Deployment of Electric Buses: Planning the Fleet Size and Type, Charging Infrastructure and Operations with an Optimization-Based Model

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Abstract. The current awareness about climate change creates the urgency in adjusting the services provided in public transport towards more sustainable operations. Recent studies have shown that the integration of electric vehicles into existing fleets is an alternative that allows reducing CO_2 emissions, thus contributing to a more sustainable provision of services in the sector. When the aim is to achieve a full electrification of a bus fleet, several decisions need to be planned, such as i) the number of buses that are required, ii) the types of batteries used in those vehicles, iii) the charging technologies and strategies, iv) the location of the charging stations, and v) the frequency of charging. Nevertheless, although several planning studies have focused on the full electrification of a bus fleet, no study was found considering all these planning decisions that are deemed as essential for an adequate planning. Our study thus contributes to this gap in the literature, by proposing an optimization-based planning model that considers all these planning dimensions in the decision-making process related to the integration of electric buses in a public bus transport system – the *MILP4ElectFleet* model. All these decisions are evaluated while ensuring the minimization of investment and operating costs. The *MILP4ElectFleet* model is applied to the Carris case study, a Portuguese public transport operator in the metropolitan area of Lisbon.

Keywords: Electric bus fleet · Public transport · Optimization

1 Introduction

As concerns about climate change are increasing, governing agents are implementing strategies and adopting measures with the potential to mitigate greenhouse gas emissions (GHG) and especially CO_2 emissions. According to the International Energy Agency (IEA), the energy, industry, construction and transport sectors are the main contributors to global emissions. In 2019 the transport sector, in particular, was responsible for 24% of direct CO_2 emissions, out of which approximately 75% came

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from road transport (cars, trucks, buses and motorcycles) (IEA 2020), indicating the need for more radical actions in road transport management and policies.

In the European Union, in order to enhance sustainable development, the European Guidelines for Developing and Implementing a Sustainable Urban Mobility Plan (SUMP) bring together the stakeholders of a city and aim to implement mobility measures aligned with the Paris Agreement (Rupprecht Consult 2019). One well-established initiative has been the implementation of Low Emission Zones that serve the objective of reducing emissions and mobility-associated environmental impacts. In this context, transport management actions related to improvements in the emissions efficiency of vehicles arise, and the evolution of electromobility has been strongly stimulated worldwide in the use of both light and heavy vehicles such as buses. Hence, the need to efficiently integrate electric buses in the fleet of current bus operators of public transport emerges, and so do the challenges for transport operators. Cities such as Paris, London, Los Angeles, and Copenhagen follow the C40 Fossil Fuel Free Street Declaration that pledges to procure only zero emission buses from 2025 and ensure to operate emission-free fleets by 2030 (C40 Cities). Planning and management strategies are required to determine technical and economic aspects of the transition to fleet electrification.

Operating bus networks is per se a complex process that involves a variety of decisions ranging from strategic to operational ones. Particularly, when the aim is to achieve full fleet electrification, key decisions involve the location of charging stations (conditioned or arbitrary), the choice of charging technologies and strategies, the typology of vehicle powering batteries and the frequency of charging. And to ensure the economic viability of the electrification of bus network operations, the costs of fleet size, battery typology and charging systems need to be addressed and eventually minimized.

From a business perspective, electrifying bus fleets imposes additional costs to both cities and operators, worldwide, who are still having cost barriers and are using grants to cover the expenses of all the stages of electric bus integration ranging from procurement to operation (Li et al. 2018b). The purchasing cost of electric buses is higher than the corresponding of the conventional ones (Rothgang et al. 2015). At the operational phase, the costs of movement and charging infrastructure need to be considered. Decisions on the type of charging infrastructure to be employed is determinant for the resulting operating costs, which depending on the service frequency, the circulation length and the speed of a transit system, may have a great impact on the performance of different charging infrastructures (charging stations, charging lanes – via charging-while-driving technologies – and battery swapping stations) (Chen et al. 2017). As the charging process can follow different strategies, namely be slow or fast, energy consumption varies in accordance to vehicle's weight, weather conditions and route's characteristics. The costs of purchasing a battery bus for slow charging are quite high, but its operating costs are generally lower compared to other charging strategies (Lajunen 2018). Overall, several operational aspects influence the total costs incurred by the adoption of electric vehicles.

Profitable choices of bus fleets are not obvious and thorough consideration of the total costs is vital in making decisions on the battery type to be employed, the charging infrastructure to be installed, the charging network to be designed and the frequency of charging to be planned. Previous work has focused on the full substitution of conventional bus fleet from electric buses to make decisions on the fleet management (Wang et al. (2017); Tang et al. (2019)). Nevertheless, while several studies aimed at planning the full electrification of a bus fleet while considering the minimization of costs and identifying the dimension of the fleet, battery types, charging infrastructure and frequency of charging, none of them considers simultaneously all these four planning aspects. This study aims to fill in this gap in the literature.

