PLATON –

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

Deliverable: M4 WP 5.1 Requirements Analysis and
WP 5.4 Graphical User Interface (first three project months)

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Editor: Olaf Czogalla, ifak
Contributors: Krzysztof Krawiec, SUT
Gerfried Cebrat, EUC
Mikhail Kovalyov, UIIP

Grant beneficiary of WP leader:
Institut für Automation und Kommunikation e.V.

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Bundesministerium für Verkehr und digitale Infrastruktur
Invalidenstraße 44
10115 Berlin

Contents

1 Introduction

The deliverable presents the results of the project work carried out by consortium partners in the WP 5.1: Requirements Analysis (of the planning tool) and for the first three project months of the WP 5.4: Graphical User Interface (of the planning tool).

The results of WP 5.1 are focused on the requirements of the planning tool that have been collected and structured during analysis of possible use cases of the tool. The results are strongly related to the planning process that has been defined in WP2. The needs of transport planning operators, municipal planners, and the management board of transport operators as the main stakeholders where included in the described planning process.

In accordance with the requirements of the planning tool, a wireframe model of the graphical user interface has been designed and sketched in a mock-up version in order to define interfaces between tool components and the graphical user interface.

2 Requirements of the planning tool

In result of the project activities of WP2 it was recognized, that three target groups of potential users exist to be addressed by distinguished components of the tool:

A) Public transport agency management board

B) Urban transport planner in municipality or similar authority

C) Transit operations planner in the public transport-operating agency

Distinguished components of the tool must address the varied requirements of the target groups. In the following sections, the requirements are described that have been derived from dedicated use cases that were identified and analyzed. A common database for each of the components shall be established to ensure a seamless data exchange between tool components as well as to allow an application of the tool in arbitrary public transport areas.

Regarding the key qualifications of the project partners as well as their engagement in the reported work packages and their planned resources, it has been coordinated and reconciled among partners a participation and allocation of contributions to the planning tool as shown in Figure 1.

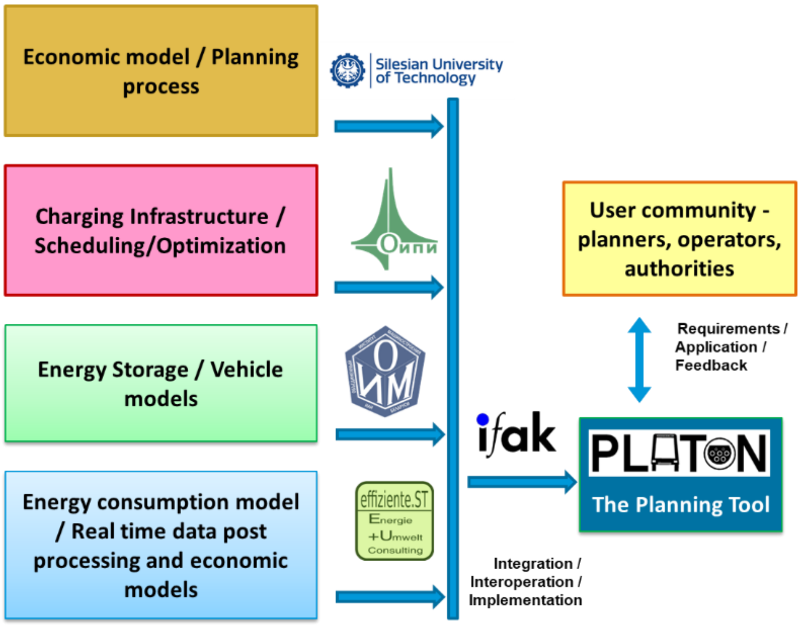


Figure 1 Allocation of partners contributions to the planning tool of the Platon procect

The allocation is based on different domains of dependencies in the deployment process, which have been identified in the earlier course of the project and were reported in the Deliverable 2.1.

The Polish Partner Silesian University of Technology (SUT) is working on “Economic models” and their application in the “Planning process” of bus fleet electrification. The National Academy of Sciences of Belarus - United Institute of Informatics Problems (UIIP) is developing models for a complex optimization problem, which is to determine a fleet of e-buses and their traffic intervals, to determine places for charging stations and transformers, assignment of charging stations to their potential locations, assignment of charging stations to the transformers and assignment of charging stations to the routes such that all e-buses can feasibly drive and the power reserve of any transformer is not exceeded, for a given set of urban routes. The objective is to maximize the ratio of the total value of the conversion decision (positive ecological or social-ecological effect expressed quantitatively) to the total cost of this decision. UIIP is also working on a mathematical model and a method for minimizing the number of depot charging points for a given fleet of e-buses serving a given set of urban routes. These problems are mainly related to the infrastructural side.

Problems related to the bus vehicle and fleet specific side are worked out by National Academy of Sciences of Belarus - Joint Institute of Mechanical Engineering (JIME). The models cover those of “Energy Storage” like battery models under consideration of energy consumption during bus operational revenue cycles and temperatures, battery type etc., as well as “Vehicle models” covering different types of bus vehicles including their modelling parameters and capabilities.

The Austrian “Energie und Umwelt” consultancy (EUC) has developed a model of “Energy consumption” and tested under conditions of real time data that are collected during conventional bus operation cycles that are post processed by algorithms in order to assess energy consumption of electric bus vehicles. The main responsibilities beside project coordination of German institute ifak are the tasks of “Integration” of these different model approaches and ensure the “Interoperation” of the various tools to be developed. Ifak will help to implement these approaches into an -easy to use- toolset for practitioners of public transport operating companies in order to support the decision and planning process of bus fleet conversion.

The functionality of the PLATON planning tool will include the capabilities of the models that are developed under the lead of responsive partners of the project. Therefore the models must be implemented in a way that allows for their integration or interoperation using well defined interfaces for data exchange. For example, the economic model should take into consideration the Total Cost of Ownership (TCO) of electric bus operation, including the deprecated procurement costs, maintenance costs, personnel and energy costs and their influence on fares with respect to different countries. The model of charging infrastructure, scheduling and optimization of electric bus operation should enable the user of the tool to vary the vehicle allocation for a given set of boundary conditions and constraints such as passenger capacity and energy storage capacity of the buses as well as existing charging infrastructure taking the available energy grid into account.

For the model of Energy storage and Bus vehicles is important to keep the data updated considering a very dynamic market of bus vehicles. It should allow to select various parameters of batteries and vehicles that are required for simulations of a single bus and the entire bus fleet as well as the energy consumption of single vehicles and the bus fleet under consideration of different variants of charging strategy such as opportunity charging, depot charging or in-motion charging.

From the planners point of view it is rarely the case, that all parameters are at hand which are necessary to describe the electrification of an urban bus fleet for a given public transport network and its services. Therefore, it is not only valuable but also essential to reprocess field data in form of real time datasets that have been measured by means of GNSS devices. By reprocessing these datasets, it is feasible to obtain a highly reliable assessment of energy consumption under real conditions that take into e.g. terrain data, velocity profiles depending on traffic conditions and the road network. In result of analysis of this reprocessed data set, it is created a feedback loop for parameters of the models that can be validated in this way.

The integration of all base models into one toolset will be achieved by implementing the algorithms and dataset of each model into one implementation whenever it seems appropriate. However, if the usability of the toolchain requires a decentral approach there can also be implemented a distributed solution that communicates over IP based protocols.

2.1 Public transport agency management board

The basic use cases for a tool to support management decisions are those to justify strategic decisions on electrification regarding the procurement of vehicles, investments in infrastructure and planning directives for the further development of the transport network.

The following subjects can express the use cases envisaged for the tool component A):

- How much buses are needed for the fully electrified bus fleet to fulfil the contractual public transport mission?
- What are the annual total costs of ownership (TCO) of the public transport operator's fully electrified bus fleet under country specific economic conditions?
- Which bus models and makes in relation to which charging technology are fitting best to the needs of the public transport operator?
- Can the versatile scheduling and deployment of e-bus vehicles on various routes be achieved during the daily vehicle cycle.

In order to meet the essential requirements, needed in the procurement process for economic decision support about electric bus make, model, and type, powertrain dimensioning, battery size and range a multitude of influencing variables must be taken into account. For example, the transit operations policies such as frequency and passenger ridership influence the quantity and capacity of bus vehicles, the route length and geometry like terrain grades influence the required power and battery configuration.

The input data sets required for the tool component A) *Economical decision assistance tool component* are:

- Operational Characteristics
    - Annual distance per year
    - Years in service
    - Average passenger mass
    - Average number of passengers

- Infrastructure
    - Operational costs (maintenance)
    - Capital costs of charging infrastructure
- Economics
    - BEB capital costs (depending on model and make)
    - Depreciation, Interest and Repayment costs
    - Battery pack costs per kWh
    - Maintenance costs per km
    - Energy costs per kWh

The input data must be specialized for each country or be configurable such that procurement costs, investment costs, infrastructure costs, energy costs, wages, depreciation, etc. can be adapted to the country of application.

The expected output information for the tool component A) *Economical decision assistance tool component* are:

- Procurement decision support (feasibility) on bus quantities, make and models
- Total cost of ownership for annual and medium-term financial planning

In the following sections it is outlined a methodical framework that has been designed to solve problems being addressed by the use cases of the *Economical decision assistance tool component.*

2.1.1 Total Cost of Ownership of the investment in e-buses under the country specific conditions

Electric buses are usually cheaper in the field of operation, when compared to conventional buses. However, acquisition costs are significantly higher. For many municipalities, local governments and bus operators, costs are a key aspect of fleet renewal, aiming to achieve a 100% electric-powered fleet. Having regard to the economic reality in which transit company operate, the cost dimension appears to be a key one.

Total Cost of Ownership (TCO), understood as an estimation of all the direct and indirect costs involved in acquiring and operating electric buses over their lifetime in a transit company, is one of the key figures related to the fleet conversion issue. TCO calculation is insofar difficult as we need to take into account different rules and regulations in various countries. It is noteworthy that each state has its own specificity we must include without limiting any functionality of the tool.

There are many factors that influence the TCO values. In general costs related with the fleet conversion may be divided into the following groups:

- Cost of acquisition:
    - purchase price of buses with battery pack and spare battery pack (considering depreciation rules)
    - self-financed and external acquisition costs (taking into account subsidies)
- Running costs
    - energy costs
    - maintenance costs of e-buses
- Infrastructure costs
    - cost of charging (with a breakdown into plug-in, pantograph and inductive charging)
    - self-financed and external charging infrastructure costs
    - maintenance costs of infrastructure
- External costs

Obviously, there are much more costs related with the fleet exchange process. Above, only these the most important ones are presented. Abovementioned costs may also be shown in terms of cost of pass·km (passenger·kilometre) and cost of bus·km (bus·kilometre). The whole is complemented by the liquidation proceeds.

The tool for transport operators and management to calculate the Total Cost of Ownership of e-buses will be based on efficient economic model. The construction of these models seems to be a challenge as e-buses are quite a young technology and no experience have been gained for the whole life cycle of the bus in real conditions.

This model should take into account all the significant factors (technical, economic, organisational and ecological) affecting the fleet conversion process and have an impact on the TCO. In particular, the following are involved: a number of electric buses purchased and their parameters, a number and type of charging facilities, depreciation issues, etc. It is planned, that the model will take into account a change (increase) in the number of electric buses operated by a transit company.

The TCO is also influenced by the size of the municipality in which electric buses are planned to be operated. Depending on whether a city is small, medium or large (which has an influence on the daily and annual mileage), TCO dimensions will change. In general, the greater is annual mileage (more effective fleet utilization), the more cost-effective is the use of electric buses. This functionality of the PLATON tool component is to be designed for the executives of the transit company.

2.1.2 Number of electric buses needed to fulfil the timetable

One of the three variants can be followed in order to achieve a 100% electric bus fleet. These variants are presented in Figure 2. The first one assumes a maintenance of the current timetable without change the structure of vehicle cycles. Two others allow for changes in the structure of vehicle schemes.

In the first strategic variant, there would be no change in the number of electric buses needed to fulfil the existing timetable. However, the condition for the success of this approach is a high density of charging stations across the transport network. Otherwise, some vehicle cycles may be impossible to be operated by electric buses. However, this does not change the fact that a dense charging network will have a significant negative impact on the cost of deployment of electric buses and may cause economic constraints.

