

Article

A Reference Architecture for Interoperable Reservation Systems in Electric Vehicle Charging

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Abstract: The charging infrastructure for electric vehicles faces the challenges of insufficient capacity and long charging duration. These challenges decrease the electric vehicle users' satisfaction and lower the profits of infrastructure providers. Reservation systems can mitigate these issues. We introduce a reference architecture for interoperable reservation systems. The advantages of the proposed architecture are: it (1) considers the needs of the most relevant electric mobility stakeholders, (2) satisfies the interoperability requirements of existing technological heterogeneity, and (3) provides a classification of reservation types based on a morphological methodology. We instantiate the reference architecture and verify its interoperability and fulfillment of stakeholder requirements. Further, we demonstrate a proof-of-concept by instantiating and implementing an ad-hoc reservation approach. Our validation was based on simulations of real-world case studies for various reservation deployments in the Netherlands. We conclude that, in certain high demand situations, reservations can save significant time for electric vehicle trips. The findings indicate that a reservation system does not directly increase the utilization of the charging infrastructure.

Keywords: smart cities; electric mobility; sustainable transport; electric vehicles; charging stations; reservation; reference architecture; interoperability

1. Introduction

Electric mobility is expected to play a vital role in the decarbonization of our society, specifically in reducing the air pollution caused by traditional transportation [1,2]. Major stakeholders of electric mobility are the electric vehicle (EV) users, electric mobility service providers, charging station (CS), and grid operators. Despite the fact that an increasing number of EVs is introduced to our cities, their amount is still not comparable to combustion-engine vehicles.

Seamless integration of EVs into our daily lives has not happened yet due to several reasons, some of which are (1) insufficient charging infrastructure compared to the availability of petrol stations [3], and (2) long charging times [4]. Consequently, these challenges lead to decreased EV users' satisfaction and inefficient utilization of the underlying infrastructure (i.e., charging and grid) resulting in reduced profits for the corresponding providers and operators.

A reservation system for electric mobility can mitigate the above-mentioned challenges and benefit the various involved stakeholders. Such concepts were proposed for the charging of EVs [5–7]. However, those contributions lack a holistic view on reservation systems. More precisely, most of the derived solutions consider only a subset of relevant stakeholders in specific scenarios (see Section 2 for

details) and do not satisfy interoperability requirements. In this context, interoperability denotes the fact that two or more independent sub-systems can cooperate, despite the underlying heterogeneity in infrastructure, communication technologies, and software implementations.

For the success of reservation in the electric mobility context, it is required to identify and consider the needs and requirements of the above-mentioned stakeholders in EV charging. Furthermore, a generic architecture model is needed that serves as a reference for implementing an interoperable reservation system. A reference architecture is a concept that is generalized and structured for the depiction of one or more constituent components (e.g., stakeholders) of a system [8]. Such a reference architecture can be instantiated for a particular scenario or configuration. Currently, for practical applications, only an *ad-hoc* type of reservation can be instantiated and implemented (see Appendix A). This is due to the fact that most of the charging hardware supports this feature. Ad-hoc reservation is a limited form of reservation that immediately reserves the connector of a given CS for a specific user. The corresponding connector of the CS gets unlocked when this user arrives at the station. Additionally, only one ad-hoc reservation can be active at a time on a specific connector of a given CS. There are open questions regarding ad-hoc reservations, such as: (1) whether they bring sufficient benefits for the different stakeholders to justify their deployment, and (2) how do ad-hoc reservations compare against other types of reservation that can be implemented with future technologies?

In this paper, we apply a structured design science research methodology [9]. We first identify the requirements of the aforementioned stakeholders for the reservation of charging stations. We contribute to the body of research by providing a reference architecture by taking into account the identified stakeholders' requirements. The reference architecture was developed based on the E-Mobility Systems Architecture (EMSA) framework [10], which ensures interoperability-by-design on all layers. Based on a morphological analysis [11], we provide an approach to instantiate different reservation system types. Subsequently, we advance the state-of-the-art by enabling the configuration of different reservation system instances besides the ad-hoc one. In order to compare the different reservation approaches and demonstrate their usefulness, we ran agent-based simulations on charging and mobility data from the Netherlands. We find that, in high demand situations, full-fledged planned reservation brings significant time savings to EV users, compared to minimal benefits from ad-hoc reservations. At the end of this paper, we present the implementation of an ad-hoc reservation for demonstration purposes as a proof-of-concept (PoC). Our work makes the following contributions:

- Requirements of the stakeholders were identified for reservation in electric mobility.
- An interoperable reference architecture was derived for reserving charging stations.
- Morphological methodology was adopted to instantiate different reservation systems.
- The system's interoperability was analyzed and verified with the iScore methodology.
- The stakeholder requirements were validated with agent-based simulations.
- A proof-of-concept was implemented for demonstrating ad-hoc reservation.

