PLATON –

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

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1 Introduction

The deliverable presents the results of the project work carried out by consortium partners in the WP 2 Planning Process design.

The results of this work package are focused on the planning process of bus fleet conversion, including the used methods and the process description elements. The content of this deliverable is in compliance with two previous deliverables (2.1: Requirements and 5.1: Requirements and Graphical User Interface). Hence, the information on stakeholders involved in the process and other issues related with requirement analysis, contained therein, was not repeated in this deliverable.

In the deliverable, structures of multi-level planning process are provided by IFAK, dividing the issue into three levels: legislative governmental, strategic corporate planning and transport operation ones.

The authors have paid particular attention to the definition of the conversion process planning with the use of methods related to graph theory and process engineering methods. Strategic context is provided as well as various aspects of public transport organisation and technology, to the extent necessary for a description of the planning process of conventional bus conversion to a 100% electric fleet. The following section of the deliverable presents a general scheme of the planning process. Particular attention has been paid to the description of decision support system for electric bus deployment based on vehicle cycle approach proposed by SUT.

An outline and assumptions of the optimization problem of the planning process based on frequencies being developed by UIIP is presented in this deliverable.

In the latter part of this deliverable, factors for energy consumption for vehicle cycle evaluation is deliberated by JIME.

2 Issues of the fleet conversion

2.1 Strategic context

An important aspect of public transport management is to make strategic decisions on network design as well as continuous conversion of bus fleets to make them meet current environmental parameters enforced by the present law. The context for these decisions is the growing environmental awareness of the society that traditional, combustion-driven transport is encumbered with extensive external costs. At present there is a vital discussion on the future of the bus fleets operating public transport in cities and agglomerations. Entities responsible for bus fleet development are struggling with a challenge that may be defined in the form of a question: how to adapt the fleet to the growing ecological awareness?

Public transport companies (transit companies) may adopt various scenarios of fleet exchange, taking into account financial capacities and the date limits described in the White Paper [White Paper, 2011], or another national or international strategy paper. In the White Paper, there are two important date limits: half the use of conventionally-fuelled cars in urban transport by 2030 and phase them out from cities by 2050, as well as achieving CO_2-free city logistics in major urban centres by 2030. One of the options is to convert current conventional or mixed fleet into all-electric bus fleet. These two important dates are highlighted in Figure 1, which depicts three possible scenarios of bus fleet exchange resulting in decreasing share of conventionally-fuelled buses:

A) Passive scenario wherein a public transport company protracts the process of fleet exchange awaiting expected effect of electric buses' technological maturity.

B) Normative scenarios, assuming linear or quasi-linear financing and execution of fleet exchange wherein 50% of conventional fleet is replaced by electric buses in 2030.

C) Active scenario wherein the fleet is exchanged, as soon as possible, by getting a grant for innovative, environmentally-friendly activity.

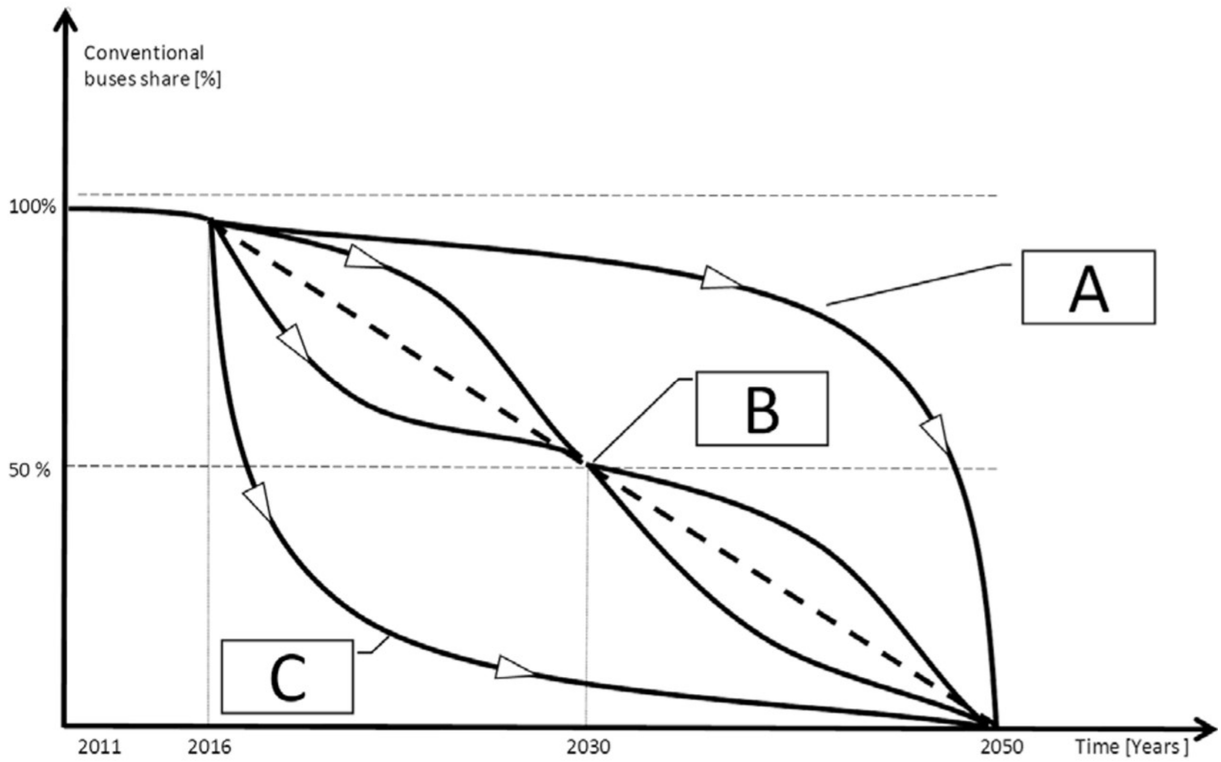

Figure 1 Scenarios of bus fleet conversion to be carried out by public transport companies (Krawiec et al, 2016)

All these variants have advantages and disadvantages involving opportunities and threats, for the particular public transport company. These include perspectives to gain funding, which affects the total cost of the exchanging process, the level of fleet homogeneity in the sense of a bus brand and technological generation of the fleet, the complexity of the exchange process.

2.2 Outline of public transport organization and its influence on the fleet conversion planning process

In conventional terms, organisation of public transport basically looks in a way that public transport vehicles (buses) run on defined transport lines (bus lines). Characteristic elements of transport lines are: routes (route of a line on the road network) and the timetable. The timetable can be viewed in two different ways:

- From the point of view of passengers for whom it is a basic element of the public transport offer.
- From the point of view of transport (transit) companies (public transport operators) for whom it is a vehicle work plan.

Scheduling vehicle work is complex, but necessary to handle the timetable (for passengers) properly – the following should be taken into account:

- Route alignment – path over which the bus travels.
- Level of service (weekdays, weekends, etc.) and a differentiated number of services realized in a given route variant.
- Interval (frequency).
- Traffic conditions changing in the course of a day resulting in different travel times of individual inter-stop sections.
- Compensatory stopping times at terminus bus stops (terminal time) to mitigate the effects of potential delays.
- Number of buses to operate a set of vehicle cycles.
- Working time of drivers.

When a transit company is about to start operation of electric buses, it need to consider some technical and organizational issues, briefly described in the following section of this deliverable. Economic issues are crucial too, but these are a subject of further works within the consortium under WP 4 (Efficient Models and Methods; Task: Economic Models).

2.3 Technical and organizational constraints

Electric buses are characterized by different technical and operational parameters than conventional vehicles. Despite advantages (high efficiency of electric drive, lack of local emissions of harmful substances at the place of use of the vehicle, low noise emission and lower operating costs resulting from lower, prices of electric energy in relation to diesel oil), electric buses have disadvantages too. They include, in particular, the following: greater cost of purchase, insufficient operational range to carry out an all-day vehicle cycle in all the terrain and weather conditions, the need for purchasing and operating additional technical infrastructure (charging facilities in a depot and beyond, depending on charging type) and the power grid limitations. Of those mentioned above, insufficient operational range (and the resulting need of recharging) is a crucial issue under consideration in the planning process.

Alongside technical constraints, one should also consider organisational factors, listed in Table 1. Some of them have their roots in technical issues. However, the organisation of work in a transit company is crucial to dealing with these technical difficulties. Thus, these matters have been classified as organizational issues.

Table 1. Organizational factors in the transit company being significant from the viewpoint of planning process

Group of the factors	Name of the factor
Geographical factors	Assigning electric buses to routes and vehicle cycles
	Determining the number of the vehicles and daily work plan, communication with other transport systems
	Real time telematics system for vehicle control and communication including e.g. Automatic Vehicle Location

Group of the factors	Name of the factor
	Coordination of planning for the development of the transport network and electric infrastructure in the city area
Factors related with technical maintenance area	Maintaining (service) of battery electric vehicles in-house
	Setting up opportunity/depot charging stations for electric buses
	Energy supply and business relationships with energy supplier
Other factors	Mental attitude to the fleet renewal process of the management board of a transit company
	Support of local authorities

Of course, not all the factors listed in Table 1 are of the same importance. At this stage, economic issues were also omitted (for the reasons set out above). However, with regard to the significance of the limited range problem, as well as noting the subordinate position of a transit company to the authorities and bus manufacturers, the challenge of rational deployment of electric buses (built in available battery technology, having limited range) seems to be a key one. Therefore, one may reflect on the properties (characteristics) of individual routes considered to be operated by electric buses.

In order to deploy electric buses, transit companies have to decide on the assignment of electric buses to specific bus routes. There is no doubt that the parameters of public transport lines have a large impact on the performance of electric buses. Depending on the route characteristics (urban, sub-urban, inter-urban, etc.) the disadvantages of electric buses can be either more or less perceptible from the public transport operator (transit company) point of view [Krawiec and Kłos, 2018]. These properties are listed in Table 2.

Table 2. Parameters of bus routes significant from the viewpoint of electric bus deployment in a transit company (own study based on [Krawiec and Kłos, 2018])

Group of the parameters	Name of the parameter
Parameters related to the timetable	Line frequency
	Line regularity
	The frequency of terminus stops
	The set of time spent in the terminus stops
	The number of services
	Passenger flow volume
	Operating speed
	Schedule speed
	The set of time intervals in which charging is possible
	Vehicle kilometres travelled
	Vehicle hours travelled
	The frequency of the line
The parameters related to the line route	Traffic conditions
	The number of scheduled bus stops due to the timetable
	The number of stops of the bus not covered by the timetable
	Technical classes of the roads within a line route
	Locations of the line route to the city centre
	The existence of dedicated bus lanes within a line route
	The existence of priorities for city buses within a line route
	Vertical profile
Operational parameters	Number of buses in operation per line
	Bus capacity
	Bus length
	Reliability of operation
	Punctuality
Technical parameters	Access to the power grid at the terminus stops
	Access to the power grid at the intermediate stops

Group of the parameters	Name of the parameter
	Reliability of vehicles
	The demand for energy (fuel consumption by Diesel buses)
Economic parameters	Costs dependent on vehicle kilometres travelled
	Costs dependent on vehicle hours travelled
	Costs dependent on the number of buses in operation

These parameters are relevant in terms of electric bus assignment to routes and vehicle cycles. Nonetheless, the planning process of electric bus deployment in transport network (bus fleet conversion problem discussed herein) is becoming more complicated when we consider the fact that in nearly every situation the process will need to be carried out step-by-step, towards a 100% fleet of electric buses in public transport company.