In the second variant a maintenance of the current timetable with acceptable changes in the structure of vehicle cycles. From the passenger point of view, no timetable modifications will be visible. Nevertheless, due to insufficient bus range resulting from the battery technology and the need to allow a certain amount of time for charging, extra operational work becomes necessary. Thus, it will be necessary to calculate how many additional electric buses are needed to make this technical inconvenience unnoticeable to passengers. In other words, the objective is to assess the 'side-effect' of the induction of e-buses in transport network which is an additional operational work, expressed in the number of extra buses needed to fulfil the existing timetable

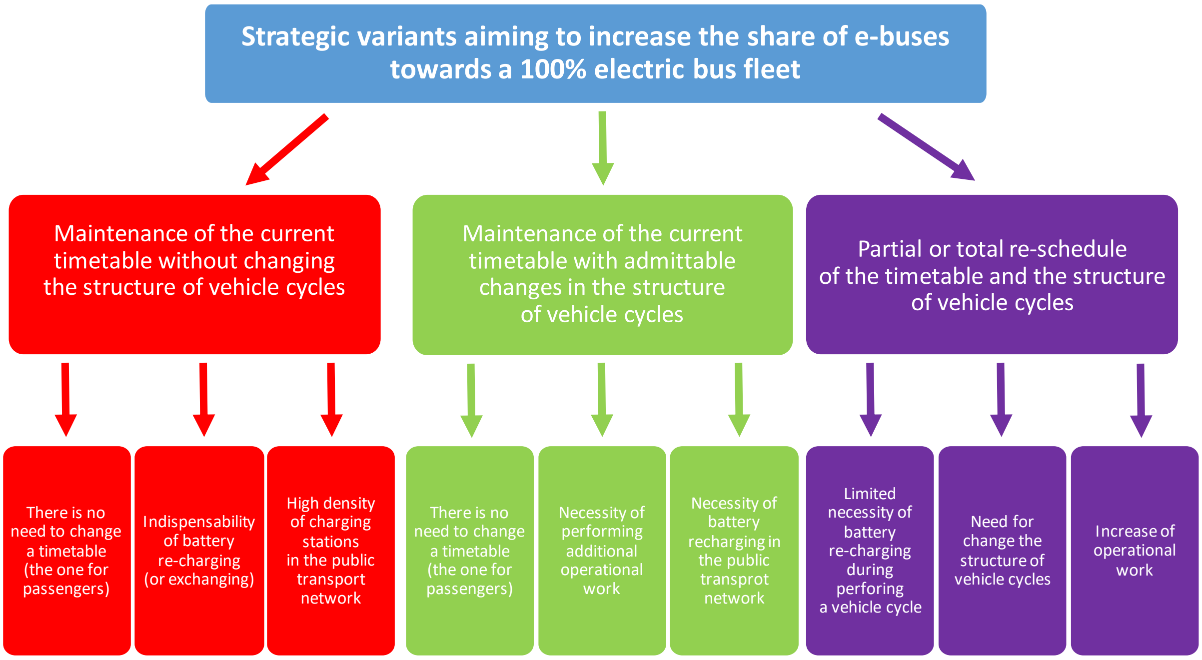


Figure 2. Strategic variants to achieve a 100% electric bus fleet

In the third variant, a new bus timetable (which implies new vehicle cycle scheme) is to be constructed. Here, there is no obligation to keep the public transport offer on the same level. Nevertheless, the question: *How many electric buses are needed to fulfil the timetable?* is still justified. This question, taking into account charging constraints, can be paraphrased in the following way: *How many more e-buses do we need to purchase to operate a transport network?*

Like the previous functionality, this one is to be created for transport executives, responsible for acquisition of new electric buses.

2.1.3 Suitable battery configuration and charging strategy for a given area

Due to limited operational range of electric buses, the decision on charging scheme becomes a key choice to be taken by transit company. There are a few charging configurations, split by charging methods:

- Plug-in charging
- Pantograph charging
- Inductive charging

The first two charging systems (plug in and pantograph charging) are the most popular now. It should be noted that these two are often combined. Inductive charging is used to a much lesser extent, mainly due to significantly higher costs. Battery swapping is technically possible, but in principle not applied in practice.

In Table 1, a comparison of connections in some charging systems used in electric buses is presented. The table presents continuous and fast charging powers of pantographs manufactured by subsequent companies, as well as induction and plug-in systems.

Table 1. Comparison of connections in e-bus charging systems

Types	Continuous charging power [kW]	Fast charging power [kW]	Max charging current [A]
Schunk pantograph	375	750	1000
Siemens pantograph	60	120	Lack of data
Siemens inverted pantograph	450	600	Lack of data

Types	Continuous charging power [kW]	Fast charging power [kW]	Max charging current [A]
ABB pantograph	50	450	Lack of data
EC Engeenering pantograph	Lack of data	600	Lack of data
Bombardier induction system	200	200	Lack of data
CCS 1.0 plug-in	80	80	200
CSS 2.0 plug-in	350	350	500
CHAdeMO 1.2 plug-in	200	50	80

Present day charging configurations are often classified according to charging speed as well. Such an approach has practical justification in view of the time needed for charging. Charging time is one of the crucial parameters. It depends on many factors, such us: battery type, characteristics and capacity as well as charging station type. In general, there are two strategies: overnight charging and opportunity charging (Figure 3). Charging in depot is often referred as ‘slow’ due to lower charging current used when charging during the night. For the same reason, it is common to refer overnight charging as ‘fast’ charging.

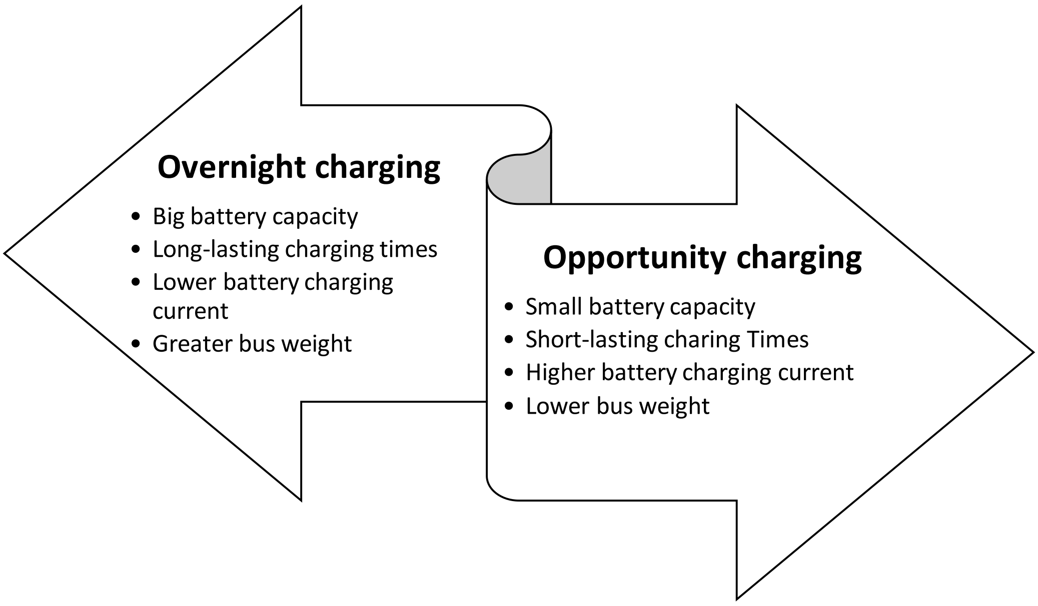


Figure 3. Trade-off between charging strategies

Overnight charging involve so-called ‘slow’ charging (with the use of lower charging current) and battery stabilizing during the night and – if needed – recharging of battery during one or more stops intended for charging (often with the use of pantograph). A general idea of this charging scheme is presented in Figure 3.

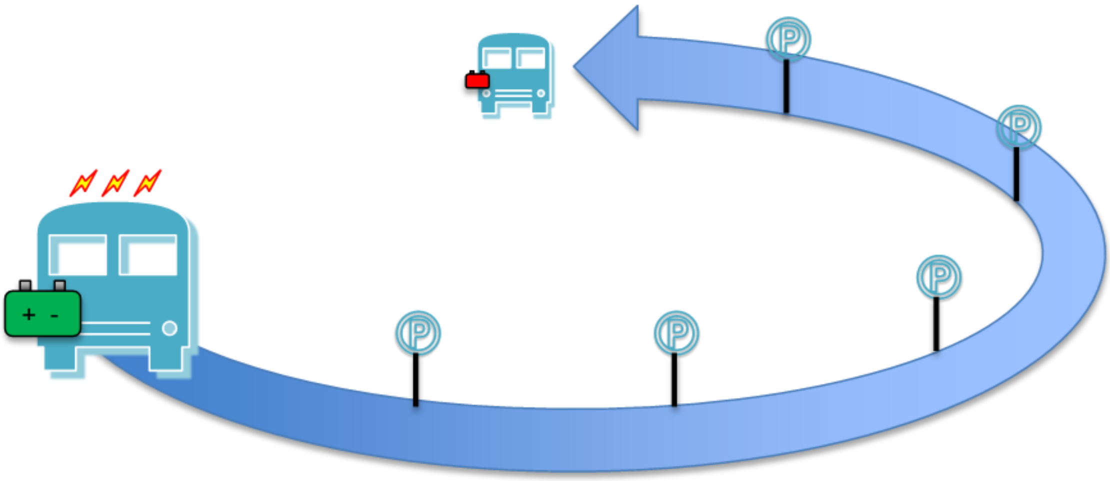


Figure 4. Overnight charging scheme

In opportunity charging, however, there is frequent recharging, but during relatively short stoppages. In view of economic constraints, it is hardly possible for the bus to be recharged in every stop. Hence, only selected ones are chosen to be equipped with charging facilities. Opportunity charging scheme is presented in Figure 4.

When planning charging strategy and configuration, we should not forget about the limitations of the power grid. Local conditions play an important role here. This seems to be one of the major challenges when constructing the PLATON tool.

Searching for a suitable charging strategy is strictly associated with a battery configuration. On the on hand, one need to choose the right battery pack type of which the most popular are:

- Lithium iron phosphate (LFP)
- Lithium nickel cobalt aluminium oxide (NCA)
- Lithium nickel manganese (NMC)
- Lithium manganese oxide (LMO)
- Lithium titanate oxide (LTO)

The battery pack is used in combination with a battery management system (BMS). On the other hand, one should also bear in mind the issue of consistence of battery systems with charging configuration.

Another challenge is to take the fact of battery capacity loss into account. Since no electric buses have been used for long enough to experience the real characteristics of this process, we must be based on modelling. This problem is linked with calculation of TCO, as after some time, new battery pack will become necessary for purchase. Unfortunately, this will increase the total cost of the ownership (TCO) of electric buses for the transit company. In choosing the proper charging scheme and battery configuration, technical and economic issues are intertwined.

This functionality has more than one target group. It is intended to support strategic planning and investments (management level in transit companies in cooperation with municipal transport planner), but it can be also appreciated by operational planners during in their daily management of e-bus fleet.

2.2 Urban transport planner

Apart from direct planning of transit operations to accommodate problems of electric vehicle deployment, the harmonization of public transport and electric power domain must be tackled.

The super-ordinated municipal planning level is entitled to coordinate any planning activities connecting the public transport network and required charging infrastructure with the electric power grid such as planning of charging facility locations, specification of locally and timely power demand during transit operations.

The planning authority is also responsible for transit demand specifications such as headway policies and stop spacing in various urban districts, stated in the relevant urban public transport plan.

The following subjects can express the use cases envisaged for the tool component B) *Transport and energy sector coupled planning tool component*:

- What type of charging infrastructure and charging technology configuration (overnight/opportunity charging) corresponds best to the local public transport operator strategy?
- Where have to be localized charging facilities in the public space?
- How can the integrated planning of transit network be achieved based on geo-information by considering the medium voltage power grid?

- How can the demand-specific urban public transport plan (policy headways, stop spacing) be harmonized with electrical energy supply.

- Is the planned configuration of vehicle, route and daily cycle feasible from the viewpoints of transport technology and estimated energy consumption rate?

The input data sets required for the tool component
B) *Transport and energy sector coupled planning tool component* are:

- Digital street map
- Public transport specifications
    - Location of stops
    - Geographic shape of routes
    - Schedules
- Electricity network for medium voltage grid
    - Geographic shape of power lines
    - Transformer locations
    - Charges for electricity withdrawals at peak time and non-peak time

The expected output information for the tool component
B) *Transport and energy sector coupled planning tool component* are:

- Location of charging facilities
- Spatial-temporal power network
- Electrical load of charging stations in dependence of vehicle schedule
- Investment decision support for municipality and PT agency

In the following sections it is outlined a framework of methods that has been developed and implemented to solve problems being addressed by the use cases of the *Transport and energy sector coupled tool component.*

The erection of opportunity charging facilities at transit stops along an electrified bus route is subject to decisions on location of bus service stops, the availability of energy supply, the type of charging standard and operations. An important precondition for the construction of charging infrastructure is the spatial proximity to power lines of medium voltage (1 kV up to 30 kV) to supply sufficient energy for charging stations.

Therefore, the location of charging stations is influenced by both the location of bus stops and by the proximity to energy supply. The availability of transformer stations from medium voltage to low voltage is essential for the cost of charging infrastructure, which is a significant share of total cost of ownership (TCO).

Eventually new transformer stations and additional cabling to charging stations have to be build adding up to anyway cost figures. A method is described to support the decision process by means of geographical information about power grid including locations of transformer stations, road network, and transportation network including transit stops.

The attributed geographical information is administered within a spatial database system with geographic processing functionality. The approach is implemented by algorithms in standardized structured query language (SQL) of the applied spatial database system with geographic functional extensions.

2.2.1 Variants of location finding for opportunity charging facilities

Transit operations planning like vehicle and crew scheduling is nearly a daily practice for public transport agencies, especially under constraints of restricted range of electric vehicles and need for regular opportunity charging during the revenue service cycle.

A planning tool component for this domain area is capable to solve optimization problems such assignment of transport tasks to both electric and conventional vehicles, changes in network design, development of timetables under consideration of charging stops at opportunity charging locations.

One of the basic decisions in the planning process of bus fleet electrification is about the configuration of charging infrastructure in relationship with the required battery size of the deployed electric buses. Considering an average daily mileage of about 250 km at an average energy consumption rate (ECR) of 1.5 kWh/km (including auxiliary electrical loads, such as heating, ventilation, air conditioning and powered steering) the required theoretical battery capacity would amount to 375 kWh. For practical transportation-technological reasons a maximum depth of discharge (DOD) of 60% should be accepted in order to avoid premature battery ageing as well as to allow enough reserved capacity and range. In this realistic case, the theoretically required battery capacity amounts to 937 kWh.

