INSTITUTO UNIVERSITÁRIO DE LISBOA

Transition to Electric Buses Networks: A Mixed-Fleet Approach

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Master in Management of Services and Technology

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ABSTRACT

As the environmental concerns increase, companies are called upon to adopt environmentally friendly solutions in their operations. Since the transportation sector counted for about ¼ of the global carbon dioxide emissions in 2010, transport providers agencies have been aiming to incorporate electric vehicles in their operations. This trend is observable in bus urban networks. In order to electrify the bus fleet and make the respective fleet planning decisions, it is necessary to address the necessary infrastructure requirements considering some operational constraints and the company´s objectives.

This dissertation proposes a tool based on an optimization model, the *MixedBusFleet*, that aims to support transport providers to achieve the electrification of their fleets by minimizing investment costs, operational costs and the external costs of emissions. The *MixedBusFleet* model considers: (i) location of charging station; (ii) frequency of charging; (iii) charging strategy; (iv) battery type; (v) fleet dimension and; (vi) an emissions factor. The literature analyzed throughout this study identified that there is no previous work that incorporates all these planning objectives in one approach. Therefore, the proposed model aims to fill this gap.

To illustrate the potential of the model, it was applied to part of the network of a public transport company operating in Lisbon. The case study comprised of 17 bus routes with predefined demand. The results showed that 133 buses are required to serve all the demand requiring a total investment of €24 950 000 and 5 fast charging facilities were installed in final stops.

Keywords: Public transportation; mixed fleet; electric vehicles; optimization

JEL Classification System: C61 Optimization Techniques; L91 Transportation: General; R41 Transportation: Demand, Supply and Congestion; R42 Transportation Planning

RESUMO

À medida que as preocupações ambientais aumentam, as empresas são incentivadas a adotar soluções ecológicas nas suas operações. O setor de transporte foi responsável por cerca de ¼ das emissões globais de dióxido de carbono em 2010, então, as empresas de transportes têm procurado incorporar veículos elétricos nas suas operações. Para eletrificar uma frota de autocarros e tomar as respetivas decisões de planeamento, é necessário considerar as necessidades de infraestruturas, algumas restrições operacionais e os objetivos da empresa.

Esta dissertação propõe uma ferramenta baseada num modelo de otimização, o *MixedBusFleet*, que visa apoiar as empresas na eletrificação das suas frotas, minimizando os custos de investimento, custos operacionais e os custos externos de emissões. O modelo *MixedBusFleet* considera: (i) localização da estação de carregamento; (ii) frequência de carregamento; (iii) estratégia de carregamento; (iv) tipo de bateria; (v) dimensão da frota e; (vi) um fator de emissão. A literatura analisada ao longo deste projeto não identificou estudos que incorporassem todos os objetivos de planeamento indicados numa abordagem. O modelo proposto visa então, preencher essa lacuna.

Para ilustrar a o potencial do modelo, o mesmo foi aplicado a parte de uma rede de transporte público em Lisboa. O estudo de caso é composto por 17 rotas de autocarros com procura pré-definida. Os resultados revelaram que são necessários 133 autocarros para satisfazer a totalidade da procura, o que requer um investimento total de €24 950 000 e que é necessária a instalação de 5 estratégias de carregamento rápido em paragens.

Palavras-chave: Transporte público; Frota mista; Veículos elétricos; Otimização

JEL Classification System: C61 Optimization Techniques; L91 Transportation: General; R41 Transportation: Demand, Supply and Congestion; R42 Transportation Planning

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1. INTRODUCTION

Throughout the years, society has been more aware of the environmental impact it has on our planet. There has been a shift in people's mind sets, as we are realizing that almost everything we do on our daily basis has a consequence and an impact on the world.

This awareness is changing the way people live their lives and the way companies do business, as consumers are increasingly placing higher value in companies that respect and preserve the environment in their activities. However, implementing environmental-friendly processes can be a challenge for enterprises not only due to financial investments but also due to the changes required in the company's operations to adjust to this environment-friendliness orientation.

One of the main concerns when addressing climate change is air pollution and, consequently, governments are starting to impose some rules and measures regarding this subject. In response to these environmental threats, the European Union (EU) has been a global environmental leader through a range of instruments, such as environmental action programs and institutional legislative frameworks (Paril & Tóthová, 2020).

The transport sector is an important source of emissions of a wide range of gaseous air pollutants and of suspended particulate matter (PM) of different sizes and compositions (Krzyzanowski, Kuna-Dibbert, & Schneider, 2005). Transport activities counted for about 23% of global carbon dioxide emissions in 2010 and 27% of end-use energy emissions with urban transport counting for about 40% of end-use energy consumption. Carbon dioxide persists in the atmosphere for over a century with long-term warming effects (Pachauri & Meyer, 2014). The most common pollutant gases among diesel and compressed natural gas (CNG) buses are CO (carbon monoxide), THC (total hydrocarbon), CO_2 (carbon dioxide) and NO_x (nitrogen oxides). CNG buses issue greater road emission of CO, THC and CO_2 when compared with diesel buses, on the other hand, the diesel bus surpasses the emissions of NO_x, when compared with CNG buses, by 958% (Merkisz, Fuc, Lijewski, & Pielecha, 2016).

Environmental concerns with CO_2 emissions and other combustion pollutants, in combination with improved battery technology have introduced the new era of electric battery-powered vehicles (Michaelides, 2020). Electric vehicles (EVs) contribute to the reduction of CO_2 emissions of transportations activities, especially in urban areas (Penna, Afsar, Prins, & Prodhon, 2016) (Cortés-Murcia, Prodhon, & Afsar, 2019). EVs are an attractive solution because they have no local GHG emissions and produce minimal noise in comparison to conventional internal combustion vehicles (ICVs) (Cortés-Murcia, Prodhon, & Afsar, 2019), contributing in this way to the effort to control noise pollution that is present in most cities. On the other hand, EV applications face some difficulties and disadvantages, since their acquisition cost is higher, compared to fueled cars, they have limited driving range, they require long charging time and there is a lack of charging infrastructures (Cortés-Murcia, Prodhon, & Afsar, 2019) (Penna, Afsar, Prins, & Prodhon, 2016).

It is, therefore, important to develop a tool and strategy that supports the decision and execution of the electrification of a bus fleet in an efficient and realistic manner. Most electric bus fleet adoption models focus on the purchasing process rather than the replacement process. When switching the entire fleet or most part of it to a different technology, transport providers (agency or public corporation that provides public transportation in a given region) must consider two important tradeoffs: (i) cost of owning and operating the buses; and (ii) emissions produced by the buses. These costs are subject to the market´s conditions and the technology´s evolution and so, can be assumed to vary over the years (Islam & Lownes, 2019).

However, as electromobility technologies have advanced, the available bus types evolve heterogeneously according to a variety of important features, including the battery energy capacity, price and operating characteristics such as charging time and autonomy.

Replacing an entire bus fleet from conventional buses to electric buses require great financial investment and thorough planning and evaluation. Consequently, companies are not able to switch to a full electrified fleet overnight.

Within this context and taking into consideration the trend of incorporating electric vehicles in the operation of public transportation, there is the need to plan the adequate incorporation of electric buses in a mixed public fleet, considering all the challenges and constraints above mentioned.

1.1. Research question and objectives

The research question of the dissertation is as follows: “Considering the transition to electric bus fleets, how can transport providers make decisions on their fleet’s composition and charging scheme?”.

The main objective of the present study is to explore the transition to electric bus fleets and the subobjective is the development of a tool that aids this transition in a cost-effective way.

1.2. Methodology

The methodology that will be followed during this thesis comprises: i) the analysis of existing studies regarding the electrification of buses networks; ii) the identification of the most used technologies and most frequent planning decisions when studying the electrification of a bus fleet; iii) the development of a planning model that supports transport providers in the electrification of their buses' fleets using the General Algebraic Modeling System (GAMS); iv) the application of the model to a case study – the operation of a public transport operator, Carris, in the metropolitan region of Lisbon, Portugal; and v) the definition of different scenarios in which the path to full electrification is addressed and analyze the obtained results.

1.3. Structure

This dissertation is composed by six chapters. The **first chapter** discloses the context of the problem, its research question and objectives and the methodology followed. The **second chapter** addresses the literature review, where the main concepts and theoretical domains take place as well as the presentation of different studies surrounding the addressed context already exposed. The **third chapter** describes the methodology followed in order to achieve the objectives displayed in the first chapter. The **fourth chapter** follows with the model formulation. The **fifth chapter** presents the case study and its data and assumptions and provides the analysis of the case study as well as the analysis of the different scenarios used in the simulation and the computational results regarding each one of the simulations. Finally, the **sixth chapter** presents the conclusions of the conducted study as well as the limitations and suggestions for future research on the topic.

2. LITERATURE REVIEW

This chapter presents a review of the literature that analyzes the technical and economic aspects related to the bus mixed fleets and their modelling approaches. The review process aims to support the decision-making process of the integration of electric buses in the bus fleets of public transport companies. At the end of the chapter, a summary of the analysis of the analyzed studies is presented, as well as the contribution of this dissertation to the existing literature.

2.1. ELECTRIC BUS BATTERY TYPES, CHARGING STRATEGIES AND INFRASTRUCTURES

Battery electric vehicles combine the advantages of operational low costs (when comparing fuel prices with electricity prices) and flexibility in defining routes. Nevertheless, some operational issues may be challenging when adopting electric vehicles in a fleet as the operation of this system depends on well-planned schedules and charging stations to overcome the low autonomy of the buses (Sebastiani, Luders, & Fonseca, 2016).

Lithium batteries are the most suited technology for electric vehicles due to their excellent performance, such as energy density, power density and high efficiency (Gohlich, et al., 2018) and (Sinhuber, Rohlfs, & Sauer, 2010). The battery chosen for the buses must be carefully selected due to the demanding cycling profiles in electric fleets as they can severely impact the battery performance and life time, resulting in higher costs (Carrilero, et al., 2018). Regarding the assessment of batteries and charging technologies, Carrilero, et al. (2018) present their respective strengths and weaknesses in relation to their use in battery electric buses. The authors compare three types of lithium ion (Li-ion) batteries as they represent the preferred technology for hybrid and full electric buses due to their high energy and power density. Different types of lithium batteries are also explored by Rothgang, Rogge, Becker, & Sauer (2015) where seven types of lithium batteries are considered and compared using influencing factors like chemistry, the estimated cycle depth, the charging strategy, the peak power and cooling demand. After analyzing the different types of batteries, the ones considered as the most promising by both studies are Lithium Iron Phosphate (LFP), Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Titanium Oxide (LTO). Table 2.1 summarizes the three Li-ion type batteries characteristics.

