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UNIVERSIDADE D COIMBRA

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DECISION SUPPORT FOR PLANNING A BUS RAPID TRANSIT CHARGING INFRASTRUCTURE

Dissertation in the context of the Master in Energy for Sustainability oriented by Professor Carlos Henggeler Antunes and co-oriented by Professor João Pedro Trovão and presented to the Department of Mechanical Engineering of the University of Coimbra.

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Abstract

Nowadays, one of the biggest concerns worldwide is Climate Change and its irreversible effects on the balance of the Earth's ecosystems. Therefore, several institutions, organizations, and governments are developing policies, measures, and technologies to mitigate such effects. In this context, the electrification of public transportation systems plays a decisive role in greenhouse gas emissions attenuation. Moreover, electric vehicles have many advantages when compared to their fossil fuel counterparts, including air quality improvement, noise reduction, and energy efficiency enhancement. Despite those benefits, electric vehicles still suffer from the low driving range, and the time-consuming battery recharges. To provide solutions to those issues and to increase the feasibility of electric mobility, the development of technologies in charging infrastructures, control methods, and battery capacity becomes crucial. In this context, the present research provides a framework for the planning of the charging infrastructure of a Bus Rapid Transit (BRT) system dealing with the minimization of the implementation costs of fast-charging stations. The work initially presents a Multi-criteria Decision Analysis study to assess which types of rapid transit systems can offer a more convenient solution for metropolitan areas. The main objective of this analysis is to evaluate whether a BRT system can be a viable solution for this purpose when compared to other rapid transit systems. Then a Mixed Integer Linear Programming model is developed to optimize the location of fast-charging stations in a BRT network, considering the cost of implementation, number of chargers, total charging time, and battery life cycle.

Keywords: fast-charging, Bus Rapid Transit, electric mobility, optimization, public transportation

Resumo

Atualmente, uma das maiores preocupações mundiais é a mudança climática e seus efeitos irreversíveis no equilíbrio dos ecossistemas da Terra. Portanto, várias instituições, organizações e governos estão desenvolvendo políticas, medidas e tecnologias para mitigar esses efeitos. Nesse contexto, a eletrificação dos sistemas de transporte público desempenha um papel decisivo em termos de atenuação das emissões de gases de efeito estufa. Além disso, os veículos elétricos possuem muitas vantagens quando comparados aos seus equivalentes de combustíveis fósseis, incluindo melhoria da qualidade do ar, redução de ruído e melhoria da eficiência energética. Apesar desses benefícios, os veículos elétricos ainda sofrem com a baixa autonomia e recargas demoradas da bateria. Para fornecer soluções para esses problemas e aumentar a viabilidade da mobilidade elétrica, o desenvolvimento de tecnologias nas infraestruturas de carregamento, métodos de controle e capacidade de baterias torna-se crucial. Neste contexto, a presente pesquisa fornece uma abordagem para o planejamento da infraestrutura de carregamento de um sistema de Autocarro de Trânsito Rápido (BRT), que trata da minimização dos custos de implementação das estações de carregamento rápido. O trabalho apresenta inicialmente um estudo de Análise de Decisão Multicritérios afim de avaliar quais tipos de sistemas de trânsito rápido podem oferecer uma solução mais conveniente em áreas metropolitanas. O principal objetivo desta análise é avaliar se um sistema de BRT pode ser uma solução viável para esse fim, quando comparado a outros sistemas de trânsito rápido. Em seguida, um modelo de Programação Linear Inteira Mista é desenvolvido para otimizar a localização das estações de carregamento rápido em uma rede BRT, considerando o custo de implementação, número de carregadores, tempo total de carregamento e ciclo de vida da bateria.

Palavras-chave: carregamento rápido, Autocarro de Trânsito Rápido, mobilidade eléctrica, otimização, transporte público

Summary

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Abbreviations and Acronyms

AHP	Analytic Hierarchy Process
BEB	Full Battery Electric Bus
BRT	Bus Rapid Transit
CPLEX	IBM ILOG CPLEX Optimization Studio
DM	Decision Maker
DoD	Deep of Discharge
ELECTRE	Elimination and Choice Translating Reality
EM	Electric Motor
EV	Electric Vehicle
FCEB	Fuel Cell Electric Bus
FRLM	Flow Refueling Location Model
GHG	Greenhouse Gas
GIS	Geographic Information System
HEB	Hybrid Electric Bus
ICE	Internal Combustion Engine
IEA	International Energy Agency
IoT	Internet of Things
ITDP	Institute for Transportation & Development Policy
LRT	Light Rail Transit
MCDA	Multi-criteria Decision Analysis
MILP	Mixed Integer Linear Programming
OR	Operations Research
pphpd	Passengers per hour in peak direction
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
SBDC	Supercapacitor Bus Driving Cycle
SDG	Sustainable Development Goals
SoC	State of Charge
TCO	Total Cost of Ownership
UN	United Nations
V2G	Vehicle-to-Grid
ZeEUS	Zero Emission Urban Bus System

1 Introduction

The transportation sector is one of the major fossil fuel consumers. Alone, it contributes around 14% of the total GHG global emission – approximately 4524.3 MtCO2 per year (**Figure 1**). Therefore, actions to increase efficiency in this sector allied to the implementation of alternative driving technologies can play a crucial role in the global emissions mitigation [1]. The deployment of Electric Vehicles (EV) in an urban framework helps to diminish the dependency on fossil fuels and reduce emissions if powered with renewable energy. Moreover, EVs improve air quality, reduce noise, and increase energy efficiency [2]. Driven by those benefits, some forecasts indicate that the share of EVs sales will grow from 6% to 35% until 2040, attesting that the electric mobility revolution is already a reality [3].

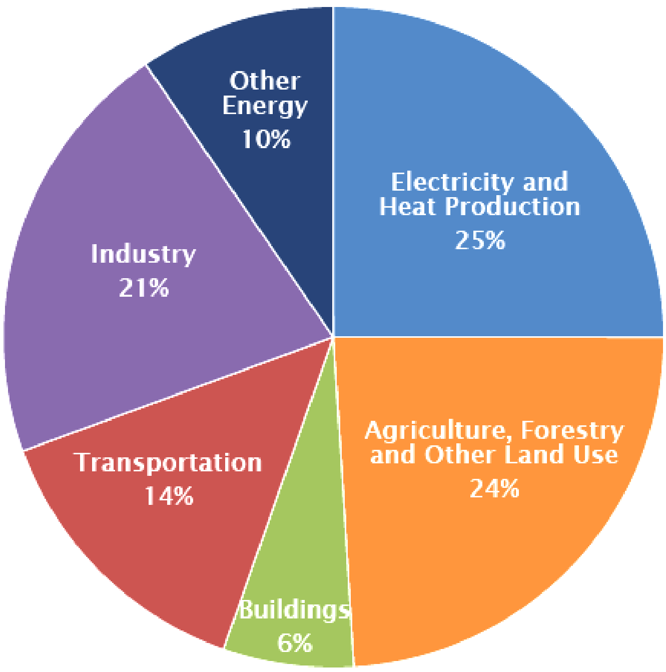


Figure 1 – Global GHG emissions by Economic Sector (%). Source: IEA (2019)

However, it is also important to highlight that private EVs cannot deliver a sustainable solution in terms of space-efficiency in metropolitan areas. Urban congestion and parking will be significant problems unless public collective transportation systems become the ultimate solution in urban environments [4]. More specifically, in a global context, "*buses are the true* *backbone of collective transport, with bus systems accounting for 80% of all public transport passenger journeys worldwide"*, as indicated in [5]. Thus, addressing solutions to public bus transportation refers directly to the improvement of life quality, emissions mitigation, and climate change. Moreover, with the development of Smart Cities and the Internet of Things (IoT), EVs can make a substantial impact in contributing to a more efficient operation of the power grid. For instance, in the realm of Smart Grids, EVs can be charged using smart charging schemes considering the grid status and renewable generation availability and/or be used in Vehicle-to-Grid (V2G)[1] mode to provide ancillary services to the grid [6]. The transition to a 100% electric public mobility, however, will not be easy. New infrastructures must be developed and implemented to make feasible the utilization of such technology [7].

1.1 Motivation

As formerly mentioned, the employment of EVs in public transportation has a great emission mitigation capacity. More specifically, in this work, the focus will be on the planning configuration of fast-charging facilities in Bus Rapid Transit (BRT) fleets. The motivation for such an approach comes from two principal reasons:

- As a technology that is growing in prominence in the past few years, charging still presents open questions to deal with;
- Due to the environmental concern that this work is addressing, the BRT system holds characteristics to enhance the quality of public transportation in several countries with different economic situations.

In terms of the progress of Full Battery Electric Bus (BEB) technology, some new features are in the process of development and can improve even more the quality of this type of transportation. The study in [8], for instance, deals with the feasibility of autonomous driving e-buses, using lidar technology. [9] presents the development of a Supercapacitor Bus Driving Cycle in the city of Hong Kong. Another interesting study is introduced in [10], which proposes a novel efficient braking energy recovery system. Although those studies and new technologies developments are very relevant, the most important features that need development are those who directly deal with the driving range – more specifically batteries and charging facilities.

[1] V2G is a concept that describes the possibility of communication between an EV and the power grid, allowing the return of the vehicle's stored electricity to the grid. For instance, such a system could be used to regulate the grid frequency or to do integration with renewable energy generation surplus.

As the study of [11] indicates, the range anxiety and the distance inconvenience are the fundamental barriers to mass electrification of the transportation sector.

The advantage of a bus-based system is that those obstacles can be surpassed since the routes and the range distance of the itinerary of those vehicles are previously known. Therefore, charging points can be planned in a way to provide enough energy for a certain period, e.g. an entire day of work. Furthermore, in the case of a BRT, the traffic is not a problem, as that system owns a dedicated lane to transit. All those characteristics can be used as a means to potentialize the electrification of bus-based systems. Summarizing, the scenario seems to be very positive, but to improve the quality, feasibility, and costs of electric BRT fleets, new strategies of optimal charging facilities locations and battery capacity need to be developed. Therefore, this work aims to contribute with decision support for planning a BRT charging infrastructure.

1.2 Objectives

As stated in [12], *"battery-electric buses continue to struggle with concerns related to their limited driving range and time-consuming recharging processes"*. To deal with those issues, there are different procedures to charge a BEB: overnight charging, opportunity charging, and in-motion charging [13]. These concepts are generally used with the following meaning.

- Overnight charging refers to a charging scheme where the vehicle stays parked for an extended period (usually a few hours), and during this time-window, the vehicle's battery is charged;
- Opportunity charging refers to a charging scheme where battery charging is done when the vehicle is waiting for the passengers to board in the bus-stop;
- In-motion charging refers to a scheme where the battery charging is done while the vehicle is moving.

Several studies pointed out that opportunity charging can be the best solution in the future [13]–[16]. The study of [17] observes that the battery's size is directly related to the price of a BEB – producing heavier and more costly vehicles when compared to diesel counterparts. Thus, the study concludes that the best option, to surpass those barriers, is to implement opportunity fast-charging techniques to provide recharging throughout the day and consequently decreasing the battery sizes. Based on those works, it becomes understandable that addressing solutions to fast-charging and battery capacity issues can be crucial to the progress of electric bus-based systems. Hence, this study aims to develop decision-aid models and implement a computer solution to minimize the number of fast-charging stations points and the related implementation costs applied to a BRT network.

Main Objectives

The main objectives of this dissertation are twofold. First, this work is focused on ranking the most suitable options for public transportation in metropolitan areas. The main goal of this analysis is to assess whether a BRT system (mainly those empowered by electric vehicles) could be a feasible solution for such a purpose when compared to other rapid transit systems. Then, driven by the results of the first analysis, the aim is to implement a mathematical model to optimize the location of charging stations in a BRT network. Those objectives are summarized below.

1) Develop a decision-aid study to assess which types of rapid transit systems can provide the most convenient solution for urban areas using a multicriteria evaluation.
2) Develop a model to minimize the number of fast-charging stations location and implementation costs of an electrified BRT system.

Specific Objectives

To accomplish these main objectives, specific objectives have been defined.

- Review the literature concerning Multi-criteria Decision Analysis (MCDA) applied to an urban mobility decision aid context, and Mixed Integer Linear Programming (MILP) approaches applied to charging points distribution.
- Create a comprehensive MCDA model to compare different types of rapid transit systems according to multiple evaluation criteria.
- Create a MILP mathematical model to deal with a BRT network and charging infrastructure.
- Develop a computer application to simulate and test the optimization methodology, including sensitivity analysis to the changes of some model coefficients to capture uncertainty.
- Implement a case study to apply the mathematical model.

The convergence of these goals aims to provide a novel contribution by developing new approaches for decision support in the planning of the implementation of charging facilities to BRT based systems.

1.3 Dissertation Content

Chapter II presents an overview of urban mobility. Section **2.1** introduces the concept of BRT, as well as the advantages of this type of transportation system when compared to other counterparts. Also, this section presents the important role that the BRT can play in a global public transportation system. Section **2.2** brings an overview of technologies regarding electric buses – types, charging strategies, battery and market forecasts.

Chapter III is dedicated to present the MCDA developed in this dissertation. Section **3.1** provides the basic concepts of MCDA approaches. The characteristics and applicability of the PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) method in a comparison of different types of rapid public transportation systems are presented in section **3.2**. The main perspectives of the analysis are presented in section **3.3** and the different scenarios considered in the analysis are detailed. Section **3.4** presents an analysis of the results. The conclusions are shown in section **3.5**.

Chapter IV presents the mathematical model and computational implementation. The developed Mathematical Programming process and the basic concepts of Integer Programming are presented in section **4.1**. The bibliography review, the mathematical model developed, and information about the computer implementation are introduced in **4.2**.

Chapter V details the case study developed. An overview of the infrastructure characteristics, travel times and operation model of the case study is introduced in **5.1**. In section **5.2**, the scenario framework, as well as the sensitivity analysis, are detailed. The results and discussion of the case study are presented in **5.3**. The chapter is concluded in **5.4**.

Chapter VI is dedicated to present the conclusions of this research as well as future work development.

2 Urban Mobility Review

As a basis for this work, it is essential to provide an overview of some critical points regarding urban mobility. As formerly mentioned, the study aims to develop a decision-aid model related to the implementation of a BRT system in an urban context. Therefore, the concept of such a system will be presented in the next subsection, defining the advantages of this transportation method and its potential in the development of urban mobility in the future. Then, an overview of electric-buses, mainly BEB, will be introduced, providing an examination of battery technology, charging approaches, and market trends of such vehicles.

2.1 Bus Rapid Transit

The preeminent transport challenges faced by several metropolitan areas can be summarized as traffic jams, pollution, delivering delays, and inadequate pedestrian facilities. To provide solutions to those obstacles, most governments are investing in new public transportation systems. The study of [18] highlights that *"the BRT is part of the response to continued rapid urbanization effects ongoing in most countries, but particularly, the larger cities in the developing world"*. Flexibility and speed can be highlighted as the reasons for the increasing utilization of such a system.

Moreover, [19] states that the BRT can deliver a high-quality massive transportation service that costs *"between 4 and 20 times less than an LRT (Light Rail Transit) system and between 10 and 100 times less than an underground type system".* Therefore, BRT is a very efficient and cost-effective transport solution. In terms of operation, the BRT is a mode of transportation that incorporates the flexibility of buses and the speed of rail transit. The idea behind the working system is straightforward: the traffic of the buses is made through a dedicated lane – this strategy makes possible a quicker, safer and better bus service. Moreover, the BRT incorporates features mainly used in underground systems, such as off-board fare collection, platform-level boarding, and articulated vehicles. Those characteristic delivers many advantages, which are summarized in **Table 1**.

Table 1 – Advantages of the BRT System. Adapted from [20]

Benefits	**Description**
Economic	• Low implementation cost; • Better operation cost efficiency; • Reduced travel times; • Improved work conditions.
Social	• More equitable access throughout the city; • Reduced accidents.
Environmental	• Reduced GHG emissions; • Reduced noise levels.
Urban form	• More sustainable urban form, including densification of major corridors; • Reduced cost of delivering services.

The BRT system is becoming very popular worldwide, principally driven by its advantageous characteristics. The study of [21] states that "*the reasons for this phenomenon include its passenger and developer attractiveness, its high performance and quality, and its ability to be built quickly, incrementally, and economically. BRT also provides sufficient transport capacity to meet demands in many corridors, even in the largest metropolitan regions". * **Figure 2** confirms this movement, showing the evolution of newly implemented systems worldwide.

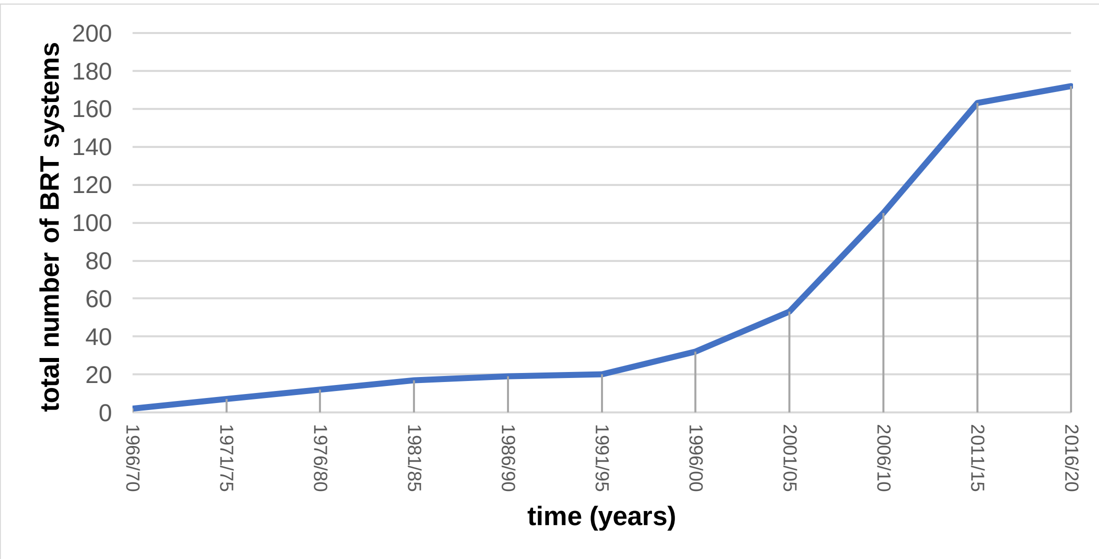


Figure 2 – Implemented BRT systems worldwide. Source: Global BRT Data (2020)

Table 2 provides a comprehensive view of the places where the BRT systems are already installed. It is essential to highlight that Latin America possesses a more significant number of systems installed, mainly driven by its costs and easy implementation. The first BRT system in the world was implemented in the city of Curitiba (Brazil). Due to its success, the system has been spread along, first in the country and after in Latin-America. For instance, the system implemented in Bogotá (Colombia) is the biggest in the world, carrying 2.4 million passengers per day [22]. It is also relevant to mention that the system is gaining fast prominence in Asia, mainly in China. The city of Guangzhou, for example, owns one of the most technologically advanced and fast BRT systems worldwide. Moreover, the country has already 11 new BRT systems in the construction phase.

