PLATON -

Planning Process and Tool for Step-by-Step Conversion of the Conventional or Mixed Bus Fleet to a 100% Electric Bus Fleet

Deliverable 4.3: Efficient Charging Infrastructure
Part of Milestone M3
Main work package: 4 Efficient Models and Methods
Work package: 4.7 Charging Infrastructure Optimization Component

Due Date: December 31, 2019

Report term: July 1, 2018 – December 31, 2019

Funding code: EME/03/PLATON/2018

Project term: January 1, 2018 – June 30, 2020

Editor: Mikhail Y. Kovalyov (UIIP-NASB)
Contributors: Nikolai Guschinsky (UIIP-NASB)
Mikhail Y. Kovalyov (UIIP-NASB)
Boris Rozin (UIIP-NASB)
Olaf Czogalla (ifak)

Grant beneficiary of WP leader:
The United Institute of Informatics Problems of the National Academy of Sciences of Belarus (UIIP-NASB)

Funding organization of WP leader:
National Academy of Sciences of Belarus (NASB),
Independence Ave. 66, 220072, Republic of Belarus, Minsk

Abstract

Three optimization problems are formulated and analysed for a given set of public transport routes intended for the introduction of electric buses. In the first problem, denoted as Opt, fast-charging technology is assumed. This problem is to determine a fleet of electric buses, places for charging stations and transformers, assignment of charging stations to the selected places, assignment of charging stations to the transformers and assignment of charging stations to the routes such that all the electric buses can feasibly drive, the required traffic (inter-bus) interval is maintained, and the output power of any transformer is not exceeded. The objective is to maximize the total value, provided that the total capital cost and the total operating, depreciation and energy cost do not exceed their upper bounds. The total passenger capacity of the replaced conventional vehicles can be considered as the value to be maximized.

In the second problem, denoted as DepOpt, a slow-charging technology is assumed. This problem is to determine the required electric power supplied to the depot by the city power grid, the type and the number of charging stations of this type in the depot, types of e-bus batteries and charging times of each e-bus while it is in the depot such that the total daily cost of the equipment and the consumed energy is minimized, provided that the arrival and departure times of e-buses to/from the depot, the dynamic upper bound on the supplied power and functions of charge and discharge of the batteries are addressed.

The third problem, denoted as OptSched, is to determine a balanced route timetable such that the same average traffic interval of all public vehicles of the same route is maintained and departures of public vehicles of the same passenger capacity assigned to the same route are distributed as smoothly as possible over departures of all public vehicles in the most representative time period. Mathematical models for all problems are described.

Contents

1 Introduction

This Deliverable describes results of the project PLATON on the determination of the efficient charging infrastructure for electric buses, which is an important element of the transition from the conventional public buses to fully electric buses. We call an electric bus as an *e-bus* and a fleet of e-buses as an *e-fleet*. An e-bus is equipped with an electric storage device (battery) which requires re-charging to be operational. We consider only charging technology according to which e-buses charge their batteries at static charging stations. Battery swapping technology is not considered as well as on-the-move charging.

An e-fleet is characterized by the e-bus *types* and quantities of e-buses of each type. An e-bus type is characterized by the following unique parameters: a set of types of appropriate charging stations, charging time to the recommended *State of Charge (SOC)* level when departing from a charging station of the same type at the same location (depot or e-bus stop), *feasible drive indicators* between any two given stops of the same route, energy consumption for the same route over the year, capital, operating, depreciation and energy costs over the year, and passenger capacity. Feasible drive indicator specifies whether a fully charged e-bus can drive between two given stops of a given route without re-charging or not. These indicators can be calculated based on the single-charge range (distance) provided by the e-bus manufacturer. Note that e-buses of different types can be equipped with batteries of the same type or different types and they can be charged at stations of the same or different types.

A *route* is characterized by the depot and the *route cycle*, which is a sequence of stops visited cyclically by e-buses assigned to this route. A *decisive* time period is the time period such that the traffic (inter-bus) intervals are not changed within this period, and the decisions made for this period with respect to the e-bus fleet and the charging infrastructure ensure their feasible operation in any other time period. With a certain degree of uncertainty, decisive time period can be characterized by the highest *SOC loss* of e-buses when driving over the same route segments, the highest passenger transfer demand and the smallest traffic intervals.

In this Deliverable, three optimization problems are formulated and analyzed. One of these problems, denoted as OPT, is to determine an e-fleet, places for charging stations and transformers, an assignment of charging stations to the selected places, an assignment of charging stations to the transformers and an assignment of charging stations to the routes such that all the e-buses can feasibly drive, the required traffic interval is maintained, and the *output power* of any transformer is not exceeded. A fast-charging technology is assumed. The objective is to maximize total *value* (positive ecological and social effect expressed quantitatively), provided that the total *capital cost* and the total *operating, depreciation and energy cost* do not exceed their upper bounds. It is assumed that OPT will be solved repeatedly for several successive planning periods (years). Decisions made in the past periods are used as a part of the input for the future period.

Results on the problem OPT are described in Section 2. In the problem OPT, it is assumed that any e-bus charges at least once at a non-depot charging station in each route cycle. This assumption is valid for e-buses with fast-charging batteries. A generalization to the case of slow-charging batteries, where some e-buses can charge only one or two times during the day, or where some e-buses can complete several cycles with one charge is also considered.

The second problem, denoted as DEPOPT, considers a given fleet of e-buses with slow-charging batteries and fixed timetables, which charge at the same depot. The problem is to determine cost-effective dynamic quantities of the electric power supplied to the depot by the city power grid, the type and the number of identical charging stations of this type in the depot, as well as the types of the batteries to feasibly charge e-buses such that arrival and departure times of the e-buses to/from the depot and functions of charge and discharge of the batteries are properly addressed. Results on the problem DEPOPT are described in Section 3.

The third problem, denoted as OPTSCHED, is to determine a *balanced* (with respect to the passenger transfer demand) route timetable such that the same average traffic interval of all public vehicles of the same route is maintained and departures of public vehicles of the same passenger capacity assigned to the same route are distributed as smoothly as possible over departures of all public vehicles in the decisive time period. Results on the problem OPTSCHED are described in Section 4. Section 5 contains concluding remarks.

2 Problem Opt

Problem Opt is difficult from the modeling and computational perspectives. In order to make it observable and solvable in a reasonable time, a number of assumptions are imposed. They are given in Section 2.2. Input data, data derived from the input data, output data and data derived from the output data for the problem Opt are described in Sections 2.3, 2.4, 2.5 and 2.6, respectively. Formal definition of the problem Opt is given in Section 2.7. An adaptation of the suggested model for the case of e-buses with high-capacity batteries which can operate with one or two charges during the day, or which can make up to k cycles on any route without recharging, is described in Section 2.8. The next section contains a bibliography of publications on the operation of electric vehicles.

2.1 Bibliography

We classify bibliography on the topics related to the operation of electric vehicles (EVs) into several categories. They are given below followed by the relevant citations. If a publication falls into several categories, we classify it into the most relevant to our opinion category.

History, statistics and perspectives of employment of EVs and corresponding infrastructure: ZeEUS eBus Report [87], Stevic [70], Li [44], Ahmad et al. [3], Anderson et al. [2], Mathieu [48, 49], Nicholas and Hall [57], Todorovic and Simic [75], Mega-E project (https://www.electrive.com/tag/mega-e/), Zap-Map database (https://www.zap-map.com/statistics/).

Analysis of EV testing and real-life operation: Barnitt [5], Wang and González [77], Erkkilä et al. [14], Smidt et al. [67], ZeEUS Demonstrations [88], Foltiński [19], Rogge et al. [65], Hanlin [28], Olsson et al. [58], Eudy and Jeffers [15], Gao et al. [23], Leou and Hung [43], Christensen et al. [10], Neaimeh et al. [56], Khan et al. [38], Xylia and Silveira [85], Gallet et al. [22], Morganti and Browne [55].

Comparison of EVs and vehicles with other power source: Feng and Figliozzi [16, 17], Hallmark et al. [27], Lajunen [42], Mohamed et al. [51].

Simulation of EV operations: project CACTUS (http://www.cactus-emobility.eu/), Schoch [68], Teoh et al. [73, 74], Mohamed et al. [52], Marmaras et al. [47], Xylia et al. [84], Fiori et al. [18].

Optimization of EV operations and required infrastructure: Alonso et al. [4], Wen et al. [80], Yu et al. [86], Juan et al. [36], Hiermann et al. [31], Quak et al. [64], Desaulniers et al. [12], Wielinski et al. [82], Kunith et al. [41], Bruglieri et al. [7], Pelletier et al. [60, 61, 62, 63], Froger et al. [20, 21], Xylia et al. [83], Montoya et al. [54], Liu and et al. [45], Liu and Wei [46], Hosseini and Sarder [33], Wang et al. [78], Wang et al. [79].

Analysis of the relevant literature shows that the variety of real-life situations of electric public transport employment exceeds the number of the existing appropriate mathematical models, and each real-life case requires specific consideration and specific mathematical model.

2.2 Assumptions

The following assumptions are imposed in the problem OPT.

1a) For each route, the depot, the bus stops and the order of their visiting by e-buses are given.

2a) Fleet of conventional vehicles can be replaced partly.

3a) Each route is associated with a single depot. If a route is served by at least one e-bus, then at least one appropriate charging station must be opened at the depot of this route.

4a) Routes can intersect at depots, terminal stops and en route stops.

5a) Any e-bus assigned to a route is charged to the recommended SOC level each time when it visits location with a charging station of the type assigned to this type of e-bus and this route. If this assignment is not made for an appropriate quadruple (e-bus type, route, charging station location, charging station type), then, from the modeling point of view, an e-bus visits the charging station location without charging. A situation when this assumption is not valid, i.e., when an e-bus can pass a charging station assigned to it without charging is discussed in Section 2.8.

