A Concise Guide on the Integration of Battery Electric Buses into Urban Bus Networks

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With the increasing market penetration of battery-electric buses into urban bus networks, practitioners face many novel planning problems. As a result, the interest in optimization-based decision-making for these planning problems increases but practitioners’ requirements on planning solutions and current academic approaches often diverge. Against this background, this survey aims to provide a concise guide on optimization-based planning approaches for integrating battery-electric buses into urban bus networks for both practitioners and academics. First, we derive practitioners’ requirements for integrating battery-electric buses from state-of-the-art specifications, project reports, and expert knowledge. Second, we analyze whether existing optimization-based planning models fulfill these practitioners’ requirements. Based on this analysis, we carve out the existing gap between practice and research and discuss how to address these in future research.

Keywords: electric buses; fleet transformation; charging location; vehicle scheduling; survey.

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1 Introduction

Cities all around the world struggle with poor air quality, partially caused by transportation. To this end, battery-electric buses (BEBs) constitute a promising solution to improve urban air quality due to their local zero emissions. As a result, the market penetration of BEBs has steadily increased in the past years (see Figure 1). As Table 1 shows, cities all around the world started to integrate BEBs into their public transportation network and many other cities plan to do so (cf. Guida & Abdulah 2017, Glotz-Richter & Koch 2018, Sustainable Bus 2020c). Consequently, practitioners are increasingly concerned with novel planning tasks and decision-making related to the deployment of BEBs into existing fleets.

When integrating BEBs, complex planning decisions arise for fleet operators, who must consider both strategic and operational aspects simultaneously. At strategic level, operators must decide on the bus fleet’s transformation and the installation of sufficient charging infrastructure. Herein, interdependencies and compatibilities between on-board charging devices of BEBs and charging power levels of charging stations further complicate planning decisions. At operational level, fleet operations planning must ensure the bus timetable’s operational feasibility under minimal costs. Accordingly, integrating BEBs into urban bus networks requires advanced optimization-based planning models that can cope with these complex and interdependent planning decisions.

Academics respond to these planning requirements from practice by developing optimization-based planning models, and the number of scientific publications on planning models for BEBs has increased considerably (see Figure 2). However, due to the high inherent complexity of planning tasks, state-of-the-art optimization-based planning models often rely on simplifying assumptions, e.g., regarding (partial) recharging procedures, vehicle scheduling, or energy consumption, although these aspects can be of great importance for practitioners. For example, a simplifying assumption on the energy consumption may not be cost-efficient as buses get equipped with oversized battery capacities or may even lead to infeasible schedules as buses may run out of energy during real-world operations.

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Figure 1: Number and market penetration of BEBs in the European Union from 2013 to 2020, assuming a market volume of 160,000 buses, based on EAFO 2020.

Figure 2: Number and three years moving average of publications on optimization-based planning for BEBs between 2013 and 2020.
Table 1: Number of conventional buses and BEBs in cities all over the world.

| City* | # BEBs | # Buses | Reference               |
|-------|--------|---------|-------------------------|
| Antelope Valley, USA | 49     | 88      | AVTA 2020                |
| Amsterdam, NL         | 31     | 203     | GVB 2020                 |
| Berlin, DE            | 121    | 1,440   | BVG 2018, BVG 2020       |
| Cluj-Napoca, RO       | 41     | 297     | Varga et al. 2020        |
| Hamburg, DE           | 35     | 1,000   | Hamburger Hochbahn 2020  |
| London, UK            | 280    | 9,142   | TfL 2019a, TfL 2019b     |
| Madrid, ESP           | 82     | 2,109   | Sustainable Bus 2020b    |
| Manchester, UK        | 32     | 750     | Stagecoach 2020b, Stagecoach 2020a |
| Moscow, RU            | 300    | 11,000**| Moscow Gov. 2019, Liksutov 2020 |
| Nur-Sultan, KZ        | 100    | 1,082   | Astana LRT 2018, Sustainable Bus 2020a |
| Santiago de Chile, CL | 285    | 2,430   | Red 2019, Intelligent Transport 2019 |
| Shenzhen, CN          | 16,359 | 16,359  | Li et al. 2019           |
| Vienna, AT            | 7      | 450     | Wiener Linien 2020a, Wiener Linien 2020b |

* We refer to specific transport operators in cities (see references) so that overall data for the cities may differ.
** including trams

Against this background, we provide a concise guide on integrating BEBs into urban bus networks for practitioners and researchers. Herein, we focus on all planning tasks that are particularly affected by the integration of BEBs. Specifically, we focus on transforming a bus fleet, installing charging infrastructure, and ensuring a fleet’s operationality. In contrast to the existing review of Clairand et al. 2019 that focuses on electric vehicles in public transportation from a power system perspective, we focus on carving out all modeling requirements which are relevant to practice from a transport optimization perspective.