Table 2 – BRT worldwide implementation. Source: Global BRT Data (2020)

Region	Passengers (day)	Nº of Cities	Extension (km)
Africa	491,578 (1.47%)	5	131
North America	912,598 (2.73%)	19	588
Latin America	20,506,977 (61.44%)	55	1,816
Asia	9,411,593 (28.2%)	43	1,593
Europe	1,613,580 (4.83%)	44	875
Oceania	436,200 (1.3%)	4	96

To summarize, the BRT system combines rapid transit features (i.e. speed, flexibility, efficiency) with economic advantages [2] (implementation and maintenance costs). Those characteristics can potentialize the effectiveness of public transportation in metropolitan areas. Moreover, the system makes an important contribution in terms of emissions mitigation. If operated using BEBs, the advantages go even further, regarding the improvement of air quality, noise reduction, and energy efficiency enhancement.

2.2 Electric Buses

An electric bus *"can operate by different degrees of electrification that depend on the configuration of the propulsion system"* [23]. Some can be continuously fed by external sources – for instance, a trolleybus that is powered by overhead wires. Other ones can store the

2 In the case of Full Battery Electric Bus, the lifespan of the batteries, as well as the recharging times (in order to minimize the battery degradation), increase the maintenance costs.

electricity on-board, typically in batteries. Several electric buses fit into this category, for instance:

- Hybrid Electric Bus (HEB): The traction power of this technology is provided by an Electric Motor (EM) as well as an Internal Combustion Engine (ICE). In some cases, the HEB battery can also be charged using plug-in technology to allow the connection with the grid [24].
- Fuel Cell Electric Bus (FCEB): Uses hydrogen fuel cells to generate electricity on-board during operation.
- Full Battery Electric Bus (BEB): This type of vehicle uses the energy stored in the battery to provide the EM propulsion.

Table 3 – Performance electric buses compared to diesel buses. Based on [25]

	HEB	**FCEB**	**BEB**
Purchase Price	+50%	+200%	+80%
Maintenance Cost	More	Much More	Less[3]
Operation Cost	Less	More	Much Less
Infrastructure	More	Much More	More
Range	Quite Equal	Less	Much Less
Weight	More	More	More
Refuel Time	Less	More	More/Equal[4]
Energy Efficiency[5]	+10%	+150%	+450%
Emissions	-20%	-75%	-85%

To show the differences between the technologies, **Table 3** brings a comparison between diesel buses and electric buses. As can be noticed, the Achilles heel of the alternative powertrain technologies is related to the infrastructural costs and vehicle prices. Nevertheless, BEBs present several advantages. For instance, the operation and maintenance costs are low, the energy efficiency is very high, and the emissions are low. Therefore, the BEBs appear as the best and most viable option for the electrification of public transportation. This technology still faces some challenges, regarding the range, weight and refuel time factors. However, these

[3] Degradation and swapping of batteries not included.
[4] Fast-charging refueling time range: 3-10 min [37], [38], [81], [82].
[5] Recharging process not included.

issues can be overcome with different charging strategies – this topic will be better developed in the following sections.

2.2.1 Full Battery Electric Bus

The BEBs are the vehicles mainly used in electric public transportation nowadays. Therefore, it is vital to present a short overview of this technology, concerning two vital aspects of the presented research – charging possibilities and battery technology.

a) Charging Possibilities

There are three different main types of charging possibilities when dealing with BEB: static, stationary and dynamic [26], [27].

- Static strategy: This strategy is mainly used when the BEB is going to stay parked for an extended period – generally over the night at the depot. During this time, the vehicles are charged. This approach allows for a longer recharging time. Therefore, the charging infrastructure costs are lower when compared to other strategies, as the chargers are designed to have charging powers in a range of 30 – 50 kW. Those vehicles can reach, typically, a 300 km daily range. On the one hand, this driving range provides a daily operation similar to diesel buses without recharging during the day. On the other hand, the prices of such vehicles are highly increased by the battery's costs – due to the needs of high capacity levels. The weight of such vehicles is also bigger than usual buses, and therefore fewer passengers can be carried.
- Stationary strategy: This charging strategy is also executed while the BEB is not moving. However, it is made only for a short period, or when there is an opportunity to charge – for instance, while the passengers are boarding or while the vehicle is parked at the end-stop. Therefore, the charging must be fast – around 3 to 10 minutes. Due to this fact, the charging powers are in a range of 150 – 600 kW, thus requiring high infrastructure costs. Nevertheless, this strategy allows the vehicles to have smaller batteries. Thus, they are cheaper and lighter. Moreover, as the charging points are placed over the route, the driving range becomes almost unlimited.
- Dynamic Strategy: This charging strategy allows charging while the vehicle is in motion. This approach is possible by means of Inductive Power Transfer (IPT) [28] or through fast-charging systems via catenary. However, this strategy is still in the development phase, and the related infrastructure costs are very high. However, this technology can be beneficial in

the future, as some studies point out the battery's size reduction potential that the IPT can bring.

It is also important to elucidate the concepts of fast/slow-charging and overnight/opportunity charging. Although they are correlated, those definitions are not the same. Fast-charging and slow-charging are concepts related to the power delivered by the charger – for instance, power ranges between 30/50 kW are defined as slow-charging and power rates between 150/600 kW as fast-charging. On the other hand, overnight charging and opportunity charging are definitions associated with charging strategies. **Table 4** summarizes the differences between the three charging possibilities presented above.

Table 4 – Differences between distinct charging strategies. Adapted from: [29]

	Static	**Stationary**	**Dynamic**
Strategy	Overnight charging at the depot	Mid-day opportunity charging due to facilities in the route	Mid-day opportunity charging due to charging lanes
Charger type	30 up to 150 kW (for buses with high range)	150/300/450 kW (fast-charging)	25/50/150 kW
Charging technology	Mostly plug-in	Mostly pantograph Plug-in (less common)	IPT
Typical Range	100 – 300 km/day	200 – 500 km/day	100 – 200 km/day
Refuel Time	3 – 8h	3 – 10 min	10 – 15 min
Costs drivers	**1** High Battery costs **2** Low charging infrastructure costs **3** Low maintenance costs	**1** Low battery costs **2** High charging infrastructure costs **3** Medium maintenance costs	**1** Low battery costs **2** Very high infrastructure costs **3** Very low maintenance costs

As can be noticed, all possibilities carry advantages and disadvantages. Thus, there is no standardization of charging strategy nowadays. However, the literature suggests that the opportunity charging can play a decisive role in the improvement of the BEB's feasibility systems [13]–[16]. The work of [29], for instance, concludes that *"for longer routes, opportunity charging saves 10-20% [of the Total Cost of Ownership (TCO)], as it enables a significantly smaller battery"*. The financial advantages combined with the enhancement of driving range – allowed by the fast-charging – places this charge strategy as the most promising. Therefore, the research to be developed addresses solutions to fast-charging facilities optimization.

b) Battery Technology

As previously mentioned, the batteries are the costliest element of an electric vehicle. Moreover, they are responsible for the heavyweights of the BEBs. This fact is due to the high energy density needed to operate those vehicles. The electric bus batteries are generally based on lithium-ion technology. The capacity of such batteries is not constant during their lifetime, due to many factors such as charging-discharging cycles, temperature, high Deep of Discharge[6] (DoD), and other technical issues [30]. Furthermore, the fast-charging approach increases the ageing of a battery as at high State of Charge[7] (SoC) the charging current must be decreased to avoid exceeding the battery upper limit voltage [31]. Therefore, in order to enhance the battery's lifetime, an SoC window must be implemented, to keep the values of maximum and minimum charging in an optimal range – usually, this window range is between 20% to 80% of the battery's capacity.

Another critical factor that must be highlighted is the relation between recharging infrastructures and the batteries' requirements. For example, energy-optimized batteries are more suitable for overnight or less frequent charging situations [32]. If the charging regularity becomes more frequent – in an opportunity charging approach, for instance – the storage needs will be decreased, as well as the size of the battery. On the other hand, to reduce the charging time, the power of the charger must be increased. Another important concept when dealing with batteries is the definition of the charging rate (C-rate). When charging at 1C, the battery will be fully loaded in one hour [33] – increasing this rate means that the battery will charge faster.

[6] DoD is defined as the capacity that is discharged from a fully charged battery, divided by nominal battery capacity.
[7] The level of charge of a battery is measured by the SoC (%).

2.2.2 Financial Analysis and Market Trends

Although the implementation costs are high, the BEBs present low operation and maintenance costs. Therefore, in the long run, investing in this type of vehicle delivers a higher financial advantage than other counterparts. The study of [34] brings another interesting outcome. Commonly, the costs related to health care savings are not estimated in financial comparisons. Taken this factor into account, it becomes even more advantageous investing in the BEB (**Figure 3**).

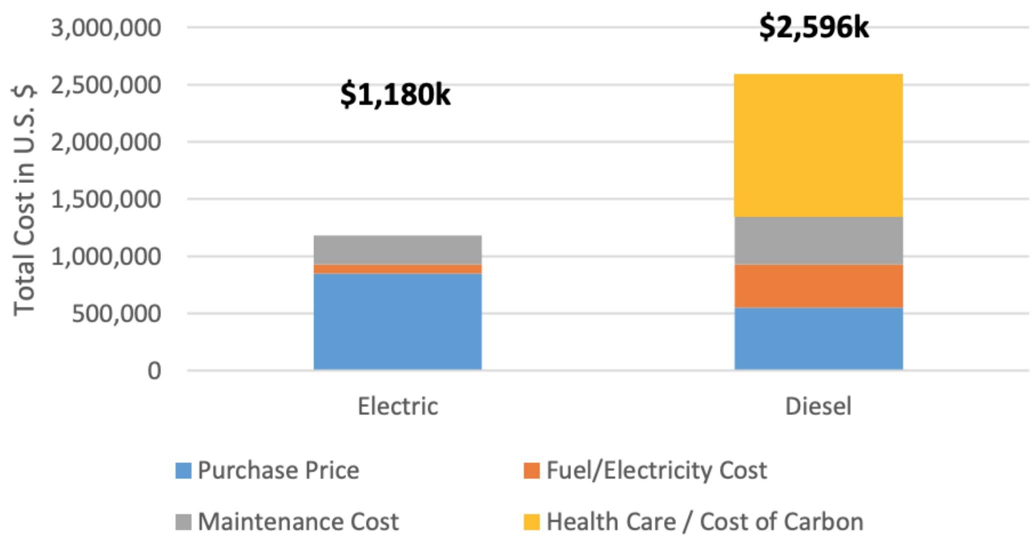


Figure 3 - Lifetime Cost of Electric Buses vs Diesel Buses (US$). Source: [34]

The study in [34] highlights that this result is due to the BEB not emitting gases in its operation, improving the air quality of urban centers. Thus, health problems related to pollution would decrease significantly.

Moreover, the price difference between BEB and Diesel Buses is decreasing more and more driven by the reduction of the battery price. As [35] points out, *"the current battery technology of choice for electric buses is lithium-ion, the price of which has dropped 80 percent since 2010, and is projected to drop another 50 percent by 2020 or 2025."* Therefore, the use of BEBs on a large scale seems to be feasible in operational and financial terms. The European Union (EU) is already financing the deployment of such vehicle fleets in the continent through the project Zero Emission Urban Bus System (ZeEUS) [36]. Some forecasts point out that until 2025, electric bus sales will be higher than the corresponding fossil-fuel buses (**Figure 4**).

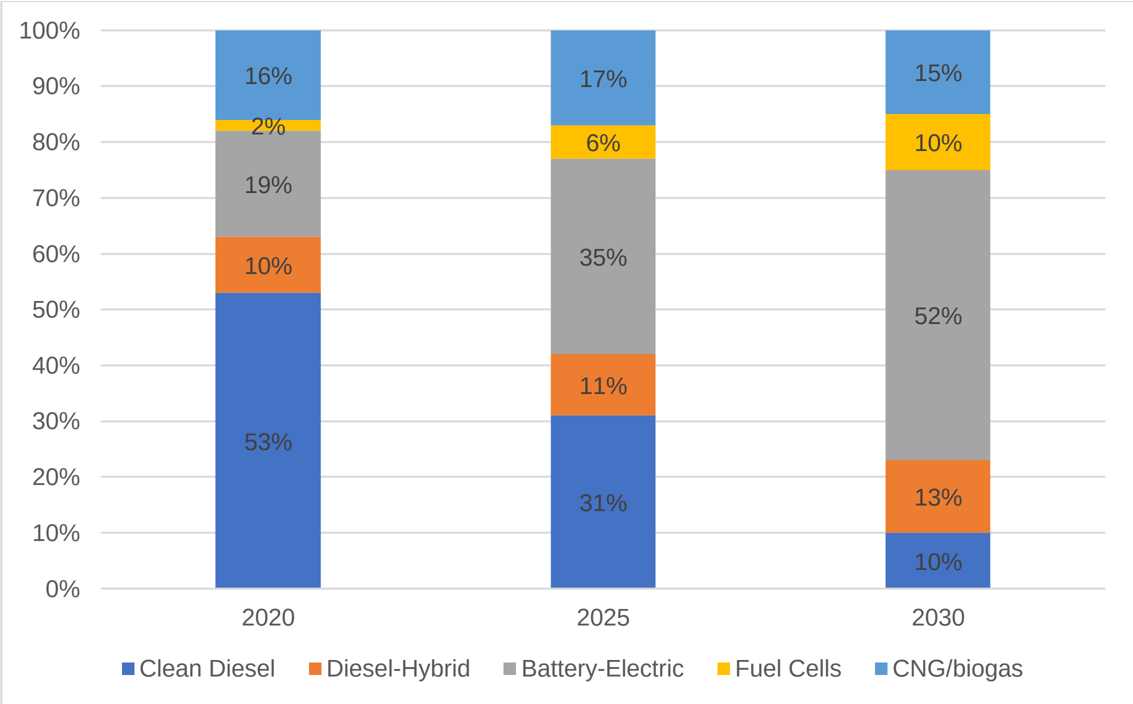


Figure 4 - European Urban Bus Market Evolution (%). Source: [37]

This trend is not only restricted to Europe. China owns the biggest BEB fleet in the world and is still investing in its expansion. Moreover, the study of [38] points out that the electric buses will displace the fossil fuels counterparts in the next decade.

3 Multi-criteria Decision Analysis for Public Transportation Systems

A comparison of different types of rapid public transportation systems was developed to assess which types of transportation can provide the most convenient solution for urban areas in terms of economic, environmental and technical evaluation criteria. The comparison of different types of technology is carried out using an MCDA approach. This MCDA study uses the PROMETHEE method and allows the consideration of different kinds of impacts, avoiding difficult measurements and unit conversions [39].

3.1 Multi-criteria decision analysis – basic concepts

In nearly all real-world situations, the decision-making process involves selecting the most suitable option, ranking options or sorting them into categories of merit, considering multiple evaluation criteria. MCDA deals with complex problems, which are characterized by *"incommensurate and conflicting criteria or objectives such as cost, performance, reliability, safety, productivity, affordability, and others"* [40]. The decision aid process requires structuring and analyzing potential actions or alternatives, criteria, and problematics [41].

- Potential Action or Alternative: The concept of *potential action* refers to the *"object of the decision, or that which decision aiding is directed towards"* [41]. It is called "potential" for the reason that any action does not bring the notion of feasibility or possibility of implementation – thus, a potential action could just have the role of being interesting to the decision aiding process. By *alternatives,* defined in a particular modeling case, refers to that two different potential actions cannot operate jointly. It is essential to highlight that the potential actions are not necessarily exclusive – there are real-world situations where different actions can be implemented simultaneously.
- Criteria: A *criterion* can be defined as an element constructed for *"evaluating and comparing potential actions"* [41], according to a decision-maker's (DM) point of view. The criteria can be presented in different scales, such as qualitative (verbal or numerical

scale) and quantitative. The concept of *Family of Criteria* refers to a finite set of criteria, and it is usually defined at the beginning of a decision aiding process. As highlighted [42], the term *family* means that the *"set of criterion functions supports exhaustively the pragmatic preferences of the DM"*.

- Problematic: A *multicriteria problem* can be defined as the situation in which a DM, after defining a set of actions and criteria, wishes to determine a subset of actions, considered as the best of the set of actions (choice problematic), assign actions to different categories defined *a priori* (sorting problematic), rank the alternatives from best to worst (ranking problematic) [43].

The identification of a final solution for a specific decision situation depends on the particular evaluation criteria and different actions that the DM considers as relevant. There are several methods to deal with MCDA problems, such as Analytic Hierarchy Process (AHP), PROMETHEE, ELECTRE (elimination and choice translating reality), and others [44]. In this work, the PROMETHEE method was selected as the evaluation tool. There are some characteristics in the problem that point out the use of this method. The capability of evaluating the performance of alternatives according to each criterion in absolute terms, the independence towards scales (also allowing evaluation criteria measured in qualitative scales), and the possibility of modeling different types of preferences parameter functions can be highlighted as significant features for the selection of this method.

3.2 PROMETHEE – basic concepts

PROMETHEE is a multi-criteria approach based on the exploitation of an outranking relation, which is characterized by the limited degree to which a disadvantage on a particular viewpoint may be compensated by advantages on other viewpoints [45]. Initially developed by Prof. Jean-Pierre Brans and his co-workers, this family of methods has been improved by other researchers [46]–[48]. PROMETHEE can deal with complex problems encountered in many different fields, like engineering, management, business, transportation [49]. The PROMETHEE family of outranking methods includes PROMETHEE I for partial ranking of alternatives and PROMETHEE II for the complete ranking of alternatives. There are other versions such as PROMETHEE III (ranking based on intervals), PROMETHEE IV (ranking of the alternatives with continuous viable solutions), PROMETHEE V (problems with segmentation constraints), PROMETHEE VI (human brain representation), and the visual interactive module GAIA [49].

More recently, [50] proposed two new approaches, called PROMETHEE TRI, for dealing with sorting problems and PROMETHEE CLUSTER for nominal classification. However, versions I and II are more frequently present in the literature, and they will be applied as a decision support tool in this work. The outranking process of those two methods will be briefly detailed in the following.

3.2.1 PROMETHEE stepwise procedure

Let us define a set of alternatives A = {a_i,…,a_n} and a set of criteria G = {g_1,…,g_q}. For each criterion g_k, k=1, …, m, a DM evaluates the performance of an alternative a_i, i=1, …, n, over an alternative a_j, j=1, …, n. The outranking process for PROMETHEE I and II approaches is summarized in **Figure 5** below.

