An optimization approach for sustainable logistics

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Abstract

A development that considers the economy, together with environmental concerns has been increasingly adopted in order that a more sustainable future is secured for those ahead of us.

In this project, sustainable development is directly related to the researched problem. As the incorporation of alternatively fuelled vehicles is a step forward in the reduction of the harmful externalities, to the environment and the society, generated by transportation activities within supply chains. As a result, the project concerns the development and implementation of a location routing problem, that comprises the routing optimization regarding a fleet of electric trucks and the potential siting of recharging infrastructure. This model will also include, in its objective function, two of the three sustainable development pillars.

In addition, this project is based on the operations of a Portuguese retailer group that still serves its stores using diesel trucks. The model assesses, as a consequence, the feasibility of the transition from a diesel-truck based operation into an e-truck based one. This, considering real-life based parameters from the retailer's operations and other parameters from the existing literature that compares e-truck and diesel-truck operations. And, according to the results, this transition is feasible, considering the economic and environmental dimensions. This is because the higher upfront investment associated with e-trucks is compensated with lower maintenance and energy costs along with less emissions.

Keywords: Sustainable development, location routing problem, urban logistics, optimization, electric vehicles

Resumo

Um desenvolvimento que considera a economia juntamente com questões ambientais tem vindo a ser cada vez mais uma preocupação, por forma a garantir um futuro mais sustentável para as gerações vindouras.

Nesta dissertação, o desenvolvimento sustentável está diretamente relacionado com o problema em estudo. Uma vez que a utilização de veículos mais verdes permite a redução das externalidades negativas ao ambiente e sociedade resultantes das atividades de transporte nas cadeias de abastecimento. Como resultado, o projeto aborda o desenvolvimento e a implementação de um problema de localização e de rotas, que inclui a otimização das rotas de uma frota de camiões elétricos e a possível localização da infraestrutura de recarga. Este modelo incluirá também, na sua função objetivo, dois pilares do desenvolvimento sustentável.

Além disso, este projeto baseia-se nas operações de um grupo retalhista português que ainda abastece as suas lojas através de camiões diesel. Assim, o modelo avalia a viabilidade da transição de uma operação com camiões diesel para uma baseada em camiões elétricos. Tal, tendo em conta parâmetros baseados em dados reais das operações do retalhista e outros parâmetros baseados na literatura existente e, que comparam as operações de camiões elétricos e camiões diesel. Por fim, de acordo com os resultados, esta transição é viável tanto na dimensão económica como na ambiental. Isto, uma vez que o investimento inicial mais elevado associado aos camiões elétricos é compensado por custos de manutenção e energia mais baixos, juntamente com menores emissões.

Palavras-chave: Desenvolvimento sustentável, problema de localização e de rotas, logística urbana, otimização, veículos elétricos

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List of abbreviations

CO$_2$: Carbon Dioxide

DC: Distribution Center

DJSI: Dow Jones Sustainability Index

EC: European Commission

ECV: Electric Commercial Vehicle

EU: European Union

EV: Electric Vehicle

FCEV: Fuel-cell Electric Vehicle

FREVUE: Freight Electric Vehicles in Urban Europe

GHG: Greenhouse Gas

GSCM: Green Supply Chain Management

ICE: Internal Combustion Engine

LCA: Life Cycle Assessment

LCV: Light Commercial Vehicle

LRP: Location Routing Problem

MILP: Mixed Integer Linear Programming

MIP: Mixed Integer Programming

PHEV: Plug-in Hybrid Electric Vehicle

SC: Supply Chain

SD: Sustainable Development

SSC: Supply Chain Management

SSCM: Sustainable Supply Chain Management

TBL: Triple Bottom Line

TCO: Total Cost of Ownership

USA: United States of America

ZEZ: Zero Emission Zone

1. Introduction

In 1987, sustainable development was defined, by the World Commission on Environment and Development (WCED, 1987), as the "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Over the recent years, governments, organizations and the society have been shifting their views so that a sustainable development (SD) is effectively the path being tracked. It is based on the respect for the three sustainability pillars, represented by the triple bottom line (TBL), (Roca & Searcy, 2012). Only when the different policies respect and follow the three pillars at once, economic, environmental and social, it is possible to prevent harming those ahead of our generation. Governments and organizations are, therefore, under pressure to increasingly incorporate sustainable policies. Among them, transportation represents a fundamental economic aspect, as it greatly impacts the society through the movement of goods throughout complex supply chains, impacting everyone's daily lives.

Thus, this dissertation aims to promote a more sustainable transportation system, where not only the economic aspect is considered, but also the environmental one. However, the environmental aspect still has a long path towards sustainability, as road freight transport currently represents as much as 9% of the global greenhouse gases (GHGs) emissions, (Shell, 2021). Additionally, social impacts, especially for those living and working in densely populated urban areas, are also of great importance as pollution and congestion greatly impact the health and well-being of the population.

Furthermore, important targets were set by the UN (UN, 2023), so that practices change, towards SD. 17 goals were defined and the project is closely related with 3 of them, the 3rd, the 9th and the 11th, as they aim to promote a greener mobility, and directly impacting sustainability and climate change. Greener transportation means will especially impact urban areas, turning them increasingly pleasant to their inhabitants, workers and visitors. The goals are directly related to the project as they regard a more sustainable transportation and the necessary infrastructure to enable it. These are the 3rd – "good health and well-being", the 11th – "sustainable cities and communities" and the 9th – "industry, innovation and infrastructure". These objectives, if achieved, mean that substantial improvements on the necessary infrastructure have to be performed, in order that a feasible eco-friendlier transportation is enabled. Moreover, if greener transportation is more and more adopted, it will also benefit the health and well-being of the society, especially those living and/or working in cities, which are greatly affected by pollution.

1.1. An Evolving Mobility

As a consequence of this global shift towards sustainability, mobility has dramatically changed over the years. Recently, its transformation is once again on the global agenda, as societies strive for mobility that impacts less the people and the planet. The introduction, in the early 1900's, of Internal Combustion

Engine (ICE) vehicles, was of vital importance for the economy as it led to more economic output, due to the exchange of goods within countries and among them. However, the widespread usage of vehicles has downsides, for instance, the constant congestion in urban areas, increased pollution and reduced space for walking or cycling around the cities. Despite being in many ways harmful to our society, mass transportation remains of major importance. Hence, minimizing the damage created by the broad usage of polluting vehicles is a priority.

Cleaner technologies have been developed throughout the years to tackle the pollution's problem, for example, fully electric vehicles (Evs) with electricity stored in batteries; plug-in hybrid vehicles (PHEVs), which run either on electric mode, like a fully EV does, or by using diesel-powered ICE. Gas-powered solutions are also under usage and might be an option, to power vehicles, as they release significantly less pollutants. Lastly, fuel-cell electric vehicles (FCEVs), powered by hydrogen, might be a future solution, especially for long-haul transportation.

In the following sub-sections, it will be discussed the main driver for mobility evolution and, consequently for the uptake of greener means for freight transportation, which is the regulatory environment. Governments are doing so due to the high pollution levels, especially in urban areas, where the increasing last-mile deliveries. Lastly, the eco-friendlier vehicles, as they become more efficient and less expensive, may present themselves as feasible and cost-effective solutions for greener transportation, so that companies are able comply with the stricter regulations.

1.1.1. Regulatory Environment

As stated by (Furnari et al., 2020), "the regulatory push to reduce emissions is driving the interest in e-Trucks (Electric Trucks) upwards across the transports' sector". This push is being undertaken, for instance, by the European Union (EU), where carbon dioxide (CO_2) emissions, in newly built trucks, are required to be reduced by 30%, as of 2030, (European Commision, 2021).

California is another example, as it legislated that, by 2025, all automakers must offer a fully electric model and, by 2045, only e-Trucks will be allowed to be sold in the state. These stricter legislations will likely reduce the interest in ICE trucks and increase it for e-trucks. This will lower impacts deriving from the trucks' circulation across the countries imposing these stricter regulations.

Efforts to increment cleaner vehicles' usage are also being carried out by major cities all around the globe. Over 40 cities around the world banned diesel and gasoline ICE trucks in their city centers (Furnari et al., 2020). Reducing these harmful emissions will also prevent early deaths directly related to pollution. In order that these damaging impacts are reduced, it becomes crucial to increase the usage of cleaner mobility means. Hence, it is of major importance, in this project's context, the introduction of environmentally friendly vehicles for goods' distribution within cities.

Governmental incentives are another measure to increase greener mobility means uptake. They are awarded to those buying eco-friendlier options rather than ICE powered ones. This measure enables

Total Cost of Ownership (TCO) parity among options as the overall costs throughout the life span of eco-friendlier solutions become equivalent when compared to the costs of owning an ICE vehicle of the same segment.

Although price reductions have occurred in recent years, many eco-friendly options are still highly expensive. Thus, several manufactures offer not only ICE powered cars or fully electric versions, but also plug-in hybrid options are available on the market. PHEVs, as stated by (Forbes, 2021a), could work as a bridge to fully electric cars, by accelerating their adoption. The adoption might even happen if the TCO equivalency is not met, since PHEVs solutions can be used on urban areas where zero-emission zones exist.

1.1.2. Eco-Friendly Vehicles

At first, governments promoted more efficient ICE vehicles, in order to reduce their emissions, but then it became clear that more had to be done, (European Environment Agency, 2013). As a consequence, the push for other technologies like the referred electric, hybrid, gas and hydrogen powered vehicles have been rapidly growing throughout recent years.

Furthermore, these vehicles, even though operational constraints persist, are now more capable of fulfilling different customers' needs and, as a result, the public acceptance has been growing. From the several options that were referred, Evs will be the focus of this dissertation as it will be assessed whether or not these options allow to run a profitable operation. Such will be done by assessing whether or not the e-trucks' TCO is comparable to their conventional counterparts, for daily transportation and distribution in well-planned urban routes for medium-duty trucks. However, difficulties in the batteries' capacity are still a major obstacle. Factors like the long charging times and a reduced coverage of the existing grid also prevent, especially, heavy-duty trucks to cope with long distances, (Alarcón et al., 2023a). Hence, it is especially challenging to integrate e-Trucks on interregional and international journeys and, therefore, it becomes difficult to have reliable and profitable operations on such terms.

The European market is set to be the first, among the major economic blocs, to achieve, for the different segments, TCO parity and might achieve it, for several vehicle types, within the next decade. As explained by Deloitte, (Nallusamy et al., 2016), policy changes, like circulation restrictions for some vehicles and financial incentives will pave the way for fleets' electrification, especially in cities. For instance, in a ten-year period, e-trucks are set to reach between 10% and a third of the entire market, depending on how strict legislation becomes. The inflection point, in the distribution sector, when the introduction of Evs becomes systematic and accelerated, is set to be around 2025.

Nowadays, the problems related to the energy storage and recharging, for those carriers that have predictable routes throughout the year, do not represent a major concern already. Conversely, for vans and trucks performing transportation services that change in a regular basis, it might prove difficult to manage operations in a feasible and cost-effective way. Hence, the introduction of electric trucks is likelier to occur, initially, in carriers operating predictable routes. Chargers represent another difficulty requiring further investment from companies, (McKinsey & Company, 2021). Conventional charging solutions are not evenly distributed around both urban areas and interregional routes and, therefore, feasibility is impacted, especially for vehicles being driven for an entire shift.

Another obstacle to be tackled is the lengthy recharging process, since in order to be charged rapidly, it is required fast-charging solutions. These solutions, if placed in service stations or accessible in the warehouses where trucks and vans load and/or unload, would represent a more cost-effective option and it would help to solve the feasibility problem. Charging the vehicle overnight, when the driver is resting and amid journeys or when goods are being loaded or unloaded, would enable the usage of these trucks for an entire shift. This would promote the adoption of greener solutions and, at the same time, reduce the necessary upfront costs as smaller batteries would also be feasible in this context.

1.2. Objectives

The main objective of this dissertation is to develop a mathematical optimization model aimed at constituting a decision support tool on assessing:

- the economic and environmental feasibility of the transition from diesel-based distribution operations into e-truck based ones;
- if the operations are negatively impacted by the transition
- if recharging stations need to be placed and, if so, where.

Furthermore, it should ensure that demand is met considering the operational constraints posed by the transition. The developed model is then to be applied based on the case-study developed by (Figueiredo, 2009), on the distribution of a Portuguese retailer, from its depot into its stores, which is still based on diesel-trucks. Thus, the objectives of the dissertation are:

- Develop a contextualization of the main topics covered by the dissertation as well as the motivation to develop the present work, which means the reason why these different aspects have the importance in our society to be covered. It is also outlined the goal of the dissertation, meaning what the developed work aims to respond and contribute to;
- Perform a literature review on the main subjects related to the project and also define the relevant concepts as well as identify the most adequate methodologies to address the problem. It is aimed to understand the problematics being addressed and to understand the challenges faced when integrating greener distribution means.
- To formulate a generic optimization model that assesses the feasibility of the transition, whilst the operational set-up is not compromised and still delivers the retailer’s goods on time;
- To present the base case in which this dissertation is based along with the literature that enabled to fill the existing gaps on the required parameters to run the model and simulate the distribution process with e-trucks;

- To apply the developed model and critically analyze the results, also by performing a sensitivity analysis to the critical parameters to test the feasibility of the results and, lastly, identify a possible set of improvements.

1.3. Project Structure

The dissertation is structured into seven chapters, all of which begin with a description of how they are organized and the content presented. Additionally, all chapters close with a concluding section in which the topics to be retained are summarized. The seven chapters are outlined as follows:

- **Chapter 1 – Introduction**
  This first step of the project corresponds to its introduction. The characterization of the environment on which this problematic arose, and its importance in today's society, along with the definition of the problem addressed in this project. It also includes the presentation of the objectives and structure of the work.
- **Chapter 2 – Problem characterization**
  In this step, after having defined what was the problem and characterized its context, it is performed the characterization of the existing main options to solve it and, from those options, the identification of the one, ECVs' integration in urban logistics, to be further studied. It was also identified the mains features as well as limitations that ECVs present.
- **Chapter 3 – Literature review and methodology selection**
  In the third step, a literature review was performed on the relevant topics concerning the dissertation. Research was focused on topics such as SSC, logistic operations and the distribution of goods, especially focusing on Evs, and the LRP, which will be the problem to be resolved. This problem is a matter of interest due to the identification of research gaps in this field.
- **Chapter 4 – Problem Statement and model formulation**
  This chapter provides a detailed description of the problem, a list of the decisions and assumptions that were considered, and an outline of the performance metrics that will be used to analyze the model's output. This step will then present the formulation of the mathematical model. It will be based on the base case-study used for this dissertation along with mathematical models present in the literature, which were adapted to the specific problem in hands. Afterwards, the mathematical formulation was implemented in GAMS software.
- **Chapter 5 – Case-study and data collection**
  In the fifth step, the collection and treatment of relevant data will be performed. Specifically, the constitution of the model sets is defined and the values adopted for the parameters are presented. It will also be presented the base case-study and why it was considered to be relevant for the model application. The gathered data will be, then, included into the model in order to obtain relevant experimental results. This, in order to validate the model through computational experiments.

- **Chapter 6 – Analysis on the results and conclusions**

  This is the chapter devoted to the presentation and discussion of the results, as the obtained data is subject to a critical analysis and compared to other data present in the literature and the one returned by the base case. This, in order to understand if the transition towards an e-truck based operation is feasible and what are the impacts in the different pillars of SD. A sensitivity analysis was also carried out to understand to which extent the transition might be affected by the variation of the main drivers, in economic and environmental terms.

- **Chapter 7 – Conclusions and future research**

  In the final chapter of the dissertation, the key findings are summarized. It also includes proposals for future research to further improve the presented model, in order that it becomes closer to real-life scenarios.

2. Companies in a changing world

This chapter presents a comprehensive overview on the distribution and transportation sector. It is aimed to identify the most relevant factors impacting the decision tool to be implemented. Its importance is based on the fact that, even though major improvements in efficiency occurred, road-based freight transport still releases a massive amount of GHGs. Thus, it represents a major air pollution driver, being responsible for around 20% of the CO_2 emissions, the main GHG, in the EU member states, as well as being a major contributor to the existing urban traffic congestion, (Eurostat, 2022). The analysis performed in this project is therefore of major importance, as one of the solutions to this problematic is the broad usage of greener mobility means. Another objective is to understand the needs, the interests and concerns, in this transformation, for the different stakeholders.

This analysis will focus on urban environment operations. Throughout the following sections, it will be presented the challenges and opportunities that companies have when operating in cities, along with the comparison among the different energy sources and the means by which they are stored. Moreover, it is also referred the advantages and disadvantages the different vehicle types present to the drivers and to the companies operating them. Projects implemented by international corporations and it is presented what their plans are to further incorporate more sustainable solutions. The existing differences and challenges in these markets will also be analyzed, as well as an overview on the Portuguese case. Lastly, the relevant aspects on the relations among key stakeholders are summarized.

2.1. Evolving environment

In order that harmful impacts, resulting from intensive road-based freight transport, are reduced, the EC ordered automakers to severely reduce harmful pollutants' emissions from their newly built commercial vehicles, as these emissions are still growing due to a rising transportation. In order to reduce these impacts, fleets, within EU, have to turn greener over time. A 15% decrease, between 2025 and 2030, on the average CO_2 emissions from the produced vehicles when compared to the emissions recorded in comparable vehicles during 2019 and 2020, is demanded.

From 2030 on, it is mandatory a 31% reduction for Light Commercial Vehicles (LCVs), weighting less than 3,5 tons, and a 30% decrease on heavier vehicles, (European Commission, 2021-a). Moreover, from 2025 on, several European cities will only allow, in the city centers, vehicles with no local emissions, the Zero Emission Zones (ZEZs), or require companies and individuals to pay a fee whenever they enter restricted areas (FREVUE, 2017).

Lastly, as also stated by the EU, (European Commission, 2021-c), especially, the 2030 target will require further disruptive developments to comply with the regulations. These developments will demand substantial investments from both public and private organizations, (FCA, 2020), complicating these vehicles' uptake.

Moreover, as previously mentioned, several alternatives are already in place. Besides Evs and PHEVs, which use batteries to store the energy, other technologies of storing energy friendlier to the environment exist. One fuel already under usage, which powers 0,4% of the trucks currently sold in the EU, is the methane, as a fossil fuel, the natural gas, or as a renewable gas, the biogas, this according to (European Automobile Manufacturers' Association, 2023). Whereas e-trucks represent 0,6% of the new vehicles sold in 2022. The referred hydrogen is another possibility, but only suitable for future applications. These technologies will be further analyzed in this chapter.

2.1.1. Automakers' green solutions

Firstly, it is presented the advantages and disadvantages that the referred options created in order to lower the transportation sector's emissions, which are summarized in Table 1. This, in accordance with the different reports and articles developed by official institutions as well as research articles and reviews present on the literature.

The different aspects, resulting from my research, will be thoroughly explained throughout the following sections. Furthermore, the table's explanation on why the option for urban logistics is either for Evs or a PHEVs, which will be analyzed throughout the following sections, (Ministério da Economia, 2017).

Table 1: Comparison among greener alternatives

	Natural Gas and Bioagas	Hydrogen (FCEV)	Fully-electric Vehicles	Plug-in Hybrid Vehicles
Automakers:	**FCA (IVECO)** **Volvo trucks**	**Daimler** **DAF**	**Volvo Trucks Renault Rivian** **Grupo Volkswagen PSA** **Daimler Trucks (USA and Europe)**	
Long-haul	✓	✓	✗	✓
TCO parity	✓	✗	✓	✓
ZEZs	✗	✓	✓	✓
Suitable recharging / refueling grids	✗	✗	✗	✓
Governmental Incentives	✓	✓	✓	✓
Observations:	If biogas is used, overall CO_2 emissions are close to zero, however local emissions in cities persist	Fuel-cells and hydrogen are still expensive Hydrogen, especially, the green one, is still scarce and difficult to be produced, stored and distributed	Long-haul prototypes were already tested, but are still not feasible in many cases (apart from well-planed routes) TCO parity only for light and medium duty	Long-haul and high payload transportation are not decarbonized Recharging grid outside urban areas is not a problematic

In Table 1, it is possible to notice that both gas and hydrogen powered vehicles are not suitable solutions to turn urban logistics greener in the near future, but for different reasons. Firstly, some insights on the methane powered ICE vehicles will be given. This technology will not be thoroughly explored in this project since, unlike EVs and PHEVs, and as it can be seen in Table 1, it cannot be used if ZEZs exist in the area being served. However, it will be briefly presented due to its importance in the process of decarbonizing long-haul transportation. These ICE vehicles are being used nowadays due to their reduced emissions, in both tank-to-wheel and well-to-tank assessments, when compared to the diesel-powered counterparts, (Volvo Trucks, 2019).

Between natural gas and biogas, the major difference regards their origin. Biogas, unlike natural gas, is not a fossil fuel. Thereby, vehicles using biogas present a lower impact when the Life Cycle Assessment (LCA) is considered. Biogas is a greener source of energy since it is renewable and an overall 95% cut on CO_2 emissions is possible. These vehicles also allow a major reduction in both noise levels and other harmful emissions, for instance, particulate matter and nitrogen oxides, when compared to similar diesel engines. Iveco and Volvo both present LNG (Liquified Natural Gas) trucks, with Iveco also presenting a model using compressed natural gas. Volvo claims its solution reduces emissions by 20% in comparison to an equivalent diesel version. Moreover, both automakers state that this technology allows similar performance and range, when compared to diesel trucks, making this a suitable option for long-haul transportation, which combined with lower fuel prices and lower fuel consumptions, gas powered trucks enable a lower TCO, as well. The lack of widespread infrastructure for refueling causes major operational constraints and, therefore, poses a great restriction to this technology's uptake, (IVECO, 2017).

FCEVs use fuel-cells powered by hydrogen and are another possible sustainable solution. However, this technology is only sustainable if the hydrogen used is the green one, i.e., produced using renewable energy and obtained from water electrolysis. The produced electricity is then used to power an electric engine (DAF, 2020). This technology is believed to be a future solution for both long-haul transportation and urban logistics, as it does not produce local impacts. Thus, several brands have been investing in its development. Daimler, for instance, has recently presented a hydrogen-powered truck, which uses liquid hydrogen, due to “a far higher energy density in relation to volume than gaseous hydrogen” and, therefore, the range significantly increases, (Daimler, 2020-b).