6a) At a charging station location, the same charging station type can be assigned to different e-bus types, in which case e-buses of these types share charging stations of this type at this location.

7a) If e-buses of the same type and the same route are decided to be charged at a location with appropriate charging stations, then they are assigned to the charging stations of the same type.

8a) The *First Come, First Served* rule is applied for e-buses competing for charging at an en-route stop.

9a) Each charging station at the same location is connected to the same m transformers, $m \in \{1, 2\}$. If $m = 2$, then, at any time, only one arbitrary transformer link is active for each charging station.

10a) Some e-buses, transformers, charging stations and links of their locations with transformers can already be in operation. We call them "old" and we call "new" e-buses and infrastructure elements to be decided.

11a) Duration of a single run of any e-bus between two charges does not exceed the duration of the decisive time period.

2.3 Input data

There are the following input data.

- Upper bound ucc on the total capital cost.
- Upper bound uoc on the total operating, depreciation and energy cost.
- Duration dtp of the decisive time period.
- *Electric network* $E = (NE, EE)$, which is a *weighted bipartite graph* with a set of *nodes* (locations for charging stations and transformers) NE and a set of edges (transformer links) EE.
- *Transportation network* $G = (NN, R)$, which is a *weighted digraph* with a set of *nodes* (bus stops) NN and a set of *directed circuits* (routes) R , see Fig. 1 for an illustration. There, T_i, $i = 1, 2, 3, 4, 5$, denote terminal stops, Route-1 is (Depot-1,T_1,1,2,T_2,T_1,Depot-1), Route-2 is (Depot-2,T_3,1,2,T_4,T_3,Depot-2) and Route-3 is (Depot-3,T_5,3,T_2,2,T_5,Depot-3).

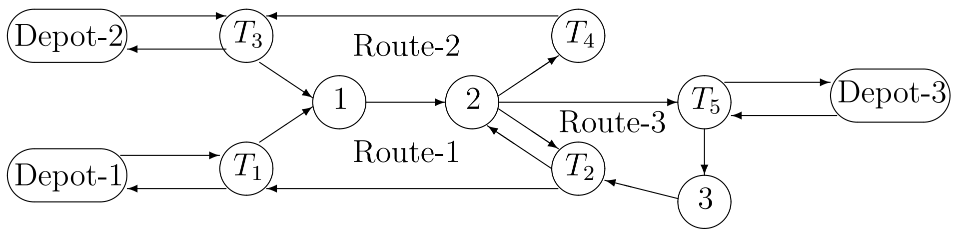

Figure 1: Network of three routes.

- Set NE is partitioned into the set T of *transformer* nodes corresponding to eligible transformer locations and the set NS of *parent* non-transformer nodes corresponding to eligible charging station locations.

- Set NS contains a subset NO of nodes at each of which at least one old charging station of any type is opened.

- Set NN is partitioned into the subsets ND of *depot nodes*, NT of *terminal stops* and NR of *regular (en route) stops*, respectively.

- Each node $j \in NN$ is associated with a *parent* node $p(j) \in NS$. Several nodes from NN may correspond to the same node from NS.

- Set of routes R is built over the nodes of the set NN. The same node (bus stop) can belong to different routes.

- Arc $(i, j) \in r$, $r \in R$, represents a directed segment of a route, going from node i to node j.

- Edge $(q, p) \in EE$ represents an *eligible link* of transformer node q and non-transformer node p.

- Set VC of *conventional vehicles types*. Conventional vehicle type $b \in CV$ is associated with *passenger capacity* cap_b of a conventional vehicle of type b.

- Set C of *charging station types.*

  Type $c \in C$ is associated with the following input parameters.

- Nominal power po_c of one charging station.

- Capital cost cc_c^{cap}, which is the cost of purchase and installation of one charging station without the transformer connection costs.

- Operating and depreciation cost cc_c^{ope}, which is the cost of operating one charging station in a year plus the depreciation cost. It includes the maintenance cost and it does not include the energy cost.

- Set B of *e-bus types.*

  E-bus type $b \in B$ is associated with the following input parameters.

- Set C_b of *appropriate charging station types.* An e-bus of type b can only be charged at a station of type $c \in C_b$.

- Set NM_b of nodes j from NN. If node j belongs to a route to be served by an e-bus of type b then at least one charging station of type $c \in C_b$ must be opened at node $p(j)$.

- *Passenger capacity* cap_b of one e-bus.

- Capital cost cv_b^{cap} of one e-bus.

  Each non-transformer node $p \in NS$ is associated with the following input parameters.

- Set C_p of appropriate charging station types.

- Number m of *links* of any node $p \in NS \backslash NO$, at which a new charging station will be opened, with the transformer nodes.

- Number nc_{pc} of old charging stations of each type c, which have already been opened at $p \in NO$, $c \in C_p$.

- Upper bound uc_{pc} on the number of charging stations of type c to be opened at $p \in NS$, $c \in C_p$. This parameter can be skipped or set to infinity if there is no need in this upper bound.

- (Tight) upper bound ct_{pbc} on the charging time of one e-bus of type $b \in B_c$ at a charging station of type $c \in C_p$ installed at $p \in NS$ to the recommended SOC level or an estimation of this time. If p is associated with a regular stop, then ct_{pbc} accounts for the time required for passenger loading/unloading. If p is associated with a terminal stop or a depot, then ct_{pbc} accounts for the required setup time.

- Duration t_j^{depot} of a time interval of maximum length, in which all e-buses assigned to the depot at node $j \in ND$ are in this depot. In most cases, it is a night time interval.

Each transformer node $q \in T$ is associated with

- transformer electrical *output power* o_q to supply all charging stations in the decisive time period,

- transformer electrical power oo_q that is used to supply old charging stations in the decisive time period, and

- transformer capital (building) cost cb_q.

Each edge $(q, p) \in EE$ is associated with

- cost cl_{qp} of linking transformer node q and non-transformer node p.

Route $r \in R$ is characterized by the following input parameters.

- Set B_r of e-bus types eligible for serving route r.

- Set VC_r of conventional vehicles types serving route r.

- Upper bound ut_r on the average length of the traffic interval of all e-buses and conventional buses of any type on route r in the decisive time period.

- Sequence $\pi_r = (j_0, j_1, \ldots, j_r)$ of stops, where j_0 is the depot stop $j_l = j_r$ is a terminal stop and among $j_2, \ldots, j_{r-1}$ there are all regular stops and terminal stops of this route if they exist. Nodes $j_1, \ldots, j_{r-1}$ are visited cyclically in this order. We write $j \in \pi_r$ and $(i, j) \in \pi_r$ to indicate that node j and arc (i, j) belong to the sequence π_r.

- *Eligible drive indicator* $ei_{r(i,j)b}$: $ei_{r(i,j)b} = 1$ if an e-bus of type b can feasibly drive from stop i to stop j of the sequence π_r, provided that a charging station of type $c \in C_b$ is installed at $p(i) \in NS$, else $ei_{r(i,j)b} = 0$, $i \in \pi_r$, $c \in C_i$, $j \in \pi_r$, $b \in B_r$. For a specific e-bus type, eligible drive indicator is calculated based on the recommended SOC level, minimum SOC level and driving conditions over the route segment (i, j). Route segments can be of the following types: 1) (j_i, j_h), $0 \leq i < h \leq r$, 2) (j_i, j_0), $1 \leq i \leq r$, if $i = 1$, then it includes stop j_1 twice, 3) (j_i, j_h), $2 \leq h < i \leq r$, which includes stop j_1 and does not include stop j_0, and 4) (j_i, j_i), $1 \leq i \leq r$, which includes stop j_i twice and does not include stop j_0.

  Remark. *If the detailed information required to calculate eligible drive indicators is not available, then the simplified approach can be used, according to which these indicators are calculated based on the single-charge range (distance) provided by the e-bus manufacturer, and the distance between the two nodes of a given route.*

- Number nbo_{rb} of old e-buses of type b on route r.

- Number nvc_{rb} of conventional vehicles of type b on route r to be (partly) replaced by e-buses.

- Duration d_{rb} of any single cycle of any e-bus of type b in the decisive time period, without the charging time. It does not exceed the duration of the decisive time period.

- Duration do_{rb} of any single cycle of any old e-bus of type b in the decisive time period, including the charging time.

- Duration dc_{rb} of any single cycle of any conventional vehicle in the decisive time period.

- Set CO_{rb} of charging station types installed at all nodes $p(j)$, $j \in \pi_r$, for charging old e-buses of type b on route r.

- Operating, depreciation and energy cost (or its estimation) cv^{ope}_{rb} of all runs of one e-bus of type b over route r in a year, $b \in B_r$.

- Route *preference coefficient (weight)* w_r, $w_r > 0$.

- Function $co_r(Z)$ whose value approximates the total harmful emission of conventional buses of the total passenger capacity Z operating on route r.

- Function $fu_r(Z)$ whose value approximates the total fuel consumption of conventional buses of the total passenger capacity Z operating on route r.

Remark. *Let Z_r denote the total passenger capacity of new e-buses assigned to route r. We assume that the value of a (partial) conversion of route r into the electric mode is a function $v_r(Z_r)$ of Z_r. We suggest three approaches to its calculation: 1) $v_r(Z_r) = w_r Z_r$, 2) $v_r(Z_r) = w_r co_r(Z_r)$, and 3) $v_r(Z_r) = w_r fu_r(Z_r)$. In particular, $v_r(Z_r) = Z_r$ can be used.*

2.4 Derived input data

The following data are derived from the input data.

- Set $NS_c \subseteq N$ of nodes eligible for opening a charging station of type c, $NS_c = \{p \in NS \mid c \in C_p\}$.

- Set $B_c \subseteq B$ of e-bus types eligible for charging at a station of type c, $B_c = \cup_{b \in B} C_b$.

- Set $TO \subseteq T$ of transformer nodes at each of which at least one old transformer exists, $TO = \{q \in T | oo_q > 0\}$.