The contribution of this paper is fourfold. First, we derive model requirements relevant for practitioners based on specifications of state-of-the-art BEBs, project reports, and expert knowledge. Second, we identify various problem classes related to the integration of BEBs: fleet transformation problems (FTPs), charging location problems (CLPs), charging location sequence assignment problems (CLSAPs), sequence assignment problems (SAPs), and vehicle scheduling problems (VSPs). We then analyze to which extend existing works within these problem classes fulfill the respective practitioners’ requirements. Third, we analyze the scientific literature concerning methodological aspects and practitioners’ requirements, present results, and discuss scientific developments over time. Based on these analyses, we finally identify research gaps and promising research perspectives.

The remainder of this paper is as follows. In Section 2, we derive practitioners’ requirements based on state-of-the-art specifications, project reports, and expert knowledge. In Section 3, we analyze existing optimization-based planning models with regard to covered practitioners’ requirements and applied solution methods to identify research gaps and perspectives in Section 4. Section 5 concludes this survey with a short summary of its main findings.

## 2 Practitioners’ Requirements

In the following, we identify practitioners’ requirements relevant for planning the integration of BEBs into urban bus networks. Herein, we cluster the practitioners’ requirements into the following cate-
Categories: total costs (T), bus fleet management (F), charging infrastructure (I), energy consumption (E), charging procedure (C), vehicle scheduling (S), and deadheading & detours (D). We structure this section based on these categories. Moreover, Table 2 gives an overview of all derived practitioners’ requirements and sorts them into each specific category.

**Total Costs (T)** Although most countries subsidize their public transportation systems, public transport operators (PTOs) must ensure cost-efficient bus network design and operation. Costs associated with the design and operation of a bus network include not only the investments in (respectively the replacement of) buses, batteries, and charging stations, but also all subsequent expenditures associated with the respective technologies. For example, (electric) motors, batteries, onboard charging devices, and charging station devices have to be checked, repaired, or exchanged regularly. Consequently, when integrating BEBs, practitioners aim at minimizing costs for buses (T1), batteries (T2), charging infrastructure (T3), maintenance costs for buses and batteries (T4), maintenance costs for charging infrastructure (T5), as well as costs for fuel or energy (T6), respectively (cf. Init 2019, ViriCiti 2019).

**Fleet Management (F)** As buses have a limited service life of about 12 years (cf. Aber 2016, Lajunen 2018), PTOs must replace buses regularly, such that it is necessary to consider fleet purchases and sales (F1) within a multi-period planning horizon (F2) when aiming at optimal planning for a fleet’s transformation.

Bus fleets often consist of heterogeneous buses (F3) that differ concerning drive train technologies and other specifications that allow for a variety of services, e.g., public transport and school buses (cf. Akiyama et al. 2001). Due to demand and weight restrictions, decisions on passenger capacities (F4) of buses need to be accounted for separately, e.g., whether solo, articulated, or bi-articulated buses with different passenger capacities are required.

In addition to these aspects, technical characteristics of BEBs may also differ concerning battery

| ID | Requirement                           | ID | Requirement                           |
|----|--------------------------------------|----|--------------------------------------|
| T  | **Total Costs**                      |    |                                      |
| T1 | Buses                                | I3 | Heterogeneous charging power levels  |
| T2 | Batteries                            | I4 | Charging stations per location       |
| T3 | Charging stations                    | E1 | Non-linear energy consumption        |
| T4 | Maintenance of buses and batteries   | E2 | Heterogeneous energy consumption     |
| T5 | Maintenance of charging stations     | E3 | Stochastic energy consumption        |
| T6 | Fuel or energy costs                 | C  | **Charging Procedures**              |
|    |                                      | C1 | Partial recharging                  |
|    |                                      | C2 | Non-linear recharging               |
| F  | **Fleet Management**                 |    |                                      |
| F1 | Fleet purchases and sales            | S  | **Scheduling**                      |
| F2 | Multi-period planning horizon        | S1 | Trip assignment                      |
| F3 | Heterogeneous bus types              | S2 | Sequence assignment                  |
| F4 | Passenger capacity                   | D  | **Deadheading and Detours**         |
| F5 | Heterogeneous BEBs                   | D1 | Deadheading                          |
| I  | **Infrastructure**                   |    |                                      |
| I1 | Charging power level selection       | D2 | Detours for recharging               |
| I2 | Locations of charging stations       |    |                                      |

Table 2: Practitioners’ requirements for planning the integration of BEBs.
materials and general specifications (F5). Table 3 lists state-of-the-art BEBs with specifications, while Table 4 lists state-of-the-art batteries with specifications. Both tables highlight the heterogeneity of state-of-the-art BEBs and battery technologies. While BEBs mainly differ in passenger and battery capacity, batteries differ in volume and mass density, as well as in their c-rate, i.e., the number of full charging processes per hour, and over their lifetime. Herein, not only a battery’s technology, but several additional factors such as its utilization, the charging behavior, and its operating temperature affect the battery’s lifetime (cf. AICTS 2018, Wang et al. 2019, Proterra 2020, Daimler 2020). Regardless of the technology, the battery capacity degrades over time (cf. Pelletier et al. 2017). Technical solutions are in place to ensure operational robustness such that the usable battery energy remains constant, i.e., the depth of discharge (DoD) is monitored and continuously adjusted (cf. Denomme 2012, Franca 2018, MAN 2020).