Table 2.1 - Lithium ion battery types and characteristics

Battery	Strengths	Weaknesses
LiFePO4 (LFP)	• High cycling life • Good power parameters • High thermal stability • Competitive price	• Low voltage • Low specific energy • Slow charging rate • High self-discharge
LiNiMnCoO2 (NMC)	• Good specific energy • Long operating life	• Not the safest option (in case of accident, massive amounts of toxic, flammable leakage could be produced) • Expensive
Li4Ti5O12 (LTO)	• Excellent thermal stability • Can be charged/discharged at very high current rates without affecting its cycle-life • High durability, resulting in the possibility of ultra-fast charging and regenerative braking can be applied • Excellent cold temperature performance	• Reduced cell voltage • Lower theoretical capacity parameters when compared to other Li-ion technologies • Expensive

For the electric fleet to be as efficient as possible, a careful allocation of resources such as the allocation of buses to each route and fast charging stations in strategic stops, is necessary. Kunith, Mendelevitch, & Goehlich (2017) developed an optimization model where the minimum number and location of required charging stations for a bus fleet as well as the adequate battery capacity for each bus route was determined for the electrification of a diesel bus subnetwork in Berlin. The findings of the study revealed that the extension of dwell times and the existence of a charging point and bus-line-specific power evaluation can lead to lower infrastructure costs and that the costs for batteries can be notoriously reduced trough battery optimization. The authors of the paper have also, in previous, years addressed the issue of optimizing fast-charging infrastructure for electric urban bus networks. In 2016, Kunith, Mendelevitch, Kuschmierz, & Goehlich (2016) developed an optimization model which aimed to determine the minimum number and location of required charging stations for a bus network and the results pointed that the charging power has a crucial impact in the number of charging stations and that extension of dwell times decreases the infrastructures requirements. However, the extension of dwell times is only possible by adapting the schedule or by increasing the number of buses. The authors stated that it is important to investigate a possible trade-off between the charging infrastructure and the battery capacity, this scenario was later addressed by the authors in the paper before mentioned.

There are a considerable number of researches on operations' optimization that also aimed to minimize total costs and energy consumption. A case study in Stockholm determined the location of bus charging infrastructures for electric buses considering the availability of two charging options: (i) points in the main public transport stops and (ii) at the beginning and the end of bus routes (Xylia, Leduc, Patrizio, Kraxner, & Silveira, 2017). The study concluded that lower fuel costs for electric buses can compensate the high investment costs incurred in building charging infrastructures, while reaching a reduction of up to 51% of emissions and up to 34% in energy used in the bus fleet. When addressing the employment of fast-charging stations, it is important to take in consideration that fast-charging can lead to high electricity demand charges. He, Song, & Liu (2019) addressed this issue by formulating a model with the objective of minimizing the total costs of vehicle batteries, fast-charging stations, energy storage systems and electricity demand charges. This study was applied to a bus fleet in Salt Lake City (Utah) and concluded that the analysis of the trade-off between fast-charging station costs and battery costs reveals that strategically deployed fast-charging stations can effectively reduce the battery costs and the costs of the whole system and that the total system cost increases nearly proportionally with the increase of the demand charge rate.

Charging infrastructures can be stationary (charging stations and battery swapping stations) and dynamic (charging lanes) (Chen, Liu, & Yin, 2017). Charging stations and battery swapping stations are stations where the buses need to stop for the service, while charging lanes charge vehicles while they are in motion. This technology can be used trough conductive or inductive charging. Conductive charging charges buses via lines overhead or metal bars in the pavement and inductive charging transmits electric power via inductive coupling, magnetic resonance coupling or microwaves (Vilathgamuwa & Jayathurathange, 2015). Drivers using charging lanes do not need to stop for charging and will experience a faster travel time, therefore drivers with a higher value of time (VOT) will most likely prefer charging lanes (Chen, Liu, &

Yin, 2017).

Regarding the charging strategies, there are six charging strategies that may be considered when addressing battery electric buses (Carrilero, et al., 2018):

- Slow charging – Adequate for buses with large batteries. Slow charging allows flexible routing or route changes but reduces the availability time of the bus and the possibility of long routes;
- Fast/opportunity charging – Buses with small batteries that can be charged at a higher power than those that charge via slow charging. This strategy results in higher availability of the bus but smaller free range;
- Regenerative braking – The loss of kinetic energy from braking is stored and later fed back to provide power to the electric motor. Regenerative braking produces more aggressive battery degradation than fast charging;
- Combination of slow charging with opportunity charging – The bus uses slow charging at the end of the route and fast charging on-route. This strategy entails higher hardware inversion costs;
- In motion charging/hybrid trolley – Buses with small batteries are charged through overhead wires on selected sections of the route;
- Physical change of batteries – The drained battery is replaced with a charged battery at a designated switching station. The physical change of batteries is a faster system and minimizes the electricity costs.

Normally, full size batteries are paired with overnight charging at the depot and smaller batteries are paired with opportunity charging at the end terminal or along the route (Laurikko, et al., 2015). All typologies have pros and cons, there is no universal perfect solution, therefore, it is necessary to evaluate each case individually and take the needs of the system and its shareholders in consideration. Proper systematic design is crucial to take into consideration in order to develop a successful city bus electrification (Laurikko, et al., 2015). Laurikko, et al. (2015) developed a TCO calculation model in which electric buses with different designs and operation concepts were analyzed and compared with other technologies and concluded that, while electric buses have the potential to be economically competitive in the best urban use case, when taking into consideration the reduced TCO, it is necessary careful system engineering and technology with high usability and reliability. Electric buses have not yet reached this level but as technology advances at a fast pace, it is expected a major activation in commercial-driven electric bus systems deployment in the upcoming years.

Still on a TCO minimization approach, Rogge, Hurk, Larsen, & Sauer (2018) conducted a study based on a case study of real-world electrification scenarios of two different cities: (i) Scenario A in Aachen, Germany that represents a constant-frequency operation in an urban environment; and (ii) Scenario B in Roskilde, Denmark that relates to an operation with different frequencies in the peak hours and operation on a more regional environment, in which distances are generally larger and the average speed of operation is slightly higher compared to the Aachen scenario. The fleets were composed by two types of electric buses, one lightweight bus with strictly limited range and the other being a high range bus and the results showed that in both scenarios, A and B, the lightweight bus leads to more energy efficiency with energy consumption savings ranging from 27% in scenario A to 32% in scenario B. However, with this type of bus, the deadheading mileage increases and, therefore, this limited range requires additional vehicles and several charging phases throughout the circuit leading to additional driver costs. Despite the TCOs of both bus types being relatively close, the additional costs of the lightweight bus reveals to be beneficial for vehicles and drivers for reduced energy costs. The authors also concluded that bus routes with peak vehicle demand seem to be beneficial for the operation of depot charging battery buses.

2.2. How to plan the transition to an electric fleet?

The transition from conventional vehicles to electric vehicles in the public transport sector involves several challenges and comprises several phases that, gradually, can lead to the total fleet electrification.

The use of conventional buses (diesel, gasoline) for transportation has recently been categorized as undesirable due to their carbon footprint. Considering the shift towards more sustainable transport, these types of buses entail several constrains such as the limited available hydrocarbon reserves, the constant growth of all types fuel prices and the permanent environmental degradation (Gabsalikhova, Sadygova, & Almetova, 2018). As a result, policy makers and car manufacturers believe that the solution to this problem is the application of energy saving technologies and the transition to electric transmission trough environmentally friendly power units like the electric buses. Electric buses present several advantages compared to traditional buses since they are practically noiseless, easy to operate, reliable and with long lifetime.

The electrification of vehicles is becoming a trend, not only for private vehicles but also for public transport. Some countries are working towards both the end of selling petrol and diesel vehicles in the coming years and the application of restrictions to the circulation of polluting cars (Pereirinha, et al., 2018). According to Pereirinha, et al. (2018), the main challenges in the electrification of road transportation are: (i) the need for suitable batteries; (ii) charging process management, i.e., the return of energy from the vehicle to the grid and the need of smart grids to deal with the vehicle's charge; (iii) the battery recycling and replacement; (iv) the standardization of electric vehicles; and (v) the need of education and technical formation for EV's.

When dealing with the selection of the most suitable battery and charging system, different sizing and battery charging scenarios can be considered to analyze the impacts of the adoption of electric vehicles in a bus fleet (Cardoso-Grilo, Kalakou, & Fernandes, 2020). Sinhuber, Rohlfs, & Sauer (2010) conducted a study in Aachen, Germany that discusses the battery sizes, their charging system and battery lifetime costs per kWh. The authors concluded that electricity costs slightly rise as the depth of cycling decreases (energy capacity consumed during the operation between two recharges) due to higher battery weight and that battery cells with higher cycle life may entail better cost efficiency than cells optimized for energy density. From this study it is also important to highlight that less frequent charging does not reduce the overall charging time and does not contribute to the vehicle's availability for operation. Lajunen (2018) also concluded that the energy consumption of electric buses depends not only on the weight of the bus, but also on weather conditions and the operating route. This study, which approaches the technical and economic performance of electric city buses in different operating conditions, explores the factors influencing the lifecycle costs of electric buses operation in which different charging methods have been considered. Lajunen (2018) simulated the lifecycle cost of a bus fleet in Finland and California with three different types of charging: (i) slow (overnight); (ii) end of route; and (iii) opportunity charging. The author concluded that the lifecycle costs of the opportunity charging buses were the highest due to the higher costs related to charging devices and that the slow and end of route charging had similar costs. However, the battery replacement after ten years of operation for slow charging buses increases substantially the total costs, electing the end of route charging buses the most cost-efficient electric bus option. Another study of an electric battery-supplied bus (EBB) in an urban transportation context of the city of Padova, with the aim to improve battery efficiency and duration was conducted, where an optimal strategy for the battery selection and management was performed and the sustainability of the fleet was evaluated (Andriollo & Tortella, 2015). The simulation considered vehicles with 8 meters and 11 meters to assess their energy consumptions and pollutant emissions and concluded that the replacement of conventional buses with electric ones is beneficial when considering energy consumption and pollutant emissions. Although the small size bus fleet (8 meters) proved to be the most viable solution, the larger bus fleet (11 meters) was found to lead to higher benefits and the capacity to meet most of the public transport service requirements.