- Set R_b of *eligible routes* for e-buses of type b, $R_b \subseteq R$, $R_b = \{r \in R | r \in B_r\}$.

- Set R_j of routes meeting at j, $R_j = \{r \in R | j \in \pi_r\}$.

- Set $TE_p \subseteq T$ of transformer nodes eligible for linking with the non-transformer parent node p, $TE_p = \{q \in T | (p, q) \in EE\} \subseteq T$.

- Set BO_r of old e-bus types serving route r, $BO_r = \{b \in B_r | nvo_{rb} > 0\}$.

- Total passenger capacity $pas_r = \sum_{b \in VC_r} nvc_{rb} cap_b$ of conventional vehicles on route r in the decisive time period.

2.5 Output data

A solution X of the problem OPT can be represented by the following variables.

- $R(X)$ - set of routes, each of which is served by at least one new e-bus.
- $B_r(X)$ - set of e-bus types $b \in B_r$ such that at least one new e-bus of this type is assigned to route $r \in R(X)$. Note that $B_r(X)$ can include e-bus types of old e-buses.
- Number $NC_{pc}(X)$ of new charging stations of type $c \in C$ at non-transformer parent node $p \in NS$ to serve new and old e-buses.
- Set $L_p(X)$ of transformer nodes $q \in TE_p$ to be linked with the non-transformer parent node p, $p \in NS \backslash NO$.
- $c_{jrb}(X)$ - unique new or old charging station type to charge old or new e-buses of type b assigned to route r at node $p(j)$. $c_{jrb}(X) = False$ if no charging station type is assigned to old or new e-buses of type b on route r at node $p(j)$.
- $NV_{rb}(X)$ - number of new e-buses of type b assigned to route r in the decisive time period.

2.6 Derived output data

The following data are derived from the output data.

- Set $R_{jcb}(X)$ of routes served by at least one old or new e-bus and such that their old and new e-buses of type b are charged at stations of type c at node $p(j)$, $RO_{jcb} \subseteq R_{jcb}(X) \subseteq R_j$, $R_{jcb}(X) \subseteq R_b$, $j \in NN$, $p(j) \in NS_c$, $b \in B_c$, $c \in C$.
- Set $S_c(X)$ of parent nodes $p \in NS$ at each of which an least one new charging station of type c is opened, $S_c(X) = \{p \in NS_c \mid NC_{pc} > 0\}$.
- $S(X) = \cup_{c \in C(X)} S_c(X)$ - set of parent nodes at each of which an least one new charging station of any type is opened.
- $B_{jc}(X) = \{b \mid c_{jrb}(X) \neq False, b \in B, r \in R_b\}$ - set of e-bus types of all routes meeting at j to be served by new or old charging station of type c at the associated parent node $p(j)$, $j \in NN$, $p(j) \in S(X)$, $c \in C(X)$.

- $NN_p(X) = \{j \in NN \mid c_{jrb}(X) \neq False, p(j) = p, b \in B(X), r \in R(X)\}$.

- $B^{pc}(X) = \cup_{j \in NN_p(X)} B_{jc}(X)$.

- $B(X) = \cup_{r \in R} B_r(X)$ - set of e-bus types such that at least one new e-bus of this type is assigned to some route.

- $R_b(X)$ - set of routes $r \in R_b$ to each of which at least one new e-bus of type b is assigned, $b \in B$, $R_b(X) = R_b \bigcap R(x)$.

- $C(X) = \{c \in C | S_c(X) \neq \varnothing\}$ - set of charging station types such that at least one new charging station of this type is opened.

- $R_j(X)$ - set of routes meeting at j, with at least one old or new e-bus assigned to each route, $j \in NN$, $p(j) \in S(X)$.

- $R^p(X) = \cup_{j \in NN_p(X)} R_j(X)$, $p \in S(X)$.

- $SR_{rb}(X)$ - sequence of nodes j of route $r \in R_b(X)$ at each associated parent node $p(j)$ of which at least one new or old charging station is opened to serve e-buses of type $b \in B(X)$ assigned to this route, $SR_{rb}(X) = (j_0^{rb}, j_1^{rb}, \cdots, j_{n_{rb}}^{rb})$, $j_k^{rb} \in \pi_r, k = 1, \ldots, n_{rb}, j_0^{rb} = j_0, n_{rb} \leq r - 1$.

- $SR(X) = \bigcup_{r \in R(x), b \in B_r(X)} SR_{rb}(X)$.

- $Z_r(X) = \sum_{b \in B_r(X)} cap_b NV_{rb}(X)$ - total passenger load of e-buses of route r in the decisive time period.

  Denote $\lceil\lceil x \rceil\rceil = \lceil x \rceil$ if $x - \lfloor x \rfloor > 0.1$, else $\lceil\lceil x \rceil\rceil = \lfloor x \rfloor$.

- $nvc_{rb}(X)$ - number of conventional vehicles of type b left on route r, $nvc_{rb}(X) = \left\lceil\left\lceil \frac{\max\{0, pas_r - Z_r(X)\} nvc_{rb}}{pas_r} \right\rceil\right\rceil$, $b = 1, \ldots, b^* - 1$, $nvc_{rb^*}(X) = \left\lceil\left\lceil \frac{\max\{0, pas_r - Z_r(X)\} - \sum_{b=1}^{b^*-1} nvc_{rb}(X) cap_b}{cap_{b^*}} \right\rceil\right\rceil$, $nvc_{rb} = 0$, $b = b^* + 1, \ldots, |VC_r|$, where $cap_1 \leq \cdots \leq cap_{|VC_r|}$, $VC_r = \{1, \ldots, |VC_r|\}$, $\sum_{b=1}^{b^*-1} nvc_{rb}(X) cap_b < \max\{0, pas_r - Z_r(X)\}$ and $\sum_{b=1}^{b^*} nvc_{rb}(X) cap_b \geq \max\{0, pas_r - Z_r(X)\}$.

- $NV_r(X) = \sum_{b\in B_r(X)} NV_{rb}(X)$ - number of new e-buses of all types assigned to route r in the decisive time period.

- $VC_r(X)$ - set of types $b \in VC_r$ of conventional vehicles such that $nvc_{rb}(X) > 0$.

- $AT_r(X) = \frac{dtp}{total\ number\ of\ vehicles\ on\ route\ r\ in\ decisive\ time\ period}$ - average length of the traffic interval of all e-buses and conventional vehicles left on route r in the decisive time period,

$$AT_r(X) = dtp \Big/ \Big(\sum_{b\in B_r(X)} \frac{dtp}{d_{rb} + \sum_{j\in SR_{rb}(X)\setminus ND} ct_{p(j)bc^*}} NV_{rb}(X) +$$

$$\sum_{b\in BO_r} \frac{dtp}{do_{rb}} nbo_{rb} + \sum_{b\in VC_r(X)} \frac{dtp}{dc_{rb}} nvc_{rb}(X) \Big) =$$

$$1 \Big/ \Big(\sum_{b\in B_r(X)} \frac{NV_{rb}(X)}{d_{rb} + \sum_{j\in SR_{rb}(X)\setminus ND} ct_{jbc^*}} + \sum_{b\in BO_r} \frac{nbo_{rb}}{do_{rb}} + \sum_{b\in VC_r(X)} \frac{nvc_{rb}(X)}{dc_{rb}} \Big),$$

where $c^* = c_{jrb}(X)$.

- $ATE_r(X) = \frac{dtp}{total\ number\ of\ e-buses\ on\ route\ r\ in\ decisive\ time\ period}$ - average length of the traffic interval of all e-buses on route r in the decisive time period.

$$ATE_r(X) = 1 \Big/ \Big(\sum_{b\in B_r(X)} \frac{NV_{rb}(X)}{d_{rb} + \sum_{j\in SR_{rb}(X)\setminus ND} ct_{p(j)bc^*}} + \sum_{b\in BO_r} \frac{nbo_{rb}}{do_{rb}} \Big),$$

where $c^* = c_{jrb}(X)$.

- $BN_{pc}(X) = \left\lceil \left\lceil \sum_{r\in R^p(X)} \sum_{b\in B^{pc}(X)} \frac{ct_{pbc}}{ATE_r(X)} \right\rceil \right\rceil$ - estimation of the total number of old and new e-buses of all types arriving to the charging stations of type c at the non-depot stop j during their charging time interval, and hence, requiring the same number of charging stations of type c working in parallel, at the parent node $p = p(j)$, $j \in NE$, $p \in (S(X) \cup NO)$.

- $BN_{pc}(X) = \left\lceil \left\lceil \sum_{r\in R^p(X)} \sum_{b\in B^{pc}(X)} \frac{(nv_{rb}+NV_{rb}(X))ct_{pbc}}{t_p} \right\rceil \right\rceil$ - lower bound on the required number of charging stations of type c at the parent node p for charging old and new e-buses of all types arriving to the depot node j, $j \in ND$, $p = p(j)$, $t_p = t_j^{depot}$, $p \in (S(X) \cup NO)$. If this number is insufficient in a real-life case, then an extra charging station can be installed.

- $M_q(X) = \{p \in S(X) \mid q \in L_p(X)\}$ - set of new non-transformer nodes linked with transformer node q.

- $T(X)$ - set of transformer nodes each of which is linked with at least one new charging station.

- $TP_q(X) = \sum_{p \in M_q(X)} \sum_{c \in C(X)} po_c NC_{pc}(X)$ - total instant power demand of new charging stations linked to transformer node $q \in T(X)$ in the decisive time period.

- $V(X) = \sum_{r \in R(X)} v_r(Z_r(X))$ - total value.

- $CC(X) = \sum_{c \in C(X)} \sum_{p \in S_c(X)} cc_c^{cap} NC_{pc}(X) + \sum_{r \in R(X)} \sum_{b \in B_r(X)} cv_b^{cap} NV_{rb}(X) + \sum_{p \in S(X) \setminus NO} \sum_{q \in L_p(X)} cl_{qp} + \sum_{q \in T(X) \setminus TO} cb_q$ - total capital cost.