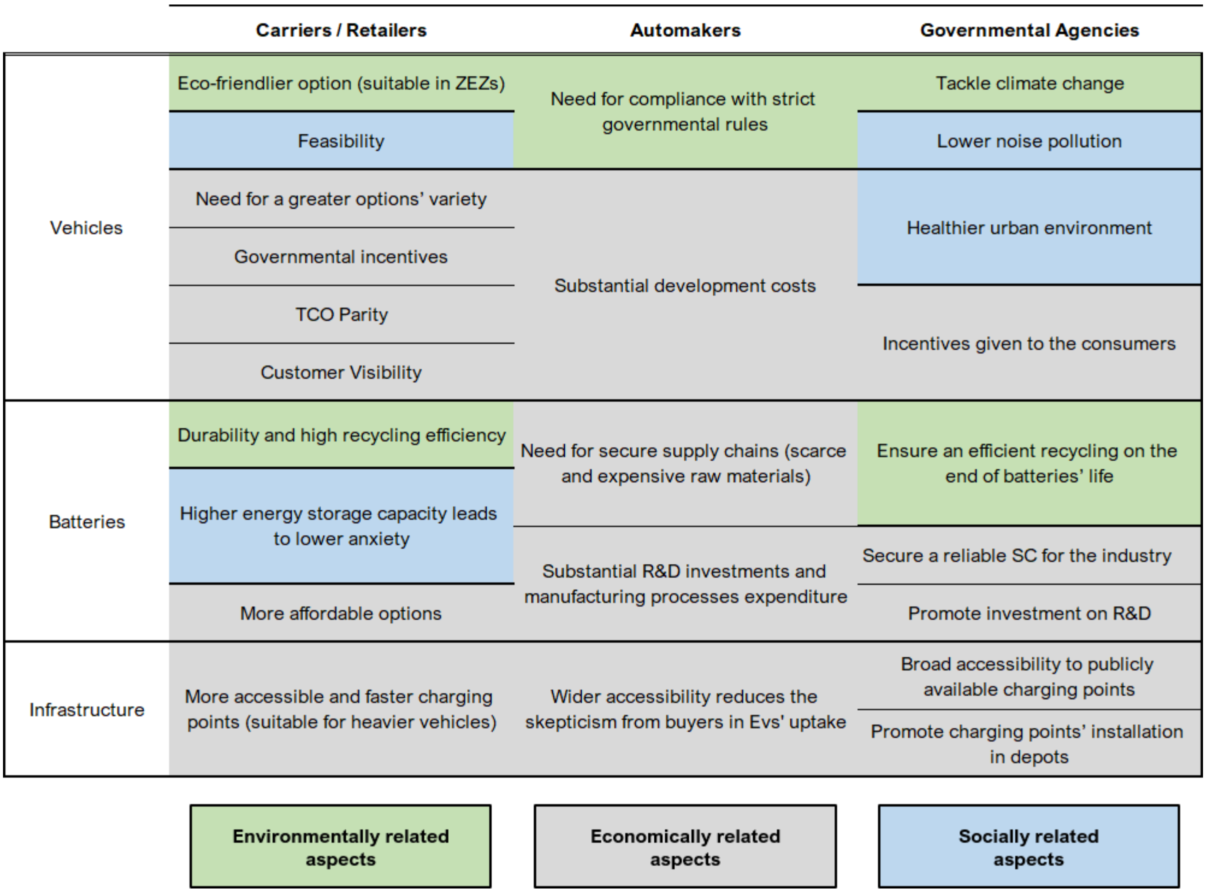
Moreover, Daimler has already completed millions of kilometers around the globe to test the technology, learning that it was quite similar, in terms of its features, when compared to a similar diesel truck. This turns it suitable for multi-day, difficult to plan long-haul transportation, (Daimler, 2020). However, as a DAF report refers, it is still not possible to mass produce FCEVs, due to the extremely low temperatures and high pressures required for hydrogen storage. Hydrogen is also still scarce and, consequently, so it is its distribution network. Thus, this is not a cost-competitive solution for now. DAF believes that only in a 5 to 10-year period, this technology will be available to the public, (DAF, 2020). In fact, SCANIA, another important automaker, has discarded fuel-cell electric trucks' projects in favor of electric solutions, which are, to the company, feasible, more energy-efficient and less expensive solutions, (Forbes, 2021b).

2.1.2. The Electrified options

As referred, the most explored solutions in this project will be both Evs and PHEVs. The objective is to understand what are, in real world conditions, their capabilities as well as the future expectations for these solutions. Table 2, likewise Table 1, summarizes the research performed on relevant literature sources and refers what are, according to the authors, the main advantages and disadvantages in the economic, environmental and social pillars that the different aspects represent, when electrifying fleets, to key stakeholders. These aspects will be explored along with some examples for the brands producing these vehicles, the models on the market and the features presented, especially those concerning urban distribution, (Nallusamy et al., 2016).

As represented in Table 1, a great advantage favoring both Evs and PHEVs, in urban environments, regards its suitability for ZEZs. Furthermore, as Table 2 refers, these operations are even possible at a similar TCO, when compared to an equivalent diesel solution. A factor contributing to TCO reduction, in Evs and PHEVs, is the cost for batteries, which has significantly dropped, for instance, in a ten-year period, the cost per kilowatt-hour represents only 13% of what it was a decade ago. Thus, automakers such as Daimler, MAN and Volvo are developing, and offering, the market with eco-friendlier trucks, as the interest for them has grown, (World Economic Forum, 2020).

Table 2: Advantages and disadvantages that Evs present to the different stakeholders



	Carriers / Retailers	Automakers	Governmental Agencies
Vehicles	🟩 Eco-friendlier option (suitable in ZEZs)	🟩 Need for compliance with strict governmental rules	🟩 Tackle climate change
	🟦 Feasibility		🟦 Lower noise pollution
	⬜ Need for a greater options' variety	⬜ Substantial development costs	🟦 Healthier urban environment
	⬜ Governmental incentives		
	⬜ TCO Parity		⬜ Incentives given to the consumers
	⬜ Customer Visibility		
Batteries	🟩 Durability and high recycling efficiency	⬜ Need for secure supply chains (scarce and expensive raw materials)	🟩 Ensure an efficient recycling on the end of batteries' life
	🟦 Higher energy storage capacity leads to lower anxiety	⬜ Substantial R&D investments and manufacturing processes expenditure	⬜ Secure a reliable SC for the industry
	⬜ More affordable options		⬜ Promote investment on R&D
Infrastructure	⬜ More accessible and faster charging points (suitable for heavier vehicles)	⬜ Wider accessibility reduces the skepticism from buyers in Evs' uptake	⬜ Broad accessibility to publicly available charging points
			⬜ Promote charging points' installation in depots

🟩 **Environmentally related aspects**

⬜ **Economically related aspects**

🟦 **Socially related aspects**

Although many advantages exist, a major downside restricts the uptake of more environmentally friendly options, which is the unsatisfactory charging grid. Otherwise, the operations with Evs and PHEVs in urban environments are likely to be more comparable to those performed by ICE vehicles. Moreover, it is also worthwhile to mention green logistics' importance to the carriers and retailers' clients, since customers prefer their products transported and delivered in an eco-friendlier way. Thus, companies offering these solutions have a considerable advantage over their competitors.

Furthermore, opting for Evs presents some other financial advantages for the owners, as referred in Table 2. The Portuguese Association for Electric Vehicles, (UVE, 2022), refers that in Portugal the benefits comprise acquisition encouragements through direct payments and tax reductions to companies when purchasing either Evs or PHEVs. However, not all PHEVs are benefited, since those with an all-electric range lower than 50 kilometers or emitting over 50 g/km are not considered. Another benefit concerns taxes' reductions on the companies' operations' revenues whenever eco-friendlier solutions are used. Other benefits are, in some cases, reduced highway tolls for Evs as well as cities councils that do not require companies nor individuals to pay when parking an EV, (Org, 2013).

TCO is as reduced as the more distance the vehicle is operated with. Parity is possible at around between 60km and 200km of daily drive, depending on if it is light or medium duty vehicles, respectively, (Basso et al., 2022). Moreover, the longer the depreciation period, the more pronounced are the savings. Both vehicle types, especially if subsidized, are able to present TCO parity or even lower ownership costs due to lower operational costs and to the benefits companies enjoy when integrating these vehicles in their fleets.

The EC, (European Commission, 2021-b), estimates that customers will be able to save up to 4.000€ over the lifetime of an average new van bought in 2030. It is therefore aimed that buyers, for instance, carriers and retailers, when presented with less costly and more reliable options, will opt more often for Zero and Low-Emission Vehicles, i.e., according to European regulations, a vehicle with CO_2 emissions between 0 and 50 g/km. However, heavy-duty Evs and PHEVs, even with a long depreciation period do not allow, in most cases, TCO parity with a comparable ICE truck. Only the need to use these trucks in ZEZs leads to their usage. An example is the "congestion charge" paid to enter in London restricted areas, where operating electric or plug-in hybrid trucks is cost-efficient since the heavier and the more pollutant the vehicles are, the bigger the fee is, (Mayor of London, 2019).

For both medium and heavy-duty trucks, DAF considers that plug-in hybrid models are the best solution, since in urban centers a fully electric operation is possible, whereas outside them, where longer distances are usually driven, a diesel engine is, according to DAF, still the most advantageous option. This is because, as the company refers, for longer ranges, cleaner diesel solutions have greater autonomy and flexibility. DAF hybrid solution, for instance, presents an all-electric range of around 50 km in urban areas which is, according to the company, a suitable range for urban operations, (DAF, 2020).

Another matter of concern regards the limited range of options over 7,5 tons, which negatively impacts these options' suitability to the companies' operations. In order to address this gap, more companies are launching heavy-duty models. Daimler trucks, both in the United States of America (USA) and Europe, has been testing and introducing new models. In the European market, the semitruck eActros Long-Haul has a significantly improved range, when compared to prior versions, being capable of covering 500km with a single charge (from fully charged until the battery is empty). This range, in combination with the EU law regarding driving time between compulsory 45-minute breaks every 4,5 hours, enables, with a fast-charging solution, a profitable and feasible operation. However, its feasibility, still depends on how accurate are, the operations' planning. The eActros, in Europe and eM2 in America are heavy-duty e-trucks, according to (Daimler, 2019), tailored for "local distribution, pickup and delivery and last-mile logistics applications". These operations are, therefore, possible to be performed with no local emissions as the trucks' ranges are 200 and 370 km, respectively. Daimler also refers that ranges were tested in real-world conditions since, for several months, these trucks were driven, for around 1,5 million kilometers, in urban routes and highways.

Another decisive factor is the EV maintenance costs. As translated in Table 2, Evs require less maintenance, as electric engines have longer service time intervals, when compared to similar diesel vehicles. Moreover, (Fuhs, 2008) refers electric engines are capable to convert the vehicle's kinetic energy back to electrical energy and store it, in a process known as regenerative braking system. It occurs when braking with the engine to decelerate the vehicle or driving in a downhill road. An example of that cost reduction is FUSO eCanter, a LCV, that according to the company is capable to reduce costs by 1.000€ every 10.000 km, (Daimler, 2020-a).

An EU funded project, Freight Electric Vehicles in Urban Europe (FREVUE, 2020), is also worth to be mentioned, as it demonstrated EV capabilities and suitability, especially, for urban freight transport. In partnership with several city councils and carriers, 80 fully electric LCVs were deployed across 8 cities. The vehicles were operated by different companies, between 2013 and 2017, under real-world conditions. Moreover, most vehicles currently on the market were found to have sufficient range for most urban operations, (FREVUE, 2017). The study also states that the longer the different stakeholders, like operations' managers and drivers, operate Evs, the more confident they become towards Evs' adoption. However, drivers' concerns over range persist, resulting in anxiety issues, as Table 2 refers. Hence, and as the report states, it is important to keep a healthy margin, so that drivers are confident and the anxiety fades away.

The report also mentions that the main problematic regards efficiency, as it varies due to factors like driving habits and conditions as well as the outside temperature. The US Department of Energy, (U.S. Department of Energy, 2021), refers that the range might be reduced up to 30% in the event of extremely cold temperatures. Lower temperatures also increase the batteries' resistance when charged, resulting in a slower charging, and even part of that the energy might be lost, as well. The same institute states that automakers have been developing solutions in order that the range is less impacted by extreme temperatures, for instance, devices that control the temperature at which the battery operates so that efficiency increases, but room for improvement remains.

Table 2 also refers that the technologically related raw materials are another source for concern. They are essential to Evs, as they are incorporated in a much higher proportion, since a higher demand for batteries, increases the demand for lithium, cobalt and nickel than ICE vehicles require. Electric engines, by their turn, require components with rare earths in their composition, (European Battery Alliance, 2022). Hence, their demand grows with a more widespread adoption of Evs. In order that supply is secured to meet future demand, it was realized the necessity to reduce the dependency on foreign countries and, at the same time, guarantee the sustainability of these materials' supply chains. Consequently, the EU created the European Raw Materials Alliance, which aims to create a circular economy around these key raw materials, through their recycling, (Jyothi et al., 2020). Since, negative environmental impacts when mining them are extremely high and also because most of them are considered by the EU as critical raw materials. For instance, most rare earths are sourced from China, which might pose a problem for automakers in terms of reliability, so in the future an efficient recycling industry is set to be created to assure Evs' production. The recycling of electric vehicles also focuses on power electronics due to the presence of precious metals, which is a highly efficient process as the remaining ones are.

A final matter of concern are the health impacts originated by the widespread usage of fossil fuel powered vehicles. The FREVUE project simulated that electrifying 10% of the vehicles in London alone would save as much as 1 billion pounds (around 1,1 billion euros, (ECB, 2021)) per year, through less air quality related diseases' treatments. Thus, fleets' electrification represents a major step forward in reducing the harm caused on the health of those living and working in urban areas.

Overall, even though electrification of the commercial fleets cannot be completed in the short term, it is possible that Evs become a major segment of the market with a continued and sustained price reduction as well as a more diversified portfolio presented by the automakers. It allows that, by its turn, more suitable options to the different companies' needs are created and, as a consequence, the confidence and favorable views on Evs increase as well as the demand. Resolving these barriers, as stated in the report (FREVUE, 2013), "will take time, financial support and collaborative commitment from industry, government and society". However, "by working together, continued electrification and decarbonization of freight fleets can be achieved".

2.1.3. Charging grid

As mentioned, charging grids are still underdeveloped. Hence, several projects are being implemented in order that charging solutions become more accessible to the public. To respond to the insufficient charging grid, cities, governments and private companies are committed to increase their accessibility since, as several studies suggest, (World Economic Forum, 2020), there is a strong correlation between battery-Evs' uptake, not only with the vehicle's TCO, but also with the available charging grid. This is since, even though customers have preference for alternatively powered vehicles, only a satisfactory distribution of publicly available infrastructure for charging and refueling in Europe will enable that companies, and also individuals, trust these solutions to use them in their daily operations.

The Portuguese government, for example, has been stimulating that a wider and more dispersed grid is possible, through promoting its expansion and adequacy to those using it, (Governo de Portugal, 2021). Places such as public buildings, hotels, shopping malls or parking lots are providing the public with accessible charging points along with those present in several streets and routes, so that Evs are able to circulate around urban areas, or between them, without major constraints. Furthermore, as stated in its ten-year mobility program, (República Portuguesa, 2020), the Portuguese government not only wants a charging grid dispersed throughout the country, but it also wants that fast-charging points are widely available so that longer trips using Evs are possible and, for instance, a wider usage of e-trucks is possible, as well. In its plan, all the densely inhabited municipalities, should have available a grid that enables massified usage of electric vehicles.

Currently, in Portugal and throughout the EU, the ultra-fast recharging grid is still sparse, (Eurostat, 2023). For instance, there are only 10 ultra-fast charging solutions operational in Portugal, which are the ones suitable for heavier vehicles and their placing along routes would significantly favor electric heavy-duty vehicles' uptake. Those located in the Lisbon Metropolitan Area can be stated in is provided by the public agency managing the Portuguese recharging grid, (MobiE, 2023).

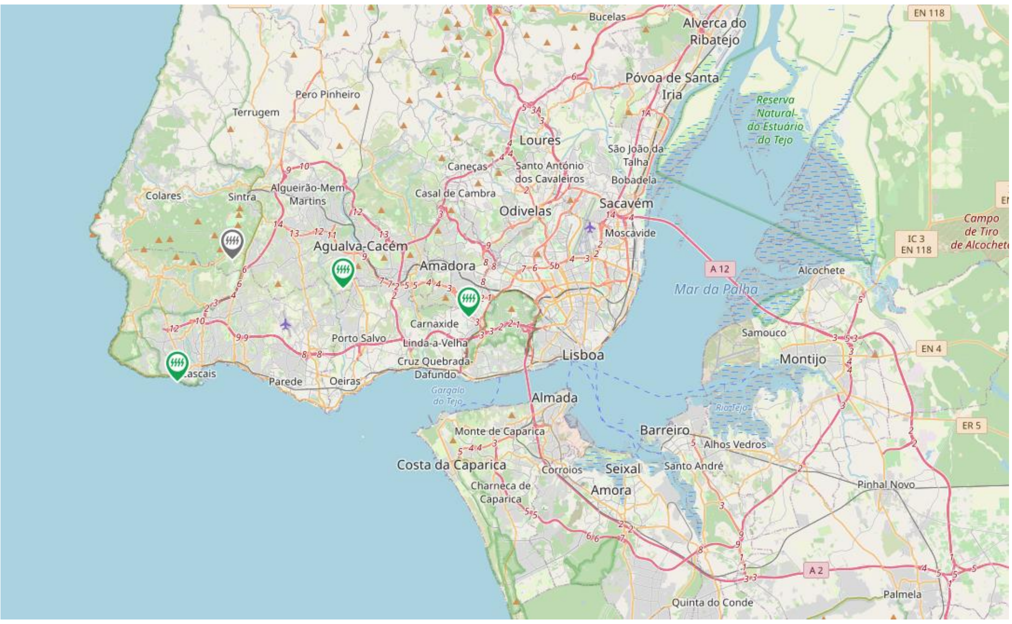


Figure 1: Location of ultra-fast charging solution in Lisbon Metropolitan Area (MobiE, 2023)

Another important matter is the installation of fast-charging solutions at depots, as they enable recharging the vehicle during the night or breaks and, therefore, enabling its operation in the daily shift. For instance, recharging during the night helps on lowering the energy costs since, as stated by (Mobi.e, 2023), a Portuguese public agency, the electricity prices at the depots, during the night, can be up to three times lower than those at a publicly available charging point. Depots with charging stations are especially advantageous for city operations, as a unique charge could be sufficient to assure an entire shift's operation. However, if recharging is necessary, placing faster charging options where drivers stop, enables them to charge their vehicles while the vehicles are idle.

Charging heavy-duty trucks with conventional solutions currently takes days. However, if fast or ultra-fast charging stations are used, the required time might drop to only 45 minutes, which is, as referred, the duration of mandatory breaks. An example are the solutions presented by the company i-Charging, which has launched a range of fast charging stations. The firm claims that the chargers are designed to deliver 50kW, an output of a standard fast charger, and up to 450 kW (for the ultra-fast charging solutions that are commercially available at the moment), making this technology capable of charging e-trucks. The company states that it was "designed with fleet operators in mind", since by installing these charging stations, it is possible that a an "unlimited number of outputs" is supported through scalability on site, (i-Charging, 2023).

Another important matter regards the interoperability among charging points and vehicles. Until 2017 several types of chargers' sockets were used, as different automakers would use one of the available types. However, afterwards, EU legislation turned compulsory that alternating current chargers must use a single type of plug (Type 2), (EUR-Lex, 2014). Furthermore, for direct current, high power, recharging points, EU legislation requires that "electric vehicles shall be equipped, for interoperability purposes, at least with connectors of the combined charging system, Combo 2". This, in order that the different vehicles are able to recharge, without having to look for recharging points compatible with the vehicle. However, in the USA, for instance, that is not the case, no standardization exists and, therefore, each automaker, and charging station, opts for a different socket connecter, posing difficulties in the EV uptake as drivers find it more difficult to recharge their vehicle, (U.S. Department of Energy, 2020).

It is, therefore, necessary to account all these variables when optimizing the routes that the various fleets' vehicles will cover. Hence, the referred aspects have to be considered when planning the integration of more sustainable means in the operations.

2.2. Businesses' plans

Several institutions worldwide have been promoting a more sustainable transportation, since addressing the existing problematics in logistics is crucial when reducing the negative impacts that the broad usage of ICE vehicles have on society. Local, regional and national authorities have been working towards a more sustainable distribution within cities in which companies play a major role to tackle down the impacts they have while performing their operations.

An example is the Lisbon's city council that has signed a pact with several organizations, in order that their impacts are reduced, through electrifying their fleets and encouraging their partnering companies to follow their pace, (FREVUE, 2020).

Another aspect is that, in accordance with European directives, the Portuguese government and the Lisbon Council, (CM Lisboa, 2020), aim to achieve a decarbonized urban distribution. Hence, these authorities have been promoting a distribution with lighter and more compact vehicles, that have reduced impacts, and other logistic solutions, for instance, micrologistics. Together, Micrologistics and cargo-bikes, or electric LCVs, might enable feasible and economically attractive solutions for the decarbonization of last-mile logistics. Which are especially suitable for the historic areas of the city, as the city council states.

2.2.1. The electrical transition characteristics

Currently, several companies are implementing projects to turn their operations more sustainable. An example concerns micrologistics, as shown in the left side of Figure 2. Furthermore, it is also being promoted that bigger distribution centers are located in the city surroundings, as shown in the right side of Figure 1. This, in order that electric LCVs are operated to perform optimized routes, especially in periods with lower traffic and, consequently, lower congestion and noise pollution, so that harmful impacts are reduced. Being, therefore, plans of major impact in the environment and society.

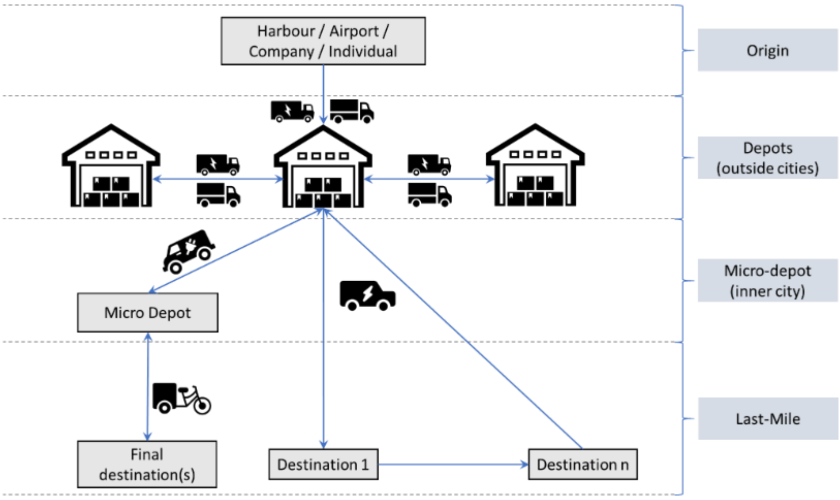


Figure 2: Scheme representing the current set-up of a distribution network

DPD, for instance, has implemented this solution in various countries. The most developed project is in London, where 7 micrologistics centers are operated, each with a fleet of small, compact and electric quadricycles that perform a route around the neighboring areas. That center has its parcels delivered by an electric van, a Canter eFuso, that covers a route between the micrologistics centers and a distribution center outside the city, where the parcels first arrive, (WBCSD, 2019).