The total cost of ownership can be used as a key performance indicator that includes all costs that occur during the life cycle of a bus system, i.e. this tool not only considers the operational cost but also acquisition costs, infrastructure investments, capital financing costs, personnel costs and emission costs (Gohlich, et al., 2018). Gohlich, et al. (2018) presented a TCO model that comprises all the costs that occur during the life cycle of a bus fleet and to deal with the uncertainties of the variation of future energy cost, the authors performed the project-evaluated-and-review-technique (PERT) method, which portraits cost trends via a beta distribution that is used to derive a distribution function from discrete prognosis values. The simulation of the model was conducted for the year of 2017 and 2025 and for four scenarios, namely, one of diesel buses used as a reference, two opportunity charging cases and one depot charging case. The results show that the deployment of electric bus fleets lead to higher total costs in 2017 and, consequently, in 2025 it becomes a more cost-effective solution. Both in 2017 and 2025, the diesel scenario is the one where the energy cost has more weight in the TCO. When switching to either opportunity charging, the energy costs decrease significantly and although, as expected, the acquisition cost of vehicles increases, the TCO is lower (both in 2017 and 2025) than in the diesel scenario. The depot charging, however, represents the least attractive solution both when compared to the other three scenarios, accounting with significant acquisition vehicles costs.

Gao, et al. (2017) developed a tool that associates bus electrification feasibility with real-world vehicle performance, city transit bus service reliability, battery capacity sizing and charging infrastructure. This study arose from the limitation related to the bus fleet ability to maintain a periodic schedule on the route. There can be a need of extended duration of charging if the remaining energy in a battery after a circuit is insufficient for the bus to perform the next circuit. This extended duration of charging may lead to in a schedule delay or in a need for an additional bus, therefore, it is important to understand the impact of electric bus charging needs when maintaining a consistent schedule. The authors concluded that regenerative braking (dissipative force that depletes the energy that is effectively stored as vehicle kinetic and potential energy) energy recovery is highly associated with energy savings because it reduces battery consumption and that the use of high power ultrafast charging plays a critical role in reducing the battery capacity needed for both short and long routes at the same time as it eliminates the need for proactive charging events and avoids service interruptions or delays due to charging requirements. Analyzing these results, Gao, et al. (2017) stated that multiple battery capacity configurations and flexible battery swapping practices based on schedule routes will lead to significant cost savings.

Trough the studies presented in this subsection of the literature review, we can conclude that when transitioning to an electric fleet there are some operational concerns that need to be addressed, such as the type and capacity of the battery, the charging strategy, and, of course, the financial impacts of such choices. It is, therefore, necessary to study the available options regarding each aspect and do an analysis of trade-offs (emissions, costs, demand satisfaction, etc.) that best suits the situation at hand.

2.3. INTRODUCING THE MIXED FLEET

Replacing an entire bus fleet from conventional buses to electric buses require great financial investment and planning. Consequently, companies are not able to switch to a full electrified fleet overnight, this is a change that, for the majority of the cases, will happen in a gradual way.

The impossibility to immediately switch to a full electrified fleet is frequently disregarded by most authors. The switch to an electric fleet requires, at some point, the coexistence of different propulsion technologies with different characteristics and requirements and this can influence the bus scheduling process (Rinaldi, Picarelli, D'Ariano, & Viti, 2020). The objective of the model is to minimize daily operational costs and the results show that introducing electric buses to an existing fleet can lead to significant savings regarding operational costs if vehicle scheduling is optimized. On the other hand, when the number of conventional buses to be replaced rises, the returns effect decreases due to exogeneous aspects. This phenomenon requires cooperation and discussion by the different stakeholders involved in order to seize the potential benefits of a full electrified fleet.

Rinaldi, Picarelli, D'Ariano, & Viti (2020) developed an approach that considers the charging and discharging dynamics of a mixed fleet of fully electric and hybrid-electric buses.

The transition to electrified fleets are frequently determined by fleet electrification targets, which imposes the number of electric buses that should be in the fleet in a given time period (Pelletier, Jabali, Mendoza, & Laporte, 2019). Consequently, companies often adopt a mixed fleet for their buses network, which can be composed by two or more types of buses (eg., electric, hybrid, diesel, CNG).

Pelletier, Jabali, Mendoza, & Laporte (2019) introduced a bus fleet replacement problem whose solution provides a transition plan that respect the electrification targets in a cost-effective way. The problem is identified as an electric bus fleet transition problem (EBFTP) whose formulation takes into consideration electrification targets, vehicle purchasing and salvaging decisions, several types of electric buses (EBs) with different charging configurations, charger type-specific infrastructure investment and demand charges. The problem is solved using data obtained from a bus operator in France and four types of buses were considered (diesel, hybrid, CNG and electric). It is important to note that each type of bus is available in two sizes: (i) 40 feet; and (ii) 60 feet. The authors focus on two major issues introducing the model: (i) the timing of EB purchases and (ii) the selection of the type of EBs to acquire.

The timing of the EBs purchases relates to the battery prices, that have been continuously dropping in the last decade while their lifespans and energy storage have been improving. This phenomenon encourages companies to wait as long as possible to benefit from lower battery prices and latest technology improvements. However, the authors also mention that due to the uncertainty of future battery and fuel prices and additional technology improvements, the companies may benefit in adopting this technology in the near future as the potential savings on EB energy and maintenance costs are already known to provide significant savings when compared to diesel buses.

Regarding the selection of EBs to acquire, as mentioned in the previous sub-topic, there are some trade-offs to consider when analyzing this aspect of the process. The battery size can have significant impacts on the outcome of the problem as larger batteries do not require en route charging while smaller batteries do. By selecting a larger battery there will be higher investment costs and fewer seats for the passengers, however, this type avoids further infrastructure investment costs with en route charging that a smaller battery requires. Adopting smaller batteries also implies additional decisions, such as the kind of en route charging infrastructure to be installed.

The study of Pelletier, Jabali, Mendoza, & Laporte (2019) suggests that EBs with medium-size batteries charged at depots overnight and at bus line terminals with fast plug-in charges during the day are consistently chosen as the 40 feet buses in the analysis context. The analysis also suggests that while 60 feet EBs present a promising business case in the longer term, articulated CNG buses are the most cost-effective intermediate alternative to articulated diesel buses until battery prices have decreased sufficiently.

Islam & Lownes (2019) investigated fleet replacement optimization by minimizing the Life Cycle Cost (LCC) of owning and operating a fleet of buses and required infrastructures while reducing GHG emissions simultaneously. The LCC is an estimate of the total purchasing, operating maintenance and salvage cost of an alternative over the life span of the vehicle. This tool is mostly a cost analysis tool and does not consider energy consumption or provide emission estimates (Xu, et al., 2015). These authors provide an optimum fleet mix consisting of hybrid electric and battery electric vehicles using date from the Connecticut Department of Transportation (CTDOT), that trough a mixed integer program provides an output that consists in the number of buses purchased in a year, number of buses salvaged in a year, charging infrastructure built, existing number of buses and infrastructure, and cost breakdown in a year.

Regarding the design of transit bus fleet while accounting for tradeoffs among costs, level-of-service requirements, and restrictions on emissions and energy consumption Durango-Cohen & McKenzie (2017) developed an optimization model whose objective was to minimize acquisition, operation, and disposal costs. This model considered four types of buses (diesel, hybrid diesel-electric, CNG and hydrogen fuel-cell) and used data from the National Renewable Energy Laboratory transit bus evaluation and demonstration studies conducted over the period of 2003-2009. The authors analyze scenarios with different demand fluctuations, i.e. peak vs. off-peak. In the peak scenarios the mix of buses is driven by the need to satisfy passenger demand and, as a result, diesel buses with the largest capacity appear in the optimal solutions for all the peak scenarios considered. The off-peak analysis concludes that smaller buses with more frequent service can allow a high level of service and may not cause large increases in capital and operating costs. Another interesting conclusion of this study is that hydrogen fuel-cell (HFC) buses that are known for their environmentally friendly operation, only save emissions when the demand is low due to the fact that their emission per passenger is actually very high.

A contribution to the mixed bus fleet management (MBFM) problem literature is addressed by (Li, Lo, Xiao, & Cen, 2018). The authors propose a new life additional benefit-cost (NLABC) approach, whose purpose is to maximize the total net benefit of early bus replacement, where both the optimal fleet size and composition under budget constraints can be determined. The model considers four types of buses (electric, CNG, hybrid-diesel and diesel) and used data of transit lines in Hong Kong and includes vehicle routing to study bus services coordination among multiple routes. The NLABC approach considers the whole lifespan of a new replacement bus and its benefit is defined as the savings in external costs associated with emissions reduction in the lifespan of a new replacement bus. The study showed that the MBFM scheme is significantly more cost-efficient than the single bus type fleet management scheme.

2.4. REVIEW OF EXISTING MODELLING APPROACHES

Due to the low variety of buses and the management complexity of heterogeneous fleets, the literature of bus fleeting is not extensive (Durango-Cohen & McKenzie, 2017).

The literature review has shown that optimization techniques have been widely employed in studies that aim to determine the optimal integration of electric bus in the fleet of bus operators based on costs (both operating and investment costs) and considering operational constraints related to the route length, bus capacity and bus schedules. Table 2.2 provides an overview of the afore-mentioned optimization studies that approach the integration of electric buses in existing fleets of public transport. This table makes it clear that no study jointly considers all the planning decisions that are considered as essential for an adequate planning (number of vehicles, location of charging stations, frequency of charging and selection of charging technology and battery types). Also, few studies consider the minimization of both operating and investment costs, with investment costs being related to investments in different vehicles with different types of batteries as well as with investments in charging infrastructure.

Due to the impossibility of companies to switch to full electrified fleets overnight, as mentioned in this chapter, it is important for the models consider a mixed bus fleet that respects a certain percentage of electric buses in the fleet.

Another important factor to take in consideration is the emissions related to the operation of the bus, whether that factor is the social cost of the emissions or the amount of CO_2 that is released to the atmosphere during the bus operation.

Within this setting, there is room to develop more comprehensive planning models that jointly consider all these dimensions. The current paper aims to fill this gap in the literature.

Table 2.2 - Key planning decisions and objectives within optimization studies focused on the integration of electric buses in public transport fleets (X depict the features considered in each study).