It is obvious that a full day vehicle cycle without intermediate recharging of the battery pack is not feasible, given the present technological state of the art. Typical battery sizes of battery electric buses (BEB) that are presently (2019) on the market are 160 kWh for 12 meter long BEB’s and 240 kWh for articulated 18 meter long BEB’s.

Provided the deployed BEB’s are equipped with above sized battery packs, the charging configuration requires opportunity charging at one or more stops along the route of revenue service. The bus route is determined by the stops to be serviced. The location of stops is determined by the given transit demand of the residential districts or business districts, respectively. The recharging of batteries can take place at terminal stops when the timetable allows for enough charging time between arrival and departure for the next duty cycle. Ideally, the recharging time can be combined with the legal resting time of the driver.

Alternatively, opportunity-charging facilities are established at regular transit stop locations if timetable requirements allow for short trip interruptions or short connections to near electric power transformers offer favorable conditions. In the following it is described a systematic approach to identify potentially suitable locations for the establishment of charging infrastructure under consideration of spatial relationships between electrical power grid, road network and transportation network.

2.2.2 Initial data sets for location analysis for charging facilities

2.2.2.1 *Electrical grid*

Basis for the supply of electrical power for fast charging stations are power lines of medium voltage (1 kV up to 30 kV) which are laid as earth cables in general alongside public roads. Only medium voltage power lines are dimensioned such that the energy demand of fast charging processed of 200 kW and above are met.

The medium voltage grid is provided as a geographical line feature shape file, which is imported into a geographical data base system with geographical processing functionality (PostgreSQL/PostGIS) [1][2].

2.2.2.2 *Power transformer stations*

The establishment of fast charging facilities requires either their connection to an existing power transformer station, or a new-built direct connection to the medium power line, which includes also the construction of a new transformer.

Transformer stations are located at distributed locations to provide the connection to the low voltage grid (400 V) for the energy supply of households. The transformer locations of the medium power line are provided as a geographical point feature shape file.

2.2.2.3 *Road network*

The road network is required for calculation of distances from transit stops locations to existing or planned power transformer stations by route searches within the road network. The required cable lengths correspond to the calculate distances of found road network routes.

The road network was obtained from OpenStreetMap (and contributors) over free access sources and was processed in various steps to transform the given raw network data into a node/link topology.

2.2.2.4 *Transit stops*

The local public transport operator provided transit stops including terminal stop locations including their unique identifier, names and geographical coordinates. Each stop represents an exact location for passenger boarding and alighting the public transport vehicle. In many cases, single stops belong to a larger common logical stop with the same name, e.g. in the simplest case for opposite travel directions.

A combined view of the initial data sets is shown in Figure 5 and illustrates the principle of geographical superposition that is essential for the developed evaluation method. The electrical medium power grid is displayed in light blue over the light grey road network. Dark blue squares mark the location of transformer stations; orange squares mark the location of transit stops.

Figure 5. Layers of initial data sets used in the cost evaluation of alternative opportunity charging locations

Table 2. Cable line costs at different surfaces

No	Surface	Costs	Comment
a.	Stone pavement	200 EUR/m	at an estimated share of 30%
b.	Asphalt	300 EUR/m	at an estimated share of 60%
c.	Green surface	100 EUR/m	at an estimated share of 10%
d.	Cable costs medium voltage	30 EUR/m	
e.	Cable costs low voltage	50 EUR/m	
f.	Average costs medium voltage	280 EUR/m	
g.	Average costs low voltage	300 EUR/m	

2.2.3 Problem solution to minimization of overall connection costs

The problem of connection cost minimization is solved by calculating the costs of the following alternatives:

A. Connection of a charging facility (i.e. the transit stop) to an existing transformer station that exists already in the power line.

B. Connection of the charging facility (i.e. the transit stop) to a new (to be) constructed transformer station in a minimal road distance to the medium voltage line including

The connection costs from existing transit stops to existing or potentially to be newly built transformer stations have been analyzed based on the following algorithm and cost figures provided by the utility supply firm:

1. Input data are the distance lengths of all transit stops to nearest existing transformer stations determined by route search in the GIS spatial database (PostgreSQL/PostGIS). As stated above, the road map base used for route search is OpenStreetMap.
2. For each transit stop search for the nearest transformer station and determine the route length for this stop/station pair. The result for each stop/station pair is saved into a separate field and denoted as alternative A.
3. The distance length from a transit stop to the nearest point in the medium voltage grid is determined by nearest neighbor search from transit stop to medium volt-age grid to find the nearest point and route search from transit stop to nearest grid point.

4. The result for each stop/nearest-grid-point pair is saved into a separate field and denoted as alternative B.
5. Use the cable line costs LC, according to information of the supply firm provided in Table 1.
6. The cost TS for a medium voltage transformer station is 40.000 EUR plus incidental costs of 2.200 EUR = 42.200 EUR
7. To account for both alternatives A and B the total costs TC are determined as follows:

$$TC(A) = LC \cdot distance_{stop/station(A)} \tag{1}$$

$$TC(B) = LC \cdot distance_{stop/nearestpoint(B)} + TS \tag{2}$$

For decision-making, a comprehensive table was created to calculate total costs based on distance lengths for both alternatives A and B. As such, the management decision (to build new/ use existing) is supported by substantial calculations for each individual case to identify suitable stop locations for charging infrastructure investment.

The processing steps of cost determinations for the described connection alternatives are shown exemplarily in Figure. 6. Basis of calculations are path searches in the conditionally prepared road network between geographical locations of transit stops and either existing transformer stations or new-to-be-built transformer stations as the fundamental precondition for the establishment of the charging facility. The conditionally prepared road network (A) must have the precondition of a routable network, i.e. to possess the property of a node-/link topology of a directed graph. It is necessary to emphasize this requirement, since the basic road network being used for the described method has a priori not this required property. However, this requirement can be achieved in a series of spatial database processing steps of splitting and noding of the network, which are not described further here. The routability is indicated in Figure. 6 part A by distinguished markings for the beginning and endings of edges. Part B displays the geographic overlay of the medium power electric grid, which is in general laid along the road network but constitutes a separate network, shown in turquoise color. The overlay is essential to enable the search for relationships by using geographical functionality of the relational spatial database extension (PostGIS) [2].

In Figure. 6 part C additional point locations layers of transit stops (emphasized in purple color) and existing transformer stations (emphasized in green color) are shown. Both layers are input information for the algorithm to determine the shortest distances from transit stop to existing the nearest transformer station or to the nearest point in the electric power grid.

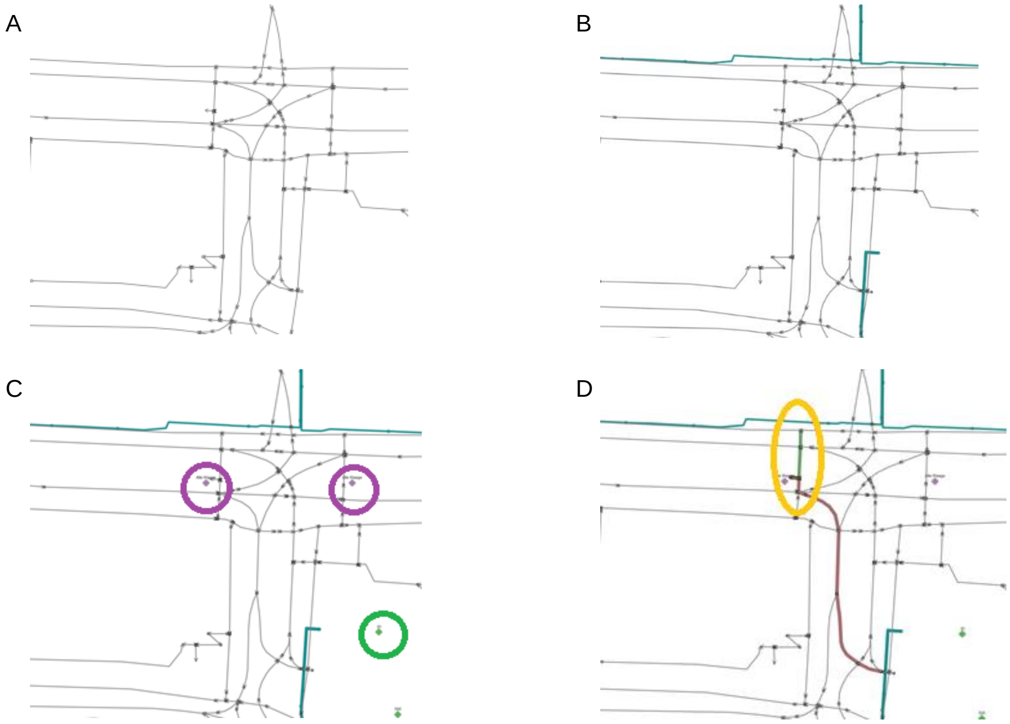


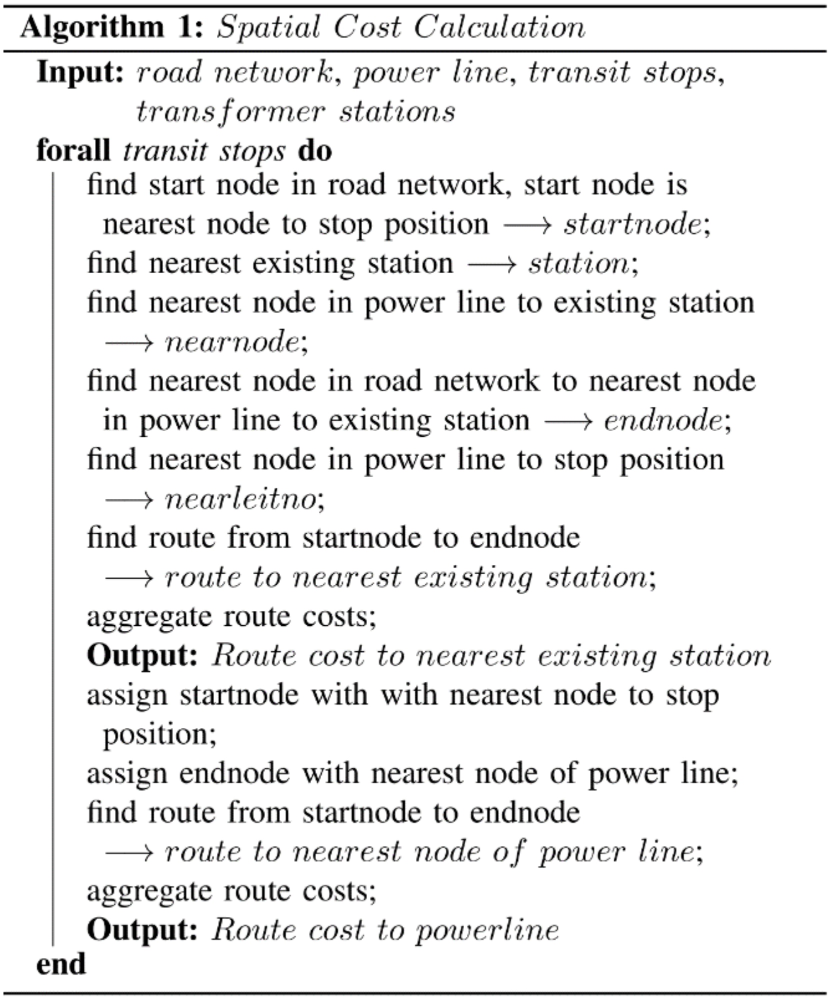
Figure. 6. Processing steps of cost determination for connection alternatives of transit stops to existing or new transformer stations

In the first step the algorithm searches for the shortest path in the road network. Therefore the start node is found as the nearest node of the road network to the given transit stop position. For nearest neighbor search it was applied a generic solution, developed by Boston GIS Consulting [3] licensed for open source usage in PostGIS. Secondly, the nearest existing transformer station to the given transit stop is found. In the third step the nearest node of the electric power grid is searched which has the shortest distance to the given transit stop. Thirdly, the end node, as the nearest node in the road network to the nearest node in power line, is found which itself is nearest to an existing station. Finally, the nearest node in the power line to the position of the transit stop is searched.

The route costs in units of distance are aggregated by applying the *K* shortest path routing algorithm based on Yen’s algorithm [4] from determined start node to end node and saved in a variable representing the route cost to the nearest existing transformer station (alternative A).

For alternative B the start node is assigned as the nearest node of the road network to the transit stop position and the end node is assigned to the nearest node of the road network to the nearest node of the power line. The route costs in units of distance are aggregated by applying the K shortest path routing algorithm from the latter start node to latter end node. The result is saved in a variable representing the route cost of the nearest road network node to the nearest node of the power line as a potential location of a new to-be-built transformer station (alternative B).

The algorithm, described in Algorithm 1 ends after for all transit stop locations the route costs for alternatives A and B were determined.