In the context of electrifying transport, this paper aims to contribute to the electrification of public transport with the proposal of an optimization-based model that can be used to support the decision-making process of transport operators on the selection of electric bus types, location of charging stations, and also on the frequency of charging. The proposed model is based on a Mixed Integer Linear Programming (MILP) model, hereafter called *MILP4ElectFleet*, which allows determining the minimum number of electric buses with the minimum charging requirements to secure the routes currently offered by the public transport operator. As far as loading is concerned, this model makes it possible to identify the need for investment in charging stations with different charging strategies, as well as the required frequency of charging. The model also makes it possible to identify the required investment in vehicles with different battery types. To illustrate the applicability of the model, it is applied to the operation of a public transport operator (Carris) in the metropolitan region of Lisbon.

The remainder of this article is organized as follows. Section 2 presents a brief literature review on bus fleet electrification. Background information on the problem under analysis is explored in Sect. 3. Section 4 presents the mathematical details of the optimization-based model proposed in this study. The results obtained are explored in Sect. 5, and key conclusions and future research are presented in Sect. 6.

2 Literature Review on Bus Fleet Electrification

This section is focused on the review of studies that analyze technical and economic aspects related to bus fleet electrification and aim to support the decision-making process of integrating electric buses in the bus fleet of public transport companies. A review of the methods is summarized at the end of the section and the contribution of this paper is presented.

2.1 Electric Bus Battery Types, Charging Infrastructure and Strategies

Battery characteristics (size and useful life among others) are determinant aspects for the design of electric transport networks. For instance, the requirements in recharging activities of electric buses decrease fast as the maximum driving range increases (Wang et al. 2017). Hence, battery performance has direct impacts on the costs and the performance of electric fleets as well. The most common batteries in electric mobility are lithium ion batteries, and there are three types to cover different operational requirements (Carrilero et al. 2018):

- *Lithium Iron Phosphate - LiFePO4 (LFP):* a common technology in electric buses with the advantages of having a high cycling-life, good power parameters, high thermal stability and competitive price but comparing with other types of batteries, the technology has a low nominal voltage (3.2 V), low capacity (90–120 Wh/kg) resulting into larger and heavier batteries that charge slower degrade faster.
- *Lithium Nickel Manganese Oxide Cobalt - LiNiMnCoO2 (NMC):* has a capacity of 150–220 Wh/kg which allows greater autonomy and smaller size, aspects that constitute it suitable for smaller buses but is more expensive than LEP and entails safety risks (is environmentally dangerous) in case of an accident.
- *Lithium Titanate - Li4Ti5O12 (LTO):* has excellent thermal stability and can be charged frequently with no impacts on its lifecycle but is more expensive than the others and it has a low voltage rating (2.4 V) and a reduced power capacity resulting in larger and heavier batteries.

The charging infrastructure types (battery swapping stations, plug-in charging stations and wireless charging facilities (Chen et al. 2017)) may be employed for recharging all battery types. Depending on the transport system, different infrastructure types might be advantageous. For bus rapid transit corridors, the use of charging lanes enabled by currently available inductive wireless charging technology might be appropriate. On the other hand, for transit systems, swapping stations can result into a lower total cost than charging lanes and charging stations, but when there are low service frequencies and short circulations, swapping stations might be the proper choice (Chen et al. 2017).

The charging mode can also vary and six charging strategies can be considered by bus operators (Carrilero et al. 2018): (1) *Slow charging*, in which charging is performed in about 6 h; (2) *Fast charging or opportunity charging*, with larger power charges; (3) *Regenerative braking,* with energy independence due to the exploitation of the energy generated while braking but with faster battery degradation compared to fast charging; (4) *Combination of fast charging and opportunity charging* for buses that use slow charging at the end of the route and fast charging during the route; (5) *Moving charge (trolley bus)* for buses charged through overhead cables in sections of a route; (6) *Physical exchange of batteries* when batteries are replaced at battery exchange stations when batteries reach low levels.

2.2 Operational Aspects of the Electrification of Bus Fleets

The passage from conventional vehicles to electric ones in the business of public transport entails several challenges and comprises of several phases that could gradually lead to full electrification.