- $OC(X) = \sum_{c \in C(X)} \sum_{p \in S_c(X)} cc_c^{ope} NC_{pc}(X) + \sum_{r \in R(X)} \sum_{b \in B_r(X)} cv_{rb}^{ope} NV_{rb}(X)$ - total operating, depreciation and energy cost.

2.7 Formal definition of Opt

Problem Opt can be formulated as follows.

$$\max_X V(X), \text{ subject to}$$

$$CC(X) \le ucc, \quad (1)$$

$$OC(X) \le uoc, \quad (2)$$

$$Z_r(X) \le pas_r + \min_{b \in B_r(X)} \{cap_b\} - 1, \; r \in R(X), \quad (3)$$

$$Z_r(X) \ge \min_{b \in VC_r} \{cap_b\}, \; r \in R(X), \quad (4)$$

$$TP_q(X) + oo_q \le o_q, \; q \in T(X), \quad (5)$$

$$AT_r(X) \le ut_r, \; r \in R(X), \quad (6)$$

$$c_{jrb}(X) \in C_{p(j)} \cap C_b, \; j \in SR_{rb}(X), \; r \in R_b(X), \; b \in B(X), \quad (7)$$

$$ei_{r(j_k^{rb}, j_{k+1}^{rb})b} = 1, \; j_k^{rb} \in SR_{rb}(X), k = 0, \ldots, n(r,b) - 1, ei_{r(j_{n(r,b)}^{rb}, j_1^{rb})b} = 1, r \in R_b(X), b \in B(X), \quad (8)$$

$$nc_{pc} + NC_{pc}(X) \le uc_{pc}, \; p \in S_c(X), \; c \in C(X), \quad (9)$$

$$\sum_{c \in C_b} (nc_{p(j)c} + NC_{p(j)c}(X)) \ge 1, \; j \in NM_b, p(j) \in S(X), \; b \in B(X), (10)$$

$$nc_{pc} + NC_{pc}(X) \geq BN_{pc}(X),\ p \in S(X) \cup NO,\ c \in C, (11)$$

$$|L_p(X)| = m,\ p \in S(X) \backslash NO. (12)$$

Constraints (1) and (2) bound the total capital cost and the total operating, depreciation and energy cost from above. Constraints (3) limit the total passenger capacity of new e-buses on each route $r \in R(X)$ by the total capacity of conventional vehicles on this route plus the capacity of the largest e-bus selected for this route. Constraints (4) state that the total passenger capacity of new e-buses on each route $r \in R(X)$ should be at least the minimal capacity of a single conventional vehicle on this route. Constraints (5) ensure that the total instant power demand of new and old charging stations linked to the same transformer does not exceed the output power of this transformer. Constraints (6) specify upper bound on the length of the average traffic interval of all e-buses assigned to the same route. Constraints (7) ensure that an appropriate charging station is opened at each node associated with the nodes from the sequence $SR_{rb}(X)$. Constraints (8) guarantee that any new e-bus can feasibly run over the route to which it is assigned if appropriate charging stations are opened at the nodes associated with the nodes from the sequence $SR_{rb}(X)$. Constraints (9) limit the total number of old and new charging stations of any type at any node from above. Constraints (10) state that at least one old or new charging station of a type $c \in C_b$ must be opened at a node associated with the node from the set NM_b if this node belongs to a route served by at least one new e-bus. At least, depot is such a node. Constraints (11) guarantee that the number of old and new charging stations of type c opened at node p is sufficient to serve e-buses of all types assigned to this charging station type and node. Constraints (12) guarantee that the number of new links of a non-transformer node, at which at least one new charging station is open and no old charging station was open, with transformer nodes is equal to m.

Note that the solution in which no new e-bus is used and no new charging station is opened is feasible for the problem Opt. Furthermore, an optimal solution of Opt is an *efficient (Pareto-optimal)* solution of a tri-criteria problem of maximizing $V(X)$ and minimizing $CC(X)$ and $OC(X)$, see terminology and results for the multi-criteria problems in Steuer [71], Vincke [76], Roy [66], Collette and Siarry [9] and Ehrgott [13]. A solution is an efficient solution if there is no other solution which is no worse in all criteria values and strictly better in one of the criteria values than the efficient solution.

2.8 Adapting Opt for the case of e-buses with slow-charging batteries

In this section, a problem is studied which differs from Opt in that Assumption 5a) is not valid, and batteries of e-buses of certain types, which we call *special*, have enough capacity to drive with a single charge at a depot during the day (*single-charge* e-buses), or with one charge at a depot and one charge at a non-depot node during the day (*two-charges* e-buses), or they can drive up to k cycles, $k \geq 2$, for any route (k*-cycle* e-buses). Charging of single-charge and two-charges e-buses takes place in time periods outside the decisive time period, while charging of k-cycle e-buses can take place inside and outside this period. We adapt the model Opt for this case. The adaptation consists of the additional assumptions and the extension of the input and output data for Opt. The additional assumptions are

12a) The same number of special e-buses operate the entire day.

13a) Special e-buses and non-special e-buses cannot be charged at the same charging station. Types of their charging stations are different.

14a) The required number of charging stations at a non-depot node for charging two-charges e-buses is equal to the number of these e-buses.

The input data are extended by

- Set $BS_1 \subseteq B$ of special single-charge e-bus types.
- Set $BS_2 \subseteq B$ of special two-charges e-bus types.
- Set $BSC_k \subseteq B$ of special k-cycle e-bus types.

It is assumed that sets BS_1, BS_2 and BSC_k are pairwise disjoint. The derived input data are extended by

- Eligible drive indicator $ei_{r(i,j)b}$ for special e-buses: if $b \in (BS_1 \cup BS_2)$, then $ei_{r(i,j)b} = 1$ for any route segment (i,j) such that $i \neq j$ and any route r. If $b \in BS_1$, then $ei_{r(i,i)b} = 1$, and if $b \in BS_2$, then $ei_{r(i,i)b} = 0$ for any non-depot node node i and any route r. This definition ensures that a single charging point at the depot is sufficient for e-buses of types from BS_1 and that a single charging point at the depot and a single charging point at a non-depot node are sufficient for e-buses of types from BS_2. Single-charge and two-charges e-buses are supposed not to be charged at these points in the decisive time period, because in the decisive time period they are assumed to operate without charging.

- Upper bound on the charging time of one e-bus of type $b \in BS_2$ at a charging station of type $c \in C_b$ installed at a non-depot node $j \in N_c$ in the decisive time period is $ct_{jbc} = 0$.
- Sequence $\pi_r^{(k)} = (j_0, (j_1, j_2, \ldots, j_r), (j_1^2, \ldots, j_r^2), \ldots, (j_1^k, \ldots, j_r^k))$, $j_1^h = j_r^h$, $h = 2, \ldots, k$, of stops for route r if it is served by a k-cycle e-bus, where j_i^h is the h-th copy of the node j_i with the same parent node $p(j_i^h) = p(j_i)$ and the same other input characteristics of the node j_i, $h = 2, \ldots, k$. Calculation of eligible drive indicators for k-cycle e-buses is the same as for normal e-buses, but with respect to the sequence $\pi_r^{(k)}$.

The output data is modified for e-bus types from BS_2 as follows.

- $BN_{jc}(X) := \sum_{r \in R_j(X)} \sum_{b \in B_{jc}(X)} (nv_{rb} + NV_{rb}(X))$ - required number of charging stations of type $c \in C_b$, $b \in BS_2$, at the non-depot node j, $j \in NE \cap (S(X) \cup NO)$.

The new input and output data must be accounted in the mathematical programming model (1)-(12). Particularly, in the constraint (9)

$$nc_{pc} + NC_{pc}(X) \leq uc_{pc},\ p \in S_c(X),\ c \in C(X),$$

if $c \in C_b$, $b \in BS_2$, then the definition of $BN_{jc}(X)$ in the previous paragraph must be used.

3 Problem DepOpt

E-buses equipped with high-capacity batteries (hundreds of kWh) represent a large part of the commonly used types of e-buses (Goehlich et al. [26], Leou and Hung [43], Olsson et al. [58]). These e-buses are able to operate the whole day without recharging, and they are charged in a depot for 2-8 hours depending on the battery size and charging station power to restore the full battery charge, mainly at a night time (report of the project ZeUS [87]).

Analysis of operation of overnight charged e-buses show that their driving range can be increased by charging their batteries during the day time of low passenger transfer demand, when not all e-buses are needed. An important issue of the charging process is the dependence of the SOC level on the charging time duration. Montoya et al. [54] show that this function is concave. In the interval $[0, t]$ of the SOC level where t is a certain threshold (in the example of [54] it is 80%) this function is linear, and after t its slope gradually drops.

Consider a set R of routes and a set TR of trips during the day on these routes, carried out by a set J of e-buses that are charged in the same depot by the charging stations of the same type $c \in C$. The e-buses can be of several types e from the set EB equipped with batteries b of several feasible options from the set $B^e \subseteq B$ compatible with the charging station type. Each battery option b is characterized by the minimal $\underline{s}_b$ and maximal $\bar{s}_b$ SOC levels and the function of SOC recovery at a charging station, which depends on the charging time and the initial SOC level.

E-bus $j \in J$ is characterized by the following unique parameters: a subset $TR_j \subseteq TR$ of trips to be served by this e-bus, an e-bus type $e \in EB$, a set B_j, $B_j \subseteq B$, of feasible battery options, and energy consumption depending on the trip from the set TR_j, selected battery option and its initial SOC level. A single most representative day is considered. At the beginning of the day, before the departure from the depot, all the e-buses are assumed to be fully charged, and any e-bus can operate the whole day without recharging. Selection of the type of the charging stations, batteries options for e-buses and distribution of recharging operations over time can minimize the number of the required charging stations and the total cost of the charging infrastructure, batteries and consumed energy, which is the topic of this section.

