Comparative Assessment of Charging Alternatives for Freight Carriers Using Scenario-Based Multi-criteria Evaluation

Master of Science Thesis
May 2025

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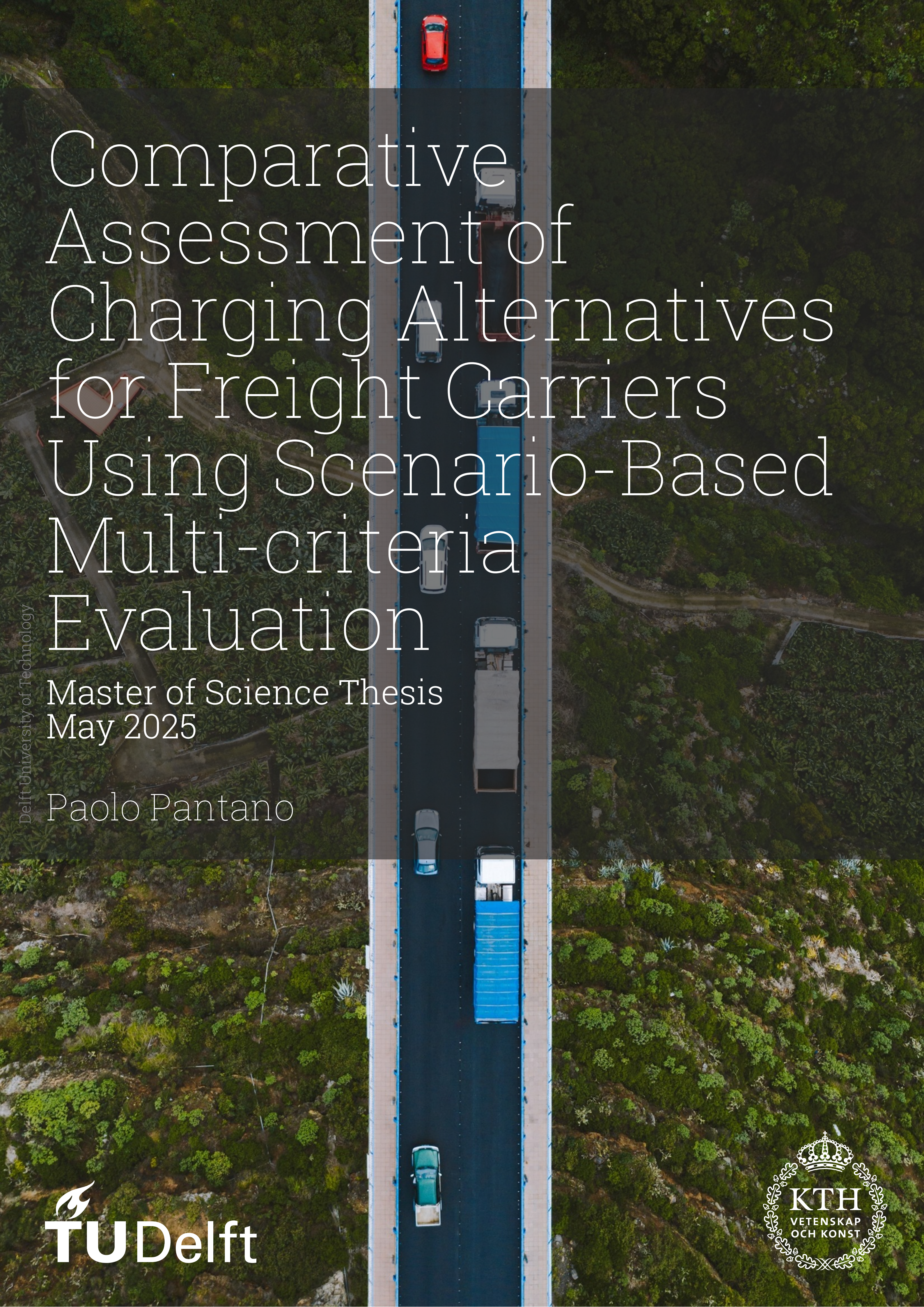

Comparative Assessment of Charging Alternatives for Freight Carriers Using Scenario-Based Multi-criteria Evaluation

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by

Paolo Pantano

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Preface

Writing this last part of my Master's Thesis report, I look back on the great time I had. Starting from a fruitful exploratory conversation with Lóri Tavsszy and ending with a final presentation at the office of SCANIA, it was a life-changing experience for me, and I learned a lot from going outside my comfort zone. Getting to know a new city, Stockholm, and the many people and cultures there sparked my interest in seeing more of the world in the future. Furthermore, being at the Integrated Transport Research Lab(ITRL) at the Kungliga Tekniska Högskolan (KTH) taught me a lot about the passion a group of people can have for research. For all these wonderful experiences, I would like to thank a few people.

First of all, Lóri Tavasszy and Anna Pernestal for creating this opportunity at ITRL and connecting me with two great supervisors at the lab. Nadia Pourmohammadzia, for her sharp feedback and support to help me get the best out of this research.

I also want to thank all the people at ITRL, who inspired, helped, and welcomed me as a family. My time at the lab will remain a special memory, and I wish you lots of luck in all your future efforts to change the transport world. I want to especially thank Bhavana, Claudia, Simon, Albin, Elisa, and Andres for the support they gave me during my thesis.

Lastly, I want to especially thank two persons who have been instrumental in this thesis work and have been my mentors along the way: Zeinab Raoofi and Vivek Venkatesh Shenoy. I will cherish memories of our Friday afternoon sessions that could go on for hours, discussing the thesis while having fun. You supported me through more difficult times and motivated me to make the best out of this work. I learned a lot and was inspired by your passion for research, and we built a friendship that will last forever. Thank you!

Paolo Pantano
Delft, May 2025

Summary

The road freight transport market accounts for 40 % of the carbon dioxide emissions of the transport sector globally. To reduce these emissions, battery electric trucks (BETs) have the greatest potential as they are zero-emission vehicles. However, compared to the private electric vehicle market, this market faces significant implementation barriers, as seen from the low BET sales. This is mainly due to the optimized market and low profit margins limiting freight carriers from investing in BETs. Furthermore, BETs face serious operational challenges due to long charging times and low operational flexibility. The way to charge the BET plays a big role in finding solutions to these challenges. In recent years, new technologies such as Electric Road Systems (ERS) and battery swapping have been developed next to depot charging and on-road charging. This study gains insight into the preferences of different freight carriers for charging alternatives, using a scenario-based multi-criteria decision analysis(MCDA). Four charging alternatives: depot charging, on-road charging, ERS, and battery swapping, are compared from a freight carrier's perspective on ten criteria identified through literature review, expert interviews, and a survey. The criteria are: Investment costs, operational costs, lifetime of the battery, charging time, operational flexibility, payload capacity, emission reduction, pioneering, complexity of implementation, and strategic policy alignment. To compare the charging alternatives, the criteria weights were obtained through the best-worst method and the analytic hierarchy process, and the performance of the alternatives on the criteria was calculated for daily distance use cases. These performances and weights were combined to arrive at a final ranking of alternatives. This was done for different freight carrier groups based on daily distance, sectors, company sizes, and countries of operation. The results show that financial and operational criteria were considered most important by all the segments of freight carriers. Furthermore, depot charging appeared to be the preferred alternative in most cases, and battery swapping scored best for larger daily distances. However, in almost all freight carrier groups, depot charging, ERS, and battery swapping had similar scores. This result advocates for stakeholders to consider investing in the charging alternatives to give the freight carrier the possibility to choose the charging alternative that is best for them. On-road charging had the lowest score for all the freight carrier groups. This result mismatches with the current investments in the charging alternative and showcases the need to reconsider these investments. Due to the number of criteria and the difficulties in obtaining many responses from freight carriers, the criteria performance and weights can be studied in more detail in future research. Also, using better weighing and evaluation methods and improved research on the four alternatives in a similar scenario can improve the quality of the results in future studies. Also, looking at the problem from different perspectives in future studies can provide great insight into which charging alternatives will shape the future of BETs.

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Nomenclature

Abbreviations

Abbreviation	Definition
AHP	Analytical Hierarchy Process
BET	Battery Electric Truck
BWM	Best-Worst Method
CCS	Combined Charging System
CPO	Charging Point Operator
ERS	Electric Road System
FCEV	Fuel Cell Electric Vehicle
GVW	Gross Vehicle Weight
kW	Kilowatt
kWh	Kilo Watt Hour
MCDA	Multi-Criteria Decision Analysis
MCS	Megawatt Charging System
MECE	Mutually Exclusive and Collectively Exhaustive
OEM	Original Equipment Manufacturer
TCO	Total Cost of Ownership

1 Introduction

Almost ten years ago, the Paris Agreement [1] set long-term goals to limit temperature rise by 1.5 degrees by reducing the emission of greenhouse gases. Worldwide, the transport sector is the second largest greenhouse gas emitter behind electricity and heat production [2]. Freight transport and logistics are responsible for almost 40% of these emissions[3]. Thus, it is clear that the transport sector and especially the transportation of goods by road is a sector that has to reduce greenhouse gases drastically. This is already incorporated in policy, as the European Commission has set HDV emission reduction targets of 45% for 2030, compared to 2019 [4]. To meet these targets, several alternative propulsion methods have been developed in the last decades, including alternative bio-fuels, fuel cell electric vehicles (FCEV) using hydrogen and battery electric trucks (BET) [5]. BETs and FCEVs are zero-emission vehicles, which means they emit no emissions while driving. Of course, no alternative is entirely zero emission, as the production of electricity, hydrogen, and batteries will produce emissions[6]. However, BETs have the greatest overall potential in reducing emissions [5]–[8]. Despite the great potential of BETs, many challenges come with this propulsion method, including: reduced range, reduced payload capacity, long charging times, and increased vehicle investment costs [9], [10].

1.1. Problem statement

These challenges can be seen in the developments of the different electric vehicle markets: while the market for private electric cars is booming and already accounts for 18 % of sales globally in 2023[11], the heavy duty electric vehicle market is long from meeting these goals and does not show promising signs of growth, with only 1.2 % of European heavy duty truck sales in Q3 2024 being BETs[12]. Looking at the last few years, apart from a peak in 2023, a stagnation of growth has been seen as the market and technology reach it's current limits and the pioneers aren't followed by the early majority [12], [13]. There are several challenges, including market characteristics, technology limitations, and the lack of development of infrastructure[9], [10], [14].

The challenges of electrifying the road freight market have several solutions. First of all, the market characteristics of the freight transport market hinder the transition to BETs greatly[15], [16]. In a globalized world, companies and their customers are used to low transport costs, and the competition among transporters to offer this low transport cost is fierce[17]. There are some signs of green logistics demand by customers and therefore companies, but the majority of the market remains focused on minimizing costs[10]. This has led to logistic service providers and freight carriers operating on small profit margins. With the investment cost of BETs currently being 2 to 3 times higher than that of traditional diesel trucks and many small freight carrier companies having limited financial resources, the investment costs to electrify are impossible to bring up for the majority of carriers[18]. Only a few pioneers and the biggest freight carriers in the market can currently afford to buy a few BETs, but this is usually more part of a marketing strategy than to electrify the entire fleet[17].

Another challenge is the limitation of current technology. Although development is rapid, trucks are more challenging to electrify than private cars due to higher operational demands. The current BETs cannot meet the demands of certain situations/applications, leading to less efficient operations by BETs, which is not feasible for a freight carrier. The main issues are long charging times, reduced payload capacity due to heavier batteries, and limited range of batteries[9], [10]. In a market where profit margins are low, companies need to compensate for high BET investment costs with lower operational costs. Although BETs are more efficient and electricity is cheaper than diesel, the low operational costs cannot make up for the high investment costs in the TCO[19], [20] for most transport types. Lastly, the current range of BETs creates risks for operations that many companies cannot afford in this flexible market, and for some operations, using a BET is simply not yet possible[18].

Lastly, a big challenge in the electrification of the road freight transport market is the lack of development of infrastructure for BETs[21]. This includes the availability of trained technicians in battery-powered truck technology and available charging infrastructure. Especially the lack of charging infrastructure is a big challenge [14], [22]. Whereas the on-road charging infrastructure combined with home-based charging is sufficient for most private electric car use cases, the logistics of BETs are different. The development of public charging infrastructure is picking up, but the growth rate is not promising. Starting charging points is a risk due to low BET sales. Furthermore, the requirements of the transport market ask for high-voltage fast chargers, which take much more time to request in the current overcrowded electricity grids in Europe[23], [24]. This is also one of the challenges for depot charging (equivalent to home-based charging for private cars) as they require a high-demand connection to the electricity grid, which can take years to obtain[25], [26].

1.2. Research objectives

A common factor in all three of these challenges is how BETs charge their batteries. How the BET is charged has an influence on business models and thus market characteristics and determines the performance of the trucks. As this choice of charging alternative plays a big role, stakeholders need to know which alternatives can be successful in the future. This allows them to put their efforts and investments in charging alternatives with the best prospects. As new alternatives such as Electric Road Systems (ERS) and battery swapping emerge, there is a need to compare several charging alternatives on their utility. Comparing the alternatives can be done from different perspectives, such as the perspectives of grid operators, OEMs, government, and freight carriers. But ultimately, to what extent the charging alternatives meet the demands of freight carriers will shape the number of sales of BETs that use a certain charging alternative and thus their rates of adoption. Therefore, the objective of this study is to give insight into which charging alternative is preferred by the freight carriers. As the market of freight carriers consists of different segments with different needs and possibilities, the study aims to provide insight not only in general but also more specifically for different segments of freight carriers.

Providing these insights can be valuable not only to freight carriers themselves but also to the other stakeholders that are involved in the electrification of the road freight transport market. This enables all stakeholders to act accordingly to the needs of the end users, the freight carriers. Acting with these insights, investments and efforts can be spent more efficiently, and this can help to quickly lower the barriers and solve the challenges of electrification. This is important, as there is no time to lose considering the current state of climate change.

1.3. Research gap and contribution

Similar to the objective of this study, many studies have looked at parts of the decision-making for a useful charging alternative. A literature review was performed to find a gap in the literature and to make a contribution. This literature review will be described more extensively in section 2.2. In this section, the gaps in the literature will be discussed shortly, and the contribution to the literature that this study aims to make will be explained.

In the literature, many studies focus on the usability of charging alternatives. This usability often compares original diesel trucks with a charging alternative or the standard on-road charging with the alternative. There are comparative studies for depot charging [5], [27], on-road charging [19], [28], [29], Electric Road Systems [30], [31] and battery swapping [32]. The perspectives of these studies vary between an energy grid perspective[20], [26], a government perspective[30], [33], technological perspective[34]–[36] or freight carrier perspective. Of the latter, multiple studies have been conducted [34], [37]–[40]. These studies often cover only certain parts of the comparison, for example the financial [16], [19], [37], [41], [42], operational/technical [29], [35], [36], [40], [43]–[45] and social [15], [46] aspects. Only a few studies compare charging alternatives on all these different types of aspects at once[38], [39], [47], [48]. Furthermore, these comparative studies of charging alternatives are rarely for many alternatives at once [29], [34], [40], [49], [50], meaning most of the collected information on charging alternatives is determined in different contexts. Lastly, many studies only look at a specific case study or use case [19], [20], [34], [48] and only a few studies compare the usability of charging alternatives under different circumstances[31], [37], [49]. The literature is even more limited when comparing the usability of charging alternatives for different segments of freight carriers, which has only been done in a few studies [22], [49], [51].

To conclude, in the literature, many studies look at different parts of the usability of charging alternatives from a freight carrier perspective. However, studies that give an extensive overview of factors, use cases, segments of freight carriers, and charging alternatives are missing in the literature. Addressing this research gap is essential for stakeholders seeking to understand the decision-making processes of various types of freight carriers when selecting their charging alternatives.

Therefore, this study contributes to the existing literature by filling that research gap and providing an extensive and complete overview of the charging alternatives and their usability for different types of freight carriers. This contribution can help stakeholders in the market to better understand the thinking of freight carriers and the different charging alternatives. This can lead to better decision-making regarding efforts and investments in these charging alternatives and the market in itself.

1.4. Research questions

From the problem statement and research objective, several research questions are formulated. Starting with the main research question:

> *What are the most favorable charging alternatives for diverse freight carrier segments across different operational contexts?*

To answer this main research question sufficiently, some sub-questions have been formulated that shape the study:

> *What is a good method to evaluate charging alternatives for different segments of freight carriers on all relevant factors?*
>
> *Which charging-related factors influence the choice of a charging alternative?*
>
> *What are the distinctive charging alternatives that should be compared?*
>
> *Which freight carrier's segmentations are expected to make a difference in choosing a charging alternative?*
>
> *How does the importance of charging-related factors vary across freight carrier segments?*
>
> *How do various charging alternatives perform on different evaluation criteria?*
>
> *How does the most favored charging alternative differ among various freight carrier segments?*
>
> *What are the key considerations for stakeholders (e.g., policymakers, freight carriers, OEMs) in a real-world context given the favored charging alternatives?*

These sub-questions will form the structure of the research, and their results will be discussed in chapter 4, chapter 5, chapter 6, chapter 7, and chapter 8.

1.5. Method choice

The study will use Multi-Criteria Decision Analysis (MCDA) [52] to answer the research questions. To perform the MCDA, first, the relevant criteria for the analysis will be established. This is done through literature, expert interviews, and a survey for freight carriers themselves.

Secondly, to obtain overall scores for the charging alternatives, the weights of the criteria need to be established. This is done prescriptively with the Best-Worst Method[53] and the Analytical Hierarchy Process[54]. These are pairwise comparison techniques to give weights to the criteria with a limited number of responses that were expected from freight carriers. As the goal of the study is to find the best charging alternative per segment of freight carriers, a survey is created that is sent to different types of freight carriers across Sweden and the Netherlands. The results of the survey are validated by also sending the survey to experts in the field.

For the overall scores for the charging alternatives also the performance on the criteria has to be established. This is done through assumptions, equations, and parameters that were found through literature review and expert interviews.

Lastly, combining the weights and performance of the criteria, rankings will be made of the charging alternatives for different segments of freight carriers.

1.6. Scope of the study

This study focuses only on the method of charging BETs, which includes: depot charging, on-road charging, ERS, and battery swapping. These alternatives are considered the most used and promising ones and have significant differences between them. This is explained further in section 4.1.

These charging alternatives are compared from the perspective of freight carriers. This means that the comparison is made for a fleet owner who has to choose a new (electric) truck for their freight-carrying company. As this study will also look at different types of freight carriers, there are some traits of freight carriers from which segments are made. The scope of these freight carrier segments includes the different daily distances, different sectors, different company sizes, and different countries of operation. How these segments are made is explained further in section 4.2.

The countries of operation include Sweden and the Netherlands, as the study was performed as a collaboration between TU Delft, KTH, and ITRL. This means that when the charging alternatives are compared, this is done in a Dutch or Swedish context. Furthermore, this context is a static future scenario between 2030 and 2040. It is assumed that during that period, the transition to electric driving in the road freight transport market is still ongoing, but the technology and charging infrastructure are more developed than nowadays. This scenario is explained in more detail in subsection 6.1.1.

1.7. Thesis structure

This thesis is divided into 9 chapters, all describing important parts of the study and its findings. A short explanation per chapter is given below:

- **chapter 1: Introduction –** Introduces the motivation of the research. It formulates a problem statement and shows the gap in the current literature. It introduces the contribution of the research and shows the research questions. Finally, it shortly touches upon the methodology used in the research.
- **chapter 2: Literature Review–** Discusses the literature review that has been done in preparation and during the research project. This literature review was done to get a grasp of the problem context and to gain an insight into the performed research on charging alternatives.
- **chapter 3: Methodology–** Sets out the methodology used to answer the research questions. Explains the steps that were taken and shows the timeline of these steps. The steps are explained and referenced, and decisions regarding the method are explained.
- **chapter 4: Definition of alternatives, freight carrier segments and criteria–** Shows the process of arriving at the final set of alternatives, freight carrier segments, and criteria of the research.
- **chapter 5: Weights of criteria–** Presents the criteria weight results from interviews and an online survey. Contains different tables and figures to show the results clearly and describes the differences among segments.
- **chapter 6: Criteria performance–** Describes the process and outcomes of the criteria performance of different charging alternatives. The process includes literature review, scenario and use case choice, calculations, and lastly, validation by experts in the field.

- **chapter 7: Ranking of charging alternatives–** Concludes and combines the different results and shows the ranking of charging alternatives for different freight carrier comparisons.
- **chapter 8: Discussion–** Interprets the results, gives recommendations based on these findings, highlights the possible limitations of the method. and discusses the possibilities for future studies.
- **chapter 9: Conclusion–** Summarizes the major findings from the results and concludes these findings. Formulates recommendations for different stakeholders from the findings and suggests future work for academia to further study the subject.

2 Literature Review

In this chapter, different parts of the literature review that have been performed for this study are shown. Literature review was done to get a grasp of the problem context, but also to find the research that has already been done for this problem context. An overview of the literature mentioned in this chapter can be found in Table 2.1. Next to these subjects, literature review was also performed later in the study to obtain the set of alternatives and criteria (subsection 4.3.3) and to determine the performance of alternatives on these criteria (section 6.3 and section 6.3).

Table 2.1: *An overview of the studies in the literature review* and the different subjects and perspectives they cover. (DC = depot charging, OR = on-road charging, ER = ERS, BS = battery swapping)

Source	Charging alternatives	Freight carrier perspective	Use-cases	Overall view	Carrier segments
Al-Hanahi et al.[14]	DC/OR		✓		
Spiller et al.[9]	**All**			✓	
Teoh[55]	DC/OR				✓
Gillström[10]	-			✓	
Karlsson and Grauers[19]	DC/OR	✓			
Mareev et al.[28]	OR	✓			
Decisio et al.[30]	ER			✓	
Rogstadius et al.(2023)[56]	ER		✓		
Zhu et al.[32]	BS		✓		
Çabukoglu et al.[36]	DC/OR/BS		✓		
Rogstadius et al.(2024)[7]	OR/ER		✓		
Speth et al.(2019)[34]	**All**	✓			
Speth et al. (2021)[40]	**All**	✓			
Wilmsen[50]	DC/OR/BS	✓			
Furnari et al.[49]	**All**		✓		✓
De Saxe et al.[31]	OR/ER		✓		
Speth et al. (2024)[27]	DC/OR		✓		
Liimatainen et al.[29]	-				
Schot[38]	ER	✓		✓	
De Nie[39]	ER	✓		✓	
Topsectorlogistiek[51]	DC/OR	✓	✓		✓

2.1. Challenges to electrification of the road freight transport market

First of all, at the start of the research, an idea of the context of the problem was created through different sources in the literature. For this context, the following literature was used:

Al-Hanahi et al.[14] study the existing literature on the challenges of electrifying the road freight transport market. It focuses on the challenges of depot charging and on-road charging and gives an overview of studies that try to find different solutions to these challenges. The challenges for depot charging include: upgrading the electricity grid infrastructure, peak demand electricity prices, operational challenges, and the lifetime of the battery. Some challenges related to on-road charging include fitting charging infrastructure with operation schedules, utilization rates of charging stations, charging costs, and limits of the electricity grid. Some solutions to the named challenges are discussed and include optimizing charging locations and smart charging strategies.

Spiller et al.[9] discuss different challenges of electrifying the road freight transport market. Through literature review, they address six challenges: economics of transition, fleet operation, manufacturing, grid infrastructure updates, equitable transition, and market and environmental externalities. The article suggests solving these challenges through policy and alternative charging methods. These policy measures have the potential to tackle multiple challenges at once. However, much is unknown about the effects of different types of policy, and therefore, many future studies are necessary. The article poses some open questions to give inspiration for these future studies.

Teoh [55] wrote a conceptual paper on charging strategies. The paper states that charging strategies are the result of charging behavior and charging opportunities. From the literature, the study gathers perspectives on different charging strategies and defines some alternatives. It states how different aspects can influence whether a charging strategy works for a certain driver or company. This indicates that there is no single best alternative, but that they are different for different users. The paper states that future studies should look further than just at TCOs and also look at whether charging strategies fit the operational needs.

Gillström [10] performed an interview study and two workshops to identify the barriers and enablers of electrifying the road freight transport market. The barriers were clustered into practical and technological barriers, financial barriers, institutional barriers, and social and cultural barriers. The article also discusses the link between the barriers with the market characteristics, and that the market will and must probably change from the transition to electric driving, as nowadays the stakeholders who take the highest risks do not benefit the most. To enable the transition, the article reasoned that closed and static subsystems should be electrified first.

2.2. Studies on charging alternatives

To find a research gap and learn from the studies that have already been performed on several charging alternatives, this literature review was performed. From this literature review, it was found that only a few studies investigate the charging alternatives from different freight carriers' perspectives with a holistic view. Furthermore, only a limited number of studies compare multiple charging alternatives at once. The identification of this research gap is explained in section 1.3. In this section, the most important studies in the literature are mentioned, and their conclusions are shown.

First of all, the following studies look at BETs in general compared to other propulsion methods, such as diesel, often from a systems perspective:

Çabukoglu et al. [36] study whether BETs are a viable option to reduce transport emissions in Switzerland. The study focuses on the system impacts of electrification and the adoption under different parameters. These parameters include gravimetric energy density, available charging infrastructure, and the use of battery swapping. The study concludes that currently, BETs are not able to replace diesel trucks, but given changes in the market and beyond the vehicle, the option has potential.

Liimatainen et al. [29] studies for all registered tonkm in Finland and Switzerland whether it has the potential to be electrified. It does this by using a commodity-level analysis. The study concludes that in Switzerland, 71 % can be electrified compared to 31 % in Finland. The study suggests doing future research by also including battery swapping and ERS, to see the real potential, but also to see which alternative has the best potential.

Other studies investigate the role and interplay of depot charging and on-road charging. These studies often don't compare with other propulsion methods but try to establish the best way to drive electric vehicles with the more standard charging alternatives:

Karlsson and Grauers [19] study the cost effectiveness of electrification for a long-distance line-haul freight carrier. The study looks at the combination of depot chargers and on-road charging. It also looks at the need for charging point operators to have sufficient capacity and utilization rates. It concludes that electrification can be economically viable for these freight carriers, given certain percentages of on-road charging and utilization rates of charging stations.

Speth et al. [27] study the choice between depot charging and on-road charging in different use cases. It concludes that, for most cases, depot charging is used, and Megawatt charging is necessary for long-haul trips.

Furthermore, a few studies also look at other charging alternatives such as ERS or battery swapping. This often means that these alternatives are compared to the regular charging alternatives or other propulsion methods:

A team of Decisio, EVconsult, and Sweco[30] compares Electric Road Systems in the Netherlands to diesel trucks and regular EFVs for the Dutch Ministry of Infrastructure and Water Management. The study focuses on the cost-effectiveness of emission reduction, the need for a sufficient ERS network, and the need for certain adoption levels. The study does this for different daily distance use cases. It concludes that the success of ERS is highly dependent on the speed of development of batteries.

Rogstadius et al. [56] study whether ERS can be a viable charging method to reduce greenhouse gases. The study models the competition with regular charging alternatives such as depot charging and on-road charging, based on cost-minimizing freight carriers. The study concludes that policy support is necessary to make ERS a success in Sweden, but could then give significant benefits regarding BET adoption, overall transport costs, and emission reduction.