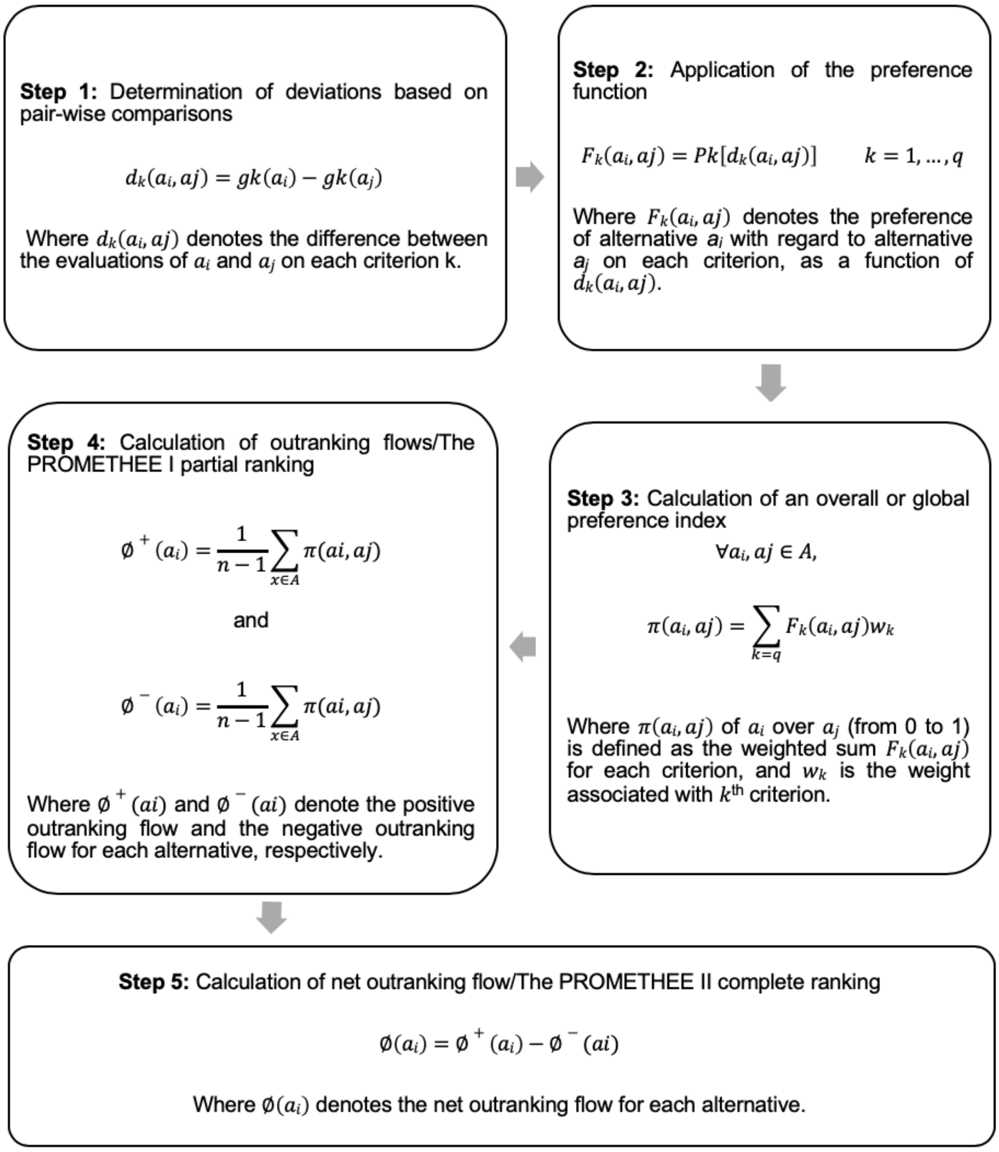
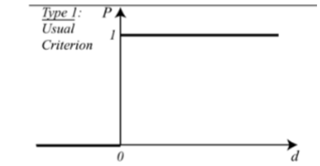
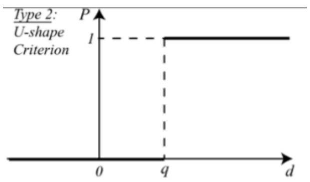
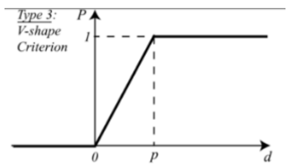
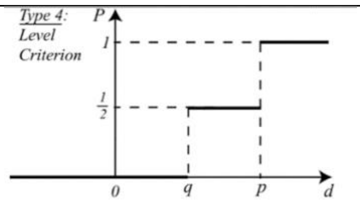
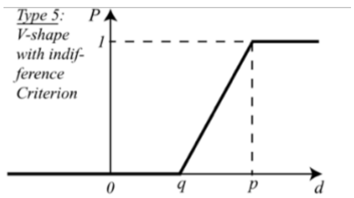
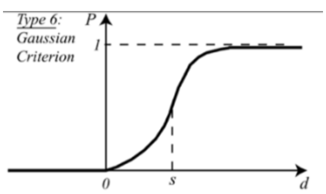


Figure 5 - Stepwise procedure for PROMETHEE I and II. Adapted: [49]

- Step 1: the DM evaluates the preference of the alternative a_i over a_j by measuring the difference of their evaluations on each criterion g_k. This comparison results in $d_k(a_i, a_j)$, which indicates how much alternative a_i performs better than alternative a_j on criterion g_k.

- Step 2: A preference function P_k is used to transform $d_k(a_i, a_j)$ into a preference degree F_k. There are different shapes of preference functions, allowing the DM to define an indifference threshold q_k or a preference threshold p_k for each criterion. **Table 5** presents each one of these preference functions, in terms of the difference of criterion evaluations (d_k), the indifference threshold (q_k), the preference threshold (p_k), and the preference function (P_k).

Table 5 - Preference function shapes. Source: [45]

Generalized criterion	Definition	Parameters
	$P_k(d_k) = \begin{cases} 0 & d_k \leq 0 \\ 1 & d_k > 0 \end{cases}$	-
	$P_k(d_k) = \begin{cases} 0 & d_k \leq q_k \\ 1 & d_k > q_k \end{cases}$	q_k
	$P_k(d_k) = \begin{cases} 0 & d_k \leq 0 \\ \dfrac{d_k}{p_k} & 0 \leq d_k \leq p_k \\ 1 & d_k > p_k \end{cases}$	p_k
	$P_k(d_k) = \begin{cases} 0 & d_k \leq q_k \\ \dfrac{1}{2} & q_k \leq d_k \leq p_k \\ 1 & d_k > p_k \end{cases}$	p_k, q_k
	$P_k(d_k) = \begin{cases} 0 & d_k \leq q_k \\ \dfrac{d_k - q_k}{p_k - q_k} & q_k \leq d_k \leq p_k \\ 1 & d_k > p_k \end{cases}$	p_k, q_k
	$P_k(d_k) = \begin{cases} 0 & d_k \leq 0 \\ 1 - e^{-\frac{{d_k}^2}{2{s_k}^2}} & d_k > q_k \end{cases}$	s_k

- Step 3: The global preference index $\pi(a_i, a_j)$ is defined to quantify the global preference of a_i over a_j, which is defined as the aggregation of all preference degrees F_k by considering the weights w_k associated with each criterion k. Note that the DM should define the values of the weights w_k.
- Step 4: The aggregation of $\pi(a_i, a_j)$ defines the notion of the outranking flow score. $\phi_+(a)$ represents the positive outranking flow and $\phi_-(a)$ represents the negative outranking flow.
- Step 5: The combination of the two partial outranking flow scores results in the complete outranking flow score $\phi(a)$ [45].

3.3 Main perspectives of analysis

This section presents an MCDA-based analysis framework to assess rapid transit alternatives for public transportation. **Figure 6** describes the process flow applied to this MCDA analysis.

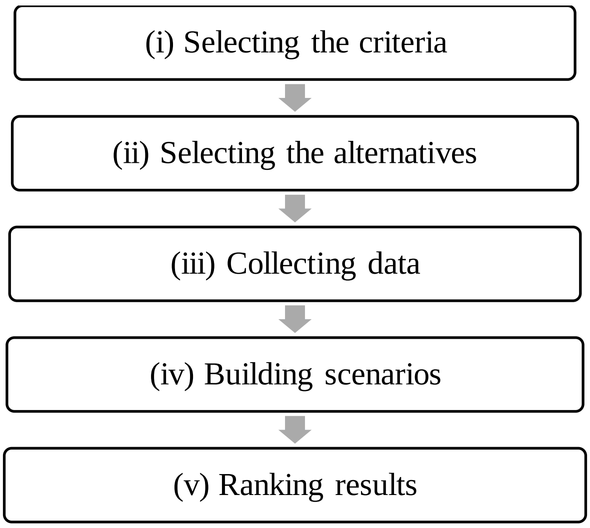


Figure 6 – MCDA process flow chart.

The two initial steps are concentrated on finding the alternatives to be analyzed and the multiple evaluation criteria that are relevant. The third step is focused on collecting enough data to run the MCDA analysis. An exhaustive search in articles, public transportation company websites and reports was made to provide the most relevant and up-to-date information for the study [51], [52], [61], [53]–[60]. The fourth step is dedicated to developing the most suitable scenarios to be analyzed, and it will be better detailed in the results section. The last step consists in evaluating the complete ranking analysis in order to determine the best actions for each one of the proposed scenarios. The Visual PROMETHEE Multicriteria Decision Aid Software[8] was used to obtain the results. This tool, which has been developed in the *Université Libre de Bruxelles*, allows the user to structure, visualize and analyze decision-making problems.

3.3.1 Alternatives and Criteria

In this section, the alternatives and set of criteria are presented. In this work, the evaluation criteria are divided into three categories[9]: Economic, Environmental, and Technical.

- Economic: Providing cost-effective solutions for public transportation is a significant concern.
- Environmental: This work aims to choose environmentally friendly transportation solutions to be used in cities, improving population welfare.
- Technical: Technical factors are indispensable for this analysis, as they provide valuable information related to the operation of a rapid transit system.

After defining the set of criteria, the work was focused on the development of the hierarchy of fundamental objectives. This concept is defined as the reasons why the DM cares about the decision and, more importantly, how the available alternatives should be evaluated [62]. Its interpretation is a procedure that requires the involvement of the DM, in general assisted by an analyst with technical expertise. It is necessary to discover the points-of-view of the DM interested in the action instead of looking only at the singular characteristics of each alternative. The present work addresses this through a review of the literature of MCDA studies related to the transportation field [63]–[66]. Moreover, the study framework presents replicability; therefore, other actors could use the same scheme to help its decision-making process in different contexts. ***Figure 8*** presents the tree of fundamental objectives. The shaded boxes represent the objectives that were chosen to be the criteria for the evaluation model.

[8] Developer's website: www.promethee-gaia.net

[9] A Social category was considered in a preliminary phase of this work, but it was then discarded as its application is more related to the place where the rapid transit system will be implemented than to the system itself. However, in situations where the location of implementation is previously known, it becomes critical to introduce social criteria in the analysis.

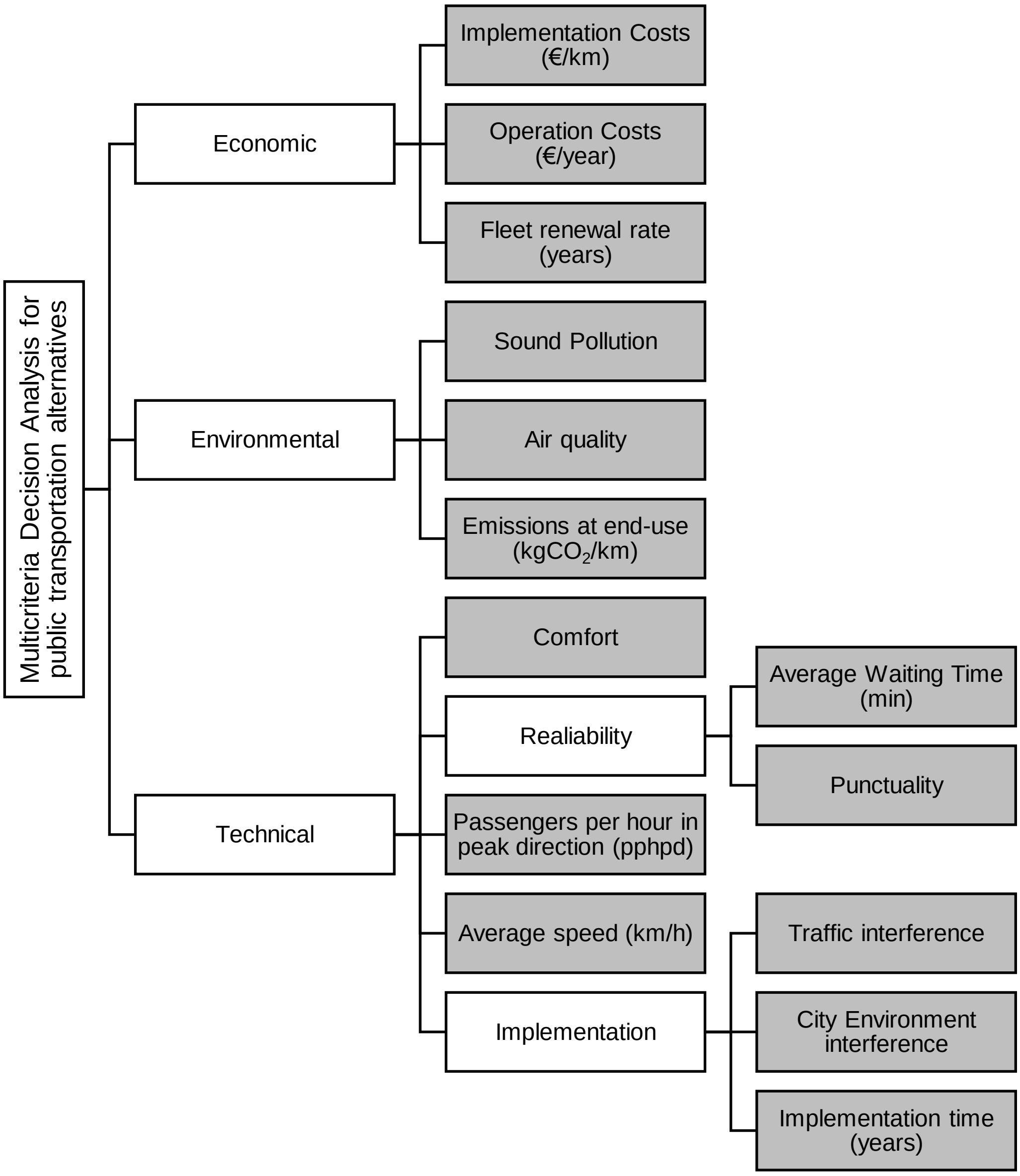


Figure 7 - Tree of fundamental objectives.

Table 6 summarizes the analyses, presenting the criterion name, definition, measurement scale (quantitative or qualitative), and if it will be maximized or minimized.

Table 6 - Description of the criteria.

Ref.	Criteria	Definition
g_1	Implementation Costs (minimize)	Average cost to build a rapid transit system per kilometer ($/km)
g_2	Operation Costs (minimize)	Average cost to operate a rapid system line per year ($/year).
g_3	Fleet renewal rate (maximize)	Time to renew the fleet of a rapid transit system (years).
g_4	Sound Pollution (minimize)	How much a rapid transit vehicle impacts the environment in terms of noise (qualitative – see **Table 7**).
g_5	Air Quality (maximize)	How much a rapid transit vehicle impacts the environment in terms of air pollution (qualitative – see **Table 7**).
g_6	Emissions at end-use (minimize)	CO_2 per kilometer is emitted by a vehicle in the end-use operation (gCO_2/km).
g_7	Comfort (maximize)	How comfortable a rapid transit vehicle is (qualitative – see **Table 7**).
g_8	Average Waiting Time (minimize)	Average time needed to wait to take a ride (minutes).
g_9	Punctuality (minimize)	How punctual a rapid transit system is (qualitative – see **Table 7**).
g_{10}	Passengers per hour in peak direction (maximize)	Number of passengers per hour in peak hours that can be carried in one direction of the line.
g_{11}	Average Speed (maximize)	Average speed that a rapid transit vehicle can reach (km/h).
g_{12}	Traffic Interference (minimize)	How much a rapid transit system impacts the traffic after been implemented (qualitative – see **Table 7**).
g_{13}	City Environment Interference (minimize)	How much a rapid transit system impacts a city environment (i.e. traffic, streets, ground) while been implemented (qualitative – see **Table 7**).
g_{14}	Implementation time (minimize)	Time needed to implement a rapid transit system in a city (years).

As mentioned previously, the PROMETHEE method allows the user to include the evaluation criteria measurement in qualitative terms. For the sake of clarity, **Table 7** presents the qualitative scale definitions and their values.

Table 7 - Qualitative scales and their reference values.

Definition	Scale Value
Very Bad	1
Bad	2
Average	3
Good	4
Very Good	5

Table 8 introduces the alternatives selected for the MCDA analysis: an electric BRT system, a typical diesel BRT system, a Metro system, and an LRT system. Those systems are the most common and prominent public transportation alternatives in cities. Other possible choices were also considered; however, as the present work is addressing rapid transportation options to be used in city traffic, they were discarded (i.e. train, trolleybus, bus).

Table 8 – Description of the alternatives.

Ref.	Alternative	Description
a_1	E-BRT	Bus Rapid Transit line operated with an electric bus fleet and ten stops [58].
a_2	BRT	Bus Rapid Transit line operated with a diesel bus fleet and ten stops [58].
a_3	Metro	Mass Rapid Transit line operated with six wagons vehicles and ten stops [67].
a_4	LRT	Light Rail Transit line operated with six wagons vehicles and ten stops [68].

3.3.2 Scenario Definitions

The MCDA will consider four different scenarios to provide more diversified results. They are Baseline, Economic based, Environmental based, and Economic & Environmental based. Due to the scope of this research (aimed mainly to providing sustainable solutions for urban mobility), the selected scenarios address the most suitable characteristics for the analysis. Each scenario is presented in detail below.

- **Baseline**

The baseline scenario was set to be a reference for the other scenarios. Therefore, the weights are the same, and the preference functions for all criteria are set up as "Usual".

- **Economic based**

This scenario highlights the criteria related to economic factors. For this purpose, the Economic category's weight was set with 50% and the weights of g_1, g_2 and, g_3 where split in an egalitarian way (17% each). Moreover, the preference function of g_1, g_2 and, g_3 were set as "Linear". The preference threshold was set as 30%, and the indifference threshold was set as 5%.

- **Environmental based**

This scenario highlights the criteria related to environmental factors. To this effect, the Environmental category's weight was set with 50% and the weights of g_4, g_5, and g_6 where split in an egalitarian way (17% each). Moreover, the preference function of g_6 was set as "Linear". The preference threshold was set as 30%, and the indifference threshold was set as 5%.