Problem DepOpt studied in this section is to determine the cost-effective maximal electric power supplied to the depot, the type and number of identical slow-charging stations in the depot and types of the batteries for e-buses such that e-buses can feasibly serve a given set of routes (successfully fulfill all the required trips).

Assumptions of the problem DepOpt are given in Section 3.1. Input, derived input and output data are described in Sections 3.2, 3.3 and 3.5, respectively. A formal problem formulation is presented in Section 3.4.

3.1 Assumptions

The following assumptions are imposed for the problem DepOpt.

1b) Each e-bus serves a subset of trips assigned to it.

2b) Each trip originates and terminates in the same depot for all the e-buses. E-buses are charged in this depot. The depot is equipped with identical slow-charging stations of one of the given types. The output power of each charging station is a given constant.

3b) Any e-bus can be equipped with a high-capacity battery (hundreds of kWh) to be selected from a given set of options. Any battery enables any e-bus to operate without recharging the whole day.

4b) Initial SOC level of the battery option b must be in the interval $[\underline{s}_b, \bar{s}_b]$.

5b) The daily schedule of any e-bus is given by a set of time pairs (departure from depot, arriving to depot).

6b) Initial SOC levels of all the e-buses must be recovered for any day prior to the beginning of the next day. Therefore, the most representative day in terms of the energy consumption and traffic intensity is considered.

7b) The following data are assumed to be given: the charge loss functions for all e-bus types and battery options on the corresponding trips over the day, and the functions of restoring SOC levels of e-bus batteries at the charging stations depending on the station type, charging time and starting SOC level.

8b) The loss of the SOC level of a non-operating e-bus is negligible.

9b) The time of changing e-buses at any charging station is negligible.

10b) The dynamic nature of the electric power supplied to the depot by the city power grid is taken into account.

3.2 Input data

- Set R of routes. Each route $r \in R$ is associated with its length l_r.
- Set C of slow-charging station types in the depot.

  Type $c \in C$ is associated with the following input parameters.
- Nominal power P_c of one station.
- Annual capital cost $cost^{cap}(c)$ of one station.
- Annual operating and depreciation cost $cost^{ope}(c)$ of one station.
- Set B of feasible slow-charging battery options.

  Each option $b \in B$ is associated with the following input data.
- Interval $[\underline{s}_b, \bar{s}_b]$ of feasible SOC levels.
- Cost $cost_b$ of the battery.
- Subset $C_b \subseteq C$ of feasible charging stations types.
- Concave increasing piecewise linear functions $f_{bc}(\tau)$ defining the resulting SOC level of battery b after charging at a station $c \in C_b$ during time τ if the initial SOC level is equal to s_b^{min}, $s_b^{min} \leq \underline{s}_b$. This function is defined in the interval $[0, \tau_{bc}^{max}]$, where τ_{bc}^{max} is the maximal duration of battery b charging from SOC level s_b^{min} to SOC level s_b^{max}, $s_b^{max} \geq \bar{s}_b$.
- Charging rate f'_{bc} of the battery b at the charging station $c \in C_b$.
- Convex increasing piecewise linear function $N_b(s_b^{low})$ of maximal number of charge/discharge cycles of battery b in its lifetime, depending of its average discharge level s_b^{low}. This function is represented by linear functions $\alpha^\nu + \beta^\nu s_b^{low}$ defined on the segments $[s_b^\nu, s_b^{\nu+1}]$, $\nu = 1, \ldots, \gamma - 1$, where $s_b^1 = s_b^{min}$, $s_b^\gamma = s_b^{max}$ and $\alpha^\nu + \beta^\nu s_b^\nu = N_b(s_b^\nu)$, $\nu = 1, \ldots, \gamma - 1$.
- Set TR of trips during the day.

  Each trip $p \in TR$ is associated with the following input parameters.

- Sequence of routes $\pi_p = (r_p^1, \dots, r_p^{m_p})$, $r_p^k \in R$, $k = 1, \dots, m_p$.

- Time interval $[\underline{t}^p, \bar{t}^p]$, where $\underline{t}^p$ is the departure time from the depot and $\bar{t}^p$ is the arrival time to the depot. It is assumed that $\underline{t}^p < \bar{t}^p$. If an arrival to the depot occurs on the next day, then this arrival time is increased by 24.

- Set EB of feasible e-bus types. Each type $e \in EB$ is associated with a subset $B^e \subseteq B$ of feasible battery options.

- Set $J = \{1, \dots, n\}$ of e-buses.

  Each e-bus $j \in J$ is associated with the following input data.

- E-bus type $e_j \in EB$.

- Subset $TR_j = \{\xi_j^1, \xi_j^2, \dots, \xi_j^{n_j}\} \subseteq TR$ of daily trips such that $\bigcup_{j \in J} TR_j = TR$, $TR_{j'} \bigcap TR_{j''} = \emptyset$, $j' \neq j''$, where ξ_j^p is the p-th trip of the e-bus j, $p = 1, \dots, n_j$.

- Subset $B_j \subseteq B^{e_j}$ of feasible battery b options.

- Concave increasing piecewise linear functions $\varphi_{jbp}(s)$ for each pair (battery $b \in B_j$, trip $p \in TR_j$) defining SOC levels of the battery b for e-bus j of type e_j after its p-th trip ξ_j^p, which depends of the initial SOC level s, $\xi_j^p \in TR_j$.

- Annual number $\overline{N}_j = N_j(TR_j)$ of charge/discharge cycles of any battery $b \in B_j$.

- Discrete set $\Theta_D = \{p_D^1, p_D^2, \dots, p_D^{\bar{k}}\}$ of feasible values of maximal electric power p_D supplied to the depot by the city power grid, $p_D^k < p_D^{k+1}$, $k = 1, 2, \dots, \bar{k} - 1$.

- Annual cost $cost(p_D)$ of the infrastructure (transformers, cables, etc) to support maximal power value p_D supplied to the depot, $p_D \in \Theta_D$.

- Time dependent stepwise function $c_e(t)$ of electric power rates.

- Time dependent function $P(t, p_D)$ of the power supplied by the city power grid, $P(t, p_D) \leq p_D$.

3.3 Derived data

Based on the initial data, the following derived data are obtained.

- Subsets B_{cj} of all feasible battery options $b \in B_j$ such that $c \in C_b$, $c \in C$,$j \in J$.
- $\underline{t} = \min\{\underline{t}^p|, p \in TR\}$.
- $[\underline{t}^p, \bar{t}^p]$= $[\underline{t}^p - \underline{t}, \bar{t}^p - \underline{t}], p \in TR$.
- Set $T = \{t_i|i = 1, \ldots, m\}$ of the time moments at which the e-bus fleet or the number of charging stations in operation can change.
- Sets I_j^p of indices of the time intervals $[t_i, t_{i+1}], i = 1, ..., m-1$ in which e-bus j can be charged after p-th arrival to the depot, $p = 1, \ldots, n_j$, $j \in J$, $I_j^p = \{\underline{i}_j^p, \underline{i}_j^p + 1, \ldots, \bar{i}_j^p - 1\}$, $t_{\underline{i}_j^p} = \bar{t}_j^p, t_{\bar{i}_j^p} = \underline{t}_j^{p+1}$, $p = 1, \ldots, n_j - 1$, $I_j^{n_j} = \{i \in \{1, \ldots, m-1\}|t_i < \underline{t}_j^1$ or $t_i \geq \bar{t}_j^{n_j}\}, j \in J$.
- Convex decreasing piecewise linear function $\chi_b(s_b^{low}) = \frac{1}{N_b(s_b^{low})}$. Function $\chi_b(s_b^{low})$ is represented by linear functions $\theta^\nu + \vartheta^\nu s_b^{low}$ defined on segments $[s_b^\nu, s_b^{\nu+1}]$, $\nu = 1, \ldots, \gamma - 1$, where $s_b^1 = s_b^{min}$, $s_b^\gamma = s_b^{max}$ and $\theta^\nu + \vartheta^\nu s_b^\nu = \frac{1}{N_b(s_b^\nu)}$, $\nu = 1, \ldots, \gamma - 1$.
- Lower bound P_i on the power supplied by the city power grid in the time interval $[t_i, t_{i+1}]$.
- An electric power rate c_{ei} in the time interval $[t_i, t_{i+1}]$.
- Upper bound $k_{ci}(P_i)$ on the number of charging stations $c \in C$ determined by the lower bound P_i on the supplied power in the time interval $[t_i, t_{i+1}]$.

3.4 Formal definition of DepOpt

Variables to be determined.

- p_D – maximal power supplied to the depot.
- c - type of charging stations in the depot, $c \in C$.
- K - number of charging stations.
- **b**=$(b_j|j \in J)$ types of batteries $b_j \in B_j$ for all e-buses j of the e-fleet J.

- s_j^{dp} – SOC level of the battery b_j of e-bus j at the time moment $\underline{t}_j^p$ of its $p-th$ departure from the depot, $p = 1, \ldots, n_j$, $j \in J$.

- s_j^{ap} – SOC level of the battery b_j of e-bus j at time moment $\overline{t}_j^p$, of its $p-th$ arrival to the depot $p = 1, \ldots, n_j$, $j \in J$.

- u_j^{ap} – time needed for charging e-bus j from SOC level s_j^{min} to SOC level s_j^{ap}, $p = 1, \ldots, n_j$, $j \in J$.

- u_j^{cp} – charging time of the e-bus j in the time interval between its p-th arrival to and $(p+1)$-th departure from the depot, $p = 1, \ldots, n_j - 1$, $j \in J$.

- δ_j^i – charging time of the e-bus j in time interval $[t_i, t_{i+1}]$, $i = 1, \ldots, m-1$, $j \in J$.