2.4 Staging of actions in a step-by-step bus fleet conversion

Due to the technical risk related to the new technology to be implemented, vibrant development of batteries used in electric buses and all the company's budget related matters, one-off induction of electric buses to all the vehicle cycles viable to be operated, seems to be nearly always impossible. The planning process should therefore be carried out in stages. This is shown in Figure 2, describing the origin of the issues of the bus fleet conversion planning process.

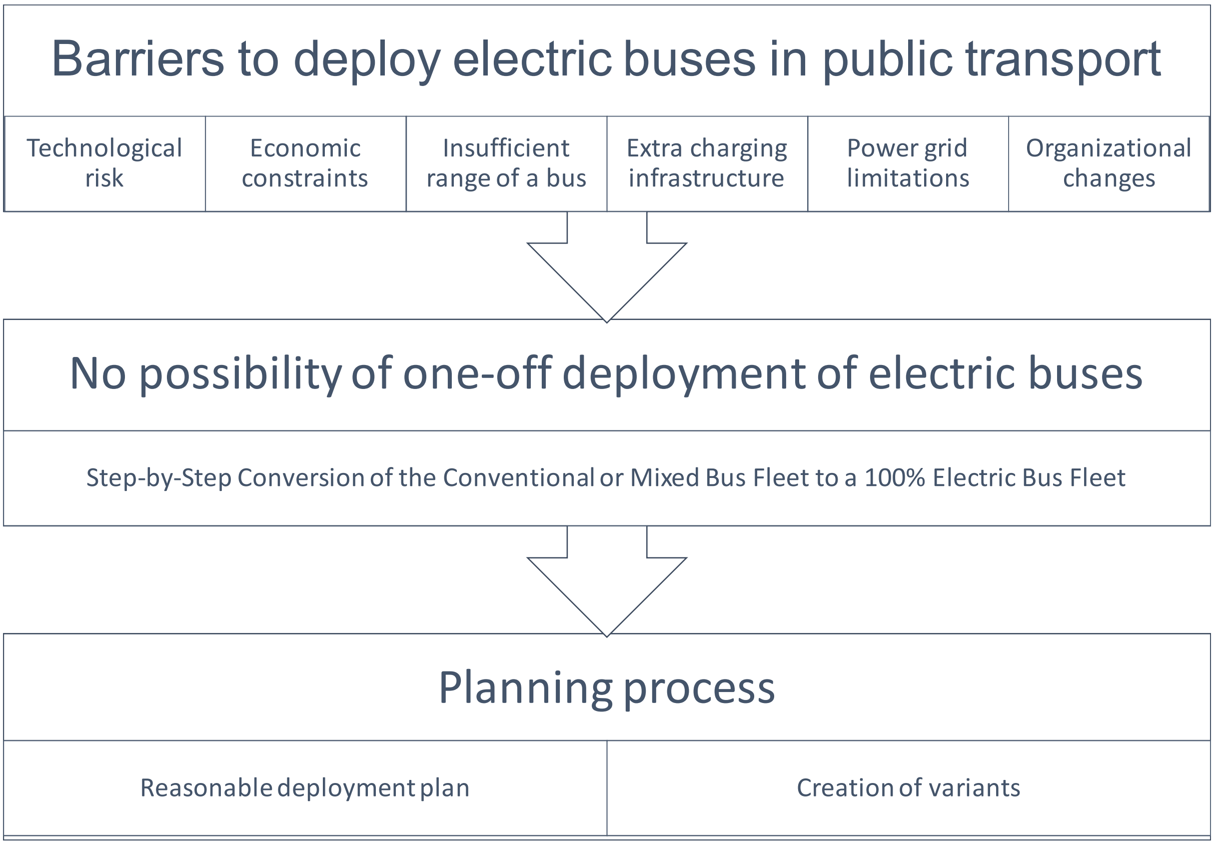

Figure 2 The genesis of the issues of the bus fleet conversion planning process

Because of the barriers to deploy electric buses in public transport listed in the scheme, a one-off deployment of these vehicle seems impossible to carry out. Hence, the two main threads of the planning process seem to be the most relevant:

- Reasonable deployment plan of electric buses in the transport network being operated by a transit company analysed.
- Creation of the fleet conversion variants, having regard to the local conditions in which a process takes place.

The choice of vehicle cycles to be operated by electric buses becomes a problem that should be supported using the methods related process engineering. For this purpose, the characteristics of technical parameters of electric buses available in the market (at the moment of analysis) should be examined, bearing in mind the importance of limited range (to operate all the vehicle cycles) and establishing of new charging infrastructure.

Striving for a 100% stake of electric buses it is necessary to apply intermediate stages which assume step-by-step conversion. Figure 3 illustrates multifarious ways to achieve a fully electric bus fleet. Various markings of lines in the picture have been introduced to improve readability of the approaches presented therein.

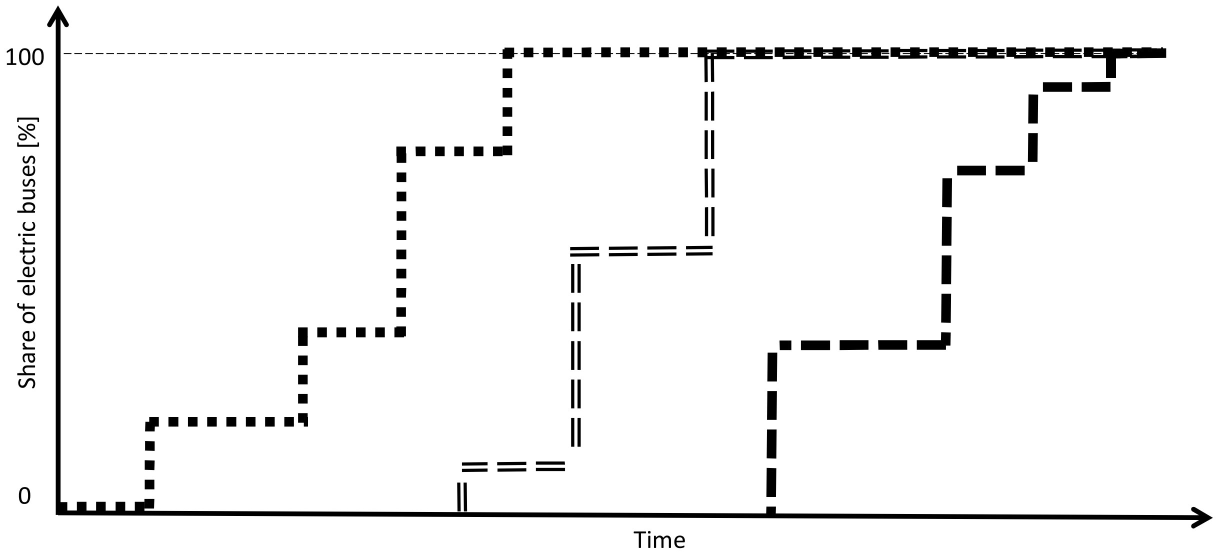

Figure 3 Intermediate stages in bus fleet conversion process in a transit company

Decisions on subsequent purchases of electric buses are taken at different time points, depending in particular on financial resources, but also on technical and organizational circumstances. It should be noted that time points in which intermediate stages in fleet conversion process take place are theoretical. These time points may also result from the designed planning process, being a subject of this deliverable.

To solve these problems, within PLATON consortium basic stages in the transition from conventional to fully-electric bus fleet has been presented. The basic stages in transition to electric bus fleet are described in the Deliverable 2.1 (Requirement Process). In Figure 4 the scheme illustrating basic stages in transition to electric bus fleet is reminded. In this deliverable we consider such issues as routes operational feasibility in more details.

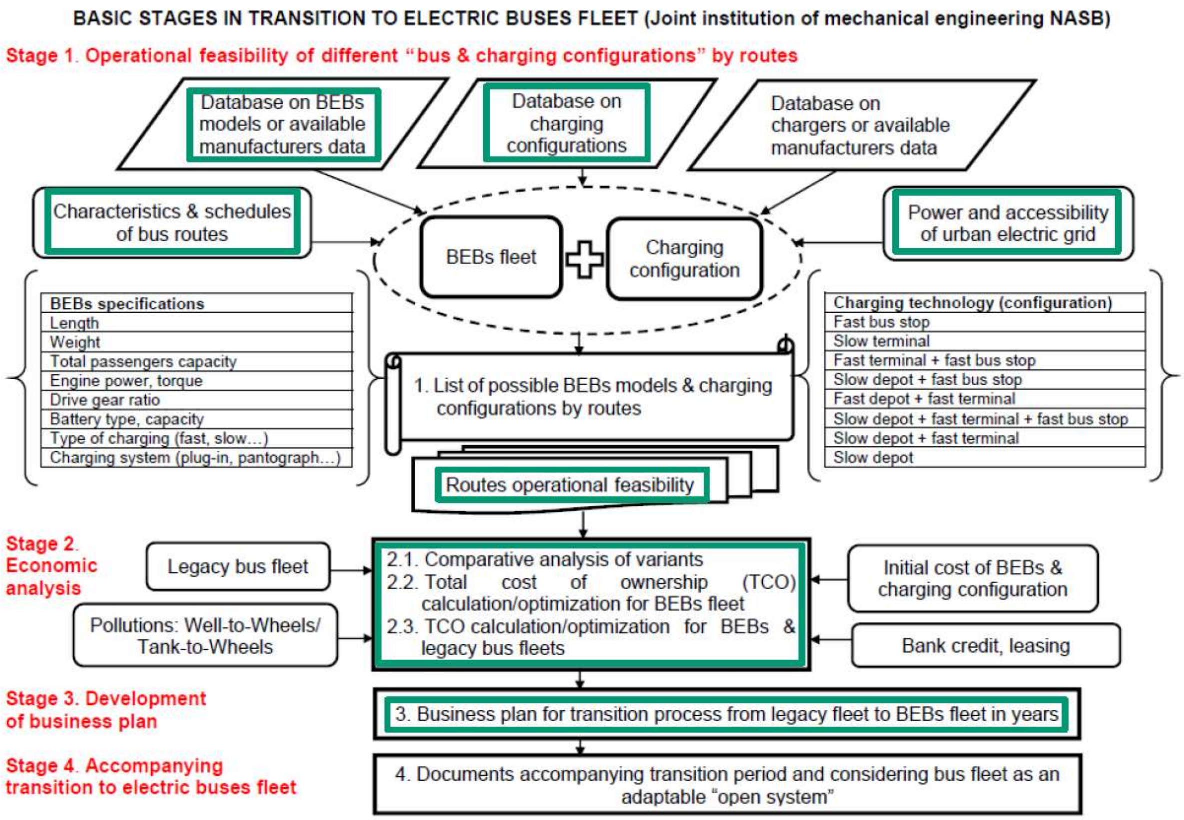

Figure 4 Basic stages in transition to electric bus fleet

Moreover, we mention comparative analysis of variants to calculate the Total Cost of Ownership (TCO), characteristics & schedules of bus routes as well as power and accessibility of urban electric grid. 'Business plan for transition process from legacy fleet to BEBs (battery electric buses) fleet in years' is indeed a subject of the planning process design, elaborated herein. Excess of the minimum required number of buses to operate the vehicle cycles planned, on the one hand increases the operational reserve, on the other, however, increases the costs. Modelling of the enterprise's policy in this regard is the subject of the company's day-to-day business activities. Hence, we don't deal with it focusing solely on the required and possible number of vehicle cycles to be operated by electric buses.