- **Economic and Environmental based**

This scenario highlights the criteria related to economic and environmental factors together. To do so, the Economic and Environmental category's weight was set with 50% of priority and the weights of g_1, g_2, g_3, g_4, g_5, and g6 where split in an egalitarian way (9% each). Moreover, the preference functions of g_1, g_2, g_3, g_6 were set as "Linear". The preference threshold was set as 30%, and the indifference threshold was set as 5%.

3.4 Results

The data is presented in **Table 9**, which resulted from a thorough search for up-to-date information in the literature and other sources.

Table 9 - Data acquired to run the MCDA study.

	E-BRT	**BRT**	**Metro**	**LRT**
Implementation Costs (Mi€$/km)	20 [54]	8.2 [54]	129 [55]	34.8 [51]
Operation Costs(Mi€$/year)	0.20 [56]	0.224 [56]	1.15 [55]	1.37 [57]
Fleet renewal rate (years)[10]	8 [56]	30	40	40
Sound Pollution	Low	High	Low	Low
Air quality	Good	Bad	Average	Good
TTW emissions (gCO2/km)	30 [58]	63 [58]	30.5 [52]	23 [52]
Comfort	Average	Average	Good	Good
Waiting Time	Up to 3 [59]	Up to 3 [59]	Up to 2 [55]	Up to 5 [51]
Punctuality	Average	Average	Good	Good
pphpd[11]	16,000 [53]	16,000 [53]	50,000 [55]	19,000 [57]
Average Speed (km/h)	26 [61]	23.95 [61]	33 [55]	27.8 [51]
Traffic Interference	Average	Average	Very Low	Average
City Environment Interference	Low	Low	Very High	Average
Implementation Time (years)	3 [60]	3 [60]	10	5

The results provided by the PROMETHEE's complete ranking are presented in two different forms.

10 The fleet renewal rate for the E-BRT alternative is related to the battery lifespan time (around 6 to 8 years).
11 Passengers per hour in peak direction

- PROMETHEE flow table: Shows the positive, negative and complete outranking flow scores.
- PROMETHEE Network: In this type of representation, actions are displayed by nodes and arrows are drawn to indicate preferences. Incomparabilities are thus very easy to detect. Moreover, the software Visual PROMETHEE uses an enhanced network representation, instead of drawing the nodes at arbitrary locations.

a) Baseline Results

The results indicate that Metro performs better than the other rapid transit systems, in a scenario without restrictions. E-BRT and LRT reached the same score, and BRT presented the worst result. The flow table results are shown in **Table 10**.

Table 10 - Flow Table Results for the Baseline scenario.

Ranking	**Action**	ϕ	$\phi+$	$\phi-$
1	Metro	0.1429	0.5238	0.3810
2	E-BRT	0.0714	0.4286	0.3571
3	LRT	0.0714	0.4524	0.3810
4	BRT	- 0.285	0.2616	0.5476

The results point out that, if a DM does not have any limitation in terms of capital, ground interference or time of implementation, the Metro alternative performs much better than the others. It is also interesting to highlight that LRT and E-BRT have the same performance. Moreover, the result of this experiment reveals that the main weakness of a diesel BRT is the environmental issue related to the combustion engine. **Figure 8** presents the network results for this scenario.

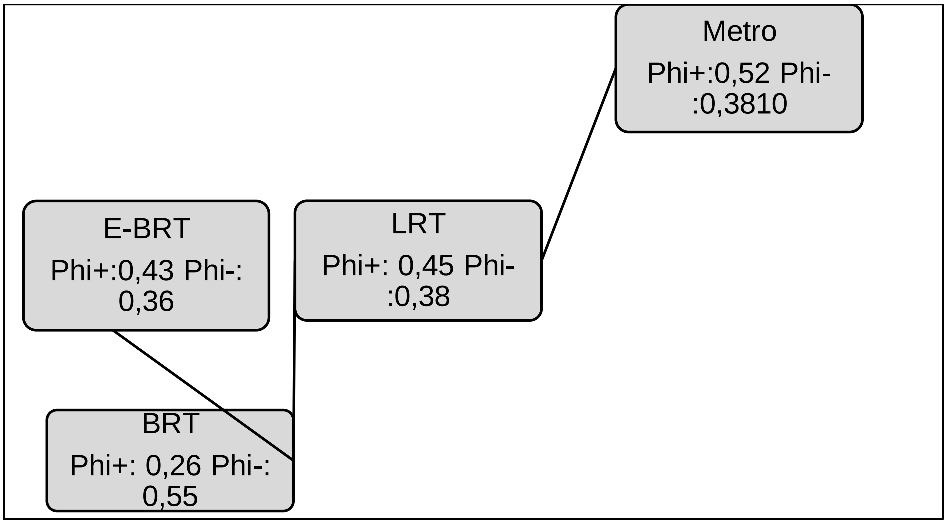


Figure 8 – Network results for the Baseline scenario.

b) Economic-based Results

The result stats that E-BRT performs better than the other rapid transit systems, followed by BRT, in an economy-based scenario. The LRT system presents results slightly worse than the BRT. Metro, as expected, presents the worst results among all the alternatives. The flow table results are shown in **Table 11**.

Table 11 - Flow Table results for the Economic based scenario.

Ranking	**Action**	ϕ	ϕ+	ϕ-
1	E-BRT	0.0594	0.4494	0.3900
2	BRT	0.0011	0.4142	0.4131
3	LRT	- 0.007	0.4076	0.4151
4	Metro	- 0.026	0.4205	0.4467

These results indicate that the BRT systems (electric and diesel) appear to be the best options in economic terms. This result was expected, as both alternatives present low-cost implementation and maintenance. The E-BRT performs even better than the diesel counterpart, as its environmental criteria have better scores. The LRT performance is close to the diesel BRT. Although it has higher implementation and maintenance costs, the LRT system compensates it with proper environmental criteria values and a high fleet renewal rate. The Metro is by far the worst option in economic terms. For instance, in this analysis, the implementation cost of a Metro system is six times higher than the E-BRT and almost sixteen times higher than a diesel BRT. The maintenance costs are also high when compared to the BRTs alternatives, just losing to the LRT. **Figure 9** presents the network results for this scenario.

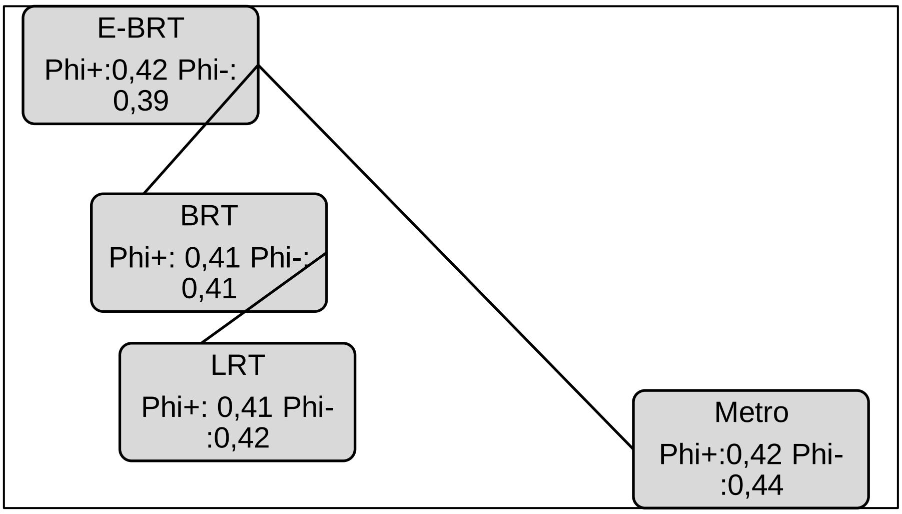


Figure 9 – Network results for the Economic based scenario.

c) Environmental-based Results

The E-BRT presents better performance when the environmental criteria are highlighted. The LRT system also shows good results, following closely to the first position. The Metro and BRT are the worst alternatives in environmental terms. The flow table results are shown in **Table 12**.

Table 12 – Flow Table results for the Environmental based scenario.

Ranking	**Action**	ϕ	$\phi+$	$\phi-$
1	E-BRT	0.2539	0.5033	0.2494
2	LRT	0.2263	0.5057	0.2794
3	Metro	0.0744	0.4521	0.3777
4	BRT	- 0.554	0.1633	0.7179

These results indicate that the electrical traction of the E-BRT plays an important role in terms of environmental performance, as it provides zero emissions in the utilization phase. For comparison, the diesel counterpart presents the worst results, mostly as a result of its fossil fuel-powered engine. The LRT alternative also presents a good evaluation of environmental criteria, due to its lower emissions in the operation phase. However, the E-BRT holds better economic criteria improving its final performance when compared with the LRT. Despite the good environmental attributes that the Metro system holds, its high associated costs push its performance down. **Figure 10** presents the network results for this scenario.

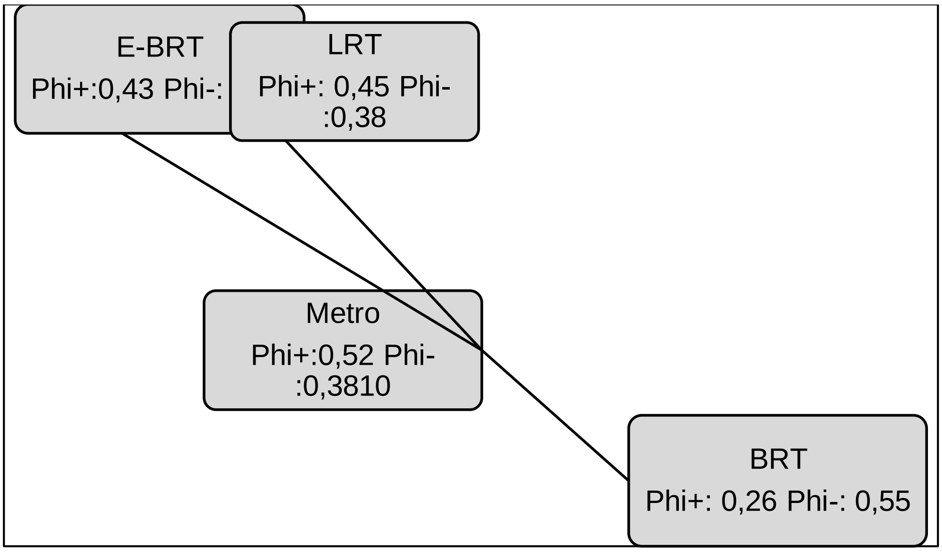


Figure 10 – Network results for the Environmental scenario.

d) Economic and Environmental based Results

In this combined framework, E-BRT, Metro and LRT, respectively, are the best alternatives. All three options have excellent performance, with E-BRT presenting a slightly better result. The flow table results are shown in **Table 13**.

Table 13 – Flow Table results for the Econ. & Environmental based scenario.

Ranking	**Action**	ϕ	ϕ+	ϕ-
1	E-BRT	0.0954	0.4236	0.3282
2	Metro	0.0903	0.4707	0.3805
3	LRT	0.0852	0.4446	0.3593
4	BRT	-0.270	0.2743	0.5452

In a scenario where the economic and environmental factors are taken into account, the results are interesting since all the three electric-powered systems perform almost at the same level. This result is driven by the different characteristics of each alternative. E-BRT presents better economic factors, the LRT presents better environmental factors, and the Metro presents the best technical factors. This result is also significant to indicate that E-BRT is a feasible solution for urban transportation when compared to other more consolidate alternatives. **Figure 11** presents the network results for this scenario.

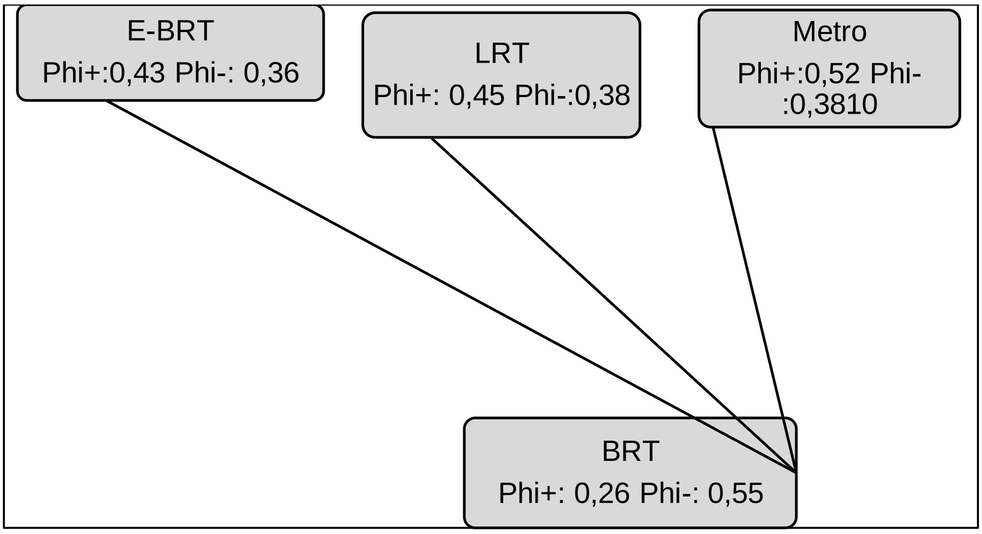


Figure 11 - Network results for the Economic and Environmental based scenario.

3.5 Conclusions

This chapter presented an MCDA study concerning different rapid transit systems. The objective of the study was to determine the most suitable transportation alternative for urban areas by evaluating the alternatives in terms of economic, environmental and technical criteria. The outranking PROMETHEE approach was used as the selection tool. The fourteen evaluation criteria were divided into three categories, and four alternatives were chosen to be assessed (E-BRT, BRT, Metro, and LRT). To improve the evaluation process, four different scenarios were stablished: baseline, economic-based, environmental-based and economic & environmental based. An extensive literature review was carried out to develop the scenarios, define the entities under evaluation and collect up-to-date and accurate data.

The results indicate that in a scenario without restrictions, the Metro alternative appears as a better option. However, considering economic factors, the BRT systems (electric and diesel) appear to be better alternatives. This result is driven by low-cost implementation and maintenance presented by such vehicles. The E-BRT performs even better than the diesel counterpart, as its maintenance cost is slightly lower and mainly because its environmental criteria scores are better. Concerning the environmental evaluation, the E-BRT presents better results followed closely by the LRT. Both options present good evaluation in environmental criteria, highlighting that the LRT has fewer emissions in the operation phase. However, the E-

BRT has better economic criteria scores thus improving its final performance. The last scenario (economic and environmental based) finds the E-BRT as a better option, followed closely by Metro and LRT.

The MCDA study outcomes indicate that Bus Rapid Transit systems, mainly the electrical option, are feasible alternatives to be used in urban areas. Therefore, to enhance the penetration of this technology, more solutions in terms of charging and electricity storage must be addressed. This research will deal with this issue, dealing with the location of fast-charging stations in urban areas.

4 Optimization Model and Simulation

The results presented in chapter 3 indicate that the BRT alternative, based on electric buses, can be a feasible alternative for public transportation in metropolitan areas. To implement such systems, among other factors, the location of the charging points must be well planned. Therefore, the work presented in this chapter will introduce a framework for the strategic planning of a charging infrastructure of a BRT system, involving the minimization of the number of charging stations, battery capacity and implementation costs. The chapter begins by introducing some basics concepts concerning the mathematical programming process, as well as some notions of integer programming. After that, the mathematical model developed in this work will be presented. After the conceptual mathematical modeling, the model was implemented in the IBM ILOG CPLEX Optimization Studio (CPLEX). Subsequently, to provide sounder results, the model was simulated in a variety of possible situations that can be faced in the real world. Such analysis will be presented afterward (see chapter **5**).

4.1 Mathematical Programming process

In the present work, an analytical approach was used by developing a mathematical programming model that followed some systematic steps [69]. These steps will be briefly described in the following. It is relevant to point out that those different stages can overlap and interact which each other.

a) Formulating the model

The first step is the formulation of the model. The process generally starts with the definition of the decision variables. The decision variables can be defined as the answers that the DM is searching for. After defining the decision variables, the next step is to define the objective function to be optimized, which acts as a measure of performance of the solutions defined by the instantiation of the decision variables. The constraints define the feasible region, resulting from limitations of different nature, restricting the range of variation of the decision variable values. The model formulated in this work will be presented in section **4.2.2**.

b) Gathering the data

The collecting data process is, in general, the most costly and time-consuming step of the mathematical modeling process. The data must contain valuable and reliable information concerning all the aspects of the model formulation (namely the objective function and constraint coefficients). In this work, the data needed was obtained in two different ways: research in reports, papers, company's product datasheets in order to acquire the most available data concerning prices, specifications and operation functions of charging technology and electric buses. Other data refers to the information needed to simulate a BRT system network (e.g. number of stops, distances between stops, charging time, etc.). This data was gently provided by the Metro Mondego S.A.

c) Obtaining an optimal solution

After building the mathematical structure and gathering enough data the model instantiated with the data is dealt with by a solver, which implements an algorithmic devoted to the type of model (linear, mixed-integer linear, non-linear).

d) Applying sensitivity analysis

Performing a sensitivity analysis of the mathematical model implemented is one of the most essential and advantageous steps in the optimization process. It allows the DM to evaluate some impacts that could occur in the real-world by modifying some parameters of the model. For instance, some data uncertainty can be added to the problem to observe how much the model is sensitive for such variations. The sensitivity analysis conducted in this dissertation will be presented in chapter **5**.

e) Testing and implementing the solution

In practice, after having obtained an optimal solution to the model instantiated with given data and applied a sensitivity analysis, the final outcome must be tested to verify if the model really represents the real-world situation. After testing, the solution is ready to be implemented. For this work, which has a more prospective character, the testing and implementation stages were not carried out.

4.1.1 Integer Programming

Integer linear programming refers to mathematical optimization where all relations are linear and (all or some) variables are limited as integers. It is called a mixed-integer linear programming (MILP) model when some of the variables are integers, but not all. The integer linear program can be defined as:

$$\text{Maximize } \sum_{j=1}^{n} c_j x_j \ , \tag{1}$$

subjected to:

$$\sum_{j}^{n} a_{ij} x_j = b_i \qquad (i = 1,2, \dots, n). \tag{2}$$

$$x_j \geq 0 \qquad (j = 1,2, \dots, n), \tag{3}$$

$$x_j \text{ integer} \qquad (\text{for some or all } j = 1,2, \dots, n). \tag{4}$$

Integer linear programming models have a large number of applications, driven mainly by the broad modeling capabilities that the integer, and particularly binary, variables can provide. For instance, MILP models allow for the modelling of logical constraints, compound alternatives and representation of non-linear functions. All those features can enhance the mathematical modeling process for specific real-world situations. In the context of the present work, the literature review (see **4.2.1**) suggests that, for implementing a charging planning decision problem, a MILP model is required. In the proposed problem, the number of charging facilities is an integer, but other variables (time, battery capacity, discharged energy, etc.) may be defined as continuous.