Variables related to battery b_j SOC levels and e-bus j charging times are illustrated in Fig. 2.

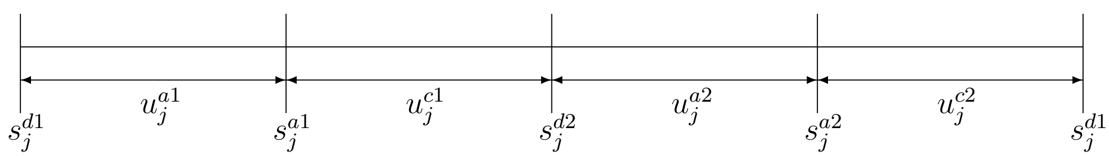

Figure 2: Variables

It is convenient to introduce the following notations.

- $s_j^a = (s_1^{ap}, \ldots, s_{n_j}^{ap}), j \in J$.

- $\mathbf{s}^{\mathrm{a}}$=$(s_1^a, \ldots, s_n^a)$.

- $u_j^c = (u_1^{cp}, \ldots, u_{n_j}^{cp}), j \in J$.

- $\mathbf{u}^{\mathrm{c}}$=$(u_1^c, \ldots, u_n^c)$.

- $s_j^{low} = \sum_{p=1}^{n_j} \frac{s_j^{ap}}{n_j}$.

To facilitate further presentation, we will use index j instead of b_j in some notations if there is no ambiguity. Problem DepOpt can be formulated as follows.

$$\min F(p_D, c, K, \mathbf{b}, \mathbf{u}^{\rm c}, \mathbf{s}^{\rm a}) =$$

$$= \frac{cost(p_D)}{365} + \frac{K}{365}(cost^{cap}(c) + cost^{ope}(c)) + \sum_{j\in J} \frac{cost_{b_j}\overline{N}_j\chi_j(s_j^{low})}{365} + \sum_{i=1}^{m-1} c_{ei} \sum_{j\in J} f'_{jc}\delta_j^i, \tag{13}$$

subject to

$$s_j^{ap} = \varphi_{jp}(s_j^{dp}), p = 1, \ldots, n_j, j \in J. \tag{14}$$

$$s_j^{ap} = f_{jc}(u_j^{ap}), p = 1, \ldots, n_j, j \in J, \tag{15}$$

$$s_j^{dp+1} = f_{jc}(u_j^{ap} + u_j^{cp}), p = 1, \ldots, n_j - 1, j \in J, \tag{16}$$

$$s_j^{d1} = f_{jc}(u_j^{dn_j} + u_j^{cn_j}), j \in J, \tag{17}$$

$$u_j^{cp} = \sum_{i\in I_j^p} \delta_j^i, p = 1, \ldots, n_j, j \in J, \tag{18}$$

$$0 \le \delta_j^i \le (t_{i+1} - t_i), i \in I_j^p, p = 1, \ldots, n_j, j \in J, \tag{19}$$

$$\delta_j^i = 0, i \in \{1, \ldots, m-1\} \setminus \cup_{p=1}^{n_j} I_j^p, j \in J, \tag{20}$$

$$\underline{s}_j \le s_j^{ap} \le \bar{s}_j, p = 1, \ldots, n_j, j \in J, \tag{21}$$

$$\underline{s}_j \le s_j^{dp} \le \bar{s}_j, p = 1, \ldots, n_j, j \in J, \tag{22}$$

$$0 \le u_j^{dp} \le \tau_{jc}^{max}, p = 1, \ldots, n_j, j \in J, \tag{23}$$

$$0 \le u_j^{cp} \le \tau_{jc}^{max}, p = 1, \ldots, n_j, j \in J, \tag{24}$$

$$\sum_{j\in J} \delta_j^i \le \min\{k_{ci}(P_i), K\}(t_{i+1} - t_i), i = 1, \ldots, m-1, \tag{25}$$

$$p_D \in \Theta_D, \tag{26}$$

$$c \in C, \tag{27}$$

$$K \le \lfloor p_D/P_c \rfloor, \tag{28}$$

$$b_j \in B_{cj}, j \in J. \tag{29}$$

Constraints (14) define SOC level s_j^{ap} of e-bus j at the time of its p-th arrival to the depot if at the time of its p-th departure from the depot it was equal to s_j^{dp}. Constraints (15) define charging time u_j^{ap} required to restore the SOC level s_j^{ap} of the e-bus j from its minimal SOC level s_j^{min}. Relations (16) specify SOC level s_j^{dp+1} of e-bus j at the time of $p+1$-th departure from the depot after its charging over time u_j^{cp} in the interval between p-th arrival to and $p+1$-th departure from the depot. Constraints (17) require that the initial SOC levels s_j^{d1} of all e-buses must be restored prior to their first departure from the depot on the next day. Constraints (18) represent the total charging time u_j^{cp} of e-bus j between its p-th arrival to the depot and $p+1$-th departure from it. Constraints (19) indicate that charging time δ_j^i of the e-bus j in time interval i is positive and does not exceed its duration. Constraints (20) set charging time δ_j^i to zero for e-bus j in the time interval i, when the e-bus is outside the depot. Constraints (21) specify the range of the SOC level s_j^{ap} of e-bus j at its p-th arrival to the depot. Similarly, constraints (22) specify the range of the SOC level s_j^{dp} of e-bus j at its p-th departure from the depot. Constraints (23) require that the charging time u_j^{dp} of e-bus j at its p-th departure is positive and it does not exceed the upper bound. Similarly, constraints (24) require that the charging time u_j^{cp} of e-bus j in the interval between its p-th arrival and $p+1$-th departure is positive and it does not exceed the upper bound. Constraints (25) limit the total charging time of all e-buses J in the time interval i by the available charging time derived for the parallel charging stations from the given supplied power. Constraint (26) restricts the power supplied to the depot by a given range. Constraint (27) indicates that type c of charging station can be selected from given set C. Constraint (28) limits the number of charging stations K by an upper bound derived from the supplied power. Constraints (29) state that the battery type of e-bus j can be selected from a set B_{cj}.

Problem DepOpt is to determine the maximal power supplied to the depot, option of the battery of each e-bus, type of the charging stations and their number as well as charging times of each e-bus while it is in the depot such that the total daily cost of charging stations, batteries and consumed energy is minimized, provided that the SOC levels for all e-buses are restored before the next day starts, and the dynamic upper bound on the supplied power is satisfied.

3.5 Output data

- Optimal value p_D^* of the power supplied to the depot.
- Optimal type c^* of the charging stations.
- Minimal number K^* of charging stations of the type c^*.
- Optimal battery options $b_1^*, \ldots, b_n^*$.

- Optimal charging times $\mathbf{u}^{c*}$.
- Optimal durations (δ_j^{i*}) of charging the e-buses $j \in J$ in the time intervals $[t_i, t_{i+1}]$, $i = 1, \ldots, m-1$.
- Optimal SOC levels $\mathbf{s}^{a*}$ e-bus batteries upon arrivals to the depot during the considered day.
- Unused charging time resource $t_i^{ch} = \min\{k_{ci}(P_i), K^*\}(t_{i+1} - t_i) - \sum_{j\in J}(\delta_j^{i*})$ in the time interval $[t_i, t_{i+1}]$, $i = 1, \ldots, m-1$.
- Total unused daily charging time resource $\bar{t}^{ch} = \sum_{i=1}^{n} t_i^{ch}$.
- Share $\Psi^{ch} = 1 - \frac{\bar{t}^{ch}}{\sum_{i=1}^{n} \min\{k_{ci}(P_i), K^*\}(t_{i+1}-t_i)}$ of the used daily resource of charging time in the depot.
- Optimal value Φ^* of the daily cost.

4 Problem OptSched

In this section, we will call new and old e-buses and conventional vehicles as buses. The same problem OptSched is solved for each route $r \in R(Q^*)$, where Q^* is a solution of Opt. The input of the problem OptSched for any route r consists of the numbers $v_b := NV_{rb}(Q^*) + nbo_{rb}$ of e-buses of type b and the numbers $v_b = nvc_{rb}(Q^*)$ of conventional vehicles of type b for $b = 1, \ldots, n$, where $n := |B_r(Q^*) \cup BO_r \cup VC_r(Q^*)|$. All buses assigned to route r are assumed to depart with the same average traffic interval $AT_r(Q^*)$ in the decisive time period. The objective of the problem OptSched is to distribute departures of buses of the same type assigned to the same route as uniform as possible over the departures of all buses serving this route in the decisive time period. The timetables which address this objective are called *balanced*. It is assumed that buses of different types have different passenger capacities. Therefore, a balanced timetable ensures a uniform allocation of bus capacities over time in the decisive time period of the same route.