The remainder of this paper is structured as follows: In Section 2, we study existing scientific contributions. In Section 3, we first analyzed the stakeholder and system requirements. Then, we present four reservation approaches and define the relevant research questions. In Section 4, we propose the design of our artifact and present the reference architecture model. In Section 5, we evaluated our solution approach by (i) verifying the system requirement of interoperability and (ii) validating the most important stakeholder requirements with an agent-based simulation case study. The paper is concluded in Section 6, and a PoC of an ad-hoc type of reservation is given in Appendix A.

2. Related Work

In existing research literature, contributions related to the charging of EVs can be classified into two major research clusters: charging scheduling and charging station selection.

2.1. Charging Scheduling

The scientific works in the first cluster focus on finding the optimal charging plan/schedule, by considering time and charging rate. In this context, those contributions consider that the EV is not in motion (e.g., parked) and needs to be charged. Under these assumptions, most of the works address the problem of regulating the charging process of EVs so that it minimizes the peak demand and cost, as well as flattens the overall demand of EVs. The main stakeholders taken into account by these contributions are EV users and grid operators, e.g., Distribution System Operators (DSOs). Furthermore, those works consider the objectives: (1) reducing peak loads in the power grid and (2) providing a sufficiently charged battery for the next trip. Such contributions fall under the category of so-called “valley filling” or “smart charging” techniques. Examples for such approaches can be found in [12–17], a comprehensive survey is provided by [18]. To the best of our knowledge, there exists no contribution in this research cluster that proposes reservation for managing the underlying infrastructure more efficiently. For instance, a reservation system in this context is vital to realize demand-side management either by public or private charging stations, through direct load control (e.g., canceling a reservation) or capacity planning. In this paper, we identify the relevant requirements for an implementation of such demand-side management between a DSO and its customers (e.g., private or public charging stations).

2.2. Charging Station Selection

Contributions in the second research cluster focus on finding the optimal charging station with respect to its proximity (compared to the planned trip) and corresponding availability (e.g., utilization). In this context, they consider EVs executing a planned trip and searching for charging stations close to the planned route. Under these assumptions, most of the works address the problem of minimizing the waiting time for charging as well as reducing the trip time. The main stakeholders involved in these contributions are EV users and the CS operator. Those approaches consider the following key objectives: (1) improving the EV users’ comfort and quality of experience and (2) maximizing the profit of the CS operator. The contributions in this cluster can be distinguished into short (e.g., city) and long (e.g., highway) distance trips. For highway scenarios, [19,20] predict the waiting time for charging by estimating the queue length at a specific charging station. Thus, those approaches select the charging station with a minimal utilization (e.g., queuing time) as the best charging option. Another approach that considers either the minimum waiting time or nearest distance to the charging station for the long distance scenario is discussed in [21]. For the urban (e.g., city) scenarios, the work in [22] considers a pricing scheme to decrease congestion and increase the profit of the CS operator. The corresponding pricing scheme is adapted based on the number of EVs to be charged during each time slot. Several authors have proposed reservation schemes for the above-mentioned two scenarios (highway and city) to improve the strategies for selecting charging stations, thus minimizing the waiting time for charging. To achieve this, all the proposed approaches necessitate anticipated mobility information such as traffic info, arrival time of the EV at the charging station, charging duration, etc. Furthermore, those approaches study the transmission of such information. For instance, vehicular ad-hoc networks are considered in [23,24] and a reservation-based scheduling scheme is proposed. The main objective in [23] is to improve EV users’ satisfaction by decreasing the waiting time as well as the cost for charging, while maximizing the utilization of the corresponding charging station. In [24], the main goal is to increase the acceptance ratio, where the EV users specify the amount of energy (i.e., kWh) as well as the arrival time at the charging station for reservation. On the other hand, the existence of communication infrastructure (e.g., road side units) is considered in the contribution of [20] such that the main objective is to minimize driving time as well as charging expenses. In [5], a decision-making model is suggested for reserving charging stations, by considering traffic conditions and available charging resources at the charging stations. The authors assume the existence of a reliable and secure communication network with short delays for information transmission. In [7,25] the authors present a real-life implementation of a reservation concept for EV charging stations. Both implementations are

based on the Open Charge Point Protocol (OCPP) protocol for the communication with the charging station to realize reservation. The implementation of [7] is ad-hoc for exchanging information between the mobile device and the central management system. The implemented end-to-end reservation system in [25] is based on standard data models and communication protocols.