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Algorithm 1: Spatial Cost Calculation
Input: road network, power line, transit stops,
       transformer stations
forall transit stops do
    find start node in road network, start node is
      nearest node to stop position $\longrightarrow$ startnode;
    find nearest existing station $\longrightarrow$ station;
    find nearest node in power line to existing station
      $\longrightarrow$ nearnode;
    find nearest node in road network to nearest node
      in power line to existing station $\longrightarrow$ endnode;
    find nearest node in power line to stop position
      $\longrightarrow$ nearleitno;
    find route from startnode to endnode
      $\longrightarrow$ route to nearest existing station;
    aggregate route costs;
    Output: Route cost to nearest existing station
    assign startnode with with nearest node to stop
      position;
    assign endnode with nearest node of power line;
    find route from startnode to endnode
      $\longrightarrow$ route to nearest node of power line;
    aggregate route costs;
    Output: Route cost to powerline
end
```

2.2.4 Evaluation method of resulting cost figures

In result of the spatial database supported cost analysis, a comprehensive table of cost figures has been created that is subject to further evaluation by the following steps.

Both distance lengths A and B of equations (1) and (2) are compared under consideration of the potential costs for a new transformer station in comparison of the cost for longer cable costs:

- If the cost for alternative A is greater than for alternative B the decision is recommended to build a new transformer station and to connect it to the nearest point in the medium power line.

- If the cost for alternative B is greater than for alternative A the decision is recommended to connect to the nearest transformer station by newly laid cable using the shortest road path.

Table 2 shows a small excerpt from the extensive decision table of the costs evaluation that has been an output of the spatial database supported cost analysis.

Beside the columns of transit stop ID and the calculated distances A and B it is shown the evaluated costs for each alternative and the recommended decision for new construction. Special cases where taken into account when the transit stop is located outside the area where the medium voltage power line shape is not available and the transit stop is located directly on the medium voltage power line (B = 0). In the latter case, the new construction decision is obviously more economical.

Table 3. Excerpt from decision table of cost analysis

ID	A in m	B in m	TC(A) in EUR	TC(B) in EUR	Recommendation
1511	216	209	64.800	104.900	Use existing
1512	N/A	N/A	78.900	47.300	New construction
1611	N/A	N/A	N/A	N/A	
1612	N/A	N/A	N/A	N/A	
1711	N/A	N/A	N/A	N/A	
1712	N/A	N/A	N/A	N/A	
1811	284	324	85.200	139.400	Use existing
1812	284	324	85.200	139.400	Use existing
1911	168	0	50.400	42.200	New construction
1912	200	23	60.000	49.100	New construction
2011	228	24	68.400	49.400	New construction
2012	237	10	71.100	45.200	New construction
2111	1009	3	302.700	43.100	New construction
2112	1091	0	327.300	42.200	New construction
2213	487	56	146.100	59.000	New construction
2214	587	123	176.100	79100	New construction

Evaluation of Table 2 directs to many cases in which geographical relations of transit stops locations and transformer station locations have to be considered as well as incorporated into the final decision-making.

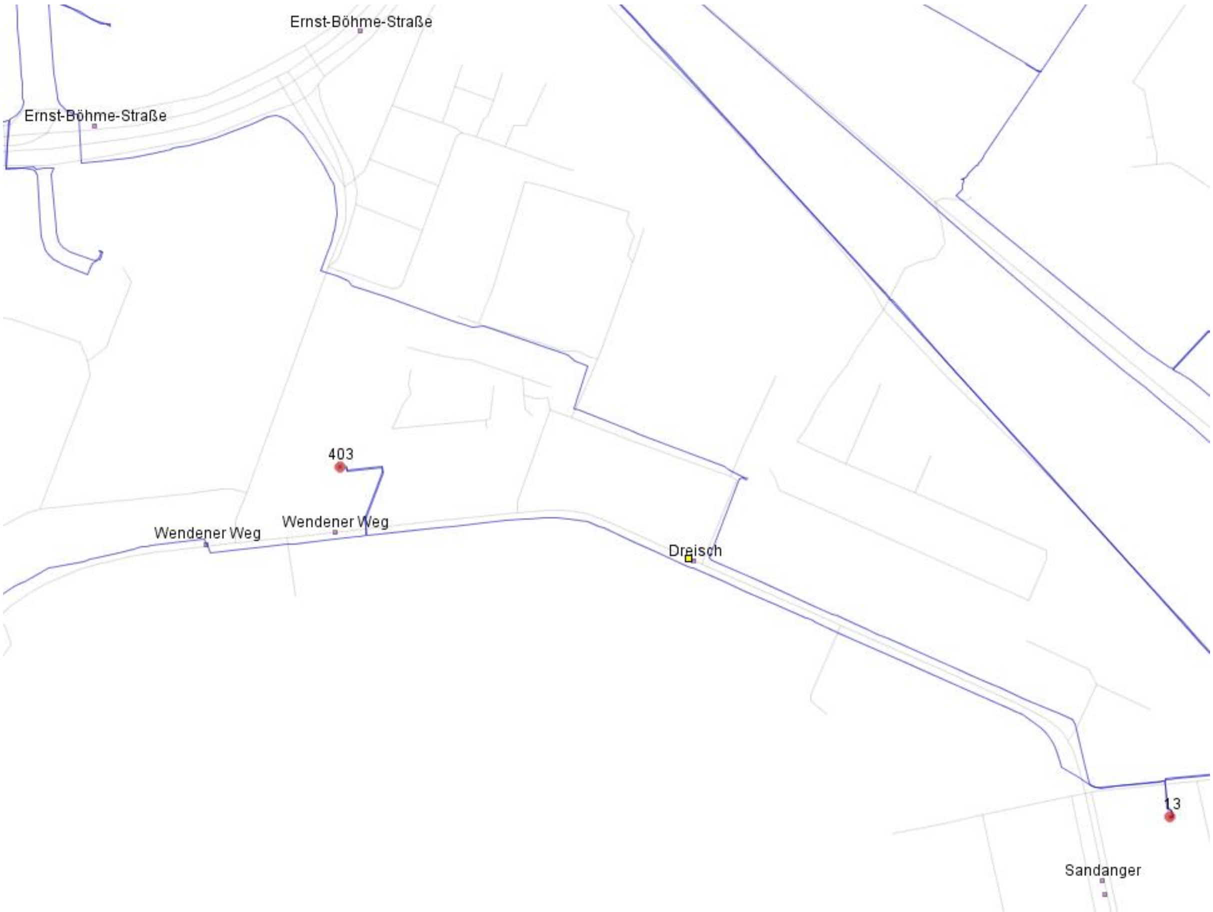

Figure. 7. Variant of transformer station usage for a subsequent transit stop

In Figure. 7 such a case is shown where the distance to a transit stop (“Dreisch”) to both transformers (“13” and “403”) is disproportionately long in geographical relation to subsequent transit stop (“Wendener Weg”). In this case, the reasonable recommendation would be given to use the subsequent transit stop for construction of the opportunity charging facility.

Furtherly, transit stops should be excluded for construction of opportunity charging facilities, if construction costs exceed a predetermined cost rate. Regarding the required capacity reserves of the BEB vehicles it is also evident that a significant subset of transit stops is being short-listed for opportunity charging.

By complete evaluation of Table 2, the decision on new station construction or connection to existing station can be made based on substantial analysis and reasoning of geographical relations.

2.3 Public transport operations planner

Transit operations planning like vehicle and crew scheduling is nearly a daily practice for public transport agencies, especially under constraints of restricted range of electric vehicles and need for regular opportunity charging during the revenue service cycle.

A planning tool for this domain area is capable to solve optimization problems such assignment of transport tasks to both electric and conventional vehicles, changes in network design, development of timetables under consideration of charging stops at opportunity charging locations.

The task of crew scheduling is not included as a capability of the tool component for optimization problems since it is not considered as specifically related to the fleet electrification planning process.

The following subjects can express the use cases envisaged for the tool component C) *Tool component for optimization problems*:

- How can a given number of electric buses be deployed and scheduled best to fulfil the overall daily transport vehicle cycles.
- How can vehicle schedules be adapted to achieve a preferred evenly distributed energy consumption over the course of a day?
- How can the optimized schedule avoid electrical peak demand loads?
- How do changes in network route design affect the public transport schedule and timetable development?

The input data sets required for the tool component C) *Tool component for optimization problems* are:

- Digital road map
- Stop locations
- Existing routes
- Charging locations
- Bus frequencies: departure and arrival times

- Charge levels of batteries
- Passenger load per edge

The expected output information for the tool component
B) *Tool component for optimization problems* are:

- Timetables
- Schedules
- Network (changed) design under electric vehicle conditions/constraints

In the following sections it is outlined a methodical framework that has been designed to solve problems being addressed by the use cases of the *Tool component for optimization problems*.

A mathematical model and a method for minimizing the number of depot charging points for a fleet of electric buses (e-buses) serving a given set of urban routes have been developed.

The model is based on simulating discharge processes of e-buses according to their itineraries of the most representative day and on optimizing the use of the depot parallel recharge points over time. It is assumed that e-buses are equipped with high-capacity batteries (hundreds of kWh) which keep sufficient energy for executing the daily itinerary and are recharged in the depot.

The batteries are slow charging (2-6 hours). The constraints include the requirement to fully restore the charge of the batteries and to address the available dynamic power supply provided by the city electrical grid.

The input data are departure and arrival times of e-buses from/to the depot, the charge levels of the batteries when the e-buses return to the depot, the functions of batteries charge depending of the current charge level and the charging time, and lower and upper bounds on the number of the depot charging points.

2.3.1 Formulation of assumptions for the complex optimization problem

The following assumptions are imposed:

1. For each route, the depot, the bus stops and the order of their visiting by e-buses are given.
2. Fleet of conventional buses can be replaced partly.

3. 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.
4. Routes can intersect at depots, terminal stops and en-route stops.

5) 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. It this assignment is not made for an appropriate quadruple (e-bus type, route, location, charging station type), and then from the modeling point of view, an e-bus visits the location with no charging.
6) 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.
7) 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.
8) Each charging station in the same location is connected to the same m transformers, $m \in \{1,2\}$. At any time, only one arbitrary transformer link is active for each charging station.
9) 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.
10) Duration of one cyclic run of any e-bus in the DST time period is the same for the same e-bus type and the same route.
11) Duration of one cyclic run of any e-bus, including all intermediate charging times, does not exceed the duration of the DST time period.

2.3.2 Input data for the complex optimization problem

Lowercase letters are used to denote numerical data and uppercase letters are used to denote sets and, later on, decision variables. There are the following required input data.

- Upper bound *uoc* on the total operating cost.
- Duration *dst* of the DST time period.
- *Transportation and electrical network G* = (NN,R,EE), which is a *weighted mixed multigraph* with set of *nodes* (locations for charging stations and transformers) NN, set of *directed circuits* (routes) R and set of edges (transformer links) EE, see Figure. 8 for an illustration. There, 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).

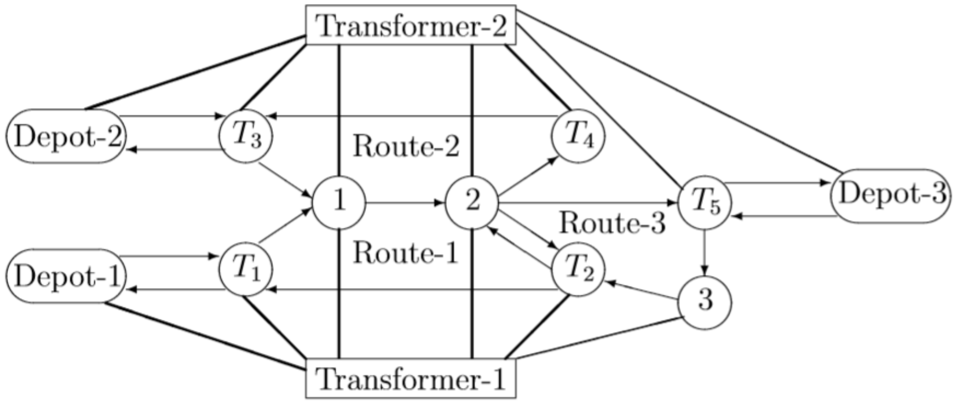

Figure. 8. Network of three routes

- Set *NN* is partitioned into set T of *transformer* nodes corresponding to eligible transformer locations and set *N* of non-transformer nodes corresponding to eligible charging station locations.
- Set *T* contains a subset *TO* of transformer nodes at each of which at least one old transformer exists with a positive power reserve for e-buses.
- Set *N* is partitioned into set *ND* of *depot nodes* eligible for opening a depot charging station, set *NT* of *terminal nodes* eligible for opening a terminal stop charging station, and set *NE* of *en-route nodes* eligible for opening an en-route charging station.
- Set *N* contains a subset *NO* of non-transformer nodes at each of which at least one old charging station of any type is opened.
- Set of routes *R* is built over nodes of the sets *ND, NT* and *NE*. The same node can belong to different routes.
- Subset $R_0 \subseteq R$ of routes served by at least one old e-bus.
- Arc $(i,j) \in r$, $r \in R$, represents a directed segment of a route, going from a non-transformer node *i* to a non-transformer node *j*.
- Edge $(i,j) \in EE$ represents an *eligible link* of transformer node *i* and a non-transformer node *j*.
- Set *B* of e-bus types.
- Subset *BO*, $BO \subseteq BO$, of types of already operating (old) e-buses.
- 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^{cap}_c , which is the cost of purchase and installation of one charging station without the transformer connection costs.
- Operating cost cc^{ope}_c , which is the cost of operating one charging station in a year.
- Set $N_c \subseteq N$ of nodes eligible for opening a charging station of type c.

- Set $NOc \subseteq NO$ of nodes at each of which at least one old charging station of type c is opened.
- Further input variables are included in the paper document [5] of the Annex to this report.

2.3.3 Output data of the complex optimization problem

A solution X of the problem `P-Four` can be represented by the following variables.