4.2 Mathematical Approach

In this section, the mathematical model will be presented. As already mentioned, the main objective of this study is to minimize the number and determine the location of fast-charging stations of an electrified BRT system. The mathematical model was implemented in the CPLEX Optimization Studio [12]. This software offers a dedicated mathematical programming modelling language coupled with a solver to obtain the optimal solution of linear, integer and mixed-integer models [70].

[12] https://www.ibm.com/products/ilog-cplex-optimization-studio

4.2.1 Literature Review

There is a considerable number of mathematical optimization approaches concerning facility location problems. The work in [71] presents a solution for alternative-fuel vehicles. The main objective was to develop a location-allocation model for optimally locating refueling facilities for range-limited vehicles. To reach this goal, the authors based the methodology on a MILP formulation called Flow Refueling Location Model (FRLM). The test problems indicate that if the driving range is too short, it may become impossible to refuel all vehicles, even with facilities located at every node. Using a similar mathematical formulation, the work of [72] tries to identify the optimal locations for EV fast-charging stations in the city of Barcelona. To reach this goal, the authors propose two different methodologies: the use of a classical flow-capturing optimization model to address the mobility characteristics in the network and an advanced flow-capturing optimization model to minimize the fast-charging related costs. The results indicate that the application of the fast-charging facilities could reach a range cost reduction of 5% to 10%. The work in [73] presents a study on the location of slow EV charging stations for a neighborhood in Lisbon using a maximal covering model. The aim is to optimize the demand covered within an acceptable level of service and to define the number and capacity of the stations to be installed.

Some works also introduce economic-related aspects. The work of [74] focused on identifying the return of investments of EV charging stations, proposing a MILP model based on Geographical Information System (GIS) to identify the optimal location of such facilities. The model considers the geographical distribution of traffic flow and different charging possibilities based on the land-use classification to reach the optimal profit of the charging stations. The authors conclude that the adoption of this methodology can encourage investments and increase the penetration of EV in cities. The study in [75] is focused on BEB fleet size and cost-optimized depot charging infrastructure, minimizing the TCO of the fleets. The methodology is based on the Electric Vehicle Scheduling Fleet Size and Mix Problem with Optimization of Charging Infrastructure (EVS-FMC). The two case studies reveal that the fleet costs are influenced significantly by considering the bus type and its technical specifications. Furthermore, the authors suggest that a mixed bus fleet could be advantageous in terms of minimizing the TCO, depending on the operational characteristics of the route. The study of [76] compares the cost competitiveness of different types of charging infrastructure – charging stations, charging lanes and battery swapping stations. A MILP model was built to optimize the fleet size and battery capacity and consequently to minimize the infrastructure and fleet costs. The conclusion indicates that the speed of operation, service frequency, and route length can profoundly influence the cost competitiveness of the charging infrastructures. All these works reveal the importance of dealing with the economic aspects of EVs charging facilities.

In a more specific way, the literature presents some findings related to the implementation of fast-charging facilities in BEB transportation systems. The study of [78] analyses the feasibility and energy store requirements of fast-charging battery buses. The research is based on real-world data in the city of Münster. Moreover, the paper also presents a study on the impacts of fast-charging on the electricity grid. The results show the necessity to focus on entire vehicle schedules, instead of on individual trips, to enhance the system practicability. The study also presents an interesting result concerning the tradeoff between the required battery capacity and passenger capacity. The authors conclude that a reduction of the demanded passenger capacity enables an increase of the installable battery capacity so that the required charging power of the vehicle can be reduced.

All the presented studies in this section will be considered in the fast-charging points mathematical location modeling. As a contribution, the presented research aims to provide a framework to facilitate the implementation of BRT systems in urban contexts.

4.2.2 Mathematical Model

The mathematical model developed in this study will be presented in the following. **Table 14** introduces the nomenclature if the indices, parameters and variables that are going to be used in the model.

Table 14 - Nomenclature.

Indices	**Description**	**Range/unit**
j	bus stop	[j = 1,…,n]
Parameters	**Description**	**Range/unit**
K_j	infrastructure costs of the charger	[€]
$S_{(i,j)}$	length of the route segment (i,j)	[km]
η	bus battery discharging rate per km	[kWh/km]
β	charging power of the charger	[kW]
α	scale factor	$\frac{1}{3600}$
E^{low}	lower safety energy margin for battery discharge	[kWh]
E^{high}	higher safety energy margin for battery charging	[kWh]
E^{aux}	auxiliary energy necessary to run the vehicle	[kWh]
DT_j	dwell time at the bus stop j	[s]
Variables	**Description**	**Range/unit**
x_j	binary variable indicating if a charger is located at the bus stop j	{0,1}
e_j	Battery stored energy at stop j	[kWh]
c_j	energy-charged at the bus stop j	[kWh]
$d_{(i,j)}$	energy consumed in the route segment (i,j)	[kWh]

The objective function (5) minimizes the infrastructure costs and provides the location to place the charging stations.

$$\min \sum_{j=1}^{n} K_j \; x_j \tag{5}$$

subject to:

$$x_j = \begin{cases} 1, & \text{if a station is placed at location } j \\ 0, & \text{otherwise} \end{cases} \qquad j = 1, \dots, n \tag{6}$$

$$e_j = e_i - d_{(i,j)} + c_j \qquad j = 1, \dots, n \tag{7}$$

i is the immediate predecessor node of *j* in the route.

$$d_{i,j} = \eta \, . \, S_{(i,j)} + E^{aux} \qquad j = 1, \dots, n \tag{8}$$

$$c_j = x_j \, . \mathrm{DT}_j \, . \beta \, . \alpha \qquad j = 1, \dots, n \tag{9}$$

$$e_i \geq d_{(i,j)} + E^{Low} \qquad j = 1, \dots, n \tag{10}$$

$$e_j \leq E^{high} \qquad j = 1, \dots, n \tag{11}$$

Constraints represent the system and the characteristics of the charging. The constraint (6) states that x_j is a binary decision for all stations.

The constraint (7) ensures that the currently stored battery energy e_j when the bus is leaving the stop *j* is equal to the previous energy level e_i at the stop *i* minus the energy consumed $d_{(i,j)}$ on the travel route segment *(i,j)* plus the energy charged c_j at the bus stop *j*.

The constraint (8) establishes that the energy consumed $d_{(i,j)}$ on the travel route segment *(i,j)* is the discharging rate η multiplied by the length route segment $S_{(i,j)}$ plus the auxiliary energy rate E_{aux} necessary to operate the auxiliary features of the bus.

The constraint (9) guarantees that the energy charged c_j at the bus stop *j* is only viable if the binary variable x_j indicates whether a charging station is built at a bus stop *j*. If x_j is equal to 1, then the energy charged c_j at the bus stop j is proportional to the charging power β multiplied by the charging time (dwell time) DT_j at the bus stop j. Moreover, the scale factor α (1/3600) accounts for the dimensions of the charging power (kW) and the charging time (seconds), in order to provide the correct value of energy (kWh) charged in the battery.

The lower safety margin for battery discharge E_{low}, defined as a security level during operation, is introduced in (10). This constraint guarantees that the energy level e_i at the stop i must be higher than the lower safety margin E_{low} plus the energy $d_{(i,j)}$ on the travel in the route segment (i,j) to ensure that sufficient energy is available to reach the next stop.

The higher safety margin for battery charging E_{high}, defined as a security level during operation, is defined in (11). This constraint ensures that the energy level e_j will be within the security operation levels.

5 Case Study

The chapter introduces the case study analyzed in this dissertation. The first part details the bus network, highlighting the infrastructure of the line, travel time and system operation. The second part describes the case study scenario framework as well as the parameters defined in the analysis. The last part is dedicated to present the outcomes and discussion.

5.1 Infrastructure

The analysis is conducted with the BRT "Metrobus do Mondego" as a base. This BRT system is located in the region of Coimbra, Portugal. All the information used in this case study (stops, distances, and dwell times) was gently provided by the Metro Mondego S.A. – company in charge of the BRT system implementation.

The system is divided into two services: suburban and urban. The suburban line (Lousã line) connects the city of Serpins to Coimbra in a single 30 km long track. The urban service starts in Coimbra, where two lines (Urban Lousã Line and Hospital Line) connect different points of the city. The complete network has a length of 41.9 km, 24 road/pedestrian intersections, 41 bus stops, and dedicated lanes all over the track. **Table 15** details the BRT network in terms of extension, number of stops, and average distance between stops.

Table 15 - Metrobus network data.

Line	Extension (km)	Number of Stops	Average distance between stops (km)	Total travel time (min)
Lousã Line	30.9	17	1.9	58
Lousã Line (urban service)	6.8	15	0.5	18
Hospital Line	4.2	9	0.5	24
Total	41.9	41	1.0	-

It is important to highlight that such operational characteristics are interesting, as the model can be tested into two different situations. In the suburban service, the buses stay more time at the stops and reach higher speeds. The urban service presents less time at the stops and inferior average speed. Furthermore, the bus stop distances in the urban service are shorter and the arrivals are more frequent. All those aspects were considered account in the analysis. In the following, both services will be detailed. **Figure 12** presents the complete Metrobus system network.

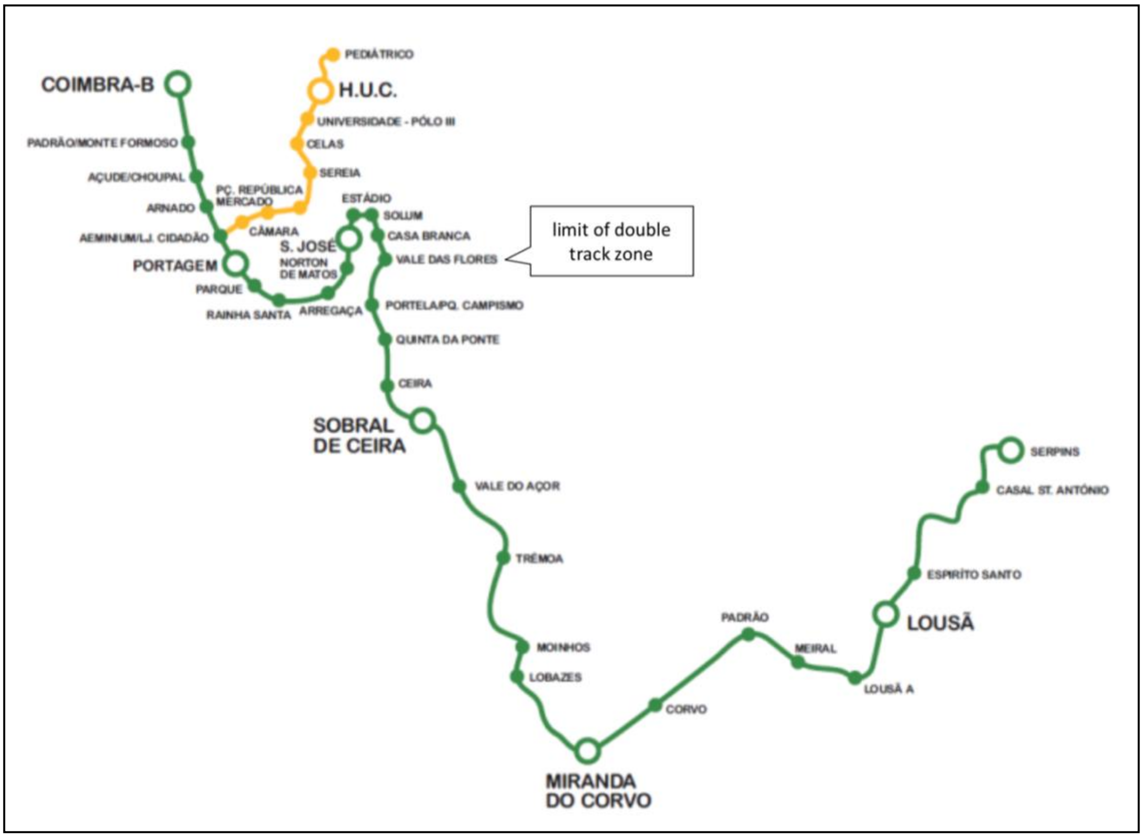


Figure 12 – Complete Metrobus network.

- **Suburban Service**

The suburban section (Lousã Line) connects small cities and villages to Coimbra (the biggest city of the region). The service is divided into 17 stops in a 30.9 km single track. The commercial speed of the buses (**Figure 13**) is high; therefore, the average distance between stops (1.9 km) is not an issue. For instance, is expected that all the 37 km from Serpins to Coimbra-B will be covered in 76 minutes.

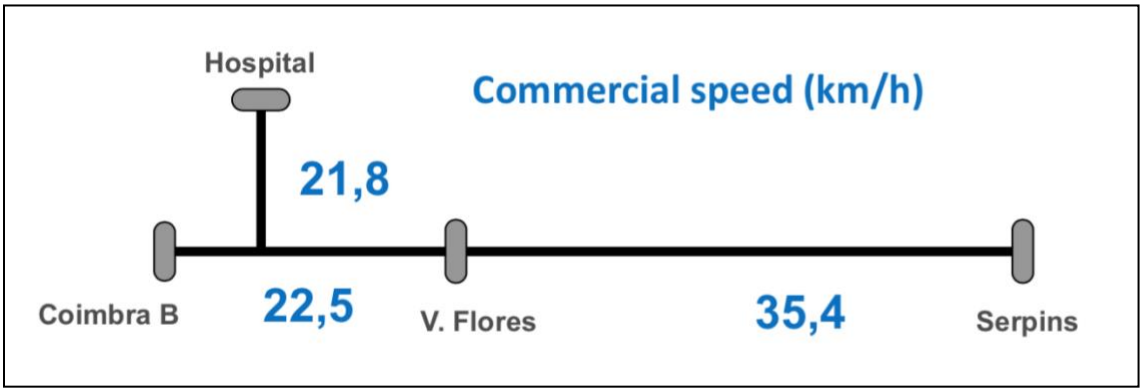


Figure 13 – Commercial speed (km/h) of the sections.

- **Urban Service**

The urban section connects different points of the city of Coimbra. The service is divided into two different lines. The Hospital line connects *Loja do Cidadão* to Coimbra Hospital (HUC), having 4.2 km length and 9 stops. The section holds a double track, meaning that the bus traffic runs in both directions. The other urban section is a continuation of the Lousã line; however, instead of having a single track, it has a double one and connects *Vale das Flores* to Coimbra main train station (Coimbra-B). This line has 6.8 km length and 15 stops.

5.2 Scenario Framework and Analysis Parameters

This section details the scenario framework and the sensitivity analysis.

a) Scenario Framework

Table 16 introduces the main features of the BRT system – those characteristics are considered in the mathematical model and will be detailed in the following.

Table 16 - Features of the BRT system.

Characteristics	Values
Charging Power [kW]	150/300/400
Battery boundaries [%]	20 – 80
Battery capacity [kWh]	90/220/440
Auxiliary power [kW]	15 (mild)/20 (warm) /30 (cold)
Discharging rate [kWh/km]	1.26 (mild) /1.53 (warm) /2.2 (cold)

- Charging Power: The major objective of this dissertation is to present location solutions for fast-charging infrastructures in a BRT system. Therefore, the charging power of that equipment must be contained in the fast-charging power range [150 – 400 kW]. The most common commercial fast chargers are up to 300 kW charging power. However, for simulation purposes, 400 kW charging power will also be adopted as a feasible solution.
- Battery boundaries: As previously mentioned, the battery's aging is directly related to fast-charging. To address this issue, an SoC window must be implemented, normally ranging between 20 % to 80 % of the battery's capacity. The analysis takes this factor into account.
- Battery capacity: The opportunity charging approach combined with the fast-charging can reduce the battery size of the electric buses, as already mentioned. Therefore, in this study, it was proposed to work with a wide battery capacity range (90 – 440 kWh) to observe its influence on the charging infrastructure implementation.
- Auxiliary power: The total energy used on a bus trip depends directly on the auxiliary power expenditure. This value can vary for different reasons, but mainly for cooling and heating needs.
- Discharging rate: The average discharging rate of an electric bus can vary depending on external factors, namely: vehicle weight, traffic density, and weather. For this analysis, the discharging rate is going to be a default value of 1.26 kWh/km [79].

Also, the proposed framework includes a cost analysis concerning the implementation of the chargers in the bus route. **Table 17** presents those values.

Table 17 - Buses and Chargers costs.

Type of Bus	**Price (US$)**
Volvo 7900E (90 kWh)[13]	135,000
Proterra XR (220 kWh)[14]	330,000
Proterra E2 (440 kWh)	660,000
Type of Charger	**Price (US$)**
ABB 150 kW	37,500
ABB 300 kW	75,000
ABB 400 kW	100,000

[13] https://www.volvobuses.com.pt/pt-pt/our-offering/buses/volvo-7900-electric/specifications.html
[14] https://www.proterra.com/vehicles/catalyst-electric-bus/

It is important to highlight that together with the chargers' implementation (and its related costs), this work will introduce the costs related to acquire a bus fleet – in order to bring more realism to the final outcomes. For all analyzed scenarios, the cost of purchasing a fleet of 30 buses will be considered – the total implementation costs will vary according to the type of bus that will be tested. As already mentioned, the Metrobus BRT network is divided into a suburban and urban lines. For the analysis to be presented only the Lousã Line (Serpins to Coimbra-B) will be evaluated. The reason for such decision is that the two different tracks hold similar characteristics and would be too much redundant information to be presented.

Table 18 – Lousã Line main characteristics

Characteristics	Values
Total distance (km) per trip	37.7
Total travel time (min) per trip	76
Number of Stops	32
Day work time window (hour)	16
Round trips	6

Table 18 presents the main characteristics of the line. As the objective of this scenario is to simulate a complete day of work, a 16 hours day work time window (e.g., 6h to 22h) will be considered. Thus, in a full day, a bus will perform around 6 round trips.

b) Sensitivity Analysis

Three different scenarios were created for this sensitivity analysis concerning different: charging powers, battery capacities, and charging times. **Table 19** summarizes all the parameters that will be used in those analysis.

Table 19 - Parameters in the sensitivity analysis.

Characteristic	Values		
Charging Power [kW]	150	300	400
Bus Battery Capacity [kWh]	90	220	440
Charging Time [s]	120	180	300
Discharging rate [kWh/km]	1.26		
Auxiliary Power [kW]	15		

The first scenario is focused on different charging power options to assess the influence (and how much) different charging powers affect the system. Thus, three different charging power (150/300/400 kW) will be evaluated in each one of the different perspectives. The other parameters are: charging time of 120 seconds, bus battery capacity of 220 kWh, and auxiliary power of 15 kW.

The second scenario is focused on different bus battery capacities. As already mentioned, the battery is the costliest feature of a bus. Therefore, providing solutions to reduce the capacity of such batteries – and its related costs – could be an interesting solution in terms of reducing the final implementation costs of the fleet. For this reason, this scenario aims to evaluate the possibilities of working with bus fleets with smaller battery capacities. To this effect, three different values (90/220/440 kWh) will be evaluated. The other parameters are charging power of 300 kW; charging time of 120 seconds; and auxiliary power of 15 kW.