3 Structures of multi-level planning process

Being reported already in Deliverable 2.1, there were identified various dependencies between entities of several domains in the process of bus fleet electrification. These domains include among others the legislative and governmental domain that is responsible to define the general obligations and requirements of public transport services for the area of their territorial community and the corporate domain of a transit company that is responsible for the implementation and realization of the planned specifications. Planning processes of these domains cover the different operational levels, of Legislative-governmental level, Strategic corporate planning level, and Transport operations planning level which are elaborated in more detail in the following sub-sections.

3.1 Legislative-governmental level

General requirements of public transportation are the policies that describe the quality of services such as the frequency of departures, the distances between stops and their accessibility, the timely service intervals for weekdays and holidays and more factors, stated in the relevant urban public transport plan.

These general requirements constitute a planning document that is adopted by the legislation and forms the basis for transit tendering process and the resulting contracting with entrustment of a local public transport operating agency (PTO). It is in the nature of public transport industry that businesses rely on public funding from local, provincial or federal budgets. These public funds are subject of mid-term financial planning and legislative resolutions of the respective bodies. The amount of funding is closely related to defined public transport service quality and gives -in general- no room for profit-oriented business opportunities. Therefore, the legal form of public transport operator corporations is mostly a publicly owned limited liability company. The shares of these PTO are in most cases in full ownership of the territorial community or their affiliated holdings, that are in many cases local public municipal utilities.

The super-ordinated legislative-governmental planning level in the municipality 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. These planning steps cannot be executed without consultation and cooperation with the local public municipal utilities for energy, gas, water and sewer supply. In many cases these partly or fully city owned corporations act as holding for the local public transport operating agency. Therefore, these coordinated planning tasks must be carried out on a higher level than on the strategic corporate level of the PTO.

It is an advantage of the full ownership of the PTO that the territorial community is entitled and enabled to influence the planning process of both public transport service quality and fleet conversion towards BEB deployment. That is, if the political will exist and the financial funding is assured by the majority of the legislative body, the bus fleet conversion process can be initiated and executed by the fully owned local PTO. However, economic principles such as thriftiness and economic efficiency apply for any of these financial actions likewise, which is controlled by the supervisory board of the PTO, that is comprised in general of members of the ownership legislative body.

3.2 Strategic corporate planning level

The supervisory board and shareholders body are responsive to control the corporate management board of the public transport operating agency. The corporate management, i.e. the Chief Executive Officer is responsible for preparation and executing strategical decisions about the conversion process, the decision of route-wise transition or vehicle-cycle oriented transition, the procurement of bus models and makes, types and battery configurations including charging infrastructure decisions.

Planning processes that are required to prepare decisions in the mentioned fields must be carried out within the planning department of the PTO. These processes must take into consideration the TCO for the complete life cycle. The most important elements of TCO are bus, battery acquisition (capital costs), depreciation costs, personnel costs, energy costs, infrastructure and maintenance costs.

It can be assumed that across the European market the capital costs are equivalent whereas country related standards for vehicle's interior equipment will pose a tremendous impact on the price level for battery electric buses even for the same model and make. The capital costs that are strongly influenced by the general interest level.

The average years in service as well as the lifetime of the battery pack determine the depreciation costs. Personnel costs are mainly determined by the general wage level that differs remarkably even throughout countries of the European Union, especially between countries of the European Monetary Union and non-EMU members. The general price level is also strongly influenced by the energy prices, which are one of the main elements of the TCO. The energy price level is determined largely by the structure of power generation and the resulting energy mix of the referring country. For high price countries such as Denmark and Germany (at 0.30 €/kWh for households in 2017) the introduction of individual and public e-mobility will become more difficult than in lower priced countries such as Lithuania and Hungary (at 0.10 €/kWh for households in 2017, according to Eurostat), even though discounts for industrial mass consumers like PTO exist.

A recent study about the potential of electrification of two bus routes in the German city of Dessau (Saxony-Anhalt) led to the decision to decline the procurement and operation of BEBs in the city, even though the funding commitment of 80 percent of the extra capital costs for BEBs and charging infrastructure were given by the state government. However, since the cost of ownership is not funded directly but indirectly over the operating subsidy from the city's budget, the decision was made to abstain from electric bus deployment in the city of Dessau as announced in June 2019.

Because of this conditions, electric buses have also hardly been used anywhere in Germany to date. According to industry figures, only around 100 out of 35,000 buses are fully electric. According to McKinsey, there are around 1500 BEBs operational in Europe.

Any of these influencing factors must be accounted for through TCO and lifecycle analysis at the strategic corporate planning level in order to provide the foundation for decision–making processes in the supervisory board and shareholders body.

3.3 Transport operations planning level

If analyses of the strategic planning in the character of a preliminary planning led to a positive decision concerning the introduction of battery electric buses, the focus of the planning process shifts from legislative-governmental domain and economic domain towards the problems of public transport domain that is in a close relationship with the electric power domain.

The responsible party for these planning processes is again the public transport operating agency. Instead of strategical corporate planning tasks rather operational planning problems are to be addressed by specialized experts of transport technology who are supported by tools with capabilities of solving optimization problems such as electric vehicle fleets operating under range restrictions and opportunity charging requirements.

The general problem of public transport operations planning like vehicle and crew scheduling is almost a daily practice for public transport agencies, for which exist specialized software tools to generate operational schedules for bus vehicles, their assignment to vehicle cycles over a daily revenue service or the entire weekday services. Especially under constraints of restricted range of electric vehicles and need for regular opportunity charging during the revenue service cycle, the scheduling problem must be extended to meet these particular widened requirements.

A planning tool for this task area must be 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.

As the transit demand is considered as relatively fixed because it depends closely on land use, zoning and housing preconditions, the transport network must be developed such that the given demand is met by the public transport services on the supply side. Therefore, the network design – that consists of stop locations and routes composed of subsequent stops - is in general existent and may be altered only moderately.

The challenge is to combine the relatively fixed network design with the choice of charging locations which are mostly constrained by the vicinity of power substations with transformers connected to the medium power range from 10 kV up to 30 kV.

In the prevailing number of cases it is expected that charging facilities be located at terminal stops as turning points of bus routes, at which the time needed for recharging can be combined with resting time of drivers. Charging facilities at regular bus stops along the route are expected to contradict endeavours of public transport acceleration as a paradigm of urban public transport policy mainly known from bus prioritization at traffic light controlled intersections.

A tool component supporting these planning processes is expected to function relatively autonomously with regard to the above mentioned planning levels, but must be interoperable concerning data exchange with basic input data of the transport region of interest. An interface definition and documentation must contain not only the mathematical semantic description of the required input data contents but also the data model and data architecture in order to achieve the required interoperability.

4 Planning process design

4.1 Definition of vehicle cycle in the public transport network

Public transport operators (in other words: transit companies) operates a specific number of buses. These may include conventional Diesel buses or mixed fleet (consisted of, among other types of buses, hybrid buses, CNG buses, LNG buses, electric buses). These buses operate the network of stops in a convenient manner for passengers. Bus schedule (timetable for passengers) is defined for bus lines as well as the departure times of services from each bus stop of these lines. Each of the bus lines has at least one terminus (but in most cases two). Between the timetable for passengers and the buses a link is provided, which is a schedule for the use of individual buses for the operation of subsequent bus lines. The schedule of bus operations on bus routes is essential to carry out the timetable for passengers, taking into account organisational and economic constraints. As long as the timetable containing departure times of services from each bus stop is the most important from the passenger's viewpoint, for transit companies the most important issue is to route the buses in such a way to ensure the realization of the timetable. The instrument and effect of such scheduling for an individual bus is a vehicle cycle being the operating schedule of each bus during the day. It should be noted, that the number of vehicle cycles must not be less than the number of buses owned or leased by the company. This is shown in the equation (1).

$$card(VC) \leq card(BUS) \tag{1}$$

where:

$card(VC)$ – cardinality of the set of vehicle cycles

$card(BUS)$ – cardinality of the set of buses owned or leased by the company

Excess of the minimum required number of buses to operate the vehicle cycles planned, on the one hand increases the operational reserve, on the other, however, increases the costs. Modelling of the enterprise's policy in this regard is the subject of the company's day-to-day business activities. Hence, we don't deal with it focusing solely on the required and possible number of vehicle cycles to be operated by electric buses.

Example 1.

Associated partner of PLATON project – PKM Jaworzno – in one of the archival bus schedules (we do not disclose current data due to trade secrets), had 57 vehicle cycles $card(VC) = 57$, having at that time 61 buses $card(BUS) = 61$.

The simplest and the most accurate description of the vehicle cycle is to use graph theory in its application to transport modelling.

A directed graph G is identified with the graph of the structure of public transport network. $V(G)$ is a set of vertices of the graph G, and $A(G)$ is a set of its arcs. A set of vertices of the graph G is identified with the set of bus stops, denoted by $V(G) = \{v_1, v_2, \dots, v_n\}$. Cardinality of the set $V(G)$ is thus the number of vertices of the graph G, which is interpreted as the number of bus stops and is equal to n, that is $card\big(V(G)\big) = n$.

Cognately, a set of arches of this graph is identified with the set of inter-stops $A(G) = \{a_1, a_2, \dots, a_m\}$. Cardinality of the set $A(G)$ is thus the number of arcs of the graph G, which is interpreted as the number of (existing in the timetable) links between two bus stops and is equal to m, that is $card\big(A(G)\big) = m$.

A **vehicle cycle** may be thus defined as is defined as <u>**a finite sequence of arcs graph**</u> G. This may be interpreted as follows:

Vehicle cycle is the operation of a vehicle (bus) through the course of a day of transit service (including pull-out and pull-in) which consists of handling a sequence of bus stops (including depots) under handling one or more bus routes.