Lisbon city council believes this is also a solution appliable in its city. In fact, DPD plans to create a micrologistics center in Lisbon, especially, to serve the historical center, where small distribution vehicles impact less those areas, (DPD, 2023). CTT has also been performing operations alike the ones shown on the right branch of Figure 1, using electric LCVs, such as vans and scooters, in order to distribute parcels and mail in the city center (CTT, 2021).

However, many companies have not been able to electrify their fleets yet, many are opting for a distribution with gas-powered vehicles due to their lower impacts. Intermarché, for instance, distributes its goods from the distribution centers in different French urban areas into the different stores by using natural gas and biogas powered trucks. Since the infrastructure is reduced, the company installed, in its distribution centers, gas containers in order to be able to operate cleaner operations at such a scale. DHL and also CTT have been opting for gas-powered trucks as well, but mainly for the operations among depots and from harbors/airports to the depots, as shown in the upper part of Figure 1. This solution, according to both DHL and CTT, has proven itself feasible and allows that transportation in predictable operations is less harmful. IKEA has opted for a similar solution. However, it differs from the already referred examples as the company is getting its supplies itself, in Italy, from different locations using liquefied biogas powered trucks. They already cover around a third of the domestic transport flows, as claimed by the company, (CTT, 2021); (DHL, 2019); (IKEA, 2021); (José & Mendonça, 2022).

DB Schenker, one of the biggest carriers operating in Europe, has also been turning its fleet greener, (DB Schencker, 2018). The company refers that it is the company operating the largest fleet of FUSO eCanter, an electric LCV, that the company uses only for inner-city and short-radius operations. The company claims that a range of 100km together with overnight charging in the company's depot, enables a reliable operation in real world conditions. The company also states that it is moving terminals out of the cities, so that its operations are more sustainable. The company states that the terminals it is building, located along expressways and highways, "increase the security of customers' shipments and (…) impact on efficient and secure logistics operations". In result, the company keeps a profitable operation while cities face lower pollution, traffic and noise levels and, therefore, its inhabitants are less impacted.

Another example is the Japanese retailer Rakuten, (Rakuten, 2021), listed as one of the most sustainable retailers by Dow Jones Sustainability Index (DJSI), (Jones & World, 2023). It has been focusing on avoiding re-deliveries, since it not only impacts the company financially, but also the environment, especially if an ICE vehicle is used, as more journeys are needed. In order to address this problematic, Rakuten has been widely using, to deliver the products to the clients, pick-up points in post-offices, convenience stores or lockers installed in publicly accessible locations.

DHL, by its turn, has been investing in pick-up solutions, as well, and by 2025, it also intends that 70% of its pick-up locations, and other delivery services within cities, are served either by bicycles or electric vehicles, (DHL, 2019). IKEA is also working towards zero-emission home deliveries and has been successfully testing new electric vehicle prototypes for last-mile delivery in 19 countries. By 2025, 100% of home deliveries are to be done by electric vehicles, (IKEA, 2021).

Another point concerns the automakers' plans for their businesses' foreseeable future, as it will be increasingly important to electrify the fleets being used, especially for transportation within urban areas.

PSA, a company also listed in the DJSI as one of the most sustainable worldwide, has the intention that all the models it produces will offer either a fully electric or a plug-in hybrid version by 2025, (PSA, 2017). This would significantly impact companies operating LCVs, as a wider range of alternative options would allow an increased uptake by the companies, easing the transition into a more sustainable transportation. Daimler owned Fuso has a similar objective, claiming that by 2039, all of its commercial fleet will be emission-free, in a tank-to-wheel assessment, for the markets in North America, Europe and Japan.

At last, some carriers and e-commerce companies have been investing in start-up companies in order that purpose-built vehicles are put into inner-city operations. DPD is an example of that as it has been purchasing these vehicles in order to maximize the accessibility of the drivers to the parcels as well as to maximize the safety of the public. In the case of Volta's truck, bought by DPD, the driver is sitting in the middle of the cabin to better perceive what is happening around the vehicle, namely regarding to pedestrians and cyclists, (DPD (UK), 2021).

Another example is Amazon, (Amazon, 2020), which has been investing on the company Rivian and purchased from this start-up 100 thousand electric vans, which will be put into operation during the next ten years. The company intends to place delivery stations near large Amazon customer populations and, to serve its customers, these vans would be perfectly suitable, especially in densely populated areas. This case, of a distribution process that uses Evs to transport parcels into cities, from depots outside their boundaries, is shown in Figure 3.

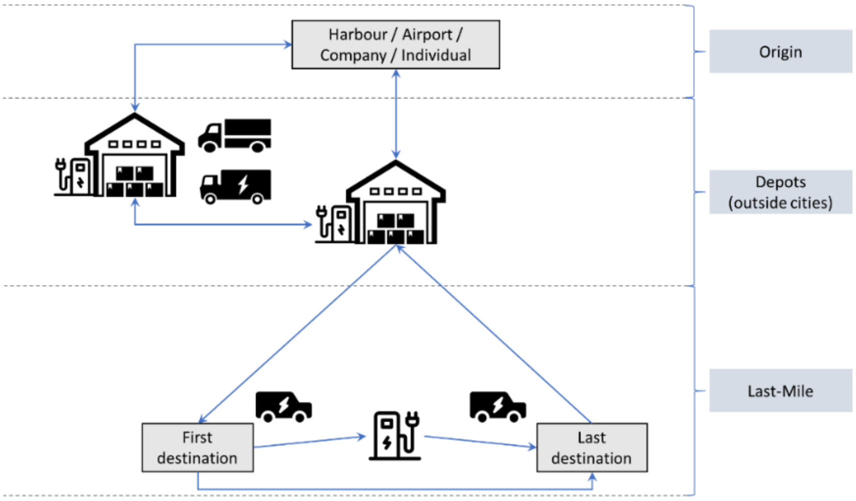


Figure 3: Scheme representing the model to be implemented in the dissertation

2.2.2. Stakeholder Interactions

Throughout this chapter, it was referred the different relationships established among the different stakeholders. It was also referred what are, for the different ones, the main demands to one another as well as the main drivers to include more sustainable practices into their operations. This, especially in what refers to the inclusion of Evs and PHEVs in their fleets, which are summarized in Figure 4. The interactions this figure displays regard the following stakeholders:

- Automakers – companies producing and manufacturing the vehicles.

- Carriers and retailers – firms purchasing and operating the vehicles.
- End-customers – those served by companies that operate the referred vehicles.
- Governmental agencies – local councils, national governments and other supranational institutions, for instance, the EU.
- Infrastructure promoters – recharging and refueling facilities.
- Key raw material suppliers – suppliers of critical raw materials, such as lithium, cobalt and rare earths, for batteries and electric engines, (European Commission, 2021-b).
- General public – population of the different countries.

In the figure, it is clear that most stakeholders' demands refer to a smoother transition into a more electrified fleet, so that their operations are not endangered in this process. The carriers refer that for a lower impact in their business, a reliable and economically viable operation, at a comparable TCO, is necessary. This means that the infrastructure has to be adequate and the available range of options, presented by the manufacturers, less expensive and more suitable for the different operations. Hence, in order that this transition is possible, it is necessary that the government promotes it. This, can be done through direct incentives to the alternatively fueled vehicles' uptake and, also, for the development of improved solutions as well as the creation, together with the infrastructure promoters, of the necessary recharging grid. Thus, it is necessary to address, simultaneously, the operational constraints that Evs present. Namely, the still inadequate recharging infrastructure, in order that the quality requirements, from the transportation companies' customers, are met along with the SD requirements from the general public.

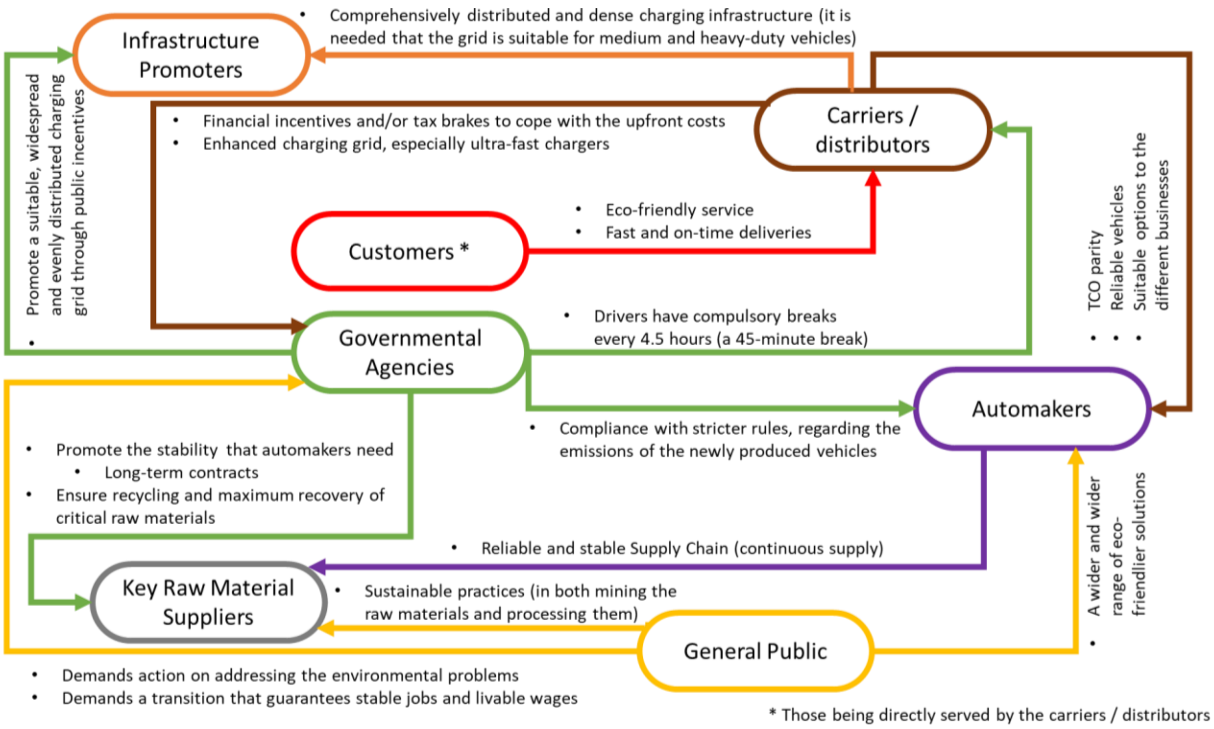


Figure 4: Flow chart on the interactions among stakeholders

2.3. Chapter conclusions

To summarize, the solution chosen to be the basis for the master thesis' model was the routing of ECVs from a distribution center into several city center locations, since this problem will assess how charging infrastructure should be implemented in order that distribution operations are not jeopardized. Thus, in the dissertation it will be necessary to consider, in large operations as the ones referred, the interaction between the location of the depot and the demand points, along with the assessment of the to-be location of recharging stations and, whether or not, they are required

This, in order that it is possible to effectively operate a profitable and feasible distribution in urban environments using eco-friendlier vehicles and, in this case, Evs. Moreover, in the following chapter, a literature review will be presented on the main topics related with the model to be developed, some of which were already analyzed throughout this chapter. The following chapter will be, therefore, focused on the SD within the context of supply chains and what are the main characteristics for the planning and operationalization of a sustainable supply chain. It will also be further explained how that relates with sustainable logistics and the modelling of a Location Routing Problem.

3. Literature Review

In the previous chapters, it was emphasized the key role companies play when addressing the sustainability problems, the world is currently facing, as these problematics pose major risks on the lives of the generations to come. Pursuing a SD is, therefore, the way not to jeopardize the future generations' quality of life, as it promotes a long-term sustainable growth, (Dubey et al., 2017).

In this sense, over recent years, stricter environmental policies have been enacted, for instance the referred ICE vehicles ban in some city centers. Customers have also put pressure on regulators and in the companies in order to improve the undertaken practices, (Rajeev et al., 2017). The literature directly relates the companies' operations' impacts, namely their supply chains and the way they are adapting to this new environment, on whether a SD is effectively being pursued or not. As stated by (Nilsson & Göransson, 2021) "the challenges of sustainable development require whole supply chains and networks to drive change and innovation." However, as the same article refers, most of existing research on sustainable innovations is on a company level, which mostly seeks short-term cost-reduction and/or profit maximization. Real change towards SD demands collaboration among the several stakeholders, which "is by far the most frequently observed main driver for sustainable development."

Thus, the literature review will focus on what has been covered regarding SD, namely, how SCs impact SD and what is being done in order to reduce their impacts on the environment and on the society without compromising the economic pillar. It is then presented that, within SCs, a major source of interest in the transition is the transportation of goods, which is the main thesis' focus. Thus, it will be referred what are the sustainable logistics' planning main characteristics as well as those to be considered when modelling a Location Routing Problem and the main methods to solve it. Lastly, it will also be referred the existing research gaps that can be further explored.

3.1. The supply chain

At first, the awareness of the positive implications that environmental sustainability will have on future generations' lives, led to the creation of a new study field, Green Supply Chain Management (GSCM). Which means the integration of environmental thinking into SCs, as stated by (Barbosa-Póvoa et al., 2018). GSCM assesses the impacts in the environment of the activities performed throughout the SC and how greener and more efficient operations change the existing impacts. According to (Srivastava, 2007), GSCM includes, in the SC strategic thinking, the impacts of the "product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life." However, GSCM fails to address one of the pillars of the TBL, the existing social problematics, as the same source states. In order address this gap, a new, and broader, concept arose, the Sustainable Supply Chain Management (SSCM), which became the leading research topic, from 2010 onwards, as more and more authors integrate in their research the three pillars of the TBL.

3.1.1. Towards a more sustainable supply chain

The Sustainable Supply Chain (SSC) is the direct result of the implementation of the SSCM and aims to further improve the practices performed by the different stakeholders throughout it, so that they attain sustainability within their own operations. Hence, SSC integrates the different stakeholders as they strive to work closely, from the raw material producer to the customer, in order to continuously adapt and improve their activities and products, (Nilsson & Göransson, 2021).

Initially green, and then, sustainable management programs have also been implemented in order improve SC activities so that costs were reduced and, at the same time, the brand awareness improved. Customer satisfaction, and their loyalty, to the company would, therefore, increase revenues and sales through greater market share or new induced markets, resulting also in less risks posed to the future of the different companies within the SC. Furthermore, this is a project concerning the mix of tactical and operational decisions with SD concerns. Namely, the economic and environmental ones, which as stated by (Sar & Ghadimi, 2023), SSC related papers have not been really focused in, which emphasizes the importance of this master thesis research.

SSCM was defined by (Rajeev et al., 2017), as "The creation of coordinated supply chains through the (…) integration of economic, environmental, and social considerations with key inter-organizational business systems. Which are designed to efficiently and effectively manage (…) the procurement, production, and distribution of products or services in order to meet stakeholder requirements and improve the profitability, competitiveness, and resilience of the organization over the short-and the long-term". Thus, SSCM demands, in order to be properly implemented, that SCs develop new methods accounting the three pillars of sustainability: economic, environmental, and social. The latter two, as stated by (Barbosa-Póvoa et al., 2018), have been lacking a detailed assessment in the literature, as the indicators regarding these pillars are difficult to quantify, especially the social one. Operational research methods, as the one that will be used in the dissertation, have, as a consequence, to consider trade-offs among the different indicators concerning the three pillars. There are several indicators, among which:

- Economic pillar – Regarding the economic pillar, most studies aim to address cost related decisions or profit maximization. However, infrastructure problems could, for better economic assessment, include the net present value (NPV) of the investment. In this project, since recharging infrastructure is the focus in the location routing problem (LRP), then this will be an economic metric to be considered.
- Environmental pillar – Regarding the environmental pillar, the LCA metric is a metric allowing a more comprehensive perspective of the impacts caused by a product or service. Since it accounts the different stages from the extraction of the required raw materials until the end of life of the product, or the products, required for the service, (Corona et al., 2019). Other metrics are partial, as they only account some of the resulting impacts. However, partial metrics have been widely used in the literature. These metrics are, for example, the amount

of GHGs released, the amount of waste created or the share of renewable energy consumed, (Sar & Ghadimi, 2023).

- Social pillar – Regarding the social pillar, this has been the least covered pillar in the different studies. Indicators referred by (Barbosa-Póvoa et al., 2018) to be commonly used concern job creation and the well-being of the worker. For the latter, indicators such as the safety, the health, the workload and the discrimination in the professional environment were referred. Other indicators present in the literature, (Bosona, 2020), which are closely related to the topic of this project, are traffic safety and noise levels.

3.1.2. Planning a Sustainable Supply Chain

When planning any SC, it is necessary to consider what are the main characteristics of the SC to be executed. As also referred by (Barbosa-Póvoa et al., 2018), three different structures are considered in the literature:

- Forward – the most prevalent structure in the literature, where the flow of goods is characterized for their one-way direction, from the supplier towards the consumer.
- Reverse chain – this has been a topic of growing interest among the academic community as stated by (Dolati Neghabadi et al., 2018). In what concerns to logistics, this form of SC mainly focuses on the return flows of products, i.e., activities of collecting and gathering waste or end- of-life products in order that they are properly treated. Some of the collected items are remanufactured, and then resold/redistributed.
- Closed-loop supply chain – as referred by (Nilsson & Göransson, 2021) it combines both forward and reverse flows, turning it into the most sustainable option when planning a SSC. As referred by the author, several authors have been considering more and more this option also due to the concept of circular economy. This concept is classified by the same source as “a growing field of practice and research, targeting one-way, linear concepts on an SC level.” As there is the need of “going from linear, one-way supply chains to circular supply chains”, which led, as a consequence, to the creation of closed-loop SCs.

Furthermore, (Barbosa-Póvoa et al., 2018) review article refers that, when planning a SC, either aimed to be sustainable or not, the SC is divided into three different planning categories, in order to address the different problematics when outlining the SC. They are the strategic, tactical and operational levels. These levels are further explained below:

- The strategic one is for the long-term planning, which means outlining the main decisions for the following years and decided by the executive management level.
- The tactical level refers to shorter planning cycles, the medium-term planning, normally around one to two years, concerning with inventory planning and flows of material and production.

- The operational level in a SC includes “demand fulfillment, production, transportation, scheduling and monitoring activities”, which are activities planned in a daily or weekly basis, that is to say short-term planning, (Rushton, A., Croucher, P. and Baker, 2014).

The combination of different decision levels is often undertaken and, in this particular project, such will be carried out. It will be explored, within a LRP problem towards a model of a green urban logistics, which results contribute to build a more sustainable SC. It combines tactical decisions, namely the location of recharging infrastructure and the feasibility of the transition into an e-truck based distribution process. This, combined with operational decisions, namely the routing of electric commercial vehicles (ECVs) distributing goods within the city of Lisbon and its surroundings.

3.2. Sustainable urban logistics

A more sustainable transportation is considered as a crucial factor for sustainability in logistics, which, by its turn, is a key component in supply chain management. In this interaction, it is where a greener transportation directly connects to the implementation of a SSC. In this dissertation, the matter chosen to be the research field was, more specifically, the urban distribution, as it is an important part of the transportation process due to its impacts in the economy and environment. As it is referred by (Dubey et al., 2017) this is a topic of growing interest among the academic community, as there has been an increasing quantity of research papers and reviews being published on the different areas of green logistics and urban distribution.

This interest is directly resultant from the will to further integrate greener means of transportation within supply chains. But include as well, in that consideration, a more efficient management of the fuel consumption, and which fuel is being used, if it is renewable or not, as well as the resulting GHG emissions. Furthermore, e-commerce is, as stated by (Bosona, 2020), more fuel-efficient than individual shopping trips, when buying in brick-and-mortar stores.

As the same source states, this is a process that requires the combined effort of a significant number of different stakeholders, which complicates its planning. For instance, carriers, suppliers, retailers or e-commerce providers and the client, amongst others. The transport service providers, usually, bring the goods from distribution centers (DCs) located outside the cities, in its surrounding areas, and delivers them to different city locations. For instance, the client’s home, to the clients’ stores or, as referred by (Wygonik & Goodchild, 2018), to pick- up points such as, lockers or service points, for instance, small shops and gas, bus or railway stations.

3.2.1. The main drivers for the ECV uptake

In the previous chapter, it was denoted the impact in the city life resultant from urban goods distribution. The factors cited by (Bosona, 2020), for this increment are no different from those already referred, which are the growing world population and the trend of this growing population moving into cities (urbanization). However, the growing purchasing power is also leading to an increased consumerism and, more recently to a shift in where the consumable goods are bought, which is the change from brick-and- mortar stores to e-commerce. The combined influence of these factors in the growth of urban logistics has been more and more discussed in the literature. It was also referred in the previous chapter that freight transportation and last-mile logistics play important roles in the different countries' economies. Which, according to (Oliveira et al., 2017), emphasizes the growing importance that the urban logistics has in today's society.

The same author also refers that several reports highlight the substantial negative impacts that last-mile transportation has over SD, within the urban areas it serves. A main driver for the lack of environmental sustainability in several current practices is, according to (Asghari & Mirzapour Al-e-hashem, 2021), the serious depletion in natural resources, namely fossil fuels, that is occurring.

This, along with the pollution generated from combusting these fossil fuels, led to increased efforts put onto a transition. Another key driver is the public, (Nilsson & Göransson, 2021, as more and more consumers demand companies to be both environmentally and socially responsible. Hence, as referred in the previous chapter, for no local emissions in urban logistics, there are two main options. One of them is the FCEVs. However, these vehicles have been neglected so far in the literature due to its low availability and costs. Hence, the other option, Evs with batteries storing electricity, are the main focus of this project, as Evs have been more and more the option considered, by the different carriers in their effort to decarbonize transportation, as it was referred in the previous chapter.

(Nilsson & Göransson, 2021 also refers several social impacts that are driving the introduction of ECVs. Firstly, health impacts resulting from the pollutants released by ICE vehicles, especially, in urban areas due to the high concentration of residents and their proximity to road networks. Hence, the increasing demand for last mile activities, performed into the inner-city areas, affect the livability and safety of those living in those regions and, therefore, need to be addressed. As (Schiffer & Walther, 2017) refers, ECVs significantly reduce both noise and air pollution, which makes, especially at nights, living in cities more comfortable and healthier, allowing also that distribution can be performed during the night. This could be done with no impacts on the population and allowing cost savings to the carriers as the efficiency of the transportation is positively impacted. These vehicles are, therefore, an effective way to reduce negative externalities.

Thus, the advances that EVs have been undergoing, combined with lower security dilemmas and the push by the governmental authorities are promoting the enlargement of the share of Evs and PHEVs. Furthermore, (Asghari & Mirzapour Al-e-hashem, 2021) also states that there is the possibility to achieve a transportation with net-zero emissions, if the electricity is generated by renewables, resulting in no overall impacts, in a well-to-wheel consideration, pushing further the will to incorporate ECVs into fleets.

Regarding the economic pillar, costs are also a big factor when adopting alternative means of transportation into the fleets. ECVs present important economic advantages since they have lower operational costs when compared to the conventional diesel-powered trucks. Thus, as stated in (Schiffer

& Walther, 2017), vehicle fleets incorporating ECVs might be able to greatly reduce their operational costs, reductions that are higher the more the vehicle is used. In carriers that the vehicles are operated for several hours a day, the gains are, therefore, significant.