- Frequency $FR_{rb}(X)$ of new e-buses of type b on route r in the GFE block of cycles, $FR_{rb}(X) = 0$ if and only if no new e-bus of type b is assigned to route r, $r \in R_b$, $b \in B$.
- Set $R_{jcb}(X)$ of routes r such that $fr_{rb} + FR_{rb}(X) \geq 1$ and their old and new e-buses of type b are charged at stations of type c at node j, $R_{jcb} \subseteq R_j$, $j \in N_c$, $b \in R_b \cap B_c$, $c \in C$.
- Set $S_c(X)$ of nodes $j \in N_c$ at each of which an least one new charging station of type c is opened.
- Number $NC_{jc}(X)$ of new charging stations of type $c \in C$ at non-transformer node $j \in S_c(X)$ to serve new and old e-buses of any appropriate type $b \in C_b$.
- Set $L_j(X)$ of transformer nodes $i \in TE_j$ to be linked with non-transformer node j, $j \in N \backslash NO$.

Solution X can be used to calculate the following values.

- $B_r(X) = \{b \in B_r \mid FR_{rb}(X) > 0\}$ - set of e-bus types such that at least one new e-bus of this type is assigned to route $r \in R$.
- $B(X) = \cup_{r \in R} B_r(X)$ - set of e-bus types such that at least one new e-bus of this type is assigned to any route $r \in R$.
- $R_b(X) = \{r \in R_b \mid FR_{rb}(X) > 0\}$ - set of routes, to each of which at least one new e-bus of type b is assigned, $b \in B$.
- $R(X) = \cup_{b \in B} R_b(X)$ - set of routes, each of which is served by at least one new e-bus.
- $C(X)$ - set of charging station types such that at least one new charging station of this type is opened.
- $S(X) = \cup_{c \in C(X)} S_c(X)$ - set of nodes at each of which an least one new charging station of any 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, $j \in S(X)$.
- $SR_{rb}(X)$ - sub-route of route $r \in R_b(X)$ at each node of which at least one new or old charging station of a type $c \in C_b$ is opened to serve e-buses of type $b \in B(X)$ assigned to this route (nodes with no charging station to serve e-buses of type b on route r are removed from the original route).

- Further output variables are included in the paper document [5] of the Annex to this report.

2.3.4 Problem formulation

Denote by *X* the set of feasible solutions X of the problem **`P-Four`**. It is defined as the following system of relations, Figure. 9.

$$Z_r(X) = \sum_{b \in B_r(X)} cap_b FR_{rb}(X) \leq pas_r,\ r \in R(X), \tag{1}$$

$$TP_i(X) = \sum_{j \in M_i(X)} \sum_{c \in C(X)} po_c NC_{jc}(X) \leq o_i,\ i \in T(X), \tag{2}$$

$$lfr_{rb} \leq FR_{rb}(X) \leq \min\left\{ufr_{rb}, pas_r - \sum_{b' \in B(X), b' \neq b} lfr_{rb'}\right\},\ r \in R_b(X),\ b \in B(X), \tag{3}$$

$$\sum_{(i,j) \in SR_{rb}(X)} ei_{r(i,j)b} = sr_{rb}(X),\ r \in R_b(X),\ b \in B(X), \tag{4}$$

$$\sum_{j \in SR_{rb}(X)} io_{jrb}(X) = nsr_{rb}(X),\ r \in R_b(X),\ b \in B(X), \tag{5}$$

$$\sum_{j \in SR_{rb}(X) \backslash ND} ct_{jbc^*} \leq dc_{rb},\ c^* = c_{jrb}(X),\ r \in R_b(X),\ b \in B(X), \tag{6}$$

$$nv_{rb} + NV_{rb}(X) = nv_{rb} + \lceil d_r FR_{rb}(X) \rceil \leq uv_{rb},\ r \in R_b(X),\ b \in B(X), \tag{7}$$

$$nc_{jc} + NC_{jc}(X) \leq uc_{jc},\ j \in S_c(X),\ c \in C(X), \tag{8}$$

$$\sum_{c \in C_b} (nc_{jc} + NC_{jc}(X)) \geq 1,\ j \in NM_b \cap S(X),\ b \in B(X) \cup BO, \tag{9}$$

$$nc_{jc} + NC_{jc}(X) \geq \sum_{b \in B_{jc}(X)} ct_{jbc} FN_{jb}(X),\ j \in S(X) \cup NO,\ c \in C, \tag{10}$$

$$|L_j(X)| = m,\ j \in S(X) \backslash NO, \tag{11}$$

$$\frac{1}{FR_{rb}(X)} \in Z_+,\ NC_{jc}(X) \in Z_+,\ NV_{rb}(X) \in Z_+,\ \forall r, b, c, j. \tag{12}$$

Figure. 9. System of relations

Constraints (1) limit passenger flow intensity served by new e-buses for each route. Constraints (2) ensure that the total instant power demand of new charging stations linked to the same transformer does not exceed power reserve of this transformer. Constraints (3) specify lower and bounds on the frequency of new e-buses.

Constraints (4) 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 of the sub-route $SR_{rb}(X)$. Constraints (5) ensure that a required charging station is opened at each node of the sub-route $SR_{rb}(X)$. Constraints (6) require that the total charging time of any new e-bus of a certain type assigned to a certain route in one cyclic run does not exceed upper bound established for this type and route.

Constraints (7) ensure that the total number of old and new e-buses of the same type assigned to the same route does not exceed upper bound established for this type and route. Constraints (8) limit the total number of old and new charging stations of any type at any node from above.

Constraints (9) state that at least one old or new charging station of a type $c \in Cb$ must be opened at a node from the set NMb if this node belongs to a route served by at least one new e-bus. At least, depot is such a node.

Constraints (10) guarantee that the number of old and new charging stations of type c opened at node j to serve e-buses of types $B_{jc}(X)$ (of all routes) is enough to serve at most one old or new e-bus of this set at a time, assuming that these e-buses arrive to node j evenly and the number of the required charging stations is a continuously divisible resource. The latter assumption is a simplification of reality.

The right-hand side of the relation in (10) is a lower bound (underestimation) of the number of required charging stations, because uneven arrival if e-buses and discreteness of the number of charging stations increase the maximum number of the required charging stations over time.

Constraints (11) 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. Constraints (12) specify feasible domains of the variables.

The problem **`P-Four`** can be formulated as follows:

$$\max_{X \in \mathrm{X}} V(X),\ \min_{X \in \mathrm{X}} CC(X), \qquad \min_{X \in \mathrm{X}} OC(X), \qquad \min_{X \in \mathrm{X}} TP(X).$$

The traditional approach is to consider *Pareto front* in the criteria space. In our case, the space is (total value, total capital cost, total operating cost including energy cost, total instant electrical power). Each point of the Pareto front is associated with an efficient solution such that 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.

In real life decision making problems, the cardinality of the Pareto front is huge. Presenting all efficient solutions to the decision maker will be too much time consuming and will make the decision choice process hard. Furthermore, the decision maker can hardly know his or her preferences for selecting an appropriate solution from all efficient solutions. Therefore, we present a randomized approach to solving the problem **`P-Four`** in the the paper document [5] of the Annex to this report.

3 Graphical User Interface rapid prototype wireframe

In order to design a set of decision assistance tools the presumable users have been recognized, as expressed in the previous sections. The group of transport operation planners may be differentiated between transport operators with and without self-operated electric power substations in the transport service area.

In addition, city administration or public transport associations are most likely interested in the potential options of electrification at a less detailed level. Since it is not feasible to produce a multitude of tools, a joint approach is needed.

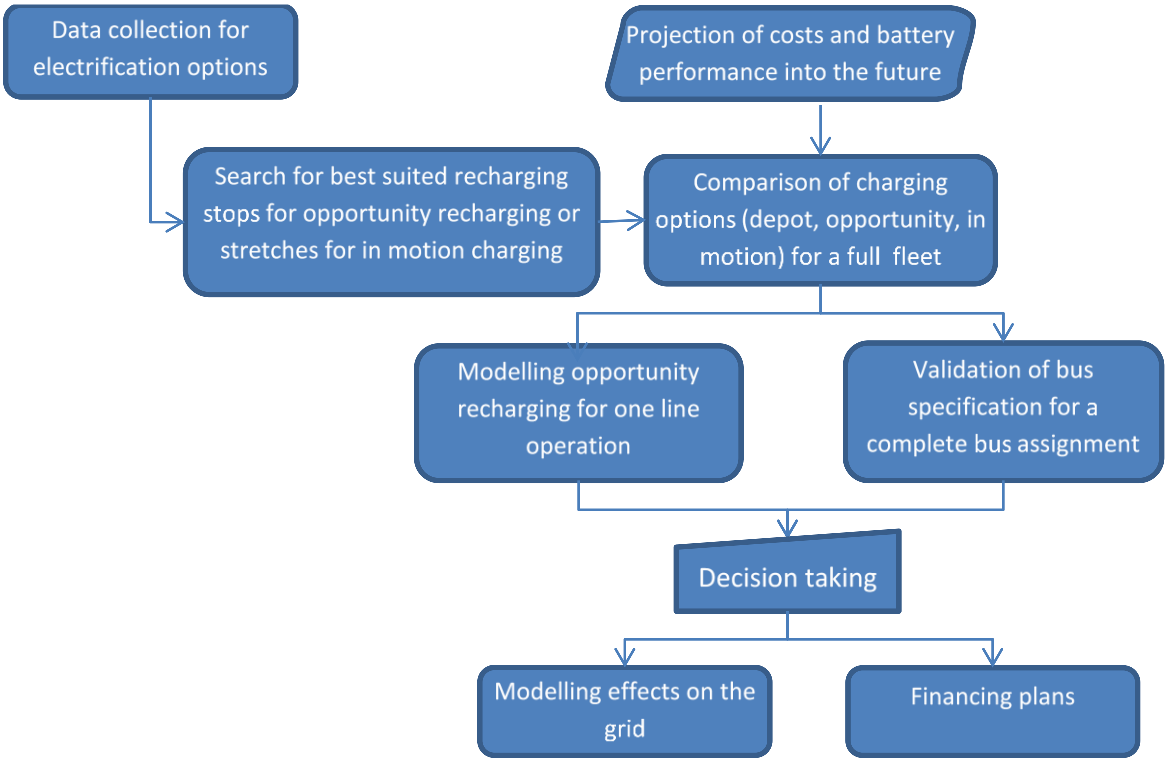

Figure. 10. A workflow for fleet conversion towards battery electrified buses

Figure. 10 presents an overview of a viable workflow for fleet conversion towards battery electrified buses. In this process, a further condition has to be considered, that because of the tendency to use articulated buses, existing bus depot capacities are increasingly running out of space.

The significant tasks or use cases to be covered by the tool may be envisaged as:

- Checking the alternatives for a test case to be implemented instantly
- Optimize the roll out of an electric fleet, and thereby minimizing stranded cost

For immediate implementation, it is necessary to know what kind of bus makes/models and battery sizes are existing. For long-term planning, it will be necessary to know the battery prices for a variant without opportunity recharging. For existing trolley bus operation the dual mode operation might be a third variant to depot charging and opportunity recharging. Opportunity recharging can be sub-classified into the variants: charging at one end terminal, charging at both end terminals, intermediate ultra-fast recharging and combined variants.

Provided it is possible to adapt the time horizon for planning, it will allow covering both short term and long-term decision support. The most important differentiation for defining the interface for the cost model is whether the operator has in-house maintenance, paid by an external operative leasing company, or not.

Several public transport operators follow their self-established and predefined rules on how to acquire bus vehicles. The procurement is a political process and the buses often feature a low utilisation rate (counted in operation hours per year) depending on the bus type. Occasionally the procurement rules cannot be validated using economic analyses. An economic model shall allow coping with those boundary conditions, i.e. for public transport operators, which have to perform with a limited yearly budget, but do not need to fulfil the criteria of minimum cost for the total cost of ownership, including depreciation of capital assets.

3.1 Process steps evaluated

There are at least four processes to be distinguished in the evaluation for the development of a basic wireframe model representing the set of tool components:

1. Pre-planning
    - a) Decision taking for a specific recharging scheme, or a combination between them
    - b) Rebuilding the network and adapting network and depot locations to have lower TCO or yearly cost by electrification or constructing variants causing minimum adaptation cost with regards to personnel, depots etc.
    - c) Adapting routes or depot location to get nearer to electric power substations, lowering grid access investments – also opportunities shall be exploited if the POIs may be connected when rerouting into the vicinity of the 20 kV grid or transformers.
2. Specifying buses with respect to battery capacity and recharging power
3. Constructing or modifying the timetable for the electrified routes
4. Managing bus assignment according to State of Health (SOH)

Within the project PLATON, the main emphasis is laid onto the first two steps whereas the steps 3 and 4 are addressed by the theoretical groundwork that is described in the preceding section.

It should be noted that real world measurements could reveal that recharging times are sufficient at terminal stops if possibilities to shortening the tours are exploited. This could include the establishment of separate bus lanes and bus priority pre-emption at traffic lights. It has to be validated if the measures could compensate for added investments into electric operation.

Occasionally it is communicated that electric buses have lower availability compared to diesel buses, so there should be assumptions for Mean Time Between Failure (MTBF) and Mean Time To Failure (MTTF), which are expected to increase in the future.

Realistic long-term assumptions of increased maintenance cost seem not to be plausible. If more buses are needed because of their low autonomy in the long run, an exchange of the opportunity-charging variant has to be considered.

3.2 Wire frame specification

As it was envisaged in the proposal, the decision assistance system to be developed in result of the research carried out in the project PLATON will be web based, i.e. the user front end is browser based whereas the back end calculations will be performed on the server side.