At a first stage, different scenarios of battery sizing and charging can be employed to analyse the feasibility and efficiency of electric bus implementation. Analysis of the energy requirements of a bus network in the city of Aachen in Germany, showed that charging at certain bus stops results into higher infrastructure costs compared to charging at bus terminals (Sinhuber et al. 2010). This happens because batteries don't store enough energy to complete their operation. By simulating the life cycle cost of a bus fleet using 4 routes in Finland and California, Lajunen (2018) explored the potential of three types of charging: slow (overnight), end of route and opportunity charging. The authors found that while the initial costs of opportunity charging costs are quite high, they are quite flexible in terms of operation. Considering a 12-year lifespan for buses and comparing them with a diesel model, charging at the terminal becomes the most efficient, having only 7% more costs, while overnight charging has 26% more and opportunity charging has 35% more costs. However, simulation tests have demonstrated that while overnight charging implies a lower investment, allows greater schedule flexibility and longer useful life of batteries, it requires bigger batteries, more space, more energy and less passenger seats (Rothgang et al. 2015).

The use of different batteries introduces flexibility in the charging system. Based on real data of the operation of a bus fleet for a full year, further work indicated the need for flexibility in the charging system of the bus fleet. Employing multiple battery configurations and flexible battery swapping practices in electric buses, could result into the use of smaller batteries with shorter charging events (e.g., at a designated bus stop at the end of the route) through ultrafast charging for both short and long routes increasing in the case the battery degradation rate (Gao et al. 2017). Such flexibility, however, implies that the bus fleet satisfies similar demand volumes along all the network.

The cost of battery charging activities is part of the total cost of the fleet electrification which can be assessed through the estimation of Total Cost of Ownership (TCO) and the analysis of the viability of an investment made in infrastructure to support electric mobility and the costs of vehicle acquisition, operation and maintenance. Göhlich et al. (2013) presented a financial forecasting method for innovative urban transport systems, employing a Monte Carlo simulation in order to respond to future uncertainties related to technology and market aspects. Applying the TCO methodology for the Berlin bus system, including vehicle costs, financial costs, operating costs, infrastructure costs and emissions costs, they introduced the concept of charging buses while performing routes in addition to charging only at night, which requires larger batteries and consequently higher weight and consumption of buses. Due to technical limitations, the long-range electric buses are limited, considering the batteries range capacity and size, implying a higher investment. Laurikko et al. (2015) presented the TCO to obtain the equivalent annual cost incurred in owning and operating a fleet of electric buses considering drivers' labour costs, capital costs of the vehicle (including battery), maintenance and fuel costs. Rogge et al. (2018) analysed the viability of electric fleets in the city of Aachen (Germany) and the connection of Roskilde-Copenhagen (Denmark) from a TCO perspective based on an optimization model that considered investment costs in the fleet and infrastructure, operating costs, energy consumption, schedules, distances and availability of charging station in order to the fleet size, fleet models, optimization of the loading process and minimization of TCO.

It is evident that there are many parameters to consider when making decisions on the design of an electric bus network and the focus should lie on both technical and economic aspects. Depending on the network design, different configurations might be appropriate. In this line, several studies have attempted to find the optimal network design focusing on costs minimization and following operational restrictions. The combination of electric charging infrastructure, batteries and energy consumption is a major theme in the deployment of an electric bus fleet in order to both reduce emissions and increase energy efficiency, as well as to guarantee the operation carried out by bus fleets minimising infrastructure costs wherever possible. In this context, Kunith et al.

(2014) developed a MILP model to minimize the cost of implementing charging stations for an infrastructure with opportunity charging type serving a route (15-h service, length of 28.5 km, 30 stops) by determining the minimum number and location of charging stations required based on certain operational and technological constraints (battery consumption). Different energy consumption scenarios representing different traffic volumes and different weather conditions, with different battery capacities and charging infrastructures were analysed. Further on, they employed opportunity charging for the complete substitution of the diesel fleet in Berlin and as an alternative to its existing electric trolley-bus fleet that need to be continuously connected to the electric grid in order to define the infrastructure requirements when employing different battery types (Kunith et al. 2017). Advancing on this MILP model, the cost of batteries was additionally considered to cater for the electrification cost (Kunith et al. 2016).

Previous work on operations' optimization has also aimed to minimize total costs and energy consumption. A case study in Stockholm determined the location of bus charging points considering the availability of two charging options: (a) points in the main public transport stops (eg. Next to train stations) and (b) at the beginning and the end of bus routes (Xylia et al. 2017). For the city of Padova, investments on batteries and operating costs on a ten-year time horizon were minimized in order to determine the location of the battery recharging/replacement points in a bus network and assess the sustainability performance of the bus fleet (Andriollo and Tortella 2015). Focusing on the employment of fast-charging infrastructure, flexible battery sizes and the addition of demand charges to total costs, the results of total cost minimization model for a bus fleet in Salt Lake City (Utah) highlighted that bus operators need to consider the trade-off between fast-charging station cost and bus battery cost as properly deployed fast-charging stations have the potential to reduce both the battery cost and the total costs (He et al. 2019).