It is also worthwhile to mention that, to the best of the authors knowledge, up until 2010 research articles were mainly concentrated on classic routing problems. However, from 2010 onwards, routing problems have been covering more and more the problems related with pollution and energy consumption.

3.2.2. The factors impacting urban distribution with Evs

As (Goeke, 2019) states, EVs are also considered to be a feasible option for goods distribution, especially, for the region this dissertation is mainly focused on, urban areas. However, (Dündar et al., 2021) states that, even though progresses have been made by different companies in terms of setting sustainable goals for their operations, most fail to effectively implement the necessary modifications to their operations in order to achieve tangible targets. The difficulties, faced by the companies, in the process of implementing the necessary changes, in the complexity of a global SC, are real and many lack the necessary tools to support the modifications needed.

The presence of several uncertainties, concerning the technologies being developed, are a risk many companies are not eager to take. In this context, the factors impacting the design, the planning and the operations in a SSC are of great importance to be considered, especially in the model to be implemented, so that the it reflects the reality more accurately.

Firstly, when operating a commercial fleet, the satisfaction of the clients is of primary importance and, therefore, their concerns are the major factors, that need to be considered by logistics operators, (Bosona, 2020). At the same time, it is possible to maintain the same operating costs, or even reduce them, by pursuing more sustainable operations as well as the company getting a higher recognition for its sustainable business model. As a consequence, the same author states “sustainability of SC and operations of logistics service providers have attracted significant research attention.”

Moreover, some of the factors impacting last mile operations when using ECVs are specific to these vehicles, but conventional factors have to be considered, as well. According to (Melacini et al., 2018) and (Kumar & Alok, 2020), factors influencing the difficulties faced by the companies distributing, especially into cities, parcels or other goods, and, in consequence, impacting the profitability and feasibility that the delivery operations using ECVs present, are:

- Total Cost of Ownership.
  - Upfront costs – higher purchasing costs when buying an EV, which are impacted by:
    - Governmental incentives to the acquisition of Evs.
    - Battery costs.

    - Lower operation costs: energy and maintenance.
- Size of the operated fleet and its degree of homogeneity, (Schiffer & Walther, 2017).
- An ageing battery loses capacity in storage and increases the resistance to recharging, leading to higher recharging times. Furthermore, this factor, the battery decay, has had little attention in the literature, (Dündar et al., 2021).
- Availability of a suitable charging infrastructure:
    - Located in the points where it is needed the most.
    - Suitable for the vehicles willing to use it.
    - Resilient to handle the demand peaks for recharging.
- The transport capacity that the carrier is able to offer the client:
    - An important factor might be the insufficient supply, from manufacturers, of heavy-duty electric trucks capable of handling large loads of goods.
- Social impacts, for instance, the range anxiety that many drivers experience when driving an electric vehicle:
    - (Kumar & Alok, 2020) refer that a factor impacting range is the ability of the driver to use eco-driving techniques in order to significantly reduce the energy consumption and, therefore, increase the range the vehicle is capable of.

In addition to these factors, other issues that might greatly impact the costs are, according to (Bosona, 2020):

- the service level the company aims to offer the client;
- the type of the product being transported, refrigerated transportation or not;
- the area being covered;
- the environmental awareness of the clients being served, as the more they prefer eco-friendlier services, the more the company strives to serve them with greener vehicles.

Another factor regards the time-windows and the introduction, on the operations of the collection and delivery of the goods being handled by the company at night. Firstly, the looser time windows are, the easier it is to create and implement profitable delivery routes, especially in congested urban areas. Moreover, operating the vehicles in off-peak hours and/or during the night, by using vehicles with reduced noise levels, for instance ECVs, can improve the sustainability of the last-mile distribution process. This is an important factor since, energy consumption is reduced in these cases, reducing, as a consequence, the operation costs, (Bosona, 2020).

At last, in real-world conditions, (Schiffer & Walther, 2018), it is possible that it is required to recharge the vehicle in the middle of the shift and, therefore, the possibility for partial recharges has to be accounted. This, either in publicly available charging points, in the firm's own charging points or at clients' depots. The cost of the energy is, usually, more expensive when recharging during the day, when compared to full recharges during the night, and, therefore, it should be minimized. However, in order to better serve the client, it is usually accounted by the different models. Moreover, if synergies among different stakeholders are established, the usage of this expensive infrastructure is maximized and, therefore, there is not the need to install charging points that will have little usage. Furthermore, the more the privately owned recharging points, either by the company or by partner companies, are used, the lower the energy costs, as publicly available ones are more expensive options.

3.2.3. Electric vans compared to electric cargo bikes in distribution

In the previous chapter, it was presented the case for smaller depots being used for local distribution within smaller areas, by using electric tricycles. This case was not picked due to the scope of this dissertation. This is because, as it will be more thoroughly presented in the following sections, this scope implies the conjugation of charging infrastructure and the distribution of pallets for several hours within a relatively vast area, which is more than what a tricycle could cover.

As stated by (Sheth et al., 2019), electric assist cargo bicycles may serve as an economically viable option depending on the characteristics of the operations being performed and on the road infrastructure and/or geographical conditions. As the same author refers, cargo bikes are, usually, more cost-effective than vans for delivery routes closer to the DC, routes no longer than 10 kilometers and vehicles delivering up to 10 parcels per stop. However, for lower distances, the parcels per stop could be more.

Additionally, in order that cargo bikes are efficient, a high density of residential houses and/or business offices is required and the volume being delivered, in each stop, should be small, (Oliveira et al., 2017). By their turn, delivery vans are more cost effective when the goods' transportation covers a greater distance from the DC, especially, if the DC is located out of the area being served, and the volume of goods being delivered, at each stop, is higher.

Thus, for the purpose of this project, the focus will be delivery vans, as what it is aimed is to have bigger parcels delivered and/or covering longer distances and/or going among several depots.

3.2.4. Risks that may affect the profitability of last-mile logistics

In the literature, some risks were identified by the authors. Most of these risks are not specific to the last mile logistics using ECVs. However, it has to be accounted as it greatly impacts real-world distribution processes. The risks, referred in this sub-section, are different from those referred so far, nevertheless worthy to be mentioned as they impact daily delivery operations.

A first problematic identified by (Bosona, 2020), regards delivery failures, which negatively impact the company and, if a fossil fuel would be used, the environment would be negatively impacted as well. Another negative impact resulting from failed deliveries is higher operating costs due to the consequent redeliveries. These occur for at least 10% of total deliveries and, in some cases, may occur more than once, around 2%. The author states that the risk could be reduced by providing the client with specific time windows for the parcel delivery, but that it would also have negative effects, since it would compromise the efficiency of the routing process. Furthermore, last mile logistics is, according to the same source, time sensitive and longer lead times mean a reduced quality in the service. This and also considering that the bigger the lead times are, the lower is the customer satisfaction, then direct impacts in the revenues and economic sustainability occur. Another concern regards the possibility of lost/damaged packages.

At last, as previously referred, geographical conditions, of the served areas, greatly impact the service. (Ewedairo et al., 2018) refer that, factors having significant implications are, for instance, the difficult orography, population density, restrictions to conventional trucks' circulation or the service area, including historical centers. These are, usually, characterized for narrower streets and/or little availability of facilities for a faster movement of the goods.

Other risk factors interfering in the operations are more connected to the usage of ECVs. For instance, the low profit margins that the logistic business offers and that most customers are not willing to pay a premium price for a more sustainable service, (Dündar et al., 2021). Hence, the upfront costs of the ECVs, and the associated infrastructure, are for many carriers prohibitive.

Another problematic, referred by the same author, arising from the growing interest for alternative forms of mobility concerns the conflicting interests, (Dündar et al., 2021). It is referred that the different stakeholders, for instance, the city councils, the general public, the carriers or the suppliers want to act in their own interest and, therefore, if the interests are not coincident, and the interaction among them is insufficient and, as a consequence, operations such as the last-mile logistics in urban areas, become more complex and the introduction on alternative technologies is inhibited.

Thus, it is significantly important to account the listed risks led to the continuous development of new algorithms more tailored to the planning of the delivery services, considering the vehicles' characteristics and the existing constraints, (Eskandarpour et al., 2015). Hence, modelling LRPs, specific for urban deliveries seems to be the most rightful decision when considering the introduction of ECVs into carriers' fleets. As it will be thoroughly explained in the following sections.

3.3. The Location Routing Problem

Over recent years, as referred by (Drexl & Schneider, 2015), the LRP researchers have been working on the different research gaps this research field still present. Since, despite being one of the most studied subjects on the literature, research on multi-objective LRPs is far from being exhausted. Furthermore, LRPs combine two basic planning tasks in logistics. Generally, a LRP regards decisions on siting locations, for instance, plants, depots or other infrastructure, that are jointly taken with routing decisions for the fleet of vehicles to be used.

Besides extensive literature on classic LRPs, the case for the LRPs considering, specifically, electric vehicles, a first research paper was performed by (Yang & Sun, 2015), which modelled simultaneous routing and siting decisions concerning the location of a set of battery swapping stations.

For instance, in this dissertation, it is aimed to decide where to locate the recharging infrastructure that will recharge the vehicles in their daily operations. This type of model is therefore important to be considered when making decisions on whether to create, or not, recharging infrastructure or when deciding on the delivery routes for the model to be developed. This also because if these decisions were taken separately, the results that would be given by two separate models, one for location of recharging stations and another one for routing, would be suboptimal, when compared to the ones obtained by implementing a LRP. In this problem, an optimization, based on a mathematical model, is performed, where at least two decisions, are taken interdependently, according to the models (Schiffer & Walther, 2017), (Schiffer & Walther, 2018) and (Schiffer et al., 2021).

- The location of the set of recharging stations that should be built from a finite set of possible options (one possibility per demand point) in order to serve the vehicles used by the carrier.
- The set of routes to be introduced in the planning, and the order in which, each customer would be served and by which vehicle.

Furthermore, these two decisions are interdependent and, as mentioned by (Drexl & Schneider, 2015), in order to minimize costs, it has to be considered a trade-off. When modelling the LRP, the trade-off between the investment in ECVs, along with the TCO they will represent to the company, and the minimization of the investment on recharging infrastructure, which means creating the minimum recharging points possible. Thus, simultaneous siting and routing decisions are necessary, since the number of vehicles needed is directly influenced by the number of charging stations sited and vice versa.

Furthermore, (Schiffer et al., 2018) mention that LRPs involving ECVs involve conflicting aspects, which have to be balanced in order that a feasible operation is possible, especially if real-world conditions are considered. The real-world aspects, to be considered are:

- The routing planning requires that the limited range presented by ECVs when compared to their ICE counterparts is accounted as well as the recharging times. Moreover, it has also to be considered what are the recharging points being used (conventional, fast or ultra-fast), since these plug-in recharges last longer when compared to the time required to fill an ICE vehicle's tank. Furthermore, it has to be considered the driving patterns, where the referred eco-driving might play a big role in increasing the vehicle's range. This, along with the roads in which the vehicle is going to circulate, since the average velocity and the existing congestion play an important role in the overall range.
- The necessary infrastructure to support the batteries' recharging, both in the depots, where the vehicles stay during the night, and outside them, when the vehicle stops to deliver products or in publicly available recharging points along the planned routes. This decision is also interdependent to the first one, as these decisions, for the number of recharging points, is based on the range covered by the vehicles and quantity of vehicles purchased. It has also to be accounted the constraints to the installation of facilities, namely the capacity constraints, in this project's case, the number of ECVs to be charged at the same time and

the velocity at which they are charged, along with the upfront costs for the infrastructure installation.

The source also states, as referred in the previous chapter, that these difficulties, and the costs associated, are effectively hampering the uptake of the ECVs into commercial fleets. This is because the necessary investment is substantial, and for many carriers, prohibitive, which along with the distrust towards ECVs presented by many operators, results in a low uptake. This is the main reason why LRPs are important in this context, since if the number of vehicles purchased and recharging points installed are minimized, as they are dependent on one another, then it is easier to increase the incorporation of ECVs into fleets.

3.3.1. The characteristics and solution methods of a LRP

(Drexl & Schneider, 2015), in their review article on LRPs with ECVs mention that there are numerous variants to consider when modelling these LRPs. The most important characteristics that are referred in the literature were gathered by the author and are summarized, as follows:

- Relevant data to be considered in the problem:
    - Deterministic – in this situation the author refers that all the data to implement the model is already known.
    - Stochastic – in this type of data, it "is given in the form of probability distributions".
- Planning Periods:
    - Static – when it is only considered one planning period.
    - Dynamic – conversely to the first one, it considers multiple planning periods, mostly when the demand is uncertain. It is the type least addressed in the literature.
    - Periodic – it regards the planning of the visiting patterns to the customers, namely, the intervals between visits. Moreover, in contrast to the dynamic period, all relevant data is known.
- Infrastructure location options:
    - Discrete – potential locations are given as a set of vertices, from which a subset will be chosen to locate the infrastructure.
    - Continuous – in contrast to the previous one, there is no set of potential locations, the facilities can be located anywhere in the area.
    - Network locations – this type considers not only the set of vertices to locate infrastructure, but it also considers the possibility of locating infrastructure along the routes considered in the model and connecting the vertices.
- Types of problems addressed by LRPs:
    - Generalized LRPs – This type of LRP aims to find feasible routes starting and finishing at the same facility in order that each client's location is visited only one single time.
    - Split delivery LRPs – In contrast to the previous type, it allows that the client is visited more than once, by one or more vehicles, until the demanded goods are delivered.

- Pickup-and-delivery LRPs – This problem differs from the previous ones, as there is the possibility to load and distribute goods from and to several different locations. There is also the case where customers simultaneously pick-up goods and deliver others to the carrier to be delivered.
- Inventory LRPs – this final type of problem concerns the integration, into the planning, of inventory management in the located facilities.

Furthermore, the same source considers two more fundamental types, the number of echelons considered in the model and whether the model considers more than a single objective or not. For this latter type, it was stated that most of the reviewed studies, by the author, only consider a single objective and, usually, concerning the minimization of the operational costs or investments on facilities.

(Karaoglan et al., 2012) state that LRPs might be solved through formulating exact algorithms, namely, as found in the reviewed articles, mixed integer programming (MIP) and mixed integer linear programming (MILP) and, therefore, getting an optimal solution. However, since this is a NP-hard problem, heuristics / metaheuristics might be appropriate methods as well. The latter resolution methods, in contrast to exact resolution methods (linear algorithms), are not aimed to find optimal solutions to the problem. Instead, they find solutions close to the optimum, especially when the problem under consideration is a medium or large-sized one. Which means that they involve a high degree of complexity. Moreover, although there is a considerable number of different heuristic and meta-heuristic methods to be employed in solving a more complex problem, there is no consensus in the literature in which is/are the most suitable method(s) to solve it, (Dündar et al., 2021).

3.3.2. The algorithms present in the literature

Having characterized the LRP, it is now summarized the main contributions found in the literature, in this field, specifically, concerning ECVs in Table 3. This, in order to better understand what has been considered as well as to understand what has not been assessed until now.

Table 3: Summary of the main characteristics presented by different LRP models

Articles	Planning period			Objective		SD Pillars		
	Static	Dynamic	Periodic	Single	Multi	Economic	Environmental	Social
Yang & Sun (2015)	x			x		x		
Schiffer & Walther (2017)	x				x	x		
Schiffer et al. (2018)	x			x		x		
Schiffer & Walther (2018)	x			x		x		
Schiffer et al. (2021)	x			x		x		

Articles	Parameters		Potential Locations			Recharging at customer sites	Partial Recharging	Recharging rate
	Deterministic	Stochastic	Discrete	Continuous	Network			
Yang & Sun (2015)	x		x					
Schiffer & Walther (2017)	x		x			x	x	x
Schiffer et al. (2018)	x				x	x	x	x
Schiffer & Walther (2018)	x		x			X	x	x
Schiffer et al. (2021)	x		x			x	x	x

As previously referred, the first one to be found in the literature was (Yang & Sun, 2015). However, this research paper considers the location of battery swap stations instead of recharging points. In contrast to that, all the remaining research papers considered as the location problematic the sitting of recharging points. Moreover, as can be seen in Table 3, all the papers presented models using MIP exact methods (Schiffer & Walther, 2018), (Schiffer & Walther, 2017), (Schiffer et al., 2021) and (Yang & Sun, 2015), with the exception for (Schiffer et al., 2018) which considered a MILP one. However, all the research papers used, as resolution methods, metaheuristics for greater computational efficiency when solving the models.

Additionally, only one of the papers, (Schiffer & Walther, 2018), considered that there was the possibility to locate recharging infrastructure outside the considered set of vertices, namely, along the routes connecting those vertices. Regarding the objective functions, it was only considered economic objectives, even though these are research models that consider a more SD, via introduction of ECVs into the fleets. Moreover, as can be seen in Table 3, only (Schiffer & Walther, 2017) considered more than one objective function, as it considered the minimization of both fleet and recharging infrastructure upfront costs as well as the minimization of operational costs.

All models considered a single echelon in their formulation. Moreover, three considered last-mile distribution and one another, (Schiffer et al., 2021), considered mid-haul logistics, with distribution between distribution centers and clients' warehouses. Furthermore, all the research papers considered:

- A restricted freight capacity for each vehicle.
- Limited time windows available for freight delivery.
- Constant energy consumption rate during the distribution.
- Vehicles' partial recharging at customer sites is possible.

The latter characteristic was not considered only by (Yang & Sun, 2015), since this article considered battery swap stations instead of recharging points. Furthermore, (Schiffer et al., 2021) was the only one to consider the natural decay of the capacity presented by the battery in the model. Moreover, (Schiffer et al., 2018) states that a LRP model where uncertainty is included, can be described either as a robust model, if the data does not follow a probability distribution, or as a stochastic model, otherwise. Furthermore, robust models, the most studied ones in the literature, in order to consider uncertain parameters uses a set of discrete states. At last, the following assumptions are used by the same author when formulating a LRP robust problem:

- Constant vehicle speed along the route.
- Relieve alterations along the routes are neglected.
- The electricity consumed by the vehicle is linearly dependent on the travelled distance.

The recharging time necessary to charge a battery is linearly dependent on the amount of energy charged into it, since the recharging rate is constant. Additionally, since the optimization model to be implemented considers different dimensions within its objective function which are likely to be conflicting among them. In such a case, especially in multi-objective functions, it is advisable that a compromise solution, among the different objectives, is found (Eskandarpour et al., 2015). This, in order that the solution found is the one better addressing the three sustainability pillars. In order that a compromise solution is achieved, different methods can be used when solving the LRP. These methods are, according to the review performed by the same author, as follows:

- Weighted sum of the different objectives.
- Epsilon-constraint method.
- Metaheuristics tailored for these multi-objective models.
- Multi-criteria decision tools.

3.4. Chapter Conclusions

Throughout this chapter, it was reviewed the relevant literature related with LRPs incorporating ECVs into the considered fleet. It was identified the main reasons, found in the literature, that justify the necessity to change how SCs are planned. Namely, regarding the logistic processes towards SSCs and the main problematics arising when promoting these changes. Moreover, it was described the main characteristics and factors, also concerning the referred problematics, that are considered in the literature when formulating an optimization model. Namely, the LRP, as it is summarized in Table 3 and in the sub-section "The algorithms present in the literature".

At last, the main gap found on the literature concerns the inexistence, to the best of my knowledge, of LRP models considering the three dimensions of the TBL. Little attention has also been paid to LRPs, that consider solely ECVs, especially that address the distribution process into different points within urban areas. Moreover, from those that were found, not a single one considered other objectives than economic ones.

4. Problem Statement and Model Formulation

This chapter aims to present the main characteristics of the LRP model for the transition from a diesel-truck based operation into an e-truck based distribution. This, given the literature reviewed and a case study of a distribution process to fulfill the demand in different stores of a Portuguese Retailer, (Figueiredo, 2009). It is presented afterwards the mathematical formulation of the model to be developed in this dissertation. To this end, the chapter was divided into three sections. The first one consists of the problem statement, which includes the detailed problem description, the decisions supported by the model, its assumptions and the performance measures to evaluate the model results. The second section presents the mathematical formulation of the optimization model. Namely, the notation used in the model: sets, parameters and variables; the dimensions that constitute the objective function and the model constraints associated with this model. The third section concludes the chapter.

4.1. Problem Statement

This optimization model was created to address the LRP regarding the operation of a retailer's distribution with e-trucks, which helps to close the gaps, in the existing research, that were mentioned in the literature review chapter, namely:

- The little attention to LRPs, that consider solely ECVs, especially considering the distribution into different points within urban areas and also assess the location of recharging stations;
- Also, to the best of my knowledge, not a single one of these LRPs has considered other objectives than the economic ones. Thus, a single objective function that considers economic and environmental factors will be developed.

As a consequence, in this dissertation, it will be modelled and discussed important tactical-operational planning considerations, including whether or not recharging stations should be sited and, if so, where. It is also performed an assessment on the economic and environmental feasibility of the transition from a diesel-truck based operation into an e-truck based one.

Moreover, it is important to mention that the option for an e-truck instead of a PHEV was taken following the complexity that a PHEV would bring to the process. This since two energy sources would have to be considered and, also, because the end-goal is to understand if a distribution free of fossil-fuels is possible.

Lastly, the problem under analysis is defined as static, single echelon, where each customer (vertex) is visited once, departing from a single depot located outside the city. The distribution will be performed by the most suitable type of e-truck from the existing two types (21 or 24-pallet ECVs). They will leave the depot charged up to 80% and, when necessary, partial recharges, in the recharging points installed in the considered subset of the visited vertices, are possible. Lastly, it is also important to mention that no inventory decisions are relevant.

4.1.1. Problem description

This problem is based on the distribution into different stores ($i_d \in I$) of pallets to satisfy their daily demand, according to the data provided by the case study, (Figueiredo, 2009). These stores belong to a Portuguese Food Retailer group and the considered stores are located in the northern area of the Lisbon Metropolitan area and are served from a common distribution center located in Azambuja, ($i_c \in I$). This distribution process from the depot is still performed using diesel-trucks and the aim of this study is to test:

- Whether, or not, it is feasible to transition from a diesel-based operation into an e-truck based one;
- Whether, or not, one or more recharging stations need to be placed at the different stores in order that the operational flow is not compromised.

These stores are served using two types of trucks, one type with a load capacity up to 21 pallets and another type with a load capacity up to 24 pallets ($k \in K$). These trucks are able to supply the stores either in the morning or in the afternoon ($s \in S$), depending on the time-windows associated with each store. The truck is driven by the same driver throughout the day, that leaves, in each shift (morning or afternoon), up to two times the depot ($n \in N$). Nevertheless, to serve the total demand of the different stores, the model considers that there are up to three 24-pallet trucks and up to nine 21-pallet trucks, and respective drivers, available.