De Saxe et al. [31] study the potential battery size reductions by ERS in different scenarios and use cases. It looks at different daily trip lengths and routes, but also at different sizes of the ERS network. The study concludes that, averaged over all cases, ERS can reduce battery sizes from 41 up to 75 % for different network sizes. Furthermore, depot charging is shown to be more effective than on-road charging in the study.

Zhu et al.[32] study the potential of battery swapping compared to fast charging. It compares the system costs per tonkm of the charging alternatives, given different recharge distances. It also studies the optimal recharge distance and utilization rate for battery swapping.

Schot [38] wrote a master's thesis that studies perceptions of ERS of different stakeholders, including freight carriers. The study identifies enabling and disabling factors in the decision-making, such as potential cost reduction, emission reduction, stimulating policies, and predictable cost estimations.

De Nie [39] wrote a master's thesis that studies the decision-making characteristics of ERS for small and medium-sized freight carriers in the Netherlands. Through interviews and literature search, the study portrays an image of which factors influence the choice of small and medium-sized freight carriers to choose for ERS. The study finds many factors of different types, such as political interest, varied external control, and future perspective.

Lastly, a few studies look at many different charging alternatives at once:

Rogstadius et al. [7] look at different propulsion methods and their potential to reduce emissions in EU road transport. Three types of fuels, three types of BETs, and hydrogen fuel cell trucks are considered. The alternatives are compared in a simulation model, including mostly cost parameters. From the study, it emerges that BETs have by far the greatest potential to reduce emissions, and their adoption can be accelerated by using ERS.

Speth et al. [34] compare the technological and economic features of diesel, battery swapping, and ERS trucks for a specific use case. The use case is a route between Berlin and Peine in Germany. Depot and on-road charging are not involved in the comparison. The study concludes that both battery swapping and ERS can be a good option when looking from a TCO perspective.

Speth et al. [40] compare regular BETs, battery swapping, and ERS trucks on a 500 km daily trip. The study compares the options on seven dimensions, including TCO, technical readiness, and operational flexibility. It bases its findings on several pilot projects in Germany. The study concludes that regular BETs and battery swapping are beneficial due to the possibility of operating in niches. ERS trucks have the lowest costs but need a high upfront investment that entails financial risks.

Wilmsen [50] wrote a master's thesis that compares battery swapping and slow and fast on-road charging. The study compares the alternatives on TCO and the boundary conditions given certain business models. It concludes that battery swapping has lower costs, but is harder to scale due to the standardization of batteries.

Furnari et al. [49] compare different charging strategies for different use cases. These charging strategies include battery swapping, ERS, and combinations of depot and on-road charging. The use cases are based on the length of operation, the flexibility of operation, and the cold-chain requirement. The study is not open about its methods, but it concludes that depot charging is the cheapest option. They also discuss the impact of operational needs on the battery size.

Mareev et al. [28] study the necessary battery dimensioning when on-road charging during rest times is used. The study does this for several distances and also looks at the system costs for these scenarios. In many scenario's the BETs can perform at the same cost as diesel trucks.

Furthermore, some research has been done on the different needs of different freight carriers when talking about BETs and charging. One of them is a report of a study by Topsector Logistiek in the Netherlands [51], which does a comparison of different sectors in the urban transport market regarding charging. The study looks at the necessary charging infrastructure given the needs of different sectors of freight carriers in urban logistics. The study concludes that for different sectors of freight carriers, different charging infrastructure has to be built to make them operationally viable.

3
Methodology

In this chapter, the chosen method and its parts are explained. Also, the methodology to obtain results for these parts and the overarching research is presented. In section 3.1, the motivation and justification for using an MCDA is explained, and the method is explained by naming the different parts and the steps to perform them. Furthermore, in section 3.2, section 3.3, section 3.4 and section 3.5 the methodology of these different steps is explained in more detail.

3.1. Research design

In this section, the overarching method, the Multi-Criteria Decision Analysis (MCDA), is introduced and explained. Also, the timeline of the method is shown, including the different steps of the method that will be explained in the following sections.

3.1.1. Multi criteria decision analysis

This study aims to give insight into the decision-making between charging alternatives of different types of freight carriers. From the literature review, it was learned that this comparison between charging alternatives should be made on different types of factors. In most studies, the TCO [34], [56] or operational capabilities [19], [28], [36] of the charging alternatives are used to compare them. In some qualitative studies, it was shown that social aspects also steer the decision-making of freight carriers[15], [38], [39], [46]. This indicates that the choice of charging alternative is in reality not a single objective decision-making process but a multi-objective one. This means that the alternatives should be assessed on multiple criteria to find the most favorable alternatives given all the objectives. A multi-objective decision-making problem can be tackled with several methods, including utility functions, agent-based models, linear optimization methods, or multi-criteria decision analysis. For this study, an MCDA was the favored method for two reasons. First of all, some of the identified objectives and thus criteria are qualitative, meaning a utility function or agent-based model was difficult to use[57], [58]. Furthermore, the identified alternatives are chosen to be separate and thus discrete alternatives, meaning a linear optimization method where parameters are changed quantitatively to obtain continuous alternatives cannot be used either. With an MCDA, quantitative and qualitative criteria can be combined in the analysis through scoring and normalization, and separate alternatives can be handled[52], [59].

The MCDA offers the possibility to analyze the alternatives on different types of criteria and give a certain score to each alternative[52], [59]. With this score, a ranking of alternatives can be made. However, a corresponding utilization to this score cannot be made, as can be done for utilization functions by using the logit model or multinomial logit model[60], [61]. However, as can be learned from the research gap, a more descriptive method, such as MCDA, has not yet been performed for this problem, and thus, the resulting insights into the decision-making process itself can already provide sufficient information for stakeholders to distribute their efforts and investments efficiently.

Given these reasons, a Multi-criteria Decision Analysis was chosen as the method to use. An MCDA is a decision support tool that is used to choose between alternatives when there are multiple (conflicting) objectives[52]. The decision problem is divided in smaller sub-problems by defining different criteria to asses the alternatives. For each criterion, performance by the alternatives can be measured. To find the best alternative for a stakeholder, weights are assigned to the criteria. This enables giving an overall performance value per alternative. Using these overall performance values, a ranking of the alternatives can be made.

To give an example of an MCDA application, the decision-making problem of buying a car is used. When buying a car, the customer might have three options. Car A might be the cheapest option, Car B might be the most stylish, and Car C might have the best driving experience. With all the options performing best for different criteria, it can be hard to choose between them. Using an MCDA, weights can be assigned to the different criteria based on their relevance to the customer. Using these weights and the performance on the criteria, the best car on all criteria can be chosen.

3.1.2. Research steps

Using the MCDA method requires several steps to be performed. All the steps, including their goals and methodology, have been summarized in Figure 3.1. As can be seen from the figure, defining the context is the first step. This includes finding a good set of alternatives and criteria. The used methodology for this step is explained in section 3.2. As a second step, the weights of the criteria for different freight carriers need to be determined. How this was done is shown in section 3.3. The third step is about calculating the performance of all the criteria for different alternatives. These calculations are explained in section 3.4. The last step is to combine the results of the first three steps to rank the alternatives for different types of freight carriers. How these results were combined is explained in section 3.5.

3.2. Defining criteria and alternatives

The first step of the MCDA was to define the context[62]. This context consists of a set of alternatives and a set of criteria. How these sets were chosen was based on the goals of the MCDA that follow from the main research question from section 1.4.

First of all, the set of alternatives needs to be determined. When choosing a set of alternatives, it was important to ensure that the set is as Mutually Exclusive and Collectively Exhaustive (MECE)[63] as possible. Mutually exclusive means that the alternatives shouldn't overlap: Comparing two very similar alternatives will not yield interesting results. Furthermore, collectively exhaustive alternatives cover the widest range of possibilities. This means that no important alternative should be missed. In case of charging alternatives, this means that the most prominent distinctions in techniques should be considered, and no important charging alternatives should be missed.

For the set of criteria, a similar approach should be taken. The set of criteria must be as Mutually Exclusive and Collectively Exhaustive (MECE)[63] as possible. This means that two criteria cannot overlap, and all relevant criteria must be included. Some criteria might be very similar to each other or can be combined into a single criterion. Therefore, it was important to distinguish the criteria that differ from each other. Also, to ensure collective exhaustiveness, it was important to include all the criteria that make a significant difference for the freight carriers between the alternatives. Criteria that have the same performance among alternatives are not relevant. Then, it was also important to consider that there might be differences in how stakeholders of the market see the relevant criteria. For an energy company, the load on the grid might be an important criterion, while that is of (almost) no relevance for the freight carriers. But even while looking with the same perspective, different stakeholders might have different ideas of what is important. Academic experts might think certain criteria are vital, while they are not considered by the freight carriers at all.

How this context was obtained and validated to be MECE is explained in the following subsections.

3.2.1. Literature review

First of all, a short literature review was performed to find and select the relevant charging alternatives. Most of this review was already performed when defining the research objective and scope. However, to define the bounds of the alternatives and how to separate them, the charging methods were studied in more detail. No clearly defined methodology was used for this.

Figure 3.1: The steps of the research

Next, a literature review was performed to find and select relevant criteria for the choice of a charging alternative. The literature search tries to find any research that compares options of sustainable transportation for road freight transport, preferably BEV methods. These studies were found by using the following search queries:

> (”freight carrier” OR ”logistic operator” OR ”logistic haulier” OR ”haulier”) AND (”electric trucks” OR ”electric freight vehicles” OR ”BEV” OR ”electric freight transport”) AND (”preferences” OR ”criteria” OR ”needs” OR ”factors”)

From these studies, all relevant factors or criteria on which the alternatives were compared or assessed were noted down. This created a large table of criteria that influence the choice of a propulsion fuel or charging technique. From this table, the criteria that were mentioned most often were noted down. Then, from these criteria, the ones that made a difference among the charging alternatives of this research were extracted. Criteria that used synonyms were merged into a single term, and this left a list of relevant criteria from the literature.

3.2.2. Expert interviews

Expert interviews are a vital part in understanding which criteria are relevant for freight carriers in the electrification. Experts in the field of electrification of the road freight transport network are approached and asked for interviews. Especially experts on the charging alternatives are approached, as it was assumed they know what criteria their charging alternative performs best on, and as a result, makes them the better option. Also, experts who are or have been in close contact with a lot of freight carriers are approached as they understand the needs of the freight carriers. These experts can also help in formulating the criteria in an understandable way for the freight carriers, as there might be some differences in the language used between academia and the transport market itself. The expert interviews that were conducted are shown in Table 3.1.

3.2.3. Freight carrier validation

As part of the search for criteria, validation of the considered criteria by freight carriers was performed. This was done by attending a webinar on electrification for the forestry transport industry in Sweden. At the webinar, around 150 participants attended, including freight carriers, academic experts, OEMs, and logistics service providers. After the webinar, a short survey was shared with the attendees in which the question was asked what they consider relevant criteria when choosing a charging alternative. The survey got 8 responses, including 4 freight carriers, 2 academic experts, 1 OEM, and 1 anonymous. This survey validates the criteria as it can confirm that these are the criteria that are considered by the freight carriers themselves. Also, potentially missing criteria can be discovered. The survey can be seen in Appendix B.

Table 3.1: Overview of interviewed experts involved in the development and selection of evaluation criteria

Organization and role	Expertise
Forestry transport electrification project, researcher	Electrification of forestry transport.
Regional initiative for logistics, project manager	Battery Swapping pilots and initiatives.
ERS technology company, business development manager	ERS business application
R&D OEM, business strategy analyst	Depot charging
R&D OEM, project leader	ERS
Swedish university, doctoral candidate	Policy mix for electrification of road freight

3.3. Criteria Weights

The second step in ranking the alternatives with MCDA is finding the weights for the criteria[52]. In this research, the weights of different freight carriers for the criteria are obtained through an online survey, of which the methodology is described in subsection 3.3.1. To validate these weights, the same survey was sent to experts in the field and three stakeholder interviews are performed, described in subsection 3.3.2.

3.3.1. Online survey

First of all, an online survey was used to obtain weights from different freight carriers and experts for the criteria. The used methods are described and explained in subsection 3.3.1 and Equation 3.3.1. The final format of the survey is shown in Equation 3.3.1, and how the survey was distributed is explained in Equation 3.3.1.

Best Worst method

To find the weights of the criteria, a tool must be chosen. Several tools exist, including Analytical Hierarchy Process (AHP), Analytical Network Process (ANP), superiority and inferiority ranking (SIR), Stepwise weight assessment ratio analysis(SWARA), Weighting method using continuous interval scale, imprecise weight estimates (IMP), and many others[64]. Some of them, including AHP, ANP, and BWM, are pairwise comparison methods[54]. These methods help make the weights matrix by using relative preferences of the respondent[65]. However, many inconsistencies occur in the matrix, and it takes a lot of time comparing each criterion with the others[66]. For those reasons, J. Rezaei proposed a new MCDM method to derive weights[53].

This is the Best-Worst Method. This MCDM method uses fewer pairwise comparisons, which makes the method less time-consuming and more understandable, leading to more consistent results [53]. Furthermore, the method requires fewer data than other methods, such as AHP. Usually, 5 to 6 responses per group are sufficient to give good descriptive answers of weights with the BWM [53]. From the interviews that were used to find the criteria (subsection 3.2.2), it was learned that it is difficult to reach freight carriers as they are busy and uninterested in participating in academic research. For those reasons, it was expected to have less quantity of data from the freight carriers, advocating for the use of BWM, which could provide high-quality results with a limited number of responses. In the method, the respondent chooses the best and worst criteria and compares these with the others. The respondent compares the best, or most important, criterion with the others by assigning how much more important that criterion is on a scale of 1-9. Then, the respondent compares all the criteria with the worst, or least important, criterion by saying how much more important they are on a scale of 1-9. This comparison is shown in Figure 3.2.

This results in two vectors with preferences:

$$
\begin{aligned}
A_B &= (a_{B1}, \ldots, a_{Bn-2}) \\
A_W &= (a_1W, \ldots, a_{n-2W})
\end{aligned}
\tag{3.1}
$$

Then, the final weights $(w_1^*, \ldots, w_n^*)$ can be calculated by minimizing the absolute maximum distances $|w_B - a_{Bj}w_j|$ and $|w_j - a_{jW}w_W|$ for al j between the preferences and the final weights. This is shown in Equation 3.2.

$$min\xi^L$$

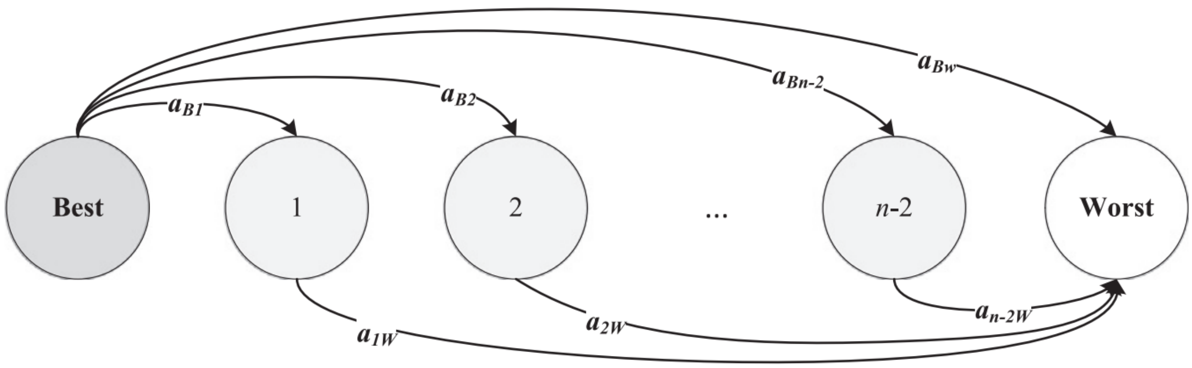

Figure 3.2: This figure visually shows the pairwise comparison between the best and worst criteria and the other criteria(1,2, n-2). The relative preferences are shown as a_{B1} to a_{Bn-2} and a_{1W} to a_{n-2W} [53]

Subject to:

$$\begin{aligned} |w_B - a_{Bj}w_j| &\leq \xi^L, \forall j \\ |w_j - a_{jW}w_W| &\leq \xi^L, \forall j \\ \sum_j w_j &= 1 \\ w_j &\geq 0, \forall j \end{aligned} \tag{3.2}$$

Solving this linear problem can give final weights $(w_1^*, \ldots, w_n^*)$ for all criteria. As a byproduct, the consistency can also be extracted with the variable ξ. A ξ close to zero can indicate that the respondent was very sure of their answers.

Normally, the Best-Worst Method is performed with a group of experts in interviews [53]. However, for this research, it was chosen to use an online survey. This approach was chosen after supervisors and interviews with experts indicated that freight carriers have a busy schedule, and the necessary number of responses would be impossible to achieve through interviews. The survey, however, has a trade-off, as the quality of results was lower because the message did not come across entirely, and different interpretations of the questions occurred. This resulted in many responses being filled in a way that does not match the answer format of the Best-Worst method, but rather an Analytical Hierarchy Process. These responses were still used in the weight collection, and thus this method will be explained in Equation 3.3.1.

Analytical Hierarchy Process

As some of the responses to the survey were filled in as a Likert scale of importance for the criteria, a technique to convert them to an AHP-matrix was used[67]. Then, from this AHP-matrix, the weights for the criteria could be determined[54], [68].

First, the traditional AHP pairwise comparison matrix was made. Using Equation 3.3.

$$\hat{a}_{ij} = |Sc_{ik} - Sc_{jk}| + 1 \tag{3.3}$$

The Likert scores can be put in the AHP matrix. Using the outcome of Equation 3.3, comparing the higher score with the lower score and the 1/outcome for the comparison other way around. Then, to convert the AHP matrix to weights, the columns of the matrix are normalized by dividing the entries by the column's sum. Lastly, the average of each row was taken to get the weight for each criterion. These results are then combined with the weights from the BWM answers.

Format of the survey

The survey was made in Microsoft Forms. This platform is supported by TU Delft and gives many options to make a survey. The survey was provided in three languages: English, Swedish, and Dutch. The first three sections contain questions about the role in the market, company, and operation characteristics. Then, in the following two sections, the pairwise comparison for the BWM was presented. Due to limitations of the platform, no conditional questions based on the choice for best and worst criteria could be used. This made it difficult to make the interpretation of the questions similar. This problem was addressed by providing an explanation in the survey, a self-recorded explanation video, and an infographic that was sent together with the survey. Still, not all respondents interpreted the comparison correctly. The influence of these limitations will be discussed in chapter 8. An example of the online survey and the infographic can be found in Appendix B.

Validation of the understandability of the survey was done before sending the survey to the freight carriers. First of all, the understandability was checked with several academic experts. These experts include four members of the Integrated Transport Research Lab (ITRL) at the KTH in Stockholm. Another reference was one of the inventors of the Best-Worst method. Next to them, an expert in the field from an electrification initiative in Sweden was asked about the understandability of the survey for freight carriers. Lastly, a final version of the survey was checked with a representative from a logistics service provider in the forestry transport industry in Sweden. All feedback on the understandability of the survey was taken into account and used to come to the final version.

Distribution of the survey

The distribution of the survey was done in different ways. First of all, transport associations such as TLN, EVOFENEDEX, VERN-NL in the Netherlands, and Sveriges Åkeriföretag and FAIR transport in Sweden were approached to send the survey to their members. Similarly, electrification initiatives such as CLOSER and the TREE project in Sweden are asked to distribute the survey to their members and followers. Thirdly, another method of distributing the survey was using email addresses from websites with contact details of freight carriers, such as FAIR Transport and EVOFENEDEX. Fourthly, some of the biggest freight carriers in Sweden and the Netherlands are contacted through their websites. Lastly, a project meeting of the TREE project was used to find respondents.

In order to validate and compare responses from freight carriers, the survey was also sent to experts from different stakeholder groups in the field. These include Academic experts, CPOs, OEMs, and the government. Distribution among these experts was done through contacts of supervisors and by sharing a LinkedIn post with multiple networks.

3.3.2. Stakeholder interviews

Stakeholder interviews are used to gain extra insights and to validate the weights of the criteria. At the end of most interviews, the online survey was filled in together with the interviewee. This helps to ensure the right interpretation of the question. The interviews gave background information on the choices in the survey and are therefore very useful for the understanding of the final results. The interviewed stakeholders are shown in Table 3.2.

Table 3.2: Overview of interviewed stakeholders involved in the validation of weights of the evaluation criteria

Organization	Role	Expertise
Dutch transport branch	Head of sustainability	Sustainable transport for logistics
Dutch transport branch (small freight carriers)	Chairman	50 year experience in logistic business
Large logistics company	Director of sustainability	Fleet management and logistics

3.4. Criteria Performance

The third step in the method of this research is the determination of performance on the criteria [52], [62]. For each of the different criteria, performance values are searched in the literature, as can be read in subsection 3.4.1. To gain more insights into values and to make realistic assumptions in the calculations, several experts are interviewed, as will be explained in subsection 3.4.2. These found values and assumptions are then transferred into the right scenarios to compare them with each other, described in subsection 3.4.3.

3.4.1. Literature search

Using a literature review, first of all, the assumptions for the calculations were determined. This process was assisted with expert interviews but was also validated and strengthened from findings and conclusions in the literature.

Furthermore, with the literature review, performance parameters from several studies are found and used. This literature mainly consisted of studies that were already mentioned in section 2.2. Furthermore, literature that was suggested during the research by experts was used. Lastly, for the missing parts, a directed literature search was performed. When using the above-mentioned sources of literature, it was essential to take into account the conditions under which the values were determined in the studies. This ensured the calculations in the scenario were error-free and transparent.

As the research on charging alternatives can sometimes be performed by possibly biased experts on the technology, it was important to find several sources for most parameters. This limited the effect of bias some researchers might have in defining or predicting parameters and ensured robust and realistic outcomes of the calculations. In chapter 6, the used references are shown and the motivation to choose the final parameter or the set of final parameters. The impact of these parameters and validation of them was done in several ways, by calibrating the calculations, discussions with supervisors and experts, and ultimately, a sensitivity analysis.

3.4.2. Expert interviews

To ensure the use of good values and assumptions in the calculations, expert interviews are performed. All interviewed experts are specialized in certain charging alternatives but have a general understanding of the other alternatives. For the less established charging alternatives, such as ERS and battery swapping, multiple experts are consulted, as assumptions and values can be more uncertain. In this way, the possibility of biased answers was minimized. The consulted experts for validation are shown in Table 3.3.

Table 3.3: Overview of interviewed experts involved in validation of the performance assumptions, equations, and parameters

Organization and role	Expertise
Swedish university, Professor	Expert on Battery Swapping
Battery swapping start-up, Director	Research and business experience Battery Swapping
R&D Original Equipment Manufacturer, Business strategy analyst	Expert on depot charging
Swedish infrastructure institution, Technical expert	Expert on charging infrastructure in Sweden
Swedish research institution, Researcher	Multiple studies on ERS applications
ERS technology developing country, Business development manager	ERS business application
German university, scientific associate	6 years working with an ERS pilot project

3.4.3. Scenario and use cases

Calculations of the found performance parameters from the literature into the scenarios and use cases are very important. The calculations ensure that the outcomes are compared for a similar scenario. This was necessary as in the literature, the performance outcomes are calculated in very different conditions. This can, for example, be different battery sizes, operational needs, or a moment in time. In the scenario that was used for this research, such parameters will be fixed, and the performance results will be calculated with these parameters. The final choice of these parameters was difficult, but was based on the findings in the literature and the assumptions made. Furthermore, the use cases are based on daily distance, as this was found to have the biggest effect on performance differences among the alternatives. The precise definition of the use-cases is explained in subsection 6.1.2.

3.5. Overall ranking alternatives

The last step of the method is to combine the weights and performances of the criteria from the other steps into a final score. This step will give rankings of the charging alternatives for different use-cases and respondent segments. To achieve this, the weights will be generalized for the segments, explained in subsection 3.5.1. Then, the performance outcomes of the criteria will be normalized to compare them, explained in more detail in subsection 3.5.2. Thirdly, the weights and performance results will be combined to come to rankings for the segments, explained in subsection 3.5.3. Lastly, a sensitivity analysis was performed to see the sensitivity to parameters, explained in subsection 3.5.4

3.5.1. Generalizing weights

First of all, to see differences between segments of the respondents, the weights will be generalized. This means taking the average of the weights over a segment group, as was done in [62]. The chosen segments are as follows:

- Experts and freight carriers
- Daily distances of freight carriers
- Sectors of freight carriers
- Company sizes of freight carriers
- Country of freight carriers

3.5.2. Normalizing performance

Next, to use the performance outcomes in different units for an overall comparison, the scores were normalized. This means that the scores per criterion will be normalized over the alternatives. Normalization also includes making positive and negative criteria comparable. The used formulas are

Equation 3.4 and Equation 3.5[62].

$$\bar{x} = \frac{x - x_{min}}{x_{max} - x_{min}} \text{for positive criterion like lifetime of battery} \tag{3.4}$$

$$\bar{x} = \frac{x - x_{max}}{x_{min} - x_{max}} \text{for negative criterion like operational cost} \tag{3.5}$$

This leads to a value of 1 for the best-performing alternative for a criterion and a 0 for the worst-performing alternative. The other alternatives will have a score between 0 and 1.

3.5.3. Ranking of alternatives

Lastly, using the generalized weights and the normalized performance outcomes per use case, the final rankings of alternatives can be found. This was done by taking the sum of the products of the criteria weights and performance[52], [53], [62]. This is shown in Equation 3.6.

$$\text{Overall performance charging alternative} = \sum_j w_j^* a_j \forall j \tag{3.6}$$

This sum will give a score between 0 and 1 for each alternative. In theory, the perfect alternative that is best in each criterion will get a score of 1. However, this is rarely the case in MCDA, and then the weights will determine which performance results will have the most influence on the overall performance. The overall performance outcomes can be used to rank the alternatives, but also to gain an understanding of how well the charging alternative fits its purpose. This understanding was mainly based on the relative score differences[59].

3.5.4. Sensitivity analysis

Lastly, a sensitivity analysis was performed. A sensitivity analysis is common for many different modeling techniques to see how the model reacts to changes in the parameters used[69], [70]. These changes can be due to uncertainties, future developments, or policy interventions. Furthermore, the model and its findings can be tested for their robustness to change. For an MCDA, sensitivity analysis is less common. However, there are some examples where sensitivity analysis was used for MCDA models[71]. In a review paper by Wieckowski et al. [72], 250 different research papers(2014-2023) are found that perform sensitivity analysis on MCDA models. Although many different sensitivity analysis methods for MCDA models exist, the basic idea is often the same. Sensitivity analysis can be done on either the weights, performance parameters, or criteria outputs. In the literature, often, the weights are changed to see the sensitivity[72]. However, for this study, it was chosen to study the sensitivity to the performance parameters and performance outputs, as they can give the best insight into what policy interventions can achieve and what possible developments in charging alternatives and the market can mean for the results.