Focusing on total operational costs, an optimum mix of battery electric and diesel hybrid bus operated in Connecticut was reached in Islam and Lownes (2019) by minimizing the purchasing, operating and maintaining costs of the entire fleet including costs of charging infrastructure, fuel cost, salvage value, and emission costs. Following the same perspective of objectives, Rinaldi et al. (2020) explored the optimum fleet size of hybrid and electric buses in order to minimize the total costs occurred considering the charging requirements.

2.3 Concluding Remarks

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 1 provides an overview of the afore-mentioned optimization studies aiming at planning 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. Within this setting, there is scope to develop more comprehensive planning models that jointly consider all these dimensions. The current paper aims to fill this gap in the literature.

Table 1. 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	Planning decisions					Cost-oriented objectives
	Location of charging stations	Frequency of charging	Charging strategy	Battery type	Fleet dimension	
Kunith et al. (2014)	X					Costs with infrastructures
Kunith et al. (2017)	X					
Andriollo and Tortella (2015)		X				Total operating costs
Kunith et al. (2016)						
Xylia et al. (2017)	X		X		X	
Houbbadi et al. (2019)						
Rogge et al. (2018)		X			X	
He et al. (2019)	X		X	X		
Islam and Lowens (2019)				X	X	Investment and total operating costs
Pelletier et al. (2019)		X		X	X	
Rinaldi et al. (2020)		X		X		
MILP4ElectFleet	X	X	X	X	X	

3 Electrification of a Public Bus Operator in Portugal

The Roadmap for carbon neutrality 2050 (RNC2050 2020) in Portugal has imposed the objective of reducing GHG by 50% to 60% by 2050, compared to the corresponding levels of 1990. In order to keep up with world trends, Portugal has also defined some strategies that allow to adapt to world developments, and a series of measures have been defined for the use of more efficient vehicles, namely electric vehicles. In particular, there is the example of the Action Plan for Electrical Mobility, Methodology for

Locating New Loading Points and Financial and Tax Incentives (Ministry of Environment, Spatial Planning and Energy 2015). Also, at the level of the Major Options of the Plan for 2018, the government has registered mandatory loading points in new houses and garages starting from 2019, among others.

Carris, a Portuguese public transport operator focusing its activity in the metropolitan area of Lisbon, is used as a case study in this paper. Carris aims at providing an urban surface passenger transport service by making available buses, trams, lifts and elevators. Following the national guidelines, Carris is currently evolving towards a more sustainable provision of its services, and one of the strategies followed by the company involves the integration of electric buses within its fleet. The company owns a variety of buses – standard, articulated, medium, and mini-buses – but for the moment, the investment in electric vehicles is only focused on standard buses. Accordingly, a key challenge faced by Carris involves planning the investment in additional electric standard buses while also ensuring the most efficient integration of these electric buses in its fleet. This efficient integration implies ensuring the minimum operating and investment costs (with costs varying with the number of electric buses, type of batteries used in the vehicles, as well as with the charging technologies and strategies and frequency of charging) while ensuring part of the routes currently offered by Carris in the metropolitan area of Lisbon. Particularly, the company aims at achieving the full electrification of the routes in the central area of Lisbon (a total of 17 routes), and this mainly due to the higher expected impact in the environmental quality of all the city of Lisbon.

Within this setting, the *MILP4ElectFleet* will support the following decisions:

i. How many buses are required to ensure the full electrification of the routes in the central area of Lisbon? And which types of batteries should be used in those routes?
ii. How much should be invested in different charging technologies and strategies? And where should those charging stations be located (terminal and/or stops)?
iii. What is the minimum frequency of charging for the different charging technologies and per electric bus?

4 Methodology

This section presents the mathematical details of the *MILP4ElectFleet* model.

4.1 Assumptions Used for Building the *MILP4ElectFleet* Model

Several assumptions are used so as to build the *MILP4ElectFleet* 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. A single type of battery can be used by all the buses of each route;
iv. Each bus can be charged at the terminal and/or at the stops of routes;

v. A set of route stops is selected for installing charging technologies, if needed, and multiple charging strategies can be followed;
vi. A maximum number of charges at the terminal is imposed per day;
vii. A maximum number of charges at the stops is imposed per shift, with this maximum number depending on the number of trips per route of each shift;
viii. The first shift of the day starts with all the buses fully charged.