Depending on the number of times that each driver has already left the depot in a single shift, the battery load of the truck will be at the maximum level (80% of the total capacity) or not. Thus, in order to ensure that the operation with e-trucks is feasible, this problem assesses whether or not there is a need to locate recharging stations at one or more of the stores being served ($i_p \in I$). Furthermore, its results will also enable to understand what the costs are to operate the e-truck when compared to the diesel solution.

4.1.2. Assumptions

The model presents some assumptions, as it is not possible to model in detail the entire operation of the aforementioned retailer's distribution. The assumptions include:

- The usage of the case study's scope of stores, vehicles and products, (Figueiredo, 2009), as it will be further explained in the next chapter. However, it is also worthwhile to mention that the model developed for split deliveries was not considered so as to contain the computational complexity of the problem;
- It will not be considered varying daily demand values, traffic, battery weight or the battery decay impact on the recharging process as they would also greatly increase the complexity of the model. Nevertheless, these factors will be partially assessed with a sensitivity analysis developed in excel based on the routes returned by the model, as it will be further explained below;

- It was also assumed that the costs associated with the recharging stations in the depot would be computed by considering one recharging station per truck. This, in order that there is always a recharging station available while the truck is idle for the pallets' loading process and also considering that the e-truck will require recharging in every return to the depot. Moreover, since to the best of my knowledge, no other ratio was available in the literature, a conservative assumption was considered;
- Maintenance and operational costs were computed per km in order to simplify the mathematical model and also to enable a direct comparison between diesel and electric solutions.

4.1.3. Performance Measures

The results of the developed model will be assessed through a set of performance measures, which were defined based on the TBL objectives. The aim is to optimize the functioning of the retailer's distribution operation with e-trucks taking into the model economic and environmental considerations. It is also worthwhile to mention that it is considered a single objective function composed by two distinctive dimensions, which units were all converted into a monetary cost. Thus, the performance of the optimized operation will be assessed through:

- Economic dimension – analysis of the different cost drivers associated to the transition into an e-truck based operation, namely, the required investment (on the vehicle, on the batteries and recharging stations), the maintenance for both the vehicle and the recharging stations and the cost to operate the vehicle, namely in terms of electricity;
- Environmental dimension – the costs associated with carbon emissions, as a result of electricity generation, and also the costs associated with the battery decay throughout the project's lifespan.

4.2. Mathematical model formulation

This section presents the mathematical formulation of the optimization model developed to address the previously presented problem. This mathematical model is based on three different works, in particular, the original dissertation in which this study is based on, (Figueiredo, 2009). This because the base case formulates a model for the delivery into different stores, from a single depot, where demand must be met within the established time-windows, using the minimum number of trucks and routes possible.

However, this model was not sufficient to develop this dissertation, since it did not consider the specificities of serving stores using e-trucks, namely:

- The equations for the battery balance and the associated time for recharging and limited range of the vehicles;
- The equations for sitting recharging stations and to model the recharging process.

These were retrieved mainly from the model developed by (Schiffer & Walther, 2017). This model was more generic and, therefore, the need to use some restrictions for time-windows and trucks' capacity limitations from the case study, (Figueiredo, 2009). Furthermore, from (Schiffer & Walther, 2017) mainly two primary planning approaches for electric fleets were retrieved.

- The first approach prioritized routing decisions, considering the challenges posed by the limited driving range and lengthy charging times of electric vehicles.
- The second approach was centered on the decision to place charging stations, or not, and if so, where. This aimed to define what was the necessary charging infrastructure considering the routing problem associated with electric vehicles.

This simultaneous consideration allowed to better support the decision-making process for logistics fleet operators, as it is the case for the retailers' distribution operation.

Furthermore, for the results and discussion, it was also compared the results from the modelled e-truck based operation with what would be the results for the similar diesel-truck based operation. To this end, this model objective functions were based on the work developed by (Schiffer et al., 2021). In this research paper, it was directly compared the TCO of an e-truck and a diesel-truck and, therefore, the economic dimension component of the objective function was based on the major cost drivers defined in the research paper: investment, maintenance and operation. The author also mentions the environmental impacts of emissions generated from the electrical production, diesel consumption and battery decay.

This sub-chapter will also introduce, in the following sub-sections, the notation used in the mathematical formulation of the mixed integer linear programming model as well as it will explain the objective function and the constraints to be modelled.

4.2.1. Sets

The sets and indices used in the formulation of the model are as follows:

I	Set that comprises all potential vertices indexed by I ($I \in I$)
J	Set that comprises all vertices defined as the set of choices after I is visited indexed by j ($j \in J$)
I_C	Subset of vertices I that corresponds to the depot indexed by i_c ($i_c \in I$)
I_D	Subset of vertices I that corresponds to demand nodes indexed by i_d ($i_d \in I$)
I_P	Subset of vertices I that are potential recharging points indexed by i_p ($i_p \in I$)
K	Set of electric vehicles' capacities indexed by k ($k \in K$)
S	Set representing if the operation takes place in the morning or afternoon indexed by s ($s \in$ S)
N	Set representing the number of times the truck has left the depot indexed by n ($n \in$ N).

4.2.2. Parameters

The parameters required as input data for the model to be run are as follows:

Cost parameters

evu	The electric truck unitary cost without batteries (€/unit)
buc	The cost of a set of batteries per truck (€/unit)
dvu	The diesel truck unitary cost (€/unit)
rpu	The unitary cost of setting up a level 3 charging station (€/unit)
ele	The cost of electricity (€/km) for the logistics' business
die	The cost of diesel (€/km) for the logistics' business
mae	The maintenance costs of an e-truck (€/km)
mad	The maintenance costs of a diesel truck (€/km)
mar	The daily maintenance cost of a recharging station (€/day)

Bounds' parameters

bcap	The initial battery capacity (kWh)
bstr	The minimum battery recharging level (%), being the lower boundary that avoids range anxiety
bmax	The maximum battery recharging level (in %)
$fmax_k$	The maximum freight capacity of a truck k (number of pallets)
$cmax_i$	The maximum capacity that a truck must have to be able to operate in vertex **I** (number of pallets)
ea_i	The earliest arrival-time at the demand point i_c (min)
la_i	The latest arrival-time at the demand point i_c (min)
ts	The project's time span (min)
day	The duration (in min) of the workday
dyear	The number of working days per year
num	The number of vertices considered in the model

Coefficients' parameters

rr	The recharging rate according to the specifications of the recharging station (kWh/min)
rrs	The slower recharging rate after 80% of the battery capacity has been charged (kWh/min)
bdr	The battery degradation rate (€/km)
oek	The electricity consumption rate of an e-truck (kWh/km)
tx	The discount rate for the project evaluation

Environmental parameters

pco_2	The carbon price for emissions resulting from the trucks' operations (€/gCO$_{2\ \text{equivalent}}$)
carbe	The carbon intensity, in Portugal, of a km driven in an e-truck (gCO$_{2\ \text{equivalent}}$/km)
carbd	The carbon intensity of a km driven in a diesel truck (gCO$_{2\ \text{equivalent}}$/km)

Operational parameters

d_{id}	The demand to be fulfilled at a given demand point i_d (number of pallets)
dis_{ij}	The matrix representing the distance between two consecutive vertices I and j (km)
tim_{ij}	The matrix representing the time between two consecutive vertices I and j (min)
sf	The fixed duration to prepare the truck for the loading / unloading operations (min)
sv	The time required to load or unload a pallet from a truck at a demand point or depot (min/pallet)

4.2.3. Decision Variables

Binary Variables

X_{ijkns}	1 if the arc (I,j) is travelled by truck k that left n times the depot on shift s, 0 otherwise;
Y_{ip}	1 if a recharging station is located at vertex i_p, 0 otherwise.

Positive Variables

For vertex i:

A_{ik}	The arrival-time (min) of the truck k at the vertex I;
F_{ik}	The freight load (number of pallets) at a given vertex I, in truck k;

B_{jkns} The battery load (kWh) at a given vertex I, in truck k that left n times the depot on shift s;

$W_{i_p k}$ Amount of energy (kWh) charged at charging station i_p, in truck k;

U_i MTZ Variable.

Other variables:

Z Objective function variable

4.2.4. Model constraints

This subsection will introduce, based on the mentioned assumptions, the model constraints to which the model is subject to. The constraints are grouped by theme, given the specificities of the problem, and their scope is made explicit.

Location Routing Problem Constraints

$$\sum_k \mathrm{fmax}_k \times X_{i_c i_d kns} \geq \mathrm{d}_{i_d}, \qquad \forall i_d, i_c, n, s \tag{1}$$

$$\sum_i \sum_k X_{i i_d ks} = 1, \qquad \forall i_d, n, s \tag{2}$$

$$\sum_i X_{i i_p ks} \leq 1, \qquad \forall i_p, k, n, s \tag{3}$$

$$\sum_i \sum_k X_{ijnks} = \sum_i \sum_k X_{jikns}, \qquad \forall j, n, s \tag{4}$$

$$X_{iikns} = 0, \qquad \forall i, k, n, s \tag{5}$$

Constraints (1) to (5) are the constraints commonly used in deterministic LRP models' formulation. While (1) secures that all customer demand is served, single assignment for customer visits is obtained by constraint (2), meaning that each store is only visited once.

This single assignment constraint is relaxed for charging station vertices through (3). By allowing arcs ending in a charging station to be assigned multiple times, but only if a charging station is sited and visited at the vertex i_p.

Flow conservation for any scenario is enforced by (4), and (5) eliminates the hypothesis of vehicles retuning to the previous vertex.

Miller-Tucker-Zemlin (MTZ) constraint

$$U_i - U_j + \mathrm{num} \times X_{jikns} \leq \mathrm{num} - 1, \qquad \forall k, n, s \wedge 2 \leq \mathrm{i} \neq \mathrm{j} \leq num \tag{6}$$

The MTZ constraint plays a crucial role in the optimization problem described. It is used to eliminate sub-tours, which are smaller and disconnected routes and, therefore, optimizing and creating a more efficient problem resolution.

Recharging station Constraints

$$W_{i_p k} \leq \mathrm{bmax} \times \mathrm{bcap} \times Y_{i_p}, \qquad \forall i_p, k \tag{7}$$

$$Y_{i_p} \leq W_{i_p k}, \qquad \forall i_p, k \tag{8}$$

$$W_{i_p k} \geq 0, \qquad \forall i_p, k \tag{9}$$

The charging station location decision is linked to the routing and recharging decisions by constraints (7) and (8). Constraint (7) allows for recharging at vertex i_p only if a charging station is built in that vertex. Moreover, this constraint also limits the charging amount, mainly due to the fact that charging is only linear up to 80% of the total battery capacity, but also to minimize real-life degradation that results from a full charging cycle.

Furthermore, constraint (8) implies that a charging station has to be built at vertex i_p if recharging takes place at that vertex, and a charging station must not be built if no vehicle recharges at vertex i_p. Constraint (9) implies that any recharging only takes place if 1 unit of energy is charged into the battery.

Moreover, it should be noted that the aforementioned constraints allow trucks to recharge at every store possible, even if the truck is recharged at a store not served in that route. Thus, charging stations are only visited if recharging is necessary, since otherwise a shorter path exists. This also enables that these constraints can be used in models where charging stations might not be located in the same location as demand points.

Battery Constraints

$$B_{ikns} \geq \mathrm{bstr}, \qquad \forall i, k, n, s \tag{10}$$

$$B_{i_c kns} \leq \mathrm{bmax} \times \mathrm{bcap}, \qquad \forall i, k, n, s \tag{11}$$

$$B_{i_p kns} + W_{i_p kns} \leq \mathrm{bmax} \times \mathrm{bcap}, \qquad \forall i_p, k, n, s \tag{12}$$

$$\mathrm{B}_{\mathrm{jkns}} \geq \mathrm{B}_{\mathrm{i}_d kns} - oek \times dis_{i_d k} \times X_{i_d jkns} + \mathrm{bcap} \times \mathrm{bmax} \times \left(1 - X_{i_d jkns}\right), \qquad \forall i_d, j, k, n, s \tag{13}$$

$$\begin{aligned} \mathrm{B}_{\mathrm{j}kns} \geq \mathrm{B}_{\mathrm{i}_p kns} - oek \times dis_{i_p k} \times X_{i_p jkns} + W_{i_p k} \\ + \mathrm{bcap} \times \mathrm{bmax} \times \left(1 - X_{i_d jkns}\right), \qquad \forall i_p, j, k, n, s \end{aligned} \tag{14}$$

Range limitations due to battery capacity and recharging are modeled by constraints (10) to (14), by limiting it, in the lower bound to the “anxiety level” (bstr), where drivers start to get worried about range, as stated by (Booto et al., 2021), and to the upper bound to 80% in order to increase the battery life span and also to avoid extra recharging time, as the recharging rate significantly drops.

Constraints (13) and (14) obtain the energy balance, by linking the energy level at vertex I to the energy level at vertex j. Namely, by considering energy consumption (for the driven distance between the different vertices) and recharging (both for the arcs leaving recharging points and the battery level that the trucks leave the depot with) and also preventing the vehicles from running out of energy on the middle of the route. Thus, the state of charge of a vehicle is forced to be within the battery’s capacity range, meaning that the battery capacity will stay above the minimum level that avoids the stress inherent to low battery level, constraint (10), and also enforces the trucks, leaving the depot, have their battery level limited by (11) to 80% of the battery capacity. Constraint (12) enforces the amount of recharged energy will still enable that the battery stays within its capacity limits.

It should be noted, that for the formulation of the battery energy amount in the different vertices, only the matrix that represents the distance for the trip between two points is considered, since the energy consumption rate is in kWh/km.

Lastly, constraints (13) and (14) also allow modeling partial recharges without using an additional decision variable for the battery status at arrival and departure, common in other models, (Schiffer et al., 2018, 2021; Schiffer & Walther, 2017, 2018).

Time-window Constraints

$$A_{ik} \geq ea_i, \qquad \forall i, k \tag{15}$$

$$A_{ik} \leq la_i, \qquad \forall i, k \tag{16}$$

$$ea_i < 240 \Rightarrow s \leq 1, \qquad \forall i \land s \leq 1 \tag{17}$$

$$ea_i \geq 240 \Rightarrow s \geq 2, \qquad \forall i, k \land s \geq 2 \tag{18}$$

$$\begin{aligned} \mathrm{A_{jk}} \geq \mathrm{A}_{\mathrm{i}_d k} &+ \left(tim_{i_d j} + \left(sf + sv \times \mathrm{d}_{i_d}\right)\right) \times X_{i_d jkns} \\ &- \left(\mathrm{la}_{i_c} + rr \times bcap \times (\mathrm{bmax} - \mathrm{bstr}) \right. \\ &\left. + \left(sv \times \mathrm{d}_{i_d}\right)\right) \times \left(1 - X_{i_d jkns}\right), \qquad \forall i_d, i_c, j, k, n, s \end{aligned} \tag{19}$$

$$\mathrm{A_{jk}} \geq \mathrm{A}_{\mathrm{i}_c k} + \left(tim_{i_c j} + sf + sv \times \mathrm{d}_{i_d}\right) \times X_{i_c jkns}, \qquad \forall i_d, i_c, j, k, s \land n \leq 1 \tag{20}$$

$$\mathrm{A_{jk}} \geq \mathrm{A}_{\mathrm{i}_c k} + tim_{i_c j} \times X_{i_c jkns} + rr \times (bcap \times bmax - B_{i_c kns}), \qquad \forall i_d, i_c, j, k, s \land n \geq 2 \tag{21}$$

$$\mathrm{A_{jk}} \geq \mathrm{A}_{\mathrm{i}_p k} + tim_{i_p j} \times X_{i_p jkns} + rr \times W_{i_p k} - \left(la_{i_c} + rr \times bcap \times (bmax - bstr)\right) \times \left(1 - X_{i_p jkns}\right), \qquad \forall i_p, j, k, n, s \tag{22}$$

Constraints (15) and (16) obtain time window feasibility for all vertices.

Moreover, constraint (17) states that if the earliest arrival-time at a vertex I is below 240 minutes (morning shift), then the shift is the number 1. Whilst constraint (18) states that if the earliest arrival time is equal or above 240 minutes, then the shift is the second one (afternoon).

Time window constraints are given by constraints (19) to (22). Whilst (19) holds for customer vertices, (20) holds for charging stations. Every charging station is built at a customer vertex but represented with a different subset and, therefore, the first holds for demand points and the second one for charging stations located at stores. Following the previous equation, a tighter one (21) will hold when the truck leaves the depot a second time in a single shift and the recharging time takes longer than the loading operation. Thus, the time needed at the depot is the time for recharging until 80% from the initial battery level. Another constraint, (22), holds if it is the first time that the truck has left the depot since, in that case, only the fixed and variable operational times to load the pallets into the truck are considered.

Moreover, time-window restrictions only apply to demand points. This is because time-windows for recharging points and the depot are relaxed to consider the whole operation day, whilst for the demand points, the time-windows are limited to the earliest and latest arrival times stated in Fracisco Figueiredo model.

It should be noted that for the formulation of time-windows only the matrix that represents the time duration of a trip between two points is considered. There is no need to include the matrix for distance as the only parameter required is time.

In addition, it was also assumed that, when the truck leaves the depot for the first time in a given shift (in the morning or afternoon), there is no time lost for recharging, as the truck is either idle for the night or for the lunch time (which is sufficient to recharge up to 80% in every scenario).

Lastly, when returning to the depot for reloading, the time that can be used for recharging is the variable time (sv), which is the time spent at loading pallets. This is a consequence of the truck not being idle in the first 20 minutes when approaching the depot (fixed value for the operation – sf). Furthermore, the time spent at loading the pallets, before departing for a second route in a given shift, is not sufficient for recharging up to 80% in the presented model. Thus, it was assumed that the time spent at the depot was the fixed time (sf) plus the time required for recharging up to 80%.

Freight Constraints

$$F_{ik} \geq 0, \qquad \forall i, k \tag{23}$$

$$F_{ik} \leq \mathrm{fmax}_k, \qquad \forall i, k \tag{24}$$

$$\mathrm{F_{ik}} \geq \mathrm{F}_{i_d\mathrm{k}} - d_{i_d} \times X_{i_d jkns} + (\mathrm{fmax}_k) \times \left(1 - X_{i_d jkns}\right), \qquad \forall i_d, j, k, n, s \tag{25}$$

$$\left(cmax_j - fmax_k\right) \times X_{ijkns} \geq 0, \qquad \forall i, n, s \tag{26}$$

Freight constraints are given by equations (23) and (24), for the minimum and maximum number of pallets that each truck k is able to carry, this means being within zero and 21 or 24 pallets depending on the truck being considered for each route.

Moreover, constraint (25) computes that the amount of available freight at vertex j is reduced by the demand of freight at vertex I if arc (I, j) is covered, preventing the model to create arcs to new demand stores when the truck does not have the sufficient freight load to serve it.

Lastly, constraint (26) allows to ensure the operational unloading constraints at the stores are considered, since the truck capacity must be equal or lower than the maximum capacity that the store is able to receive due to its physical and/or operational constraints.

Binary Constraints

$$X_{ijkns} \in \{0; 1\}, \qquad \forall i, j, k, n, s \tag{27}$$

$$Y_{i_p} \in \{0; 1\}, \qquad \forall i_p \tag{28}$$

Binary variables are defined in (27) and (28).

4.2.5. Objective Functions

The optimization model presents a single objective function which is intended to be minimized. This choice was driven by the primary focus on simplifying the model's complexity, as the multi-objective approach did not converge satisfactorily, with a gap persisting at over 40% when using economic and environmental objective functions. This, because from 42,05% on, the progress was very slow and it was decided to stop the run after 16,736 seconds (about four hours and 38 minutes), with an approximate gap 41,97%.

To make this possible, the two terms of the objective function were converted to reflect only one unit and, therefore, all terms were monetized.

Moreover, all values were converted to daily costs for the company. This was done in order to directly compare the operational results, which will be modelled for a working day, between the electric and diesel-based operations. Furthermore, these daily costs will enable to calculate the project's costs over its life span of 5 years and, therefore, understand if the transition is feasible. This will be done since the operations of a retailer's distribution are similar every day (Figueiredo, 2009) and, therefore, the daily costs can be used for medium / long-term decisions.

Lastly, the main components of the different dimensions considered for this study are presented as follows:

- The economic dimension value (EcoC) equals the sum of three different terms: the investment cost to acquire e-trucks (InvC), the operational cost of distribution process (OpC) and the maintenance costs of the e-trucks (MainC);
- The environmental dimension value (EnvC) equals the sum of two different terms, the environmental penalty due to carbon emissions associated with the network's transport activities (CarbC) and the battery degradation cost (DegC).

Thus, the objective function can be written as follows:

$$Minimize\ Z = EcoC + EnvC + SocC = InvC + OpC + MainC + CarbC + DegC \tag{29}$$

Economic Dimension

$$InvC\colon \left(\sum_{i_c}\sum_{j}\sum_{k}\sum_{n}\sum_{s} X_{i_cjkns} \times (evu + buc + rpu) + \sum_{i_p}\sum_{k} Y_{i_p} \times rpu\right) \times \text{Actualization Constant} \tag{30}$$

$$Actualization\ Constant = \frac{\frac{tx}{dyear} \times \left(1 + \frac{tx}{dyear}\right)^{dyear \times ts}}{\left(1 + \frac{tx}{dyear}\right)^{dyear \times ts} - 1} \tag{30.1}$$

$$OpC\colon \sum_{i}\sum_{j}\sum_{k}\sum_{n}\sum_{s} ele \times oek \times dis_{ij} \times X_{ijkns} \tag{31}$$

$$MainC\colon \sum_{i}\sum_{j}\sum_{k}\sum_{n}\sum_{s} mae \times dis_{ij} \times X_{ijkns} + mar \times \left(\sum_{i_p}\sum_{k} Y_{i_pk} + \sum_{i_c}\sum_{j}\sum_{k}\sum_{n}\sum_{s} X_{i_cjkns}\right) \tag{32}$$

As stated, the economic dimension aims to minimize the number of vehicles to be acquired and, consequently, batteries, as well as the number of recharging stations to be installed and the inherent maintenance and operational costs to run the acquired material.

The investment part, represented by equation (30), is composed by two parts. One is dependent on the number of trucks leaving the depot. This part is computed multiplying the acquisition costs per item (e-truck, battery set and recharging station) by the number of trucks leaving the depot. This is because, each e-truck requires:

- its set of batteries acquired separately from the vehicle;
- its own recharging station at the depot, which as previously mentioned, is likely to be a conservative assumption.

The second part of the investment cost is dependent on the number of recharging stations placed at the stores (a result of the binary variable Y_{ip}: whether recharging stations are placed at stores or not). In case the model results in one or more recharging stations to be placed at the stores, this value is then multiplied by the unitary cost of setting up a recharging station.

All values for the investment were then transformed into daily fixed costs. This was done by multiplying the total acquisition costs by a constant referred to as the "Actualization Constant", described in equation (30.1). This constant was calculated by the Present value formula, which computes the present value necessary to be paid considering the actualization rate, the number of payments and the time span of the project. The result, is therefore, a value that considers both the acquisition costs, divided by the time span of the project, and the associated interest rate, which will be explained below.