First, the sensitivity to performance parameters was analyzed by incrementing or decreasing a single parameter by steps of 5 %, until the first change in the ranking of alternatives was found. The steps of 5 % were chosen from preliminary tests with some parameters, where this step size found the ranking changes in enough detail, and a smaller step size meant significantly longer runtimes for the analysis. The sensitivity analysis to performance parameters was done over all the performance use cases, with the general parameters: energy consumption rate, battery cost, at-home electricity cost, and on-road electricity cost. Furthermore, the sensitivity to alternative- and use case-specific parameters was analyzed for the following parameters: battery size, battery lifetime, component cost, charging power, and ERS use cost.

Furthermore, the sensitivity to the criteria was analyzed. This sensitivity was analyzed by excluding the criteria performances from the overall alternative score. Excluding the criteria from the ranking meant assigning the same performance score for all the alternatives on that criterion. This ensured that no difference between the alternatives could be made based on that criterion, and thus the effect of excluding that criterion on the ranking was found. If the criterion was excluded and no change in the ranking occurred, that criterion had no significant influence on the ranking in the first place. This analysis was performed for all the different use cases.

4 Definition of alternatives, freight carrier segments and criteria

The first step of the MCDA is the definition of the context [62]. This includes the choice of alternatives, shown in section 4.1, and the choice of criteria, shown in section 4.3.

4.1. Set of alternatives

First of all, the set of alternatives is determined. The final set of alternatives includes all the main charging techniques and has limited overlap. The final set is listed below, with some background information and an explanation of the definition of each alternative. The details of this definition will be shown in chapter 6.

Within charging, there are different methods. These include different voltages of charging (CCS and MCS)[73], [74] but also newer technologies such as Electric Road Systems(ERS) and battery swapping. All technologies have benefits and challenges on different levels, such as system and user levels. Combining different methods and how to use these methods can shape a charging strategy. In these strategies, one of the charging methods is usually dominant, forming a charging alternative. In the next paragraphs, these charging alternatives will shortly be introduced.

Depot charging

Depot charging is mainly reliant on charging the truck at the depot. In extreme circumstances, the driver may opt for on-road charging, but the trucks and operations are designed to avoid this. This means that trucks will mainly slow charge during rest times. This can include overnight charging or charging during loading or unloading. Charging is usually cheaper as there is no charging point operator in between that tries to make a profit. However, the investment costs per vehicle are higher, as there is a need for bigger batteries to complete operations, and the charging infrastructure should be bought by the freight carrier itself [27]. This alternative has overnight depot charging as the main charging technique. Truck parameters will be adjusted so that overnight charging is sufficient to complete the whole day. Each truck has a single depot charging device, and the available time overnight is the time outside working shifts [75].

On-road charging

On-road charging is charging at stations, usually the same location as the diesel stations[76]. However, charging a truck takes a lot more time than refueling it, and the current availability of charging is low, leading to queues at peak charging hours[77]. Tackling this problem is done by charging with more power, with megawatt chargers about to step into the market[78]. These megawatt chargers can often charge the vehicle in about 30 minutes, depending on its battery size. The downsides of megawatt charging are, however, the reduced lifetime of the battery, higher charging cost, and the limited availability of the grid[79], [80]. Currently, many initiatives and joint ventures are extending the on-road charging infrastructure network to make on-road charging available for all trucks and operations in the future. This alternative uses on-road charging as the main charging alternative. On-road charging will always be fast-charging[81]. For this alternative, the battery will be full at the start of the day from some depot charging with a shared charging device or on-road charging at the end of the previous day.

Electric road systems (ERS)

Electric road systems are a less common but promising alternative. Electric roads make use of charging via a pantograph while driving. The pantograph connects to an overhead line on the highway, and in this way, the truck can drive without using electricity from the battery or even charge its battery while driving, dependent on the power on the line and the demand for power by the truck[82]. This dynamic charging results in smaller batteries, as the batteries are only needed for the last kilometers off-network to the destination[31], [83]. This can reduce investment costs for the carrier. Challenging is the high investment costs of the infrastructure, as a two-way overhead line for a single kilometer can easily cost about 3.3 million euros[30]. Since the highways are state-owned in most countries, the government is mainly responsible for building the infrastructure. Up until now, governments of Sweden and the Netherlands have not been keen on building the infrastructure, following several reports[30], [33]. This is mainly due to the high utilization rate that is needed to pay back the investments[56]. This alternative uses Electric Road Systems as the main charging technique. Similar to the on-road charging alternative, the battery is assumed to be full at the start of the day. It is assumed that no charging outside the ERS network has to be performed during the working day.

Battery swapping

Battery swapping is an alternative that is growing fast in China. This alternative swaps an empty battery for a fully charged one at a station. The swapping technique is already mature and is automated in some stations in China. In Europe, the alternative is not yet used, mainly because there are only a few stakeholders convinced of the alternative[84]. The benefits of battery swapping are the short downtime, as the swapping only takes a few minutes, and the batteries can be charged during the day, and low charging costs due to dynamic electricity prices and grid balancing[85], [86]. Battery swapping, however, asks for extra batteries in the system, increasing the investment costs. Also, the batteries must be standardized, hindering the development of batteries by different actors. In China, however, many of these challenges are tackled by shared ownership of batteries[86], [87]. This alternative assumes battery swapping as the main charging technique. The battery swapping will happen inside a self-owned system, meaning the freight carrier owns spare batteries and swapping stations for itself.

4.2. Freight carrier segments

As the charging alternatives have different challenges and benefits on different parts of the problem, it seems logical that the future of electrification will be shaped by a combination of charging alternatives, and no ultimate best alternative exists; Some alternatives suit certain freight carriers better than others. This can come from different company characteristics or operational needs. These differences among the freight carriers can influence how well a charging alternative works, but also how much it is appreciated. There are different dimensions on which the freight carriers can be segmented. The dimensions that are considered most influential are introduced shortly in the next paragraphs.

Daily operation distance

Daily operation distance is an important dimension that can have an impact on the choice of charging alternative. Among freight carriers, these daily distances can vary greatly [88]. Depending on the sector, customer locations, and available infrastructure, freight carriers can drive distances varying from just 80 kilometers to almost 1400 kilometers a day with a single truck. In the literature, these differences are often categorized in urban, short- or mid-haul, and long-haul transport[49].

Transport sector

Transport sector is another dimension that has an impact on the operational needs and thus influences the choice of charging alternative. Sectors can be determined by the type of goods that are transported [89] or the industry the goods are transported. Some of the most important transport sectors for road freight are: Waste collection, distribution of products and food, forestry transport, construction and mining, international trailer transport, and national long- and line-haul [46], [89].

Company size

Company size is one of the dimensions that determines the company's characteristics. The company size of a freight carrier is often measured in the number of employees or trucks in the fleet. The size of the company can subsequently also influence many other company characteristics, such as the number of operations, investment budget, or operation planning. For example, in the Dutch road freight transport market, about 34 % of the companies are very small - under 10 trucks - and 36% are of medium size - between 10 and 80 trucks [90]. In the market, there are a few very large companies with sometimes even thousands of trucks across European countries, but they only account for 30% of the market. However, these distributions might be subject to change due to developments in the market, such as electrification. Some experts believe the road freight transport market will have a significantly higher share of large freight carriers after the transition to electrified transport [91].

Country of operation

The country of operation is also a company characteristic that can be of great influence on the choice of charging alternative. Of course, different prices, policies, infrastructure, and geography of countries play a role[92], but also the mentality in a country can influence what freight carriers value in charging alternatives. What exactly makes the difference is difficult to say, but it is interesting to know whether charging alternatives would be a success in one country and a failure in the other.

4.3. Set of criteria

The chosen criteria are obtained through different sources. In total, 6 experts were interviewed to get a grasp of relevant criteria. An overview of the experts can be found in Table 3.1. Furthermore, an online survey was distributed to freight carriers after a seminar on the electrification of the forestry transport sector. Lastly, a literature review on relevant criteria was performed.

4.3.1. From experts

The interviewed experts are listed in Table 3.1 in subsection 3.2.2. From these interviews, the following relevant criteria were noted down as being important in choosing one of the alternatives:

- Payload capacity
  How much load on the truck is still allowed after the weight of the battery?
- Second-hand value
  When trucks are no longer fit for their operations, what will be their resale value? This influences the TCO.
- Charging cost volatility
  How much can the charging cost change during the day and over the days? A lot of change brings more risks and uncertainty, but if well used can lower the costs.
- Social factors
  The culture of 'truckers' can be deciding. How much do they like the truck; vibrations/sound, does it fit their lifestyle or planning, are they paid during a charging stop?
- Operational costs
  The cost of electricity is due to the choice of charging alternative.
- Charging time
  How much time is lost in doing operations?
- Simplicity of implementation
  How easy is it to transition to the alternative from the usual diesel alternative?
- Strategic policy alignment
  How much is the policy aligned with the alternative?
- Volume capacity
  Mainly relevant in forestry, how much freight volume is still available after the volume of the truck and battery?

4.3.2. From seminar survey

Out of 8 responses on this short survey, the following criteria/factors were repeated more than once:

- Availability of charging infrastructure(6x)
  Is there charging infrastructure available for the intended operations? This can be public or self-owned.
- Charging speed/time(3x)
  How quickly can the battery be charged to continue the operations?
- Reliability of operations(2x)
  How reliable is driving the BET, regarding driving range, charging infrastructure availability, etc.?
- Charging cost(4x)
  What are the costs of recharging the BET?

4.3.3. From literature

As was shortly introduced, a literature review was performed on articles that compare different truck drive-trains and/or charging methods. This was done by using articles that were already found for the research context and gap, but also by using the search queries that are shown in subsection 3.2.1. From these articles, the most commonly named criteria, factors, or aspects were used as inspiration. In Appendix A, the articles and the criteria in those articles are summarized. The resulting list of criteria that were most mentioned and relevant for the studied problem is listed below.

- Business model (2x)
  What is the business model of the charging alternative? Costs, profits, contract lengths, etc.
- Operation risks (5x)
  What are the risks of not being able to complete operations (on time) for the alternative?
- Compatibility (3x)
  How compatible is the charging technique with other techniques, and how compatible are the trucks and charging techniques with the alternative?
- Technological maturity (4x)
  How mature is the charging technology?
- Charging costs (8x)
  The cost of electricity given the choice of charging alternative.
- Charging time (7x)
  How much time is lost in doing operations?
- Battery cost (10x)
  What is the cost of the necessary battery for the alternative?
- Battery durability (5x)
  How long does the battery last when charged in a certain way?
- Emission reduction (7x)
  What is the difference in emission reduction between the alternatives?
- Operational flexibility (3x)
  How much operational flexibility is possible with the alternatives?
- Complexity (3x)
  How complex is it to use the new charging technology for drivers and planners?
- Availability infrastructure (8x)
  How much charging infrastructure is available at the moment?

4.3.4. Final set of criteria

The criteria from experts, the seminar survey, and the literature review inspired and justified the final set of criteria. By these input streams, it was learned which criteria should be considered as they were repeated multiple times. Even though not always by using the same synonym, the same criteria were repeated often, indicating they were high on the priority lists. The set of criteria must be collectively exhaustive to grasp the full picture. Finally, the criteria that were chosen had to meet the following requirements:

- Criteria should be relevant from a freight carrier perspective
- Criteria that have different performance between charging alternatives
- Criteria of which it is possible to determine their performance
- Criteria should be mutually exclusive

To give a clear structure to the set of criteria, the main criteria were formulated in which the criteria could be categorized. These included financial criteria - criteria that normally make up the TCO - operational criteria - the criteria that determine how well a charging alternative can meet the operational demands - and finally, social criteria - criteria that determine the image of the charging alternative and how its usage is experienced.

- Financial criteria
  - Investment costs
    Battery cost and cost for necessary charging components. This criterion was chosen as it influences the barrier for a freight carrier to step into the charging alternative. The criterion is different for the charging alternative, and it is possible to determine its performance based on the literature. The criterion is mutually exclusive, but can be seen as part of the TCO.
  - Operational costs
    Charging costs and infrastructure fees. This criterion was chosen as it influences whether, given the investment costs, the charging alternative can give cost parity. The performance between the charging alternatives is different, as different parties determine the price of charging and infrastructure fees. The criterion is mutually exclusive as none of the other criteria has a price per ridden kilometer.
  - Life-time of battery
    Warranty of battery manufacturers on the battery when charged via a charging alternative. This criterion is chosen as it determines how long a freight carrier can use the truck and thus how worthy the investment is. The performance can be determined based on the warranties of battery manufacturers and is mutually exclusive, as none of the other criteria describes a duration of the asset.
- Operational criteria
  - Charging time
    Needed time inside the working shift to charge, so lost time due to charging. This criterion is chosen as it influences how much of the time the truck(asset) of the freight carrier can be used to pay back its investment costs. The charging time can be determined based on the known charging powers and the choice of sufficient battery sizes. The criterion is mutually exclusive, as none of the other criteria models the possible time of utilization of the truck.
  - Operational flexibility
    To what extent would the truck be able to change the distance, destination, and route of the operation from day to day? The criterion is chosen as it can be relevant for freight carriers to know how easily they can change their operations day-to-day with the charging alternative. The performance can be determined based on expert interviews and the literature. The criterion is mutually exclusive as it is the only criterion that determines the day-to-day flexibility of operations.
  - Payload capacity
    How much payload capacity is left after the battery weight? The criterion is chosen as the payload capacity can influence how much worth a truck can generate per operation for the freight carrier. The payload capacity can be determined based on the different battery sizes and is mutually exclusive, as no other criterion uses the weight of the battery.

- Social criteria
  - Emission reduction
    The difference in emission reduction between the alternatives. The criterion is chosen as for a freight carrier or its customers, it can be relevant to know if the charging alternative with the least emissions is chosen. The emission reduction can be determined based on the emissions from the battery production and the lifetime of the truck. The criterion is mutually exclusive as it combines the emissions from battery sizes with the lifetime of the battery.
  - Pioneering
    Being one of the first to choose a charging alternative, leading the way in a promising charging alternative. The criterion is chosen as for a freight carrier, it can be relevant to choose a charging alternative that puts them in front of the competition. The performance can be determined from expert interviews and literature to see how far the charging alternative is in its development and adoption. The criterion is mutually exclusive as it is the only criterion using the development and adoption of the charging alternative.
  - Complexity of implementation(from diesel)
    How much change in the operations will occur when choosing the charging alternative, and how difficult are the changes? The criterion is chosen as it influences whether the freight carrier thinks it can adopt the new technology in its operations. The performance can be determined from expert interviews and literature, and is mutually exclusive as it is the only criterion considering the change needed from the original truck technology.
  - Strategic policy alignment
    The extent to which policy measures, studies, and projects are aligned with the charging alternative. The criterion is chosen as it influences whether the freight carrier can be sure of its long-term choice and investment. The performance on the criterion can be determined based on expert interviews and the literature, and is mutually exclusive as it is the only criterion considering the aligned policy to the charging alternatives.

5

Weights of criteria

As was mentioned in section 3.3, an online survey and logistic expert interviews were used to determine the criteria weights. The used format of the survey can be found in Appendix B, and the people interviewed can be found in Table 3.2.

5.1. Survey response overview

The survey was sent out to about 900 freight carriers, of whom 21 responded. The survey was also sent out to 33 experts, of whom 15 responded.

In the response group of freight carriers, on 4 different characteristics segments were made: Daily distance, sector, company size, and country. The number of responses can be seen in Table 5.1

Table 5.1: Overview of responses per segment group from the online survey

Daily distance	Sector	Company size	Country
Short(6)	Distribution(9)	Small (6)	Sweden(18)
Mid(6)	Forestry(4)	Medium(7)	The Netherlands(4)
Long(8)	Line haul(6)	Large(7)	

Out of the 21 respondents for freight carriers, 12 filled in the survey differently than the best-worst method, and 9 filled in the survey as a best-worst method survey. However, the 'wrong' answers were still useful, as the respondents misunderstood the question method and filled in the matrix as a Likert scale. These results could thus still be used to identify the importance of the weights, as is explained in Equation 3.3.1.

In the response group of experts, the only distinction was by type of expert. There were 8 academic experts, 3 OEM experts, 2 Charging point operator experts, and 2 government experts among the respondents. In this group, the percentage of correctly filled-in answers was significantly better, with 13 correctly filled in and only 2 filled in differently.

5.2. Findings from interviews

From the conducted interviews with 4 logistics experts(Table 3.2), some findings were made. These findings were mainly used to validate the results from the online survey and to understand and interpret the results that were obtained. The most important findings from the interviews will be summarized in this section.

First of all, all experts agreed on the fact that the operational needs are vital to electrify and to choose charging alternatives. Among these operational needs were charging time, driving range, but also transport efficiency. This transport efficiency was linked to the payload capacity, as a low capacity means more trucks have to drive for the same load, which leads to high operational costs. Furthermore, the experts agreed that the type of operation and its needs have a great influence on whether electrification and charging alternatives are possible right now and in the future. Two experts agreed that for short distances, the operational needs can already be met, but the other expert did not believe in any operation being able to electrify at all. However, this was mainly due to financial barriers.

These financial barriers were other important factors mentioned by two of the experts; financial barriers and the financial room of freight carriers. Financial barriers were too high at the moment. However, one of the two experts believed that when the operational costs go down, cost parity in the TCO with diesel trucks could be reached soon. The other expert did not believe this would help, as the financial room was too small to do the high initial investment in the first place. Financial room was said to differ greatly between company sizes, with larger companies being able to take more risks. One of the experts doubted electrification to be feasible for companies in Sweden and the Netherlands, as they would always have less efficient business models financially and operationally compared to Eastern European freight carriers, already a competition problem nowadays[18], [93]. This is a great concern for these companies, but also for climate goals, as the goals will only be achieved if all transport in the EU and globally reduces emissions.

Lastly, the expert from the large logistics company indicated that the company looks at the system implications of charging alternatives, not wanting to step into an alternative that will turn out to be unfeasible on a system level. Therefore, they try to convince policymakers to align policy with the alternative before committing to the charging alternative.

5.3. Weights of criteria

In this section, the different comparisons in general weight among different respondent segments will be shown. These comparisons include experts and freight carriers (subsection 5.3.1), daily distances (subsection 5.3.2), sectors (subsection 5.3.3), company sizes (subsection 5.3.4) and countries (subsection 5.3.5).

5.3.1. Experts versus freight carriers

To gain an understanding of the different views experts and freight carriers might have, the weights for these groups were generalized by taking the average weight of a group. The result of these generalizations is shown in Figure 5.1. From the figure, it can be seen that experts and freight carriers do not always think alike, even when looking at the problem from the same perspective. Remarkable differences are the overestimation by experts of the weight of operational flexibility and the complexity of implementation. Secondly, the underestimation by experts of the weight of the lifetime is remarkable. Freight carriers have almost equal weights for all three financial criteria that make up the TCO.

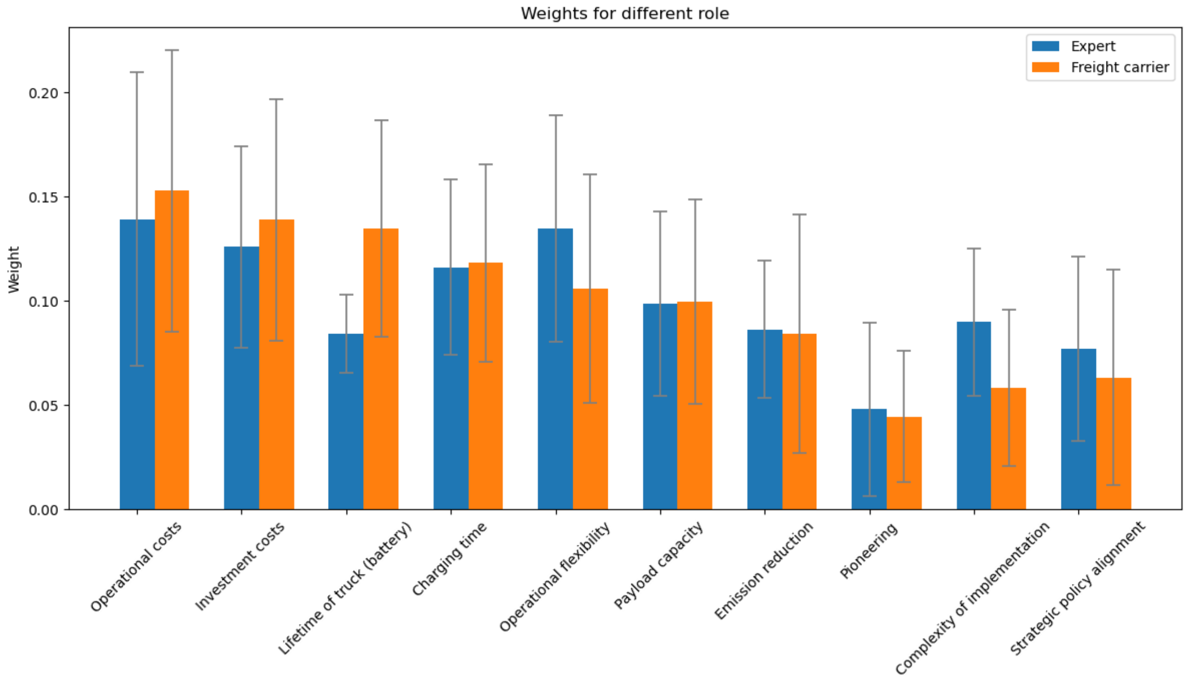

Figure 5.1: *The difference in weights between experts and freight carriers:* even when looking from the same perspective, the weights of criteria are valued differently. Experts overvalue operational flexibility and the complexity of implementation and undervalue the lifetime of the truck. Also, freight carriers have almost equal weights for the financial criteria, which make up the TCO.

5.3.2. Daily distance

To gain an understanding of the influence of the type of operations on the choice of a charging alternative, a comparison between different daily distances is made. This comparison is shown in Figure 5.2. From the figure, it can be seen that for some criteria the weights grow or decrease with the distance. First of all, operational costs, charging time, and operational flexibility grow in weight for use cases with longer daily distances. The lifetime of the truck, payload capacity, and emission reduction decrease in weight when the daily distance grows. Lastly, the complexity of implementation has a significantly higher weight for the mid-distance freight carriers, and strategic policy alignment has a lower weight for the mid-distance freight carriers.

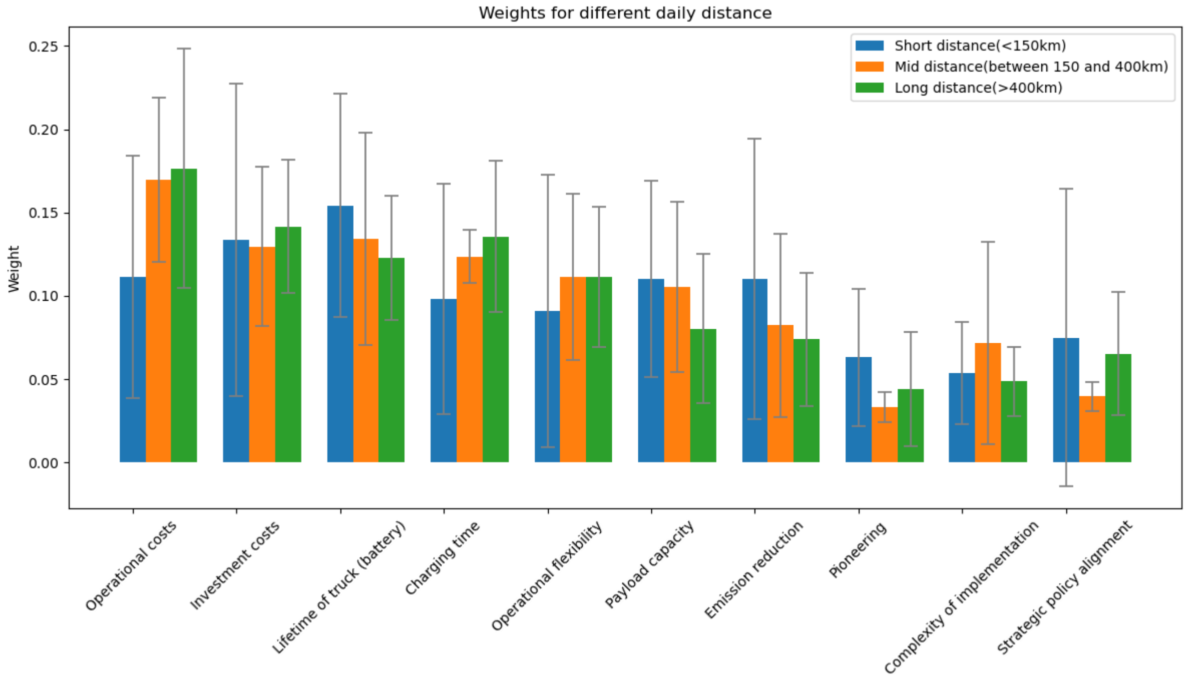

Figure 5.2: *The difference in weights between daily distances:* Operational costs, charging time and operational flexibility get more weight when the daily distance is larger; Lifetime of truck, payload capacity and emission reduction get less weight when the daily distance is larger.

5.3.3. Sectors

To gain an understanding of the different needs regarding a charging alternative for different sectors, the following comparison was made. The result of this comparison is shown in Figure 5.3. From the figure, it can be seen that different sectors have different weights for the criteria. The most remarkable differences in weights are in operational costs, charging time, operational flexibility, and emission reduction. Operational costs have a significantly higher weight for line-haul freight carriers. Charging time has the highest weight for the forestry sector. Operational flexibility has high weight for the distribution sector. Line-haul has the lowest weight for operational flexibility. The highest weight for emission reduction is in the distribution sector.

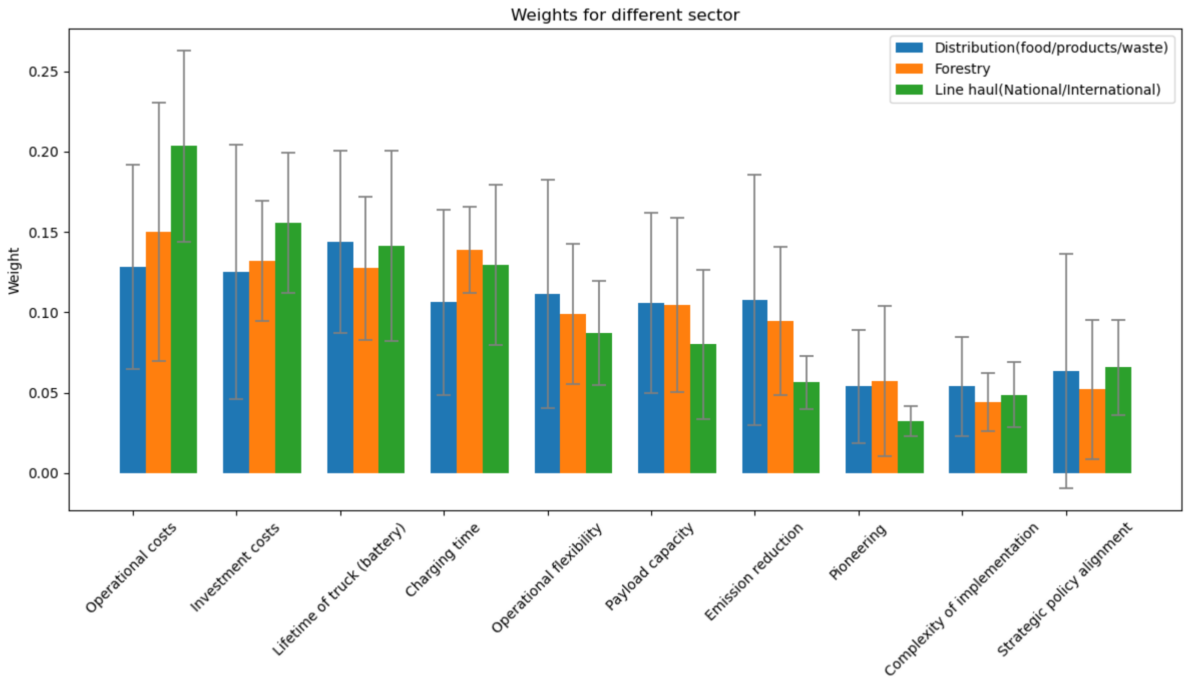

Figure 5.3: *The difference in weights between sectors:* Operational and investment costs are important for the line haul sector, charging time for the forestry sector, and operational flexibility for the distribution sector. Furthermore, there are large differences in weight for emission reduction between the sectors.