4.2 Notation

Indices and Sets

$r \in R$	Routes
$s \in S$	Shifts
$p \in P$	Batteries
$q \in Q = Q^{TN} \cup Q^{TD} \cup Q^{S}$	Charging strategies, including charging during the night (Q^{TN}) and during the day (Q^{TD}) in charging stations installed in the terminals, and also in the route stops (Q^{S})
$j \in J = J^{T} \cup J^{S}$	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 $q \in Q$ the technology of 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 $j \in J^{T}$, and routes $r \in R$ with route stop $j \in J^{S}$

Parameters

N_s^{shift}	Duration (in hours) of shift $s \in S$
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^{Trip}	Capacity (kW) required to complete each trip of each route $r \in R$
Cap_p^{Bat}	Capacity (kW) of each battery $p \in P$
CC_{qp}	Charging capacity (kW) for the charging strategy $q \in Q$ when using battery $p \in P$
C_{qp}	Energy hourly cost (€/kW) for charging strategy $q \in Q$ using battery $p \in P$
I_q	Investment (€) required per charging strategy $q \in Q$
I_p	Investment (€) required per bus using battery $p \in P$
M_q^{T}	Maximum number of charges allowed per day using charging strategy $q \in \mathrm{Q}^{\mathrm{TD}}$

M_{rsq}^{S} Maximum number of charges allowed per bus for route $r \in R$ during shift $s \in S$ using charging strategy $q \in Q^{S}$
K Minimum capacity (kW) for buses
L High auxiliary value

Variables

X_{prsq} Equal to 1 if a bus using battery $p \in P$ required for route $r \in R$ during shift $s \in S$ is charged using the charging strategy $q \in \mathrm{Q}$
Z_{qjr} Equal to 1 if charging strategy $q \in Q$ involves installing a charging technology at stop $j \in J$ belonging to route $r \in \mathrm{R}$
Z'_{qj} Equal to 1 if charging strategy $q \in Q$ involves installing a charging technology at stop $j \in \mathrm{J}$
T_{pr} Equal to 1 if a bus using battery $p \in P$ is required for route $r \in \mathrm{R}$
B_{pr}^{T} Total number of buses using battery $p \in P$ required for route $r \in \mathrm{R}$
B_{prs}^{Shift} Number of buses using battery $p \in P$ required for route $r \in R$ during shift $s \in S$
Y_q Number of infrastructures installed for charging strategy $q \in Q$
W_{rs} Available capacity (kW) for a bus with battery $p \in P$ used in route $r \in R$ at the end of shift $s \in S$

4.3 Objective Function

The key objective of the model is the minimization of total costs, including i) charging cost for different charging strategies (first term of Eq. (1)), ii) investment cost for different charging strategies (second term of Eq. (1)) and iii) investment cost for buses with different batteries (third term of Eq. (1)).

$$Min \sum_{p \in P} \sum_{r \in R} \sum_{\substack{s \in S \\ r:(r,s) \in U}} \sum_{q \in Q} \mathrm{C}_{qp} X_{prsq} + \sum_{q \in Q} I_q Y_q + \sum_{p \in P} \sum_{r \in R} I_P B_{pr}^{T} \quad (1)$$

4.4 Constraints

A key constraint of the model is given by Eq. (2). Equation (2) imposes that each bus should have 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_p^{Bus} for the first shift and W_{rs} for shifts other than the first) for a given bus is not enough to complete all the trips of the route, there is need to charge that bus using the available charging strategy.

$$NR_{rs} Cap_r^{Trip} \leq \begin{cases} \sum_{p \in P} \left[T_{pr} Cap_p^{Bat} + \sum_{q \in Q^S} X_{prsq} \mathrm{CC}_{qp} \right], \forall (r,s) \in U, s = 1 \\ W_{r(s-1)} + \sum_{q \in Q^{TD} \cup Q^S} \sum_{p \in P} X_{prsq} \mathrm{CC}_{qp}, \forall (r,s) \in U, s > 1 \end{cases} \quad (2)$$

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

$$W_{rs} = \begin{cases} \sum_{p \in P} \left[T_{pr} Cap_p^{Bat} + \sum_{q \in Q^S} X_{prsq} \mathrm{CC}_{qp} \right] - NR_{rs} Cap_r^{Trip} \forall (r,s) \in U, s = 1 \\ W_{r(s-1)} + \sum_{q \in Q^{TD} \cup Q^S} \sum_{p \in P} X_{prsq} \mathrm{CC}_{qp} - NR_{rs} Cap_r^{Trip} \forall (r,s) \in U, s > 1 \end{cases} \quad (3)$$

Equation (4) imposes that each bus cannot not goes below a minimum capacity.

$$W_{rs} \geq K \, \forall (r,s) \in U \quad (4)$$

The number of buses using each type of battery $p \in P$ for route $r \in R$ is determined based on Eqs. (5–6).