The third scenario is focused on different charging times. Varying the period that a bus will stop does not require any additional implementation costs in the system, only rescheduling of the network timetable. Thus, understanding how much the variation of the charging time affects the charging needs and the total charging time is a useful evaluation. For this scenario, three different charging times (120/240/300s) will be assessed. The other parameters are charging power of 300 kW; bus battery capacity of 220 kWh; and auxiliary power of 15 kW.

5.3 Results and Discussion

The results and discussion of the simulation are presented in this section. The three scenarios are Different Charging Powers (S1), Different Battery Capacities (S2), and Different Charging Times (S3). For each of them, it is presented the location of charging points (see **Figure 14**, **Figure 16**, and **Figure 18**), the number of chargers, the number of charging, the total charging time and the total implementation costs (see **Table 20**, **Table 21**, and **Table 22**). Additionally, plots display the variation of bus batteries energy amount per stop (see **Figure 15**, **Figure 17**, and **Figure 19**)[15]. In all simulations, it was considered the charging requirements for six round trips of the Lousã Line. Finally, enhancing the conclusions of the simulations and proving strategies for supporting decisions in the planning of a BRT charging infrastructure, section **5.3.1** compares the scenarios S1, S2, S3.

[15] To simplify the presentation, the bus stops location will be represented by numbers (see **Table A 1** for the relation of the stops names and its related numbers).

a) Scenario 1: Different Charging Powers

The simulation of S1 is based on the charging power variation. As a result, **Figure 14** presents the chargers points location in the Lousã Line. The colored dots indicate if a bus stop must have an installed charger.

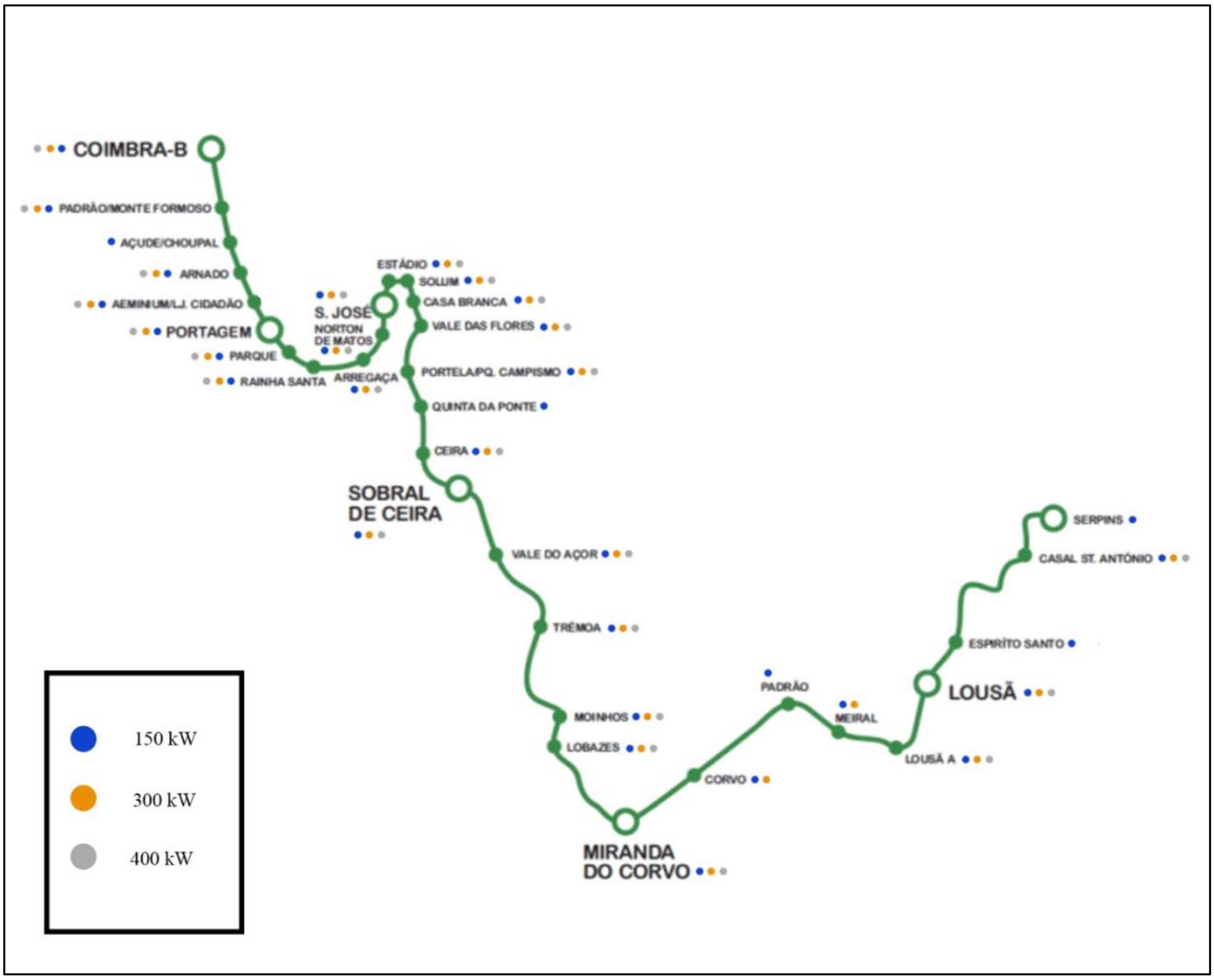


Figure 14 – Chargers Location in the BRT line (Scenario 1).

It is important to highlight; a bus will not be charged every time it passes through a station with an installed charger. The image above just presents the spots to install the chargers in order to provide enough energy to a full day of work. However, the simulation also provides information concerning the number of recharging requirements and the exact time that they will need to be performed. These data is presented in **Appendix B**.

The outcomes of the simulation are displayed in **Table 20**. Concerning the economics aspects, the solution with a charging power of 150 kW presents the best result. This outcome is driven by the difference of the analyzed charger costs. For instance, a 150 kW charger is 37.5% cheaper than a 400 kW one.

Table 20 – Results of the Simulation (Scenario 1).

	150kW	300kW	400kW
Number of Fast Chargers	32	27	25
Number of recharging	139	69	52
Total recharging time (h: min)	4:37	2:18	1:44
Chargers Costs (US$)	1,200,000.00	2,025,000.00	2,500,000.00
Bus Fleet Costs (US$)	9,900,000.00		
Total Implementation Costs (US$)	11,100,000.00	11,925,000.00	12,400,000.00

However, besides the economic aspect, other outcomes must be considered to assess the best solution for the network electrification. As expected, increasing the charging power affects directly the number of recharging operations. For instance, for a charging power of 150 kW, the bus needs to recharge 139 times. This number represents 37 % of the total charging availability[16] of the line. This number drops sensibly for higher charging powers. With a 400 kW charger, the number of charging operations required is 52– representing 14 % of the total charging availability of the line. Such a number of recharges has as a consequence two different aspects. The first one is related to the total recharging time. The simulation outcomes demonstrate that for a 150 kW charging power, more than 4 extra hours charging are needed to provide enough energy to the bus. Such an amount of time, in many cases, will be unviable to be implemented in practice. For a 300 kW charging power, the charging time drops to 2h18 (50 % lower than the 150 kW alternative) – a quite more realistic value. The result is even better for 400 kW, where the total charging time is 1h44. Therefore, to improve the implementation of a fast BRT system, the bus network should be electrified by more powerful chargers.

[16] The total charging availability of the line is a coefficient between the total number of stops (counting all the round trips) with the total number of recharging.

The other aspect is related to the battery lifespan. **Figure 15** presents the variation of a bus SoC in the simulated scenario.

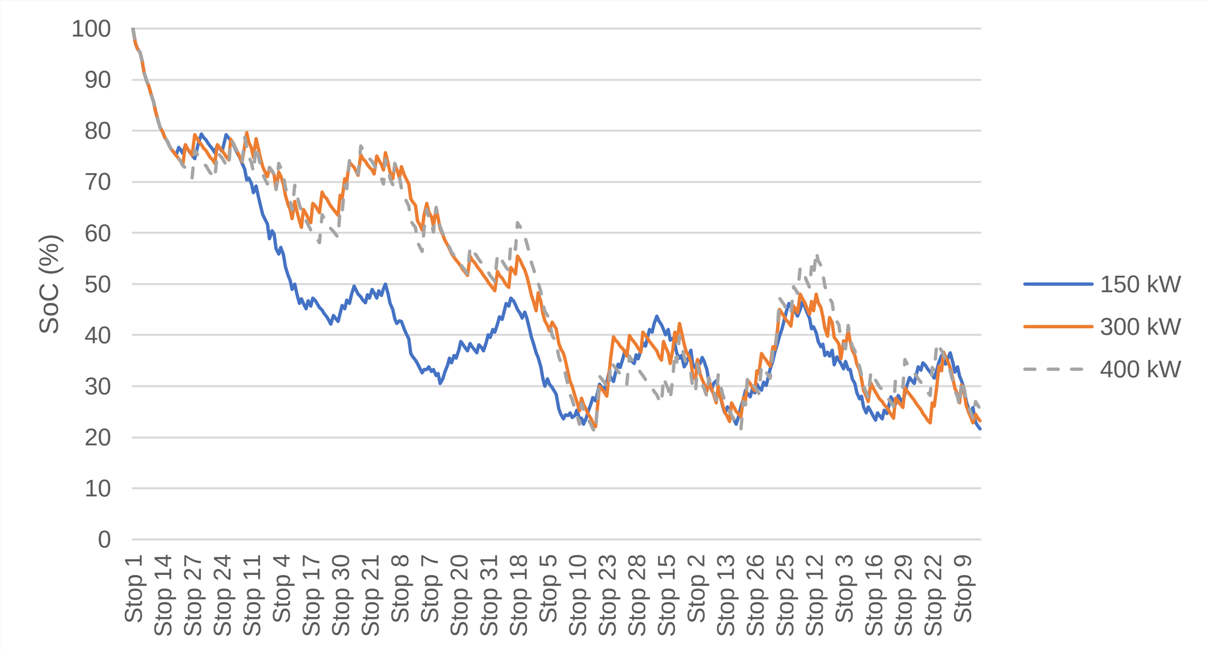


Figure 15 – Variation of the State of Charging (Scenario 1).

As can be noticed, for a 150 kW charging power, the operation level of the battery SoC is lower than the other available solutions. The main problem is that in such circumstances the battery must be recharged many times, resulting in a faster lifespan degradation. In the long run, preserving the battery lifespan can be more cost-effective for the system, as the battery will not be replaced constantly. Therefore, the implementation of more powerful chargers can be a better solution to preserve the maintenance costs at practicable levels.

b) Scenario 2: Different Battery Capacities

The simulation of S2 is based on the battery capacity variation. As a result, **Figure 16** presents the chargers points location in the Lousã Line.

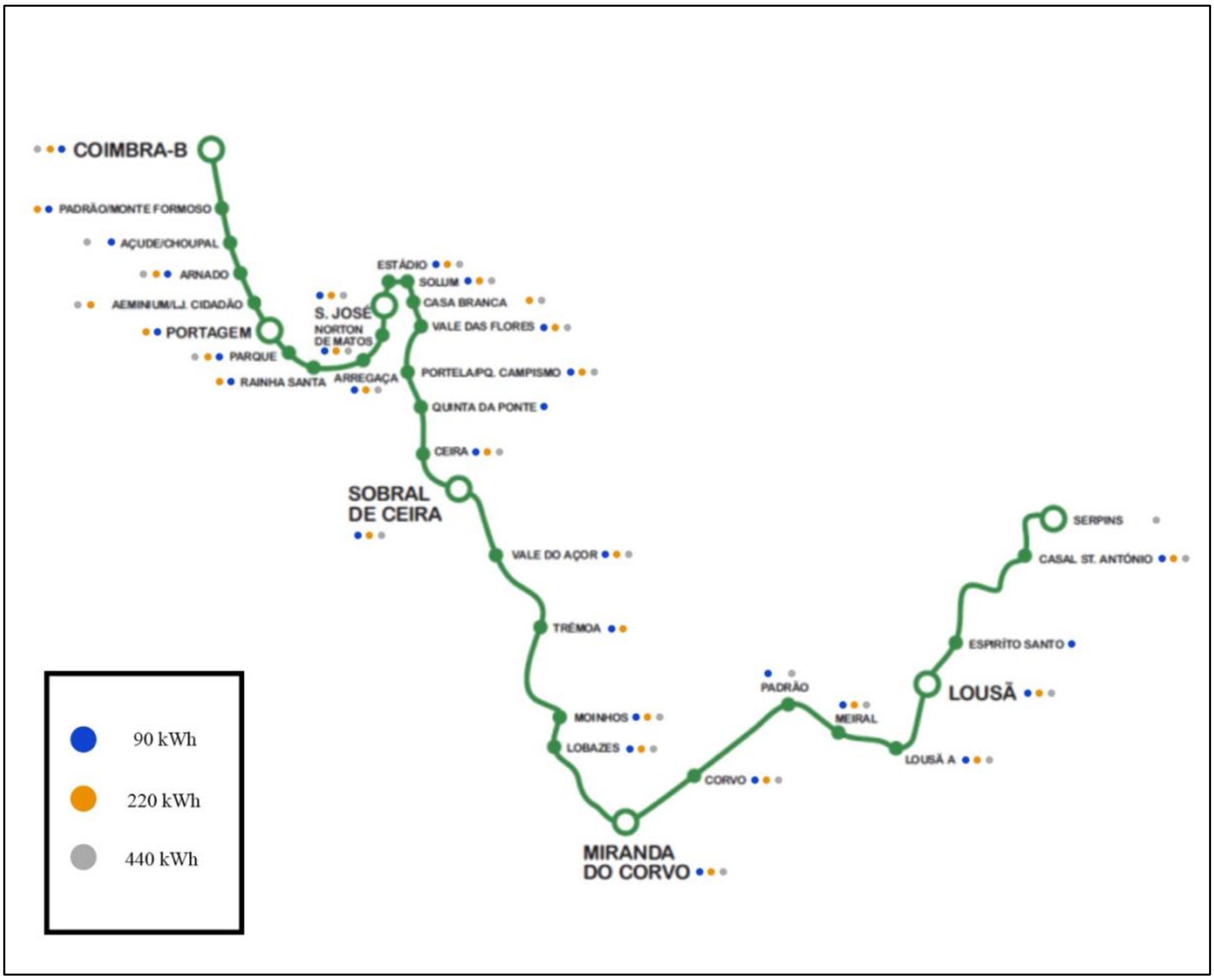


Figure 16 - Chargers Location in the BRT line (Scenario 2).

The outcomes of the simulation are displayed in **Table 21**. Concerning economics aspects, the solution with a 90 kWh battery capacity presents the best results. This outcome is driven by the difference of costs to acquire a bus fleet. For instance, a 90 kWh bus is 4 times cheaper than a 440 kWh one. Another interesting aspect is that, keeping the same charging power (for the simulation of S2 the charging power was set as 300 kW), the variation of the bus battery capacity does not cause great variations in the number of installed fast chargers. In the economic perspective, this outcome can be interesting, as cheaper fleets can be acquired with no need to increase greatly the number of chargers in the line. Therefore, the costs related to the implementation of fast chargers in the line is quite similar in the three different solutions.

Table 21 - Results of the Simulation (Scenario 2).

	90 kWh	220 kWh	440 kWh
Number of Fast Chargers	29	27	26
Number of recharging	80	69	51
Total recharging time (h: min)	2:40	2:18	1:42
Chargers Costs (US$)	2,175,000.00	2,025,000.00	1,950,000.00
Bus Fleet Costs (US$)	4,050,000.00	9,900,000.00	19,800,000.00
Total Implementation Costs (US$)	6,225,000.00	11,925,000.00	21,750,000.00

Concerning the number of recharging operations, increasing the battery capacity influences directly the decrease of its number. However, differently from the simulation S1, in this case the impact is not that large. For instance, for a battery capacity of 90 kWh the bus needs to be recharged 80 times. This number represents 21 % of the total charging availability of the line. For a battery capacity of 220 kWh, the charging requiring is 69 times, representing 18 % of the total charging availability of the line. Although the battery capacity of 220 kWh is more than two times bigger than 90 kWh, the difference between the number of times to charging is pretty close. This outcome is interesting in two different points of view. First, the total recharging time of the three solutions is not that far from each other. The solution with a battery capacity of 90 kWh needs just one extra hour to provide enough energy to the bus line when compared to the solution with a battery capacity of 440 kWh. Such outcomes indicate that the operation of buses with smaller batteries in BRT lines can be a feasible solution in terms of timetable scheduling.

The second aspect is related to the number of recharging concerns the battery lifespan. **Figure 17** presents the variation of a bus SoC in the simulated scenario.

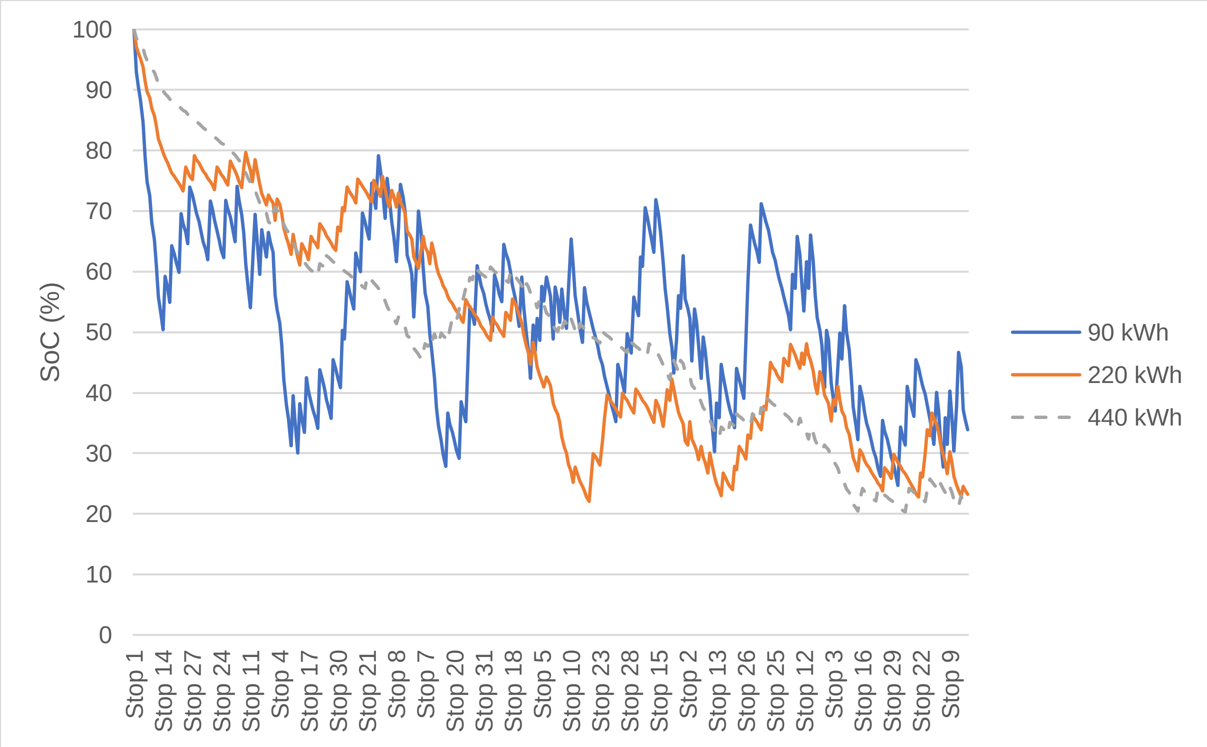


Figure 17 - Variation of the State of Charging (Scenario 2).