5.3.4. Company size

To gain an understanding of the differences in weights for the criteria among different company sizes, a comparison is made. The comparison is shown in Figure 5.4. The figure shows that there are some significant differences in weights between the company sizes. As with the daily distance, it can again be seen that the weight can grow or decrease with the company size, indicated by the 'stairs'. Growth in weight with the company size can be seen in operational costs and payload capacity. A decrease in weight with the company size is seen in charging time and operational flexibility.

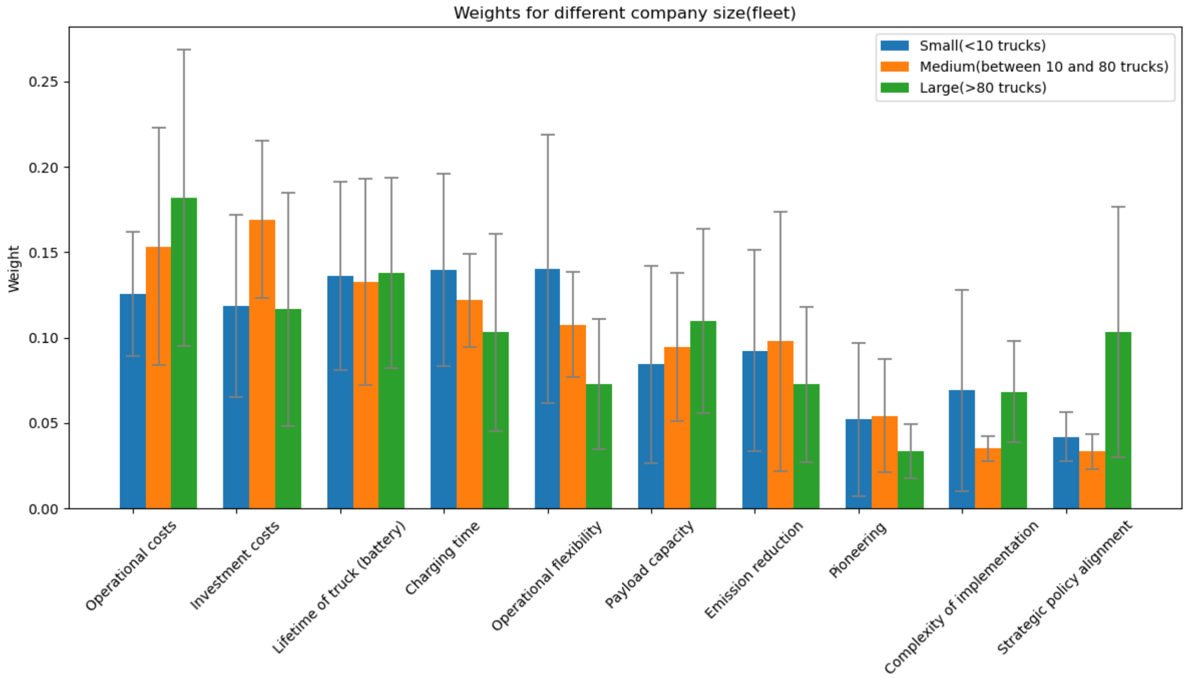

Figure 5.4: *The difference in weights between company sizes:* Operational costs and payload capacity get more weight for larger companies, and charging time and operational flexibility for smaller companies.

5.3.5. Country

Lastly, a comparison is made between the different countries in which the survey was performed to understand their different perspectives. This comparison can be seen in Figure 5.5. A remark has to be made with this figure, as the distribution of answers is not equal, with 18 answers from Sweden and only 4 from the Netherlands. However, looking at this comparison, some remarkable differences can be seen. First of all, the Netherlands has higher weights for financial criteria, with the operational and investment costs having higher weights. Secondly, Sweden has a higher weight for operational criteria such as operational flexibility and payload capacity. Thirdly, Sweden has higher weights for social criteria, with emission reduction and pioneering. Lastly, the Netherlands has more weight for strategic policy alignment.

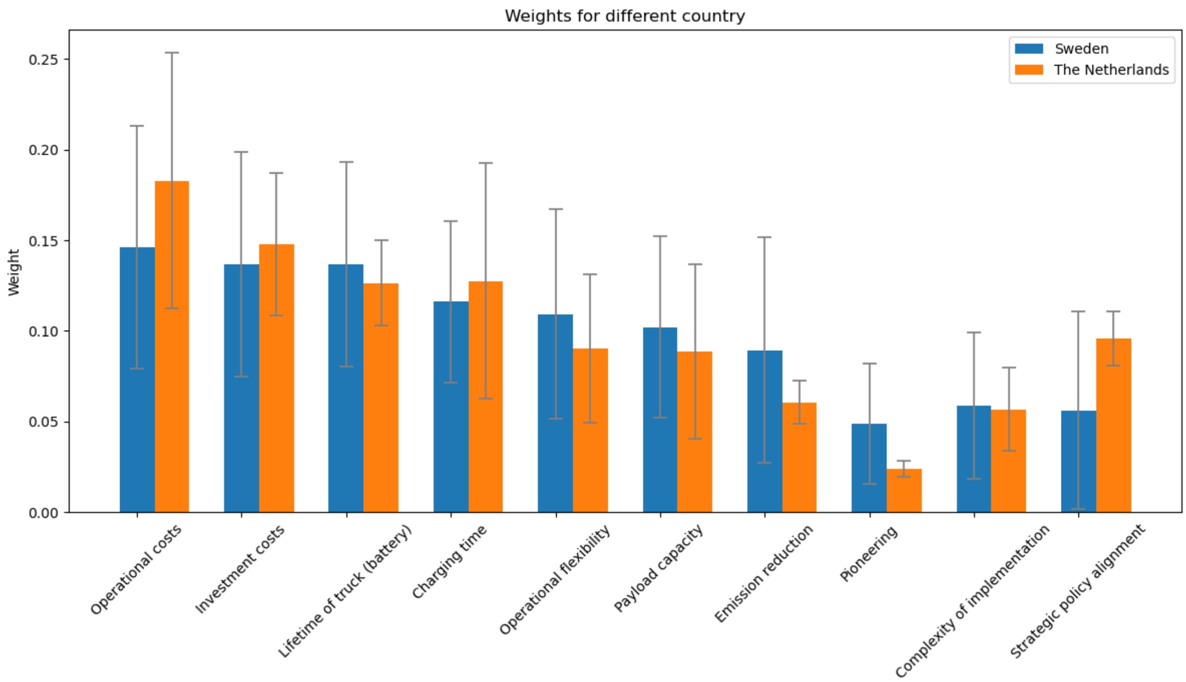

Figure 5.5: *The difference in weights between Sweden (18 responses) and the Netherlands (4 responses):* The Netherlands is more financially focused with operational and investment costs having higher weights and Sweden has more focus on operational criteria such as operational flexibility and payload capacity but also on social criteria such as emission reduction and pioneering. The Netherlands also has more weight for strategic policy alignment.

6 Criteria performance

In this chapter, the results of the third step of the MCDA will be shown: the criteria performance of the alternatives. At first, the used scenario and use cases are introduced in section 6.1. Secondly, the assumptions made for each alternative are shown in section 6.2 and the choice of parameters in section 6.3. Lastly, the performance equations and their results are shown per criterion in section 6.4.

6.1. Scenario and use cases

To compare the performance on the criteria of the different charging alternatives, it is necessary to choose a certain scenario and relevant use cases. The scenario is explained in subsection 6.1.1 and determines how assumptions are made and which parameters from the literature are chosen. The decision to consider different use cases for the calculations is explained in subsection 6.1.2 and influences assumptions that are made and parameters from literature that are chosen.

6.1.1. Scenario

The scenario determines which assumptions are made and how parameters are chosen from the literature. In order to choose the scenario, the time frame is determined. This time frame is explained in the following paragraphs.

First, the time frame for the performance calculations is a static moment in the future. A static moment in the future can be explained by Figure 6.1, where the system effects are neglected, thus creating a static system. This moment is in the transitional phase of the electrification of the road freight transport market, as can be seen in Figure 6.2; meaning that the market is not entirely electrified yet, and policy measures or technological developments to lower the barriers of electrifying are important. This phase is chosen as it best represents the way of thinking right now of the respondents of the survey. However, for future research, it can be relevant to study a steady-state phase, where the market is almost 100% electrified and certain barriers such as high investment costs don't exist anymore due to technological and supply chain developments.

Furthermore, in this transitional phase, the moment is chosen where the available charging infrastructure of all the alternatives can be sufficient, as can be seen in Figure 6.2. This ensures that a fair choice between the alternatives is possible. Furthermore, this choice of time frame influences the parameters used and the assumptions of the alternatives. Due to the deep uncertainty of developments in the technical parameters and infrastructure development, it is difficult to choose parameters and assumptions that perfectly fit this moment in time. However, in the literature, often comparisons and analyses are for similar time frames. This helps a lot in selecting the parameters and assumptions from the literature and expert interviews. The chosen time frame with sufficient charging infrastructure for all charging alternatives is expected to happen between 2030 and 2040, as this is a period that is most mentioned in the literature [27], [83], [86], [94].

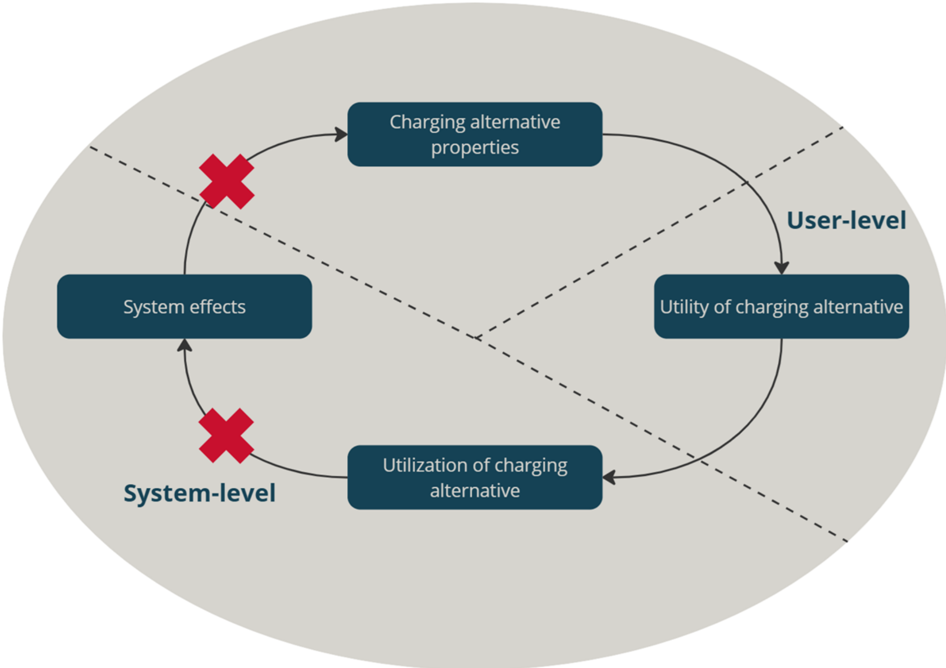

Figure 6.1: A static moment in the future: excluding the system effects in the scope of the study. To keep the criteria performance simple, the system effects of the choices made in charging alternatives are neglected.

6.1.2. Use-cases

From reasoning and literature on charging[20], [47], [49], [95], it is found that the daily driven distances of operations can make a big difference in the performance of charging alternatives for some criteria. This comes from the fact that many parameters change when the distance changes. These parameters include battery size, charging power, energy need, rest times, and battery life. These changes affect the performance of four criteria: investment costs, charging time, payload capacity, and emission reduction. This change is not negligible, and thus, four use cases are designed and used:

- **Short** daily distance (0-150km/day)
- **Mid** daily distance (150-400km/day)
- **Long** daily distance (400 - 700 km/day)
- **Double shift**(700 - 1400 km/day)
- **Combined**: A last use case is a combined use case based on the distribution of tonkm over daily distances[88].

These distances are deducted from the most named operation distances in the literature[22], [28], [49], [88]. The difference in performance of some criteria will change linearly or with some increased change along with the distance.

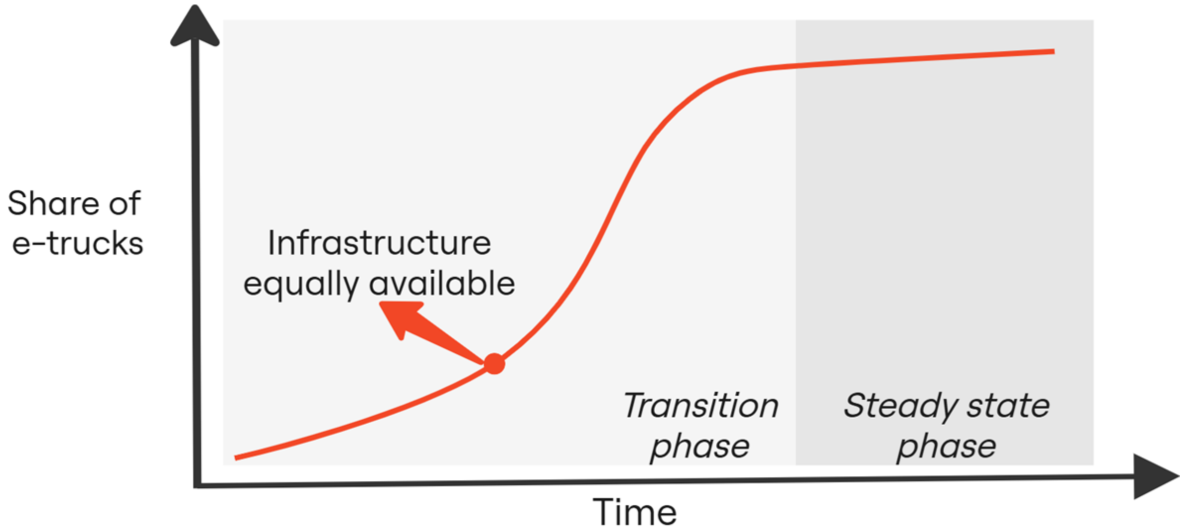

Figure 6.2: The considered time frame for the performance scenario: A moment in time where the electrification of trucks is in a transition, but the charging infrastructure of the alternatives is equally available. This enables a fair comparison of the alternatives.

6.2. Assumptions for the calculations

Some assumptions are made in general and per charging alternative to base equations and parameters on. These assumptions are listed below per alternative. The assumptions are made based on the literature review and the expert interviews that are discussed in subsection 3.4.1 and subsection 3.4.2.

Overall assumptions

- The used conversion for SEK and EUR is: 1 EUR = 11.4 SEK (4 February 2025) [96].
- Waiting times to connect to the grid are not considered in any calculation for the performance of criteria, as all grid connections, also those of on-road charging stations, ERS infrastructure, and swapping stations, have the same priority. In reality, they might not all have the same waiting times, as different voltages can have different waiting times [97].
- It was assumed that the trucks of all charging alternatives start the day with a fully loaded battery. This can be from some shared depot charger or charging in any other way the day before. This was to some extent an unfair assumption towards the depot alternative, as this alternative bears the cost of the depot charger, and the other alternatives don't. However, depot chargers are sometimes semi-public available[98]–[100] and most companies will probably own some depot chargers, although not for every single truck [49].
- All charging alternatives are assumed to use the same energy mix for their electricity, thus leading to no emission differences from the charging itself.

Depot charging alternative

- The available rest time is 14 hours between shifts as the 4,5 hour max driving time regulation is being used [75]: 2 shifts of 4,5 hours with $\pm$ 1 hour rest-time means 10 hours outside the depot and 14 hours at the depot. For the double shift use case this rest time is only 4 hours: 4 shifts of 4,5 hours and $\pm$ 2 hours of rest time means 20 non-depot hours and 4 depot hours.
- A single depot charging connection per truck is assumed.
- Battery sizes are calculated to fulfill the entire energy demand of the day on a single battery.
- Charging power will grow with the battery size to fulfill a full battery charge within the rest time.

On-road charging

- It is assumed there are no waiting times at the charging stations that could lead to longer charging times.
- The most common battery sizes in the literature per use case were chosen[22], [31], [33], [49], [94].
- A mix of 80% CCS chargers (400 kW) and 20% MCS (1000 kW) chargers was assumed for all the use cases[94]. A weighted average of this mix was used to determine the charging power in the calculations.
- The electricity cost was a combination of the home and on-road price, as it was assumed that the truck starts with a full battery from some charging at the depot. The home price was used for a single charge of battery, and the rest of the energy needed for the day was the on-road price.

Electric Road System

- The ERS trucks can charge at on-road station chargers, but their battery sizes were determined by the main usage of the ERS network.
- The battery sizes for ERS trucks were calculated with a 30% reduction in capacity from the on-road alternative, supported by literature [7], [33], [83], [101]
- From the expert interviews(Table 3.3), it was assumed that the trucks do not have to charge outside of rest times with the assumed charging infrastructure, meaning there are no charging times for this alternative.

Battery swapping

- A single intra-day swap was assumed, as more swaps were considered too complex compared to the current diesel operations. This assumption resulted from the expert interviews (Table 3.3).
- Battery sizes were chosen according to the single intra-day swap. For the double shift use case, this meant two swaps in 24 hours. This meant the batteries should be sufficiently big to fulfill the needs of half of the daily kilometers (a quarter for the double shift use case).
- A self-owned swap system was considered, meaning electricity prices were the home price and investment costs for spare batteries, and the swapping station was assumed.

6.3. Choice of parameters

All calculations were based on assumptions and parameters chosen from the literature. These included general parameters and alternative and use-case-specific parameters.

6.3.1. General parameters

First of all, the general parameters that were used in the calculations of all the alternatives and daily distances are shown in Table 6.1. These global parameters were used in the equations in section 6.4. The choice or deduction of the parameters is explained in the following paragraphs.

Table 6.1: The used global parameters from literature

Parameter	value	source
Battery cost [EUR/kWh]	150	[102]
Gravimetric energy density [kg/kWh]	4	[34]
Energy consumption rate [kWh/km]	1.5	[26], [28], [30], [78], [86]
Battery production emission [kgCO2eq/kWh]	106	[103]
At home electricity cost [EUR/kWh]	0.48 & 3[SEK/kWh]	[104]
On-road electricity cost [EUR/kWh]	0.6 & 5[SEK/kWh]	[104], [105]
ERS use cost [EUR/kWh]	0.15	[7], [92]
Battery lifetime slow charging [km]	500 000	[106]
Battery lifetime fast charging [km]	200 000	[106]

Battery cost

Battery cost is a parameter that was used in the calculation of investment costs. The chosen parameter comes from a paper that did a literature review of battery parameters and costs for battery electric vehicles by König et al. [102]. In Figure 7 of the paper, a projected value between the minimum and maximum value for 2030 was chosen.

Gravimetric energy density

Gravimetric energy density is the parameter that determines the weight of the battery based on the energy it can store. The chosen parameter came from a techno-economic comparison between battery swapping and ERS for trucks by Speth et al.[34]. In the paper, the parameter came from two different sources. Furthermore, similar numbers were found in other literature [29], [36].

Energy consumption rate

Energy consumption rate determines how much battery capacity is necessary to drive a certain number of kilometers on a full charge. The parameter is dependent on the truck and the weight of the load. However, this fact was neglected, and only one parameter was chosen for all alternatives and use cases. This parameter was based on the middle value of many sources [26], [28], [30], [78], [86]. The range of parameters that was found was between 0.7 and 2.08 kWh/km.

Battery production emission

Battery production emission determines the emission reduction based on battery size reductions. The chosen parameter comes from a literature study on the Life Cycle Assessments (LCA) financed by the Swedish Energy Agency [103].

At-home and on-road electricity cost

At-home and on-road electricity costs were used to calculate the operational costs for the charging alternatives. The home-based cost comes from an EU dashboard on recharge prices in the different member states [104]. The on-road charge cost comes from the same source but was also validated in a public document on recharge prices by Scania. For the calculations, in most cases, the Swedish prices were used, as almost all responses of the survey for the weights were from Swedish freight carriers. The Dutch prices were only used for the comparison between Sweden and the Netherlands. The percentage difference in Sweden is much higher between home and on-road prices.

ERS use cost

ERS use cost was used to calculate the operational costs for the ERS alternative. Although official billing schemes are not yet decided upon, the parameter that was used appears in two separate simulation studies, one by Rogstadius et al.(2024) [107] and the other by Börjesson et al.(2024) [92]. In Rogstadius et al.(2024), the parameter comes from a threshold to be competitive with diesel and on-road charging. In Börjesson et al.(2024), the parameter comes from a scenario where the electrification of trucks is in a transition phase, and the numbers are deducted from two sources.

Battery lifetimes

Battery lifetimes are found to be different for different charging speeds in several sources [108], [109]. However, in none of the sources numbers on the lifetime named. However, only in a Sweden-China bridge report by Liu et al, these differences are quantified in part five on page 56 [106]. From the received information of battery producers in China, who offer different battery warranties for slow and fast charged batteries.

6.3.2. Alternative and use-case specific parameters

Next to global parameters, the equations in section 6.4 also use alternative and use-case-specific parameters. These mainly included the battery sizes that are necessary to fulfill the daily distance for the use case, given the charging alternative that was mainly used. These specific parameters can be seen in Table 6.3. The choices or deductions from the literature of the parameters are explained in the following paragraphs.

Table 6.3: The alternative specific parameters that were used and their sources.

Parameter	Depot	On-road	ERS	Battery swapping
Battery size short [kWh]	225	100[22], [49]	70[33]	120[86], [87]
Battery size medium [kWh]	600	200[22], [49], [94]	140[33]	282[86], [87]
Battery size long [kWh]	1050	600[22], [49], [94]	420[33]	530[86], [87]
Battery size double shift[kWh]	2000	600[22], [49], [94]	420[33]	530[86], [87]
Component cost [10^5 EUR]	see Table 6.5	-	0.054*[33]	2.9 or 2.4[86]

Battery sizes

Battery sizes of depot charging did not come from any source but were calculated directly, given the daily distance and the corresponding energy need of the day.

Battery sizes of on-road charging were deducted from two sources that estimate battery sizes for different daily distances. First of all, Furnari et al. estimate that short daily distances can have sufficient battery capacity with 100 kWh [49]. In a study by Herlt et al, Exhibit 1 provides ranges for battery sizes for different daily distances, including long-haul and more regional transport [22].

Battery sizes of ERS are said to be reduced compared to on-road battery sizes. However, different sources named different percentages of this reduction in battery size. Therefore, it was difficult to choose one of these percentages, ranging from 30 to 70 % . In a study on ERS by Traffikverket in Sweden, a weighted average was calculated of the battery size reduction, based on how many trucks can use the ERS network to reduce their battery size [33]. In the weighted average, different sources were used to obtain the parameters, and the result of the calculation was a weighted average battery size reduction of 30 %, which was used in this study to get to ERS battery sizes from the on-road battery sizes.

Battery sizes for battery swapping were a combination of parameters from literature and calibration to the charging scenario for this alternative. First of all, Nabo et al and Liu et al [86], [106] name 282 kWh as the currently most used battery size in battery swapping in China. This was a battery size that is suitable for the mid-distance use case with a single intra-day swap of batteries. For the other battery sizes, the same logic was applied, and the daily distance was split into two and multiplied by the energy consumption to determine the battery sizes.

Component costs

Component costs were different for the alternatives. The costs for depot charging will be explained in Table 6.3.2.

For ERS, the cost of a pantograph was considered a component cost, and this cost was taken from the study on ERS by Traffikverket[33].

For battery swapping, the calculation in a study of Nabo et al was used(section 7.6). In the calculation, an example of a freight carrier with a self-owned battery swapping station is used. In the source, only the investment costs for the swapping station, including the battery capacity, were given, thus making it difficult to obtain the parameters that are necessary to scale the station investments with the different battery sizes. However, by using this total investment cost and the knowledge that the station has a capacity of 2500 kWh, the price of the batteries in this calculation can be subtracted by using the battery cost that was also shown in Table 6.1. From this, a fixed component cost of 2.36 *10^5 EUR for a battery swapping station per truck remained and was used for the equations.

Table 6.5: The chosen charging powers for the different alternatives.
with CCS (Combined Charging System) and MCS (Megawatt Charging System) as the options for on-road charging.

Alternative	Charging power[kW]	Source	Charger cost[10^3EUR]	Source
Depot 225 kWh	20	-	5	[110]
Depot 600 kWh	45	-	48	[110]
Depot 1000 kWh	75	-	70	[110]
Depot 2000 kWh	500	-	270	[110]
On-road CCS/MCS mix	520	[81], [94]	-	-

Charge powers and charger installation costs

Charge powers for the depot alternative were not deducted from the literature but were calculated, given the rest times of the different use cases and the battery sizes for the different use cases. From these charging powers, the costs for a charging connection at the depot for a single truck could be deducted from the literature. By using a report from the REEL project on depot charger installation costs for different Swedish freight carriers[110], the costs for the installation of a charging connection for a single truck could be deducted. This was done for installations with different charge powers, as the costs proved to differ greatly between charging powers. The used charging powers in this study did not always match the ones in the source. In that case, the closest charging power was used to deduct the costs from.

The charge power for on-road charging was determined by taking a mix of Combined Charging System (CCS) and Megawatt Charging System (MCS) chargers. The distribution from this mix was taken from a study of Shoman et al, where an 80 % CCS and 20 % MCS distribution is shown to be sufficient for electrification of at least 15 % of freight road transport. Given the fact that CCS is considered to provide 400 kW of charging power[94] and MCS 1000 kW of charging power[81], a weighted average of the charging powers was taken, resulting in the average 520 kW charging power that on-road chargers were assumed to offer.

6.4. Equations and results per criteria

From the assumptions and parameters, all the criteria's performances were calculated with equations. By using these equations, the outcomes were in the same units and could thus be compared. Below, the equations used are listed with some explanation. Also, the results per criterion are shown.