Such a definition allows beginning and ending of vehicle cycle at the same vertices (mainly depot) as well as multiple occurrence of the same vertices (bus stops). This issue is expanded in the example 2.

Example 2.

*There is a theoretical transport network, set out in form of graph (*Figure 5*)*

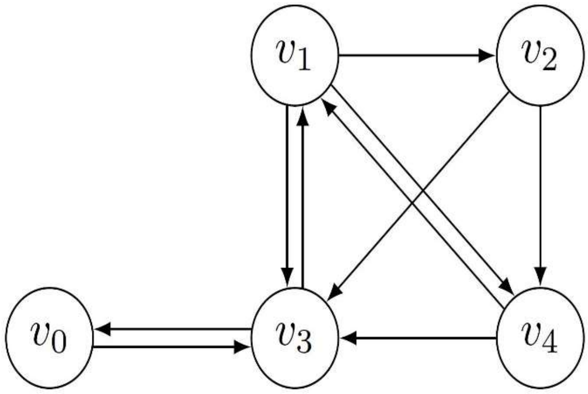

Figure 5 Graph of the theoretical public transport network

We have three buses in operation, four bus stops (v_1, v_2, v_3, v_4)*, a depot* (v_0) *and two bus lines:*

BUS LINE A:

***direction** v_4: v_3 ➔ v_1 ➔ v_4*

***direction** v_3: v_4 ➔ v_1 ➔ v_3*

BUS LINE B:

v_3 ➔ v_1 ➔ v_2 ➔ v_3 (a circuitous route)

Three vehicle cycles were defined, operated with the use of three buses:

Vehicle cycle no 1:

all-day vehicle cycle operating bus line A (in both directions):

v_0 ➔ (v_3 ➔ v_1 ➔ v_4 ➔ v_1 ➔ v_3) ➔ (…) ➔ (v_3 ➔ v_1 ➔ v_4 ➔ v_1 ➔ v_3) ➔ v_0

Vehicle cycle no 2:

all-day vehicle cycle operating bus line B:

v_0 ➔ (v_3 ➔ v_1 ➔ v_2) ➔ (…) ➔ (v_3 ➔ v_1 ➔ v_2) ➔ v_3 ➔ v_0

Vehicle cycle no 3:

all day vehicle cycle operating various bus routes (v_3 ➔ v_1 ➔ v_4 ➔ v_1 ➔ v_3) and (v_3 ➔ v_1 ➔ v_2) with a mid-day pause in the depot:

v_0 ➔ (v_3 ➔ v_1 ➔ v_4 ➔ v_1 ➔ v_3) ➔ (..) ➔ (v_1 ➔ v_2 ➔ v_3) ➔ v_0 ➔ (v_3 ➔ v_1 ➔ v_4 ➔ v_1 ➔ v_3) ➔ (..) ➔ (v_1 ➔ v_2 ➔ v_3) ➔ v_0

As a result of the fact that graph G is the directed graph, stops of the same name on both sides of the street may and should have a different number. When defining bus stops it is therefore necessary to respect the principle that two bus stops on both sides of the streets shall be considered independently. This issue is explained by the example 3.

Example 3.

*Bus stop named 'Lubowiec' operated by PKM Jaworzno is located on both sides of the 'Katowicka' street (*Figure 6*). Hence, according to the rules, there are two independent bus stops, denoted v_{31} (on the north side of the street) and v_{328} (on the south side of the street). 317, A, E, J S are the numbers of bus lines that operates bus stops numbered 31 and 328.*

Figure 6 'Lubowiec' bus stop case (© OpenStreetMap contributors)

Using GPS technology, a vehicle cycle may also be denoted in form of Shapefile or other GPS tracks. It would be optimal to collect them from the on-board equipment, being a part of Automatic Vehicle Location system. In the event that a public transport company does not have such a system, one can collect these files with the use of personal GPS loggers. It should be noted, however, that in case of extensive and complex transport networks, such a solution is not really time-efficient.

Example 4.

*Vehicle cycle denoted: '813-101' is operated by the associated partner of the PLATON project, PKM Sosnowiec, and runs through the cities of Katowice, Sosnowiec and Będzin (*Figure 7*). The depot, from which a bus pulls out to the first stop in the city centre of Sosnowiec, and to which it pulls in from the last stop in Będzin city centre, is located in the Eastern part of Sosnowiec city, in Zagórze district.*

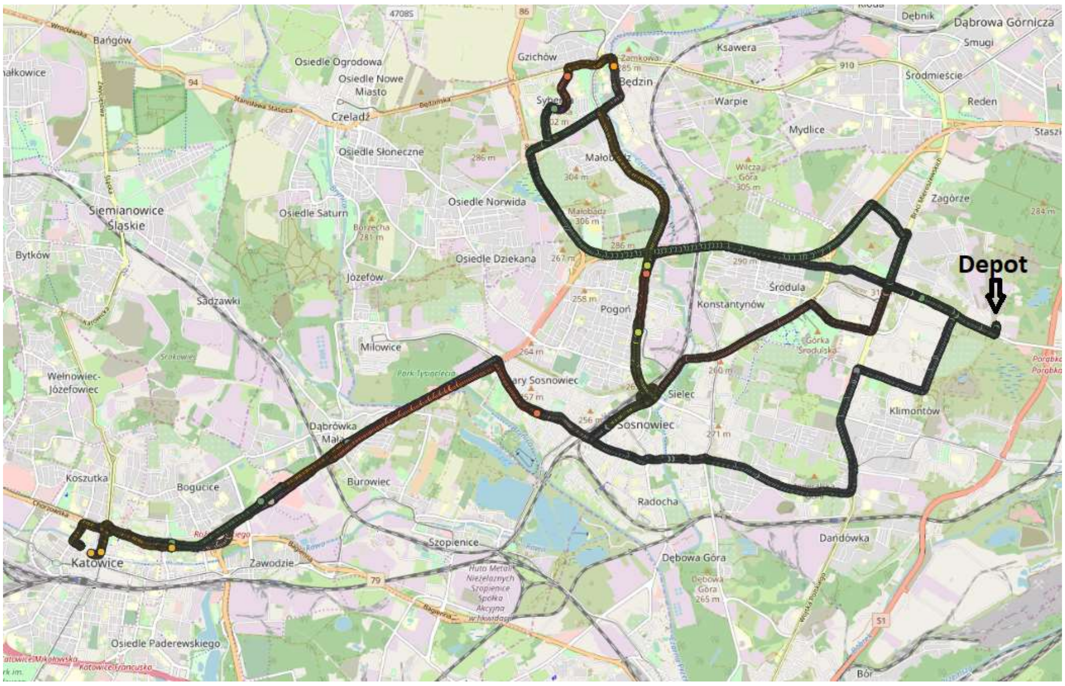

Figure 7 ‘One of vehicle cycles operated by PKM Sosnowiec (Map background © OpenStreetMap contributors)

When analysing vehicle cycle suitability for electric bus operation one should reflect on the parameters of bus stops and inter-stop sections. Considerations on this subject are presented below.

4.2 Definition of bus stop and inter-stop section parameters

For the proper definition of bus stop and inter-stop sections, we need a few parameters to be defined. In the first place, we must consider coordinates (longitude and latitude) as well as altitude of subsequent bus stops. Parameters related with battery charging are of a key importance considering the specificity of electric buses utilization in public transport. In particular, attention should be paid to the technical equipment of subsequent bus stops. This applies in particular to opportunity charging, but also to overnight charging facilities, located typically in the depot. When it comes to inter-stop sections, charging may also be possible (in-motion charging, inductive charging). Depending on the location, the acquisition of these data may vary in terms of difficulty.

Formally, we have some functions $F_W(V)$ specified functions on the vertices on the graph G . First three parameters are longitude, latitude and altitude of each stop. The latter refers to the charging method. For each charging methods available, we can assign an integer denoting these parameters. This is shown by the equation (2).

$$F_W(V) = \begin{bmatrix} (\lambda_1, \phi_1, h_1, charg_1) \\ \vdots \\ (\lambda_n, \phi_n, h_n, charg_n) \end{bmatrix} \tag{2}$$

where:

λ – longitude

ϕ – latitude

h – altitude

$charg$ – stationary charging facility available at this bus stop (if none, 0)

We proceed in the same way in the case of arcs of this graph, defining some functions $F_L(A)$, that represent the inter-stop sections of the public transport network. Here, we have a matrix of all the existing inter-stop sections with two parameters each, as set out in formula (3):

$$F_L(A) = \begin{bmatrix} (d_{11}, inmot_{11}) & \dots & (d_{1l}, inmot_{1l})) \\ \vdots & \ddots & \vdots \\ (d_{k1}, inmot_{k1}) & \dots & (d_{kl}, inmot_{kl}) \end{bmatrix} \quad (3)$$

where:

s – distance

$inmot$ – in-motion charging facility available at this inter-stop section (if none, 0)

If it turns out that travel times between to bus stops (inter-stop travel time) is constant all day long, it would be convenient to add another parameter - inter-stop travel time. In that case, formula () has been converted into formula (4):

$$F_L(A) = \begin{bmatrix} (d_{11}, inmot_{11}, t_{11}) & \dots & (d_{1l}, inmot_{1l}, t_{1l})) \\ \vdots & \ddots & \vdots \\ (d_{k1}, inmot_{k1}m, t_{k1}) & \dots & (d_{kl}, inmot_{kl}, t_{kl}) \end{bmatrix} \quad (4)$$

where:

t – time of travel through the inter-stop sections

At the so defined transport network, a process of conversion planning will take place.

4.3 General scheme of the planning process

In Figure 8 an outline of planning process is presented in graphical form is presented. This figure shows some of the main components of the planning process:

- Decision support system for electric bus deployment
- Optimal selection of electric bus fleet and charging infrastructure, and bus scheduling, subject the limited budget and bounded electric power
- Economic models for the Total Cost of Ownership (TCO) calculation

and their mutual relations. These components are marked with a thick line. The description of the planning process components is presented in the following subsections of this deliverable.

We work on an **object,** understood as a **public transport company (transit agency) operating buses on a specific, defined transport network, having at its disposal technical facilities**. At the start of the analysis, the transport network is operated by a set of conventional or mixed vehicles. **The aim** of the planning process is **an attempt to achieve a state in which a 100% of bus fleet is battery electric powered.**

Decision support system for electric bus deployment as well as optimal selection of electric bus fleet and charging infrastructure can benefit from energy consumption model, being developed to calculate the energy demand on a given route. Energy consumption model uses the databases of electric buses and charging methods. Besides, the existence of a policy maker is established, as an actor who can shape the conversion process either on macroeconomic and financial environment in which the process takes places, or based on subjective causes. The effect of these components is a detailed schedule for the bus conversion process.