Study	Location of charging stations	Frequency of charging	Charging strategy	Battery type	Fleet dimension	Emissions factor	**Mixed fleet**	**Cost-oriented objectives**
	Planning decisions							
Kunith et al. (2017)	X		X		X			Costs with infrastructures
Andriollo & Tortella (2015)		X				X		
Xylia et al. (2017)	X		X		X	X	X	Total operating costs
Rogge et al. (2018)		X			X			
He et al. (2019)	X		X	X				
Islam & Lowens (2019)				X	X	X	X	
Pelletier et al. (2019)		X		X	X		X	
Rinaldi et al. (2020)		X		X			X	Investment and total operating costs
Durango-Cohen & McKenzie (2017)						X	X	
Li et al. (2018)		X			X	X	X	
MixedBusFleet	X	X	X	X	X	X	X	

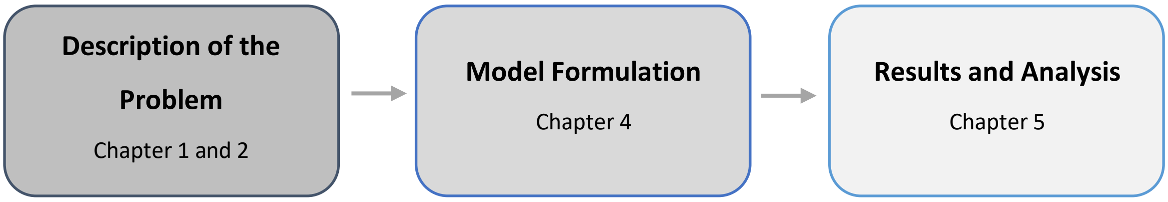
3. METHODOLOGY

To accomplish the main goal under study in this thesis, two objectives were established and a research question regarding the problem was proposed. The research question proposed is "Considering the transition to electric bus fleets, how can transport providers make decisions on their fleet's composition and charging scheme?" and its associated objectives are to: (i) explore the challenges, requirements and main aspects to take into consideration when transitioning to an electric bus network and (ii) develop a tool that can assist transport providers in performing this transition in the most cost-effective and realistic way.

In order to achieve the referred objectives, first it is necessary to perform a proper contextualization of the problem, which is addresed in Chapters 1 and 2. The tool developed in this dissertation will be applied to a case study, Carris company, which is a public transport company in the metropolitan area of Lisbon, that is aiming to electrify its fleet. In order to tackle this problem an optimization model, *MixedBusFleet,* was developed using a Mixed Integer Linear Programming (MILP) model to determine the minimum number of buses of each type (electric, diesel and CNG) with the minimum charging requirements regarding the electric buses to secure the routes offered by a transport operator. The model was solved in GAMS. Regarding the charging systems, the model makes it possible to identify the need for investment in charging stations with different charging strategies, as well as the frequency of charging. The model also makes it possible to identify the required investment in vehicles with different battery types. Besides minimizing investment and operating costs, the model also minimizes the emissions released during the operation of each type of bus.

After the application of the model with the appropriate parameters that reflect the Carris case study, the results were exposed and analyzed.

Figure 3.1 - Research design



The model followed several assumptions and key constraints, such as:

- The acquisition of further diesel and CNG buses was not considered because the aim of this study is the electrification of the fleet, i.e., the substitution of conventional buses with electric ones;
- Each route can only be performed by one type of bus;
- Diesel and CNG buses in the fleet have enough capacity to ensure the performance of the totality of the route to which they are allocated;
- All the electric buses must have enough capacity to perform the trips to which they are assigned. If the total capacity of the bus is not enough to perform the whole route in one go, then there is a need to charge, whether that may be trough fast charging or trough heading back to the terminal to charge during the day;
- The electric buses cannot perform trips if they battery goes below a certain capacity (i.e. 30kW);
- An electric vehicle can only be used in routes that have the necessary charging strategies available.

The case study is comprised of:

- Three types of buses (electric, diesel and CNG);
- 17 routes;
- 4 shifts;
- 28 stops available to install the fast charging strategy;
- 3 available charging strategies (charging during the night at the terminal, charging during the day at the terminal and fast charging at stops).

The model formulation is fully exposed in Chapter 4 and its results and analysis are addressed in Chapter 5.

4. MODEL FORMULATION

This section presents the mathematical details of the *MixedBusFleet* model.

4.1. ASSUMPTIONS USED FOR BUILDING THE *MIXEDBUSFLEET* MODEL

Several assumptions are used to build the *MixedBusFleet* model:

i. Each bus can only be used in one single route;
ii. All the routes should be ensured for all the shifts, i.e., the minimum number of buses should be enough to ensure all those routes;
iii. Each electric bus can be charged at the terminal, during the night or during the day, and/or at the stops of routes;
iv. A set of route stops is selected for installing charging technologies, if needed, and multiple charging strategies can be followed;
v. A maximum number of charges at the terminal and at the stops is imposed per day;
vi. The first shift of the day starts with all the buses fully charged;
vii. New diesel and CNG buses will not be considered for purchase, only electric buses will be acquired;
viii. Each route can only have one type of bus;
ix. Diesel and CNG buses have enough fuel in their deposits to assure the routes during the day.

4.2. NOTATION

4.2.1. INDICES AND SETS.

$t \in T, T = T^E \cup T^D \cup T^G$	Type of bus, including electric buses (T^E), diesel buses (T^D) and compressed natural gas buses (T^G). .
$r \in R$	Routes
$s, s' \in S$	Shifts
$q \in Q, Q = Q^{TN} \cup Q^{TD} \cup Q^S$	Charging strategies, including charging during the night (Q^{TN}) and during the day

	(Q^{TD}) in charging stations installed in the terminals, and charging in route stops (Q^S) for electric buses.
$j \in J = J^T \cup J^S$	Terminals (J^T) and route stops (J^S) selected for installing a charging system (if required)
$h \in H = \{(q,j): q \in Q, j \in J\}$	Charging strategy $q \in Q$ which can be installed in terminal/route stop $j \in J$
$u \in U = \{(r,s): r \in R, s \in S\}$	Routes $r \in R$ performed during shift $s \in S$
$v \in V = V^T \cup V^S =$ $= \{(r,j): r \in R, j \in J^T\}$ $\cup \{(r,j): r \in R, j \in J^S\}$	Routes $r \in R$ with terminal $j \in J^T \subseteq J$, and routes $r \in R$ with route stops $j \in J^S \subseteq J$
$ll \in LL = \{(t,q): t \in T^E, q \in Q\}$	Charging strategies $q \in Q$ available for electric bus $t \in T^E \subseteq T$

4.2.2. PARAMETERS.

F	Overall budget (€)
E_t	External cost of emissions per bus type $t \in T$ per km (€/km)
O_t	Operating cost (€/km) per bus type $t \in T^D \cup T^G \subseteq T$
D_r	Travel distance (km) of route $r \in R$
N_r^{route}	Number of minutes required to complete route $r \in$ R
NR_{rs}	Number of times each route $r \in R$ must be completed (i.e., number of trips) over shift $s \in S$ by each bus
NB_{rs}	Number of buses required for route $r \in R$ and shift $s \in S$
Cap_r^{Route}	Capacity (kW) required to complete each trip of each route $r \in R$ with electric buses
Cap_t^{Bat}	Capacity (kW) of batteries used in electric buses $t \in T^E \subseteq T$
CC_{qt}	Charging capacity (kW) for the electric buses $t \in T^E \subseteq T$ in charging strategy $q \in Q$
C_{qt}	Energy hourly cost (€/kWh) for charging strategy $q \in Q$ using electric vehicle $t \in T^E \subseteq T$

I_q^Q	Investment (€) required per charging strategy $q \in Q$
I_t^T	Investment (€) required per electric bus $t \in T^E \subseteq T$
M_q^T	Maximum number of charges allowed per day and night using charging strategy $q \in Q^{TN} \cup Q^{TD} \subseteq Q$
M_q^S	Maximum number of charges allowed per day using the charging strategy in route stops $q \in Q^S \subseteq Q$
K_t	Minimum capacity (kW) allowed for electric bus $t \in T^E \subseteq T$
L	High auxiliary value
G_t	Minimum percentage of electric buses $t \in T^E \subseteq T$ in the fleet

4.2.3. VARIABLES.

P_{trs}	Equal to 1 if a vehicle $t \in T$ is required for route $r \in R$ during shift $s \in S$
Z_{qjr}	Equal to 1 if charging strategy $q \in Q$ involves installing a charging technology at stop $j \in J$ belonging to route $r \in R$
Z'_{qj}	Equal to 1 if charging strategy $q \in Q$ involves installing a charging technology at stop $j \in J$
B_{tr}^T	Total number of buses of type $t \in T$ required for route $r \in R$
B_{trs}^{Shift}	Number of buses of type $t \in T$ required for route $r \in R$ during shift $s \in S$
B_{tr}^{S1}	Number of buses $t \in T$ required for route $r \in R$ needing to charge at the terminal during the day
B_{tr}^{S2}	Maximum number of buses of type $t \in T$ required for route $r \in R$
Y_q	Number of infrastructures installed for charging strategy $q \in Q$
W_{rs}	Available capacity (kW) for electric buses used in route $r \in R$ at the end of shift $s \in$ S
NC_{trsq}	Frequency of charging of bus type $t \in T^E \subseteq T$ for route $r \in R$ during shift $s \in S$ using charging technology $q \in Q$

4.3. OBJECTIVE FUNCTION

The key objective of the model is the minimization of total costs, considering the following cost components: i) operating costs for non-electric buses, such as fuel costs for diesel and CNG buses (first term of Eq. (1)), ii) operating costs for electric buses (second, third and fourth term of Eq. (1); iii) investment costs for different charging strategies for electric buses (fifth term of Eq. (1)); iv) emission costs of CO_2 (sixth term of Eq. (1)); and (v) investment cost for electric buses with different batteries (seventh term of Eq. (1)).

$$Min\Bigg[\Bigg(\sum_{t\in T^D\cup T^G}\sum_{r\in R}\sum_{\substack{s\in S\\ s:(r,s)\in U}} B_{trs}^{Shift}\,O_tD_rNR_{rs}\Bigg)+\Big(\sum_{q\in Q^{TN}}\sum_{t\in T^E}\sum_{r\in R}B_{tr}^{T}CC_{qt}\,C_{qt}\Big)+$$
$$\Bigg(\sum_{q\in Q^{Td}}\sum_{t\in T^E}\sum_{r\in R}\sum_{\substack{s\in S\\ s>1\\ s:(r,s)\in U}} NC_{trsq}CC_{qt}C_{qt}NB_{r(s-1)}\Bigg)+$$
$$\Bigg(\sum_{q\in Q^S}\sum_{t\in T^E}\sum_{r\in R}\sum_{\substack{s\in S\\ s:(r,s)\in U}} NC_{trsq}CC_{qt}C_{qt}NB_{rs}\Bigg)+\Big(\sum_{q\in Q}I_q^QY_q\Big)+$$
$$\Bigg(\sum_{t\in T}\sum_{r\in R}\sum_{\substack{s\in S\\ s:(r,s)\in U}} B_{trs}^{Shift}\,E_tD_rNR_{rs}\Bigg)+\Big(\sum_{t\in T^E}\sum_{r\in R}I_t^T\,B_{tr}^T\Big)\Bigg] \qquad (1)$$

4.4. CONSTRAINTS

In this section, the constraints of the model are presented.