Most of the aforementioned contributions follow a proprietary architectural design and implementation tackles only specific stakeholders (e.g., EV user and CS operator or grid operator). In this paper, enhancing the state-of-the-art approaches, we propose a generic reference architecture for reservation of EV charging stations that considers the most relevant stakeholders involved in electric mobility. For this purpose, we define the objectives and goals of the different involved stakeholders and actors. Furthermore, we identify standardized data models and communication protocols for the information exchange between stakeholders and systems, and present the underlying physical infrastructure. This leads to the design of an interoperable reference architecture model for reservation systems in electric mobility. Unlike previous approaches, the derived reference architecture is generic and satisfies interoperability requirements, and can be used to instantiate and implement customized solutions.

3. Problem Statement and Objectives

Based on the conducted literature analysis (see Section 2), the following requirements were identified for charging service from supplier and demander perspectives. For the supplier: (1) maximize the revenue by increasing the overall utilization of the charging service and improving infrastructure efficiency, (2) increase EV users' satisfaction, and (3) reduce the overhead in charging infrastructure management. The generic requirements for demander are (1) obtain the cheapest price for the best quality of service, (2) guarantee on the agreed upon service level agreements, and (3) increase the comfort level and reduce the trip time including waiting and charging.

In this section, from the above-mentioned generic EV charging requirements, we first identify and define the relevant stakeholders and their requirements for reservation of charging stations. We then present feasible reservation approaches, define our research questions that will be tackled in this paper and highlight our contributions to the body of research.

3.1. Requirements for Reservation Systems

We consider both, electric mobility service provider (EMSP) and charging station operator (CSO) as the reservation service supplier side, whereas the EV user fills out the role of the demander. The grid operator, here considered as distribution system operator, is another business actor that has stakes in the operation of a potential reservation service. An in-depth analysis of this stakeholder is out of the scope of this paper, and it is presented in Figure 1 to provide a comprehensive and complete picture for the reference architecture model.

3.1.1. Stakeholder Requirements

The four main stakeholders, their major goals (G), business cases (BC), and the respective high-level use case (HLUC) are analyzed and presented in Figure 1. For the EV user, the overall goal is to improve his/her welfare and satisfaction with using EVs. This goal includes three main aspects: (1) trip duration, (2) convenience of charging, and (3) monetary costs for the user, including the costs for charging. The trade-off between these aspects depends on the user's priorities, where choices between fast and cheap options occur regularly in transportation scenarios. In order to maintain the scope of our research, we do not explore the monetary costs in detail within this paper. Instead, we assume some fixed non-zero cost of reservation sufficient to discourage basic abuse of reservations.

For the simulation-based validation of our reservation approach (see Section 5.2), we compared various types of reservation services and systems from both point-of-views: (1) the suppliers (CS operator and EMSP) and the demander (EV user). For the EV user, we evaluated the goals of increased charging convenience (G.01) and trip duration (G.02). In the simulation case study, we measured

the trip duration, which includes the driving, waiting, and charging time as proxy of whether EV users achieved these goals. Note that driving time includes the time needed for detours to reach available CSs.

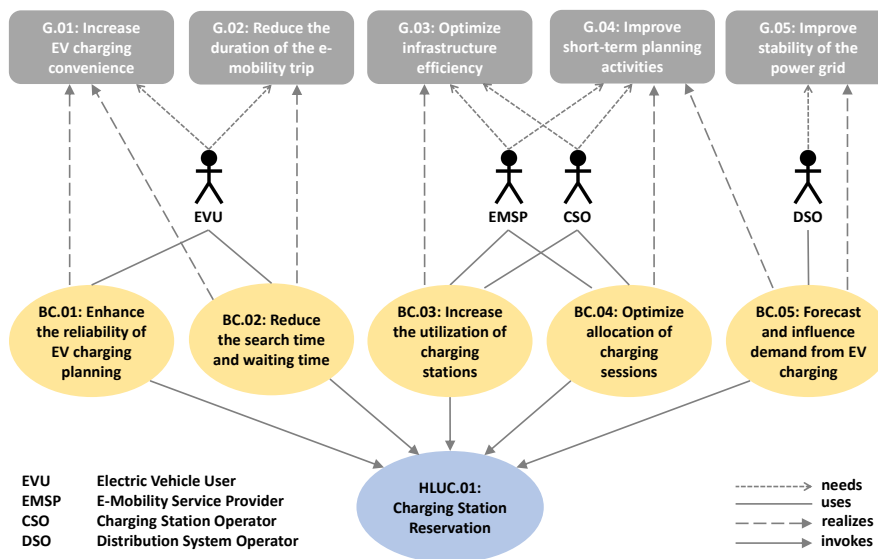


Figure 1. Charging station reservation business and requirements analysis.