The starting point for the calculation is a set of present vehicle cycles (understood as an entire route of the bus from a depot through all the stops to the depot again): either present being operated by the company or calculated with the use vehicle scheduling and optimisation methods. If we start from the set of present vehicles cycles we can use an energy consumption model which aim is to calculate a demand for energy in a detailed way. An alternative is to calculate the energy consumption either linearly or by taking a constant. A kernel of this path is a decision support system for the deployment of electric buses (e-buses) which is presented in a further part of the report in a more detailed way. By using this component, we have the opportunity to:

- Devise a detailed schedule for the bus conversion process – as a kind of a roadmap for various stakeholders towards a fleet consisting solely of electric buses.
- Formulate a static or dynamic model for a TCO calculation – which aims to show the global cost of investment, including additional technical infrastructure (primarily charging infrastructure).

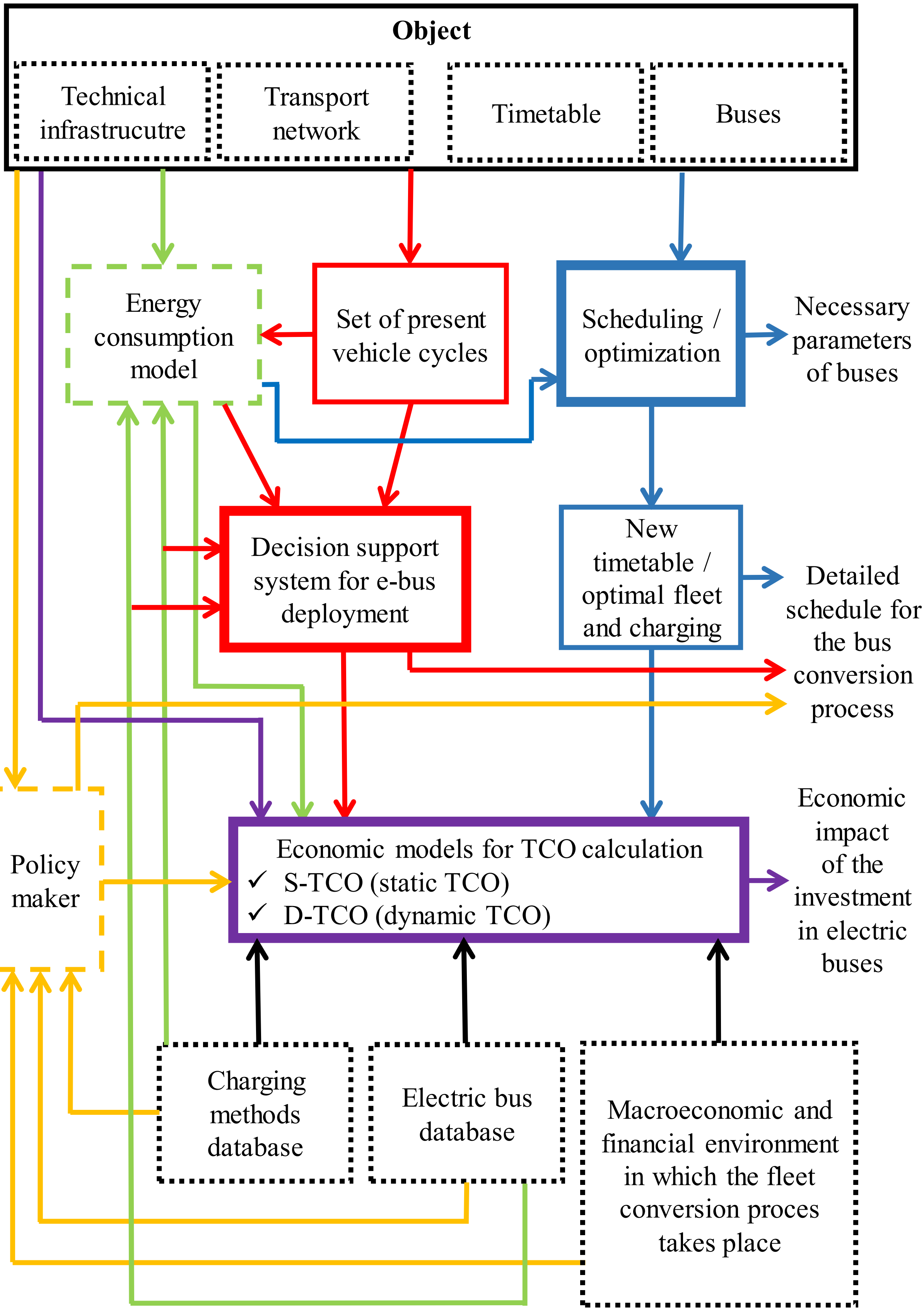

Figure 8 Scheme of the planning process

The static TCO model is different from the dynamic one, which takes into account the successive purchases of electric buses in time. The static model, however, enables the calculation of the total cost of the investment only in the case of an one-off purchase of all the electric buses remaining (or just a part of them). Model for TCO calculation is supported by databases of charging stations and electric buses. It also influenced by the financial and macroeconomic environment, in which the fleet conversion process takes place. The TCO model result in the economic report of the investment in electric buses.

On the right, there is a ‘blue variant’ in which we focus on such a re-modelling of the vehicle cycle structure, to obtain a brand-new structure of vehicle cycles that consult charging limitations (and the consequent time slots for charging). Modification of vehicle cycles structure may bring some changes in the timetable for passengers. At this point it should be noted that any changes in public transport offer may seem unwelcomed, if happening only because of the limitations of a new technology (range of electric buses). The results may also be tested with the use of TCO model. The TCO model is to be developed under WP4.

In the model the existence of a policy-maker has also been taken into account, which influence the decisions on the conversion process. In such a case, the system supports him or her for various variants of the fleet conversion concepts analysed.

4.3.1 Decision support system for electric bus deployment

An algorithm for decision support regarding bus fleet conversion towards a 100% electric fleet is depicted in Figure 9. The algorithm partially develops the decision support system (presented already in Figure 8). Here, a thread of a proper order of electric buses induction to operate subsequent vehicle cycles (and, in consequence, bus routes), is expanded.

The first step is to consider the willingness (or unwillingness) to change a structure of vehicle cycles. This very component accounts for a **one-for-one** conversion from current bus fleet owned or leased by the company (conventional or mixed) towards a 100% fleet. What is important, no changes in the vehicle cycle scheme is assumed. This means that we are trying to convert as many buses as possible, without changing the timetable for passengers.

Hence, we start with a set of present vehicle cycles which translates into a determined timetable for passengers. The vehicle cycles are the part of the **object** (already defined above). Decision support system for electric bus deployment is to test the individual vehicle cycles, currently operated by conventional bus fleet. The question is therefore as follows: **‘which vehicle cycles, using existing or planned charging infrastructure, may be operated by electric buses of available operational range’** (resulting from the battery technology applied in the buses concerned). This issue is illustrated in more details in Figure 10.

The vehicle cycles may be tested with the use of **energy consumption model** to increase the accuracy of calculations or using other available data. The most important questions to be answered are these related with the amount of energy a bus consume per one kilometre and what amount of energy a bus can be charged during one minute, using existing or planned to be installed technical infrastructure.