A key constraint of the model is given by Eq. (2). Eq. (2) imposes that each electric bus should have enough capacity (in kW) to complete all the trips of each route $r\in R$ for all the shifts $s\in S$ to which it is assigned. If the capacity available at the beginning of each shift (Cap_t^{Bat} for the first shift and W_{rs} for shifts other than the first) for a given electric bus is not enough to complete all the trips of the route, there is a need to charge that bus using the available charging strategy.

$$NR_{rs}Cap_r^{Route}\sum_{t\in T^E}P_{trs}\le\begin{cases}\sum_{t\in T^E}\Big(\big[P_{trs}Cap_t^{Bat}\big]+\sum_{q\in Q^s}\big[NC_{trsq}\mathrm{CC}_{qt}\big]\Big)\\ \qquad\forall\,(r,s)\in U, s=1\\ W_{r(s-1)}+\sum_{t\in T^E}\sum_{q\in Q^{TD}\cup Q^S}NC_{trsq}\mathrm{CC}_{qt}\\ \qquad\forall\,(r,s)\in U, s>1\end{cases} \qquad (2)$$

The capacity available at the end of each shift $s\in S$ for all the electric buses allocated to a given route $r\in R$ is computed based on Eq. (3).

$$W_{rs} = \begin{cases} \sum_{t\in T^E}\left([P_{trs}Cap_t^{Bat}] + \sum_{q\in Q^S}\left[NC_{trsq}\mathrm{CC}_{qt}\right]\right) - NR_{rs}Cap_r^{Route}\sum_{t\in T^E}P_{trs} \\ \forall\,(r,s)\in U, s=1 \\ W_{r(s-1)} + \sum_{t\in T^E}\sum_{q\in Q^{TD}\cup Q^S}NC_{trsq}\mathrm{CC}_{qt} - NR_{rs}Cap_r^{Route}\sum_{t\in T^E}P_{trs} \\ \forall\,(r,s)\in U, s>1 \end{cases} \quad (3)$$

Eq. (4) and imposes that each electric bus cannot go below the minimum capacity.

$$W_{rs} \geq \sum_{t\in T^E}P_{trs}K_t \;\; \forall\,(r,s)\in U \quad (4)$$

The number of buses required for each route $r \in R$ is determined based on Eq. (5).

$$B_{tr}^{T} = B_{tr}^{S1} + B_{tr}^{S2} \; \forall\, t\in T,\; r\in R \quad (5)$$

The number of buses required for each route $r \in R$ during shift $s \in S$ is given by Eqs. (6-9). Eq. (6) imposes the maximum number of buses required per route $r \in R$ during shift $s \in S$, Eq. (7) defines that each route $r \in R$ and each shift $s \in S$ should have in operation the number of buses that are required for the given route and shift, Eq. (8) provides the maximum number of buses required after a shift in which the buses were charging in the terminal during the day and Eq. (9) provides the maximum number of buses required throughout the different shifts.

$$B_{trs}^{Shift} \geq P_{trs}NB_{rs} \;\; \forall\, t\in T, (r,s)\in U \quad (6)$$

$$\sum_{t\in T}B_{trs}^{Shift} \geq NB_{rs} \;\; \forall\,(r,s)\in U \quad (7)$$

$$B_{tr}^{S1} \geq NB_{rs}NC_{tr(s+1)q} \; \forall\, t\in T^E, q\in Q^{TD},\; (r,s)\in U,\; s>1,\; s<|S| \quad (8)$$

$$B_{tr}^{S2} \geq NB_{rs}P_{trs} \; \forall\, t\in T, (r,s)\in U \quad (9)$$

Eqs. (10-12) are related to the selection of buses for each route. Eq. (10) defines that electric buses can only be operating using the selected type of battery, L is used as a high auxiliary value to allow for a high number of buses, if needed. Eq. (11) defines that only one type of bus can be used in each route $r\in R$ and shift $s \in S$ and Eq. (12) imposes that only one bus type can be used for all the shifts of each route.

$$NC_{trsq} \leq P_{trs}L \ \ \forall \ t \in T^{E}, (r,s) \in U, (t,q) \in LL \tag{10}$$

$$\sum_{t \in T} P_{trs} = 1 \ \forall \ (r,s) \in U \tag{11}$$

$$P_{trs} = P_{trs'} \ \forall \ t \in T, \ (r,s) \in U, (r,s') \in U, s \neq s' \tag{12}$$

Eq. (13) imposes the maximum number of charges allowed per electric bus at the terminal and per route $r \in R$ for all the shifts. The maximum number of charges allowed per electric bus at the stations per route $r \in R$ and per shift $s \in S$ is given by Eq. (14).

$$\sum_{\substack{s \in S \\ s:(r,s) \in U}} NC_{trsq} \leq M_q^T \ \ \forall \ t \in T^{E}, q \in Q^{TN} \cup Q^{TD}, r \in R, \ (t,q) \in LL \tag{13}$$

$$NC_{trsq} \leq M_q^S \ \forall \ t \in T^{E}, q \in Q^{S}, (r,s) \in U, (t,q) \in LL \tag{14}$$

Eq. (15-16) impose that an electric vehicle can only be used in routes that have the necessary charging strategies available. L is once again used as a high auxiliary value to allow for a high number of charging strategies, if needed.

$$NC_{trsq} \leq \sum_{\substack{j \in J \\ j:(r,j) \in V \\ j:(q,j) \in H}} Z_{qjr} L \ \ \forall \ t \in T^{E}, (r,s) \in U, (t,q) \in LL \tag{15}$$

$$Z_{qjr} \leq \sum_{t \in T^{E},} \sum_{\substack{s \in S \\ r:(r,s) \in U}} NC_{trsq} \ \forall \ (q,j) \in H, (r,j) \in V \tag{16}$$

The size of infrastructure that is required to charging the electric buses are given by Eqs. (17-18). Eq. (17) defines the number of infrastructures installed for a given charging strategy in the stops and Eq. (18) defines the availability of fast charging at a designated stop in each route.

$$Y_q = \sum_{\substack{j \in J \\ j:(q,j) \in H}} Z'_{qj} \ \ \forall \ q \in Q \tag{17}$$

$$Z'_{qj} \geq Z_{qjr} \ \ \forall \ q \in Q^{S}, j \in J^{S}, (r,j) \in V, (q,j) \in H \tag{18}$$

Eqs. (19-20) ensures that all the electric vehicles used start their activity (shift 1) with full charge obtained by the charging at the terminal during the night.

$$NC_{trsq} = P_{trs} \ \forall \ s = 1, t \in \ T^{E}, r \in R, (r,s) \in U \tag{19}$$

$$Z'_{qj} \ = 1 \ \forall \ q \in Q^{TN} \cup Q^{TD}, j \in J^{T} (q,j) \in H \tag{20}$$

Eq. (21) ensures that a certain percentage of the total fleet is electric. This constraint has the purpose of analyzing the behavior of the model when an electrification target is applied.

$$\sum_{t\in T^E}\sum_{r\in R} B_{tr} \geq G \sum_{t\in T}\sum_{r\in R} B_{tr} \tag{21}$$

Finally, Eqs. (23-32) define variable domains, i.e., the values that they can take.

$$Z_{qjr} \in \{0,1\} \ \ \forall\, j \in J, r \in R, q \in Q \tag{23}$$

$$\mathrm{Z}'_{qj} \in \{0,1\} \ \ \forall\, j \in J, q \in Q \tag{24}$$

$$P_{trs} \in \{0,1\} \ \ \forall\, a \in A, t \in T, r \in R, t \in T \tag{25}$$

$$B_{tr}^{T} \in [0; +\infty[\ \ \forall\, t \in T, r \in R \tag{26}$$

$$B_{trs}^{Shift} \in [0; +\infty[\ \ \forall\, t \in T, r \in R, s \in S \tag{27}$$

$$B_{tr}^{S1} \in [0; +\infty[\ \ \forall\, t \in T, r \in R \tag{28}$$

$$B_{tr}^{S2} \in [0; +\infty[\ \ \forall\, t \in T, r \in R, \tag{29}$$

$$Y_q \in [0; +\infty[\ \ \forall\, q \in Q \tag{30}$$

$$W_{rs} \geq 0 \ \ \forall\, a \in A, \ r \in R, s \in S \tag{31}$$

$$NC_{trsq} \geq 0 \ \ \forall\, t \in T, r \in R, s \in S, q \in Q \tag{32}$$

5. CASE STUDY

In this section the *MixedBusFleet* model will be applied to the case study of Carris and will be divided in two sections, the first being the introduction of assumptions and the datasets used in the model and the second being the results obtained from the model implementation. The model was implemented in the General Algebraic Modeling System (GAMS) 30.1 and solved with CPLEX 12.10 on an Intel Core i7-8650U, 1.90GHz 2.11GHz, with 16GB RAM.