Denote $V = \sum_{b=1}^{n} v_b$ and $s_b = v_b/V$, $b = 1, \ldots, n$. The value of V is equal to the number of (average) traffic intervals in the decisive time period for the same route. According to the balanced timetable objective, the number of buses of type b departed in the first k traffic intervals must be kept as close to $s_b k$ as possible for $b = 1, \ldots, n$. Introduce non-negative integer variables x_{bk} representing the number of buses of type b departed in the first k traffic intervals, $b = 1, \ldots, n$, $k = 1, \ldots, V$. Define $x_{b0} = 0$, $b = 1, \ldots, n$. Denote by x matrix with the entries x_{bk}. The problem OptSched admits the following two formulations.

$$\textbf{Problem OptSched-Sum}: \quad \min_x \sum_{k=1}^{V} \sum_{b=1}^{n} (x_{bk} - s_b k)^2, \text{ subject to}$$

$$\sum_{b=1}^{n} x_{bk} = k, \ k = 1, \ldots, V, \tag{30}$$

$$0 \le x_{bk} - x_{b(k-1)}, \ b = 1, \ldots, n, \ k = 1, \ldots, V, \tag{31}$$

$$x_{b0} = 0, \ b = 1, \ldots, n, \tag{32}$$

$$x_{bV} = v_b, \ b = 1, \ldots, n, \tag{33}$$

$$x_{bk} \in Z_0, \ b = 1, \ldots, n, \ k = 1, \ldots, V. \tag{34}$$

$$\textbf{Problem OptSched-Max}: \quad \min_x \max_{1 \le k \le V, 1 \le b \le n} |x_{bk} - s_b k|, \text{ subject to (30)-(34).}$$

Kubiak and Sethi [40] reduce problem OptSched-Sum to an assignment problem which can be solved in $O(V^3)$ time. Denote by M^* the optimal objective value of OptShed-Max and denote $v_{\max} = \max_{1 \le b \le n}\{v_b\}$. Steiner and Yeomans [69] prove that $\frac{V - v_{\max}}{V} \le M^* \le 1$ and reduce problem OptSched-Max to a single machine scheduling problem solvable in $O(V \log V)$ time. Thus, both problems are not NP-hard in the strong sense. The relation $M^* \le 1$ means that an optimal solution of OptSched-Max is such that the total number of buses departing in the first k traffic intervals never deviates from the desired number ks_b by more than one for any vehicle type. Kovalyov et al. [39] provide an extensive computer experiment with both models OptSched-Sum and OptSched-Max. Brauner and Crama [6] strengthen earlier results by demonstrating that $M^* \le \frac{V-1}{V}$ and that OptSched-Max can be solved in $O(f(n) \log V)$ time, where $f(n)$ is a function of n. We will use formulation OptSched-Max for our purposes because it is adequate and easy for implementation.

5 Conclusion

In this Deliverable, three optimization problems are formulated and analyzed. Problem Opt assumes that an e-bus charges each time when it visits a non-depot charging station. This problem is to determine an e-fleet, places for charging stations and transformers, assignment of charging stations to the specified places, assignment of charging stations to the transformers and assignment of charging stations to the routes such that all e-buses can feasibly drive, the required traffic interval is maintained, and the output power of any transformer is not exceeded. The objective is to maximize the total value, which can be related to the total passenger load of conventional vehicles replaced by e-buses, provided that the total capital cost and the total operating, depreciation and energy cost do not exceed their upper bounds. Problem Opt is a model for e-buses with fast-charging batteries. An adaptation of this model to the case of slow-charging batteries is described.

Problem DepOpt models the case of slow-charging batteries of e-buses that charge at the same depot to be equipped with the charging stations of the same type. The decision is to determine the maximal electric power supplied to the depot, the type and the number of identical slow-charging stations in the depot and types of the batteries for e-buses such that the e-buses can feasibly serve a given set of routes. The objective is to minimize the per day total cost of the required energy and equipment.

Problem OptSched is to determine a balanced route timetable such that the same average traffic interval of all public vehicles of the same route is maintained and departures of public vehicles of the same passenger capacity assigned to the same route are distributed as smoothly as possible over departures of all public vehicles in the most representative time period. The proposed models can be used in the decision support tools for planning process of conversion of the conventional bus fleet to a fully electric bus fleet.

6 References

[1] Ali, R. (2011) Effect of diesel emissions on human health: A review. International Journal of Applied Engineering Research, 6(11), 1333-1342.

[2] Anderson, J.E., Lehne, M., Hardinghaus, M. (2018) What electric vehicle users want: Real-world preferences for public charging infrastructure. International Journal of Sustainable Transportation, 12(5), 341-352.

[3] Ahmad, A., Khan, Z.A., Alam, M.S., Khateeb, S. (2018) A review of the electric vehicle charging techniques, standards, progression and evolution of EV technologies in Germany. Smart Science, 6(1), 36-53.

[4] Alonso, M., Amaris, H., Germain, J.G., Galan, J.M. (2014) Optimal charging scheduling of electric vehicles in smart grids by heuristic algorithm. Energies, 7, 2449-2475.

[5] Barnitt, R. (2006) Case study: Ebus hybrid electric buses and trolleys. National Renewable Energy Laboratory. Technical Report NREL/TP-540-38749.

[6] Brauner, N., Crama, Y. (2004) The maximum deviation just-in-time scheduling problem. Discrete Applied Mathematics, 134(1-3), 25-50.

[7] Bruglieri, M., Mancini, S., Pezzella, F., Pisacane, O., Suraci, S. (2017) A three-phase matheuristic for the time-effective electric vehicle routing problem with partial recharges. Electronic Notes in Discrete Mathematics, 58, 95-102.

[8] Chan, S., Miranda-Moreno, L.F., Patterson, Z. (2013) Analysis of GHG emissions for city passenger trains: Is electricity an obvious option for Montreal commuter trains? Journal of Transportation Technologies, 3(2A), 17-29.

[9] Collette, Y., Siarry, P., 2004. Multiobjective optimization: Principles and case studies. Springer Science & Business Media.

[10] Christensen, L., Klauenberg, J., Kveiborg, O., Rudolph, C. (2017) Suitability of commercial transport for a shift to electric mobility with Denmark and Germany as use cases. Research in Transportation Economics, 64, 48-60.

[11] Clerc, M. (2010) Particle Swarm Optimization. John Wiley & Sons.

[12] Desaulniers, G., Errico, F., Irnich, S., Schneider, M. (2016) Exact algorithms for electric vehicle-routing problems with time windows. Operations Research, 64(6),1388-1405.

[13] Ehrgott, M. (2005) Multicriteria optimization. Springer Verlag.

[14] Erkkilä, K., Nylund, N.-O., Pellikka, A.-P., Kallio, M., Kallonen, S., Ojamo, S., Ruotsalainen, S., Pietikäinen, O., Lajunen, A. (2013) eBUS - Electric bus test platform in Finland. EVS27 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, Barcelona, Spain.

[15] Eudy, L., Jeffers, M. (2017) Foothill transit battery electric bus demonstration results: Second report. National Renewable Energy Laboratory. Technical Report NREL/TP-5400-67698.

[16] Feng, W., Figliozzi, M. (2012) Conventional vs electric commercial vehicle fleets: A case study of economic and technological factors affecting the competitiveness of electric commercial vehicles in the USA. Procedia - Social and Behavioral Sciences, 39, 702-711.

[17] Feng, W., Figliozzi, M. (2013) An economic and technological analysis of the key factors affecting the competitiveness of electric commercial vehicles: A case study from the USA market. Transportation Research Part C: Emerging Technologies, 26, 135-145.

[18] Fiori, C., Ahn, K., Rakha, H.A. (2018) Optimum routing of battery electric vehicles: Insights using empirical data and microsimulation Transportation Research Part D: Transport and Environment, 64, 262-272.

[19] Foltyński, M. (2014) Electric fleets in urban logistics. Procedia - Social and Behavioral Sciences, 151, 48-59.

[20] Froger, A., Mendoza, J., Jabali, O., Laporte, G. (2017) New formulations for the electric vehicle routing problem with nonlinear charging functions. CIRRELT, CIRRELT-2017-30, Montreal.

[21] Froger, A., Mendoza, J., Jabali, O., Laporte, G. (2017) A matheuristic for the electric vehicle routing problem with capacitated charging stations. CIRRELT, CIRRELT-2017-31, Montreal.

[22] Gallet, M., Massier, T., Hamacher, T. (2018) Estimation of the energy demand of electric buses based on real-world data for large-scale public transport networks. Applied Energy, 230, 344-356.

[23] 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.

[24] Garey, M.R., Johnson, D.S., 1979. Computers and intractability: A guide to the theory of NP-completeness. Freeman, San Francisco.

[25] Gaskins, A.J., Hart, J.E., Mínguez-Alarcón L., Chavarro J.E., Laden F., Coull B.A., Ford J.B., Souter I., Hauser R. (2018) Residential proximity to major roadways and traffic in relation to outcomes of in vitro fertilization. Environ International, 115, 239-246.

[26] Goehlich, D., Fay, T.-A., Park, S. (2019) Conceptual Design of Urban E-Bus Systems with Special Focus on Battery Technology, in Proceedings of the 22nd International Conference on Engineering Design (ICED19),Delft, The Netherlands, 5-8 August 2019. DOI:10.1017/dsi.2019.289

[27] Hallmark, S.L., Wang, B., Sperry, R. (2013) Comparison of on-road emissions for hybrid and regular transit buses. Journal of the Air & Waste Management Association, 63(10), 1212-1220.

[28] Hanlin, J. (2016) Battery electric buses smart deployment. Zero Emission Bus conference, London.

[29] HEI panel on the health effects of traffic-related air pollution. (2010) Traffic-related air pollution: A critical review of the literature on emissions, exposure, and health effects. HEI Special Report 17. Health Effects Institute, Boston, MA.

[30] HEI diesel epidemiology panel. (2015) Executive summary. Diesel emissions and lung cancer: An evaluation of recent epidemiological evidence for quantitative risk assessment. HEI Special Report 19. Health Effects Institute, Boston, MA.

[31] Hiermann, G., Puchinger, G., Ropke, S., Hartl, R.F. (2016) The electric fleet size and mix vehicle routing problem with time windows and recharging stations. European Journal of Operational Research, 252, 995-1018.

[32] Horn, W.A. (1974) Some simple scheduling algorithms. Naval Research Logistics Quarterly, 21, 177-185.

[33] Hosseini, S., Sarder, M.D. (2019) Development of a Bayesian network model for optimal site selection of electric vehicle charging station. International Journal of Electrical Power and Energy Systems, 105, 110-122.

[34] IARC Working Group on the Evaluation of Carcinogenic Risk to Humans. Diesel and gasoline engine exhausts and some nitroarenes. (2014) IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, No. 105. International Agency for Research on Cancer, Lyon, France.

[35] Jochem, P., Plötz, P., Ng, W.-S., Rothengatter, W. (2018) The contribution of electric vehicles to environmental challenges in transport. Transportation Research Part D: Transport and Environment, 64, 1-4.