The Operational Costs, equation (31), regard the electric consumption of the e-truck in a day of operation. This value is calculated by multiplying the total distance that the trucks travel by the consumption rate (kWh/km) and by the electricity cost (€/kWh).

Moreover, the expected daily maintenance costs, equation (32), for both the e-truck and the recharging station are computed as follows:

- The maintenance costs for the truck are computed multiplying the total distance travelled by the different trucks by the expected maintenance costs per km driven (€/km);
- The maintenance costs for the recharging station were calculated multiplying the expected daily maintenance costs by the number of charging stations that are to be placed, both at the depot and at the different demand points.

Environmental objective

$$CarbC\colon \sum_i \sum_j \sum_k \sum_n \sum_s carbe \times pco_2 \times dis_{ij} \times X_{ijkns} \tag{33}$$

$$BatC\colon \sum_i \sum_j \sum_k \sum_n \sum_s buc \times bdr \times dis_{ij} \times X_{ijkns} \tag{34}$$

The environmental objective aims at minimizing both the carbon emissions and the battery degradation. As previously referred, both values are to be computed in Euros so that only one unit is considered. The calculation to minimize both factors is presented below.

Carbon Emissions' penalization factor is estimated by equation (33) that computes the cost of carbon emissions from the transport activities. It is composed of three terms: the equivalent CO_2 emission rate generated by the electricity consumed (in $g_{CO_2\ \mathrm{Equivalent}}$/km) multiplied by the distances travelled and by the carbon price (€/$g_{CO_2\ \mathrm{Equivalent}}$). The price considered regards the carbon emissions' spot price in the EU market for September 20, 2023. This equation results in the daily value for the cost of the CO_2 generated by the electric consumption of the vehicle.

Lastly, according (Basso et al., 2022), the battery degradation rate is accounted as the impact that each recharge has on the Total Cost Ownership of the battery, meaning the more times a battery is fully recharged, the more it costs to own it. Moreover, according to the same author, minimizing the battery decay and, therefore, increasing the life span of the battery also reduces the impacts caused by batteries' production. Nevertheless, in this model, the calculation of this impact in equation (34) was not done per recharging cycle but through driven distance. This is because the constant that could be found in literature computes the degradation rate per driven km, (Schiffer et al., 2021).

The factor is, therefore, estimated by multiplying three terms: the battery degradation rate factor, the travel distance and the cost of the battery. The battery degradation factor is a factor that was updated from a yearly value (based on an assumption of km driven and number of charging cycles) to a value that is in % of the battery that degrades per driven km. This factor is then multiplied by the cost of the battery and by the driven kilometers. This results in the daily value of the battery that is lost due to degradation.

4.3. Chapter Conclusions

In this chapter the problem was formally stated. However, the focus is placed on the optimization model that was presented. It is intended that this optimization model assists in the decision-making process regarding the routes to be considered when supplying the stores with e-trucks, also if charging stations need to be placed and how many trucks (from each capacity type) are required for such an operation.

The solution approach that is proposed conforms to exact methods given that the model has, as its resolution method, a mixed integer linear programming model. The main features of the model, which provide added value to the existing literature, are that it simultaneously assesses the operational feasibility of the transition from a diesel-truck based operation into an e-truck based one, combined with economic and environmental concerns.

Moreover, it is a tactical-operational model based on the daily operational characteristics of an e-truck operation. Nevertheless, it aims at planning the medium and long term of the new operational se-up, since varying daily demand can be neglected, also according to the base case study.

Some additional assumptions are also considered, namely the fact that traffic conditions and battery decay impacts on the recharging process are neglected in the model. Nevertheless, this neglected factors on the model will be partially assessed on excel models developed based on the routes returned by the presented model.

Furthermore, the presented model will be applied to the case study based on (Figueiredo, 2009) case study that is presented in the following chapter.

5. Case Study and data collection

This chapter aims to present the case study in which this dissertation is based along with the data that was collected to run the model previously presented. The data was gathered both from a previous dissertation work (Figueiredo, 2009), but also from the work developed by (Schiffer et al., 2018, 2021; Schiffer & Walther, 2017, 2018) since, as previously mentioned in the model formulation chapter, this author presented the generic mathematical formulation for a Location Routing Problem. Moreover, the same research papers also presented the required data to run the model and also the data required to compare the e-truck and diesel-truck operations.

Thus, this chapter presents the Portuguese retailer's distribution case study, why it was chosen as a basis for this dissertation, along with the data that was collected from the study and the division per type of parameters. This data gathering is further developed with the data collection resulting from the research papers developed by Schiffer.

5.1. Portuguese Retailer case study

This study is based on the existing study carried out by (Figueiredo, 2009) on the distribution from the retailer's distribution center located in Azambuja to a set of different stores located across the northern part of the Lisbon Metropolitan Area.

This study was used as the basis for this model feasibility assessment since it presents a type of operation where the distribution using e-trucks is usually feasible. Furthermore, the results obtained by using such a case study can be used to directly compare the as-is situation and the to-be (with e-trucks), this considering the comparability study performed by (Schiffer et al., 2021). As a consequence, the model, that was developed considering a real-life scenario, was considered to be suitable for the analysis.

5.1.1. The case study

The base case aimed at creating a model that was able to optimize the distribution process, and the associated costs, from the depot into the different stores, considering the logistic difficulties posed by carrying out the distribution of goods in densely populated areas. This, since as referred by (Figueiredo, 2009), it was evident from the parameters of the case that each of its components – the total number of stores, the total number of trucks, the types of stores and vehicles to be considered, the delivery schedules, and the time windows – would conduct to a study with a high level of complexity. Thus, it would be quite difficult to analyze the retailer's full distribution situation.

As a consequence, the base case aimed at creating a model that considered a group of representative stores in the Lisbon area. Thus, this chapter explains what stores were considered and the rationale behind that decision. The main goal was lowering the complexity associated with the problem-solving process but, at the same time, creating a model that would effectively improve the distribution process of the retailer.

5.1.2. Selection of stores to consider

From the perspective of distribution operations, retailers located in crowded metropolitan areas face logistical difficulties in terms of accessibility and unloading procedures. It is noted in (Figueiredo, 2009) that unloading operations are usually carried out under subpar circumstances in several stores. This is because many of the retailer's supermarkets are located in buildings that were not built with commercial uses in mind and do not have designated unloading docks. Drivers commonly encounter establishments that either lack dedicated parking spaces for their trucks or have limited storage space, both of which frequently make it more difficult to handle pallets during unloading operations.

Moreover, and according to an assessment performed in the base case, 65% of the stores located within the urban parameter of Lisbon lack any infrastructure to aid in unloading operations. This implies that vehicles serving these stores must necessarily have a liftgate for pallet unloading. The absence of a dedicated unloading dock with corresponding alignment to the truck results in slower unloading operations.

As a consequence, in the base case, it was used a set of steps in the base case to choose a specific group of stores in the northern part of the Lisbon Metropolitan Area. The goal was to have a group that would accurately represent how the retailer operates in that area.

The first step was the classification of the stores into two separate groups, each with different and complementary time-windows. As mentioned in the base case study, it was only considered the merchandise sent from the Azambuja-based warehouse for non-perishable products, one of the several existing warehouses, in order to simplify the model.

It was also considered a fix set of 40 stores in the analysis. Then, the area in which the study was carried out was further narrowed down to the area along the Tagus River using a strict set of criteria:

- Small and medium sized stores in the Lisbon Center, Greater Lisbon, and Cascais Line regions that are dispatched in the morning;
- Small sized stores in the Cascais Line region that are dispatched in the afternoon, along with some Greater Lisbon stores near the Cascais Line region that are also dispatched in the afternoon;

In the original dissertation, it was chosen stores from two distinct time periods in order to simplify the complexity of the problem when running it, as it could be applied to these separate sets of stores. However, in the present dissertation, the model was not run separately between the morning and the afternoon stores, in order to optimize the operations at the full day level.

Nevertheless, in the context of the actual daily dispatch planning from the distribution center, the operational schedule is also divided into two independent time periods. This division also occurs due to the fact that dispatch activities primarily occur during the early morning hours, spanning from midnight to 7 a.m. However, in the base study, it was considered different time-windows. The first time period encompassed stores that should be visited from 7 a.m. and up to 11 a.m., while the second time period comprised stores dispatched in the afternoon, starting at 2p.m.

Moreover, it is also worthwhile mentioning that some stores' typologies that were excluded, namely:

- Stores that required a specific, smaller vehicle for visiting were excluded as a result of the vehicles' reduced capacity, that would encompass more trips between distribution centers and the stores requiring such vehicles;
- It was also excluded stores that required to be served by vehicles with lower heights than the standard ones, as these vehicles would limit the type of pallets they are able to carry to a specific height when constructed at distribution centers, making it impossible to transport pallets of standard height in these specific vehicles. Thus, limiting the applicability of these vehicles to all stores.

The selected stores based on the criteria defined in the original study are listed in figure 5. A coordinate system (x, y) in kilometers was established based on a store location map extracted from the company's route planning software to determine the spatial distribution of the selected stores.

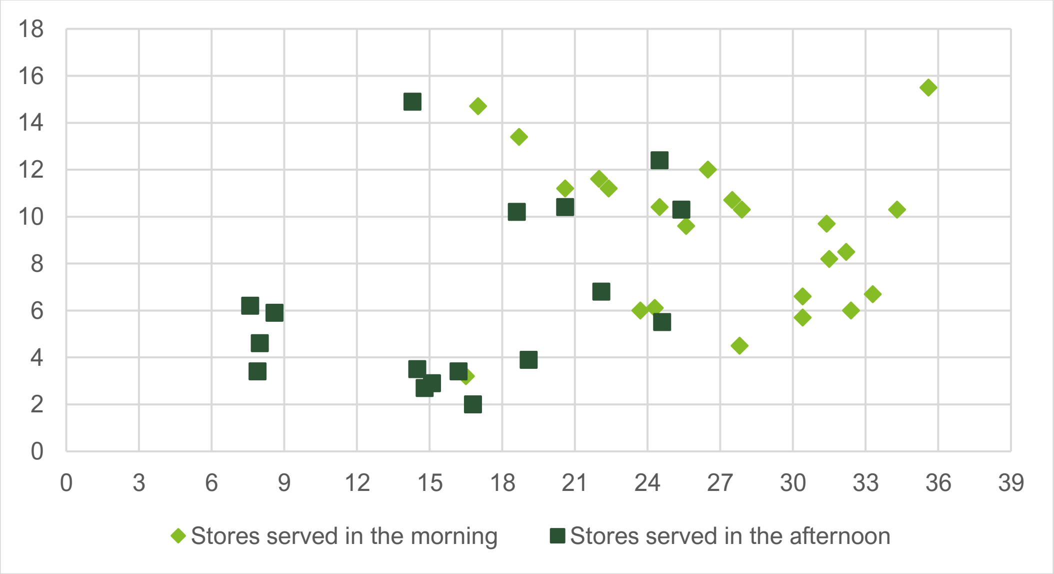


Figure 5: Store location in X and Y axis (the distribution center is not included)

5.1.3. Parameters deriving from the case study

Based on (Figueiredo, 2009), it was possible to retrieve different parameters for the study under development. In this sub-chapter, it will be presented the relevant values for this dissertation along with their context.

Operational Parameters

The operational parameters were all retrieved from the original study:

- Demand (d_{id}) to be fulfilled at a given demand point is represented in Table 4, considering the values in the original study were, at most, 3 trucks with 24 pallets' capacity and, at most, 9 trucks with 21-pallets' capacity;
- The maximum capacity that a truck might have to be able to serve each store i (cmaxi) is represented in Table 4;
- Both the earliest (eai) and latest (lai) arrival times at the different stores are also represented in Table 4;
- The matrixes representing both the distances (dis_{ij}) and time (tim_{ij}) between the different vertices are represented in Appendix A and Appendix B, respectively;
- Regarding the duration for the loading and unloading operations, the time required at each store / distribution center was fixed at, at least, 20 minutes. This value was considered the fixed duration of the loading/unloading operations (sf);
- It was also considered a variable duration (sv), which regards the expected time it takes to load or unload one pallet, which was estimated to be 2 minutes, this was due to the fact that the driver was limited to unloading two pallets at a time and also by the time it takes for the liftgate to raise and lower between the ground and the truck.

Bounds' parameters

Regarding the bounds' parameters, they were partially retrieved from the original dissertation, namely the following ones:

- The maximum truck capacity of the trucks to be considered in the simulation ($fmax_k$), considering the values in the original study were, at most, 3 trucks with 24 pallets' capacity and, at most, 9 trucks with 21-pallets' capacity;
- The maximum capacity that a truck might have to be able to serve each store i ($cmax_i$) is represented in Table 4;
- Both the earliest (ea_i) and latest (la_i) arrival times at the different stores are also represented in Table 4.

Table 4: Characteristics of the stores to be served

Stores served in the morning (7h - 11h)			**Stores served in the afternoon (14h - 17h)**		
Truck's maximum capacity to serve the store	Store	Demand (number of pallets)	Truck's maximum capacity to serve the store	Store	Demand (number of pallets)
21	Queluz II	15	21	Miraflores	7
	1º Dezembro	8		Carcavelos	10
	Graça	21		Cascais	14
	Restelo	17		Massamá	19
	Lapa	13		Mem Martins 2	18
24	Alfragide	14		Queijas	16
	Reboleira	17		Serra da Mira	0
	Benfica	9	24	Damaia	5
	Oeiras	21		Rebelva	11
	Massamá II	8		Cascais-Villa	13
	Queluz	15		Alto da Barra	7
	Tomás Ribeiro	11		Colina do Sol	16
	Duque d'Avila	20		São Marcos	11
	Fonte Nova	7		Alvide	26
	Almirante Reis	12		Sassoeiros	19
	Ferreira Borges	11		Carcavelos II	12
	Olaias	9		Alapraia	15
	Sacavém	12		Paço d'Arcos	11
33	Rinchoa	4	33	Linda-a-Velha	23
	Agualva	20		Carnaxide	7

Lastly, the presented values, which were the ones that could be retrieved from base case were not sufficient to make a meaningful comparison between the retailer's operation using an e-truck or a diesel-powered truck. To do so, it was considered by (Schiffer et al., 2021), where equivalent electric and diesel-powered solutions were compared. This was done by considering the specificities that each solution presents, namely in terms of operational limitations, environmental impacts and costs.

5.2. The data retrieved from literature

The remaining parameters' values were based on the different values provided by the research papers previously mentioned. This was done for the sake of comparability and because, as mentioned, the thesis this work is based on, does not present the values used for the calculation (in terms of costs).

Moreover, the parameter values regarding costs refer to 2020 and were then adjusted considering the inflation rates for 2021 and 2022. The usage of the values is also explained by the fact that, in his article, it was considered different sources for computing the values to be used in both types of trucks (ICEs and EVs). Also, because the trucks used in the research paper were comparable to the ones used by the retailer in its distribution operations.

Thus, this sub-chapter will present the context and values for the remaining parameters that could not be retrieved from base case study.

5.2.1. Vehicle Characteristics and Costs

For diesel-powered trucks, the average investment cost in 2020, is of 75.000€ (dvu). Operational costs are computed considering a fuel consumption rate of 0,19l/km, a fuel price for freight companies of €0.96/L, resulting in 0,18€/km (die), and maintenance costs of 0,26€/km (mad). Given the mature state of ICEV technology, it was assumed no significant technological advancements or price fluctuations during the study period.

In contrast, e-trucks in the same medium-duty class have still little offer in the market. Nevertheless, it was found that on average, the e-trucks, for this capacity segment, had a price of 160.000€ (evu).

Still very few articles explore the cost of leasing an e-truck and, since the data for this parameter is scarce, it was not considered for this study, as it was considered in the base case study. Thus, it was considered the acquisition cost divided by the operation days in order to be aligned with the data and results available from the base case study.

Operational data for e-trucks is also scarce, but (Schiffer et al., 2018) found that a study carried out by ELMO (Electrified Commercial Transport in Urban Areas), provided valuable insights. TEDi participated in this project, operating two e-trucks within a 70 km radius of their central warehouse (similar to the model conditions). This study has, therefore, allowed the derivation of real-world conditions, such as, energy consumption and recharging rates. Namely, because the trucks were operated for 158.209 km and 274.491 kWh of energy was consumed, meaning a consumption rate of around 1,74 kWh/km (oek). Operational costs are computed using an average energy price (ele) of 0,13€/kWh and distance-dependent maintenance costs of 0,13€/km (mae).

5.2.2. Battery Data

(Booto et al., 2021) presented a battery price model that incorporated a learning curve that considered the market prices from 2010 to 2016 and projected the costs up to 2030, this model estimated battery costs at €125/kWh for 2023, which matches other sources, such as (Basso et al., 2022). This represents, for the considered maximum available capacity on the market, for this type of e-trucks, of 450kWh (bcap), with an associated cost of 56.250€ (buc).

Regarding battery degradation, which accounts for calendar and cycle aging, the research paper assumes a residual capacity of at least 80% after five years of use, with a worst-case scenario for annual degradation rate of 4%. According to the author, this is based on Field experiments that have shown that batteries have a residual capacity of at least 80% after 3000 full charging cycles. Thus, a capacity of at least 80% remains after a five-year utilization period (the project's life span – ts), assuming 260 working days per year (dyear) and a conservative maximum of two full charging cycles per day or three recharging times up to 80% (bmax), which is suitable for the case associated with this dissertation. The 4% degradation per year is, therefore, a worst-case estimation that will be considered in this model in order not to favor e-trucks (as the author did in his study).

Thus, by considering the current price of the battery and the estimated degradation after 5 years and considering the same time span for this project, then the estimated daily cost regarding degradation is of 0,008€/km (bdr).

5.2.3. Charging Station Data

As stated by (Schiffer et al., 2018), in mid-haul logistics, fast charging stations are essential. Existing 50 kW to 450kW fast charging stations have setup costs ranging from 4.000€ to 44.000€, dependent on location and network topologies. It was assumed, based on the given data, that the most suitable values for this study would be the maximum recharging capacity which entails the highest unitary cost per charging stations, from the values above, meaning a recharging rate of 450kW (rr) and a unitary cost of 44.000€ (rpu). Moreover, the same author states that maintenance costs are estimated, for 2020, to be 243,66€ per year (mar).

As previously mentioned, it was assumed one charging station per vehicle, a choice that may be overly conservative, however, I could not locate data to justify an alternative ratio selection.

Moreover, it was shown by (Booto et al., 2021) that the charging curve changes linearly until 80 % of the battery capacity and then grows at a slower pace (logarithmic) but, on average, a 60% slower pace can be considered between 80% and 90% when compared to the recharging rate up to 80%, meaning that between 80% and 90% the charging rate stands at 160kW (rrs), on average. Moreover, since having a full charge takes a much longer time, it is assumed as a standard constraint that all the vehicles are charged until 80 % of their battery capacities, which was also the case in (Schiffer & Walther, 2017, 2018). The recharging rate over 80% was only considered in the excel model developed separately to assess the operational impacts after the battery has decayed 20%, at the end of its lifespan.

5.2.4. Environmental Parameters' data

The environmental parameters for diesel trucks consider the well-to-wheel CO_2 (in grams) emissions by a Euro VI truck of the same category as the e-trucks considered for this model, which entails a carbon emission of 716 gCO_2/km (carbd) traveled.

Regarding the e-trucks carbon emissions costs, it was used the values provided by the author from Germany, which were then updated for the Portuguese reality, knowing that the Portuguese electric grid is more environmentally friendly than the German one, as the data utilized indicates emissions of 288 gCO_2/km traveled in Germany. Thus, it was calculated what would be the value to be considered for a Portuguese distribution operation. This calculation considers the carbon intensity of the Portuguese electric grid in 2021 at 250 $kgCO_2/kWh$. Consequently, emissions per kilometer traveled in Portugal amount to 172 gCO_2/km (carbe). Thus, considering the current spot price for carbon emissions in the EU of 86,49€/ton (pco_2), (Trading Economics, 2023), the associated cost with the usage of electricity in Portugal can be calculated to be of 0,015€/km.

5.2.5. Actualization parameters

It was considered actualization parameters in order that the opportunity cost is considered into this study. Thus, this actualization rate was computed by considering the 12-month Euribor rate, which at the moment of this study stand at 4,16% plus the risk-free return percentage, which is derived from the Portuguese 10-year Treasury bonds that, by its turn, stand at 3,40%. Thus, the total rate used for this project is 7,56% yearly (tx).

Moreover, all the economic values that were presented are based on the study from (Schiffer et al., 2021) and, therefore, as previously mentioned, all the values refer to 2020 costs and have been adjusted for the inflation rates observed in both 2021 and 2022.

5.3. Chapter Conclusions

This chapter presented the case study in which this dissertation is based on, along with the parameters that could be retrieved from the mentioned dissertation. Furthermore, it was also presented the remaining parameters required to run the model presented in the previous chapter. These values were retrieved from the research conducted by Schiffer, as this research assessed the lifecycle costs for both diesel and electric vehicles in similar LRP problems to the one presented in this dissertation.

These values therefore enabled to run the model, which results will be presented and discussed in the following chapter of this dissertation.

6. Results and discussion

In this chapter, it will be presented the results retrieved from the application of the mathematical model previously presented.

The chapter starts by assessing the feasibility of moving from a diesel-based operation into one based on e-trucks, this considering the case-study previously described. Following that, it will be presented whether or not the results are comparable to the original model, which was based on real daily operations of the retailer. Moreover, it will also be presented the main take-aways that these results enable for other situations, namely a wider-radius operation and, lastly, a sensitivity analysis on the different drivers is presented.

It is also worthwhile mentioning that the mathematical model was run using the GAMS modelling system through the IBM ILOG CPLEX 35.2.0 solver in multi-thread mode on a computer with an Intel® Core® i7 processor with 1,8GHz and 8,0 GB of RAM.

6.1. Feasibility of the e-trucks implementation

In this sub-chapter, it will be presented the results, for the three dimensions of the model previously presented and it will be discussed the feasibility of the transition, through analyzing if:

- The operations are not disrupted, meaning that the operational set-up is feasible with an e-truck based operation;
- Whether or not the operation is economically viable;
- Assessing the environmental impacts of the transition.

6.1.1. Model application

The results when running the model show that the operation with e-trucks is feasible without major impacts in daily operations, at least when batteries are new. This, for the considered conditions and for the current battery maximum capacities (450kWh), quick recharges up to 80% and battery levels that never go below the anxiety levels.

As it is possible to state in Table 5, the minimum battery level that the battery will have upon return to the depot is 14%, which is only slightly above the minimum value to avoid range anxiety, that stands at 13%, according to (Guo et al., 2018a). That was the main driver to only consider the maximum capacity currently available on the market for these types of e-trucks, since any capacity below would greatly impact the anxiety generated for the drivers. Nevertheless, as it will be explained below, when assessing the operational feasibility with a battery decay up to 20%, it will be possible to run the operation if the maximum recharging is increased up to around 90% whenever required.