5.1. DATASETS AND ASSUMPTIONS USED FOR THE *MIXEDBUSFLEET* MODEL

The model's application aims to support the decision-making process related to the investments in electric buses to integrate a mixed fleet by Carris in order to ensure the most feasible path to the electrification of the routes in the central area of Lisbon. The case study considers an area in Lisbon which is served by a total of 17 routes $\{r_1, \ldots, r_{17}\}$, that share the same terminal (*Pontinha*) and are organized in four different shifts $\{s_1, \ldots, s_4\}$, starting at 9am, 1pm, 6pm and 11pm. The assumptions used for this application are the following:

i. Two types of lithium ion batteries are considered as possible investments by Carris: smaller 150 kW batteries [*te*=1; $Cap_{t=1}^{Bat} = 150$] and larger 300 kW batteries [*te*=2; $Cap_{t=2}^{Bat} = 300$] (Cardoso-Grilo, Kalakou, & Fernandes, 2020);

ii. Three charging strategies are considered as feasible solutions for the case study under analysis:

   a. **Slow charging during the night at the *Pontinha* terminal** [*q*=1] - charging during a 6-hours period with a charging capacity of 300 kW, corresponding to a full load of the buses [$CC_{(q=1)(te=1)}$=150; $CC_{(q=1)(te=2)}$=300] (Cardoso-Grilo, Kalakou, & Fernandes, 2020);

   b. **Slow charging during the day at the *Pontinha* terminal** [*q*=2], between shifts – charging during a 4-hours period with a charging capacity of 200 kW [$CC_{(q=2)(te=1)}$=150; $CC_{(q=2)(te=2)}$=200] (Cardoso-Grilo, Kalakou, & Fernandes, 2020);

   c. **Fast charging during the day at selected stops**, i.e., final stops for all the routes [*q*=3] - charging during a 5 minutes period with a charging capacity of 75 kW [$CC_{(q=3)(te=1)}$=$CC_{(q=3)(te=2)}$=75] (Cardoso-Grilo, Kalakou, & Fernandes, 2020).

iii. All the buses are fully charged at night, and only one charging can take place at the *Pontinha* terminal during the night and also during the day (if needed) [$M_{q=1}^{T} = M_{q=2}^{T} = 1$];

iv. Fast charging can take place after completing each trip of each route (if needed), i.e., fast charging can take 2 times during a shift:

$$NC_{trs(q=3)} \leq 2 \;\forall\; (r,s) \in U, t \in T^E \quad (14)$$

v. The slow charging system is already installed at *Pontinha*, meaning that no investment should be considered for charging strategy 1 and 2 ($I_{q=1}= I_{q=2}=0$; $Y_{q=1}= Y_{q=2}=1$). Consequently, charging during the night takes place for all the buses ($Z_{(q=1)jr} = 1$);

vi. Fast charging systems can be installed at the final stops of all the 17 routes, with an investment of €300 000 per system ($I_{q=3}$=300 000) (Gohlich, et al., 2018).

Table 5.1 - Dataset in use

Parameters	**Values**
E_t	$T^e = \{0.020\}$; $T^d = \{0.062\}$; $T^g = \{0.034\}$ €/km – assuming an average speed of 23 km/h (Li, Lo, Xiao, & Cen, 2018). These emissions comprise NO_x, PM, CO_2 and CO.
O_t	$T^d = \{0.68\}$; $T^g = \{0.46\}$ €/km – assuming an average speed of 23 km/h (Li, Lo, Xiao, & Cen, 2018)
D_r	$\begin{Bmatrix} 3.8; 7.7; 17.6; 14.6; 11.1; 19.2; 20.7; 11.9; \\ 15.7; 18.4; 16.1; 26.5; 14.6; 8.8; 15.7; 9.2 \end{Bmatrix}$ km
N_r^{route}	$\{10; 20; 46; 38; 29; 50; 54; 44; 31; 41; 48; 42; 69; 38; 23; 41; 24\}$ minutes
NR_{rs}	Between 2 and 11 trips per bus, depending on the route and shift[1]
NB_{rs}	Between 1 and 17 buses required, depending on the route and shift[2]
Cap_r^{Route}	Between 18 and 45 kW, depending on the route[3]
C_{qt}	24€ (*q*=1, *te*=1), 48€ (*q*=1, *te*=2), 24€ (*q*=2, *te*=1), 32€ (*q*=2, *te*=2) and 12€ (*q*=3, *te*=1 and *te*=2) – total cost per charge considering 0,16 €/kW (EDP, 2020)
CC_{qt}	150kW (*q*=1, *te*=1), 300kW (*q*=1, *te*=2), 150kW (*q*=2, *te*=1), 200kW (*q*=2, *te*=2) and 75kW (*q*=3, *te*=1 and *te=2*)
I_t	€350 000 (*te*=1) and €500 000 (*te*=2) (Rogge, Hurk, Larsen, & Sauer, 2018)
K_t	30 kW
G_t	50%

[1] More details about this data are available upon request to the authors.
[2] More details about this data are available upon request to the authors.
[3] More details about this data are available upon request to the authors.

In addition to these assumptions, the model application also required the use of the data shown in Table 3.

5.2. RESULTS

5.2.1. CASE STUDY RESULTS

Table 5.3 displays the results obtained for the number of buses of each type required to ensure the electrification of the 17 routes in the central area of Lisbon. The results show that, if Carris proceeds with the implementation of a mixed bus fleet with at least 50% of the fleet being electric, then, a total of 133 buses are required – 67 electric buses with 150kW capacity and 66 CNG buses. The reason only smaller capacity buses are allocated in the routes is due to the additional investment that a larger capacity electric bus requires, the model results state that it is financially beneficial to charge the smaller capacity buses more times instead of purchasing and using a larger capacity electric buses in the routes.

The total investment is €24 962 027. This investment consists of five cost components presented in Table 5.2 and it is clear that the investment related to the acquisition of electric buses composes the majority of the total costs. The results reflect that the emissions factor (external costs of emissions) does not have a significant impact in the total costs of the fleet, this effect was also mentioned by (Li, Lo, Xiao, & Cen, 2018) where the authors concluded that due to the fact that the emission costs were the lowest, the inclusion of emission consideration does not affect the scheduling or routing of the bus fleet. They were included in this study in order to evaluate their impact and to provide a more complete model that can be used regardless of the emissions factor that it is used. In this study the external costs of emissions were used, however, other users of the model might have a different emission factor that they desire to exploit and evaluate.

The total investment when employing fast charging strategies is available for 5 final stops (*j1*, *j6*, *j10*, *j12* and *j15*) and costs €1 500 000. Since charging during the day and during the night does not require any investment as Carris already possesses a slow charging system in this terminal (*j29*), the investment in charging strategies is only required in route stops.

Table 5.4 presents the results obtained for the frequency of charging per route, both slow charging at the terminal (during the day or night) and fast charging at the designated stops. This frequency means the number of charges required per bus of each route.

Table 5.2 - Total cost components in the case study

Components	€	%
Investment in electric buses	23 450 000	93.943
Investment in charging infrastructure	1 500 000	6.009
Operating costs w/ non-electric buses	6 389	0.026
Operating costs w/ electric buses	4 836	0.019
External costs of emissions	802	0.003
Total	24 962 027	100

Table 5.3 - Results of fleet composition (Number and type of buses in use for the 17 routes)

Routes	**Number of buses**		
	CNG buses	**Electric bus - 150 kW battery**	**Total**
$\mathbf{r_1}$	3		3
$\mathbf{r_2}$	4		4
$\mathbf{r_3}$		8	8
$\mathbf{r_4}$		7	7
$\mathbf{r_5}$	8		8
$\mathbf{r_6}$	10		10
$\mathbf{r_7}$	10		10
$\mathbf{r_8}$		7	7
$\mathbf{r_9}$	6		6
$\mathbf{r_{10}}$	7		7
$\mathbf{r_{11}}$		17	17
$\mathbf{r_{12}}$		6	6
$\mathbf{r_{13}}$		17	17
$\mathbf{r_{14}}$		5	5
$\mathbf{r_{15}}$	4		4
$\mathbf{r_{16}}$	9		9
$\mathbf{r_{17}}$	5		5
Total number of buses	**66**	**67**	**133**

All buses start the first shift with full charge, which means that all the buses use the slow charging system at the *Pontinha* terminal during the night (Table 5.4, first column). Since a constraint was applied that only allows 2 fast charges per shift, when the requirement of energy is higher, the electric bus is forced to return to the terminal and charge using the charging strategy at the terminal during the day, this phenomenon can be observed in route 4 (Table 5.4, second column).

Considering the frequency of charging shown in Table 5.4 and the costs presented in Table 5.2, a total daily cost of around €4 836 should be supported by Carris with such charging.

Table 5.4 - Frequency of charging per route per electric bus

Routes	Slow charging		Fast charging			
	Night	Day	Shift 9am	Shift 1pm	Shift 6pm	Shift 11pm
r_3	1		1	2	2	
r_4	1	1			1	
r_8	1		2	2	2	1
r_{11}	1			2	2	1
r_{12}	1		2	2	2	
r_{13}	1		2	2	1	
r_{14}	1		2	2	2	
Total	**7**	**1**	**9**	**12**	**12**	**2**

5.2.2. SCENARIOS ANALYSIS

Due to the uncertainty variations that can be observed of in some of the parameter values previously exposed, this section proposes and discusses the model´s results for various scenarios and analyses their results that consider different electrification levels of the fleet is proposed. Considering the objective functions defined in the previous chapter, as well as the solution methodology that was followed in the case study, it was considered that the analysis of the results should be carried out in four different scenarios (A, B, C and D). Scenarios A, B, C and D analyze the path of the fleet to full electrification, changing constraint 21 in order to meet the defined targets of 25%, 50%, 75% and 100% of electrification, respectively. For each scenario, a solution is obtained and analyzed, as well as compared among each other so that the functionalities of the model can be more accurately understood and validated.

- ***Scenario A – Electrification of 25% of the bus fleet***

Scenario A assumes a scenario with 25% of the fleet electrified. In this case, the model indicates that a fleet of 133 vehicles is required, 34 of which are electric buses with capacity of

150kW and serve routes r11 and r13 while the rest 99 CNG buses serve the remaining routes. The distribution of buses per route is shown in Table 5.5.

In this scenario the total costs totalize €12 513 240, of which: (i) €9 977 relate to the operating costs of non-electric buses; (ii) €2 352 relate to the operating costs of electric buses; (iii) €600 000 are allocated to fast charging infrastructures; (iv) the external costs of emissions are €911; and (v) €11 900 000 represent the investment in the purchase of electric vehicles.