The comparison of the SoC curves, of the three situations simulated in S2, brings a conclusion related to the battery life cycle. It is possible to notice that the solution with a battery capacity of 90 kWh has a much higher DoD than the other alternatives. This aspect has a direct influence on battery degradation. The solution curve with a battery capacity of 440 kWh, for example, has a much more consistent behavior and a less abrupt drop during the operation of the bus. Therefore, in terms of improving the battery life cycle and decreasing future maintenance costs, the simulation indicates that electric buses fleets with larger batteries are the best options.

c) Scenario 3: Different Charging Times

The simulation of S3 is based on the charging time variation. As a result, **Figure 18** presents the chargers location in the Lousã Line.

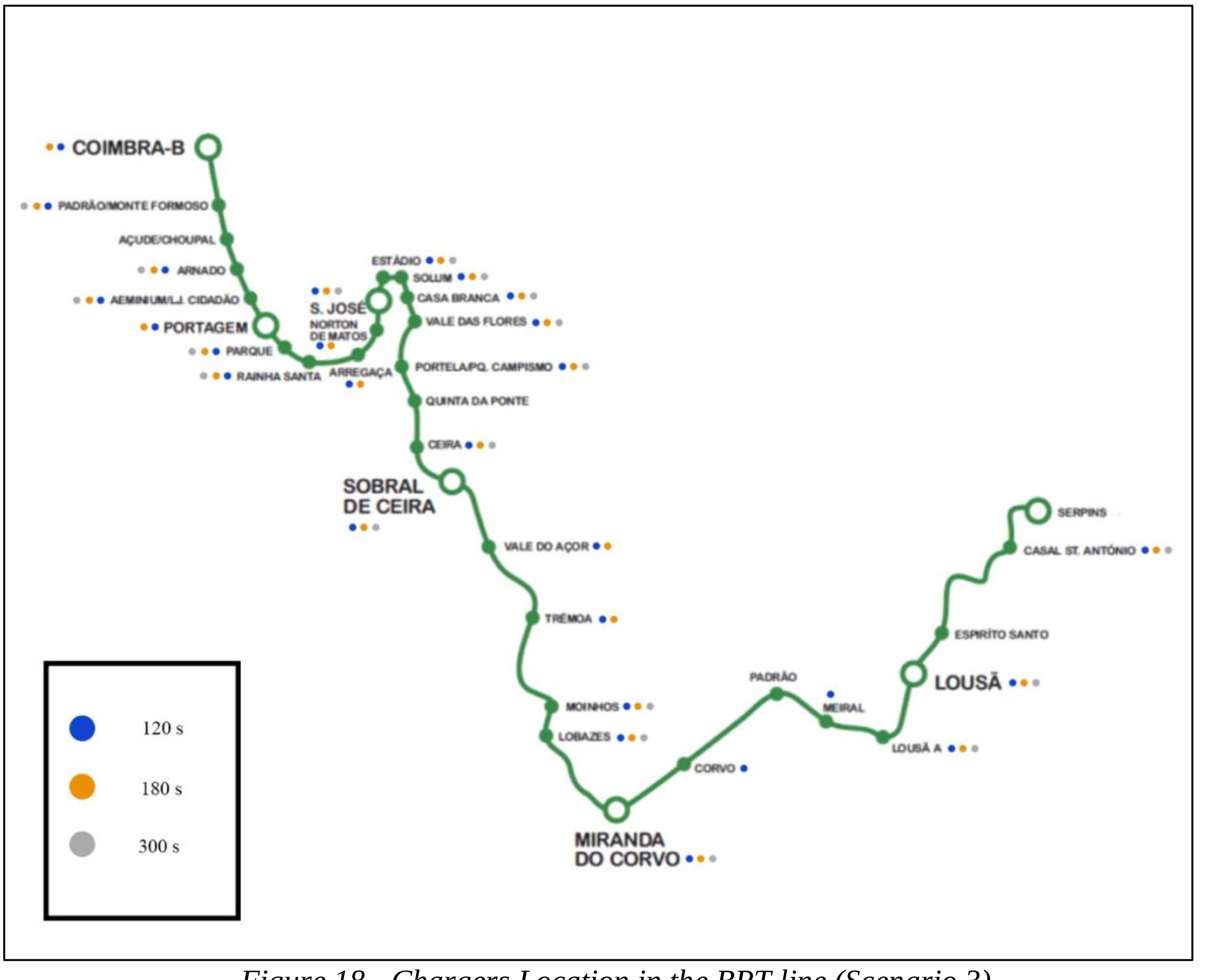


Figure 18 - Chargers Location in the BRT line (Scenario 3).

The outcomes of the simulation are displayed in **Table 22**. The need for charging and the number of chargers decreases significantly when the charging time is increased. Therefore, concerning economics aspects, the solution with a charging time of 300 s presents the best result.

Table 22 - Results of the Simulation (Scenario 3).

	120 s	180 s	300 s
Number of Fast Chargers	27	25	19
Number of recharging	69	46	28
Total recharging time (h: min)	2:18	2:18	2:18
Chargers Costs (US$)	2,025,000.00	1,875,000.00	1,425,000.00
Bus Fleet Costs (US$)	9,900,000.00		
Total Implementation Costs (US$)	11,925,000.00	11,775,000.00	11,325,000.00

Moreover, the number of recharging operations is also reduced for larger charging times. For instance, for a charging time of 120 s, the bus needs to be recharged 69 times. This number represents 18 % of the total charging availability of the line. For 300 s the charging need drops to 28 times, meaning 8 % of the total charging availability of the line. Thus, the study outcomes indicate that implementing larger recharging times could be an interesting strategy to decrease the charging requirements of a bus line. Another result is that, for the same charging power and battery capacity (for S3 the simulated values were 300 kW and 220 kWh, respectively), the total recharging time does not vary among the three simulated solutions. Considering implementation strategies for a BRT line, this is a relevant factor. A network can be planned with fewer fast chargers and a cheaper fleet, without the need to increase the total charging time. For this purpose, it is enough that specific stations have a longer stop time for buses to load.

To analyze the battery lifespan through a full day of work, **Figure 19** presents the bus SoC behavior in the simulated scenario.

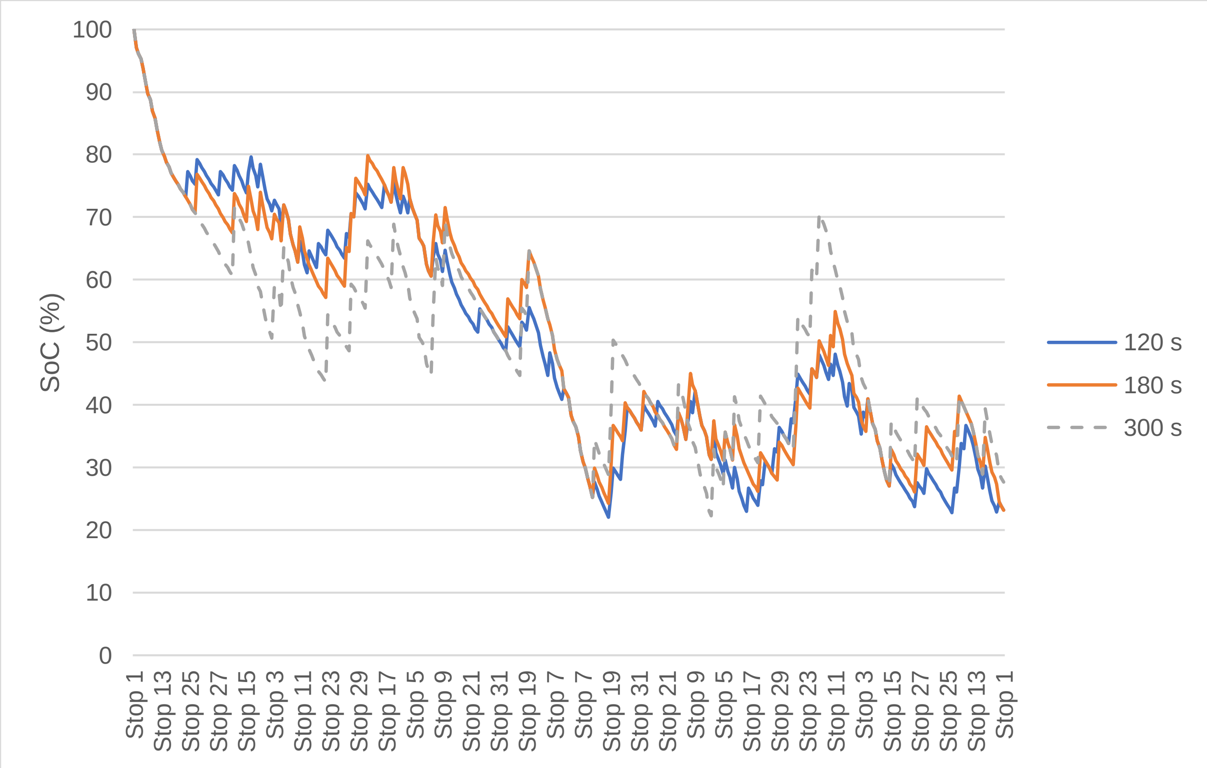


Figure 19 - Variation of the State of Charging (Scenario 3).

The behavior of the curves is very similar, although the solution with a loading time of 300 s operates at a relatively lower SoC level than the other alternatives. This is because, for such a solution, less recharging is necessary to maintain the energy levels of the batteries. In this way, to increase a bus battery life cycle, longer charging times should be performed.

5.3.1 Scenarios Comparison

In this section, a comparative synthesis of the S1, S2, S3 will be presented. Those scenarios can be comparable due to the fact that the discharging rate of all simulated possibilities is the same. For the comparison, **Figure 20** aggregates all the outcomes of the simulated alternatives. To present all data in this graphic representation, the values where normalized. **Appendix C** presents all the plots related to the aspects analyzed in the simulations (namely **Figure C 1**, **Figure C 2**, **Figure C 3**, and **Figure C 4**).

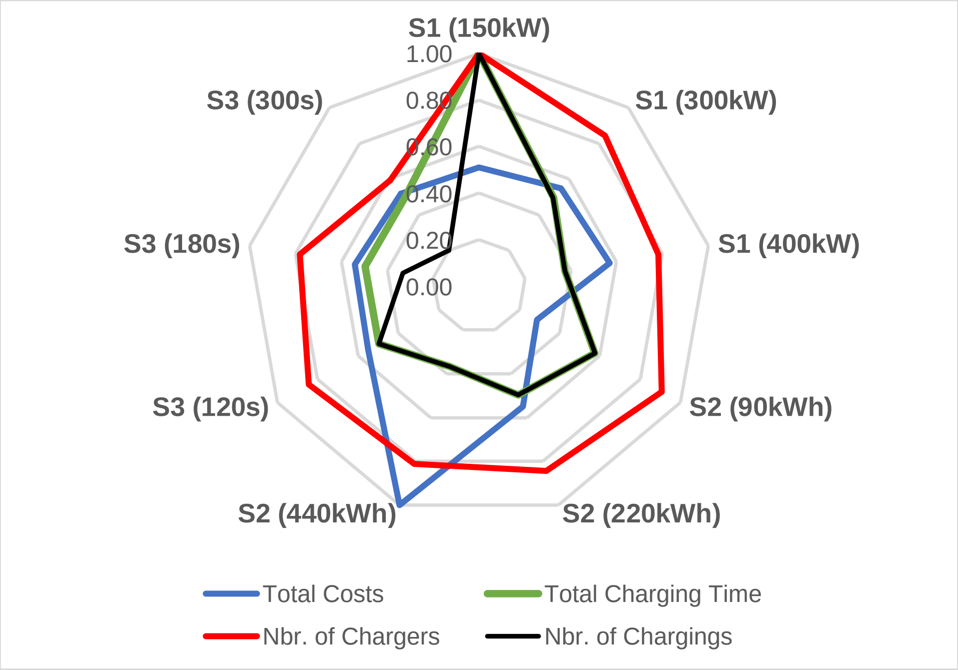


Figure 20 – Graphic comparing the simulated scenarios S1, S2, and S3.

S1, S2, and S3 are evaluated together to indicate some strategies and solutions for planning the electrification of the Metrobus BRT. Some conclusions can be made observing the results of the optimization of charging point location. It is essential to highlight that an optimal solution depends mainly on the tradeoffs between the different parameters. Such analysis will be described in the following.

In the simulated scenarios, the costs related to the implementation of the BRT system are divided into costs for the acquisition of a fleet of electric buses and the acquisition of fast chargers. Therefore, the analysis can be divided into two parts. First, the costs related to implementing the chargers can be evaluated by scenario, and then the price of acquiring a bus fleet.

In S1, the charger with the lowest power (150 kW) had the most economical cost of implementation, despite presenting more chargers in the system, due to its lower price when compared to the other solutions. In S2, the option with the largest battery capacity (440 kWh) had the lowest chargers implementation cost, since the autonomy of the buses is greater than the other alternatives. In S3, increasing the loading time proved to be the best option to decrease the expenses related to the implementation of fast chargers. Furthermore, the solution with a recharging time of 300 s has the lowest number of chargers of all the simulations. Regarding the value associated with fleet acquisition, only S2 shows variations since, in all other scenarios, the vehicles analyzed had the same battery capacity. For the reason that the cost of purchasing bus fleets with huge batteries is extremely expensive, the solution with the lowest total price of implementation is the one with the smallest battery capacity (90 kWh). Thus, in terms of decreasing the total costs of implementation, chargers with less power, buses with less energy capacity and longer charging times could be taken as the most suitable solution for the system. However, this preliminary conclusion must be better studied, considering the tradeoffs of each alternative.

For example, in S1 the solution with a load of 150 kW has a high number of recharging operations (37% of the total line) - which leads to a faster degradation of the batteries - and a total charging time of more than 4 hours (value that may be impractical for real situations). In S2, the high cost related to batteries plus the fact that, for the same charging power, different types of buses operate with a small difference in terms of recharging needs, indicates that the acquisition of fleets with smaller batteries is more interesting for implementation costs and quality of operation. In S3, the simulation pointed out that the variation of the charging time at the stops does not affect the total charging time of the system. The entire charging time is divided equally among all stations with chargers. In operational terms, this is a relevant factor, since some stations in the line can be chosen to have longer charging times (if possible), enabling the reduction of the installed fast chargers in the route. These characteristics are summarized in **Table 23** below.

Table 23 – Comparison Summary

	Charging Power	**Battery Capacity**	**Charging Time**
Implementation Costs	**-**	**- -**	+
Number of Chargers	+	**null**	++
Total Charging Time	++	+	**null**

Therefore, to decrease implementation costs, the charging power must be slightly reduced (values less than 300 kW), the battery capacity decreased (values between 90 kWh to 220kWh) and the charging time per stop increased (values greater than 120 s). To minimize the number of implemented chargers, the charging power and charging time must be increased (values up to 300 kW and 300 s, respectively). Finally, to decrease the total charging time, the charging power and battery capacity should be increased (values up to 400 kW and more than 90 kWh, respectively).

Summarizing, the simulations indicate that the most suitable solutions for electrifying the BRT networks are those which implement high charging powers, smaller batteries capacities, and more top charging times. However, the ideal solution for the implementation depends on the characteristics of specific BRT networks. Therefore, for choosing the most suitable solution for a system, the DM must select the attributes that fit better to the context of implementation. The model presented can be a useful tool to help the decision in different situations.

5.4 Conclusions

This chapter detailed the case study developed in this dissertation. Firstly, the BRT Metrobus do Mondego was described, highlighting its infrastructure and operation (see **Figure 12**). Secondly, the case study was detailed, defining three scenarios, as well as the analyzed parameters. In the last section, the mathematical model implemented in the research for the optimal location of charging points was tested in a sensitivity analysis based on the variation of three parameters (charging power, battery capacity and charging time). The analysis' outcomes indicated that the most suitable solutions for electrifying the BRT networks are those which implement high charging powers, smaller batteries capacities, and more top charging times (see **Figure 20**). Anchored in the results, a framework was developed to help the DM in the strategic planning of BRT systems, considering the cost of implementation, number of chargers, total charging time and battery life cycle. Considering the diversity of scenarios, one of the contributions of this dissertation is to propose an approach for the optimal implementation of BRT systems. Such a framework can be used as a useful tool to assist DMs that confront different BRT profiles.

6 Conclusion

A decision support approach for planning a BRT charging infrastructure was presented in this dissertation. First, a MCDA study comparing different rapid transportation systems was carried out. To obtain sounder results, four different scenarios where created, and the outcomes indicates that the electric BRT system can provide reasonable solutions for urban public transportation.

Then, a MILP mathematical model was developed to determine the optimal fast-chargers location for a BRT system. The model was solved with CPLEX. To obtain sounder results, a sensitivity analysis was performed based on the variation of three parameters (charging power, battery capacity, and charging time). The outcomes of such a study indicate that the most feasible options for the implementation of a BRT system are those solutions that rely on high charging powers, smaller batteries capacities, and more top charging times.

Anchored in this analysis, a framework was proposed to assist a DM in the strategic planning of BRT systems, considering the cost of implementation, number of chargers, total charging time, and battery life cycle.

Concerning future work developments, some ideas could be highlighted. First, the fast-charging approach requires high power capability from the electricity grid. Therefore, an analysis of the impacts of fast-charging on the grid can be carried out. Another topic is related to the effect of temperatures as the cold or hot weather impacts the discharging rate of the batteries expressively. Therefore, the model presented in this dissertation could be used to evaluate the impact of such climatic variations in a BRT system. This analysis could be used to predict the installation of additional fast chargers in a network, which would be utilized in extreme climatic situations. Furthermore, the model developed in this work could be applied as a tool to assess the effects of fast-charging in the public transport system based on electric busses or BRTs, as a whole. Last but not least, the model herein presented could be improved to provide optimal solutions in terms of the size of a bus battery and the charging power of a charger.

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Appendix A

Table A 1 below presents the Lousã's Line information concerning distances between stops, stop's names and its related number presented in the case study.