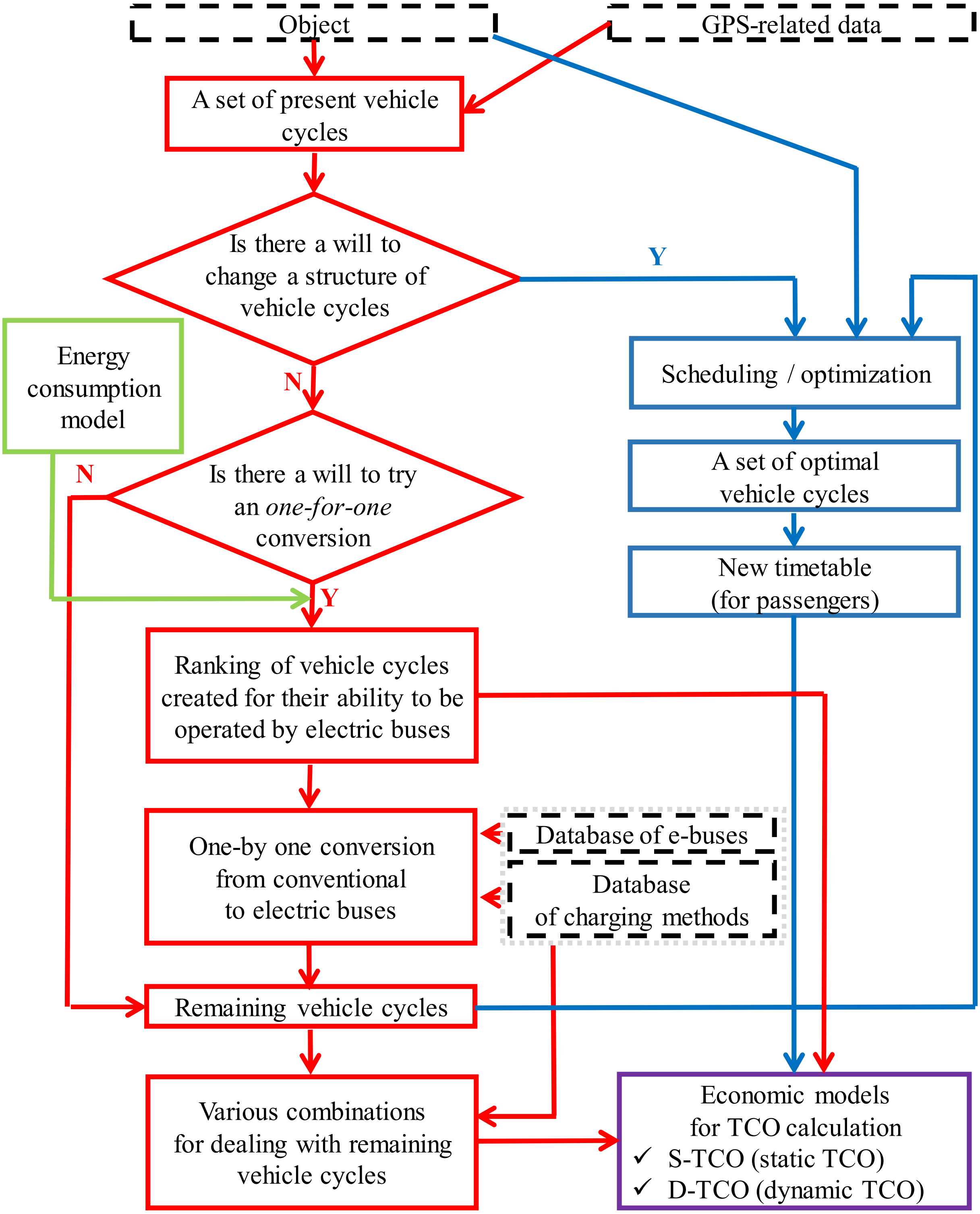

Figure 9 Scheme of the decision support system

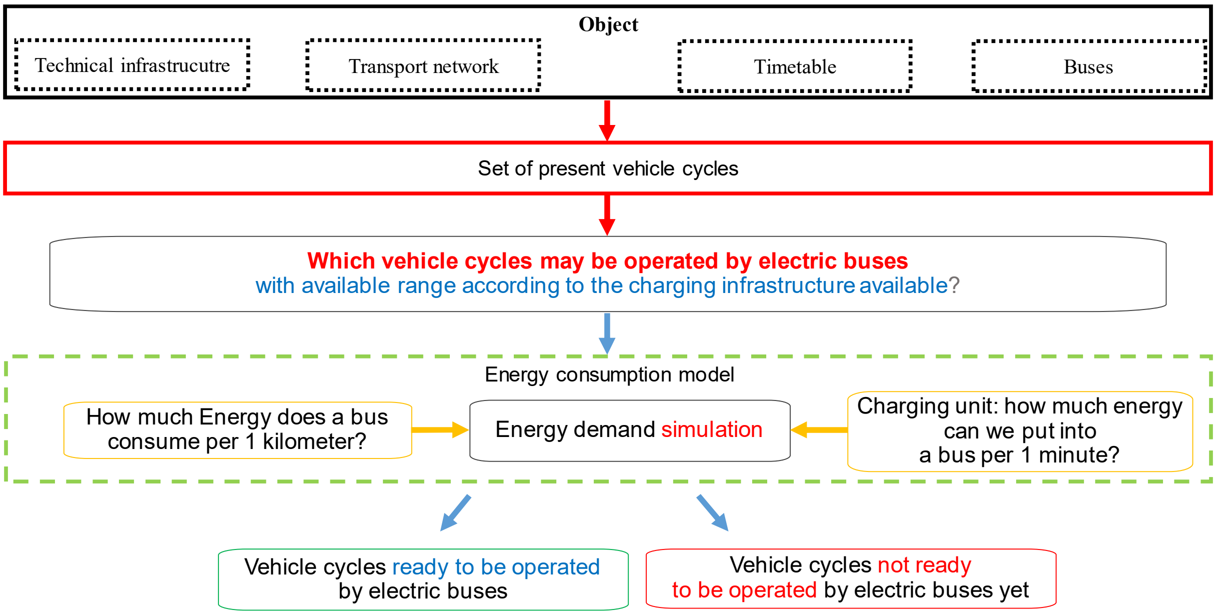

Figure 10 Testing vehicle cycles for discharging on the assumption that there is no change in bus schedule

As a result, the set of present vehicle cycles is divided into these which are possible to be operated with the use of electric buses, and these, which are not ready to be operated by electric buses yet. This is illustrated by the example 5.

Example 5.

In a given transport network there are n vehicle cycles, operated by conventional buses at the start of the simulation. Subsequent vehicle cycles are analysed for dis-charging characteristics in case of operation by electric buses.

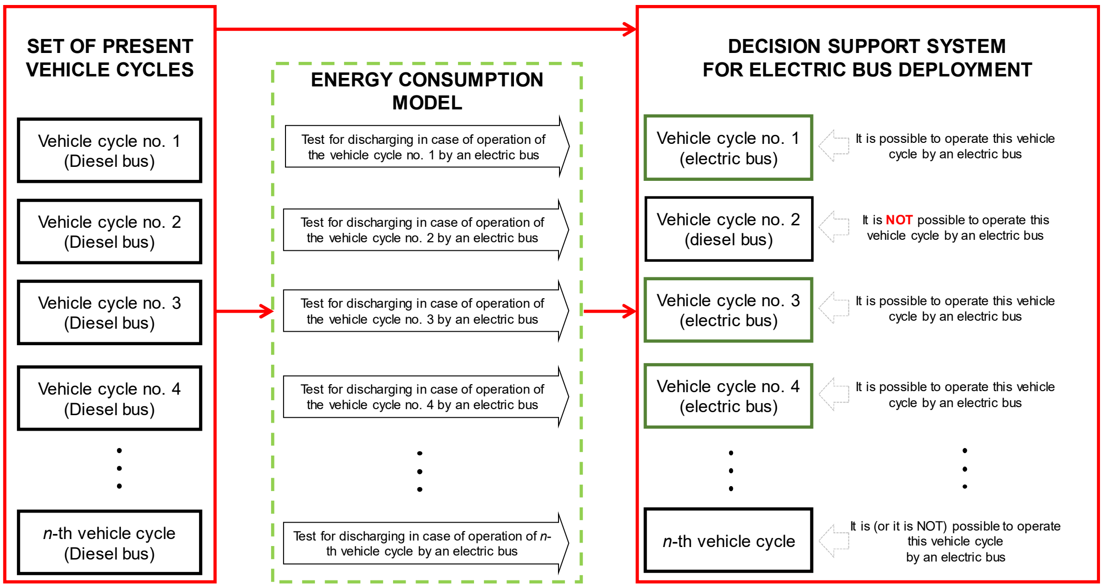

Figure 11 Partial replacement of conventional buses with electric buses without changing the bus schedule

Supposing – on the basis of simulations – battery discharge, it is not possible for this very vehicle cycle to be operated by an electric bus at this stage of technological development. If, as a result of a simulation a bus will be able to return to the depot after fulfilling the entire vehicle cycle without being discharged, that *means that there is possible to operate this vehicle cycle with the use of electric buses. Consequently, we have a set of vehicle cycles divided into these which are and which are not possible to be operated by electric buses.*

The fact that there are vehicle cycles which are not possible to be operated by electric buses does not mean that achieving a target of a 100% share of electric buses is infeasible. This only means, that these vehicle cycles are not suitable to be operated by electric buses at this stage of battery and charging technology development. Of course, due to the vibrant technology development it may turn out that some vehicle cycles that had not been ready for operation, after upgrading technical parameters, will be proven to be possible to operate by electric buses. Testing vehicle cycles for discharging may be repeated until the achievement of a 100% electric fleet in the transit company.

To sum up, it is to be expected that over time, with the increase of battery capacity, an increase in advancement in charging technologies and energy efficiency of buses, the number of vehicle cycles being ready for operation by electric buses will be increasing. Nevertheless, such action may delay the achievement of fully-electric bus fleet for a longer period of time.

Much more often, however, another problem will appear. Depending on the financial resources available, it is possible to purchase as many electric buses as it results from the analysis or less, according to the financial capacity of the transport company. In such a situation, it will be reasonable to rank these vehicle cycles from the standpoint of their ability to be operated by electric buses, including economic issues and selected parameters listed in Table 2. The main reason for such action is the attempt to answer the following question: which vehicle cycles (of those which are possible) select to be operated by electric buses first?

Figure 12 sets out this issue in more details, using some data from the *Example 5.* Here, however, these vehicle cycles are not only tested for discharging – the most suitable vehicle cycles shall be sought having regard to selected decision variables using multi-criteria decision support methods. This results in the hierarchy (ranking) of vehicle cycles ordered from the easiest vehicle cycle to the most difficult one – but still possible – to be operated by an electric bus. With the use of data from the database of buses and charging methods, we may verify the cost of tested electric bus deployment in the company.

It should be noted that this method works only for vehicle cycles susceptible for *one-for-one* conversion. Other cases are described below.

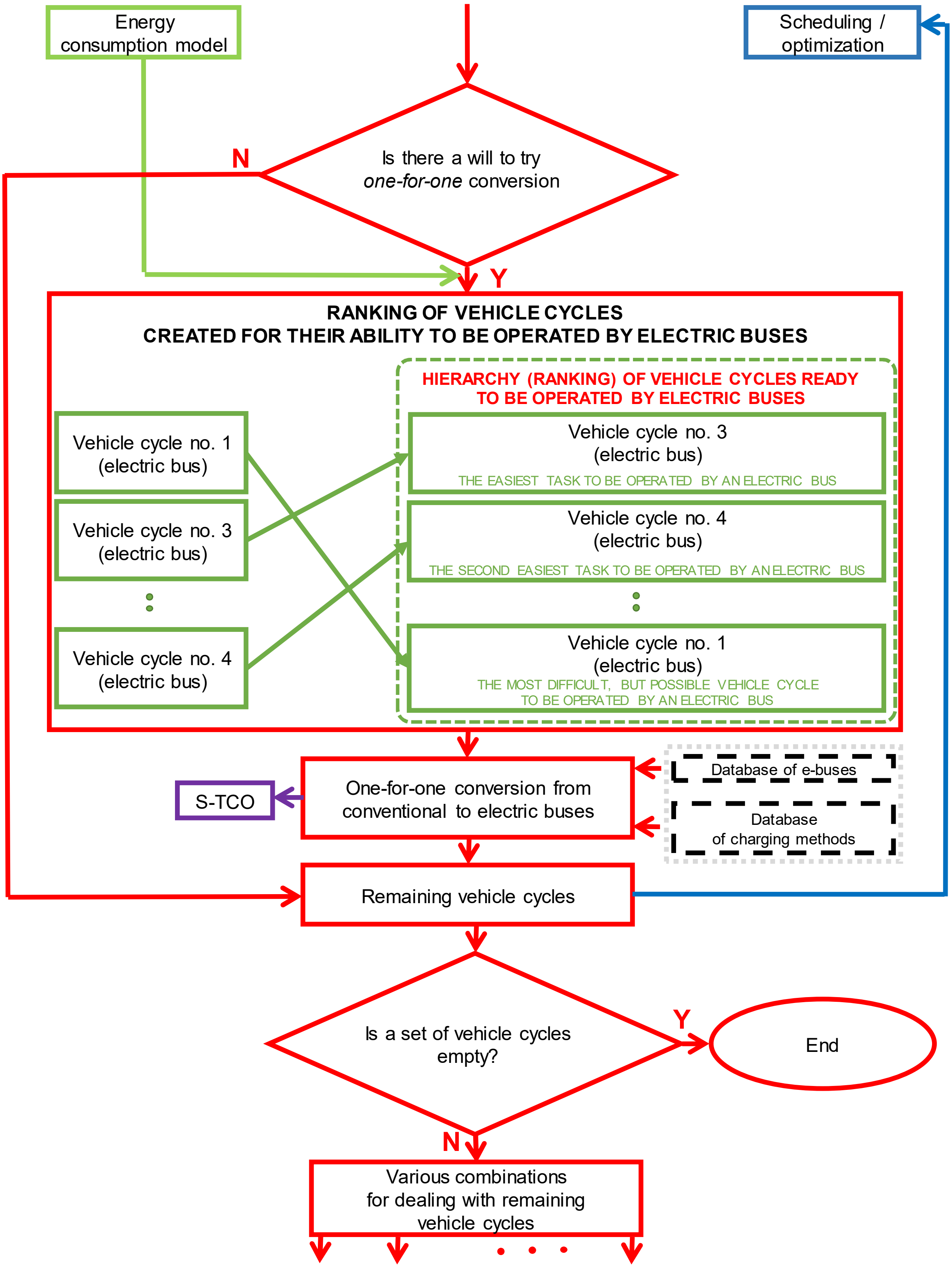

Figure 12 Testing vehicle cycles for discharging on the assumption that there is no change in bus schedule

If, as a result of the application of the abovementioned methods, or as a result of the omission of a *one-for-one* conversion stage, no serviceability by electric buses will be achieved the following possibilities are to be considered by a public transport company:

- Maintenance of the current timetable without changing the structure of vehicle cycles.
- Maintenance of the current timetable allowing changes in the structure of vehicle cycles.
- Maintenance of the current number of vehicle cycles allowing changes in the timetable.
- Partial or total re-schedule of the timetable and the structure of vehicle cycles
- Amendment to take account of the political nature of the decision to require electric buses on certain lines.
- Maintenance of the current timetable without changing the structure of vehicle cycles, awaiting for better technical parameters of electric buses to try one-for-one conversion again.