The functionality shall allow seeing the consequences of different recharging topologies. The first step is to test whether the given bus assignments may be kept with a bus commercially available without opportunity recharging. The recharging times shall be extracted from real time data.

If depot charging is not a viable option, since no new depots can be used for intermediate recharging during off peak time, the second step is to determine the recharging stops having the lowest TCO. Particular stops might be ruled out for recharging installations for reasons of monument protection or cityscape preservation.

The third step is to manually define the recharging stations and calculate the added costs compared to the optimum. A further option could be to select what routes might be electrified first, transporting as much passengers per Million € invested, or minimising the investment targeting lines with low energy demand. This scenario can be described as:

- The shortest line having one joint stop with most other lines is selected to be electrified first.
- The longest line having no joint stop with other lines is electrified last – may be rerouted, split etc.

A very important point is the transport network data model regarding the definition of nodes and edges, as shown in Figure. 11.

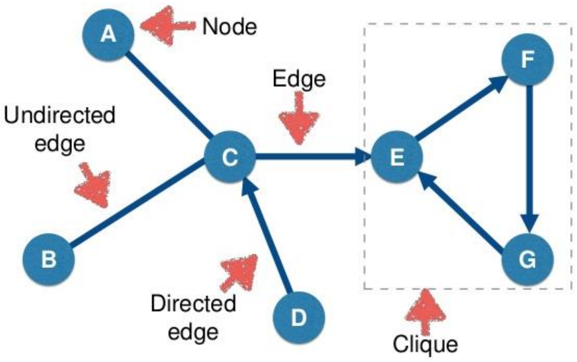

Figure. 11. Transport network data model

The user interface (see Figure. 12) will have a graphical representation of the network, in order to allow editing the network, as well as imports from standardized exchange formats that are well introduced into the public transport domain.

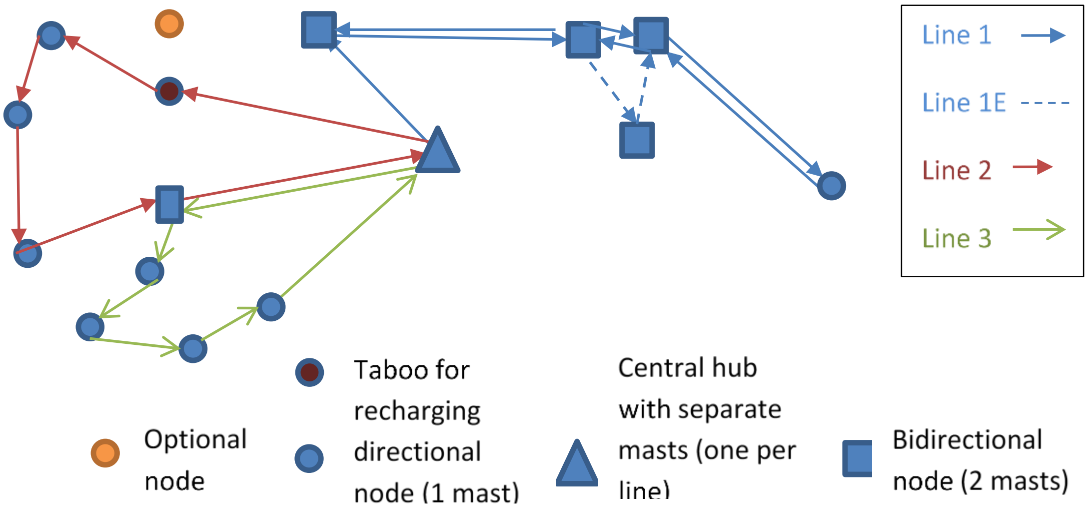

Figure. 12. Graphical user interface

The nodes are positions of the bus stops, which have co-ordinates to be presented, but which are not used for routing. The distances driven are annotated at the edges that are combined with energy demand and travel times for every hour of the day. The energy demand for calculating the State of Charge (SOC) does not require high granularity in case of depot charging and opportunity recharging:

- Depot charging needs a value for the operation period between pauses (example 5h + 4 h pause + 4 h)
- Opportunity recharging once per tour needs only cumulative values

However, in case the operational scheme shall be adapted by the planner and the position of the recharging points has to be chosen by the planner, the energy demand of the edges shall be defined and the energy demand is aggregated in the software. Buses shall start with conditioned, i.e. fully charged battery.

The transport network data model includes the following attributes of the network elements (in brackets), which are itself dependent on variables like the route:

- Node (Node-ID, Coordinates, Node type, Stop sequence (route), Dwell time (route, time of day) Road distance to medium voltage transformer station
- Edge (Edge-ID, Connecting nodes, Travel time for each hour of the day, Energy demand for each hour of the day and each bus type as well as under extreme conditions (mass and temperature)

For the Total Cost of Ownership (TCO) model that is subject to further project, work there are required the following entities and variables:

- Route (Service-ID, Head time, Hours in service (before a longer recharging takes place)
- Bus
    - Max. charging power depending on SOC
    - Connecting time to the catenary
    - Granularity battery packs in kWh
    - Lifespan vs. Depth of Discharge (DoD) curve in full cycles
    - Investment cost of the rechargeable battery
    - Usable energy in the rechargeable battery after the end of the service life (1/safety factor)
- Recharging Infrastructure
    - Fixed cost per stop location post + Cost per kW (separately for two masts and one transformer)
    - Alternatively the grid operator may charge depending on operational hours per accessible maximal power
    - Losses per kWh and per inactive hour
    - Energy price per kWh

The TCO model is planned to consider driver cost, since the productivity varies across the variants of recharging scenarios.

The input mask for the transport operations planner will contain from the current viewpoint the following elements:

- Import Data

- Save Variant
- Edit Topology
- Edit Cost

The representation of the output data to be obtained from the transport operations planner will contain the following elements from the current viewpoint:

Variant	A	B
Battery Size	kWh	kWh
Passenger Seat km		
Battery Cost	€	€
Average DoD	%	%
Battery lifetime	hrs	hrs
Average charging duration	mins	mins
Cost Recharging Infrastructure	€	€
Total Cost	€	€
Cost difference	%	%

In accordance with the requirements of the planning tool, the above described wireframe model of the graphical user interface has been designed and sketched in the illustrated mock-up version in order to define the interfaces between tool components and the handling of the graphical user interface.

4 References

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5 Annex

The annex contains a document in PDF-format that is enclosed with the delivered version of this report.

Optimal Planning of a Transfer from Conventional to Electric Public Transport

Nikolai Guschinsky, Mikhail Y. Kovalyov, Boris Rozin, Yakov Shafransky

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1 Introduction

We study an optimization problem which appears in planning of a transfer of conventional public bus service into electric bus service for a given set of routes. We call an electric bus an *e-bus* and a fleet of e-buses an *e-fleet*. An e-bus is equipped with an electric storage device (battery) which requires periodic charging. 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.

E-fleet is characterized by e-bus *types* and quantities of e-buses of each type. E-bus type is characterized by the following unique parameters: 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 given two stops of the same route, energy consumption for the same route over the year, capital and operating costs over the year, and passenger capacity.

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. *Decisive Stable Traffic (DST)* time period is a time period such that the traffic (inter-bus) interval of any e-bus type does not change within this period and the decisions made for this period ensure feasible operation of the e-fleet and charging infrastructure in any time period of the year. With a certain degree of uncertainty, DST time period can be characterized by the highest *SOC loss* of e-buses when driving over the same route segments.

The optimization problem is to determine an e-fleet and traffic intervals of e-bus types in the DST time period, to determine 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, and the *power reserve* of any transformer is not exceeded. The objective is to maximize the ratio of the total *value* (positive ecological or social-ecological effect expressed quantitatively) to the *total cost of ownership* which is the sum of the total *capital* and *operating* cost including the energy cost.

We denote this problem as Opt. It is assumed that Opt will be solved repeatedly over several planning periods (years). Decisions made in the past periods are used as part of the input for the future period.

Problem Opt is difficult from the modelling 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 3. Input and output data are described in Sections 4 and 5, respectively. A formal problem formulation is presented in Section 6. A randomized heuristic algorithm is presented in Section 7. The next section contains a bibliography of the relevant publications.

2 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 concerning employment of EVs and corresponding infrastructure: ZeEUS eBus Report [79], Stevic [62], Li [38], Ahmad et al. [3], Anderson et al. [2], Mathieu [42, 43], Nicholas and Hall [50], Todorovic and Simic [67], 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 [69], Erkkilä et al. [13], Smidt et al. [60], ZeEUS Demonstrations [80], Foltiński [18], Rogge et al. [58], Hanlin [25], Olsson et al. [51], Eudy and Jeffers [14], Gao et al. [21], Leou and Hung [37], Christensen et al. [9], Neaimeh et al. [49], Khan et al. [34], Xylia and Silveira [77], Gallet et al. [22], Morganti and Browne [48].

Comparison of EVs and vehicles with other power source: Feng and Figliozzi [15, 16], Hallmark et al. [24], Lajunen [36], Mohamed et al. [45].

Simulation of EV operations: Schoch [61], Teoh et al. [65, 66], Mohamed et al. [46], Marmaras et al. [41], Xylia et al. [76], Fiori et al. [17].

Optimization of EV operations and required infrastructure: Alonso et al. [4], Wen et al. [72], Yu et al. [78], Juan et al. [32], Hiermann et al. [28], Quak et al. [57], Desaulniers et al. [11], Wielinski et al. [74], Kunith et al. [35], Bruglieri et al. [6], Pelletier et al. [53, 54, 55, 56], Froger et al. [19, 20], Xylia et al. [75], Liu and et al. [39], Liu and Wei [40], Hosseini and Sarder [29], Wang et al. [70], Wang et al. [71].

Analysis of the relevant literature shows that the number of mathematical models and algorithms for optimal employment of electric public transport is insufficient to cover a large variety of real-life situations.

3 Assumptions

The following assumptions are imposed.

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

2) Fleet of conventional buses can be replaced partly.

3) 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.

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

5) 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, location, charging station type), then, from the modeling point of view, an e-bus visits the location with no charging.

6) 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.

7) 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.

8) Each charging station in the same location is connected to the same m transformers, $m \in \{1, 2\}$. At any time, only one arbitrary transformer link is active for each charging station.

9) 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.

10) Duration of one cyclic run of any e-bus in the DST time period is the same for the same e-bus type and the same route.

11) Duration of one cyclic run of any e-bus, including all intermediate charging times, does not exceed the duration of the DST time period.

4 Input data

Lowercase letters are used to denote numerical data and uppercase letters are used to denote sets and, later on, decision variables. There are the following input data.

- Upper bound *uoc* on the total operating cost.
- Duration *dst* of the DST time period.
- *Transportation and electrical network* $G = (NN, R, EE)$, which is a *weighted mixed multi-graph* with set of *nodes* (locations for charging stations and transformers) NN, set of *directed circuits* (routes) R and set of edges (transformer links) EE, see Fig. 1 for an illustration. There, 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).

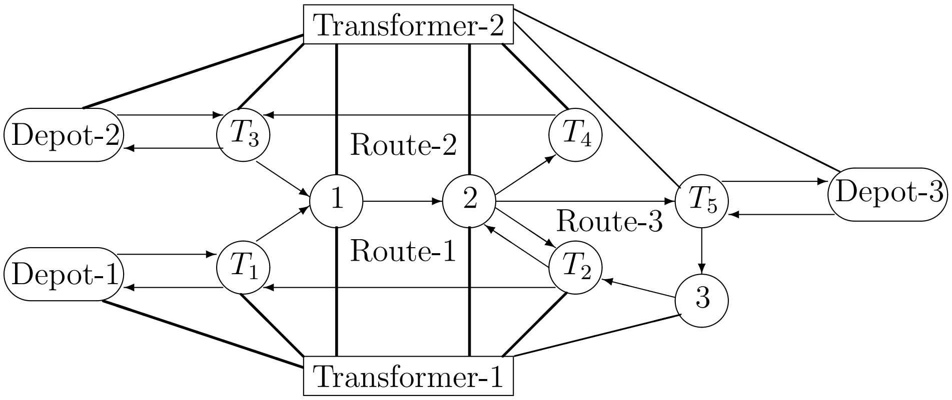

Figure 1: Network of three routes.

- Set NN is partitioned into set T of *transformer* nodes corresponding to eligible transformer locations and set N of non-transformer nodes corresponding to eligible charging station locations.
- Set T contains a subset TO of transformer nodes at each of which at least one old transformer exists with a positive power reserve for e-buses.
- Set N is partitioned into the subsets ND and NE of *depot nodes* and *bus stop nodes*, respectively, eligible for opening charging stations.

- Set N contains a subset NO of non-transformer nodes at each of which at least one old charging station of any type is opened.
- Set of routes R is built over the nodes of the sets ND and NE. The same node can belong to different routes.
- Subset $R_0 \subseteq R$ of routes served by at least one old e-bus.