Infrastructure (I) A suitable and sufficient charging infrastructure is necessary to allow for recharging BEBs. Technically, charging stations can be located anywhere in the street network. Practitioners, however, usually limit potential locations and decide on a specific charging concept: (1) depot charging between operations or overnight, (2) terminal charging between trip operations at initial and end stations of bus lines, (3) charging at bus stops during trip operations, (4) ex-route charging at charging stations which are not located at bus network stops or depots, or (5) swapping batteries at depots, terminals, or ex-route stations. Still, decisions have to be taken on a suitable charging power level (I1) and charging locations (I2); both directly affect operations regarding the quantity and distances of deadheading trips (i.e., trips without passengers), the available recharging times, and hence operational costs (cf. Floman 2019).

Table 3: State-of-the-art BEB specifications.

| Model         | # Pax | Battery Capacity | Reference |
|---------------|-------|------------------|-----------|
| BYD, eBus     | 65-150| 260-380 kWh      | Hug 2015  |
| Ebusco, Elec. Citybus 2.2 | 90-130| 363-525 kWh      | Ebusco 2020|
| Irizar, ie bus | 76-155| 90-525 kWh       | Irizar 2020|
| MAN, Lion’s City E | 90-120| 480-640 kWh      | MAN 2020  |
| Mercedes Benz, eCitaro | 80-145| 292-411 kWh      | EvoBus 2020|
| Scania, Citywide LF Elec. | 95    | 250 kWh          | Scania 2020|
| Solaris, Urbunio Elec. | 69-121| 60-550 kWh       | Tschakert 2020|
| VDL, Citea SLF(A) Elec. | 92-145| 85-420 kWh       | VDL 2020  |
| Volvo, 7900 Elec. | 95-150| 150-396 kWh      | Volvo 2020 |
| Yutong, U 12  | 86-100| 422 kWh          | Yutong 2020|

Table 4: State-of-the-art batteries and specifications.

| Technology | Mass density | Volume density | c-Rate** | Lifetime | Reference |
|------------|--------------|----------------|----------|----------|-----------|
| NMC        | 105 Wh/kg    | 140 Wh/dm³     | 0.69     | 5 a      | Akasol 2020|
| LMP        | 140 Wh/kg    | 111 Wh/dm³     | 0.2      | 10 a     | BlueSolutions 2019|
| LTO        | 53 Wh/kg     | 55 Wh/dm³      | 13.16    | 3-4 a    | Impact 2018 |

* NMC: lithium nickel manganese cobalt oxides, LMP: lithium polymer battery, LTO: lithium-titanate battery.
** based on continuous power charge.
So far, suitable charger types for buses are plug-in chargers as well as top-down and bottom-up pantographs. Some projects also tested inductive charging (cf. Chen et al. 2018, Bi et al. 2018), but concerns about electromagnetic compatibility and efficiency when using high charging power levels remain unsolved. However, experts envision potential technological advances in this area in the future (cf. Momentum Wireless Power 2020). Apparently, the manufacturers differ relatively little in shown specifications, which indicates that a quasi-standard for charging power levels and types exists. As can be seen in Table 5, the charging powers of plug-in CCS and pantographs differ notably. While all suppliers offer plug-in charging with CCS up to 150 kW, which is the maximum power reachable without liquid-cooled cables (cf. Phoenix Contact 2017), pantographs provide a charging rate of up to 600 kW. Also, the charging power level of the charging stations needs to match with the batteries installed in the BEBs (cf. Günter & Koch 2018). Therefore, it is necessary to take heterogeneous charging power levels (I3) into account in order to install a charging infrastructure that is compatible with a heterogeneous bus fleet. For example, BEBs that are supposed to charge at a bottom-up pantograph require special on-board charging devices (cf., e.g., ABB 2020c, Siemens 2020). In addition to higher specific costs (cf. ABB 2020a), these onboard charging devices may lead to tighter weight limitations for batteries and to increased energy consumption. However, they may save battery capacity, charging stations, or even buses (cf. Mathieu 2018). Finally, the number of charging stations per location (I4) is crucial to ensure that several buses may charge at the same time at the same location (cf. Floman 2019).

Energy Consumption (E) Besides the battery capacity, the energy consumption determines the driving range and recharging needs of BEBs. In general, the energy consumption is not linear (E1) to the covered distance but rather depends on characteristics such as the topography, the general climatic conditions, or the number of acceleration and deceleration processes due to bus stations or traffic lights (cf. Init 2019). Moreover, the energy consumption is heterogeneous (E2), as it differs between different types of buses and batteries. For example, there are notable weight differences between solo or articulated buses and high-temperature or ambient-temperature batteries (cf. Naumann & Vogelpohl 2015), as well as between different battery capacities, battery technologies, and charging devices. Besides, the energy consumption is stochastic (E3), as it depends on uncertainties such as the driving behavior, traffic conditions, or daily temperatures (cf. Init 2019).