This strategy is graphically depicted in Figure 13. Having remaining vehicle cycles (either because of the lack of will to carry out *one-for-one* conversion, or as a result of the test for discharging), we have various combinations for dealing with the remaining vehicle cycles. These combinations are called **variants** of the bus fleet conversion process in a public transport company.

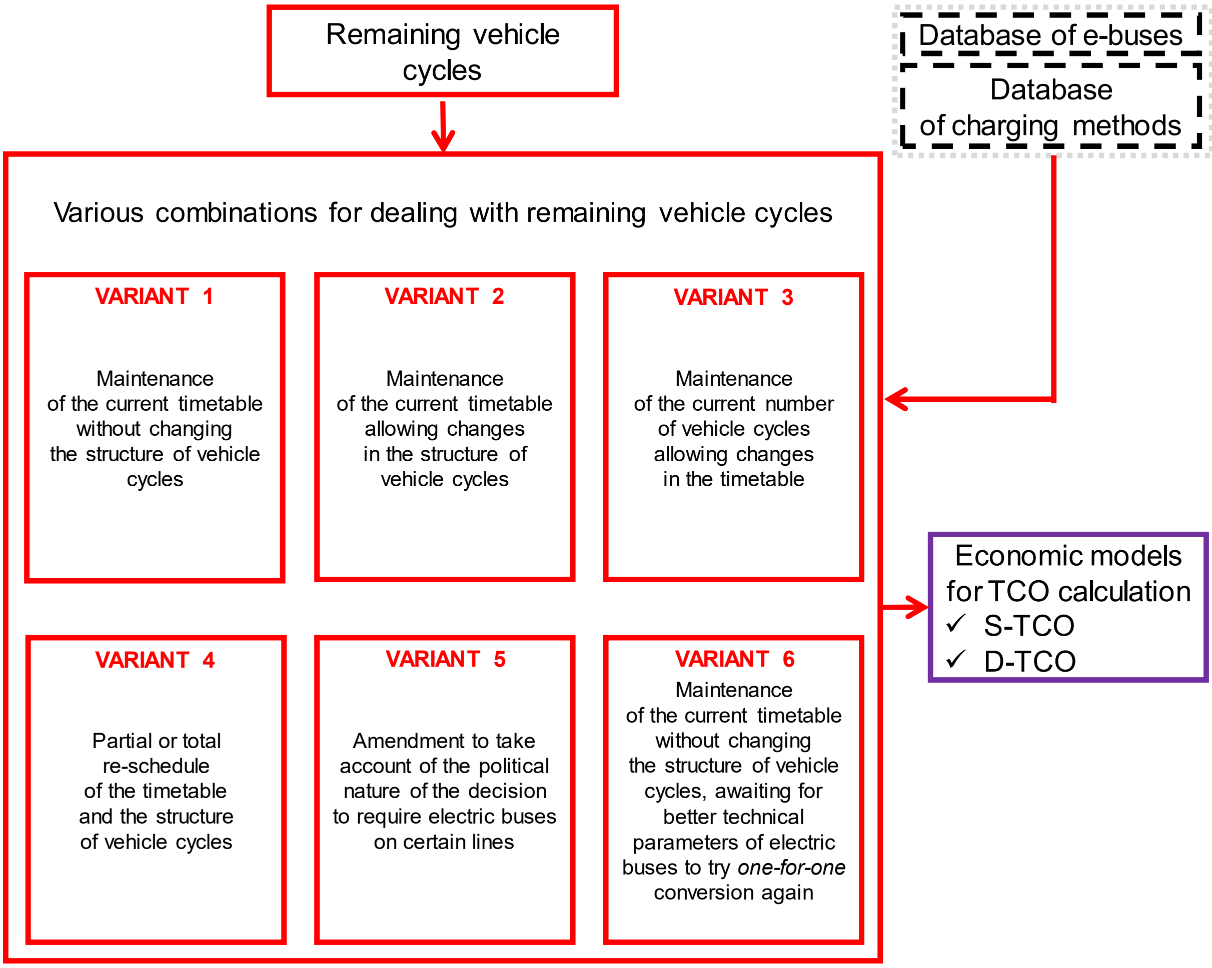

Figure 13 Aiming to replace 100% of the fleet allowing bus schedule corrections

The following is a brief description of each of these variants.

4.3.1.1 Variant 1: Maintenance of the current timetable without changing the structure of vehicle cycles

Under this variant the following actions are deliberated:

1. Sweeping the remaining vehicle cycles for having time slots in the midday (operating peak hour services):
   - Analysing the possibility of exit to the depot or the nearest bus stop.
   - For such a case, further *one-for-one* conversion is possible.
2. Analysing other vehicle cycles for any time possible to recharge batteries, if only suitable technical equipment is to be installed
3. Minimising the number of chargers in the transport network
   - The following assumption is thus needed: the access to the nearest charger, formally at another stop or a new technical stop, is not a change of vehicle cycle'.
   - In practice this means that we must add a technical stop for charging to the sequence of bus stops defined in the vehicle cycle.
4. Other vehicle cycles are to be operated in the same way, as in variants 2,3,4,6.

Output: The number of buses has not increased, we allow for minor "technical" corrections of transport tasks at the stage of minimizing the number of loaders.

4.3.1.2 Variant 2: Maintenance of the current timetable allowing changes in the structure of vehicle cycles

Under this variant the following actions are deliberated:

1. Sweeping the remaining vehicle cycles for having for time slots in the midday (operating peak hour services):
   - Analysing the possibility of exit to the depot or the nearest bus stop.
   - For such a case, further *one-for-one* conversion is possible.
2. Aggregate vehicle cycles to the bus lines
   - For each bus line of high frequency we add a vehicle cycle and install a charger at the terminus.
   - In each of the vehicle cycles assigned to this bus line, a correction of the timetable should be needed.
3. Analysing other vehicle cycles for any time possible to recharge batteries, if only suitable technical equipment is to be installed.
4. We change other vehicle cycles in a way described above, adding as few new charging facilities and vehicle cycles, as possible.

Output: at least one additional bus and loader is required; the number of transport tasks is increasing.

4.3.1.3 Variant 3: Maintenance of the current number of vehicle cycles allowing changes in the timetable

Under this variant the following actions are deliberated:

1. No change in the number of buses, but we change necessary time slots for charging.
2. Analysis of subsequent vehicle cycles for time and place necessary for charging, minimizing number of locations in which charring facilities are located in the transport network.
   - We try to minimize the impact of these changes on the transport offer for passengers.
3. We group the vehicle cycle into several subgroups (reforming the dishes completely by the way) to create a new timetable for passengers with only one common loader.

Output: There is no change in the number of vehicle cycles, brand new timetable for passenger, corrections in vehicle cycles are allowed

4.3.1.4 Variant 4: Partial or total re-schedule of the timetable and the structure of vehicle cycles

Under this variant the following actions are deliberated:

1. Sweeping the remaining vehicle cycles for having time slots in the midday (operating peak hour services):
   - Analysing the possibility of exit to the depot or the nearest bus stop.
   - For such a case, further *one-for-one* conversion is possible.
2. We choose these vehicle cycles that are possible to be operated (have enough time slots for charging) by electric buses allowing slight changes in the timetable.
3. Heuristic actions of experienced public transport planners and minimising the number of required charging facilities.

Output: Adaptive option, susceptible to phased implementation

4.3.1.5 Variant 5: Amendment to take account of the political nature of the decision to require electric buses on certain lines

Under this variant the following actions are deliberated:

1. Acting of policy-maker who forces some solutions
   - e.g. no conventional vehicles in ecological zones of the cities (including Diesel buses)
2. We choose these vehicle cycles which are affected by the actions of the policy-maker.

3. Analysis of variants 2, 3, 4 to minimize chargers.

Output: Implementation of this variant is difficult to support but beneficial to achieve transport policy effects

4.3.1.6 Variant 6: Maintenance of the current timetable without changing the structure of vehicle cycles, awaiting for better technical parameters of electric buses to try one-for-one conversion again

Under this variant the following actions are deliberated:

1. Sweeping the remaining vehicle cycles for having time slots in the midday (operating peak hour services):
    - Analysing the possibility of exit to the depot or the nearest bus stop.
    - For such a case, further *one-for-one* conversion is possible.
2. Definition of technical specifications for the bus industry for the desired technical parameters.
3. Waiting for the technical requirements to be met.

Output: Despite the fact that the variant is the easiest, achieving the share of 100% electric buses may be postponed.

4.3.2 Optimisation

4.3.2.1 Optimal selection of electric bus fleet and charging infrastructure, and bus scheduling, subject to the limited budget and bounded electric power

The following approach is suggested for planning conversion of conventional public bus service into an electrical bus (e-bus) service. A number of assumptions are imposed to make the considered planning situation more specific and appropriate for mathematical and computer modelling. They are given below.

4.3.2.2 Assumptions

The main assumptions for the optimization problem are as follows:

- Only existing public transport routes are considered. No new route can appear and no existing route can be modified with regard to the set of its stops and the passenger transfer demand
- The main objective is the minimization of the harmful emissions of the public transport vehicles
- The decision to be made concerns the selection of routes to be served by e-buses, the selection of e-bus types and quantities of e-buses of each type to serve each of the selected routes, the locations for the charging stations, the

links of these locations with the electrical substations (power transformers), the charging station types and their quantities, and the schedules of the selected e-buses and the remained conventional vehicles for each of the selected routes.