- Arc $(i, j) \in r$, $r \in R$, represents a directed segment of a route, going from a non-transformer node i to a non-transformer node j.
- Edge $(i, j) \in EE$ represents an *eligible link* of transformer node i and a non-transformer node j.
- Set B of *e-bus types.*
- Subset BO, $BO \subseteq BO$, of types of already operating (old) e-buses.
- 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 cost cc_c^{ope}, which is the cost of operating one charging station in a year.
- Set $N_c \subseteq N$ of nodes eligible for opening a charging station of type c.
- Set $NO_c \subseteq NO$ of nodes at each of which at least one old charging station of type c is opened.
- Set $B_c \subseteq B$ of e-bus types eligible for charging at a station of type c.

  E-bus type $b \in B$ is associated with the following input parameters.
- Set C_b of *appropriate charging station types.* E-bus of type b can only be charged at a station of type $c \in C_b$.
- Set NM_b of non-transformer nodes at each of which at least one charging station of type $c \in C_b$ must be opened if the node belongs to a route to be served by an e-bus of type b.

- Set R_b of *eligible routes*, $R_b \subseteq R$.

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

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

- Operating cost cv_b^{ope} of one e-bus in a year, without the energy cost.

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

- Set C_{jb} of appropriate charging station types for e-buses of type b. At node j, an e-bus of type b can only be charged at a station of a type $c \in C_{jb}$.

- Number m of *links* of any node $j \in N \backslash NO$, at which new charging station will be open, with transformer nodes. It is assumed that $m \leq |T|$.

- Set R_j of routes meeting at j.

- Set $TE_j \subseteq T$ of transformer nodes eligible for linking with node j.

- Number nc_{jc} of old charging stations of each type c, which have already been opened at $j \in N_c$, $c \in C$. Recall that, if $j \in NM_b$ and j belongs to a route served by an old e-bus of type b, then $nc_{jc} \geq 1$ for $c \in C_b$.

- Set RO_{jcb} of routes r such that their old e-buses of type b are charged at stations of type c at node j, $RO_{jcb} \subseteq R_j$, $j \in N_c$, $b \in R_b \cap B_c$, $c \in C$.

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

- (Tight) upper bound ct_{jbc} on the charging time of one e-bus of type b at a charging station of type $c \in C_b$ installed at $j \in N_c$ to the recommended SOC level or an estimation of this time, which, for the en route stop, accounts for the time required for passenger loading/unloading. For a terminal stop or a depot, it accounts for the required setup and maintenance time.

- Duration t_j^{depot} of a time interval, in which the number of all e-buses staying in the depot j, $j \in ND$, per time unit is the largest. In most cases, it is a night time interval.

Each transformer node $i \in T \backslash TO$ is associated with

- transformer electrical *power reserve* o_i to supply new charging stations in the GFE block of cycles and

- transformer capital (building) cost cb_i.

  Each edge $(i,j) \in EE$ is associated with

- cost cl_{ij} of linking transformer node i and non-transformer node j.

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

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

- Sequence $\pi_r = (j_0, j_1, \ldots, j_r, j_0)$ of nodes, where j_0 is the depot node and $j_1, \ldots, j_r$ are bus stop nodes visited cyclically in this order. We write $j \in r$ and $(i,j) \in r$ to indicate that node j and arc (i,j) belong to route 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 node i to node j of route r, provided that a charging station of type $c \in C_b$ is installed at i, else $ei_{r(i,j)b} = 0$, $i \in r$, $i \in N_c$, $j \in r$, $b \in B_r$. 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).

- Length i_{rb} of traffic interval of old e-buses of type b on route r in the DST time period.

- Upper bound ui_{rb} on the length of the traffic interval of new e-buses of type b on route r in the DST time period. This parameter can be set to a very large positive number if there is no need in this upper bound.

- Largest ratio α_{rbj}^{depot}, $0 < \alpha_{rbj}^{depot} \leq 1$, of all e-buses of type b, $b \in B_r$, arriving to the depot $j \in ND$ in the time interval of duration t_j^{depot}. If t_j^{depot} and α_{rbj}^{depot} are difficult to determine, then t_j^{depot} can be set to the duration of the time interval between arrival to the depot j of the last e-bus of the previous day and departure from it the first e-bus of the next day, and it can be set $\alpha_{rbj}^{depot} = 1$.

- Number nv_{rb} of old e-buses of type b assigned to route r, $b \in B_r$.

- Duration d_{rb} of any single cycle of any e-bus of type b, $b \in B_r$, in the DST time period. It does not exceed the duration of the DST time period.

- (Tight) upper bound dc_{rb} on the total charging time of an e-bus of type b in one cyclic run, or an estimation of this time, $b \in B_r$. This parameter cannot be skipped because it accounts for the contribution of the total charging time in the e-bus cycle time.

- *Energy cost* (or its estimation) ce_{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, $w_r \geq 0$.

- Total passenger capacity pas_r of conventional buses operating on route r.

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

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

Remark. *Let Z_r denote the total passenger capacity of new e-buses assigned to route r. We require $Z_r \leq pas_r$. 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.*

5 Output

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

- Length $I_{rb}(X)$ of the traffic interval of new e-buses of type b on route r in the DST time period.

- 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 j, $RO_{jcb} \subseteq R_{jcb}(X) \subseteq R_j$, $j \in N_c$, $b \in R_b \cap B_c$, $c \in C$.

- Set $S_c(X)$ of nodes $j \in N_c$ at each of which an least one new charging station of type c is opened.

- Number $NC_{jc}(X)$ of new charging stations of type $c \in C$ at non-transformer node $j \in S_c(X)$ to serve new and old e-buses.

- Set $L_j(X)$ of transformer nodes $i \in TE_j$ to be linked with non-transformer node j, $j \in N \backslash NO$.

Solution X can be used to calculate the following values.

- $B_r(X)$ - set of e-bus types $b \in B_r$ such that at least one new e-bus of this type is assigned to route $r \in R$.
- $B(X) = \cup_{r \in R} B_r(X)$ - 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, $b \in B$.
- $R(X) = \cup_{b \in B} R_b(X)$ - set of routes, each of which is served by at least one new e-bus.
- $C(X)$ - set of charging station types such that at least one new charging station of this type is opened.
- $S(X) = \cup_{c \in C(X)} S_c(X)$ - set of nodes at each of which an least one new charging station of any 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, $j \in S(X)$.
- $SR_{rb}(X)$ - set of arcs of route $r \in R_b(X)$ at each node of which at least one new or old charging station of a type $c \in C_{jb}$ is opened to serve e-buses of type $b \in B(X)$ assigned to this route.
- $c_{jrb}(X)$ - unique new or old charging station type to charge old or new e-buses of type b assigned to route r at node 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 j.
- $io_{jrb}(X)$ - 0-1 indicator such that $io_{jrb}(X) = 1$ if and only if $c_{jrb}(X) \neq False$.
- $B_{jc}(X) = \{b \mid c_{jrb}(X) \neq False, b \in B, r \in R_b\}$ - set of e-bus types of all routes meeting at j to be served by new or old charging station of type c, $j \in S(X)$, $c \in C(X)$.
- $NV_{rb}(X) = \lceil \frac{d_{rb}}{I_{rb}(X)} \rceil$ - number of new e-buses of type b assigned to route r in the DST time period.
- $Z_r(X) = \sum_{b \in B_r(X)} cap_b NV_{rb}(X)$ - total passenger load of e-buses of route r in the DST time period.
- $BN_{jc}(X) = \sum_{r \in R_j(X)} \left(\sum_{b \in B_{jc}(X) \cap BO} \frac{ct_{jbc}}{i_{rb}} + \sum_{b \in B_{jc}(X) \setminus BO} \frac{ct_{jbc}}{I_{rb}(X)} \right)$ - total (non-integer) number of old and new e-buses of all types arriving to the charging station of type c at the non-depot node j during their charging time intervals, $j \in NE \cap (S(X) \cup NO)$.

- $BN_{jc}(X) = \sum_{r\in R_j(X)} \sum_{b\in B_{jc}(X)\cap BO} \alpha^{depot}_{rbj} \big(\frac{t^{depot}_j}{i_{rb}} + \sum_{b\in B_{jc}(X)\setminus BO} \frac{t^{depot}_j}{I_{rb}(X)} \big)$ - total (non-integer) number of old and new e-buses of all types arriving to the charging station of type c at the depot node j during the charging time interval of length t^{depot}_j, $j \in ND \cap S(X)$.

- $M_i(X) = \{j \in S(X) \mid i \in L_j(X)\}$ - set of new non-transformer nodes linked with transformer node i.

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

- $TP_i(X) = \sum_{j\in M_i(X)\cap N} \sum_{c\in C(X)} po_c NC_{jc}(X)$ - total instant power demand of new charging stations linked to transformer node $i \in T(X)$ in the GFE block of cycles.

- $TP(X) = \sum_{i\in T(X)} TP_i(X)$ - total instant power demand of all new charging stations in the GFE block of cycles.

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

- $CC(X) = \sum_{c\in C(X)} \sum_{j\in S_c(X)} cc^{cap}_c NC_{jc}(X) + \sum_{r\in R(X)} \sum_{b\in B_r(X)} cv^{cap}_b NV_{rb}(X) + \sum_{j\in S(X)\setminus NO} \sum_{i\in L_j(X)} cl_{ij} + \sum_{i\in T(X)\setminus TO} cb_i$ - capital cost.

- $OC(X) = \sum_{c\in C(X)} \sum_{j\in S_c(X)} cc^{ope}_c NC_{jc}(X) + \sum_{r\in R(X)} \sum_{b\in B_r(X)} (cv^{ope}_b + ce_{rb}) NV_{rb}(X)$ - operating cost including energy cost.

6 Problem formulation

Problem Opt can be formulated as follows.

$$\max_X \frac{V(X)}{1 + CC(X) + OC(X)}, \text{ subject to}$$

$$CC(X) \le ucc, \tag{1}$$

$$OC(X) \le uoc, \tag{2}$$

$$Z_r(X) = \sum_{b\in B_r(X)} cap_b \Big\lceil \frac{d_{rb}}{I_{rb}(X)} \Big\rceil \le pas_r,\ r \in R(X), \tag{3}$$

$$TP_i(X) = \sum_{j\in M_i(X)} \sum_{c\in C(X)} po_c NC_{jc}(X) \le o_i,\ i \in T(X), \tag{4}$$

$$I_{rb}(X) \le ui_{rb},\ r \in R_b(X),\ b \in B(X), \tag{5}$$

$$c_{jrb}(X) \in C_{jb},\ j \in SR_{rb}(X),\ r \in R_b(X),\ b \in B(X), \tag{6}$$

$$ei_{r(i,j)b} = 1,\ (i,j) \in SR_{rb}(X),\ r \in R_b(X),\ b \in B(X), \tag{7}$$

$$\sum_{j \in SR_{rb}(X) \setminus ND} ct_{jbc^*} \leq dc_{rb},\ c^* = c_{jrb}(X),\ r \in R_b(X),\ b \in B(X), \tag{8}$$

$$nc_{jc} + NC_{jc}(X) \leq uc_{jc},\ j \in S_c(X),\ c \in C(X), \tag{9}$$

$$\sum_{c \in C_b} (nc_{jc} + NC_{jc}(X)) \geq 1,\ j \in NM_b \cap S(X),\ b \in B(X) \cup BO, \tag{10}$$

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

$$|L_j(X)| = m,\ j \in S(X) \setminus NO. \tag{12}$$

Constraints (1)and (2) bound the total capital cost and the total operating cost from above. Constraints (3) limit the total capacity new e-buses for each route by the total capacity of conventional buses used on the same route. Constraints (4) ensure that the total instant power demand of new charging stations linked to the same transformer does not exceed power reserve of this transformer. Constraints (5) specify upper bounds on the traffic intervals of new e-buses. Constraints (6) ensure that an appropriate charging station is opened at each node of the arcs from the set $SR_{rb}(X)$. Constraints (7) 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 of the arcs from the set $SR_{rb}(X)$. Constraints (8) require that the total charging time of any new e-bus of a certain type assigned to a certain route in one cyclic run does not exceed upper bound established for this type and route. 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 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 j 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 [63], Vincke [68], Roy [59], Collette and Siarry [8] and Ehrgott [12]. 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.