Table 5: State-of-the-art charger types and specifications.

| Type           | Supplier       | Charging        |
|----------------|----------------|-----------------|
| Plug-In        | ABB            | 24-150 kW       |
| CCS           | Ekonoenergetyka| 20-150 kW       |
|                | Siemens        | 30-150 kW       |
| Bottom-Up      | ABB            | 150-600 kW      |
| Pantograph     | Ekonoenergetyka| \(\leq 400\) kW|
|                | Siemens        | 60-120 kW       |
| Top-Down       | ABB            | 150-600 kW      |
| Pantograph     | Siemens        | 150-600 kW      |

Data from: ABB: ABB 2020a, Ekonoenergetyka: Ekoenergetyka 2020, Siemens: Siemens 2020.
Charging Procedures (C) Buses operate within tight vehicle schedules. Hence, when integrating BEBs, practitioners face the challenge of ensuring that any BEB operates all dedicated trips without running out of energy. To this end, the standard option is overnight depot charging that ensures a reliable operation but avoids civil works within urban areas (cf. Mathieu 2018). The alternative option is to (partially) recharge energy during operation (C1) at (fast) charging stations (cf. Günter & Koch 2018), e.g., to increase operational flexibility. The benefits of such partial recharging when routing battery-electric vehicles under consideration of time windows have been discussed in Schiffer & Walther (2017). Also, non-linear recharging processes (C2) must be considered because voltage drops due to electrochemical impedances increase with an increasing state-of-charge (SOC) (cf. Koch 2017).

Scheduling (S) In order to transport passengers, a PTO must operate a considerable amount of trips. In a typical bus network, these trips are defined by a bus timetable, i.e., (ordered) bus stations and service times. Based on this timetable, practitioners aim at identifying a feasible schedule to operate all trips of the timetable under minimal costs. Here, trips or pre-grouped sequences of trips must be assigned to the fleet’s buses while considering requirements such as battery and passenger capacities. Apparently, the importance of such a trip (S1) or sequence (S2) assignment, i.e., vehicle scheduling, even increases when using BEBs, as the state of charge of a BEB correlates to the trips operated by a specific BEB.

Deadheading and Detours (D) Deadheading trips (D1), i.e., trips without passengers, are part of the operation in most bus networks. Traditionally, these deadheading trips are either used for depot pull-in and pull-out or to overcome spatial differences between the end station and the first station of two different subsequently operated bus lines. In general, disadvantages of deadheading are higher operational costs, a lower convenience for drivers, and a rather complex vehicle scheduling. However, a significant advantage is the potentially lower number of buses required due to the more flexible vehicle scheduling (cf. Floman 2019). When BEBs are integrated, the importance of deadheading increases, as additional detours for recharging (D2) may be beneficial.

The variety of requirement categoriers shows that a multitude of planning requirements exists with strategic as well as operational implications. Moreover, many interdependencies have to be taken into account, resulting in complex planning tasks that practitioners have to solve.

3 State-of-the-Art

This section reviews state-of-the-art optimization-based planning models that focus on integrating BEBs into existing bus networks. We identified publications by screening the pertinent data banks, e.g., Web of Science, Google Scholar, ScienceDirect, with related keywords, e.g., electric buses, charging infrastructure, vehicle scheduling. We then checked all publications cited by the publications found via our data bank search in a subsequent step. To keep this paper concise, we focus on publications that use an optimization-based modeling approach and are written in English.
We group the existing publications into five problem classes. Fleet transformation problems (FTPs) focus on purchases and sales of buses with multi-period decisions. Charging location problems (CLPs) focus on finding suitable locations for charging stations. Sequence assignment problems (SAPs) focus on an assignment of trip sequences to buses. Charging location sequence assignment problems (CLSAPs) base decisions on charging station locations on a sequence assignment to consider operational feasibility. Vehicle scheduling problems (VSPs) optimize a trip assignment, i.e., a comprehensive vehicle scheduling. Table 6 gives an overview of all problem classes and the respective nomenclature.

In the following, we provide a detailed analysis of all publications structured by problem classes as shown in Table 6 before we provide a comparison of problem classes in order to derive promising research perspectives in Section 4.

### 3.1 Fleet Transformation Problems

FTPs aim at identifying a cost-optimal and multi-period bus fleet transformation plan. In this context, decisions on the purchase of buses and the installation of charging stations are necessary. The models anticipate operational aspects and costs by using simplified assumptions. They either focus on depot charging (cf. Islam & Lownes 2019), on charging at terminals (cf. Li et al. 2018b, Dirks et al. 2021), or at bus stops (cf. Pelletier et al. 2019).