Vehicle operational costs

For this criterion, a calculation per km was made. This means that the energy consumption rate of trucks was needed, charging prices per kWh, and charging infrastructure use fees per km. The calculation looks like this:

$$\begin{aligned} &\textit{Operational costs [EUR/km]} = \textit{energy consumption rate [kWh/km]} \times \\ &\qquad (\textit{electricity price [EUR/kWh]} + \textit{infrastructure use fee [EUR/kWh]}) \end{aligned} \tag{6.1}$$

From this calculation, the results in Figure 6.3 are found. From the results, it can be seen that on-road charging was the most expensive alternative, and depot charging and battery swapping are the cheapest, with ERS in the middle.

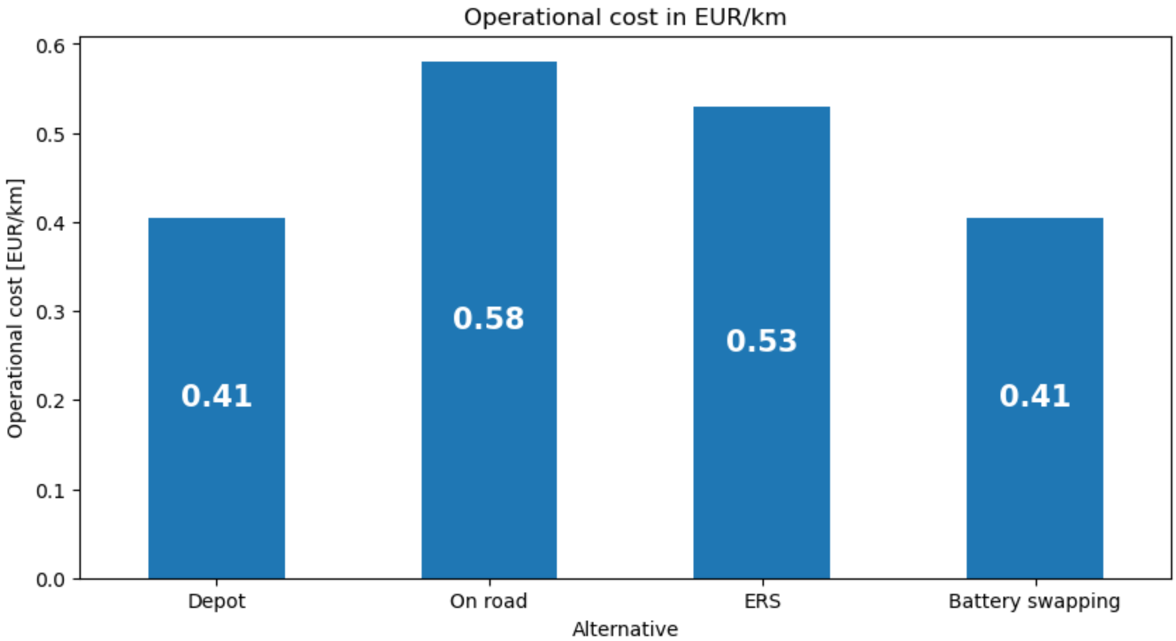

Figure 6.3: *The operational costs of the charging alternatives:* depot charging and battery swapping are cheapest as they always use the low home-based price, and ERS was in between as it uses home-based prices with some additional infrastructure usage fee. For this graph, the home and on-road prices of Sweden were used.

Vehicle investment costs

For this criterion, the investment cost of a single truck battery and its additional components was calculated, for example, a charger device at the depot that was bought for the truck. The cost of the truck without a battery was neglected, as in the literature, no differences were found between the specific trucks of the charging alternatives. In case of the battery swapping alternative, a factor for the number of batteries was used, as there needs to be some extra batteries in the system to be able to do battery swapping. Thus, the calculation for investment costs looks like this:

$$\begin{aligned} &\textit{Investment cost [EUR/truck]} = (\textit{battery size [kWh]} \times \textit{battery cost [EUR/kWh]} \\ &\qquad \times \textit{supplementary swap batteries [-]}) + \textit{component cost [EUR]} \end{aligned} \tag{6.2}$$

The result of this calculation is shown in Figure 6.4. From this figure, it can be seen that battery swapping has a large fixed cost due to the battery swapping station. Furthermore, it can be seen that the investment cost for depot charging grows significantly with the distance due to the cost of larger batteries and more powerful charging devices.

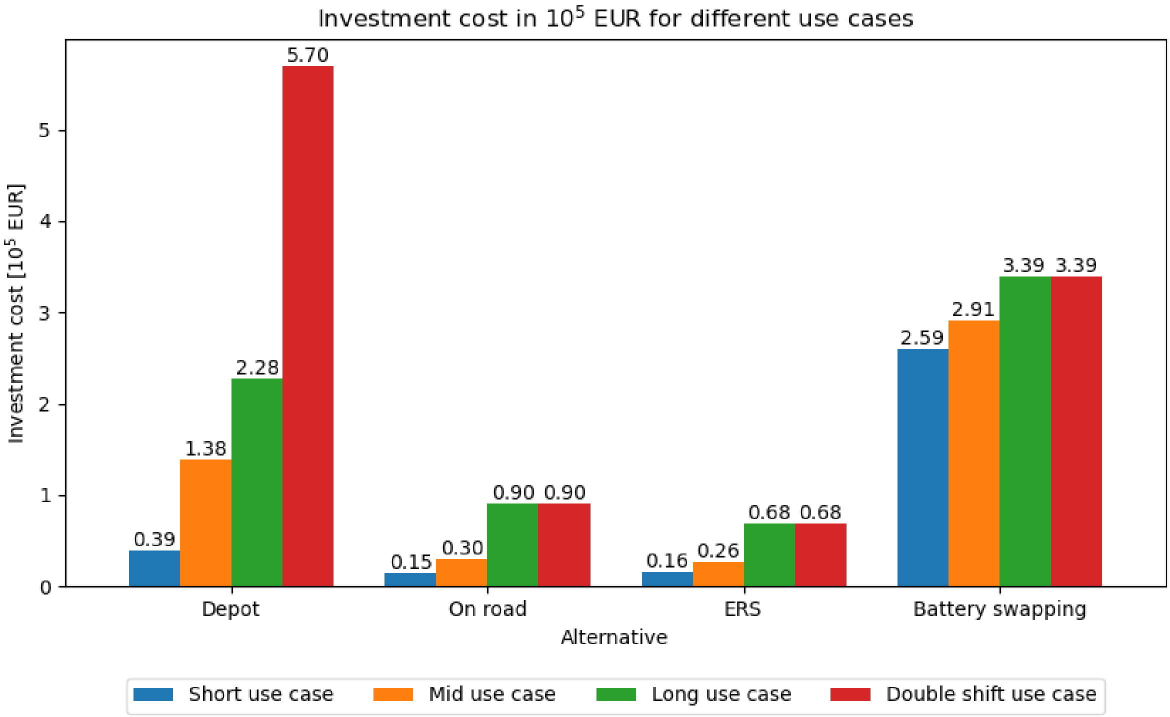

Figure 6.4: *The investment costs of the charging alternatives in different use cases:* the investment cost of depot charging grows with the distance as it needs higher voltage chargers and bigger battery sizes that are both costlier. Battery swapping has a high base investment cost due to the battery swapping station. The investment costs of all alternatives grow with the distance as they need bigger batteries for the longer use cases.

Truck (battery) lifetime

For this criterion, the battery warranties of fast-charged and slow-charged batteries are used as a base. These values can be found in section 6.3. The slow charging battery lifetimes are used for both depot charging and battery swapping, as they can always use slow charging. For on-road, the middle value between the highest and lowest lifetime was chosen, as on-road uses slow charging half of the time and fast charging half of the time. Then, for ERS, the middle value between the on-road charging lifetime and the depot charging and battery swapping lifetime was chosen, as this alternative was assumed to use fast charging a quarter of the time.

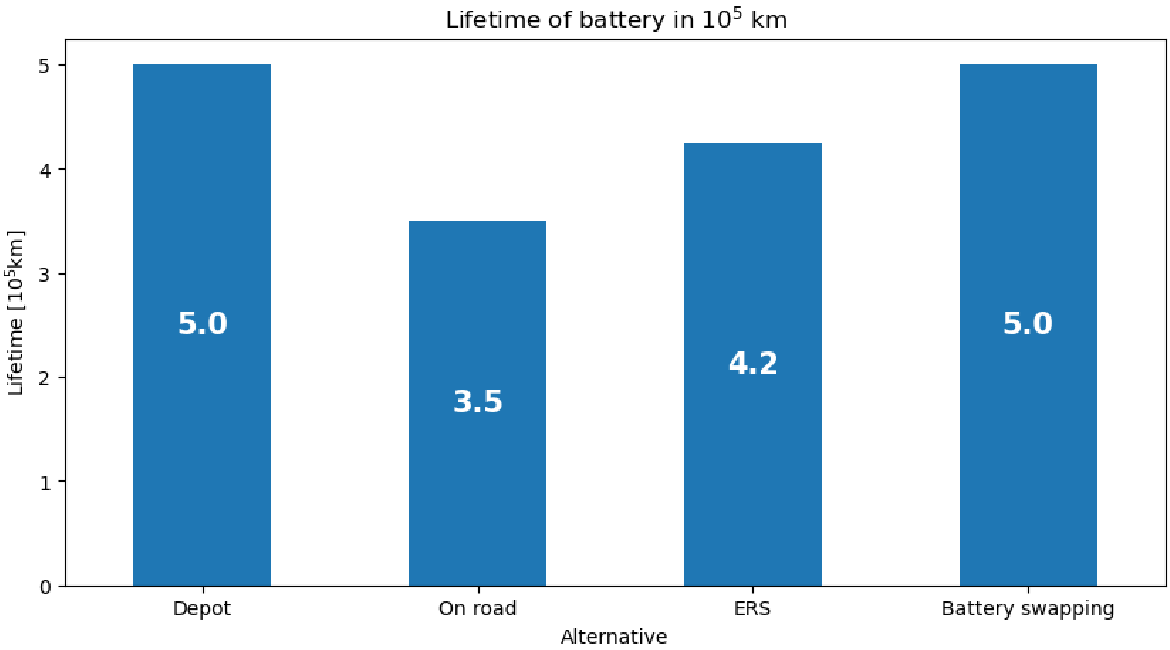

Figure 6.5: *The lifetime of the battery for the charging alternatives:* Depot charging and battery swapping have the highest battery lifetime warranty as they slow charge all the time. On-road charging has the shortest battery lifetime as it uses fast charging most often, and ERS is in between, as it can sometimes slow charge on the ERS network, depending on the availability of the network for the specific route.

Charging time

From the made assumptions, only on-road charging and battery swapping have a charging time. This charging time is the time needed to charge during the driver's working hours, meaning the driving shifts and regulatory rest time. This means that the charging time was based on the energy demand of the operation, the chosen battery size for the operation, and available charging power at the stations or time to swap the battery. Using these parameters in an equation looks like this:

$$\begin{aligned} &\textit{Charging time [minutes]} = \\ &\frac{(\textit{daily kilometers [km]} * \textit{energy consumption rate [kWh/km]}) - \textit{battery size [kWh]}}{\textit{charging power [kW]}} * \textit{60 [minutes]} \\ &\qquad - \textit{resttime [minutes]} \end{aligned} \tag{6.3}$$

The results of these calculations are shown in Figure 6.6. As can be seen, charging time becomes significantly longer when the distance increases for the on-road alternative and when the rest time is not sufficient to fully charge the battery. Only for the long-distance case, this is different as the longer rest period is almost long enough to recharge the battery sufficiently. For battery swapping, the swapping of the batteries cannot always be timed with the rest period, and thus, the full charging time is accounted for. Depot charging and ERS are assumed to have no charging time as they can charge outside working hours or during driving, respectively.

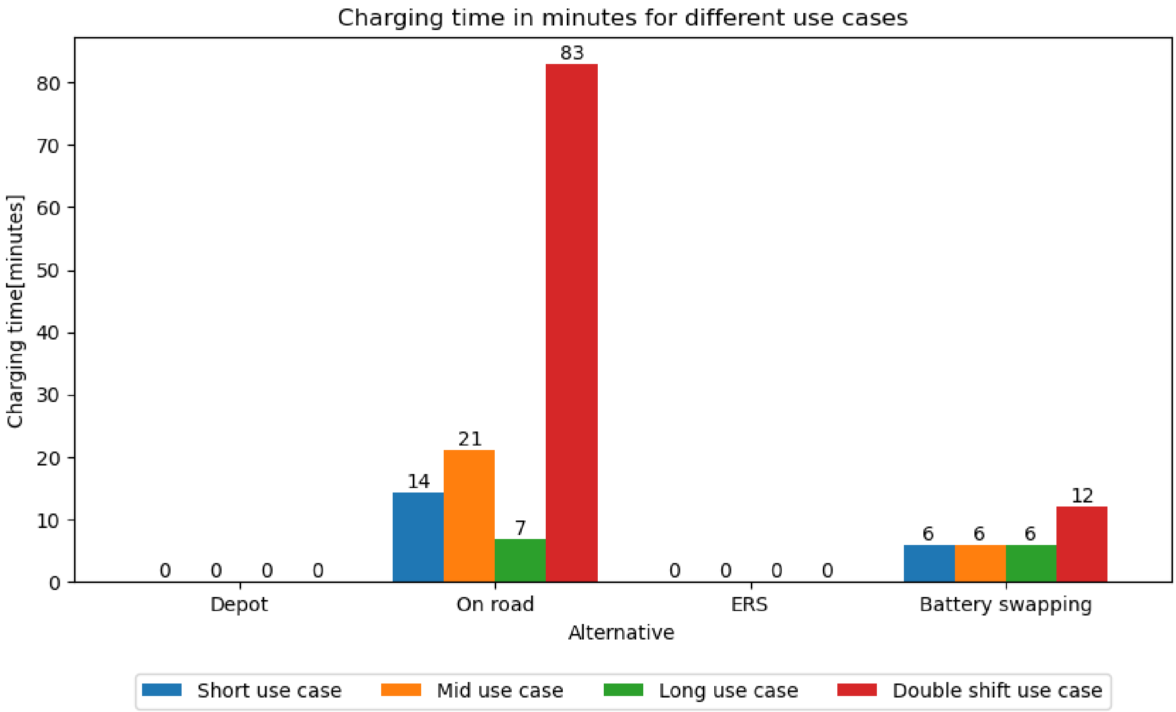

Figure 6.6: *The charging time of the charging alternatives:* Depot charging has no charging time during driving hours, as they can rely on overnight and overhead charging. Battery swapping requires the charging time necessary to swap the battery, as this cannot always be planned during the rest breaks. On-road charging has longer charging times based on how it matches with the available rest breaks and the energy needs.

Payload capacity

For this criterion, we use the EU GVW restrictions. We calculate the payload capacity after the weight of the battery. This calculation thus includes battery size, gravimetric density and the GVW restriction. Thus, the used equation is as follows and is shown in the equation below:

$$\begin{aligned} &\textit{Available payload capacity [tonnes]} = \\ &\qquad \frac{\textit{GVW restriction [kg]} - (\textit{battery size [kWh]} * \textit{gravimetric density [kg/kWh]})}{\textit{1000}} \end{aligned} \tag{6.4}$$

From the calculation, the results shown in Figure 6.7 are obtained. As can be seen, the available payload capacity shrinks when the batteries need to become larger. This effect is the strongest for the depot charging alternative.

Operational flexibility

Operational flexibility is the ability of the charging alternative to perform a different operation the next day. 'Different' could mean in distance, destination, and route. This definition of operational flexibility came from the findings of the experts' interviews.

Applying this logic, the average of the scores of these three variations will be used as a final score. This means a score on different distances, destinations, and routes, shown in Table 6.7. Below are the scores that can be given for the flexibilities.

1. Not possible to change at all
2. Possible to change with unfeasible extra charging time and planning
3. Possible to change with a lot of extra charging time and planning
4. Possible to change with some extra charging time and planning
5. Possible to change without extra time and planning

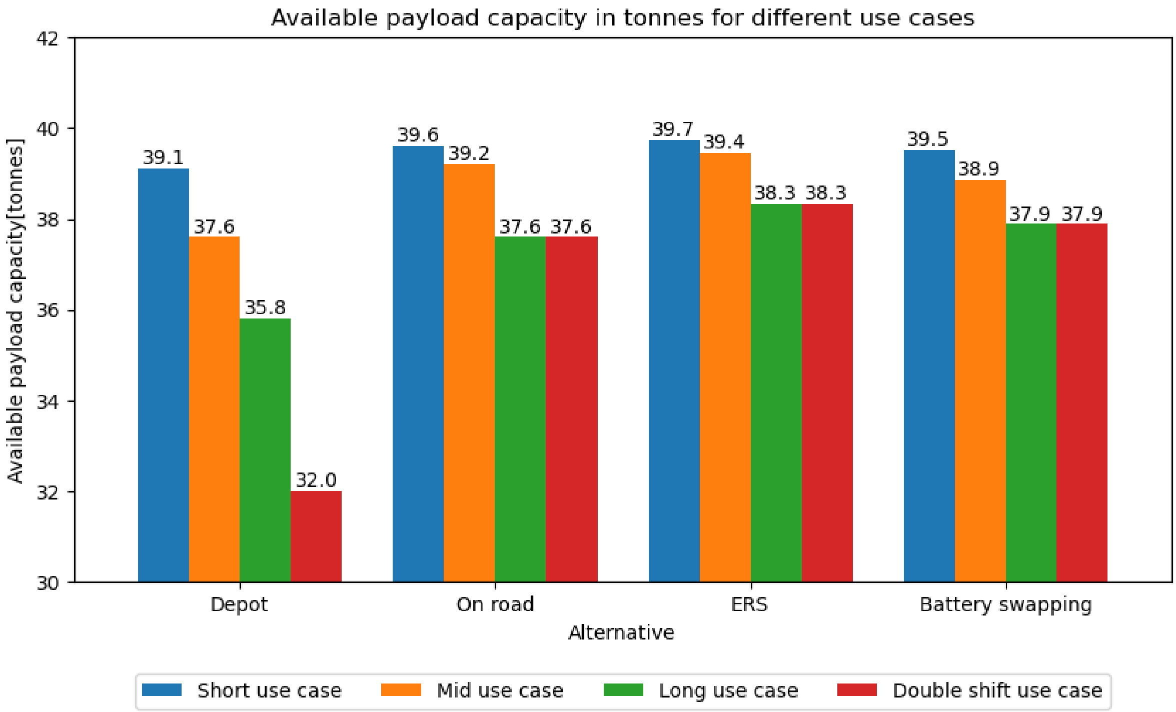

Figure 6.7: *The available payload capacity of the charging alternatives in different use cases:* for all the alternatives, the payload capacity decreases with the battery size. For depot charging, this decrease is the sharpest.

The results of these scores and the average score are shown in Table 6.7

Table 6.7: The scoring of aspects of operational flexibility

Operational flexibility	Distance	Destination	Route	Overall score
Depot	1	4	5	**3.33**
On-road	2	4	5	**3.67**
ERS	5	2	1	**2.67**
Battery swapping	4	1	5	**3.33**

The overall scores are again summarized in Figure 6.8. It can be seen that the on-road alternative is the most flexible and ERS the least. However, the differences are not large.

Emission reduction

For this criterion, we calculate the emission of CO_2 from the production of the battery per kilometer. The CO_2 emission from the battery production is calculated over the lifetime. This represents the climatological impact of the charging alternative choice[6]. The calculation will thus be based on battery production emission, battery size, and lifetime, as is shown in the following equation:

$$\textit{Battery production emission per truck [gCO}_2\textit{/km]} = \frac{\textit{battery size [kWh]} * \textit{battery production emission [gCO}_2\textit{/kWh]}}{\textit{lifetime [km]}} \tag{6.5}$$

From this calculation, the following results are obtained, which are shown in Figure 6.9. As can be seen, the on-road alternative emits the most CO_2 and ERS the least.

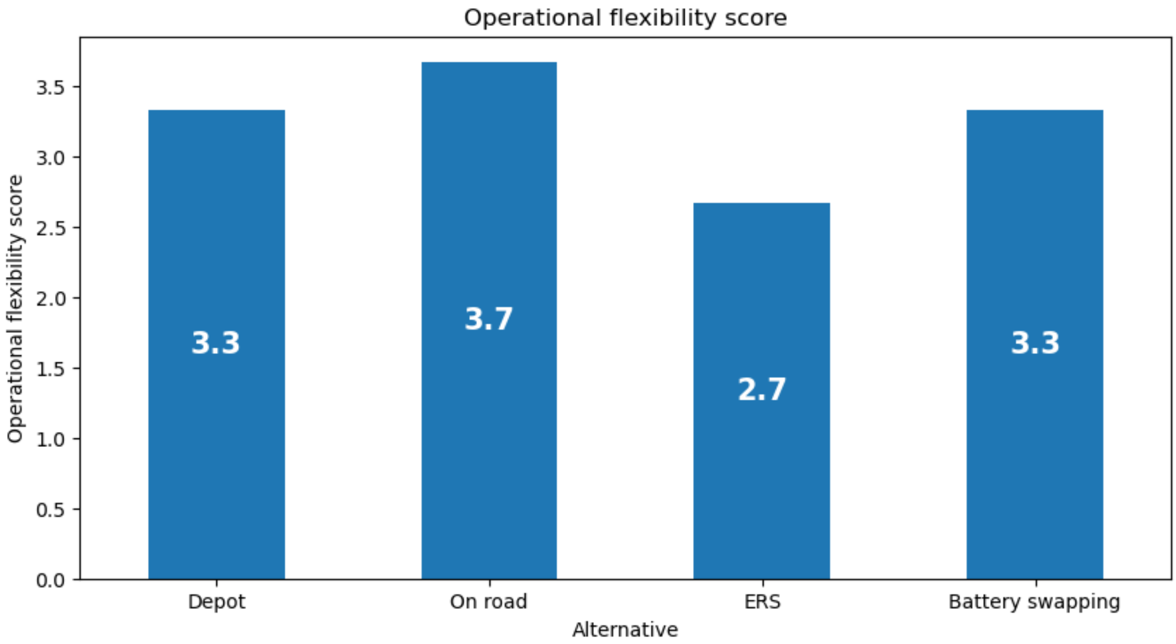

Figure 6.8: *The operational flexibility of the charging alternatives:* On-road has the highest flexibility as it can easily change distance, destination, and route due to high availability of charging. ERS scores lowest for its dependence on the network for its destination and route. Battery swapping and on-road are in between as they are flexible for route, but battery swapping is not for destination, and on-road is not for distance.

Pioneering

Pioneering means how much the freight carrier would be one of the first to use the alternative[111]. To quantify this, scores for three different categories are given. First of all, the innovation process is used from the article Energy Technology Innovation Systems [112]. Secondly, the Rogers curve is used to estimate the innovation life cycle[13], [113]. Lastly, the OEM and CPO involvement in Europe of the charging alternative is used, indicating how much the technology is adapted by the producers[76], [114]. The scores are given from 1 to 5 for how much the alternative is on the more novel side of the category, as with this criterion, the extent to which the alternative is novel is positive. The given scores are shown in Table 6.8.

Table 6.8: The scoring in aspects of Pioneering

Pioneering	Innovation process	Rogers maturity curve	OEM and CPO involvement	Overall score
Depot	1	1	1	**1**
On-road	2	3	2	**2.33**
ERS	5	5	3	**4.33**
Battery swapping	3	5	5	**4.33**

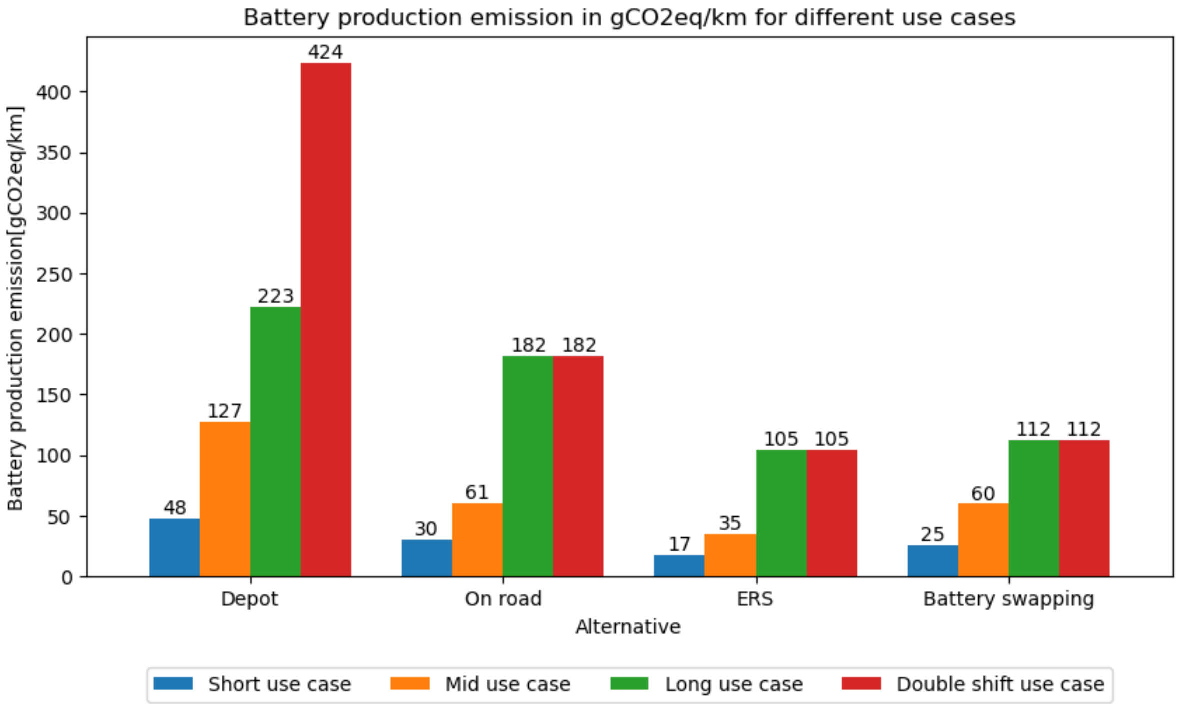

Figure 6.9: *The battery production emissions of the charging alternatives:* Depot charging has the highest emissions due to large battery sizes, and on-road has high emissions due to the low lifetime of the battery. Battery swapping and ERS have low emissions due to smaller batteries and longer lifetimes.

Complexity of implementation

The complexity of implementation is a rather subjective criterion. From literature, the categories driver effort, company change, daily planning change, non-maturity of support, and support dependency are used to get an overall score on complexity[15], [115]–[117]. For this scoring, a 1 is the lowest complexity and a 5 is the highest complexity score. The scores are based on expert interviews, supervisor discussion, and own reasoning. The final scores can be seen in Table 6.9

Table 6.9: The scoring in aspects in complexity of implementation

Complexity of implementation	Driver effort	Company change	Daily planning change	Non-maturity support	Support dependency
Depot	1	3	1	1	**1**
On-road	4	1	5	2	**3**
ERS	5	2	2	4	**5**
Battery swapping	3	5	3	5	**2**

Strategic policy alignment

[46] The extent to which policy measures, studies, and projects are aligned with the charging alternative. This criterion is, of course, subject to change, but from the current policy landscape, it is possible to give some scores to three categories. These categories include the independence of policy, current policy plans/decisions, and current projects/studies by ventures and universities[5], [9], [46], [56], [118]. The assigned scores can be found in Table 6.10.