Table 5: Energy remaining upon return to the depot after serving each store (as % of total battery)

	1st time truck left the depot	2nd time truck left the depot	3rd time truck left the depot
24-pallet trucks' routes	43%	36%	38%
	40%	29%	14%
21-pallet trucks' routes	43%	37%	33%
	43%	36%	28%
	43%	41%	27%
	39%	28%	26%
	22%	22%	-
	38%	29%	24%
	30%	36%	40%

The battery decay was not modelled mathematically as it would increase the complexity of the model. Nevertheless, by considering the same routes as the ones resulting from the mathematical model, an excel model was created to test the feasibility of the current operation throughout the lifespan of the project, considering the same recharging rates and loading/unload times, the overall operation would have little impact.

This happens because only one of the routes requires an extended recharging time when compared to the time required with a new battery. The impacted route is the one operated by the 24-pallet trucks that serves 3 stores and, in the last store served the truck has a battery level close to the minimum "anxiety level", in which the truck arrives at the depot, when the battery is new, with 14% capacity. Thus, it was performed the excel simulation in order to assess the feasibility of the model under study, which considered:

- A 90% maximum charging level of the total battery capacity (already considering the 20% decay) when leaving the depot and a minimum of 15% (meaning 13% level when new) when returning to the depot;
- For this simulation, it was also considered the lower recharging rate when the battery level exceeds 80%, where the recharging rate drops on average 60%;

This results, conserving the overall operation, in a time increase of 7,2 minutes (the extra time required for the battery to achieve 90%), this would entail an extra cost of 1,48€ to the company (in overtime), an overall operational cost increase of 0,11%. However, this could be mitigated by using the trucks with the newest set of batteries in these routes and using trucks equipped with older sets when serving routes that do not demand as much energy consumption. Thus, the overall efficiency of the operation could be improved. Nevertheless, this is likely to be only possible in a company that has at its disposable a significative number of vehicles with different ages. A small operator would probably be more impacted by this inefficiency in the operation.

This enables to conclude that, even when batteries are not new, it is possible to charge up to 90% of the new maximum battery level and still run the operation always above the minimum level of battery that prevents the anxiety to the driver, this for a project lifespan of 5 years. Thus, this model seems applicable to the daily operation of the retailer, as it considers an extended set of stores, empiric lead times and parameters streamed from different sources and put together by (Schiffer et al., 2018; Schiffer & Walther, 2017, 2018).

6.1.2. The need to reharge the e-truck

The recharging infrastructure is key for the e-truck operations, namely its location within the area being served and its recharging capacity. Thus, discussing the implementation of an e-truck based operation means having charging stations adapted to the needs of the distribution center, since a fast recharging, within the time that the truck is usually idle, significantly reduces, or even eliminates, the downtime of electric trucks caused by the extra time spent recharging them. The fact that, quick charging stations can typically provide a substantial charge in a relatively short amount of time, such as 20-30 minutes means that in operations where trucks are idle during the lunch or other breaks. Namely, the waiting time for loading and unloading, quick charging can be performed during these periods, if the required recharging capacity is correctly assessed.

As a consequence, this model assessed whether or not it would be necessary to place recharging stations at the stores in order that the operation could be put in place without creating further inefficiencies caused by the limited range.

These potential inefficiencies were not the case for the model developed, since as previously mentioned, the time spent loading the truck at the depot (the variable time of 2 minutes per pallet) will be sufficient for most of the battery recharging for the recharging capacity that was considered, 450kW. This was also the case even with battery decay, since the most relevant impact was the increase of 7,2 minutes in the overall operation in the end of the batteries' lifespan. Where the increased cost due to overtime was inferior to placing a recharging station at the store being served.

This means that in-store charging is not required in normal operating conditions for this type of operation (small radius of operation and regulars returns to the depot). Nevertheless, for operational resiliency, if no publicly available options for fast charging are available and, given that conditions are never perfect, it would be advisable to locate a single charger at a central point within each cluster of stores. This, in order to avoid disruptions caused by unexpected events (such as roadworks, accidents, traffic jams or other situations that may lead to considerably longer routes or extended waiting times for the truck).

6.1.3. The effective range of an operation with e-trucks

The current model also assessed the effective range that current batteries, when new, would enable the truck to have when leaving the depot with an 80% charging level, considering the anxiety level at 13% as the lower bound, this would result in an effective range of 168,2 km. Which is a higher value than the maximum distance from the distribution center to the farthest store and back (total distance of 158km). Thus, in urban areas, en-route or in-store charging is generally not required, as the truck will likely be able to recharge when it returns to the depot. Thus, it can be concluded that:

- For the considered case study, the primary constraint is the truck's capacity rather than battery capacity. Trucks, for the considered parameters, need to return to the distribution center before any recharging becomes necessary, because they run out of goods and therefore a new loading of products is required before the battery runs-out;
- With real-world consumption, a truck, if charged up to 80% is able to serve stores within an 84km radius from the distribution center. However, stores located farther away will therefore require in-store recharging with dedicated charging stations in order to be served efficiently with e-trucks.

Lastly, it is important to note that the 80% charging threshold is set to optimize battery health and longevity while still providing sufficient range for urban deliveries and, therefore, this value was used for the aforementioned take-aways.

6.2. The costs to operate an e-truck

It was also performed a comparison between the e-truck operation and the diesel one. Such was done by computing the life cycle costs of the project, which were based on the daily operational costs previously presented. The option for computing the total cost of the project based on the daily operational cost derives from the fact that the model is based on a daily routing optimization, considering the daily demand of the stores being served, which does not vary significantly over time, according to (Figueiredo, 2009).

As a result, it was possible to explore the differences between the TCO of a diesel-truck based operation and the one for an e-truck based operation. This, considering:

- The economic dimension of the project, namely in terms of acquisition costs (the vehicles, the batteries and the recharging stations), maintenance and the operational costs (i.e., the energy required to run the trucks);
- The costs associated with the total emissions for both types of trucks.

It was also assessed the case for an operation without charging stations being placed, only because a diesel station is also normally set up at logistic hubs and those costs were not considered in the reviewed literature nor they were, as a consequence, considered in this study. Thus, it was performed a direct comparison of e-truck operation and diesel-truck operation and also a comparison for the case where recharging stations' set-up is an additional cost to the e-truck operation. This analysis will be presented and discussed below for the three dimensions of the study.

6.2.1. The comparison between electric and diesel trucks

Firstly, it is presented the comparison between the costs to operate the e-truck (which were assessed by the model previously mentioned) and also the costs of operating a diesel-based operation. These were computed, in excel, by considering the routes returned by the model, as well as the parameters for diesel trucks previously presented. This was done to avoid further complexity when creating the mathematical model and, at the same time, be able to directly compare the benefits of the transition into e-trucks.

The information for the daily costs for the three scenarios that were considered in this analysis are presented in Figure 6, below. The values associated with the graph mean that there is an overall cost reduction (when considering charging stations' costs) of 32% and a cost reduction (not considering charging stations) of 34% when comparing to the as-is operations.

As it will be further explained, the major driver is the economic dimension, since it corresponds to 91,2% of the total costs, on average, for the three scenarios that were assessed. The economic dimension represented a bigger share (2,7% more than the diesel-truck scenario) of the total costs in the e-truck operation. This is because the costs associated with the emissions of the energy consumed is relatively higher in the diesel-truck operation.

The different costs associated with the different scenarios and the different dimensions will be further explored below.

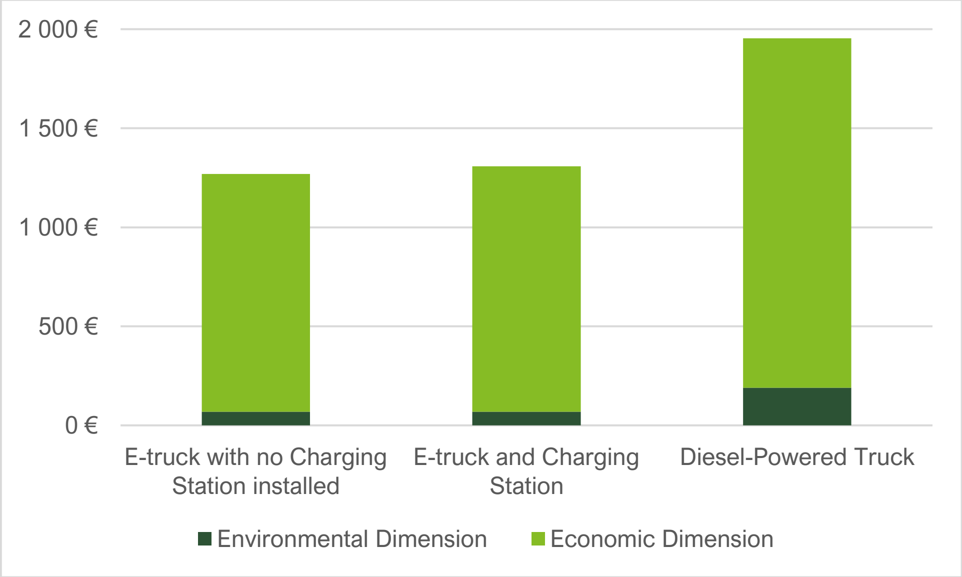


Figure 6: Break-down on the three BTL dimensions: economic and environmental

Economic Dimension

As can be observed, the economic dimension is the main driver in all the scenarios presented. It is also where the main absolute difference is the highest between the e-truck and diesel-operation. This is because, the economic cost of operating a diesel vehicle, under the considered model is 1.764€ per day, while the cost of operating an electric vehicle is 1.200€, per day (a 564€ difference), which implies that, from an economic point of view, operating a diesel truck entails a 47% higher cost.

If one charging station for every truck is considered, then the cost of operating an e-truck increases by 3% to 1.239€ per day.

Furthermore, the economic factor analysis was further broken-down to assess the impact of the different dimensions within the economic dimension: investment, operation and maintenance. This break-down can be seen in Figure 6, below. Furthermore, as it will be seen in further detail bellow, the maintenance and the operational costs (i.e., energy) are the major costs drivers for diesel trucks (representing on average 13 times more daily expenses than the amount that the investment represents), whereas the different cost drivers for an e-truck based operation are more balanced amongst the different drivers (investment, maintenance and operation). Nevertheless, the daily cost of operating the e-truck is 3,47 times higher when compared with the investment driver and the cost to maintain the e-truck is 2,55 times higher.

Thus, these two factors represent the main reasons why the e-truck operation is, economically, more attractive than the diesel based one. Despite the fact that the upfront costs are higher, throughout the lifespan of the assets, the investment has a return through significantly lower daily expenses to run the operation, which will be further explained below.

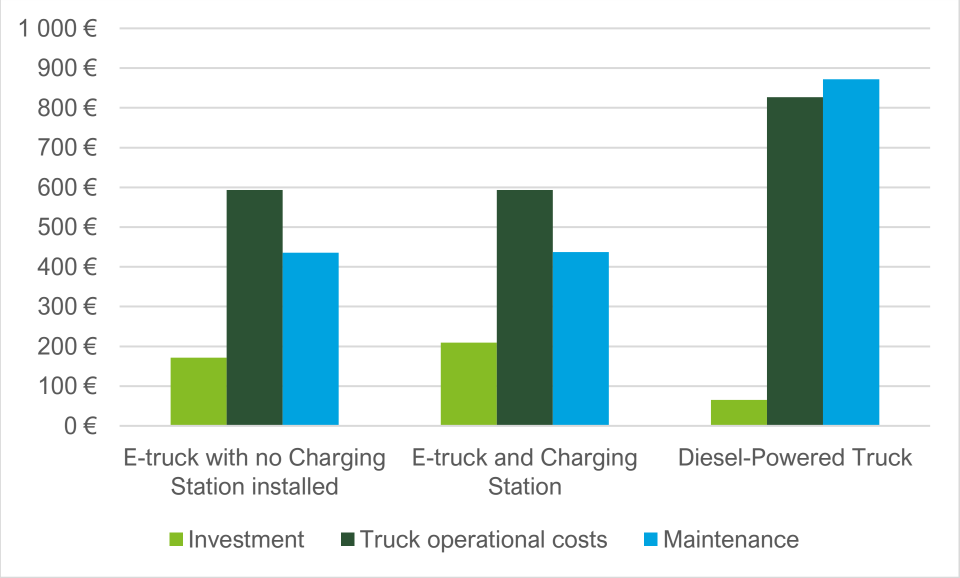


Figure 7: Break-down on the three cost drivers (investment, operation and maintenance)

Investment dimension

An e-truck based operation requires a significantly higher investment upfront, since acquiring the e-truck costs 152.882€, the acquisition of a battery pack of 450kWh costs 61.426€ and the acquisition of the recharging station costs 48.049€. This implies a total acquisition cost of 262.356€, compared to 81.901€ to acquire the diesel-powered truck. Thus, this acquisition implies 215% additional investment. Considering the actualization factor, the daily costs for the e-truck are 122€, being 49€ for the battery pack and 38€ for the recharging station. Summing up to 210€/day compared to 65€/day for the diesel solution.

Nevertheless, this is the smallest factor, within the economic dimension, in both e-trucks and diesel-trucks. Through a simulation in excel, considering the factors previously presented (since both maintenance and operational expenses are based on driven distance), if a truck is driven at least 229km per day, the upfront investment is paid off in the considered 5-year period. Which is significantly lower than the value, on average for the trucks' routes for this simulation, which stands at 415 km/day, 81,2% above the minimum threshold for economic break-even of the project. In fact, one of the trucks is below the minimum threshold for economic viability, as its daily distance is 197km, but the remaining trucks cover, at least, 415km and the maximum distance is 511km (123% above the threshold for break-even).

This enables to conclude that:

- For the presented case, it can be quite advantageous this transition, since the distribution center is on average 59,23km away from the stores and, therefore, two daily routes (to the store and back) are sufficient for break-even;
- Nevertheless, in cases, where companies do not need to operate the trucks for such long daily distances, for operations that require trucks with the considered characteristics in terms of capacity, then the transition might be more difficult. This is because of the battery costs (that can be reduced due to the lower distances to be covered) representing up to 23% of the total cost and daily distances well below 229km/day are a reality. Such is since, according to (Eurostat, 2023), 21% of the daily routes in the EU are below 150km.

Operation

The costs to operate the e-truck entail the lowest relative difference between e-truck and diesel truck. Since the diesel costs are 827€/day, which represent a 39% higher daily expense when compared to the 593€/day to pay for the electricity required for the e-truck operation.

Nevertheless, it is worthwhile mentioning that this difference is not higher mostly due to the fact that diesel-trucks still have fiscal advantages when compared to the cost of electricity for companies, as mentioned by (Schiffer et al., 2021). Since electricity for companies operating e-trucks is not subsidized nor less taxed than the electricity used by families in most EU countries, whereas the diesel for companies is less taxed than the diesel used by families.

Nevertheless, the fact that the retailer's depot could produce, up to a certain extent, its own electricity, will likely increase the economic advantage of e-trucks in terms of the cost advantages to operate them when compared to diesel solutions. This will be further explored in the sensitivity analysis.

Maintenance

Lastly, within the economic dimension, maintenance is also a major driver for the e-truck total cost of ownership advantage since it is significantly lower for e-trucks than for diesel trucks.

This is because the maintenance costs for the e-truck (including the recharging station maintenance) are half of the costs required to maintain the typical diesel-truck. And, therefore, the daily estimated cost for e-truck service is 437€, whilst this cost for diesel trucks is of 871€/day. Nevertheless, unfortunately, little discussion is possible on the expected changes over the coming years regarding the widening or shrinking difference in cost between maintaining an e-truck and a diesel truck, since little information and literature still exists on the topic, according to the research developed by (Alarcón et al., 2023b).

Lastly, it is worthwhile to mention that the absolute difference between diesel and electric trucks represent 69% of the total cost difference between operating this model with an electric truck instead of a diesel-truck.

Environmental dimension

The environmental is where the relative difference is the biggest one, since the environmental cost of operating a diesel-truck in Portugal is 177% higher when compared to the environmental cost of operating an e-truck.

The main driver is the Portuguese electrical mix, since it is based mostly in renewable energy, then the daily cost associated with carbon emissions of an e-truck is 46€, whilst for a diesel truck this value is 317% higher, at 190€ per day. The aforementioned idea of the electrical production at the distribution center would also positively impact this dimension. This is because not only the direct electricity costs but also the associated emissions would be lowered and, therefore, it would lower the environmental impacts resulting from the e-truck operations.

Another point worthwhile to be mentioned is the increase in the carbon price that has taken place in the carbon spot market, which has increased from 24,48€/ton of CO_2 in October 2021 and has reached 86,49€/ton of CO_2 in October of 2023, (Trading Economics, 2023). A price increase of this magnitude means that the e-truck emissions costs in October 2021 would be 13,02€, whilst for diesel trucks, these permits would entail a cost of 53,78€. Thus, this increase in the carbon permits represents, on average, a 3% cost increase of the total costs to operate both electric and diesel trucks.

Moreover, battery degradation entails a daily cost of 23,17€, lowering the difference, in environmental terms, between operating an e-truck and a diesel-truck to 121€, as the total environmental cost of an e-truck increases to 69€ per day. However, some facts might actually limit the real-life decay of the battery, namely: not charging the battery above 80%, except when required to complete a trip and also not letting the battery the battery discharging completely, (Guo et al., 2018b). Since, the battery decay costs represent up to 1,85% of the total daily expenses of operating an e-truck, these costs can be minimized by properly managing the battery level.

Lastly, minimization factors like the ones resulting from recycling batteries in the end of their life cycle were not included in the model developed, since no real economic assessment has been made on the economic salvage value for example, according to (Faraji et al., 2022) and (Balasubramaniam et al., 2020). Nevertheless, these studies state that most chemical elements, namely lithium, cobalt, aluminum or copper have recovery rates up to 95%, and 91% on average, which will positively impact the overall environmental impacts of e-truck operation and the electric transition, in general.

6.3. Comparison with the original case study

The results obtained here are comparable to the work performed by (Figueiredo, 2009) since all stores were served within the time-windows and by the trucks allowed at each store. Moreover, the total distance driven were 3.048km in the model that was run for this study, as can be stated in Table 6.

The lowest distance driven, presented by (Figueiredo, 2009) was 3.173km for the same conditions as the ones considered in the model developed for this thesis. This is because one of the simulations performed in the base case considered split deliveries, which was not considered in this study in order to avoid further complexity to it.

Moreover, the difference is likely explained by the fact that this study converged totally while (Figueiredo, 2009) presented a mean gap of 8,03%. The total time was also superior in (Figueiredo, 2009) optimization, since for the operation not considering split deliveries, the total time was 4.516 min, whereas for the present study, the total time was 4.431 min.

Nevertheless, close results for stores that were served together, the total distance driven and the ability to have a gap equal to zero is set to make the presented model comparable to the real-life situation described in the base case.

Table 6: Distance driven per truck (in km)

	1st time truck left the depot	2nd time truck left the depot	3rd time truck left the depot	Total distance
24-pallet trucks' routes	96	113	108	317
	96	130	158	384
21-pallet trucks' routes	94	114	133	341
	94	114	121	329
	94	113	136	343
	107	130	116	353
	128	114	107	349
	106	133	94	333
	149	150	-	299

6.4. Model take-aways

Battery Size vs. Charging Capacity

Analyzing scenarios for battery size and charging capacity it can be seen that incremental changes in battery size appear to have a more significant impact on operations than incremental changes in charging station capacity. This is primarily because lunch time or other breaks create idle time for truck recharging.

Table 7, below, represents for each route, the total energy consumed as a share of the battery capacity, which has as its maximum value at 58%. Moreover, the battery level range that can be actually used is 67% of the total battery capacity, since this is the difference between the maximum and minimum battery levels (80% and 13%, respectively). It can be stated that there is only a 9% difference between the maximum energy required (58% of the battery capacity) and the maximum of useful energy, 67%. This value is considerably small, since it means that an increase of 15,5km on the total distance, from the depot and back (considering the store located the farthest from the depot), would be the limit to stay within the range that extends the battery life. Thus, an increase in the battery capacity is what would enable a wider radius for the e-truck operations.

Table 7: Total battery required, as a %, of the battery capacity, with no degradation considered

	1st time truck left the depot	2nd time truck left the depot	3rd time truck left the depot	Battery required as % of total battery capacity
24-pallet truck	37%	44%	42%	123%
	37%	51%	58%	145%
21-pallet truck	37%	44%	49%	130%
	37%	44%	47%	128%
	37%	44%	53%	133%
	42%	50%	45%	136%
	50%	44%	42%	136%
	41%	49%	37%	127%
	58%	58%	-	116%

This can also be understood from the fact that increasing the battery capacity by 13,8% would mean that the total time spent on recharging at the depot would be limited to the time already spent on the loading operations. This happens since the extra battery capacity would enable that the truck was not required to be charged up to 80% before leaving the depot. For instance, the same increase in recharging capacity would still entail extra waiting time at the depot. Moreover, if the battery decay is considered, as previously demonstrated, the 80% maximum level will not be respected throughout the time span of the project, that is why battery capacity seems to be the major driver rather than the recharging capacity.

Nevertheless, for the considered example, an operation without in-store nor en-route charging is feasible, even if no fast-charging solutions are placed at stores throughout the lifespan of the project. According to the presented results, fast-charging solutions at the depot are sufficient to provide the required energy for the trucks to supply the different demand points and return to the store.

Challenges of Wider Radius Operations

A wider radius of operation would require fast-charging stations at most, if not all, stores, to optimize delivery operations, especially for varying demands, that imply that routes are not similar every day.

Moreover, I also took as a takeaway from some trials that I made (that did not impact the final result due to the costs involved), would be that placing charging stations would make more economic sense in smaller stores because trucks would, more likely, proceed to another store immediately afterwards. This was the case in the model, since larger stores absorb all, or virtually all, the truck-load capacity.

However, this might not make sense for some cases in reality, since charging (if it is not required to supply that given store) is likely to be more feasible in a bigger store with good accesses and space to have an idle truck charging than in a small store that requires more time to access it, particularly in densely populated areas.

Moreover, given that in-store charging will only apply to longer routes, meaning outside metropolitan areas where store dispersion is greater. Thus, what is likely to make more economic sense is placing charging hubs in stores located near to highways, if placing charging stations in all stores is not economically feasible, as stated by (Alarcón et al., 2023a).

6.5. Sensitivity analysis

In order to further analyze the robustness and feasibility of the transition from diesel-trucks towards electric trucks, it was also performed a sensitivity analysis on different factors impacting the overall sustainability of the proposed e-truck adoption: Investment, operational costs, maintenance and environmental impacts of the operation.

For this analysis, it was considered incremental changes in the different factors of 10% of their value, both upwards and downwards, considering the aforementioned results as the starting point. The lower limit and the upper limit represent deviations from the mean value of 30%. This value was considered in this analysis due to the constant evolution of the electric vehicles' market, the scarcity of reliable and thorough analysis on some drivers for the TCO of an e-truck. Namely, consumption, maintenance, as previously mentioned, but also the scarcity and volatility of some of the required raw materials, according to (Balasubramaniam et al., 2020).

Bellow, it is presented in Figure 8 the sensitivity analysis considering the referred variations for the different drivers for the TCO of the retailer's distribution with an e-truck.