Table 7 shows to which extend existing FTPs meet the practitioners’ requirements. By definition, all FTPs account for fleet purchases and sales (F1) as well as for a multi-period planning horizon (F2). While in general FTPs account for many requirements in the field of total costs (T) and bus fleet management (F), they rarely cover requirements of the other categories. The fact that requirements related to charging procedures (C), as well as deadheading and detours (D), are not covered at all indicates that state-of-the-art FTPs tend to neglect operational implications.

#### Table 6: Problem classes.

| Abbrev. | Description                                           | Section |
|---------|-------------------------------------------------------|---------|
| FTP     | Fleet transformation problem                           | 3.1     |
| CLP     | Charging location problem                             | 3.2     |
| SAP     | Sequence assignment problem                           | 3.3     |
| CLSAP   | Charging location sequence assignment problem         | 3.4     |
| VSP     | Vehicle scheduling problem                            | 3.5     |

#### Table 7: Fulfillment of the practitioners’ requirements by FTPs.

| charg. loc. | T | F | I | E | C | S | D |
|-------------|---|---|---|---|---|---|---|
|             | 1 | 2 | 3 | 4 | 5 | 6 |
|             | 1 | 2 | 3 | 4 | 5 | 6 |
|             | 1 | 2 | 3 | 4 | 5 | 6 |
|             | 1 | 2 | 3 | 4 | 5 | 6 |
| Dirks et al. 2021 | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| Islam & Lownes 2019 | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| Li et al. 2018b | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| Pelletier et al. 2019 | ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ |

T: total costs, F: bus fleet, I: charging infrastructure, E: energy consumption, C: charging procedures, S: vehicle scheduling, D: deadheading and detours.
3.2 Charging Location Problems

CLPs mainly aim at identifying charging station locations (I2) either for single bus lines or for entire bus networks. Also, some publications focus on planning locations of large-scale charging parks.

Early publications often focused on models for solving charging location problems for single multi-stop bus lines (cf. Chen & Bierlaire 2013, Kunith et al. 2013, Wehres et al. 2016, Berthold et al. 2017, Rohrbeck et al. 2018). These planning models are often based on pilot projects which focused on electrifying single bus lines for testing purposes. All these publications allow partial recharging at in-line bus stops. By definition, vehicle scheduling, as well as deadheading and detours, are neglected. Models differ in whether they account for specific characteristics such as uncertainties in energy consumption (cf. Wehres et al. 2016), battery aging (cf. Rohrbeck et al. 2018), or a non-linear recharging behavior (cf. Kunith et al. 2013).

More recent CLP publications introduced models that allow charging location planning for entire bus networks including multiple bus lines (cf. Kunith et al. 2016, Kunith et al. 2017, Sebastiani et al. 2016, Xylia et al. 2017a, Xylia et al. 2017b, Liu et al. 2018, Lotfi et al. 2020, Zhou et al. 2020). When accounting for multiple bus lines, synergies between several bus lines can be leveraged to identify better solutions compared to considering bus lines separately, as buses that operate on different bus lines can use the same charging stations. However, these models still lack the synergies that arise from deadheading. They mainly differ in decisions on technical specifications, e.g., regarding the considered drivetrains, or in applied (technical) methodologies, e.g., regarding the calculation of energy consumption.

For megacities with a high public transport demand that operate large BEB fleets, it may be reasonable to establish large charging facilities in addition to the depots, at which BEBs may either recharge or swap batteries in between operations. We refer to those facilities as charging parks. Models focusing on charging parks have been developed and applied, especially in Asian or Pacific megacities (cf. Lin et al. 2019a, Lin et al. 2019b, An et al. 2019, An 2020). For simplicity, these models are based on aggregation methodologies, in which clusters of bus routes are assigned to charging parks, and thus the recharging demand is estimated.

Table shows to which extend existing CLPs fulfill the different practitioners’ requirements. By definition, all CLPs decide on locations for charging stations (I4) and their costs (T3). However, many other requirements are neglected. While about one-third of the publications fulfill requirements in the fields of total costs (T), charging infrastructure (F), and charging processes (C), only a few cover requirements related to bus fleet management (F), energy consumption (E), and deadheading and detours (D). Also, by definition, no CLP accounts for requirements related to vehicle scheduling (S).

3.3 Sequence Assignment Problems

SAPs aim at finding an efficient vehicle schedule by predetermining feasible sequences of trips and assigning these to buses or bus types. They either focus on depot charging (cf. Ke et al. 2016, Rogge et al. 2018, Yao et al. 2020), or assume a given (fast) charging infrastructure (cf. Reuer et al. 2015, Sassi & Oulamara 2017). All SAP publications that focus on depot charging solve the assignment of trip sequences to buses with a genetic algorithm. Sassi & Oulamara (2017) and Reuer et al.
allow for charging at terminals and use a greedy algorithm or a max-flow formulation based on Kliewer et al. (2006) respectively. In addition, Rogge et al. (2018) include a comprehensive energy consumption simulation based on Sinhuber et al. (2012) with data on service trips, vehicle types, and route characteristics.