7 Randomized heuristic solution approach

Due to the difficulty of the problem Opt, our solution approach is the following. Denote by $\mathcal{X}$ the set of feasible solutions of this problem. By making a randomized choice of feasible or infeasible partial solutions, we construct a set of feasible complete solutions $\mathcal{Q} \in \mathcal{X}$, which we expect to contain solutions close to the optimal solution. A formal description of our algorithm, denoted as RAND, is given below. A feasible solution, in which no new e-bus is selected, is denoted as Q_0. Steps of the algorithm are performed sequentially, unless it is stated otherwise. Algorithm employs probabilities which are used to determine characteristics of a solution. These probabilities are control parameters of the algorithm. They can be defined by the decision maker, or set to be the same for all possible values of the same solution characteristic, in which case uniform distribution of the values is assumed. Probabilities can also be adjusted in a computer experiment.

Algorithm RAND.

Step 1. (Initialization) Set $\mathcal{Q} = \{Q_0\}$. In Steps 2-6, a partial solution Q is generated. It can be extended to feasible or infeasible complete solution.

Step 2. (Generation of a set of routes $R(Q)$ served by at least one e-bus) Define probability p_r, $0 \leq p_r \leq 1$, of including $r \in R$ into $R(Q)$. Set $p_r = 1$ for routes $r \in R_0$. Generate set $R(Q)$ by using these probabilities such that $|R(Q)| \geq 1$. Define the set of nodes $N(Q) = \{j \mid j \in R(Q)\}$.

Step 3. (Generation of a set $B_r(Q)$ of e-bus types to serve route $r \in R(Q)$) For each route $r \in R(Q)$, define probability p_{rb} of employing e-bus type b on route r, $b \in B_r$. Set $p_{rb} = 1$ if an e-bus of type b is already assigned to r. Generate sets $B_r(Q)$, $r \in R(Q)$, by using these probabilities such that $|B_r(Q)| \geq 1$ for each $r \in R(Q)$. Generate set $B(Q) = \cup_{r \in R(Q)} B_r(Q)$ and sets $R_b(Q)$ of routes served by at least one e-bus of type $b \in B(Q)$.

Step 4. (Generation of locations for charging stations and determination of charging station types $c_{jrb}(Q)$ to charge old or new e-buses of type b assigned to route r at node j) For each e-bus type $b \in B(Q)$ and each route $r \in R_b(Q)$, generate set of arcs $SR_{rb}(Q)$, at each node j of which at least one old or new charging station of a type $c \in C_{jb}$ is assigned to the e-bus type b and route r. For given route r and e-bus type b, the generation process starts by including in $S_{rb}(Q)$ arcs, connecting "obligatory" nodes of the set $NM_b \cap r$ and nodes with old charging stations $c \in C_b$ assigned to b and r. It is assumed that charging station types $c_{jrb}(Q)$ are given or they are randomly generated for these "obligatory" nodes. Then, compute current total charging time $CT_{rb}(Q) = \sum_{j\in SR_{rb}(Q)\setminus ND} ct_{jbc^*}$, where $c^* = c_{jrb}(Q)$. If $CT_{rb}(Q) > dc_{rb}$, then Q cannot be extended to a complete feasible solution. In this case, if computation time permits then perform Step 2, else perform Step 7. If $CT_{rb}(Q) \le dc_{rb}$, then perform the following computations. Consider arbitrary arc $(i_1, i_2 \in SR_{rb}(Q)$. If $ei_{r(i_1,i_2)b} = 1$, then no extra charging station is needed for the e-bus type b and route r between i_1 and i_2. If $ei_{r(i_1,i_2)b} = 0$, then include in $SR_{rb}(Q)$ with a certain probability two arcs (i_1, j) and (j, i_2), $j \in N_c \cap r$, $c \in C_{jb}$, such that $CT_{rb}(Q) + \min_{c\in C_b}\{ct_{jbc}\} \le dc_{rb}$ and $ei_{r(i_1,j)b} = 1$ or $ei_{r(j,i_2)b} = 1$. This probability can be higher if the distance from i_1 to j (respectively, from j to i_2) is larger. For feasibility, an appropriate charging station must must be opened in at least one node j between i_1 and i_2 in this iteration for the pair (r, b). If no such node can be included and computation time permits, then perform Step 2, else perform Step 7. If arcs (i_1, j) and (j, i_2) are included into $SR_{rb}(Q)$, then define charging station type $c^* = c_{jrb}(Q) \in C_b$ for this node with a certain probability such that $CT_{rb}(Q)+ct_{jbc^*} \le dc_{rb}$. Update the current total charging time $CT_{rb}(Q) := CT_{rb}(Q)+ct_{jbc^*}$. Repeat the described inclusion process until $ei_{r(i_1,i_2)b} = 1$ for any arc $(i_1, i_2) \in SR_{rb}(Q)$. Generate sets $S(Q)$, $S_c(Q)$, $C(Q)$ and $B_{jc}(Q)$, which are analogs of the same concepts defined for a feasible solution X. Note that the following relations are guaranteed to be satisfied at the end of this stage:

$$c_{jrb}(X) \in C_{jb},\ j \in SR_{rb}(X),\ r \in R_b(X),\ b \in B(X),$$

$$ei_{r(i,j)b} = 1,\ (i, j) \in SR_{rb}(X),\ r \in R_b(X),\ b \in B(X),$$

$$\sum_{j\in SR_{rb}(Q)\setminus ND} ct_{jbc^*} \le dc_{rb},\ c^* = c_{jrb}(Q),\ r \in R_b(Q),\ b \in B(Q),$$

$$\sum_{c\in C_b} (nc_{jc} + NC_{jc}(Q)) \ge 1,\ j \in NM_b \cap S(Q),\ b \in B(Q) \cup BO,$$

which are analogs of the constraints (6), (7), (8) and (10). Note that $NC_{jc}(Q)$ in the last relation is not determined explicitly, but the relation is satisfied by the definition of Step 4.

Step 5. (Generation of numbers $NC_{jc}(Q)$ of new charging stations and lengths $I_{rb}(Q)$ of traffic intervals of new e-buses) Define numbers $NC_{jc}(Q)$ of new charging stations and lengths $I_{rb}(Q)$ of traffic intervals as a solution of the following problem:

$$\max \frac{V(FR(Q))}{1 + CC^0(NC(Q), I(Q)) + OC(NC(Q), I(Q))},$$

subject to $(NC(Q), I(Q)) \in \mathcal{NF}(Q)$, where

$$V(I(Q)) = \sum_{r \in R(Q)} v_r(Z_r(Q)),$$

$$CC(NC(Q), I(Q)) = \sum_{c \in C(Q)} \sum_{j \in S_c(Q)} cc_c^{cap} NC_{jc}(Q) + \sum_{r \in R(Q)} \sum_{b \in B_r(Q)} cv_b^{cap} NV_{rb}(Q),$$

$$OC(NC(Q), I(Q)) = \sum_{c \in C(Q)} \sum_{j \in S_c(Q)} cc_c^{ope} NC_{jc}(Q) + \sum_{r \in R(Q)} \sum_{b \in B_r(Q)} (cv_b^{ope} + ce_{rb}) NV_{rb}(Q),$$

$$NV_{rb}(Q) = \lceil \frac{d_{rb}}{I_{rb}(Q)} \rceil,$$

$$Z_r(Q) = \sum_{b \in B_r(Q)} cap_b NV_{rb}(Q),$$

$$BN_{jc}(Q) = \sum_{b \in B_{jc}(X) \cap BO} \frac{ct_{jbc}}{i_{rb}} + \sum_{b \in B_{jc}(Q) \setminus BO} \frac{ct_{jbc}}{I_{rb}(Q)},\ j \in NE \cap (S(Q) \cup NO),$$

$$BN_{jc}(Q) = \sum_{b \in B_{jc}(Q) \cap BO} \frac{t_j^{depot}}{i_{rb}} + \sum_{b \in B_{jc}(Q) \setminus BO} \frac{t_j^{depot}}{I_{rb}(Q)},\ j \in ND \cap S(Q),$$

and the feasible domain $\mathcal{NF}(Q)$ is defined by the following constraints.

$$Z_r(Q) \le pas_r,\ r \in R(Q), \tag{13}$$

$$TP_i(Q) = \sum_{j \in M_i(Q) \cap N} \sum_{c \in C(Q)} po_c NC_{jc}(Q) \le o_i, i \in T(Q), \tag{14}$$

$$I_{rb}(Q) \le ui_{rb},\ r \in R_b(Q),\ b \in B(Q), \tag{15}$$

$$nc_{jc} + NC_{jc}(Q) \le uc_{jc},\ j \in S_c(Q),\ c \in C(Q), \tag{16}$$

$$nc_{jc} + NC_{jc}(Q) = BN_{jc}(Q),\ j \in S(Q) \cup NO,\ c \in C(Q). \tag{17}$$

A Particle Swarm Optimization technique is used to solve the above problem, see Clerc [10], Kennedy and Eberhart [33] and Pedersen and Chipperfield [52]. If system (13)-(17) has a solution, then perform Step 6. If it does not have a solution and computational time permits, then perform Step 2, else perform Step 7.

Step 6. (Selection of new edges linking charging stations with transformers) For each node $j \in S(Q) \setminus NO$, denote the set of transformer nodes connected to node j according to the partial solution Q as $L_j(Q)$. Denote by $M_i(Q) = \{j \in S(Q) \mid i \in L_j(Q)\}$ the set of new non-transformer nodes linked with transformer node i. Sets $L_j(Q)$, $j \in S(Q) \setminus NO$, sets $M_i(Q)$, $i \in T$, and set $T(Q)$ of new transformers are randomly determined as follows. For each node $j \in S(Q) \setminus NO$, define probability p_{ij} of linking transformer node $i \in TE_j$ with j. This probability can be higher for larger power reserve o_i and it can be higher for smaller cost

$cl_{ij} + cb_i y_i$, where $y_i = 1$ if $i \notin TO$ and $y_i = 0$ if $i \in TO$. Link each node $j \in S(Q)\backslash NO$ with m nodes $i \in T$. Calculate capital cost $CC(Q) = \sum_{j\in S(Q)\backslash NO} \sum_{i\in L_j(Q)} cl_{ij} + \sum_{i\in T(Q)\backslash TO} cb_i + CC(NC(Q), I(Q))$. Re-set $\mathcal{Q} := \mathcal{Q} \cup \{Q\}$. If computation time permits, then perform Step 2, else perform Step 7.

Step 7. Find $Q^* \in \mathcal{Q}$ such that

$$\frac{V(Q^*)}{CC(Q^*) + OC(Q^*) + 1} \quad = \quad \max_{Q\in\mathcal{Q}} \; \frac{V(Q)}{1 + CC(Q) + OC(Q)}.$$

In the currently studied real-life situations, cardinalities of the sets generated in Steps 1-4 are limited by the following values. Number of routes: $|R| \leq 21$. Number of depots: $|ND| \leq 3$. Number of types of charging stations: $|C| \leq 5$. Number of routes meeting in the same location: $|R_j| \leq 8$ for $j \in ND$, $|R_j| \leq 3$ for $j \in NE$. Number of stops of the same route which are appropriate for opening charging stations: $|N \cap r| \leq 10$, $r \in R$. Number of e-bus types which are appropriate for serving one route: $|B_r| \leq 6$, $r \in R$. Number of locations in which at least one charging station must be opened for e-buses of the same type and route: $1 \leq |NM_b \cap r| \leq 3$, $b \in B$, $r \in R$. Number of transformer links: $m \in \{1, 2\}$. Number of transformer locations which are appropriate for linking with the same charging station location: $|TE_j| \leq 3$, $j \in N$.

8 A real-life case

Public transport routes of the city of Minsk are considered. There are two e-bus depots: $Vaneeva$ (V) and $Kozlova$ (K). One old charging station is opened at depot V and each of the e-bus stops $Kirava$, $Viasnian$, $Druznaia$, $Siarova$ and $Daugabrod$. New and old charging stations are of the same type and they can charge e-bus of any type. Cost of one charging station is 250$.

In the tables below, route cycles start with a terminal stop. Another terminal stop is marked with an $*$. Notations of old bus and trolleybus routes start with A and T, respectively.

Routes with depot V

ID	Name	Cycle	Length (one way, km)	Duration (one way, min)	Traffic interva
1	$A1$	$(Kirava, Viasnian^*, Kirava)$	9.5	30	5
2	$A119c$	$(Kirava, Viasnian, Akvapark^*, Viasnian, Kirava)$	13	25	20
3	$A190e$	$(Kirava, Viasnian, RKMC^*, Viasnian, Kirava)$	15	25	
4	$T5, 6$	$(Kirava, Loshitsa2^*, Kirava)$	9	30	
5	$A69$	$(Kirava, Masiukousch^*, Kirava)$	11	35	
6	$T20$	$(Kirava, DS\ Sierabran^*, Kirava)$	9.2	40	
7	$T36$	$(DS\ Sierabran, AV\ Cantralni, YugaZapad^*,$ $AV\ Cantralni, DS\ Sierabran)$	17.5	65	
8	$A46$	$(AV\ Cantr, Masiukousch^*, AV\ Cantr)$	9	40	
9	$T58$	$(AV\ Cantr, Masiukousch^*, AV\ Cantr)$	9	30	
10	$T59$	$(Daugabrod, Siarova^*, Daugabrod)$			
11	$A38$	$(Druznaia, Karastaian^*, Druznaia)$			
12	$T43$	$(Druznaia, Siarova^*, Druznaia)$			
13	$T40$	$(Druznaia, YugaZapad^*, Druznaia)$			
14	$T63$	$(Druznaia, YugaZapad^*, Druznaia)$			

Routes with depot K

ID number	Name	Cycle	
15	$A100$	$(KalinouSlavinsk, Aeraport\ Minsk1^*, KalinouSlavinsk)$	
16	$A91$	$Viasnin, Viasnian, KalinouSlavinsk^*, Viasnian, Viasnin)$	
17	$A73$	$(Siarova, Druznaia, Viasnian, Liabiazi^*, Viasnian, Druznaia, Siarova)$	
18	$T22$	$(Karastaian, Ploscha\ Y.Kolasa^*, Karastaian)$	
19	$A44$	$(Karastaian, Viasnian, Zdanovichi^*, Viasnian, Karastaian)$	
20	$A136$	$(Karastaian, Viasnian, Zdanovichi^*, Viasnian, Karastaian)$	

Table 1: E-bus types

Name	Capacity (passengers)	Range (km)	Charging time (min)	Cost ($)
Vitovt Max Electro E433	153	15	6	475
Vitovt Electro E420	87	20	6	350
Model E321	83	30	10	400
Vitovt Mini Electro E490	75	25	6	400
Trolleybus 32100D	85	15	40	370
Trolleybus 42003D	85	15	30	400

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