseudo code for algorithms

Algorithm: Selecting at which hubs to accommodate charging stations

```
Initialize selection process
Input  all_hubs
Evaluate all possible combination of two hubs
For each combination of two hubs in all_hubs:
        Feasible_dhl_routes = evaluate_feasible_dhl_routes(combination)
        Feasible_sub_contractor_routes = evaluate_feasible_sub_contractor_routes(combination)
        Store combination with (feasible_dhl_routes, feasible_sub_contractor_routes)
Select combination with highest number of feasible DHL routes
best_combination = select_best_combinations(combinations)

Handle ties by selecting combination with highest feasible sub-contractor routes
If multiple_combination_with_same_dhl_routes_number
        best_combination = select_best_combination_with_highest_sub_contractor_routes(combination)

Gradually add additional hubs to the combination
For additional_hub in all_hubs:
        For current_combination in best_combination:
              new_combination = current_combination + additional_hub
              feasible_dhl_routes = evaluate_feasible_dhl_routes(new_combination)
              feasible_sub_contractor_routes = evaluate_feasible_sub_contractor_routes(new_combination)

              store new_combination with (feasible_dhl_routes, feasible_sub_contractor_routes)
              if feasible_dhl_routes > best_combination.feasible_dhl_routes:
                  best_combination = new_combination
              if feasible_dhl_routes == best_combination.feasible_dhlroutes:
                  best_combination =
                  select_best_combinatio_with_highest_sub_contractor_routes(new_combination)
For number_of_hubs in range(2, all_hubs):
        optimal_combinations = get_optimal_combinations(number_of_hubs)
        Feasible_dhl_routes = get_feasible_dhl_routes(optimal_combinations)
        Output optimal_combinations with feasible_dhl_routes
```

Algorithm: Swap in combination with Simulated Annealing

```
Set Number of Iterations to 10000
Set No improvement limit to 10
Set CurrentTemperature to InitialTemperature
Initialize no improvement count
Initialize best feasibility percentage
Initialize best configuration to None
Initialize best total costs to infinity
    While No improvement count is smaller than no improvement limit DO
        Set accepted status to false

        Set true indices to true for trucks in cost comparison where improvement applied is true
        Set true indices to false for trucks in cost comparison where improvement applied is false

        If length of true indices is greater than 0 and length of false indices is greater than 0 then
            Set index true to Randomly choose
            Set index false to Randomly choose

            Set potential new costs to calculate potential costs for new configuration
            If potential new costs greater or equal than max costs
                Swap cost comparison improvement applied values for chosen trucks
                For each index in updated energy information data frame Do
                    Set Truck to truck
                    If Truck exists in cost comparison then
                        Set improvement value to improvement value in cost comparison
                    Set FeasibilityPercentage to calculated feasibility percentage for new configuration
                    If FeasibilityPercentage  is smaller than BestFeasibiltyPercentage then
                        Set Accepted to True
                        BestFeasibilityPercentage = FeasibilityPercentage
                        BestConfiguration = configuration with all trucks in cost comparison havin
                        improvement applied equal to true
                        BestTotalCosts = CalculateTotalCosts for BestConfiguration
                    Else
                        Set AcceptanceProbability = EXP((FeasibilityPercentage – LastBestFeasibility) /
                        CurrentTemperature)
                        Set Accepted = Random < AcceptanceProbability
                    If not Accepted then
                        NoImprovementCount += 1
                    If NoImprovementCount >= NoImprovementLimit then
                        Break

                    CurrentTemperature *= alpha

        End while
Result  = BestConfiguration
```

Appendix H – High Level Model Overview of GSM