Table 8 shows to which extend existing SAPs fulfill the different practitioners’ requirements. By definition, all SAPs assign trip sequences to buses (S2). In total, SAPs cover many requirements relevant for practice, with requirements related to total costs (T) and deadheading (D) prevailing. Occasionally, some SAPs comprise bus fleet management (F), energy consumption (E), and vehicle scheduling requirements. Contrarily, requirements in the field of charging infrastructure (I) and charging procedure (C) are less prevalent.

|                | charg. loc. | T  | F  | I  | E  | C  | S  | D  |
|----------------|-------------|----|----|----|----|----|----|----|
| **Table 8:** Fulfillment of the practitioners’ requirements by CLPs. |
| An et al. 2019 | swapping     | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| An 2020        | stations     | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Berthold et al.2017 | stops       | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Chen & Bierlaire 2013 | stops      | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Kunith et al. 2013 | stops       | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Kunith et al. 2016 | terminals   | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Kunith et al. 2017 | terminals   | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Liu et al. 2019b | depot       | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Liu et al. 2018  | stops       | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Lotfi et al. 2020 | terminals   | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Rohrbeck et al. 2018 | stops     | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Sebastiani et al. 2016 | stops   | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Wehres et al. 2016 | stops       | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Xylia et al. 2017b | stops      | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Xylia et al. 2017a | stops       | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Zhou et al. 2020  | terminals   | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |

T: total costs, F: bus fleet, I: charging infrastructure, E: energy consumption, C: charging procedures, S: vehicle scheduling, D: deadheading and detours.

|                | charg. loc. | T  | F  | I  | E  | C  | S  | D  |
|----------------|-------------|----|----|----|----|----|----|----|
| **Table 9:** Fulfillment of the practitioners’ requirements by SAPs. |
| Ke et al. 2016  | depot       | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Reuer et al. 2015 | terminals | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Rogge et al. 2018 | depot     | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Sassi & Oulamara 2017 | terminals | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |
| Yao et al. 2020  | depot       | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  |

T: total costs, F: bus fleet, I: charging infrastructure, E: energy consumption, C: charging procedures, S: vehicle scheduling, D: deadheading and detours.
3.4 Charging Location Sequence Assignment Problems

CLSAPs link decisions on charging station locations with operational sequence assignment, thus enabling these models to consider deadheading and to exploit synergies between multiple bus lines. However, charging locations are limited to depots as well as terminals and in-line bus stops. Li et al. (2018a) & Li et al. (2019) use a time-space-energy network, predetermining all potential trip sequences a-priori. Here, charging stations are installed in dependence of selected sequences. Additionally, the authors consider passenger flows within a time-space network. Wei et al. (2018) introduce a model for both replacing internal combustion engine buses (ICEBs) by BEBs and installing charging stations at terminal bus stops. Their model considers deadheading but no partial recharging. Jefferies & Göhlich (2020) combine optimization and discrete-event simulation in order to plan a cost-efficient and feasible bus network with BEBs that charge on opportunity. While the simulation considers complex relations such as temperature-dependent energy consumption, the optimization bases on worst-case parameters.

Table 10 shows to which extent existing CLSAPs fulfill the different practitioners’ requirements. By definition, all CLSAPs not only decide on locations for charging stations (I4) and their costs (T3), but they also assign trip sequences to buses (S2).

3.5 Vehicle Scheduling Problems

The main goal of VSPs is to compute an optimal vehicle schedule that requires a minimum number of buses with limited driving ranges for a given charging infrastructure (cf. Li 2014, Paul & Yamada 2014, Wen et al. 2016, Adler & Mirchandani 2017, van Kooten Niekerk et al. 2017, Janovec & Koháni 2019, Rinaldi et al. 2019a, Rinaldi et al. 2019b, Tang et al. 2019, Liu & Ceder 2020, Teng et al. 2020). For example, models differ with respect to the considered charging station concept, e.g., whether charging stations are exclusively located at terminal or at in-line bus stops, or whether two charging stations can be visited consecutively or not. Some VSPs rely on a discretized state-of-charge (cf. van Kooten Niekerk et al. 2017) or assume a given recharging time (cf. Li 2014) to cope with the high planning complexity.

Table 11 shows to which extent existing VSPs fulfill the different practitioners’ requirements. By definition, VSPs assign trips to buses (S1) and thereby also sequences to buses (S2). As expected, most VSPs cover requirements for deadheading and detours (D), while omitting requirements of charging infrastructure (I). Moreover, VSPs rarely consider requirements of other categories. Remarkably, this also holds for requirements related to charging procedures (C). Costs for buses (T1) and energy (T2) are covered by most VSPs, as at least one of these costs results from vehicle scheduling.

|                | charg. loc. | T 1 2 3 4 5 6 | F 1 2 3 4 5 | I 1 2 3 4 | E 1 2 3 | C 1 2 | S 1 2 | D 1 2 |
|----------------|-------------|---------------|-------------|----------|--------|-------|-------|-------|
| Jefferies & Göhlich 2020 | terminals | ✓ ✓ ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ |
| Li et al. 2018a | stations | ✓ ✓ ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ |
| Li et al. 2019 | stations | ✓ ✓ ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ |
| Wei et al. 2018 | terminals | ✓ ✓ ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ | ✓ ✓ ✓ ✓ |

T: total costs, F: bus fleet, I: charging infrastructure, E: energy consumption, C: charging procedures, S: vehicle scheduling, D: deadheading and detours.
4 Analysis and Perspectives

In this section, we synthesize the analyses of Section 3, discuss reasons for the identified gaps, and outline resulting research perspectives.