Table 6.10: The scoring of aspects in strategic policy alignment

Strategic policy alignment	Independency of policy	current plans/decisions	current projects/studies	Overall result
Depot	5	3	4	**4**
On-road	3	5	5	**4.33**
ERS	1	2	2	**1.67**
Battery swapping	4	1	1	**2**

The results from the qualitative social criteria calculations are shown together in Figure 6.10. As can be seen, ERS and battery swapping score high on pioneering and on-road, and depot on Strategic policy alignment. Furthermore, depot charging is the least complex to implement, and battery swapping is the most.

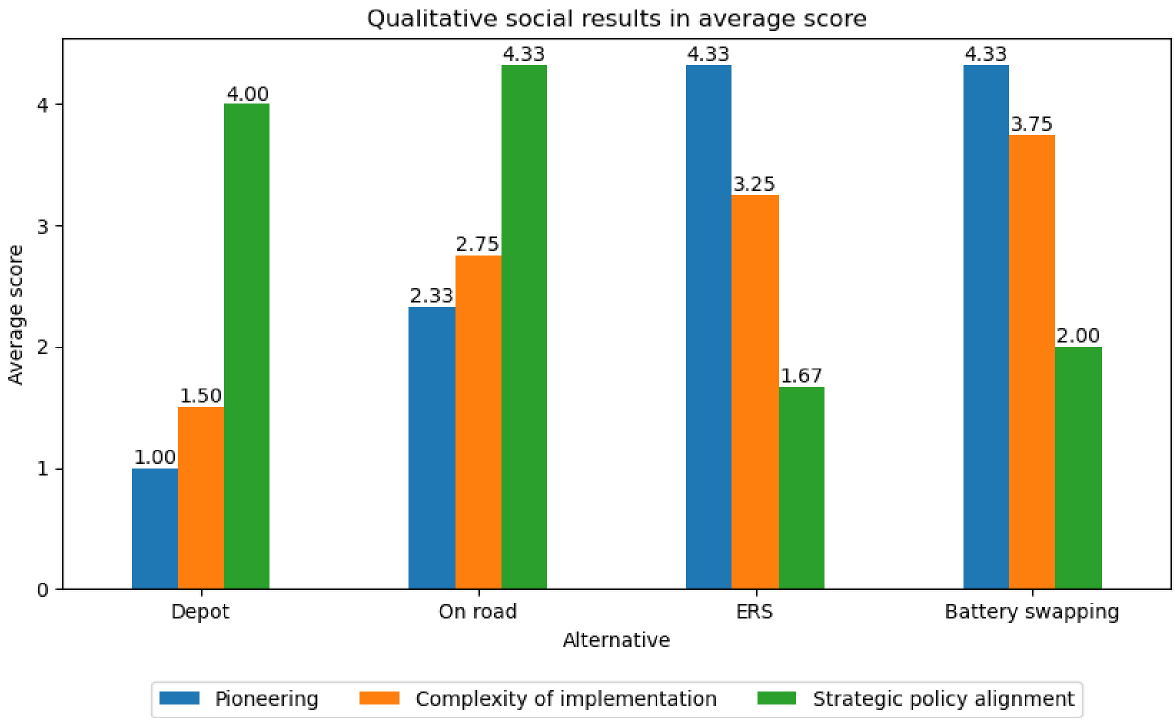

Figure 6.10: *The qualitative social criteria of the charging alternatives:* depot charging and on-road charging have, compared to ERS and battery swapping, high scores for strategic policy alignment but lower for pioneering. The complexity of implementation is highest for battery swapping due to large changes in the company, operations, and low support. Depot charging has the lowest complexity score due to a lot of support and little change in operation.

7 Ranking of charging alternatives

This chapter shows the overall results of ranking the charging alternatives for different comparisons. As was described in section 3.5, the weights are generalized and the performance is normalized. This approach enables an overall score to be assigned to the charging alternatives and allows them to be ranked. The ranking result is shown in section 7.1. To understand which parameters and criteria influence these results the most, a sensitivity analysis was performed, of which the results are shown in section 7.2.

7.1. Charging alternative ranking

In this section, the charging alternatives are ranked for different comparisons. Note that inside the subplots, the bars of the overall scores are sorted by their score. This may result in a different sequence of bars for different rankings.

Experts vs freight carriers

First of all, the comparison between experts and freight carriers can be made. For both groups, the combined use case for performance from subsection 6.1.2 is used. Next to that, the weights from the groups were used, which can be found in subsection 5.3.1. The ranking results are shown in Figure 7.1.

From Figure 7.1, it can be seen that the ERS charging alternative scores highest for the experts and the depot charging alternative scores highest for the freight carriers. On-road charging is for both groups the worst scoring alternative. For both groups, the differences between the top three alternatives are small.

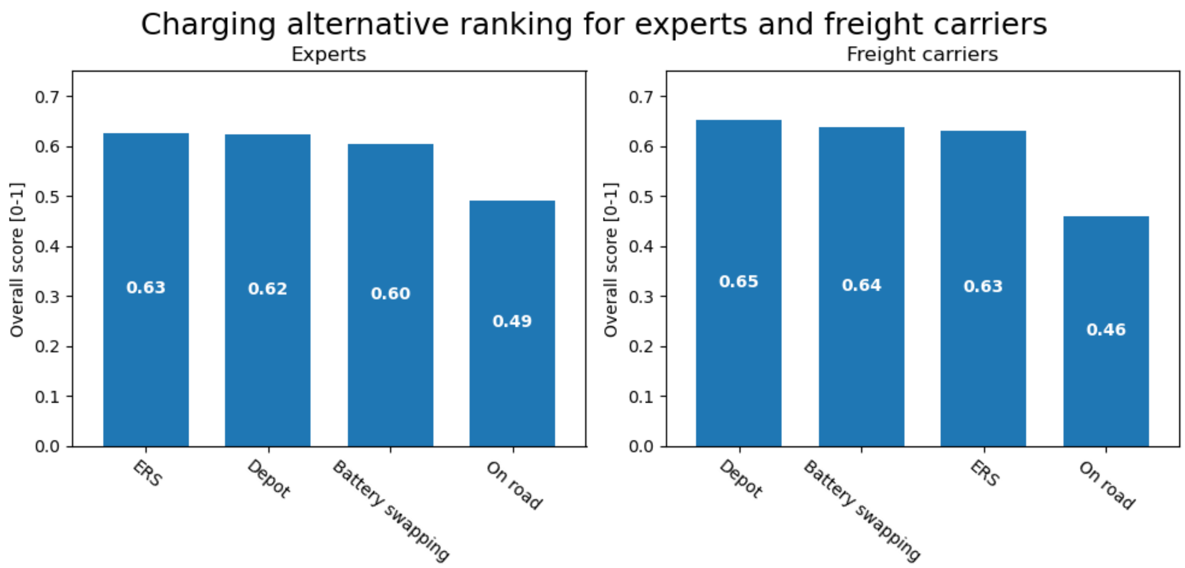

Figure 7.1: *Ranking of alternatives for experts and freight carriers:* Depot charging scores highest for freight carriers and ERS for experts. On-road charging scores the worst for both. For both groups, the three highest-scoring alternatives have very similar scores, with some slightly different rankings.

Different daily distances

Secondly, the comparison between different daily distances was made. For this comparison, the different use cases for performance from subsection 6.1.2 were used. Next to that, the weights from the different daily distances of the freight carriers were used, which can be found in subsection 5.3.2. The results of the ranking are shown in Figure 7.2.

From Figure 7.2, it can be seen that for the short, mid, and long use cases, the depot charging alternative scores the highest. For the double shift use case, battery swapping scores highest, with a larger margin over the other alternatives. Furthermore, on-road charging scores worst for all use cases, and ERS ends in second place for the short, long, and double shift use cases.

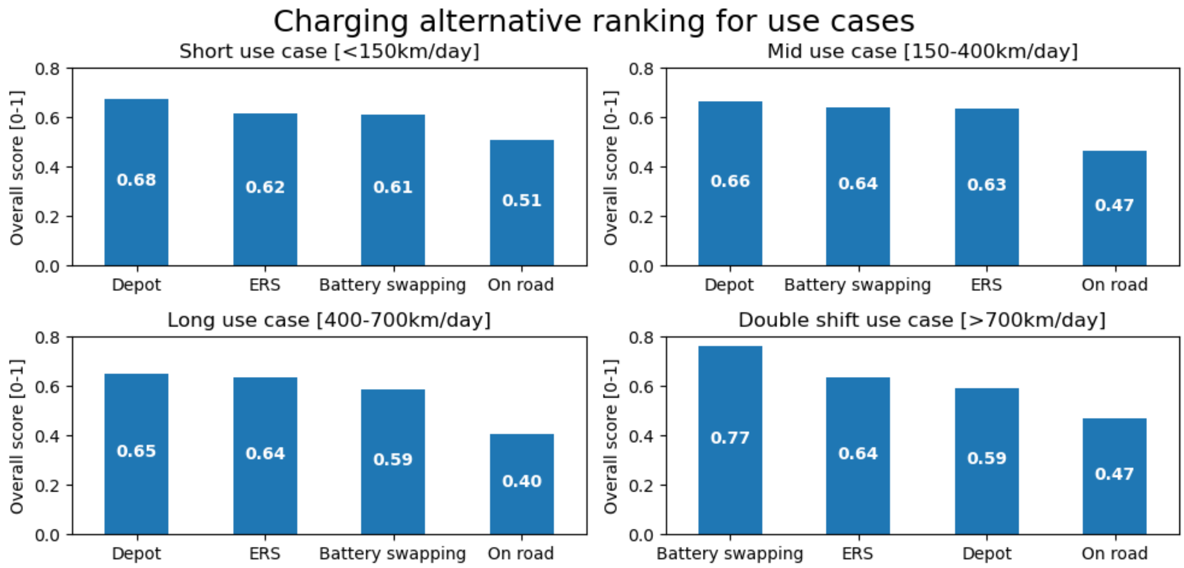

Figure 7.2: *Ranking of alternatives for different use cases:* For all use cases except the double shift use case, depot charging scores the highest by a relatively small margin. For these use cases, battery swapping and ERS are always second or third and score relatively similarly. On-road charging scores worst in all use cases by some margin. For the double shift use case, battery swapping scores highest with a relatively large margin.

Different sectors

Thirdly, the comparison between different sectors was made. For this comparison, the combined use case for performance from subsection 6.1.2 was used. Next to that, the weights from the different sectors of the freight carriers were used, which can be found in subsection 5.3.3. The results of the ranking are shown in Figure 7.3.

From Figure 7.3, it can be seen that battery swapping is the highest scoring alternative for the forestry and distribution sector. For the line haul sector, this turns out to be depot charging, by a slightly larger margin. Again, on-road charging scores worst in all sectors.

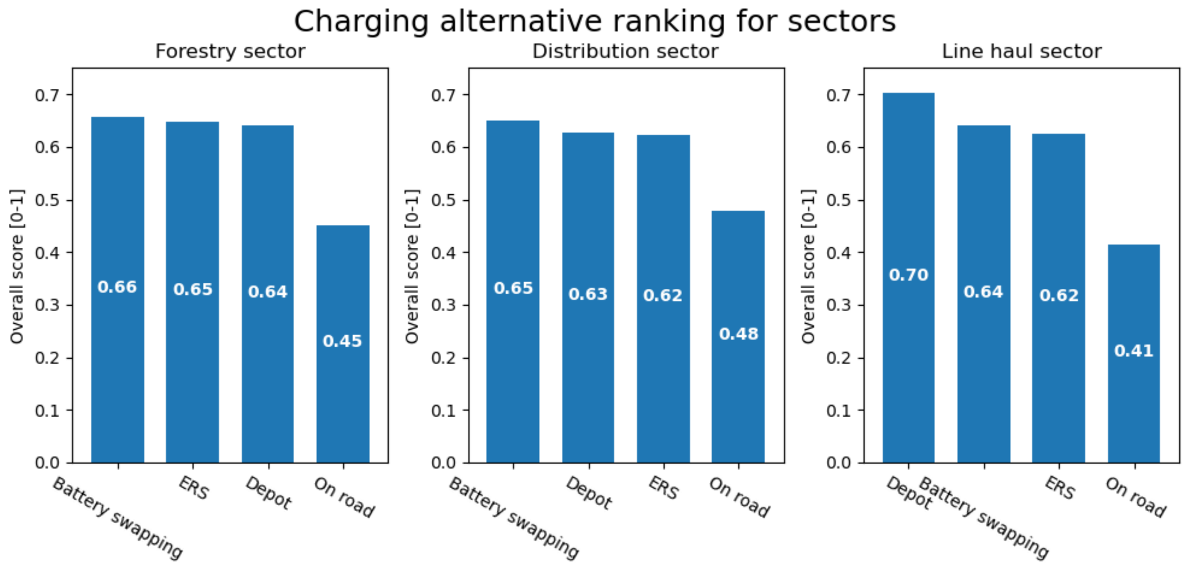

Figure 7.3: *Ranking of alternatives for different sectors:* For both the forestry and distribution sector, battery swapping scores highest, and depot charging and ERS have relatively similar scores. For the line haul sector, depot charging scores highest with a relatively large margin. On-road scores worst for all the sectors by a relatively large margin.

Different company sizes

Fourthly, the comparison between different company sizes was made. For this comparison, the combined use case for performance from subsection 6.1.2 was used. Next to that, the weights from the different company sizes of the freight carriers were used, which can be found in subsection 5.3.4. The results of the ranking are shown in Figure 7.4.

From Figure 7.4, it can be seen that ERS scores highest for small and medium-sized companies, with small margins to battery swapping and depot charging. For large companies, depot charging takes over this place with a bigger margin than the rest. For large companies in general, the differences between the top three alternatives are larger. For all company sizes, on-road charging scores the lowest of the alternatives.

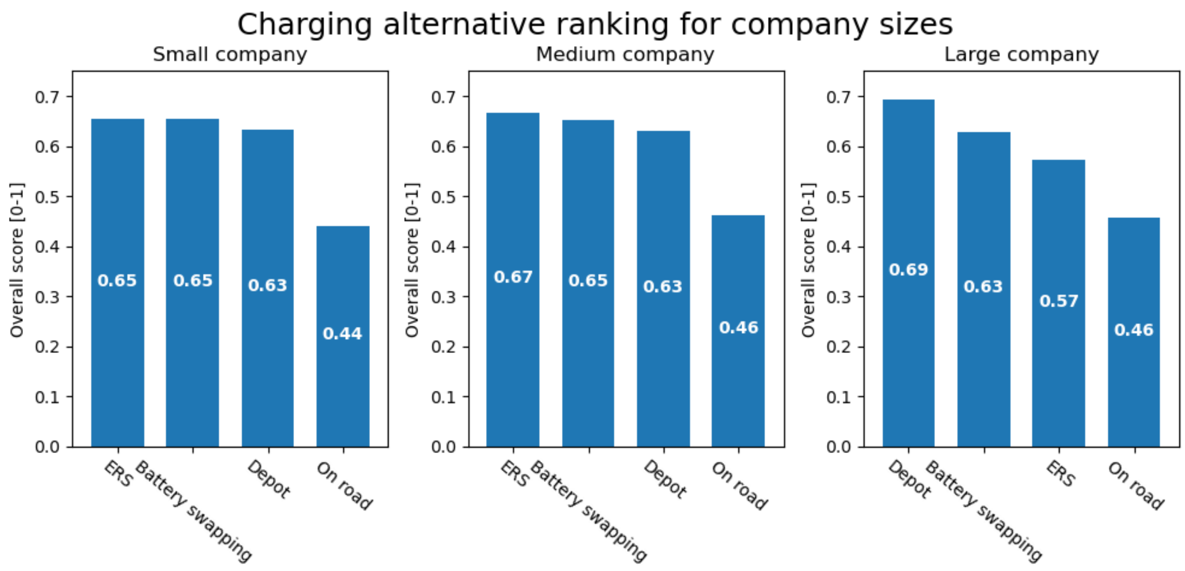

Figure 7.4: *Ranking of alternatives for different company sizes:* for small and medium company sizes, ERS scores highest, but scores relatively similar to depot charging and ERS in score. For large companies, depot charging scores higher, with slightly larger differences between the top three alternatives than for the other company sizes. For all company sizes, on-road charging scores the lowest by a relatively large margin.

Sweden and the Netherlands

Lastly, the comparison between different countries was made. For this comparison, the combined use case for performance, based on different country parameters, from subsection 6.1.2 was used. Next to that, the weights from the different countries of the freight carriers were used, which can be found in subsection 5.3.5. The results of the ranking are shown in Figure 7.5.

From Figure 7.5, it can be seen that battery swapping scores the highest for Sweden and depot charging for the Netherlands. For both countries, on-road is the worst-scoring alternative, and ERS ends up third. For the Netherlands, the differences between the top three alternatives are larger, with depot charging scoring significantly better than battery swapping.

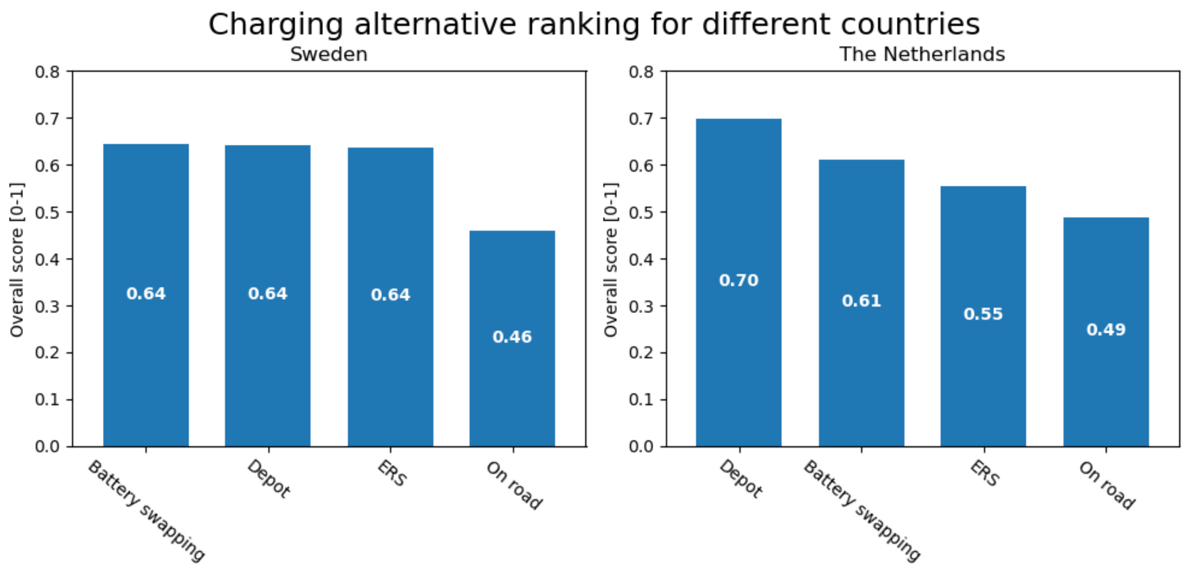

Figure 7.5: *Ranking of alternatives for Sweden and the Netherlands:* for Sweden, battery swapping scores highest, and for the Netherlands, depot charging scores highest. For both, on-road charging scores the lowest. In Sweden, the relative differences between the three highest-scoring alternatives are small, whereas for the Netherlands, these differences are larger.

7.2. Sensitivity analysis

The parameters and results of the criteria performance were analyzed using a sensitivity analysis. As the result was a ranking and this ranking was based on the relative differences between the alternatives, a conventional sensitivity analysis where parameters are changed with a certain percentage and the difference in the result is shown[69], [70], is not helpful. Although most sensitivity analyses for MCDA are done by changing the weights, in this study, it is chosen to only research the sensitivity of the performance. This is done because in this subject, it is assumed that the performance results are the most uncertain and subject to technological and economic developments. Changing parameters and criteria performance by a few percent would lead to all the scores changing relative to each other, which makes it difficult to see the sensitivity. Therefore, a method to see from which percentage of change the ranking of alternatives would change is more insightful[71], [72].

Sensitivity to general parameters

The general parameters that are used, energy consumption rate, home/on-road electricity price, and battery price, can be found in section 6.3. When changing these general parameters one by one, the ranking of alternatives can change as they have an effect on their criteria performances. The general parameters that the ranking is most sensitive to are shown in Table 7.1, and the ones it is least sensitive to are shown in Table 7.2. As can be seen, battery swapping and ERS are the alternatives that swap their ranking most often. From Figure 7.2, that makes sense, as the alternatives are often close to each other in score. From Table 7.1 it becomes also clear that the energy consumption rate for specific use cases and the electricity price on the road and at home are parameters the ranking is sensitive to. In contrast, the ranking is not very sensitive to the battery price, and for some use cases, also not to the energy consumption rate.

Table 7.1: *Ranking changes to the most sensitive general parameters:*

Use case	General parameter change	Ranking change
Short	Road price(-5%)	Battery swapping(3) ↔ ERS(2)
Mid	Energy consumption rate(-5%) Home/road price(+5%)	ERS(3) ↔ Battery swapping(2) ERS(3) ↔ Battery swapping(2)
Long	Energy consumption rate(+5%)	Battery swapping(3) ↔ ERS(2)
Double shift	Road price(15%)	Battery swapping(3) ↔ ERS(2)

Table 7.2: Ranking changes to the least sensitive general parameters

Use case	General parameter change	Ranking change
Short	Energy consumption rate (+10%)	Battery swapping (3) ↔ ERS (2)
Mid	-	-
Long	Battery price (+40%)	ERS (2) ↔ Depot (1)
Double shift	Energy consumption rate (-35%)	On-road (4) ↔ Depot (3)

Sensitivity to alternative specific parameters

Furthermore, many alternative specific parameters can be changed to see the sensitivity of the ranking to them. Among these parameters are battery lifetime, battery sizes, component investment costs, and many more that can be found in section 6.3. Again, the parameters the ranking is most sensitive to are shown in Table 7.3, and the ones the ranking is least sensitive to are shown in Table 7.4. Again, the change in ranking between ERS and battery swapping happens most often because they have an almost similar score in most of the use cases, as can be seen in Figure 7.2. But, more than with the general parameters, some other ranking changes also happen. From Table 7.3, it shows that battery lifetime is a parameter the ranking is very sensitive to. This is mainly due to the high weight the freight carriers assign to it Figure 5.2. This means that how the battery is charged and used can have a big impact on which alternative to choose. Furthermore, the ranking is sensitive to changes in battery sizes.

From Table 7.4 it becomes clear that the costs of the battery swapping stations and the depot charging connection need to go down a lot to change the ranking in favor of battery swapping and depot charging.

Table 7.3: Ranking changes to the most sensitive specific parameters

Use case	Specific parameter change	Ranking change
Short	Battery lifetime all alternatives (+-5%) Battery size battery swapping (-5%)	Battery swapping(3) ↔ ERS(2) Battery swapping(3) ↔ ERS(2)
Mid	Battery size depot/battery swapping (+-10%) Battery lifetime all alternatives (+-5%) Use cost ERS(-5%) Charge power on-road(+5%)	ERS(3) ↔ Battery swapping(2) ERS(3) ↔ Battery swapping(2) ERS(3) ↔ Battery swapping(2) ERS(3) ↔ Battery swapping(2)
Long	Battery lifetime depot/ERS (+-5%)	ERS(2) ↔ Depot(1)
Double shift	Battery lifetime ERS (-15%)	Depot(3) ↔ ERS(2)

Table 7.4: Ranking changes to the least sensitive specific parameters

Use case	Specific parameter change	Ranking change
Short	Battery swap station(-90%)	ERS(2) ↔ battery swapping(3) ↔ Depot(1)
Mid	Battery swap station(-35%)	Battery swapping(2) ↔ Depot(1)
Long	Depot charger cost(+35%)	ERS(2) ↔ Depot(1)
Double shift	Battery size on-road(+85%)	On-road(4) ↔ Depot(3)

Sensitivity to criteria

Lastly, the effect of the criteria can be shown by excluding them one by one. By assigning the same score to the performance of all the alternatives on a criterion, the effect of that criterion on the ranking can be discovered. From Table 7.5 it can be seen that operational cost, investment cost, truck (battery) lifetime, and charging time make a difference in the ranking for all the use cases. This makes sense, given their weights, shown in Figure 5.2, and the difference in performance among the alternatives, shown in section 6.4. Another interesting observation is the fact that pioneering doesn't make a difference in any of the use cases. Furthermore, for the double shift use cases the most criteria become irrelevant.

Table 7.5: Effect of excluding criteria on the final ranking

criteria	**Short**	**Mid**	**Long**	**Double shift**
Operational cost				
Investment cost				
Truck (battery) lifetime				
Charging time				
Payload capacity		No change	No change	
Operational flexibility				No change
Emission reduction		No change	No change	
Pioneering	No change	No change	No change	No change
Complexity of implementation				No change
Strategic policy alignment				No change

8
Discussion

In this discussion, the interpretation of the results of the research, the contribution to the existing literature, recommendations to stakeholders, and limitations of the used methods will be discussed.

8.1. Interpretation of results

8.1.1. Weights of the criteria

In this section, the findings regarding the weights for the criteria of different freight carriers will be discussed. First of all, the choice for a charging alternative turned out to be multi-faceted. Including ten criteria that were considered relevant made the choice complex and dependent on many factors. However, the results of the weights showed that not all criteria are considered important by the freight carriers.

In general, freight carriers focus most on financial and operational criteria in all the segments. The social criteria always turn out to be the least important. This can be explained by the tight margin market that has been optimized over the years. If the financial and operational properties of a charging alternative are not competitive, that charging alternative is not preferred.

These findings can be validated with the findings from interviews with logistics experts. In these interviews, it became clear that the challenges to electrification are mainly operational and financial. This leaves the market inactive in the transition to electrified transport. Although large companies are starting to electrify at a low pace, small companies are more hesitant in electrifying and are not content with the incentives that put them at risk of losing their business. Generally, from the interviews, it turned out that there is a different mindset among academic experts and logistics experts, with the latter being much more skeptical of the electrification of the transport market.

Experts and freight carriers

The results show that experts underestimate how important freight carriers value the financial criteria. Freight carriers care about all criteria of the TCO, as operational costs, investment costs, and truck lifetime are weighed equally. Next to that, experts overestimated the importance of operational flexibility, complexity of implementation, and strategic policy alignment for freight carriers(Figure 5.1). An explanation could be that freight carriers are willing to electrify their trucks if it financially works for them, and operational flexibility and complexity would then be issues they will deal with in smart ways.

Daily distance

The weights of freight carriers for different daily distances indicate that for some criteria weights, there is a direct relation with the daily distance (Figure 5.2). For operational costs, charging time, and operational flexibility, their weight increases as the distance grows. This can be explained, as with more daily kilometers, these criteria have a greater effect on the economics and operations of a freight carrier. For the lifetime of the truck, the payload capacity and emission reduction, the criteria weights decrease as the distance grows. For the lifetime of the truck, it is difficult to find an explanation, as the fewer kilometers trucks drive on a day, the less relevant their lifetime is. For the payload capacity, it can be explained from the fact that short daily distance operations can be used more to transport heavy bulk of goods from a factory to a facility, whereas if that were to happen on longer distances, different modes of transport would be used. Lastly, the higher weights for emission reduction in the shorter daily distance use-cases can be explained by the fact that these operations are closer to realistically electrifying and thus can be focused more on an environmental criterion, such as choosing the alternative with the least emissions.