To evaluate the impact on the charging infrastructure (G.03), we measured the mean utilization of charging stations. For a single CS, we measured the utilization in hours during which the charging station was in use. In our validation, we considered the same price of charging for all charging locations. This is a realistic assumption since many operators currently price charging in this way. Additionally, because all charging costs the same, our simulated users did not have to consider the price, which makes their decision-making more robust; they optimize their plans based only on time.

Goals G.01 and G.04 are not validated directly in this paper, but we argue that charging station reservation satisfies them by design. Reservations provide *planning* (see Section 3.2) that lets drivers travel without unexpected waits or detours. Furthermore, *reliable* and *enforceable* reservations also increase user convenience (G.01) by reducing unpleasant experiences, e.g., from an occupied CS. The knowledge about future charging sessions and optimization of their allocation also improves the short-term planning capabilities of the CS operator (G.04).

We do not address the privacy, safety, reliability, and security concerns explicitly in this paper. Even though they are important to all the stakeholders, in practice, they depend in a large part on the actual implementation of the systems and protocols. We will consider certain cross-cutting concerns, especially security and privacy, in our future work. Having said that, the system as proposed does not have any central point of control. Consider the example in Figure 1, EMSPs are part of the peer-to-peer roaming network and drivers deal with each EMSP reservation system directly. This decentralized nature of the proposed architecture avoids single point of failure and increases the barrier for attackers to steal large amounts of user data and attack the electric mobility infrastructure at scale. Regarding the privacy concerns, the reservation system as described in this paper requires unique identifiers of the vehicles in the reservation process. However, these do not need to be persistent between different reservations. Adding online payment systems could of course change this.

3.1.2. System Requirement: Interoperability

As mentioned above, the electric mobility ecosystem involves many stakeholders, each of them having its own particular objectives. All of the relevant stakeholders have their hardware devices and infrastructure peculiarities, communication technologies, as well as software systems. In order to realize a reservation system for electric mobility, it is crucial that all of the involved stakeholders and

their systems can communicate and cooperate with each other, despite the aforementioned system heterogeneity (i.e., hardware and software). This setting is realized through interoperability, which is currently missing for existing reservation systems. The IEEE defines interoperability as “the ability of two or more systems or components to exchange information and to use the information that has been exchanged” [26]. For the successful integration of charging infrastructure and related reservation services, interoperability on all levels (organizational, informational, and technical), including standardization and harmonization are essential. For evaluation, we applied the i-Score metric [27], in order to quantitatively verify this system requirement. Most measurement methodologies only provide qualitative frameworks, whereas the i-Score approach utilizes numerical metrics, and can be used for a first model-based assessment of interoperability. It has been applied and proven useful for model-driven architecture approaches in the smart grid domain [28], but is lacking an assessment of a standard’s implementation quality. Selecting a standard is not sufficient. Its implementation also needs to be tested and verified against a reference interface. Here, the i-Score provides a first indication for the interoperability of a model-based reservation system configuration. It is used as a methodology to compare interoperability between sub-systems of reservation system architectures and instances.

3.2. Feasible Reservation Types

From the EV user perspective, CS reservation approaches can be categorized along two dimensions as illustrated in Figure 2: *Reliability* and *Planning*. In order to recognize the advantages that charging station reservation brings to supplier and demander, we identified four different generic types of reservation suitable for the electric mobility context:

- Uncertain Ad-Hoc.
- Guaranteed Ad-Hoc.
- Uncertain Planned.
- Guaranteed Planned (Full).