Planning the integration of BEBs remains a complex planning task that may result in computationally intractable optimization problems. When applying such models to large-size instances of real-world bus networks, straightforwardly using off-the-shelf optimization software may find its limits depending on the problem type. Here, tailored heuristic or exact algorithms might be necessary to obtain reasonable solutions. Figure 3 shows the share of publications that use commercial solvers or develop heuristic or exact algorithms for each problem class. As can be seen, mostly commercial solvers are used to solve planning problems in the more strategic problem classes (FTPs, CLPs, CLSAPs). Contrary, commercial solvers are only rarely used to solve planning problems in the more operational problem classes (SAPs, VSPs). Here, exact algorithms based on branch-and-price and heuristic algorithms, often based on genetic or greedy algorithms, exist. While most problem classes have high combinatorial complexity, finding a solution to a strategic problem remains less time-critical than finding a solution to an operational problem, which partly explains the shift of solution approaches between the different problem classes.

| Problem Class | Total Costs (T) | Bus Fleet (F) | Charging Infrastructure (I) | Energy Consumption (E) | Charging Procedures (C) | Vehicle Scheduling (S) | Deadheading and Detours (D) |
|---------------|----------------|---------------|----------------------------|------------------------|------------------------|------------------------|---------------------------|
|   FTP         | ✓              | ✓             | ✓                          | ✓                      | ✓                      | ✓                      | ✓                         |
|   CLP         | ✓              | ✓             | ✓                          | ✓                      | ✓                      | ✓                      | ✓                         |
|   CLSAP       | ✓              | ✓             | ✓                          | ✓                      | ✓                      | ✓                      | ✓                         |
|   SAP         | ✓              | ✓             | ✓                          | ✓                      | ✓                      | ✓                      | ✓                         |
|   VSP         | ✓              | ✓             | ✓                          | ✓                      | ✓                      | ✓                      | ✓                         |

Table 11: Fulfillment of the practitioners’ requirements by VSPs.

Figure 3: Applied solution methods per problem class.
To further understand this shift of solution approaches between the different problem classes, Figure 4 shows the share of practitioners’ requirements covered by each publication and problem class as a Box-Whisker-Plot. On average, the publications achieve a relatively low coverage, indicating that the reviewed publications focus on specific requirements rather than on covering many. As can be seen, SAPs and CLSAPs cover more requirements, while CLPs and VSPs cover less requirements. CLPs usually do not account for operational constraints, which explains the low share of covered requirements linked to the high share of planning problems solved with commercial solvers. VSPs cover most operational requirements. However, solving such VSPs remains inherently hard such that although advanced solution methodologies are used, the overall share of covered requirements remains low to limit the computational complexity to its operational problem’s core. CLSAPs and SAPs show a rather high share of covered requirements. For SAPs, heuristic solution approaches are necessary to reach this share. For CLSAPs, such a heuristic sequence assignment is often included as an exogenous input, which then allows using commercial solvers to obtain good solutions.

Three out of four publications focus on real-world case studies, analyzing a specific bus network. Together with Figures 3 and 4, this suggests that often some practitioner’s requirements are withdrawn to preserve computational tractability in order to analyze one specific aspect in electric bus network optimization. In this context, we also note that common benchmark instances only exist for VSPs (cf., e.g., Wen et al. 2016, Adler & Mirchandani 2017). This shortage of common benchmark instances and solution methods suggests that academics so far lack a common definition of the respective planning problems. Vice versa, this reflects the multitude of potentially case-dependent practitioner requirements.

Figure 5 shows the share of requirements covered by publications of different problem classes in a Spider-Plot. To keep the figure concise, we aggregated the practitioners’ requirements to the categories introduced in Section 2 (cf. Table 2). Figure 5 reveals gaps in all categories, as no problem class covers all of the practitioners’ requirements. Particularly, requirements for charging infrastructure planning (I), energy consumption (E), and charging procedures (C) often remain uncovered. The reason for missing coverage in charging infrastructure planning (I) requirements is twofold. First, most models neglect charging infrastructure planning and assume a given charging infrastructure instead. Second, most models that address charging infrastructure planning focus exclusively on charging station locations but neglect additional decisions, e.g., on heterogeneous charging power levels or the

![Figure 4: Average coverage of all practitioners’ requirements per problem class.](image-url)
number of charging stations per location. The missing energy consumption (E) requirements result because most publications assume a constant energy consumption. This constitutes an unnecessary shortcoming as the consideration of realistic energy consumption is relatively straightforward from a modeling perspective. Incorporating realistic energy consumption improves the reliability of findings and decision support significantly without worsening the underlying model’s computational complexity. In contrast, the consideration of partial and non-linear recharging (C) results in a high modeling complexity; however, this complexity is manageable by using a discretized battery state of charge (cf. van Kooten Nickerk et al. 2017) or a stepwise linearized recharging function (cf. Kunith et al. 2013). Almost only FTPs consider requirements in the category of bus fleet management (F), indicating that most publications so far focused primarily on a static design of electric bus networks rather than on time-dependent cost-optimal bus fleet transformations.