$$B_{pr}^{T} \geq B_{prs}^{Shift} \forall (r,s) \in U, p \in P \quad (5)$$

$$B_{prs}^{Shift} = NB_{rs} TP_{pr} \forall p \in P, (r,s) \in U \quad (6)$$

Equations (7–8) are related to the selection of batteries for each bus. Equation (7) defines that only one type of battery can be used for buses used in each route $r \in R$. Equation (8) defines that buses can only be operating using the selected type of battery.

$$\sum_{p \in P} T_{pr} = 1 \quad \forall r \in R \quad (7)$$

$$X_{prsq} \leq T_{pr} \forall p \in P, (r,s) \in U, q \in Q \quad (8)$$

Equation (9) ensures that charging only takes place for buses required to perform routes required in a given shift. L is used as a high auxiliary value to allow for a high number of charges during each shift, if needed. On the other hand, a maximum number of charges is imposed per bus and per day (if the charging takes place at the terminal; Eq. (10)) or per shift (if the charging takes place at the stops; Eq. (11)).

$$X_{prsq} \leq \begin{cases} L \, \forall p \in P, (r,s) \in U, q \in Q \\ 0 \, \forall p \in P, (r,s) U, q \in Q \end{cases} \quad (9)$$

$$\sum_{s \in S} \sum_{\substack{r \in R \\ r:(r,s) \in U}} X_{prsq} \leq M_q^T \, \forall p \in P, q \in Q^{TD} \quad (10)$$

$$\sum_{\substack{r \in R \\ r:(r,s) \in U}} X_{prsq} \leq \sum_{\substack{r \in R \\ r:(r,s) \in U}} M_{rsq}^S \forall p \in P, s \in S, q \in Q^S \quad (11)$$

Equation (12) imposes that at least one charging strategy should be available for each route $r \in R$, in order to ensure the charging of the buses serving those routes.

$$\sum_{q \in Q} \sum_{\substack{j \in J \\ j:(r,j) \in V \\ j:(q,j) \in H}} Z_{qjr} \geq 1 \quad \forall r \in R \tag{12}$$

Equations (13–15) establish the link between decision variables related to the charging strategies. Particularly, Eq. (13) defines that no bus can be charged using a charging strategy involving a technology that is not installed, and Eqs. (14–15) define the maximum number of infrastructures that should exist for each charging strategy $q \in Q$.

$$X_{prsq} \leq \sum_{\substack{j \in J \\ j:(r,j) \in V \\ j:(q,j) \in H}} Z_{qjr} \; \forall p \in P, (r,s) \in U, r \in R, q \in Q \tag{13}$$

$$Y_q = \sum_{\substack{j \in J \\ j:(q,j) \in H}} Z'_{qj} \; \forall q \in Q \tag{14}$$

$$Z'_{qj} \geq Z_{qjr} \; \forall (r,j) \in V, (q,j) \in H \tag{15}$$

Finally, Eqs. (16–23) define variable domains.

$$X_{prsq} \in \{0,1\} \; \forall p \in P, r \in R, s \in S, q \in Q \tag{16}$$

$$Z_{qjr} \in \{0,1\} \; \forall j \in J, r \in R, q \in Q \tag{17}$$

$$Z'_{qj} \in \{0,1\} \; \forall j \in J, q \in Q \tag{18}$$

$$T_{pr} \in \{0,1\} \; \forall p \in P, r \in R \tag{19}$$

$$B^{T}_{pr} \in [0; +\infty[\; \forall p \in P, r \in R \tag{20}$$

$$B^{Shift}_{prs} \in [0; +\infty[\; \forall p \in P, r \in R, s \in S \tag{21}$$

$$Y_q \in [0; +\infty[\quad \forall q \in Q \tag{22}$$

$$W_{rs} \geq 0 \; \forall r \in R, s \in S \tag{23}$$

5 Case Study

We herein present the results obtained through the illustrative application of the *MILP4ElectFleet* model to the case of Carris. For this application, the model was implemented in the General Algebraic Modeling System (GAMS) 23.7 and was solved with CPLEX 12.0 on a Two Intel Xeon X5680, 3.33 Gigahertz computer with 12 Gigabyte RAM.