[36] Juan, A.A., Mendez, C.A., Faulin, J., de Armas, J., Grasman, S.E. (2016) Electric vehicles in logistics and transportation: A survey on emerging environmental, strategic, and operational challenges. Energies, 9(2), 86.

[37] Kennedy, J., Eberhart, R. (1995) Particle Swarm Optimization. Proceedings of IEEE International Conference on Neural Networks. IV. pp. 1942-1948.

[38] Khan, W., Ahmad, A., Ahmad, F., Alam, M.S. (2018) A comprehensive review of fast-charging infrastructure for electric vehicles. Smart Science, 6(3), 256-270.

[39] Kovalyov, M.Y., Kubiak, W., Yeomans, J.S. (2001) A computational analysis of balanced JIT optimization algorithms. INFOR, 39(3), 299-316.

[40] Kubiak, W., Sethi, S. (1991) A note on "Level schedules for mixed-model assembly lines in Just-in-Time production systems". Management Science, 37(1) 121-122.

[41] 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, 11(10), 707-720.

[42] Lajunen, A. (2014) Energy consumption and cost-benefit analysis of hybrid and electric city buses. Transportation Research Part C: Emerging Technologies, 2014, 38, 1-15.

[43] Leou, R.-C., Hung, J.-J. (2017) Optimal charging schedule planning and economic analysis for electric bus charging stations. Energies, 10, 483.

[44] Li, J.-Q. (2016) Battery-electric transit bus developments and operations: A review. International Journal of Sustainable Transportation, 10, 157-169.

[45] Liu, Z., Song, Z., He, Y. (2018) Planning of fast-charging stations for a battery electric bus system under energy consumption uncertainty. Transportation Research Record, https://doi.org/10.1177/0361198118772953

[46] Liu, X.C., Wei, R. (2018) Strategic planning and design for electric bus systems. Mountain-Plains Consortium, report MPC 18-355, North Dakota State University.

[47] Marmaras, C., Xydas, E., Cipcigan, E. (2017) Simulation of electric vehicle driver behaviour in road transport and electric power networks. Transportation Research Part C, 80, 239-256.

[48] Mathieu, L. (2018) Roll-out of public EV charging infrastructure in the EU: Is the chicken and egg dilemma resolved? A study by Transport & Environment, bit.ly/2NqZ9t1.

[49] Mathieu, L. (2018) Electric buses arrive on time: marketplace, economic, technology, environmental and policy perspectives for fully electric buses in the EU. A study by Transport & Environment, https://www.transportenvironment.org/sites/te/files/publications/Electric%20buses%20arrive%20on%20time.pdf

[50] McClellan, R.O. (2016) Critique of Health Effects Institute Special Report 19, "Diesel Emissions and Lung Cancer: An Evaluation of Recent Epidemiological Evidence for Quantitative Risk Assessment". Report. Albuquerque, NM.

[51] Mohamed, M., Garnett, R., Ferguson, M.R., Kanaroglou, P. (2016) Electric buses: A review of alternative powertrains. Renewable and Sustainable Energy Reviews, 62, 673-684.

[52] Mohamed, M., Farag, H., El-Taweel, N., Ferguson, M. (2017) Simulation of electric buses on a full transit network: Operational feasibility and grid impact analysis. Electric Power Systems Research, 142, 163-175.

[53] Mohner, M. (2016) The hidden impact of a healthy-worker effect on the results of the diesel exhaust in miners study. European Journal of Epidemiology, 31(8), 803-804.

[54] Montoya, A., Guenet, C., Mendoza, J. E., Villegas, J. G. (2017) The electric vehicle routing problem with nonlinear charging function. Transportation Research Part B: Methodological. doi: 10.1016/j.trb.2017.02.004.

[55] Morganti, E., Browne, M. (2018) Technical and operational obstacles to the adoption of electric vans in France and the UK: An operator perspective. Transport Policy, 63, 90-97.

[56] Neaimeh, M., Salisbury, S.D., Hill, G.A., Blythe, P.T., Scoffield, D.R., Francfort, J.E. (2017) Analysing the usage and evidencing the importance of fast chargers for the adoption of battery electric vehicles. Energy Policy, 108, 474-486.

[57] Nicholas, M., Hall, D. (2018) Lessons learned on early electric vehicle fast-charging deployments. International Council On Clean Transportation (ICCT), https://www.theicct.org/sites/default/files/publications/ZEV_fast_charging_white_paper_final.pdf

[58] Olsson, O., Grauers, A., Pettersson, S. (2016) Method to analyze cost effectiveness of different electric bus systems, in: EVS29 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium. Montreal, 1-12.

[59] Pedersen, M.E.H., Chipperfield, A.J. (2010) Simplifying particle swarm optimization. Applied Soft Computing, 10, 618-628.

[60] Pelletier S., Jabali, O., Laporte, G. (2014) Battery electric vehicles for freight distribution: A survey of vehicle technology, market penetration, incentives and practices, CIRRELT, CIRRELT-2014-43, Montreal.

[61] Pelletier, S., Jabali, O., Laporte, G. (2016) 50th anniversary invited article. Goods distribution with electric vehicles: Review and research perspectives. Transportation Science, 50(1) 3-22.

[62] Pelletier, S., Jabali, O., Laporte, G. (2017) Charge scheduling for electric freight vehicle. CIRRELT, CIRRELT-2017-37, Montreal.

[63] Pelletier, S., Jabali, O., Laporte, G., Veneroni, M. (2017) Battery degradation and behaviour for electric vehicles: Review and numerical analyses of several models. Transportation Research Part B: Methodological, 103, 158-187.

[64] Quak, H., Nesterova, N., van Rooijen, T. (2016) Possibilities and barriers for using electric-powered vehicles in city logistics practice. Transportation Research Procedia, 12, 157-169.

[65] Rogge, M., Wollny S., Sauer D.U. Fast charging battery buses for the electrification of urban public transport - a feasibility study focusing on charging infrastructure and energy storage requirements. Energies, 2015, vol. 8(5), pp. 4587-4606.

[66] Roy, B. (1996) Multicriteria methodology for decision aiding, vol. 12 in Nonconvex Optimization and its Applications. Kluwer Academic Publishers, Dordrecht.

[67] Schmidt, J., Eisel, M., Kolbe, L.M. (2014) Assessing the potential of different charging strategies for electric vehicle fleets in closed transport systems. Energy Policy, 74, 179-189.

[68] Schoch, J. (2016) Modeling of battery life optimal charging strategies based on empirical mobility data. Information Technology, 58(1), 22-28.

[69] Steiner, G.,Yeomans, S. (1993) Level schedules for mixed-model, Just-In-Time assembly processes. Management Science, 39(6), 728-735.

[70] New Generation of Electric Vehicles (2012) Edited by Zoran Stevic. IntechOpen, 2012, DOI: 10.5772/45641

[71] Steuer, R. (1985) Multiple criteria optimization: Theory, computation and application. John Wiley & Sons, New York, NY.

[72] Sydbom, A., Blomberg, A., Parnia, S., Stenfors, N., Sandström T, Dahlén, S.E. (2001) Health effects of diesel exhaust emissions. European Respiratory Journal, 17(4), 733-746.

[73] Teoh, T., Kunze, O., Teo, C.-C. (2016) Scenario-based electric bus operation: A case study of Putrajaya, Malaysia. Transportation Research Procedia, 12, 288-300.

[74] Teoh, T., Kunze, O., Teo, C.-C. (2016) Methodology to evaluate the operational suitability of electromobility systems for urban logistics operations. Transportation Research Procedia, 12, 288-300.

[75] Todorovic, M., Simic, M. (2019) Current state of the transition to electrical vehicles. Smart Innovation, Systems and Technologies, 98, 130-139.

[76] Vincke, P. (1992) Multicriteria decision aid. J. Wiley & Sons, New York, NY.

[77] Wang, X., González, J.A. (2013) Assessing feasibility of electric buses in small and medium-sized communities. International Journal of Sustainable Transportation, 7, 431-448.

[78] Wang, Y., Bi,J., Guan, W., Zhao, X. (2018) Optimising route choices for the travelling and charging of battery electric vehicles by considering multiple objectives. Transportation Research Part D, 64, 246-261.

[79] Wang, Y.-W., Lin, C.-C., Lee, T.-J. (2018) Electric vehicle tour planning. Transportation Research Part D, 63, 121-136.

[80] Wen, M., Laporte, G., Madsen, O.B.G., Norrelund, A.V., Olsen, A. (2014) Locating replenishment stations for electric vehicles: application to Danish traffic data. Journal of the Operational Research Society, 65(10) 1555-1561.

[81] World Health Organization. (2000) Quantification of the health effects of exposure to air pollution. Report of a WHO Working Group. Bilthoven, Netherlands

[82] Wielinski, G., Trépanier, M., Morency, C. (2017) Electric and hybrid car use in a free-floating car sharing system. International Journal of Sustainable Transportation, 11(3), 161-169.

[83] 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.

[84] Xylia, M., Leduc, S., Patrizio, P., Silveira, S., Kraxner, F. (2017) Developing a dynamic optimization model for electric bus charging infrastructure. Transportation Research Procedia, 27, 776-783.

[85] Xylia, M., Silveira, S. (2018) The role of charging technologies in upscaling the use of electric buses in public transport: Experiences from demonstration projects. Transportation Research Part A: Policy and Practice, 118, 399-415.

[86] Yu, Z., Chen, S., Tong, L. (2016) An intelligent energy management system for large-scale charging of electric vehicles. CSEE Journal of Power and Energy Systems, 2(1), 47-53.

[87] http://zeeus.eu/uploads/publications/documents/zeeus-report2017-2018-final.pdf

[88] http://zeeus.eu/uploads/publications/documents/zeeus-local-demo-brochures-mergedcompressed.pdf