Line	Nº	Stop's name	Distances (km)
Lousã (Suburban)	1	Serpins	-
	2	Casal de Santo António	0,554
	3	Espírito Santo	4,426
	4	Lousã	1,145
	5	Lousã-A	0,893
	6	Meiral	2,022
	7	Padrão	3,420
	8	Corvo	2,415
	9	Miranda do Corvo	1,000
	10	Lobazes	2,564
	11	Moinhos	1,436
	12	Trémoa	2,542
	13	Vale de Açor	2,959
	14	Sobral de Ceira	1,521
	15	Ceira	1,118
	16	Quinta da Ponte	1,047
	17	Portela/Parque de Campismo	0,779
Lousã (Urban)	18	Vale das Flores	1,032
	19	Casa Branca	0,654
	20	Solum	0,379
	21	Estádio	0,406
	22	São José	0,492
	23	Norton de Matos	0,357
	24	Arregaça	0,589
	25	Rainha Santa	0,368
	26	Parque	0,724
	27	Portagem	0,633
	28	Aeminium/Loja do Cidadão	0,370
	29	Arnado	0,389
	30	Açude/Choupal	0,502
	31	Padrão/Monte Formoso	0,400
	32	Coimbra-B	0,551

Table A 1 – Metrobus stops information.

Appendix B

This Appendix presents the plots related to the localization of the chargers and number of recharging need in each stop for the simulated scenarios (S1, S2, and S3).

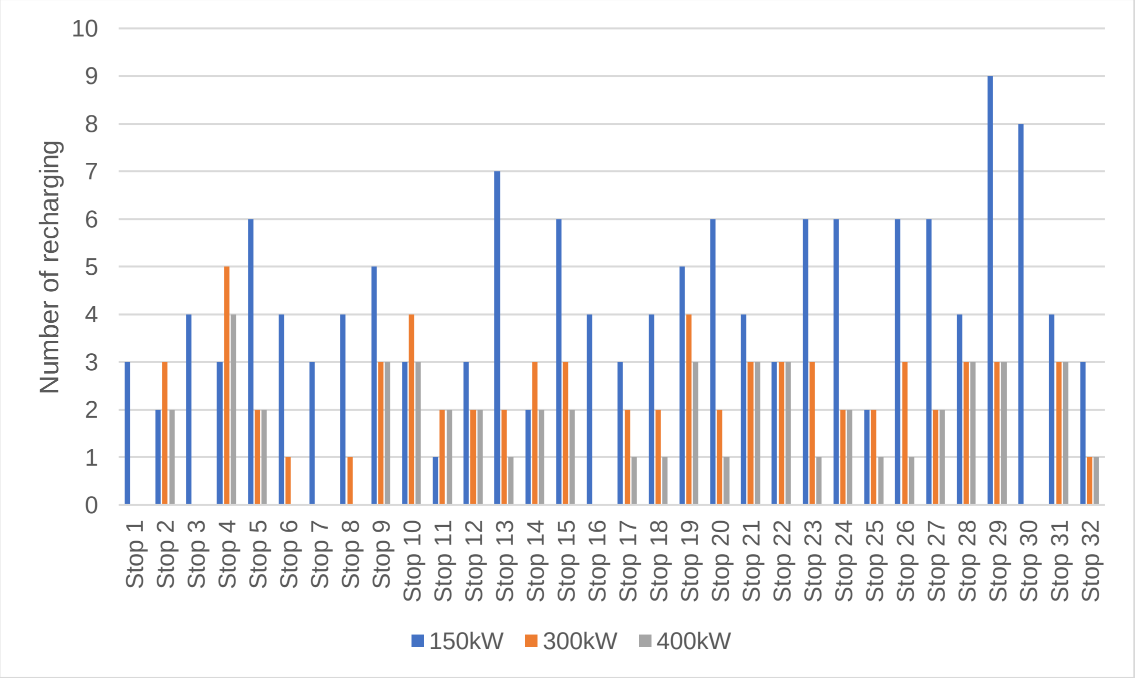

Figure B 1 – Chargers location and number of recharging per stop (Scenario 1).

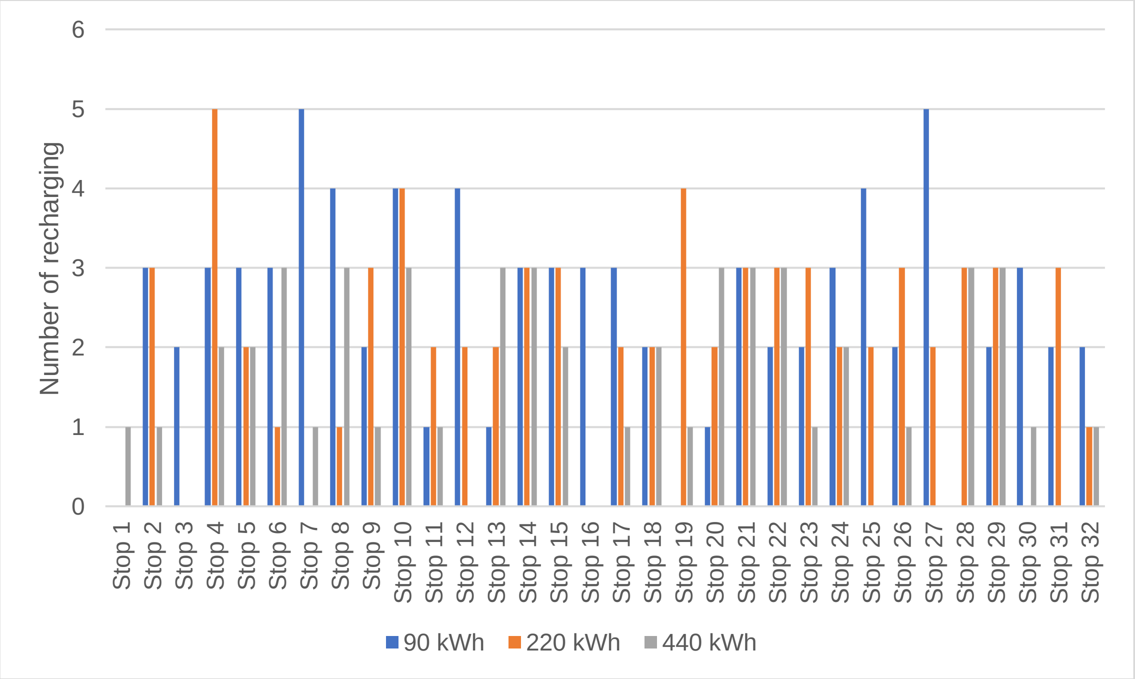

Figure B 2 – Chargers location and number of recharging per stop (Scenario 2).

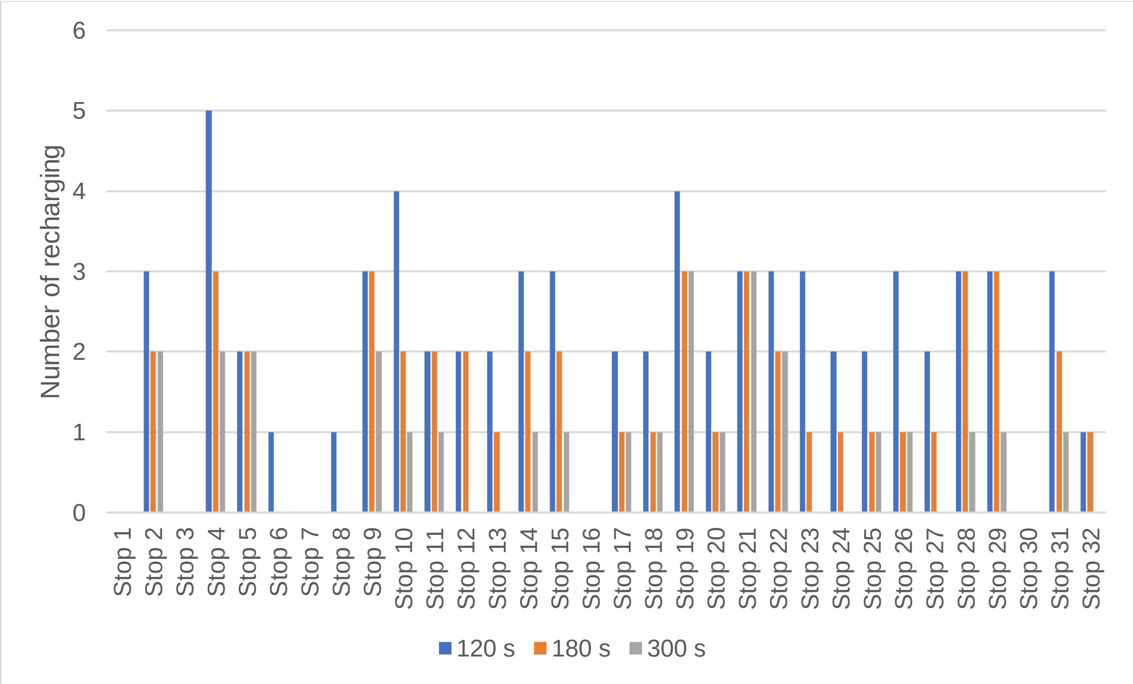

Figure B 3 – Chargers location and number of recharging per stop (Scenario 3).

Appendix C

This Appendix presents the plots related to comparison between the scenarios S1, S2, and S3. The graphs are related to the Total Implementation Costs, Total Charging Time, Number of charging, Number of chargers and Total charging availability. Those graphs are summarized in **Figure 20**.

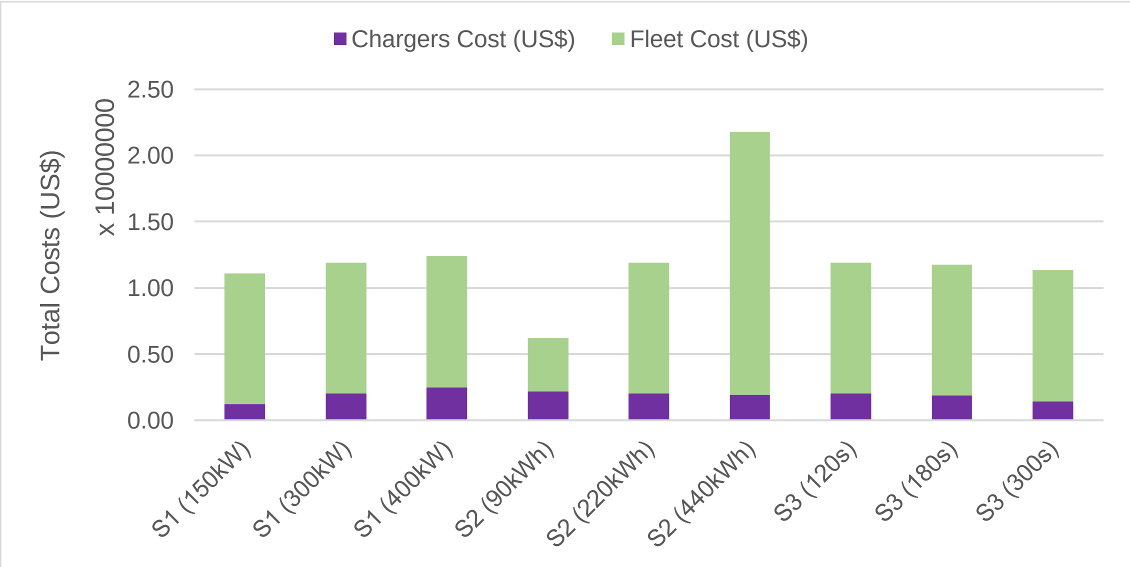

Figure C 1 – Total Implementation Costs comparison (S1, S2, S3).

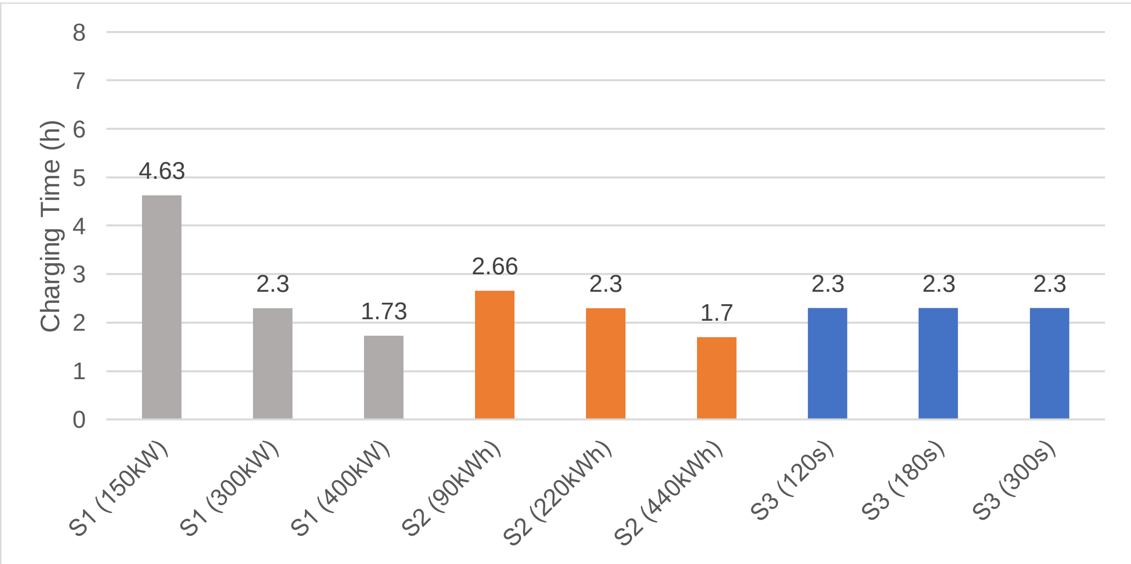

Figure C 2 – Total Charging Time comparison (S1, S2, S3).

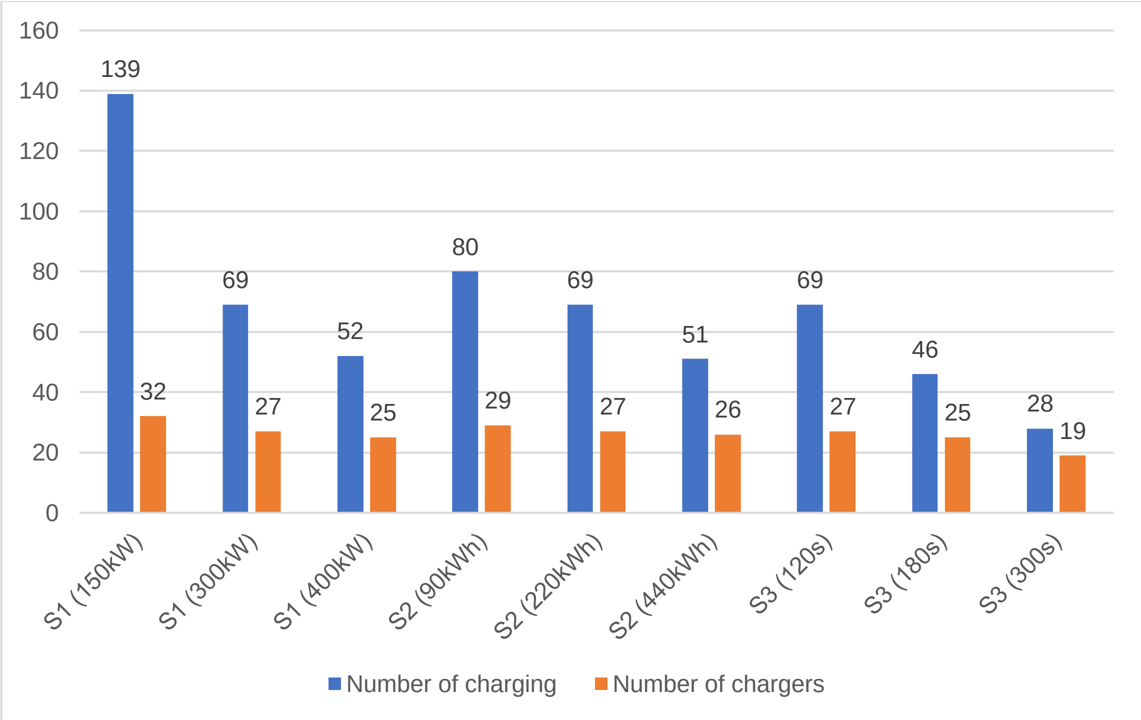

Figure C 3 – Comparison of number of charging and number of chargers (S1, S2, S3).

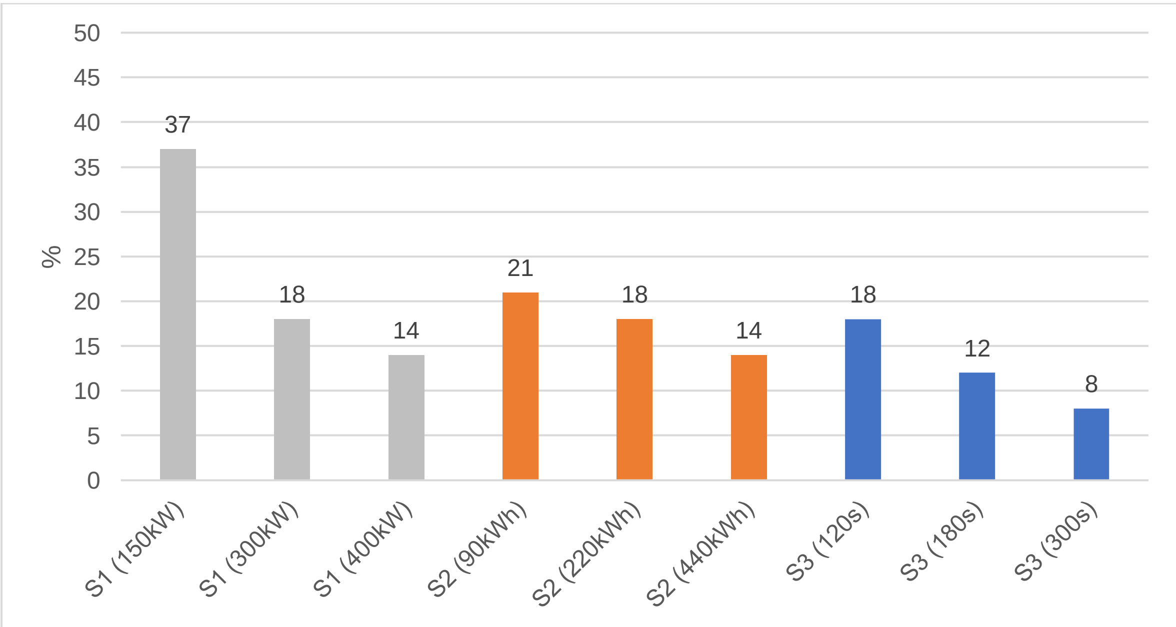

Figure C 4 – Total charging availability (S1, S2, S3).