5.1 Dataset and Assumptions Used for the *MILP4ElectFleet* Model Application

The model is applied to support decisions related to the investments in electric buses by Carris, so as to ensure the electrification of the routes in the central area of Lisbon. This area comprises a total of 17 routes $\{r_1, \ldots, r_{17}\}$, and these routes share the same terminal (*Pontinha*) and are organized in four different shifts – starting at 9am, 1pm, 6pm and 11pm. Several assumptions are used for this application:

i. Two types of lithium ion batteries are considered as possible investments by Carris: smaller 150 kW batteries [$p = 1$; $Cap^{Bat}_{p=1} = 150$] and larger 300 kW batteries $[p = 2; Cap^{Bat}_{p=2} = 300]$;
ii. Three charging strategies are considered as possible by Carris:
   a. Slow charging during the night at the *Pontinha* terminal [$q = 1$] - charging during a 6-h period with a charging capacity of 300 kW, corresponding to a full load of the buses [$CC_{(q=1)(p=1)} = 150$; $CC_{(q=1)(p=2)} = 300$];
   b. Slow charging during the day at the *Pontinha* terminal [$q = 2$], between shifts – charging during a 4-h period with a charging capacity of 200 kW $\left[CC_{(q=2)(p=1)} = 150; CC_{(q=2)(p=2)} = 200\right]$;
   c. Fast charging during the day at selected stops, i.e., final stops for all the routes [$q = 3$] - charging during a 5 min period with a charging capacity of $75\,\mathrm{kW}\left[CC_{(q=3)(p=1)} = CC_{(q=3)(p=2)} = 75\right]$.
iii. All the buses are fully charged during the night, and only one charging can take place at the *Pontinha* terminal during the night and also during the day (if needed) $\left[M^T_{q=1} = M^T_{q=2} = 1\right]$;
iv. Fast charging can take place after completing each trip of each route (if needed), i.e., fast charging can take place as many times as the number of trips of each route of a given shift:

$$M^S_{rs(q=3)} = NR_{rs} \forall (r, s) \in U \tag{24}$$

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

vi. Fast charging systems can be installed at the final stops of all the 17 routes, with an investment of 350 000€ per system ($I_{q=3}$ = 350 000) (Kunith et al. 2017). These 17 routes share 12 final stops (J^S).

In addition to these assumptions, the model application also required the use of the data shown in Table 2.

Table 2. Dataset in use.

Parameters	Values
N_s^{shift}	$\{4; 5; 5; 3\}$ h
N_r^{route}	$\{44; 44; 46; 38; 29; 50; 54; 44; 1; 41; 48; 42; 69; 38; 23; 41; 24\}$ min
NR_{rs}	Between 2 and 11 trips per bus, depending on the route and shift[a]
Cap_r^{Trip}	Between 18 and 45 kW, depending on the route[a]
C_{qp}	22,5€ (q = 1, p = 1), 45€ (q = 1, p = 2), 22,5€ (q = 2, p = 1), 30€ (q = 2, p = 2) and 11,25€ (q = 3, p = 1 and p = 2) – total cost per charge considering 0,15 €/kW (EDP, 2020)
I_p	350 000€ (p = 1) and 500 000 € (p = 2) (Rogge et al. 2018)
θ_q	$\{1; 1; 12\}$
K	50 kW

[a]More details about this data are available upon request to the authors.

5.2 Results

Planning Results: Number of Buses and Types of Batteries

Table 3 shows the results obtained for the number of buses required to ensure the electrification of the 17 routes in the central area of Lisbon, as well as for the type of batteries that should be used for those routes. Accordingly, if Carris aims at electrifying all the central area of Lisbon, a total of 141 buses are required – 97 with lower capacity batteries and 44 with higher capacity batteries -, which corresponds to an investment of 55 950 000€ (third component of cost in Eq. (1)).

Table 3. Number of buses and types of batteries in use for the 17 routes in the metropolitan area of Lisbon.

Routes	Number of buses		
	150 kW batteries	300 kW batteries	Total
r_1	–	9	9
r_2	7	–	7
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}	16	–	16
r_{14}	5	–	5
r_{15}	–	4	4
r_{16}	–	9	9
r_{17}	5	–	5
Total number of buses	97	44	141

Planning Results: Investment in Charging Strategies

Since Carris already have a slow charging system at the *Pontinha* terminal, no investment in this type of technology is needed. On the other hand, a significant investment is required in fast charging systems – 11 out of the 12 final stops should have a fast charging system, with a total investment of 3 850 000€ (second component of cost in Eq. (1)). Routes r_3 and r_4 share the only stop (*Alameda*) in which it is not necessary to have a charging system – this happens because buses used in these routes can be charged at the *Pontinha* terminal with enough capacity to complete all the trips of the routes of each shift.

Planning Results: Frequency of Charging

Table 4 shows the results obtained for the frequency of charging, both fast and slow charging, per route. This frequency should be read as the number of charges required for the set of buses needed per route – for instance, if 9 buses are needed in a given route, and if each bus needs two charges, the frequency shown in the table is 18.