Figure 8 presents the ownership and operation costs of e-trucks (considering also the cost of owning and operating one charging station per e-truck), states that for the considered variations that the model proves to be feasible, when compared to the diesel-based operation. This is because, variations, the total daily costs for operating a distribution operation with e-trucks are, at most, 77% of the diesel-based operation.

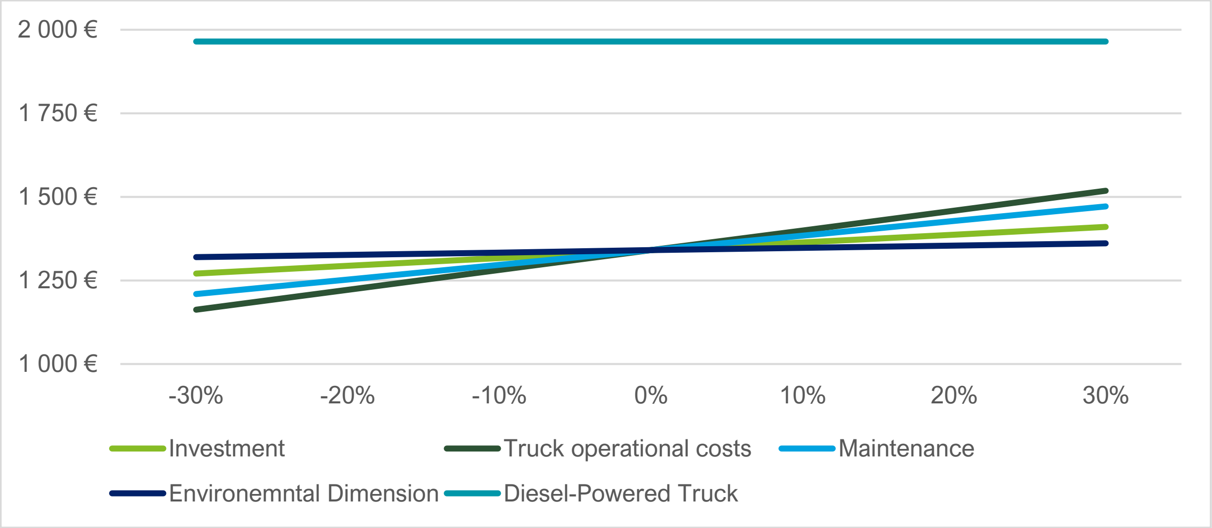


Figure 8: Sensitivity analysis of the transition (considering the impact of recharging stations)

Moreover, as stated in both Figure 8 and Figure 9, the most impactful domain is the truck operational costs. This is also aligned with the model results previously presented. Thus, incremental changes in the operational costs (namely, the cost of electricity), will be the most impactful in the total e-truck daily operating costs. This is because, as stated, the difference between electricity cost and diesel cost in €/km is low, at 39% (comparatively to maintenance cost difference, at 100%), but its overall weight on the total cost (the relative weight on the total operating costs for the values considered for electricity consumption costs in the model is 44%), makes it the most impactful factor for the sensitivity analysis.

This factor is also something to be considered in strategic level, since the renewable production at the distribution center (for instance, through solar panels) could mean a much lower cost to operate e-trucks, allowing a faster payback of the upfront costs. For instance, a 30% decrease in the electricity acquisition costs, would mean that the total daily costs considering recharging stations would stand at 57,2%, of the current value, and without considering them, the costs of operating the e-truck would stand at 55,1%. The maintenance costs remain as the second most impactful factor. However, to the best of my knowledge, no further information, on the forecasted evolution of maintenance costs over the next years, exists.

Moreover, the environmental dimension and the investment required in batteries are set to improve the overall position of the e-trucks, when compared to diesel-powered vehicles. Thus, these factors will likely positively impact the transition towards e-truck adoption and mitigate possible negative impacts coming from the investment (on the e-trucks without batteries and recharging stations) and maintenance dimensions, where less certainty on positive evolution exists. This likely positive evolution on these dimensions results from:

- The overall carbon intensity of the Portuguese electrical mix, which is expected to reduce over the coming years, since the Portuguese government forecasts that by 2030, 80% of the electric mix will be composed by renewables and by 2045 it will be totally neutral on carbon emissions (Governo de Portugal, 2021). For instance, this value stood at 64,9% in 2021(Pordata, 2023), which was the value considered for this model. Furthermore, the renewable energy as share of the electricity consumed can be higher, at an earlier stage, if, as previously mentioned, the distribution center produces its own electricity from renewable sources such as solar energy;
- According to (Schiffer et al., 2021), which based his forecast on different studies and analysis, the evolution in the battery costs per kWh is likely to also positively impact the overall TCO of a e-truck when compared to a diesel-powered solution, since the current battery costs are expected to drop by 37,5% until 2030, which is a value higher than the one considered in the sensitivity analysis, in order to have a universal lower limit to the analysis (30% decrease in each category) and also because this 37,5% is a rough estimation, so it was decided to keep the analysis conservative.

Lastly, the graph presented in Figure 9 also shows that, overall, the recharging station costs do not greatly impact the overall operation, as they do not change the major cost drivers' share in the operational and investment costs nor compromises the expected economic viability of the operation, since the minimum difference between the values in the graphs presented in Figure 8 and Figure 9 are 2,05% and the maximum difference is 2,21%.

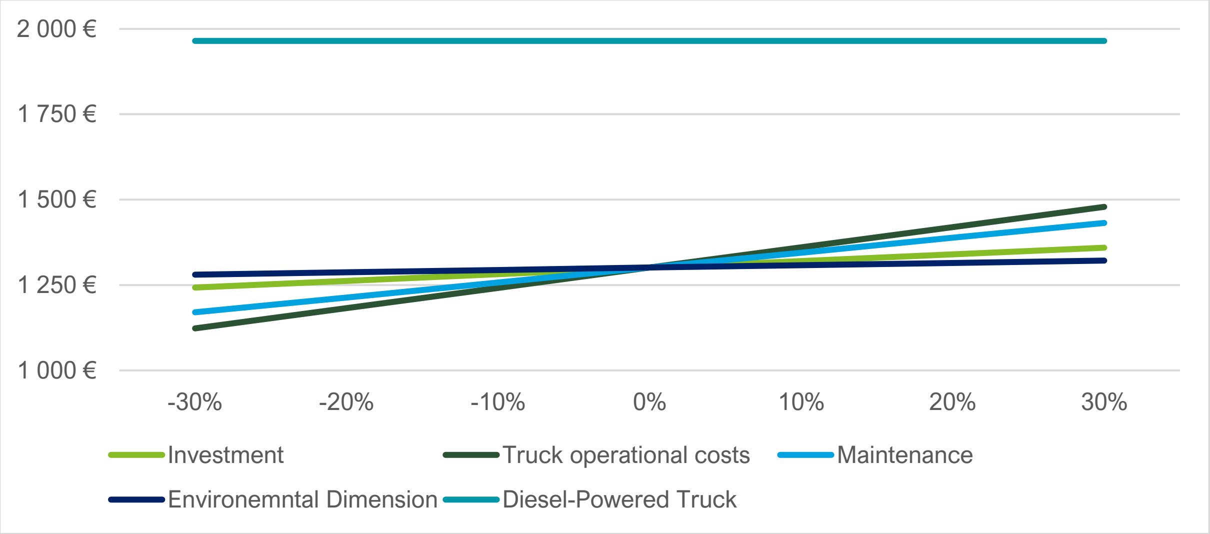


Figure 9: Sensitivity analysis of the transition (without considering the impact of recharging stations)

6.6. Chapter Conclusions

From an economic standpoint, replacing diesel-powered trucks with e-trucks for urban deliveries appears feasible. However, it relies on having suitable charging stations at loading docks and waiting areas to avoid operational disruptions. Thus, the results achieved by this model application make it clear that electric trucks make economic sense in densely populated areas near distribution centers. However, the case for stores located in non-urban areas and far from the depot would likely be a subject to be explored further.

Environmentally, the transition is quite positive, since the carbon emissions reduce significantly, especially in Portugal where the electricity mix includes 69% of renewable energy. Also, the impacts resulting from battery disposal are set to be greatly mitigated as battery recycling is increasingly feasible as, on average, 90% of the components present on batteries are recyclable. Nevertheless, the economic case for battery recycling is, for the best of my knowledge, not yet assessed.

To conclude, taking the different factors into consideration, considering the current market conditions, an e-truck distribution for retail operators, especially in heavily populated urban areas and metropolitan areas, is feasible. This is because:

- The return on investment is possible within a timespan where the operating conditions still enable efficient and effective operations. The financial payback of the investment is achieved in 3,5 years;
- Environmentally, the solution is proven to be feasible and less impactful than the as-is situation (with diesel-powered trucks).

Thus, the transition is feasible under the considered conditions and greatly impacts, in a positive way, both the economic and environmental pillars of sustainable development.

7. Conclusions

The problem addressed in this dissertation aimed at optimizing the LRP mathematical model regarding a new operational flow, in which the retailer's distribution process transitioned to one based on e-trucks. Which helps to close gaps in the existing research, namely the assessment on the applicability and feasibility of e-truck based operations considering a real-life case study.

This case is based on a Portuguese retailer's planned distribution from a distribution center to satisfy the daily demand of its stores (with limited capacity and time-windows), this model was created according to the data provided by (Figueiredo, 2009). This case was used since the distribution process from the depot is still performed using diesel-trucks and the aim of this study was to test to which extent it is feasible the transition from a diesel-based operation into a e-truck based one (economically and environmentally). Moreover, it is also assessed whether or not, one or more, recharging stations need to be placed at the different stores in order that the operational flow is not compromised.

Furthermore, from both the literature and the base case (Figueiredo, 2009), it was possible to develop a mathematical model that modelled the delivery operation. This considered the material flow into different stores, from the depot, where demand must be met within the established time-windows, using the minimum number of trucks and routes possible. This also considering the challenges posed by the limited driving range, lengthy charging times and the decision on whether, or not, to place charging stations and, if so, where, in order that the necessary charging infrastructure was created and the operational flow was not compromised. As a result, this simulation is validated for the considered case study, as the transition is feasible, especially concerning the economic and environmental dimensions.

Economically, the financial payback of the investment is achieved in 3,5 years and this return on investment is possible without endangering efficient and effective operations. This is possible due to the lower maintenance and operational costs that outweigh the higher upfront investment required by the e-truck based operation. In addition, the location of recharging station in stores is not required for the considered operational set-up, this means that only placing recharging stations at the depot would be required.

Environmentally, the solution is less impactful than the as-is situation, especially considering that over 69% of the electricity currently produced in Portugal is renewable. The battery decay is more difficult to assess. However, in terms of the costs entailed by battery disposal, together with carbon costs regarding the emissions from the electricity production, they are clearly outweighed by the emissions resulting from diesel consumption in a comparable operation.

Nevertheless, it is also worthwhile to note that, despite economically viable, a relatively long distance must be covered in order that, economically, the transition with the current e-truck operations' characteristics makes sense. This is because, the minimum distance for break-even, according to my results, is not covered by, at least, 21% of the EU trucking operations. Another situation where the economic feasibility should be further assessed is when different paths are taken every day and returns to the depot are not frequent, since the driver might have to be frequently looking for publicly available charging options, which are still sparse at the moment.

7.1. Future Research

To finalize this dissertation, it is recommended some topics that could be subject to an assessment in future analyses, in order to improve the presented model and have a more real-life like scenario for discussion, namely:

- The inclusion of the battery decay as a variable of the model, where it is understood the effective time span for which the model is feasible. Moreover, regarding battery characteristics, it could also be considered the electric energy recovered through the regenerative braking system as well as the influence of batteries' weight on the total cargo to be loaded. It can also be assessed the difference that it entails when compared to a diesel-truck operation;
- An improved formulation to include a better approximation to real-life charging rates, especially above 80%;
- Usual uncertainties associated with this type of models, such as: traffic or recharging conditions in publicly available options;
- Wider distribution areas, namely in non-metropolitan regions where distances between depots and stores as well as among stores are bigger, meaning that the necessity for recharging stations is higher;
- Distribution with a similar radius of operation but with smaller products, particularly parcel delivery (in which it would necessarily require en-route recharging), because there would not be as regular returns to the distribution center;
- Lastly, differentiation in the costs for operating different types of pallets and, therefore, the incorporation of this parameters in a future study could provide more insights on the operation. This is because the cargo load could impact the electric consumption, which was not considered in this study.

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Appendix A

Table A 1: Distance between cluster 1 vertices (in km): (Figueiredo, 2009)

	Azambuja	Massamá II	Agualva	Queluz II	Queluz	Rinchoa	Restelo	Alfragide	Reboleira	Benfica	Oeiras
Azambuja	0	56	57	56	55	66	55	51	53	48	64
Massamá II	56	0	4	1	2	8	11	7	6	8	11
Agualva	57	4	0	3	4	9	14	10	7	10	13
Queluz II	56	1	3	0	1	11	11	7	4	7	12
Queluz	55	2	4	1	0	12	9	5	3	6	12
Rinchoa	66	8	9	11	12	0	18	14	13	18	13
Restelo	55	11	14	11	9	18	0	6	7	9	11
Alfragide	51	7	10	7	5	14	6	0	3	5	16
Reboleira	53	6	7	4	3	13	7	3	0	4	14
Benfica	48	8	10	7	6	18	9	5	4	0	18
Oeiras	64	11	13	12	12	13	11	16	14	18	0

Table A 2: Distance between cluster 2 vertices (in km): (Figueiredo, 2009)

	Azambuja	Lapa	Tomas Ribeiro	Duque d'Avila	1º Dezembro	Graça	Fonte Nova	Almirante Reis	Ferreira Borges	Olaias	Sacavém
Azambuja	0	49	46	47	49	47	48	45	52	46	42
Lapa	49	0	3	4	2	4	6	4	1	6	13
Tomas Ribeiro	46	3	0	1	3	2	6	0	3	2	9
Duque d'Avila	47	4	1	0	4	2	5	0	3	2	9
1º Dezembro	49	2	3	4	0	2	9	2	3	4	11
Graça	47	4	2	2	2	0	7	1	4	3	10
Fonte Nova	48	6	6	5	9	7	0	7	8	8	11
Almirante Reis	45	4	0	0	2	1	7	0	4	1	9
Ferreira Borges	52	1	3	3	3	4	8	4	0	5	14
Olaias	46	6	2	2	4	3	8	1	5	0	8
Sacavém	42	13	9	9	11	10	11	9	14	8	0

Table A 3: Distance between cluster 3 vertices (in km): (Figueiredo, 2009)

	Azambuja	Colina do Sol	Linda A Velha	Carnaxide	Massamá	Miraflores	Mem Martins 2	Queijas	Carcavelos II	Damaia	Alapraia
Azambuja	0	49	54	55	57	56	68	58	66	51	69
Colina do Sol	49	0	10	11	8	12	20	11	3	4	5
Linda A Velha	54	10	0	1	9	2	20	9	9	7	4
Carnaxide	55	11	1	0	8	3	10	8	16	6	18
Massamá	57	8	9	8	0	10	9	3	6	9	5
Miraflores	56	12	2	3	10	0	20	10	11	9	13
Mem Martins 2	68	20	20	10	9	20	0	14	16	16	6
Queijas	58	11	9	8	3	10	14	0	9	9	7
Carcavelos II	66	3	9	16	6	11	16	9	0	3	5
Damaia	51	4	7	6	9	9	16	9	3	0	4
Alapraia	69	5	4	18	5	13	6	7	5	4	0

Table A 4: Distance between cluster 4 vertices (in km): (Figueiredo, 2009)

	Azambuja	Rebelva	Cascais-Villa	Alto da Barra	Carcavelos	São Marcos	Alvide	Sassoeiros	Serra da Mira	Cascais	Paço d'Arcos
Azambuja	0	66	72	65	66	62	74	64	66	73	62
Rebelva	66	0	7	4	1	11	9	1	2	8	5
Cascais-Villa	72	7	0	10	7	17	2	11	7	1	13
Alto da Barra	65	4	10	0	3	11	12	4	3	11	3
Carcavelos	66	1	7	3	0	10	9	1	0	8	6
São Marcos	62	11	17	11	10	0	18	9	11	17	8
Alvide	74	9	2	12	9	18	0	12	9	2	16
Sassoeiros	64	1	11	4	1	9	12	0	2	11	3
Serra da Mira	66	2	7	3	0	11	9	2	0	8	6
Cascais	73	8	1	11	8	17	2	11	8	0	15
Paço d'Arcos	62	5	13	3	6	8	16	3	6	15	0

Appendix B

Table B 1: Travel time between cluster 1 vertices (in minutes): (Figueiredo, 2009)

	Azambuja	Massamá II	Agualva	Queluz II	Queluz	Rinchoa	Restelo	Alfragide	Reboleira	Benfica	Oeiras
Azambuja	0	48	47	47	47	58	50	44	44	41	56
Massamá II	48	0	7	4	5	13	17	10	9	16	14
Agualva	47	7	0	6	6	14	20	14	12	18	19
Queluz II	47	4	6	0	2	16	17	11	9	14	17
Queluz	47	5	6	2	0	16	16	9	7	12	17
Rinchoa	58	13	14	16	16	0	22	18	17	22	17
Restelo	50	17	20	17	16	22	0	11	12	13	15
Alfragide	44	10	14	11	9	18	11	0	5	8	18
Reboleira	44	9	12	9	7	17	12	5	0	9	17
Benfica	41	16	18	14	12	22	13	8	9	0	20
Oeiras	56	14	19	17	17	17	15	18	17	20	0

Table B 2: Travel time between cluster 2 vertices (in minutes): (Figueiredo, 2009)

	Azambuja	Lapa	Tomas Ribeiro	Duque d'Avila	1º Dezembro	Graça	Fonte Nova	Almirante Reis	Ferreira Borges	Olaias	Sacavém
Azambuja	0	49	43	42	49	45	41	41	45	42	36
Lapa	49	0	8	8	6	9	12	9	2	13	23
Tomas Ribeiro	43	8	0	2	8	4	11	2	7	6	17
Duque d'Avila	42	8	2	0	9	5	11	2	7	5	16
1º Dezembro	49	6	8	9	0	7	15	6	7	10	21
Graça	45	9	4	5	7	0	15	4	9	6	19
Fonte Nova	41	12	11	11	15	15	0	11	10	13	13
Almirante Reis	41	9	2	2	6	4	11	0	8	4	15
Ferreira Borges	45	2	7	7	7	9	10	8	0	12	19
Olaias	42	13	6	5	10	6	13	4	12	0	15
Sacavém	36	23	17	16	21	19	13	15	19	15	0

Table B 3: Travel time between cluster 3 vertices (in minutes)

	Azambuja	Colina do Sol	Linda A Velha	Carnaxide	Massamá	Miraflores	Mem Martins 2	Queijas	Carcavelos II	Damaia	Alapraia
Azambuja	0	39	46	48	50	51	55	49	60	43	58
Colina do Sol	39	0	13	15	17	18	27	16	7	9	14
Linda A Velha	46	13	0	4	13	4	18	10	12	8	3
Carnaxide	48	15	4	0	11	8	15	10	17	12	19
Massamá	50	17	13	11	0	16	15	4	13	12	14
Miraflores	51	18	4	8	16	0	28	13	16	13	21
Mem Martins 2	55	27	18	15	15	28	0	18	40	18	4
Queijas	49	16	10	10	4	13	18	0	12	10	14
Carcavelos II	60	7	12	17	13	16	40	12	0	8	17
Damaia	43	9	8	12	12	13	18	10	8	0	5
Alapraia	58	14	3	19	14	21	4	14	17	5	0

Table B 4: Travel time between cluster 4 vertices (in minutes)

	Azambuja	Rebelva	Cascais-Villa	Alto da Barra	Carcavelos	São Marcos	Alvide	Sassoeiros	Serra da Mira	Cascais	Paço d'Arcos
Azambuja	0	57	63	57	58	55	65	55	60	64	53
Rebelva	57	0	12	6	3	15	14	4	5	14	8
Cascais-Villa	63	12	0	15	13	20	3	13	13	3	19
Alto da Barra	57	6	15	0	4	14	17	6	5	17	5
Carcavelos	58	3	13	4	0	15	15	4	2	14	7
São Marcos	55	15	20	14	15	0	21	12	17	21	10
Alvide	65	14	3	17	15	21	0	14	14	4	18
Sassoeiros	55	4	13	6	4	12	14	0	5	14	5
Serra da Mira	60	5	13	5	2	17	14	5	0	14	9
Cascais	64	14	3	17	14	21	4	14	14	0	18
Paço d'Arcos	53	8	19	5	7	10	18	5	9	18	0

Appendix C

Table C 1: Example of the daily routes and its characteristics for the 24-pallet trucks

Truck	Vertex	Distance between vertices (km)	Travel time between vertices (min)	Handling time at a given vertex (min)	Total time per route (min)	Total time driven per truck (min)	Total distance per route (km)	Total distance driven per trucks (km)
Truck nº1	Azambuja			44	156	497	96	317
	Almirante Reis	45	41	32				
	Sacavém	9	56	32				
	Azambuja	42	92	43				
	Queluz	51	44	35	156		113	
	Massamá II	5	52	28				
	Azambuja	48	93	44				
	Paço d'Arcos	55	47	31	206		108	
	Cascais-Villa	2	52	33				
	Azambuja	56	100					
Truck nº2	Azambuja			43	135	538	104	382
	Alfragide	62	53	34				
	Benfica	13	72	29				
	Azambuja	55	120	43	184		130	
	Linda A Velha	54	46	43				
	Azambuja	54	92	34				
	Alvide	74	65	34	198		148	
	Azambuja	74	130	44				

Appendix D

Table D 1: Comparison of the parameters considered for e-trucks and diesel trucks: (Schiffer & Walther, 2018), (Schiffer & Walther, 2017) and (Schiffer et al., 2021)

	Economic Dimension						**Environmental Dimension**	
	Investment factor			Operational factor	Maintenance factor			
	Vehicle acquisition	Battery acquisition	Set-up a charging station	Energy	Vehicle maintenance	Charging station maintenance	CO_2 permits costs	Battery decay costs
Electric truck	122,1 € / day	49,1 € / day	38,4 € / day	0,14 € / km	0,14 € / km	1,02 € / day	0,01 € / km	0,008 € / km
Diesel truck	65,4 € / day	N/A	N/A	0,20 € / km	0,28 € / km	N/A	0,06 €/ km	N/A

Appendix E

Table E 1: Daily costs per dimension and factor for the different scenarios

	Economic Dimension				**Environmental Dimension**	**Total**
	Investment factor	Operational factor	Maintenance factor	Total		
Electric truck	171,17 €	593,05 €	435,82 €	1 200,04 €	68,71 €	1 268,75 €
Electric Truck and Recharging Station	209,54 €	593,05 €	436,85 €	1 239,44 €	68,71 €	1 308,15 €
Diesel truck	65,41 €	827,00 €	871,65 €	1 764,06 €	190,12 €	1 954,18 €