Sector
Figure 5.3 shows that different sectors have different priorities. The most remarkable differences in priorities were in operational costs, charging time, operational flexibility, and emission reduction. Operational costs have a significantly higher weight for line-haul freight carriers, probably as they drive the most kilometers for single assignments. Charging time is most prioritized by the forestry sector, probably because of the lack of charging infrastructure in the regions where they operate. Operational flexibility is mainly prioritized by the distribution sector, possibly as their distribution runs can vary a lot from day to day for each truck. The line-haul sector prioritizes flexibility the least, probably as there is more room for change in their schedules. Emission reduction is most prioritized by the distribution sector. A reason might be that this sector is closest to electrifying already, and thus, making the best choice regarding the environment can become a priority for them.

Company size
Figure 5.4 shows that some significant differences in weights between the company sizes exist. As with the daily distance, again, the weight grows or decreases with the size of the company. Growth in weight with the company size can be seen in operational costs and payload capacity. This can be explained by the fact that larger companies optimize their assignments and operations more, and smaller companies execute the jobs offered to them. A decrease in weight with company size is seen with charging time and operational flexibility. An explanation might be the reduced flexibility in operations when there are just a few trucks available to share the assignments with. A small set of trucks has to perform all different assignments and cannot combine schedules effectively to reduce inefficient charge moments.

Country
From the comparison between the Dutch and Swedish freight carriers, some remarkable differences can be seen(Figure 5.5). First of all, the Netherlands has higher weights for financial criteria, with the operational and investment costs having higher weights. This can indicate that the Netherlands is more financially focused on a more centralized European market with a lot of competition regarding cheap transport. Sweden has higher weights for operational criteria such as operational flexibility and payload capacity. This can be explained as the Swedish transport network has a lower density than the Dutch network. Furthermore, Sweden seems to be more environmentally focused, with emission reduction and pioneering having higher weights. Lastly, the Netherlands puts more weight on the strategic policy alignment. This might come from the same business-minded view that causes the financial criteria to be weighed more as well.

8.1.2. Performance of the alternatives on the criteria

In this section, the results regarding the performance of the alternatives are discussed. Discussing the performance of all ten criteria is redundant, but the most important criteria, given the freight carriers' weights, will be discussed in more detail.

Looking at the financial criteria first, depot charging and battery swapping have the best performance for operational costs. For the other alternatives, the operational costs could be lower if utilization increases, although this cost reduction has limits [119]. Depot charging and battery swapping have the highest investment costs, and for depot charging, this is especially the case if the daily distances are larger and battery sizes have to be increased. The reduction of battery prices in the future can make this difference less significant, favoring depot charging in the future. For battery swapping, the cost of a swapping station might be reduced if the market grows. Then, for the lifetime of the batteries, depot charging and battery swapping perform best, with on-road performing the worst. This shows that there is no charging alternative scoring best on all three financial criteria. Knowing which alternative performs best financially thus involves combining the performance with the weights, to see which differences in performance matter the most.

Looking at the operational criteria, stating which charging alternatives perform best is also difficult. The scores for operational flexibility are close to each other. In reality, these scores might have more differences depending on the specific freight carrier situation and available charging infrastructure. For the other criteria, the depot charging, ERS, and battery swapping outperform on-road charging regarding charging time, although this again can change significantly given the available infrastructure of these alternatives and the technological developments of batteries and on-road charging speeds. Lastly, the available payload capacity is worst for depot charging at higher daily distances. For these longer distance cases, it is also doubtful whether the depot charging battery sizes of 1000 and 2000 kWh are feasible soon [120]. Concludingly, ERS and battery swapping perform best on the operational criteria in general, although a true conclusion remains dependent on the weight of the criteria.

8.1.3. Ranking of alternatives for freight carrier segments

In this section, the findings regarding the rankings of the alternatives are discussed. In general, the rankings show that no charging alternatives score highest for all different segments of freight carriers. Depot charging has the highest score for most groups, although not often with a large margin over ERS and battery swapping. For specific freight carrier groups, battery swapping and ERS score the highest. The heterogeneity of these results advocates, on one hand, for the equal distribution of efforts and investments in all of the charging alternatives, resulting in a heterogeneous charging market that can meet the specific needs of freight carriers. With these three charging alternatives developed, freight carriers could choose their best alternative, lowering barriers to transition to BETs. On the other hand, it can be questioned whether equally distributed efforts and investments in these three charging alternatives are worth it, if the differences between the charging alternatives are small in most rankings, showing there is no significant benefit for certain groups of freight carriers to choose the alternative that works best for them.

Although there is no clear winner in the rankings, there is an alternative that scores worst in all rankings: on-road charging. As a charging alternative, on-road charging, as it is modeled in this research, matches the needs of freight carriers the least. This is worrying, as most investments are made in this alternative [22]. Questions should be asked by policymakers and investors whether this alternative meets the needs of the market enough in the future, and whether the short-term gains of building the infrastructure for the charging alternative aren't outweighed by their mismatch with the freight carrier demands. Although the other charging alternatives have bigger barriers for the infrastructure buildout, the results of this study show that, for freight carriers, those charging alternatives are far better options.

Daily distance

Looking at the different comparisons, some remarkable results can be discussed. First of all, comparing the different daily distances for freight carriers, battery swapping is scoring significantly higher than the other alternatives for the double shift use case. For the use-cases with lower daily distances, depot charging scores highest, but is always closely followed in score by ERS and battery swapping. However, in the double shift use case, battery swapping scores highest and outperforms the other alternatives. This is mainly due to low charging times, limited increase of investment costs, and good lifetime of the battery and operational costs, which become increasingly more important for the groups that drive double shifts. The difference with depot charging is large in this group, mainly because depot charging investment costs increased significantly compared to the long daily distance case. This result can also be seen in the current challenge the market faces for long-haul transport, as the conventional alternatives of depot charging and on-road charging can hardly deal with the demands of this type of transport[121]. This advocates for battery swapping to be developed more in Europe, enabling the electrification of all transport use cases in the market.

A remark about depot charging for the long and double shift use case has to be made, as for these use cases, the alternatives are assumed to have a battery of 1000 and 2000 kWh, respectively. These battery sizes do not appear in most literature as they appear to be unfeasible in the chosen time frame for this study[22], [78].

Sector

The comparative results for the sectors show that battery swapping is the highest scoring alternative for the forestry and distribution sectors. The differences with the other alternatives are, however, not significant. The forestry and distribution sectors have many short trips and can thus benefit from swapping their battery each time they return to their depot. For the line haul sector, depot charging scores the best by some margin. This can be explained by the need for low operational costs and short charging times, as these trucks spend most of their working hours driving.

Company size

In the comparison of charging alternatives for company sizes, ERS scores highest both for small and medium-sized companies. For small companies, battery swapping has almost the same score. However, for small companies, battery swapping might not be realistic, as building swapping stations at the depot and destinations for only a few trucks is not feasible. A solution to this problem can be a cooperation of small freight carriers that set up a system of battery swapping stations. If this is not possible, ERS is the best option. This resonates with some of the findings from the interviews to validate the weight, where it was indicated that small and medium-sized companies do not have much financial resources and thus prefer options that reduce the upfront investments, such as ERS. For larger-sized companies, depot charging has the highest score by some margin. Large companies are also better able to build depot charging infrastructure as they can lower investment costs by taking advantage of the economies of scale, building multiple facilities at once [91]. With the current policy landscape, ERS and battery swapping do not score high for large companies that have a high weight for strategic policy alignment. Possibly, when policy and support are initialized for these alternatives, their score might change significantly, making them good alternatives for large companies.

Country

Looking at the rankings for countries, the margins between charging alternatives are different per country. For Swedish freight carriers, the top three alternatives score relatively the same, whereas for Dutch freight carriers, the differences are much larger. For Dutch freight carriers, depot charging is the highest scoring alternative. This can be caused by the high weight that Dutch companies put on strategic policy alignment. This indicates that Dutch companies await policies to be made before buying into an alternative. This matches well with their business-minded criteria weights, indicating that the Dutch are less socially focused in their central place in the European transport market. Furthermore, depot charging scores highly due to its operational flexibility, a highly valued criterion by Swedish freight carriers. Given the low density of the Swedish road network compared to that of the Netherlands, this outcome appears reasonable.

8.1.4. Sensitivity analysis

General parameters

From the sensitivity analysis of general parameters, it can be seen that the electricity price difference between home- and road-based charging and the efficiency of BETs in the future can have a significant impact on choosing between battery swapping and ERS. This means that when CPOs can reach certain utilization rates and cut their operation costs, on-road prices may fall, and the ranking of charging alternatives changes.

Looking at the least sensitive parameters, only after a 40 % increase in the battery price, the ranking of ERS and depot charging is changed in the long-distance use case. This indicates that the benefit of ERS of smaller batteries only really shows if the differences in costs become large due to the battery size reductions. This debunks some of the findings of [83], and strengthens the fears of [30] that only with high battery prices, ERS has benefits. Also, from the result of a 35 % decrease in energy consumption rate, it can be learned that more efficient BETs will favor charging on-road over depot charging for double shift use cases, as this will reduce the battery size and thus charging time significantly.

Alternative specific parameters

From the sensitivity of the rankings for alternative specific parameters, it can be seen that the battery lifetime has a big impact. This means that the scores can change significantly for some charging alternatives that limit the use of fast charging, or if battery manufacturers diminish the lifetime effects of fast charging.

Furthermore, the choice of battery size for battery swapping has a big influence on the rankings. The battery size can be reduced when companies can build swapping stations at multiple locations, allowing more than one intra-day swap to be made. Looking at the least sensitive parameters, it can be seen that the costs of a battery swapping station have to be reduced significantly to bring about some ranking changes. This can be achieved by building the stations collectively with a group of freight carriers or by the government/third party. Also, the depot charging alternative becomes less attractive if the costs of depot chargers rise too much due to, for example, high costs for a grid connection.

Exclusion of criteria

From the exclusion of criteria, it can be seen that pioneering does not make a difference in any of the rankings. This means that for freight carriers, it does not matter whether they pioneer by their choice of charging alternative. This is logical in a market where a green or progressive image matters much less than the balance sheet. The fact that emission reduction does not change the result in two use cases strengthens that argument. Also, excluding the payload capacity does not make a difference in two of the four use cases. This can be caused by the fact that for these use-cases, the vehicle weight is not often a limiting factor.

8.2. Contribution to existing literature

The findings that were presented in this discussion can be a contribution to the current literature. As stated in the introduction, there is a research gap regarding the comparative assessment of charging alternatives for different types of freight carriers. Some research was performed comparing charging alternatives, but these studies were often limited in their completeness of the comparison. With 10 criteria considered, for four different types of segmentation of freight carriers, this study has provided such a complete comparison. Furthermore, the inclusion of different use cases secured realistic performance results from which good comparisons are made. The survey responses provided useful insights into freight carriers' thinking about aspects of the decision-making regarding charging alternatives, which were based on assumptions in former research. Although many questions remain and the findings can be made more detailed given a more sophisticated research approach, this study can be a catalyst or stepping stone for more complete comparative assessment studies regarding charging alternatives for BETs.

8.3. Recommendations

From the results, the major findings and experiences of the research, some recommendations were made to different stakeholders.

8.3.1. For policy

From this study, some recommendations to policymakers can be made. First of all, the study shows that depot charging, ERS, and battery swapping have high scores for many groups of freight carriers, and on-road charging scores low for all groups of freight carriers. This result has a mismatch with the current distribution of investments and efforts for the charging alternatives. With battery swapping and ERS receiving very little policy support, there are big opportunities to electrify the market that are being neglected. Furthermore, most support is given to the worst-scoring alternative for the freight carriers, on-road charging. The lack of support for ERS is often explained by the fact that the build-out of a network is a huge risk, and the lack of support for battery swapping due to standardization issues[122]. Both of these arguments can be understood until the alternatives have more proof of concept, but the current lack of support for depot charging is more worrying. As is shown in the result, depot charging is the preferred charging alternative by many freight carriers, and this preference is backed by some studies[27], [49]. However, depot charging receives little policy support compared to the huge efforts that are put into building an on-road charging infrastructure. Lowering the barriers to a grid connection for a depot charger could be a more efficient measure for governments to electrify the road freight transport market.

Another finding from this study is that for different groups of freight carriers, different charging alternatives have the highest score. This can advocate for neutral policy support of these alternatives. However, the discussion should be held on whether the small differences in score justify this neutral look of support. If a charging alternative that requires much more support to be successful is only slightly more useful for a group of freight carriers, is that alternative worth the investment? Next to that, policymakers should think about building or supporting different charging alternatives for different groups of freight carriers. Supporting a charging alternative that is only useful to a small group of freight carriers can be unfair to other freight carriers. Therefore, it is important to consider the number of freight carriers that are helped by the investments in a certain charging alternative.

8.3.2. For OEM

From the study, a big recommendation is to invest more in developing battery swapping in Europe. The study proves that for certain use cases and freight carrier segments, battery swapping has great potential and is, for a double shift use case, the only option. With Chinese manufacturers investing in this charging alternative, a competition battle might be lost in the future if the focus of European OEMs remains solely on on-road charging. Standardization challenges can be overcome through healthy cooperation between the manufacturers and European legislation or coordination.

If, in the coming years, governments decide to fund charging alternatives such as ERS or battery swapping, freight carriers will have options in the market of charging alternatives. Given the results of this study, it turns out that for different freight carriers, different charging alternatives score best. This indicates that with different preferences, different charging alternatives give the best usage. Even within the same freight carrier company, different operations can be performed with different characteristics and needs. As we come from a diesel truck technology where the standard diesel truck could do all operations, freight carriers might want to keep that simplicity and flexibility. Therefore, OEM should see the opportunity to build a truck that is compatible with multiple charging alternatives. A truck with a charging port, swappable battery, and a pantograph can take advantage of all the available infrastructure. This could drive up the costs per truck, but if it could lead to battery size reductions, a lot of costs can be saved.

Also, if the charging infrastructure of many alternatives is available, OEMs can think about building different types of trucks with adjustable battery sizes that fit a certain type of operation best. With optimization algorithms, the optimal battery size and charging alternative for each freight carrier could be determined. This customization is a service that can help freight carriers overcome the current barriers of transitioning to BETs.

8.3.3. For freight carriers

A recommendation for freight carriers from the study is to investigate the best charging alternative for them. The study proves that there can be differences in the best charging alternatives for different freight carriers, indicating the need to investigate this choice. In the future, when the charging infrastructure for the alternatives is available, it can be interesting to invest in a heterogeneous fleet to choose a different truck from the fleet for each operation. Companies with smaller fleets could focus on a certain type of transport. This would create a so-called inter-modal road freight transport system, where long trips can be done with certain trucks and short 'milk runs' with another truck. Another opportunity lies in the compatibility between the alternatives; in the future, a single truck might be able to choose among different alternatives, given the needs of the specific operation on the day. This makes the truck versatile and the risk of the initial investment lower.

8.4. Limitations of the research and future work

During the research, many choices on the scope and method used had to be made. Due to time and to keep the results interpretable, simplifications have been made. Also, in hindsight, some limitations of the used methods were discovered. All these limitations and future studies will be discussed in this section.

8.4.1. Weights

One of the main parts of the research is the weighing of the criteria. As was discussed in section 3.3 a survey was used. From the chosen method and the processing of the results, some limitations arose. These include the subsection 8.4.1 Interpretation of survey, subsection 8.4.1 Generalization, and subsection 8.4.1 Scaling of weights.

Interpretation of survey

As the survey was online, the interpretation of respondents could have been different. This was shown by the fact that most of the freight carriers misinterpreted the way they had to fill in the survey. These are busy professionals, and the best-worst method is a different and sometimes complex method to fill in. It was found in this study that it does not always come across. From that same confusion, other parts of the survey might not have been transferred correctly. Possibly, the criteria could have been interpreted in different ways. It was made to limit this as much by explaining the criteria and their performance ranges for the quantitative criteria. However, from some of the interviews, it already showed that not everyone immediately understood the same from the criteria and their explanation.

Generalization

In generalizing the criteria weights, the method has some limitations. In the method, the average of the weights per group is taken. But, as can be seen in chapter 5, the standard deviation can be large sometimes, and from section 5.1 it can be seen that the number of responses among the groups is not always equal. This brings forward the issue of the limited number of responses, which makes the generalization of the results questionable. Furthermore, remarks can be made with the representation of the market in the responses. First of all, the freight carriers that responded might be more sustainability-focused than freight carriers in general. Next to that, it can be questioned whether the freight carriers of today will be the decision makers of the future. Market developments due to the energy transition might force the smaller freight carriers out of the market and larger freight carriers to take over their market share[91].

Scaling of weights

In the survey, the respondents could compare the criteria with a scale from 1 to 7 on relative importance. This is sufficient for a simple weighing, but for more realistic weights, it is better to be able to scale the weights. Certain criteria might be a hundred times more important than others, and other criteria might have no importance at all to the decision maker[123], [124]. These options were not given, but might have given a more realistic representation of the weights.

8.4.2. Performance

The other main part of the research was the performance of the criteria. Given the methodology, some limitations are identified. These include scattered literature, the choice for a static system, the made assumptions, and the use of linear normalization.

Scatter literature

First of all, the use of scattered literature brings some limitations. As not much comparative research has been done between the charging alternatives, the used literature for parameters and the assumptions is very scattered. This means that the alternatives have many studies in isolation for many different scenarios, but rarely altogether in the same study under similar circumstances. Although in this study efforts are made to use the parameters as equally as possible, it is impossible to be certain of the validity of the used parameters under the created scenario and use cases. Furthermore, even in focused studies for charging alternatives, large ranges in the used parameters and results were found. Lastly, for ERS, the parameters and claims have a wide range because large-scale applications have not yet been operated. This means that there is little experience in real-world applications. For battery swapping, almost no European usage is present. Therefore, mostly parameters from Chinese studies in a Chinese context are used. It is very difficult to examine whether those parameters and concepts would still stand in a European context.

Static system

The use of a static system is a limitation. As is shown in Figure 6.1 and Figure 6.2, a static moment in time is chosen. This limits the study to static effects on the choice. Feedback loops and dynamics are neglected, even though these can be very powerful[125]. Also, due to this simplification, dynamic energy pricing is not considered in the performance, although it could favor some of the alternatives.

Assumptions

First of all, the performance of the alternatives on the criteria is highly dependent on the assumptions that were made. These assumptions shape a simplified version of reality in which the alternatives could be compared. However, in real life, the freight carriers will opt for more tailored versions of charging alternatives that suit them best.

- The chosen battery sizes assume certain journeys and charge possibilities
- The current isolation of charging alternatives is not entirely realistic.
- The exclusion of dynamic energy pricing
- The assumption of a sufficient charging network
- No waiting times or buffers are assumed for the charging. This assumes a perfectly smooth charging system/market that might not be realistic.
- For battery swapping, it is assumed that the swap cannot be perfectly timed at the regulatory break; however, in real life, this might be taken into the planning of assignments
- For battery swapping, the vehicle-to-grid profits are not taken into account due to uncertainty; however, [86] claims they can play a big role in the success of the alternative.

Linear normalization

Lastly, the linear normalization that is described in subsection 3.5.2 is a limitation of the method. By linearly normalizing the performance, the outcomes are simplified. This means that the worst alternative gets a score of 0 and the best a score of 1. A more realistic approach might be to have piecewise linear normalization [126] or to have non-linear normalization. These variants can introduce more realistic validations of the performance of the criteria. For example, the normalized performance of the operational costs might stay zero until a certain threshold is reached that is acceptable for the freight carrier. From that threshold, the performance might linearly increase as the operational costs get cheaper.

8.4.3. Future work

From this study, multiple ideas for future research arose. First of all, the limitations of the research ask for further research. As was discussed in subsection 8.4.1, the survey responses and format of the survey brought limitations. From these lessons, a better and more widespread survey can be performed, reaching a larger share of the market with more realistic weighing methods. This approach enables the needs of the market to be mapped in more detail, possibly using more interviews as well to get an in-depth understanding of the needs.

Next to the weights, the performance side can be improved as was discussed in subsection 8.4.2. First of all, more comparative performance research between all the charging alternatives needs to be done to map the differences in performance. Furthermore, studying the charging alternatives in comparison to each other in dynamic (system) models can give great insights into how these alternatives can develop and be used next to each other. Next to that, more detailed assumptions for more specific cases can make the performance results more tailored to the individual needs of freight carriers. Developing a tool that can be adapted to specific needs, comparable to [127], can be super helpful to give freight carriers insights into their possibilities. Lastly, an improved MCDA on the charging alternatives can be performed by normalizing the criteria performances in a more representative way to the real world.

Lastly, a more scenario-based approach can give valuable insights into how charging alternatives are useful in different circumstances and futures. This is much needed, as the developments of the market and electrification are under deep uncertainty. These scenarios can include different infrastructure roll-outs, technological developments, and geopolitical economic developments.

9 Conclusion

9.1. Research summary

Emissions of the road freight transport sector need to be drastically reduced. The propulsion method for trucks with the highest potential to do so turns out to be battery electric trucks (BETs) in numerous studies. However, due to high operational requirements and a tight margin market, there are many challenges related to BETs. In finding solutions for these challenges, the method of charging the truck plays a big role. Therefore, policymakers, OEMs, and freight carriers must know which of the available charging methods have or have the potential to electrify the market. To gain insight into the potential of charging alternatives, it is necessary to gain insights into the preferences freight carriers have for them, as they are the end users of the technology. Currently, in the literature, there have been numerous studies on the separate charging alternatives, often from governmental or OEM perspectives, and rarely from purely freight carriers' perspectives. Furthermore, mainly the financial and operational factors are studied, neglecting social factors. Also, the heterogeneity in the needs and abilities of freight carriers in the market is often neglected, drawing too general conclusions about the usability of the charging alternatives.

This study tries to fill that research gap by providing insights with a multi-criteria comparative assessment of four identified charging alternatives - depot charging, on-road charging, ERS, and battery swapping - for different types of freight carriers. In a Swedish and Dutch context, the study looks at the charging alternatives from a freight carrier's perspective in a future scenario where charging infrastructure for all the alternatives could be built.

The methodology that is followed is based on a Multi-Criteria Decision Analysis(MCDA). This approach is chosen as it can compare the alternatives with multiple objectives, using multiple criteria. First, the context of the comparison is determined. From the literature review, stakeholder interviews, and freight carrier validation, 10 relevant criteria were selected. Then, with an online survey and interviews with logistics experts weights for the criteria were determined. This was done by using the Best-Worst method, a descriptive weighing method that can estimate the true weights from experts with a limited number of responses. In the research process, it turned out that this method was difficult to understand for freight carriers through an online survey, however, the responses could still be used by approaching them as if they were from an AHP weighing method. The next step in the MCDA was to determine the performance of the alternatives on the criteria. This performance was determined by constructing a scenario and several use cases based on the daily distances of the trucks. Using assumptions, parameters from literature, and taking these through equations resulted in performances for the criteria. The approach was constructed and validated through expert interviews. The final step of the MCDA consisted of combining the obtained weights and the performance of the alternatives on the criteria to come to final scores for the alternatives. These scores were given in different comparisons of freight carrier segments. The comparisons included daily distance, sector, company size, and country of the freight carrier. With these scores, the alternatives could be ranked for each segment. Lastly, the results were analyzed by performing a sensitivity analysis to learn the influence the used parameters and criteria had on the final rankings.

From the first step of the methodology, ten relevant criteria were established. These included financial criteria - Investment costs, operational costs, and lifetime of the battery -, operational criteria - charging time, operational flexibility, and payload capacity -, and social criteria - emission reduction, pioneering, complexity of implementation, and strategic policy alignment.

9.2. Interpretations of the results

Interpreting the results, some major takeaways can be formulated:

- Financial and operational criteria are valued more than social criteria by all the groups of freight carriers. This can be explained by the earlier-mentioned tight margin market and high operational requirements.
- The weight of operational costs and charging time increases as the daily distance of a freight carrier increases. This can be explained as these freight carriers need to minimize their costs and can have tight schedules to deliver their goods or products.
- The weight of operational costs and strategic policy alignment is much larger for large freight carriers than for small and medium-sized freight carriers. These freight carriers optimize their operations more and tailor their long-term decision more to the policy that is created.
- Depot charging has significantly higher investment costs than the other alternatives for the longer distance use cases. If battery prices continue to fall in the future, this difference might disappear, giving depot charging the edge over the other alternatives even in these longer-distance use cases.
- Battery swapping has a very high base investment cost due to the cost of a battery swapping station. If, due to economies of scale or by the collective building or third-party buildout of a swapping charging infrastructure, this base investment cost falls, the battery swapping alternative might be a much better alternative for many freight carrier groups.
- Looking at the rankings of charging alternatives for different groups of freight carriers, it is shown that often the differences are small, and no alternative scores highest for all groups. This can mean two things: or the top three alternatives should be further developed evenly as for different freight carriers there is a different option that suits them best, or: the difference between the charging alternatives is so small that it serves no use to use a charging alternative that is best suited for a freight carrier and the investments in all could better be focused on developing just one charging alternative.
- Only on-road charging consistently scores lower than the others. This mismatches with the current amount of investments and efforts that are put into this charging alternative. Although the charging alternative can help freight carriers that are close to electrifying to step into buying a BET, alternatives such as ERS and battery swapping might do this better. If the barriers of initial investment for a large-scale ERS network or the swapping station are overcome, these alternatives can provide better performance for the freight carriers and are worth the investment.

9.3. Recommendations

From the results of this study, conversations and interviews with experts, and literature that was read, some recommendations are made for different stakeholders in the field. These recommendations are listed below.

- For **policy-makers**, it is recommended to transfer the investments and efforts that are being put into the on-road charging alternative to the other three charging alternatives that score significantly higher for all groups of freight carriers. Although on-road charging infrastructure is easier to scale and serves many companies at once, it becomes clear from the results that it meets the requirements and needs of the freight carriers the least. To speed up the transition to electrification, other alternatives have far greater potential. Furthermore, good science-based discussion has to be held on whether this greater potential is worth the necessary investments for these charging alternatives. If this benefit is not higher than the costs of building all three charging infrastructures for the alternatives, it is better to focus on only one of the alternatives.

- For **OEMs**, it is recommended to start developing trucks that are interoperable and compatible with different charging alternatives. If a charging infrastructure for different charging alternatives is developed, it is of great use for freight carriers to buy trucks that are interoperable and compatible with all charging alternatives. This reduces their risk of choosing the wrong charging alternative for their situation.
- For **freight carriers**, it is recommended to do good research themselves or ask for consultation with the BET they will buy. From the results in this study, it turns out that choosing the highest-scoring charging alternative can, in some cases, make a big difference for a freight carrier. Therefore, choosing a well-suited charging alternative can allow them to step into electrification earlier and get an edge on their competition. However, it can be hard to find the best-suited charging alternative, as the differences can be small. In that case, it is recommended to choose a truck that is interoperable or to focus the operations on a specific transport task that requires a specific charging alternative, and to become a link in a chain of different modes of road freight transport.