As previously mentioned, all the buses start the first shift with full charge, meaning that all the buses use the slow charging system at the *Pontinha* terminal during the night (Table 4, second column). On the other hand, since no fast charging is needed for routes r3 and r4, all the buses used in these routes need to charge once at the *Pontinha* terminal during the day (Table 4, third column). Also, part of the buses used in the first and second shift are not required for the second and third shift, respectively. For that reason these buses leave to the *Pontinha* terminal and use the slow charging system before being in use again during the third and fourth shift, respectively (Table 4, third column).

Considering the frequency of charging shown in Table 4, and also considering the costs presented in Table 2, a total daily cost of around 11 700€ (first component of cost in Eq. (1)) should be supported by Carris with such charging.

Table 4. Frequency of charging per route.

Routes	Slow charging		Fast charging			
	Night	Day	Shift 9am	Shift 1pm	Shift 6pm	Shift 11pm
r1	9	3	–	12	12	–
r_2	7	3	7	10	12	1
r_3	8	10	–	–	–	–
r_4	7	13	–	–	–	–
r_5	8	7	–	12	15	1
r_6	10	2	10	16	22	–
r_7	10	3	10	21	27	2
r_8	7	–	–	10	10	–
r_9	6	3	6	8	17	–
r_{10}	7	–	–	10	10	–
r_{11}	17	2	17	22	26	3
r_{12}	6	2	6	10	16	–
r_{13}	16	1	16	24	32	–
r_{14}	5	2	5	12	14	–
r_{15}	4	–	–	9	6	–
r_{16}	9	6	–	15	18	–
r_{17}	5	4	5	6	15	–
Total	141	61	82	197	252	7

Computational Results

The application of the model to the case of Carris resulted in a model with 1 701 equations and 756 variables (out of which 540 are binary variables). The solution detailed above was obtained in 0.12 s with an optimality gap of 0%.

6 Conclusions

This study arises within the current context of an increasing awareness about climate change, where there is clearly the need to adopt strategies to reduce CO_2 emissions, with the transport sector arising as a key sector to be explored. Accordingly, being focused on a more sustainable provision of services in the public transportation sector, this study proposes a planning model to support the decision-making process related to the integration of electric buses in a public bus transport system.

Literature in the area shows a wide variety of studies proposing methods to support the full electrification of a bus fleet. Nevertheless, according to the authors knowledge, no study has jointly considered all the planning decisions that are considered as essential for an adequate planning, such as decision related to the number of vehicles, selection of battery types, location of charging stations, frequency of charging and selection of charging technologies and strategies.

This study fills this gap in the literature by proposing an optimization model, the *MILP4ElectFleet* model, aiming at providing guidance on: i) the number of buses required to ensure the full electrification of a bus fleet; ii) the types of batteries that should be used in those vehicles; iii) the charging technologies and strategies that should be made available; iv) the location of the charging stations; and v) the frequency of charging. And all these decisions should be made while ensuring the minimization of investment and operating costs.

Carris, a Portuguese public transport operator focusing its activity in the metropolitan area of Lisbon, is used as case study to illustrate the usefulness of the proposed model. In particular, the model is used to support the decisions related to the full electrification of the routes in the central area of Lisbon (a total of 17 routes).

Results show that 141 electric buses are required to ensure the routes in the central area of Lisbon, out of which 70% should have lower-capacity lithium ion batteries. It is also possible to conclude that a high investment in fast charging systems is required – 15 out of the 17 routes will need to ensure the charging of buses using fast charging stations, either due to the low capacity of the batteries in use, or due to the extension of the routes. Consequently, ensuring the operation of the 17 routes will imply a combination of slow charging (either overnight and during the day) and fast charging, with a daily charging cost of around 11 700€.

Several lines of further research should be pursued. First, the proposed model should be extended for a mix-fleet planning model aiming to plan a fleet including not only electric buses, but also gas and diesel buses. Such a model would be essential for planning the transition to an electric fleet for cases in which a full electrification is not possible or even desired. Secondly, the proposed model should also be extended for a multi-period model, thus allowing for a long-term planning of the electrification of the bus fleet. This long-term planning would allow exploring the impact of fast and slow charging on battery life span, as well as to quantify the costs of such an electrification in the long-term. Thirdly, other planning objectives should be included in the analysis. Particularly, the minimization of CO_2 emissions should also be included thus allowing to explore the trade-off between cost and emissions. Also, extending the application of the model to include for a higher variety of battery types and charging technologies and strategies would be more informative, as well as to account for the impact of the number of people per bus on the effective energy consumption of the bus. Finally, it will be relevant to apply the adjusted model to the entire fleet of Carris, and also to compare the results obtained for the Portuguese context with the current reality in other European countries.

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