Table 5.5 - Number and type of buses in use for the 17 routes in Scenario A

Routes	**Number of buses**		
	CNG buses	**Electric bus - 150 kW battery**	**Total**
$\mathbf{r_1}$	3		3
$\mathbf{r_2}$	4		4
$\mathbf{r_3}$	8		8
$\mathbf{r_4}$	7		7
$\mathbf{r_5}$	8		8
$\mathbf{r_6}$	10		10
$\mathbf{r_7}$	10		10
$\mathbf{r_8}$	7		7
$\mathbf{r_9}$	6		6
$\mathbf{r_{10}}$	7		7
$\mathbf{r_{11}}$		17	17
$\mathbf{r_{12}}$	6		6
$\mathbf{r_{13}}$		17	17
$\mathbf{r_{14}}$	5		5
$\mathbf{r_{15}}$	4		4
$\mathbf{r_{16}}$	9		9
$\mathbf{r_{17}}$	5		5
Total number of buses	**99**	**34**	**133**

The investment in fast charging strategies is available for 2 final stops (*j10* and *j12*).

- ***Scenario B – Electrification of 50% of the bus fleet***

The scenario where 50% of the fleet is electrified generates results equal to the case study where the electrification target is at least 50%, i.e. there are 133 buses, where 67 are electric buses and 66 are non-electric buses. The total costs and its components are the same as the case study.

- ***Scenario C – Electrification of 75% of the bus fleet***

With a fleet that is 75% electrified, the total costs increase to €38 411 475, of which: (i) €3 745 relate to the operating costs of non-electric buses; (ii) €7 008 relate to the operating costs of electric buses; (iii) €2 700 000 are allocated to fast charging infrastructures; (iv) the external costs of emissions are €721; and (v) €35 700 000 represent the investment in the purchase of electric vehicles. In this scenario the fleet is composed by 136 vehicles, being 102 electric vehicles and 34 non-electric vehicles, further details regarding the fleet composition are presented in Table 5.6.

Table 5.6 - Number and type of buses in use for the 17 routes in Scenario C

Routes	**Number of buses**		
	CNG buses	**Electric bus - 150 kW battery**	**Total**
r_1		3	3
r_2		4	4
r_3		8	8
r_4		7	7
r_5	8		8
r_6		10	10
r_7	10		10
r_8		7	7
r_9		6	6
r_{10}	7		7
r_{11}		17	17
r_{12}		6	6
r_{13}		17	17
r_{14}		5	5
r_{15}		7	7
r_{16}	9		9
r_{17}		5	5
Total number of buses	**34**	**102**	**136**

The investment in fast charging strategies is available for 9 final stops (*j1, j6, j7, j10, j11, j12, j15, j16* and *j23*).

- ***Scenario D – Electrification of 100% of the bus fleet***

It is only when the target of full electrification is set that the fleet is composed by the two types of electric vehicles available (150kW and 300 kW capacity) because is no longer beneficial to only purchase smaller battery electric buses and keep charging them in various stops, the model adopts the acquisition of 95 smaller capacity electric buses and 38 larger capacity electric buses to ensure that the demand is satisfied in the most cost-effective way.

Table 5.7 - Number and type of buses in use for the 17 routes in Scenario D.

	Number of buses		
Routes	**Electric bus - 150 kW battery**	**Electric bus - 300 kW battery**	**Total**
r_1	3		3
r_2	4		4
r_3	8		8
r_4	7		7
r_5		8	8
r_6	10		10
r_7		10	10
r_8	7		7
r_9	6		6
r_{10}		7	7
r_{11}	17		17
r_{12}	6		6
r_{13}	17		17
r_{14}	5		5
r_{15}		4	4
r_{16}		9	9
r_{17}	5		5
Total number of buses	**95**	**38**	**133**

Until the target of 100% is forced, the fleet is only composed by electric vehicles of 150kW capacity and diesel buses. In this scenario, the total costs are €55 861 131, of which: (i) €10 524 relate to the operating costs of the electric vehicles; (ii) €3 600 000 are allocated to the investment in infrastructures; (iv) €607 are related to the external costs of emissions; and (v)

€52 250 000 are related to the investment in the vehicles. Table 5.7 and 5.8 present the composition of the fleet and the frequency of charging, respectively.

The investment in fast charging strategies is available for 12 final stops (*j1*, *j2*, *j3*, *j5*, *j6*, *j7*, *j10*, *j11*, *j12*, *j15*, *j16* and *j23*).

Table 5.8 - Frequency of charging per route per electric bus in scenario D

Routes	Slow charging		Fast charging			
	Night	Day	Shift 9am	Shift 1pm	Shift 6pm	Shift 11pm
r_1	1		1	2		1
r_2	1		2		1	
r_3	1		1	2	2	
r_4	1	1			1	
r_5	1		2	2	2	2
r_6	1		1	1		2
r_7	1		1	2	2	1
r_8	1		2	2	2	1
r_9	1		1	2	2	1
r_{10}	1		1	2	2	
r_{11}	1			2	2	1
r_{12}	1		2	2	2	
r_{13}	1		2	2	1	
r_{14}	1		2	2	2	
r_{15}	1		1	2	2	
r_{16}	1		2	2	2	
r_{17}	1		2	2	1	
Total	**17**	**1**	**23**	**29**	**26**	**9**

5.2.3. DISCUSSION

In this section, the results obtained through the optimization model of the different scenarios are analyzed. As the electrification increases, an increase in investments with fast charging infrastructures is expected, as well as the purchase of electric vehicles. However, a different conclusion can be drawn regarding the operational costs and emission costs. In Figure 5.1, the operational costs of the different fleet compositions are displayed. The total operational costs, which are composed by the non-electric buses' operational costs and electric buses' operational costs decrease as the electrification of the fleet increase, totalizing €12 329, €11 225, €10 753 and €10 524 in Scenario A, B, C and D, respectively.

The effect with the external costs of emissions is similar to the total operational costs. As the electrification of the fleet increases, the external costs of emissions decreases, this phenomenon is due to the fact that the emissions of electric buses are much lower than the emissions related to diesel and CNG buses. Electric buses only emit CO_2 (such emissions of the referred gas are still lower than the emissions of the non-electric buses), while diesel and CNG buses' operations release to the atmosphere various pollutant gases, such as NO_x, PM, CO_2 and CO (Li, Lo, Xiao, & Cen, 2018). These results are shown in Figure 5.2.

Diesel buses were not allocated to the fleet in any of the given scenarios as well as the case study, despite being available. This happens because the external costs of emissions and operating costs of diesel buses are higher than the CNG buses. In order to incorporate diesel buses in the fleet, it is possible to insert a constraint that limits the number of CNG buses used or forces the usage of diesel buses. However, since that application is not relevant for this study, such constraints were not applied.

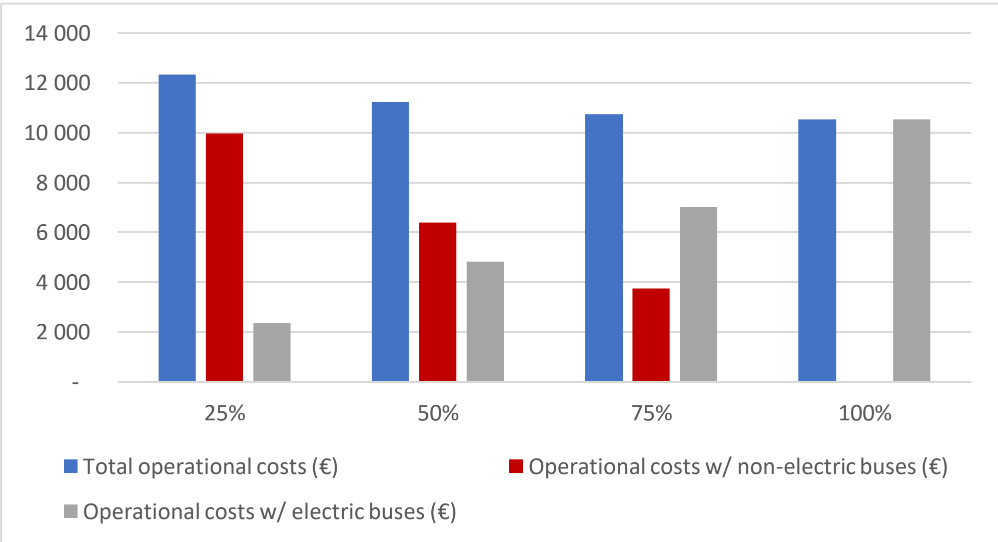


Figure 5.1 - Daily operational costs.

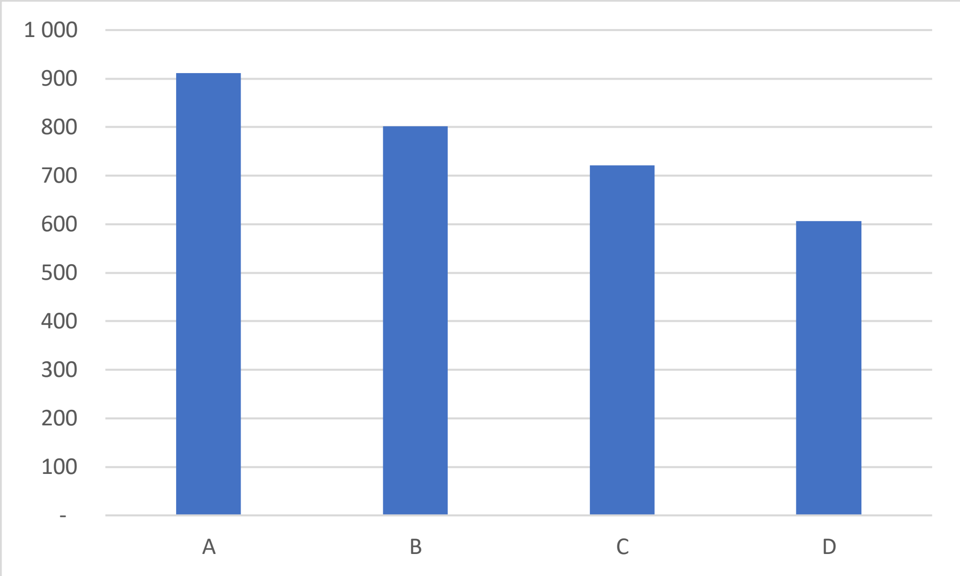


Figure 5.2 - Daily external costs of emissions.

5.2.4. Computational results

In Table 5.9 the main characteristics of the model's execution are displayed and analyzed for the case study and for each scenario. One of the most relevant characteristics is the execution time, which is the time necessary for the model to generate the solution. The number of iterations and variables needed for each model's run are also displayed, showing the complexity of the problem. The gap values (Table 5.9, third column) for every run is 0. This means that every solution presented was an optimal one.