9.4. Limitations and future work

During the research process, several limitations of the method and possible improvements were discovered. These limitations will be listed below, and some suggestions for future research are made to further fill the identified gap in research.

- One of the found limitations of the method was the ability to gain insights into the freight carriers' thinking through a best-worst method in an online survey. For reaching enough freight carriers while getting high-quality data, the approach used was not ideal. Also, the number of responses should be improved to gain a better understanding of the decision-making of freight carriers. Future studies should focus on using simpler methods for freight carriers and on using events where many freight carriers are present to increase the response rate.
- With the used method of retrieving weights of the criteria, it was not possible to scale weights or to neglect certain criteria, although this might be the case in real life. In future studies, it can be useful to allow for this option to get a better representation of the decision-making of the freight carriers.
- The method had several limitations for determining the performance of the charging alternatives on the criteria. First, scattered literature made it hard to find parameters from similar scenarios that could be used and compared. Furthermore, the static system scenario did not allow for dynamic effects that are important in a complex system, and the assumptions that were made simplified the performance calculations, neglecting the tailored solutions that might be possible in reality. Furthermore, the linear normalization that was used made some unrealistic difference in performance, as in reality, the performance might get certain scores only after or before thresholds or within certain bounds. Solving this issue can make a much more realistic performance score for the criteria. In future research, these limitations could be tackled to have a more realistic representation of the performance.

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A

Appendix A: Criteria literature review

Table A.1: Table containing all the criteria found in the literature.

Begin of Table

Source	Subject	Criteria
Schot (2022) [38]	Stakeholder perceptions of ERS	Decreased resource dependency, political urgency, political acceptance, suitable partners, decreased fuel dependency. Cost reduction, investment security, attractive business case, upfront investment, investment risk, short-term gains, economies of scale, expensive alternatives, potential gains. Lobbying, political support. Technological maturity, landscape developments, few alternatives, complementarity, await international development, grid capacity, perceived feasibility. Emission reductions, organizational ambitions. System configuration, policy.
de Nie (2024) [39]	EFV's adoption small carriers with ERS	Investments, charging opportunities, charging costs, driving range, charging time, on-road risks, responsibility and attitude of the driver, planning, battery development, complexity, maintenance, available public static charging infrastructure, own static infrastructure, driver deployment, available ERS trajectories.

Continuation of Table A.1

Source	**Subject**	**Criteria**
Speth et al. (2021) [40]	Comparing options for EFV	Technical readiness vehicle, necessity of vehicle standardization, possibility to be operated in niches, technical readiness infrastructure, long-term infrastructure cost, operational flexibility, total cost of ownership
Zhu et al. (2023) [32]	Potential battery swapping	Technology maturity, vehicle investment, station investment, battery investment, battery durability, charging time, standard transportation efficiency, recharge distance, electricity price, vehicle maintenance cost.
de Saxe et al. (2023) [31]	Electric road system or big batteries?	Battery size reduction, embodied carbon emission savings, vehicle cost reduction, vehicle energy efficiency
Noto (2023) [15]	Acceptance analysis Battery swapping stations	Safety, labor shortage and attractiveness, working conditions, general benefits for truck drivers. Effort maintenance and repair, reliability, comparison of alternative fuels, feasibility, wear and tear, charging time. Vehicle battery investment costs, operating costs, TCO, risk of rising fuel prices. General benefits of transport companies, flexibility, ownership of batteries. General benefits environment, lower CO_2 emissions. Taxes and tolls, available infrastructure. Battery ownership and risk, cheap energy, charging time, weight savings, risk of available infrastructure, battery rent prices, recycling possibilities, necessary standardization, risk of monopoly.
Speth et al. (2019) [34]	Techno-economic comparison charging alternatives	Vehicle investment, energy demand, battery capacity, battery weight, range, depreciation battery, infrastructure cost without toll, TCO.

Continuation of Table A.1

Source	**Subject**	**Criteria**
Wang et al. (2019)[48]	Stakeholder influences ERS	Energy efficiency, infrastructure reliability, technology maturity, vehicle capacity charging, standardization, infrastructure investment, public image organization, future project investments, safety, traffic flow, charging time, driving distance, driving experience, ERS lane share, business model, policy support, lead technological innovation, emission mitigation, logistics park planning
Wilmsen (2024) [50]	Sustainable business models for charging alternatives	Charging availability, entry barriers, charging price, charging location setup, dynamic pricing, charging reliability(grid), vehicle to grid connection, TCO, infra investment, electricity costs, energy use, operation and maintenance costs, charging time, scalability
Cabukoglu et al. (2018) [36]	Swiss cases study for electric trucks	Energy demand, charging behavior, usage profiles, charging delays, CO_2 mitigation potential, infrastructure availability
Anderhofstadt et al. (2019) [47]	Factors affecting purchase decision electric trucks	Service and maintenance costs, expenses for repairs, purchasing price, taxes and insurance, depreciation/resale value, being a trendsetter in env friendly technologies, being part of socially responsible activities, general excitement new technologies/innovations, ecological impact of truck manufacturing and recycling, well-t-tank emissions, well-to-wheel emissions, tank-to-wheel emissions, reliability, charging time, driving range, max payload capacity, safety features, charging infrastructure, performance/drivability, financial incentives when purchasing/operating
Connoly et al. (2017) [37]	economic viability ERS	Battery size, battery cost, emission reduction, charging costs, infrastructure availability, infrastructure investments.
End of Table		

B

Appendix B: Online Survey

B.1. Quantitative ranges in the survey

For respondents to have the same understanding of the survey and the quantitative differences between alternatives for criteria, indicative ranges were calculated and shown in the survey. It has to be said that for all these ranges, assumptions were made, and extreme scenarios and use cases were used. There was no extensive search for multiple sources, as the idea of the ranges is mainly to give an order of magnitude. Therefore, the eventual performance results may be different. The assumptions and calculations made are described below:

- Operational cost
  For this range, the difference in recharging prices between home and public charging was used, as this was assumed to be the greatest difference between depot and public charging. There might be a difference between depot and ERS as well, due to day and nighttime prices, but this required further research, which was not feasible before sending out the survey. However, there was a significant difference already. The at-home prices for Sweden(0.27 EUR/kWh) and the Netherlands(0.48 EUR/kWh) differed a lot from their public prices; Sweden(0.48 EUR/kWh) and the Netherlands(0.59 EUR/kWh) [104]. The difference in EUR/km would thus be 0.21 EUR/km for Sweden and 0.11 EUR/km for the Netherlands. Then, taking a middle value for energy efficiency, 2 kWh/km [28], we come to the calculation that the maximum difference between alternatives for Sweden is 4.8 SEK/km and for the Netherlands, 0.22 EUR/km.
- Investment cost
  For this range, we assumed that the difference would be largest because of battery sizes and charger investment between depot charging and ERS. First of all, we used a difference of 730 kWh max for depot charging and 160 kWh min for ERS [6]. Then we looked at a usual price for a single depot charging device and found 30000 EUR as a middle value[49]. Then, we took the price of batteries from another study as 150 EUR/kWh [102]. Then, the difference in price of the batteries was around 85500 EUR, and adding onto that the 30000 of the charger resulted in a maximum difference of 115000 EUR between the alternatives.
- Lifetime
  This was a difficult criterion to give a range to, as it is based on many factors. Therefore, we chose to use the numbers from a reference on battery swapping, where they claim that by slow-charging at preferred temperatures, the battery life could be prolonged by 1 to 2 years compared to fast charging[86].
- Charging time
  This was again a difficult one, as it is dependent on the situation and vehicle. However, we used again the study on battery swapping [86] as it compared the charging times of several scenarios with battery swapping. We chose to compare the charging times of 400 kWh batteries with public charging and battery swapping, and the difference over a trip of 600 km was one hour.

- Payload capacity
  Payload capacity was again based on the difference in battery sizes between depot charging and ERS [6]. Then, using 0.125 kWh/kg as a future value from a study[28], we came to a max difference of around 5 tons between the alternatives.
- Emission reduction
  Lastly, for emission reduction, the only difference is in the size of the batteries. From a study [6], it was found that an ERS-charged truck produced 386 gCO2eq/km compared to a usual BET that emitted 440 gCO2eq/km, thus resulting in a 55 gCO2eq/km maximum difference between the alternatives.

B.2. The seminar survey format

Choice aspects/criteria when choosing a charging alternative for an electric truck

Together with the transition to electric trucks the question will also arise how to charge the vehicles. Charging can be a big hurdle to make the transition and there have emerged several technologies that try to tackle these problems. Charging alternatives include: depot charging, public fast charging, Electric Road Systems or battery swapping. In this study we want to learn on what aspects/criteria these alternatives need to be assessed to find the best one for each operation or company.

1. Which stakeholder group are you a part of? *

- ◯ Forest company - Skogsbolag
- ◯ Other sending party - Annan befraktare/kopare av frakt
- ◯ Freight carrier/haulier - Åkeri
- ◯ Logistic service provider - Åkeriförening, logistikföretag
- ◯ Government/institution - Myndighet
- ◯ Academic -Forskning
- ◯ Original equipment manufacturer - Tillverkare
- ◯ Charging point operator - Laddning
- ◯ Other... - Övrigt

2. If you chose 'other', please specify your stakeholder group...

3. What do you consider as important aspects/criteria when choosing for a charging alternative for an electric truck? *

   Please name as many as you can think of. (you can separate them with comma's)

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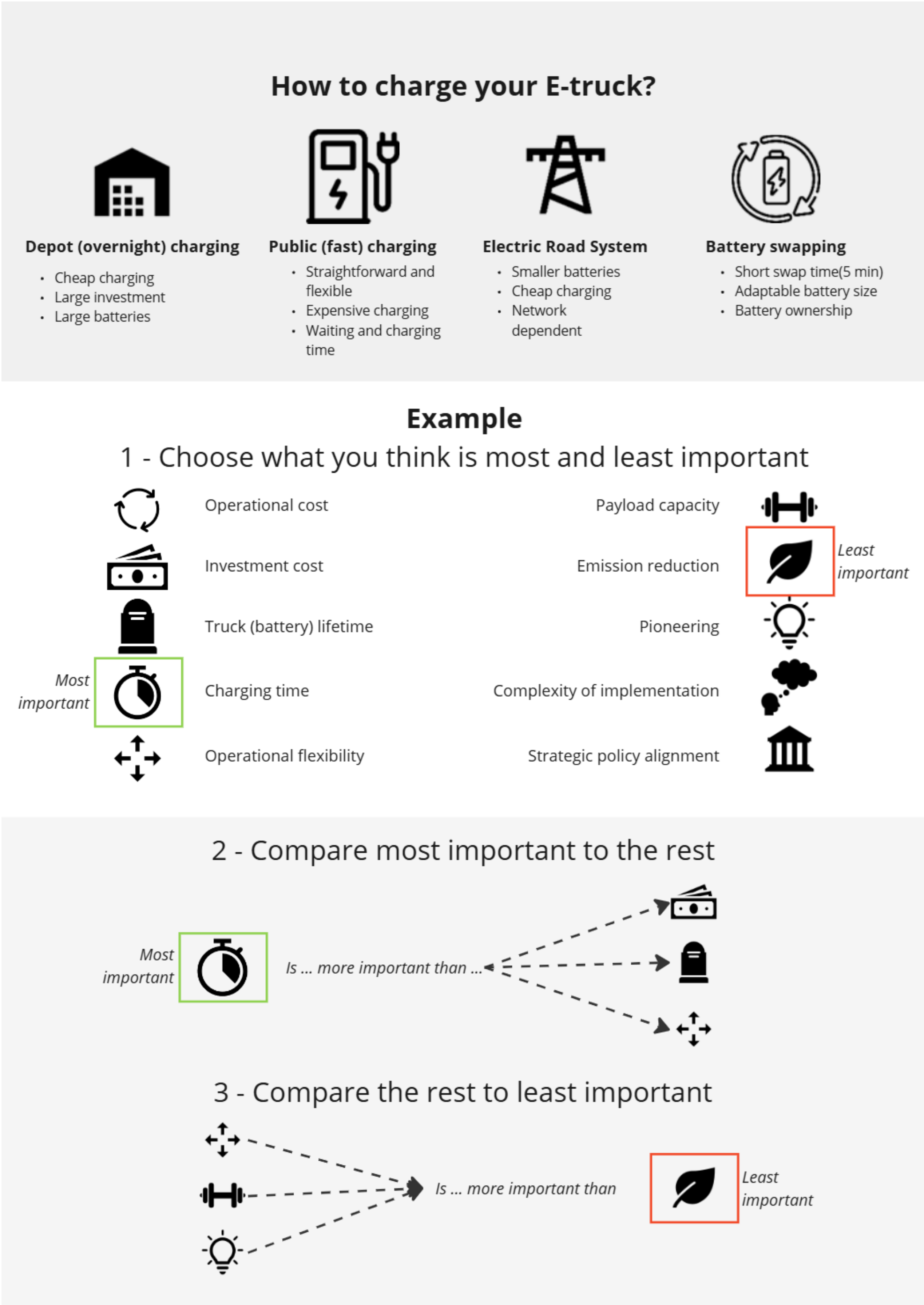
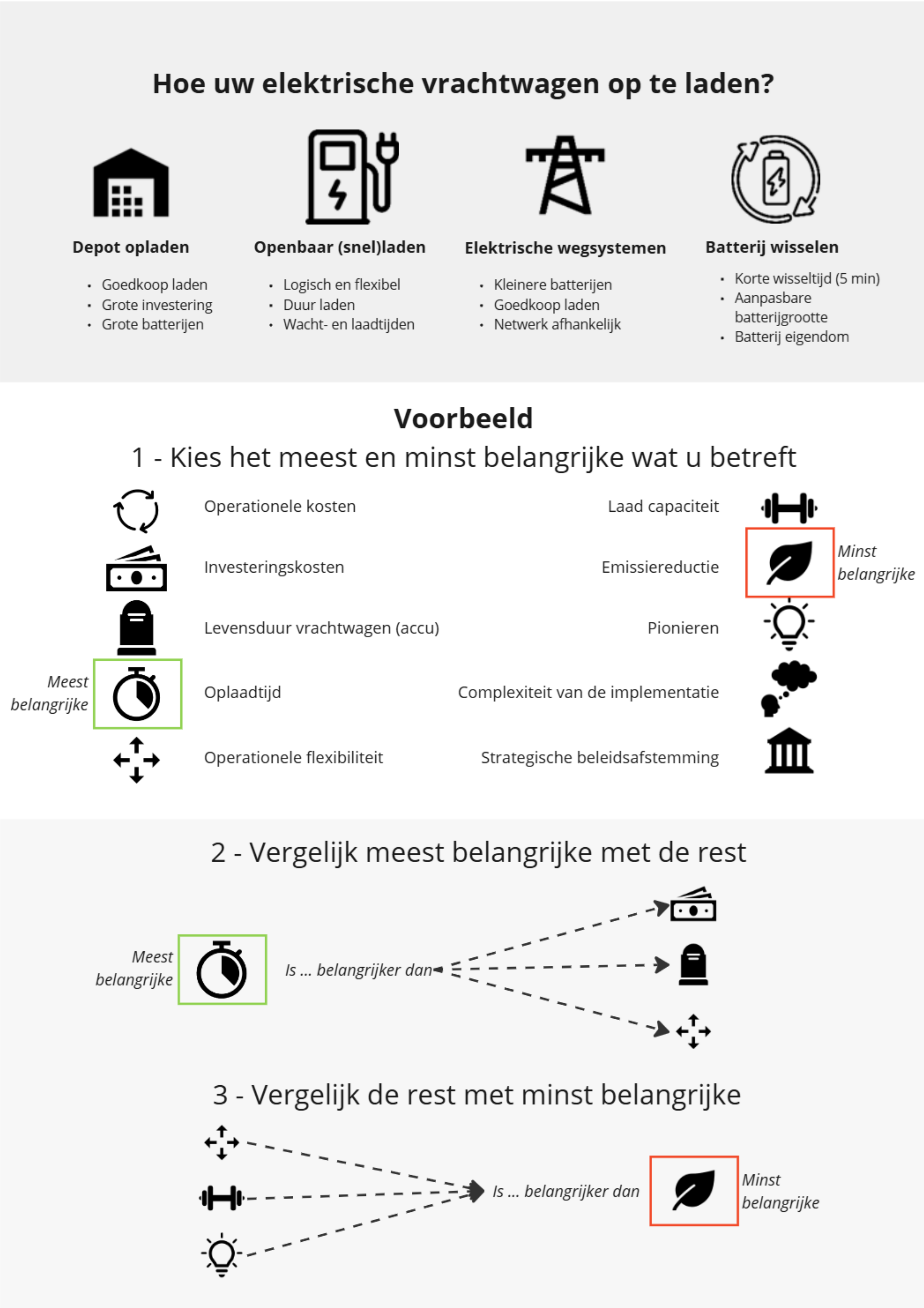
Microsoft Forms

B.3. Info-graphics for survey


How to charge your E-truck?
Depot (overnight) charging
Cheap charging
Large investment
Large batteries
Public (fast) charging
Straightforward and flexible
Expensive charging
Waiting and charging time
Electric Road System
Smaller batteries
Cheap charging
Network dependent
Battery swapping
Short swap time(5 min)
Adaptable battery size
Battery ownership
Example
1 - Choose what you think is most and least important
Operational cost
Investment cost
Truck (battery) lifetime
Most important
Charging time
Operational flexibility
Payload capacity
Emission reduction
Least important
Pioneering
Complexity of implementation
Strategic policy alignment
2 - Compare most important to the rest
Most important
Is ... more important than ...
3 - Compare the rest to least important
Is ... more important than
Least important


Hoe uw elektrische vrachtwagen op te laden?
Depot opladen
Goedkoop laden
Grote investering
Grote batterijen
Openbaar (snel)laden
Logisch en flexibel
Duur laden
Wacht- en laadtijden
Elektrische wegsystemen
Kleinere batterijen
Goedkoop laden
Netwerk afhankelijk
Batterij wisselen
Korte wisseltijd (5 min)
Aanpasbare batterijgrootte
Batterij eigendom
Voorbeeld
1 - Kies het meest en minst belangrijke wat u betreft
Operationele kosten
Investeringskosten
Levensduur vrachtwagen (accu)
Meest belangrijke
Oplaadtijd
Operationele flexibiliteit
Laad capaciteit
Emissiereductie
Minst belangrijke
Pionieren
Complexiteit van de implementatie
Strategische beleidsafstemming
2 - Vergelijk meest belangrijke met de rest
Meest belangrijke
Is ... belangrijker dan
3 - Vergelijk de rest met minst belangrijke
Is ... belangrijker dan
Minst belangrijke

B.4. The survey format for criteria weighing

Charging alternatives preferences

There are two parts of the survey. First we ask you what role you have in the market. If you selected 'freight carrier' we will ask some general questions on which type of freight carrier you are. Lastly we ask you to give the importance of choice-aspects in a few questions.

Before you start:
Please watch this short video (5 minutes) to get the necessary context of the survey and how to fill it in:
https://youtu.be/nhxPUNSFQD4

* Required

General question - Role

1. What role do you have in the transport market/field? *

- ◯ Freight carrier
- ◯ Academic/research company
- ◯ Original Equipment Manufacturer
- ◯ Charging point operator
- ◯ Government/institution
- ◯ Logistic service provider/transport association
- ◯ Other

2. Do you have any comments on your answer?

General questions - company

This part of the study includes a few general questions on your company.

3. What is your main transport sector? *

- ◯ Forestry
- ◯ Regional distribution(food or products)
- ◯ Mining/construction
- ◯ Waste collection/distribution or recycling
- ◯ National long and line-haul
- ◯ International trailer transport
- ◯ Other

4. In what country are you operating? *

- ◯ Sweden
- ◯ The Netherlands
- ◯ Other

5. How many trucks are in your fleet? *

6. Do you have any electric trucks in your fleet today? *

- ◯ Yes
- ◯ No
- ◯ Interested in buying them
- ◯ Other

7. Which employees do the planning of the transport assignments? *

This includes accepting the transport assignments and assigning them to trucks and drivers. Also includes the route assignments if multiple trips are performed on one journey.

- ◯ The truck drivers
- ◯ Transport operation manager or management team
- ◯ Other

General questions - operations

In this section we ask you some general questions on your operations for a typical day. If there is a lot of variation in your operations, please give an average and name that there is a lot of variation in a comment.

9. How many kilometers do your trucks drive on a normal day? *

Average value for an individual truck. A day is considered 24 hours, as night shifts are also included.

10. When does an individual truck drive it's shifts? *

Can also be interpreted as: what periods of the day are your trucks being used?

- ◯ Only daytime (single shifts)
- ◯ Day and nighttime (double shifts)
- ◯ Both (single and double shifts)
- ◯ Other

11. How many trips does an individual truck drive on a day on average? *

This includes all the trips that have a start and destination. So for example: Depot -> factory -> distribution center -> customer -> depot, includes 4 trips.

12. What percentage of your kilometers is on highways? *

If you have no exact data please give an estimation or a number of kilometers per day

13. When do you know the route(s)/assignment(s) for the next day? *

- ◯ Always the same route
- ◯ Week before or earlier
- ◯ Day before
- ◯ Same day
- ◯ Changes through the day
- ◯ Other

14. What is the usual weight of your operations? (optional)

Most important aspect

In this section we ask you to choose what you consider the most important aspect when deciding for a charging alternative. Next to that, we ask you to compare the importance of your choice to the other aspects.

16. What would you consider the most important aspect when choosing a charging alternative? *

The biggest difference between the alternatives is given to get an idea of the effect the alternatives have on the aspect.

Some extra explanation on the charging time difference: For a truck that drives 600 km for a trip, the best alternative would allow the truck to arrive one hour earlier than the worst alternative, with regulatory drive and rest times considered.

- ◯ Operational costs - charging, maintenance and infrastructure fees (around 0.4 EUR/km max difference between the alternatives)
- ◯ Investments costs - battery, vehicle and self-owned infrastructure (around 115 000 EUR max difference between the alternatives)
- ◯ Truck (battery) lifetime - years fit for operation (around 2 years max difference between the alternatives)
- ◯ Charging time - downtime necessary during the 4,5 hour shifts (Around 1 hour per 600 km max difference between the alternatives)
- ◯ Operational flexibility - possibility to do different operations on short notice
- ◯ Payload capacity - (around 5 ton max difference between the alternatives)
- ◯ Emission reduction - mainly battery size dependent (around 50 g CO_2eq/km max difference between the alternatives)
- ◯ Pioneering - high potential but less proof of use
- ◯ Complexity of implementation compared to diesel - complexity of operating the truck for the driver
- ◯ Strategic policy alignment - government policies are designed to align with the alternative

17. How do you see your most important aspect(answer to previous question) compared to the other aspects? *

Pay attention! This method is slightly different than you might be used to in other surveys. Watch the video (https://youtu.be/nhxPUNSFQD4) for the explanation.

Short explanation: always fill in *1-equally important* at the aspect which was your most important aspect in the previous question, as you compare it with itself. For example: Operational cost as most important aspect is *1-equally important* as itself but the Operational cost might be *Strongly more important* than the Payload capacity, so then fill in *4-Strongly more important* at Payload capacity.

Summarized: <your previous answer> is ... more important than <the entry in the table>.

	1- Equally important	2- Moderately more important	3- Significantly more important	4-Strongly more important	5-Very strongly more important	6-Extremely more important	7-Absolutely more important
Operational costs	○	○	○	○	○	○	○
Investment costs	○	○	○	○	○	○	○
Truck (battery) lifetime	○	○	○	○	○	○	○
Charging time	○	○	○	○	○	○	○
Operational flexibility	○	○	○	○	○	○	○
Payload capacity	○	○	○	○	○	○	○
Emission reduction	○	○	○	○	○	○	○
Pioneering	○	○	○	○	○	○	○
Complexity of implementation compared to diesel	○	○	○	○	○	○	○
Strategic policy alignment	○	○	○	○	○	○	○

18. Do you have any comments on your answers?

Least important aspect

In this section we ask you to choose what you consider the least important aspect when deciding for a charging alternative. Next to that, we ask you to compare the importance of the other aspects to your choice.

19. What would you consider the least important aspect when choosing a charging alternative? *

The biggest difference between the alternatives is given to get an idea of the effect the alternatives have on the aspect.

Some extra explanation on the charging time difference: For a truck that drives 600 km for a trip, the best alternative would allow the truck to arrive one hour earlier than the worst alternative, with regulatory drive and rest times considered.

- ◯ Operational costs - charging, maintenance and infrastructure fees (around 0.4 EUR/km max difference between the alternatives)
- ◯ Investments costs - battery, vehicle and self-owned infrastructure (around 115 000 EUR max difference between the alternatives)
- ◯ Truck (battery) lifetime - years fit for operation (around 2 years max difference between the alternatives)
- ◯ Charging time - downtime necessary during the 4,5 hour shifts (Around 1 hour per 600 km max difference between the alternatives)
- ◯ Operational flexibility - possibility to do different operations on short notice
- ◯ Payload capacity - (around 5 ton max difference between the alternatives)
- ◯ Emission reduction - mainly battery size dependent (around 50 g CO2eq/km max difference between the alternatives)
- ◯ Pioneering - high potential but less proof of use
- ◯ Complexity of implementation compared to diesel - complexity of operating the truck for the driver
- ◯ Strategic policy alignment - government policies are designed to align with the alternative

20. How do you see the other aspects compared to your least important aspect(answer to previous question)? *

Pay attention! This method is slightly different than you might be used to in other surveys. Watch the video (https://youtu.be/nhxPUNSFQD4) for the explanation.

Short explanation: always fill in *1-equally important* at the aspect which was your least important aspect in the previous question, as you compare it with itself. For example: Pioneering as least important aspect is *1-equally important* as itself. But another aspect such as Payload capacity might be *Strongly more important* than Pioneering, so then fill in *4-Strongly more important* at Payload capacity.

Summarized: <the entry in the table> is ... more important than <your previous answer> .

	1- Equally important	2- Moderately more important	3- Significantly more important	4-Strongly more important	5-Very strongly more important	6-Extremely more important	7-Absolutely more important
Operational costs	◯	◯	◯	◯	◯	◯	◯
Investment costs	◯	◯	◯	◯	◯	◯	◯
Truck (battery) lifetime	◯	◯	◯	◯	◯	◯	◯
Charging time	◯	◯	◯	◯	◯	◯	◯
Operational flexibility	◯	◯	◯	◯	◯	◯	◯
Payload capacity	◯	◯	◯	◯	◯	◯	◯
Emission reduction	◯	◯	◯	◯	◯	◯	◯
Pioneering	◯	◯	◯	◯	◯	◯	◯
Complexity of implementation compared to diesel	◯	◯	◯	◯	◯	◯	◯
Strategic policy alignment	◯	◯	◯	◯	◯	◯	◯

21. Do you have any comments on your answers?

End of the survey

Thank you very much for filling in this survey!

22. Which charging alternative would you choose for your electric trucks after filling in this survey? *

- ◯ Depot charging
- ◯ On the road public (fast) charging
- ◯ Electric Road Systems
- ◯ Battery swapping

23. Contact details *

Please leave some contact details below for clarification purposes and to receive the result of the study. The results in the study will be anonymized, so your name will never be published in the results. Also, your participation to the study will never be published.