Furthermore, the coverage of practitioner’s requirements varies depending on the charging station concept that a publication considers. Figure 6 shows the average and maximum coverage for each class of charging station concept for strategically-focused (FTPs, CLPs, CLSAPs) and operationally-focused (SAPs, VSPs) publications. Naturally, the considered charging station concept influences the coverage of requirements, as it affects the model complexity and thus the number of requirements that a model can cover from an overall computational complexity perspective. Among publications on strategic planning, models that focus on an ex-route charging concept, i.e., charging at charging stations not located at bus network stops or depots, cover the largest share of practitioners’ requirements. Here, a central assumption on clustering charging demand to high-capacity charging parks eases the integration of additional constraints and requirements. Contrarily, publications that focus on depot charging neglect several requirements. In contrast, publications that focus on depot charging
from an operational perspective cover more practitioners’ requirements. Here, the simple concept of depot charging allows covering various constraints and requirements at an operational level. None of the operationally-focused publications considers recharging at in-line bus stops.

Figure 7 shows to which extent existing strategic (FTPs, CLPs, CLSAPs) and operational (SAPs, VSPs) problems consider relevant cost components (T1-T6). As can be seen, most strategic problem variants consider costs for charging stations and energy. The latter indicates that strategic problem variants aim to anticipate operations to a certain extend. Naturally, most operational problem variants consider energy costs. Some also cover rather strategic cost-components such as bus costs, as scheduling operations is a prerequisite for determining an optimal number of buses. Some publications utilize a pure operationally-focused methodology but also aim at deriving strategic insights, e.g., regarding the required number of charging stations at the depot (cf. Rogge et al. 2018). We observe that overall maintenance costs are rarely considered.

Figure 8 shows the temporal course of the coverage of the practitioners’ requirements between 2013 and 2020. As can be seen, the coverage of the requirements has increased during the last years.

![Graph showing temporal coverage of practitioners' requirements](image)

**Figure 6:** Average and maximum coverage of requirements per charging location.

![Graph showing coverage of total cost requirements](image)

**Figure 7:** Coverage of total cost requirements in strategic and operational models.
The trend indicates academics’ ambition to strive for more prosperous modeling approaches closer to real-world settings. However, it also reveals that the improvement in terms of covered practitioner’s requirements is insidious such that a lot of open research questions remain to develop a comprehensive decision support system.

5 Conclusion

In this review, we outlined the gap between practitioner’s requirements and existing quantitative modeling approaches regarding the integration of BEBs into existing urban bus networks. Herein, we identified requirements relevant for practitioners based on specifications of state-of-the-art BEBs, project reports, and expert knowledge. We clustered the practitioners’ requirements in categories related to total costs, bus fleet management, charging infrastructure, energy consumption, charging procedures, scheduling, and deadheading and detours. We then identified appropriate problem categories, namely fleet transformation problems (FTPs), charging location problems (CLPs), charging location sequence assignment problems (CLSAPs), sequence assignment problems (SAPs) and vehicle scheduling problems (VSPs), and analyzed existing publications within these with regard to methodological aspects and covered practitioners’ requirements. We found that the analyzed publications cover only a subset of practitioner’s requirements, indicating a gap between academic research and practice. Only a few recent publications started to close this gap and cover some more requirements such that a variety of practitioners’ requirements remain still uncovered.

Particularly, the following main research gaps remain. First, some straightforward modeling extensions exist to sharpen the accuracy of planning approaches with respect to their real-world validity. Particularly, realistic energy consumption and recharging profiles can be incorporated without loosing computational tractability when using reasonable approximations, e.g., discretized battery state of charge or stepwise-linearized recharging functions. Moreover, additional cost components, e.g., maintenance cost can be added straightforwardly. Second, integrated modeling approaches that incorporate operational implications in strategic planning decisions promise to yield better planning solutions that meet practitioners’ requirements. To this end, it remains an open question at which level of detail good operational surrogates can be found. First recent publications indicate that incorporating a sequence
assignment decision constitutes an appropriate level of detail. Third, there exists a need for enhanced algorithmic solution techniques, which would ease the integration of additional constraints and would improve scalability of planning approaches towards large-scale instances. This is particularly the case for integrated modeling approaches that bear the highest computational complexity.

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