Table 5.9 - Computational results

Planning context	Execution time (seconds)	Gap	Iterations	Equations	Integer variables	Variables
Case Study	0.032	0	6 317	2 617	969	1 204
Scenario A	0.062	0	51 273	2 617	969	1 204
Scenario B	0.016	0	5 367	2 617	969	1 204
Scenario C	0.031	0	805	2 617	969	1 204
Scenario D	0.047	0	58	2 617	969	1 204

6. CONCLUSIONS AND FUTURE RESEARCH

6.1. CONCLUSIONS

As the concerns regarding the environment increase, various environmentally friendly practices associated with people's daily activities arise. A main contributor to air pollution is the transportation sector, namely, transport activities that are fueled by conventional methods, such as diesel or CNG vehicles. The operations of vehicles result in a wide range of gaseous air pollutants. Since buses are a widespread means of public transport, they are met high frequency in transport daily operations, and it is expected they have a significant impact on air pollution. It is, therefore, necessary to employ environmentally friendly vehicles such as electric vehicles. In this context, this dissertation aimed to explore the transition to electric bus fleets and develop a tool that aids this transition in a cost-effective way.

In the literature review, various studies are analyzed and, although there is a considerable number of studies that tackle the electrification of bus fleets and its associated implications such as the charging infrastructures, batteries and costs, there are few that address the mixed fleet problem. To the best of my understanding and as the date of this dissertation, there were no studies available that addressed a mixed bus fleet that considers: (i) the location of charging stations; (ii) frequency of charging; (iii) the charging strategy; (iv) battery type; (v) fleet dimension and; (vi) an emissions factor, in this study referred as the external costs of emissions with the objective of minimizing investment and total operating costs. To take this planning decisions in consideration, it is crucial in order to obtain the most accurate solution.

The model developed in this study, *MixedBusFleet*, addressing the planning decisions mentioned above was applied to part of the operation of Carris, which is a Portuguese public transport operator that focuses its activity on the metropolitan area of Lisbon. This case study as comprised of 17 routes with a predefined demand of buses. The results of the model showed that 133 buses are required to fulfil all the demand with a constraint that imposed that at least 50% of the bus should be electrified. This constraint resulted in 50.4% of electric buses, namely lower capacity lithium ion battery buses (150 kW), and 49.6% of non-electric buses, namely, CNG buses. The total investment was of €24 950 000 and 5 fast charging strategies were installed in 5 final stops.

This dissertation is expected to have a theoretical contribution for the literature by evaluating existing models and suggesting an optimal one. Regarding managerial contributions, it is expected that this paper will have the potential to help companies that may be interested in implementing this model in their fleets (public or not), adjusting the parameters and variables to represent their operational characteristics and requirements. By improving electric fleet processes with the model presented in this thesis, pollutant gases emissions are expected to decrease achieving in this way a societal contribution.

There are several stakeholders that can benefit from this study: companies that have electric fleets; citizens of the cities this model will be implemented, due to the reduced air and noise pollution; and if this model is utilized for public transportation, the customers will also be more satisfied to be travelling in a vehicle that does not emit pollutant gases to the atmosphere.

6.2. Limitations and Future Research

The main limitation relates to the uncertainty of some of the parameters used, such as the volatility of electricity prices and the accurate establishment of investment values for the purchase of electric vehicles and fast charging stations since the different studies analyzed consider different values which is normal since the values of such investment vary according to the brand, characteristics, etc.

The proposal for future research relies on: (i) exploring news technologies of charging and new batteries since this is a sector that is an emerging trend (electric vehicles) and, consequently, is in constant development and; (ii) applying the model with different parameters and constraints, such as limiting pollutant air emissions or consider other emissions factor (e.g. quantity).

7. References

Andriollo, M., & Tortella, A. (2015). Sustainability evaluation of an electric bus fleet for the urban public transport system of Padova, Italy. *WIT transactions on the built environment* (pp. 1-13). WIT Press.

Cardoso-Grilo, T., Kalakou, S., & Fernandes, J. (2020). *Deployment of electric buses: planning the fleet size and type, charging infrastructure and operations with an optimization-based model.*

Carrilero, I., González, M., Anséan, D., Viera, J. C., Chacón, J., & Pereirinha, P. G. (2018). Redesigning european public transport: Impact of new battery technologies in the design of electric bus fleets. *Transportation research procedia 33*, 195-202.

Chen, Z., Liu, W., & Yin, Y. (2017). Deployment of stationary and dynamic charging infrastructure for electric vehicles along traffic corridors. *Transportation research part C 77*, 185-206.

Cortés-Murcia, D. L., Prodhon, C., & Afsar, H. M. (2019, September 13). The electric vehicle routing problem with time windows, partial recharges and satellite customers. *Transportation research part E 130*, 184-206.

Durango-Cohen, P. L., & McKenzie, E. C. (2017). Trading off costs, environmental impact, and levels of service in the optimal design of transit bus fleets. *Transportation Research Prodecia 23*, 1025-1037.

EDP. (2020, 11 23). *EDP Comercial*. Retrieved from EDP Web site: https://www.edp.pt/particulares/servicos/mobilidade-eletrica/carregar-fora-de-casa/

Gabsalikhova, L., Sadygova, G., & Almetova, Z. (2018). Activities to convert the public transport fleet to electric buses. *Transportation Research Procedia 36*, 669-675.

Gao, Z., Lin, Z., LaClair, T. J., Liu, C., Li, J.-M., Birky, A. K., & Ward, J. (2017). Battery capacity and recharging needs for electric buses in city transit service. *Energy 122*, 588-600.

Gohlich, D., Fay, T.-A., Jefferies, D., Lauth, E., Kunith, A., & Zhang, X. (2018). Design of urban electric bus systems. *Design Science Volume 4* (pp. 1-28). Cambridge University Press.

He, Y., Song, Z., & Liu, Z. (2019). Fast-charging station deployment for battery electric bus systems considering elctricity demand charges. *Sustainable Cities and Society 48*.

Islam, A., & Lownes, N. (2019). When to go electric? A parallel bus fleet replacement study. *Transportation Research Part D 72*, 299-311.

Krzyzanowski, M., Kuna-Dibbert, B., & Schneider, J. (2005). *Health effects of transport-related air pollution.* Copenhagen, Denmark: World Health Organization Regional Office for Europe.

Kunith, A., Mendelevitch, R., & Goehlich, D. (2017). Electrification of a city bus network - An optimization model for cost-effective placing of charging infrastructure and battery sizing of fast-charging electric bus systems. *International Journal of Sustainable Transportation*, 707-720.

Kunith, A., Mendelevitch, R., Kuschmierz, A., & Goehlich, D. (2016). Optimization of fast charging insfrastructure for electric bus transportation - Electrification of a city bus network. *EVS29 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium.* Montréal, Québec, Canada.

Lajunen, A. (2018). Lifecycle costs and charging requirements of electric buses with different charging methods. *Journal of Cleaner Production 172*, 56-67.

Laurikko, J., Pihlatie, M., Nylund, N.-O., Halmeaho, T., Kukkonen, S., Lehtinen, A., . . .

Ahtiainen, S. (2015). Electric city bus and infrastructure demosntration environment in Espoo, Finland. *EVS28 International Electric Vehicle Symposium and Exhibition* (pp. 1-11). Goyang, Korea: Kintex.

Li, L., Lo, H. K., Xiao, F., & Cen, X. (2018). Mixed bus fleet management strategy for minimizing overall and emissions external costs. *Transportation Research Part D 60*, 104-118.

Merkisz, J., Fuc, P., Lijewski, P., & Pielecha, J. (2016). Actual emissions from urban buses powered with diesel and gas engines. *Transportation Research Procedia 14*, 3070-3078.

Michaelides, E. E. (2020, October 30). Thermodynamics and energy usage of electric vehicles. *Energy conversion and management 203*.

Pachauri, R. K., & Meyer, L. A. (2014). *Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change.* Geneva, Switzerland: IPCC.

Paril, V., & Tóthová, D. (2020). Assessment of the burden on population due to transport-related air pollution: The Czech core motorway network. *Journal of cleaner production 275*.

Pelletier, S., Jabali, O., Mendoza, J. E., & Laporte, G. (2019). The electric bus fleet transition problem. *Transportation Research Part C 109*, 174-193.

Penna, P. H., Afsar, H. M., Prins, C., & Prodhon, C. (2016). A hybrid iterative local search algorithm for the electric fleet size and mix vehicle routing problem with time windows and recharging stations. *IFAC-PapersOnLine 49-12*, 955-960.

Pereirinha, P. G., González, M., Carrilero, I., Anseán, D., Alonso, J., & Vieira, J. C. (2018). Main trends and challenges in road transportation electrification. *Transportation Research Procedia 33*, 235-242.

Rinaldi, M., Picarelli, E., D'Ariano, A., & Viti, F. (2020). Mixed-fleet single-terminal bus scheduling problem: Modelling, solution scheme and potential applications. *Omega 96*.

Rogge, M., Hurk, E. V., Larsen, A., & Sauer, D. U. (2018). Electric bus fleet size and mix problem with optimization of charging infrastructure. *Applied Energy 221*, 282-295.

Rothgang, S., Rogge, M., Becker, J., & Sauer, D. U. (2015). Battery design for successful electrification in public transport. *Energies 8*, 6715-6737.

Sebastiani, M. T., Luders, R., & Fonseca, K. O. (2016). Evaluating Electric Bus Operation for a Real-World BRT Public Transportation Using Simulation Optimization. *IEEE Transactions on Intelligent Transportation Systems 17*, 2777-2786.

Sinhuber, P., Rohlfs, W., & Sauer, D. U. (2010). Conceptual considerations for electrification of public city buses - Energy storage system and charging stations. *Emobility - Electrical power train*, 1-5.

Vilathgamuwa, D. m., & Jayathurathange, P. (2015). Wireless power transfer (WPT) for electric vehicles (EVs) - Present and future trends. In S. Rajakaruna, F. Shahnia, & A. Ghosh, *Plug in electric vehicles in smart grids* (pp. 33-60). Singapore: Springer Science+Business Media.

Xu, Y., Gbologah, F. E., Lee, D.-Y., Liu, H., Rodgers, M. O., & Guensler, R. L. (2015). Assessment of alternative fuel and powertrain transit bus options using real-world operations data: Life-cycle fuel and emissions modeling. *Applied Energy 154*, 143-159.

Xylia, M., Leduc, S., Patrizio, P., Kraxner, F., & Silveira, S. (2017). Locating charging infrastructure for electric buses in Stockholm. *Transportation Research Part C 78*, 183-200.