- E-bus fleet (e-bus types and their quantities), bus timetables and charging infrastructure (locations for charging stations, charging station types and their quantities, links with substations) are determined for a time period such that feasible operation of the transportation system in this time period implies its feasible operation in any other time period of the planning horizon. This period can be determined by the worst season, say, winter, worst day of the week, say, Monday, and time of the day with the largest passenger transfer demand, say, 7:00-9:00 a.m. We call this time period decisive
- The limited resources that are required to implement the conversion decision in a given year are the money and the output power of the transformers. The upper bounds on the budget and the output power of the transformers are given
- The involved costs are the capital and operating costs of the selected e-bus fleet, the charging infrastructure costs and the energy costs. The operating costs are given per unit (one e-bus of a given type or one charging station of a given type) per year. The energy cost is given per one e-bus of a given type per year, assuming that this e-bus runs a given number of kilometres in this year
- The involved power requirements include the nominal power of a charging station of each type and the output power of a transformer of each type
- The bus schedules are determined by the sequence of traffic intervals and the vehicle type assigned to each of these traffic intervals for the same route.
- The length of the existing traffic interval of each route in the decisive time period is used as an upper bound on the length of the traffic interval after the conversion decision has been made
- For each route, the passenger transfer demand is determined by the total passenger capacity of the currently used vehicles, which are on the route in the decisive time period. This demand must be satisfied by the selected e-buses and the remained conventional vehicles after the conversion decision has been made

Problem formulation. We suggest to solve an optimization problem, which is to determine e-bus fleet and schedules of e-buses and remained conventional buses in the decisive time period, places for charging stations and substations, assignment of charging stations to the determined places, assignment of charging stations to the substations (power transformers) and assignment of charging stations to the routes such that all e-buses can feasibly drive, the passenger transfer demand and the budget constraints are satisfied, and the output power of any transformer is not exceeded. The primary objective is to maximize the total harmful emission of the replaced conventional vehicles and the secondary objective is to construct balanced bus schedules.

Main idea to implement the step-by-step conversion. In order to implement the dynamic (step-by-step) nature of the conversion process, we suggest to solve the optimization problem repeatedly for the years of the planning horizon. The decisions made for the past years are used as part of the input for the future year. This approach is justified by the fact that the input data for the near future is more reliable and precise than that for the far future. There are two main approaches to make a decision for a planning horizon of several years: *one-stage decision* and *multi-stage decision*.

Let the planning horizon be the sequence of years *1,2,…,t*. In the one-stage decision approach, the input data are assumed to be given for each year of the planning horizon. The optimization problem is solved for each of the years *h=1,2,…,t* and the output of the optimization problem for the year *h-1* complements the input for the optimization problem for the year *h, h=2,…,t*. All *t* optimization problems are solved and presented to a decision maker at once. At the time of the decision, which can be called "now", the decision made for the year *h=1* can be implemented in full and some preliminary actions can be undertaken for the implementation of the decisions for the years *h=2,…,t.*

In the multi-stage decision approach, the input data are assumed to be given only for the year *h=1*. The optimization problem is solved for this year, and the corresponding decision can be implemented at the present time ("now"'). In the future, as soon as the more reliable and precise input data become available for the year *h*=2, the corresponding optimization problem for the year *h=2* is solved. In the same way, the decisions are made for the years *h=3,…,t*.

5 Route cycles and factors for evaluation of energy consumption

To assess the energy consumption for a separate route and a set of routes connected by idle runs of the electric bus, the concept of 'routes cycle' is introduced. Below, a definition of route cycle may be found:

***Routes cycle*: Sequence of routes and auxiliary runs such as Pull-out, Pull-in, Dead head.**

Components of the routes cycle are presented in Fig. 14.

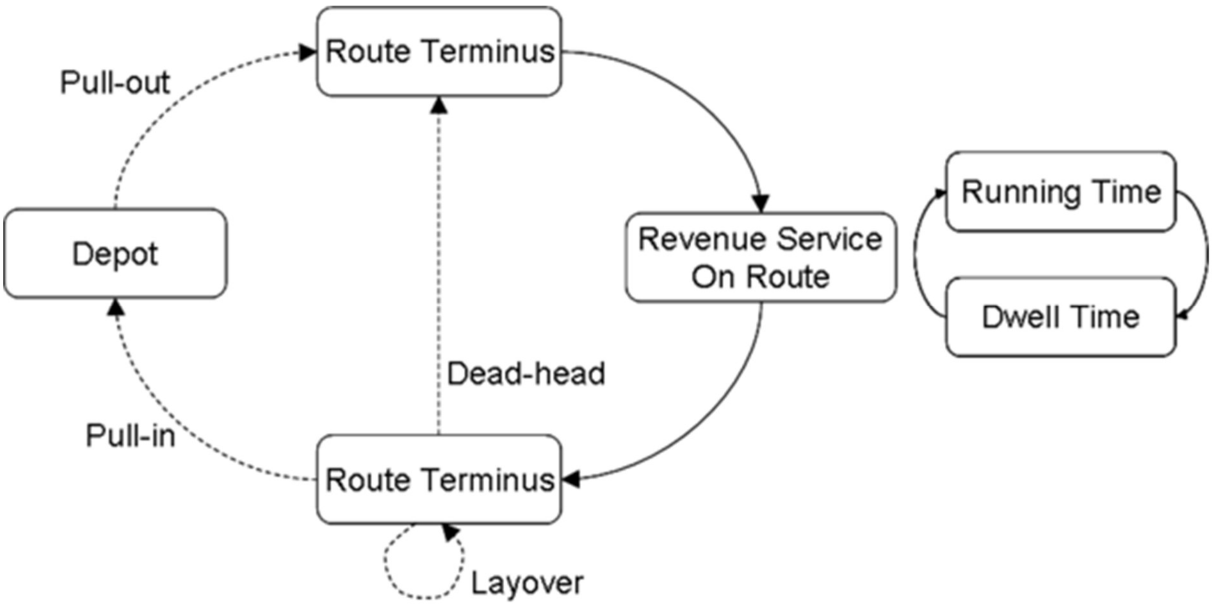

Figure 14 Components of the routes cycle

In particular cases, the route cycle (RC) may correspond to the vehicle cycle (VC) (for example, in the case "slow depot"), or a separate route (in the case of "opportunity" with chargers at the termini of the route).

RC is a more flexible concept than Vehicle Cycle. RC can be used to describe any part of the transport network (and the corresponding trips in it) and estimate its energy consumption.

The scheme for calculating energy consumption including basic factors is shown in Fig. 15.

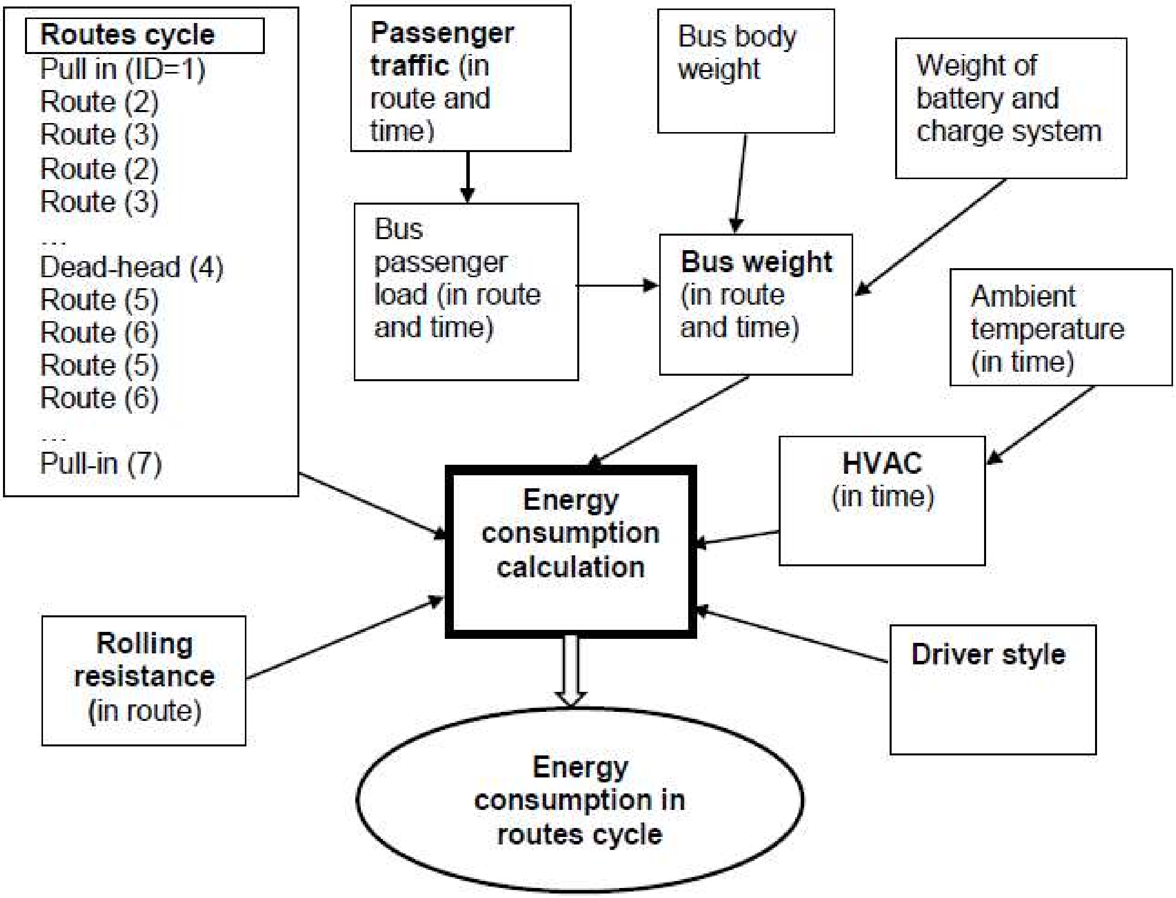

Figure 15 Scheme for calculating energy consumption in a routes cycle

The routes cycle is formed by an interested party to assess energy consumption and other electric bus properties. Hence, it may be used in the planning process for energy consumption calculation.

6 Summary

The inevitability of public transport electrification seems to be foredoomed. The correct choice of methods presented may allow a methodological approach to the achievement of a 100% electric bus fleet in transit company operating a public transport system.

Due to financial and organizational limitations, a one-off exchange of conventional buses with electric ones seems unlikely to happen in the majority of cities. This view is based on financial constraints, the structure of bus fleets and the observation of the fleet conversion process in many European cities. Hence, it should be considered at which points in time how many electric buses to exchange. In the deliverable, intermediate stages are defined – partial replacement of conventional buses with electric buses without changing the bus schedule with the aim to replace 100% of the fleet allowing bus schedule corrections.

IFAK deliberated on the structures of multi-level planning process. They distinguished three levels: legislative governmental level, strategic corporate planning level and transport operation level.

SUT focused on a general scheme of the planning process is shown in this deliverable. Particular attention has been paid to the description of decision support system for electric bus deployment based on vehicle cycle approach. As a consequence of this approach there is an attempt of ‘*one-for-one* conversion’ of conventional vehicle to electric ones. The next step is to obtain a hierarchy (ranking) of vehicle cycles from the most suitable for being operated by electric buses to the least suitable, but still possible to be operated by this kind of buses. In the event of a failure to carry out the ‘one-for-one conversion’, six variants for dealing with the remaining vehicle cycle are proposed. They differ in the degree of interference in the vehicle cycle scheme and the timetable for passengers.

UIIP presented the assumptions and problem formulation for the planning for the optimisation problem of optimal selection of electric bus fleet and charging infrastructure, and bus scheduling, subject to the limited budget and bounded electric power

JIME, in turn, contributed in vehicle cycles (route cycles) and factors for evaluation of energy consumption.

7 References

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