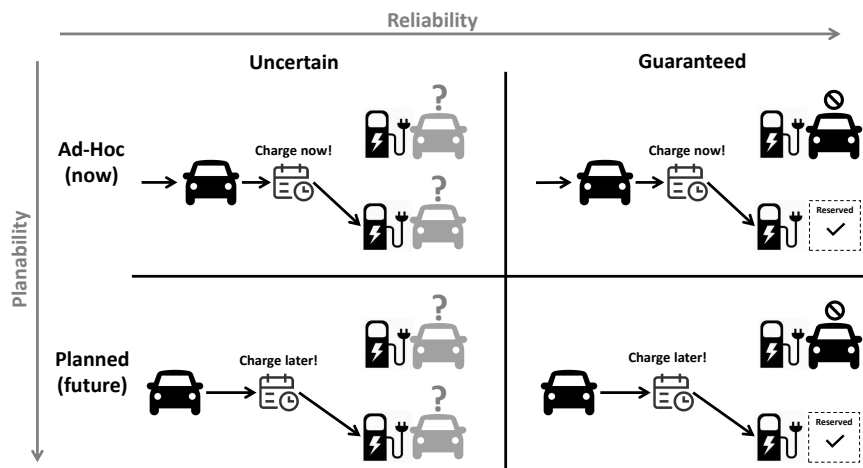


Figure 2. Feasible reservation approaches.

The vertical dimension in Figure 2 refers to the planning capability and starting time of a reservation. More precisely, “Ad-Hoc” denotes that the reservation can be placed immediately, which blocks the corresponding charging connector of a given CS from being used by other EV users for that time span. Only one “Ad-Hoc” reservation can be placed simultaneously at one connector of a given CS. “Planned” indicates that the reservation’s start time can be scheduled for some time slot in the future. This type of reservation allows for the CS connector to be used in the meantime. Further, multiple “Planned” reservations can be scheduled for one CS connector by multiple drivers at the same time. Note that the end time of the “Planned” reservation needs to be specified, while the end of the “Ad-Hoc” reservation does not.

Information about the CS connector's availability is a major requirement for the user to be able to make a reservation. The shared information can either be the current availability, meaning whether the CS connector is occupied at the moment or full availability, meaning that the EV user can get information about the future status of the desired CS connector. A CS connector that broadcasts its current availability can only offer "Ad-Hoc" reservations. As shown in Appendix A, current infrastructure can easily provide "Ad-Hoc" reservations. Full-fledged "planned" reservation for any time slot in the future is enabled by full availability information.

The reservation service's reliability (horizontal dimension in Figure 2) considers the fact that a CS may face problems with fulfilling reserved charging obligations. "Uncertain" specifies that in some approaches the availability of a charging station cannot be guaranteed despite a successful reservation, e.g., because the parking slot is occupied or blocked by some other vehicle. "Guaranteed" reservations are potentially possible if means for enforcing the bookings are in place, e.g., existing penalties and/or relevant hardware like sensors, barriers, and cameras.

3.3. Research Questions and Contributions

The stated problem reveals the need for a holistic and generic reference architecture for charging station reservation systems. As a contribution to the body of research, we consider the most relevant stakeholders: DSO, CSO, EMSP, and EV users. Furthermore, we identify each stakeholder's goals and take into account the system requirement of interoperability. Our main research questions are as follows:

- How to design a generic reference architecture that considers stakeholder requirements, ensures system interoperability, and supports instantiating customized reservation systems?
- What are the benefits for the relevant stakeholders when instantiating different types of reservation systems in practice?

To provide answers to these research questions, we developed a reference architecture for reservation systems. This includes guidelines regarding design and implementation decisions for system instances based on a morphological analysis. The usefulness of our solution artifact is demonstrated and evaluated in a suitable context in two ways: First, we verified the system requirement of interoperability with a model-based quantitative analysis with the i-Score metric. Second, we validated the stakeholder requirements with an agent-based simulation in a case study with different reservation scenarios.

4. Artifact Design and Development

In this section, we provide the design of our solution artifact as a reference system architecture model. Further, we provide details on the artifact development, including guidance on design and implementation decisions to derive relevant instances of the reference system architecture.

4.1. Reference System Architecture Model

For the modeling and engineering of the reference charging reservation system, the E-Mobility Systems Architecture (EMSA) model and framework [10] were used. The EMSA is a three-dimensional architecture model (see Figure 3), consisting of five interoperability layers (Business, Function, Information, Communication, and Component), four domains, and six zones. The EMSA is based on the standardized Smart Grid Architecture Model (SGAM) and can be used either stand-alone or in an inter-connected way. The SGAM has a strong focus on engineering energy-related systems and provides certain benefits like the smart grid standards map; the EMSA is more suitable for systems engineering in electric mobility, since it provides additional details on the respective domains.

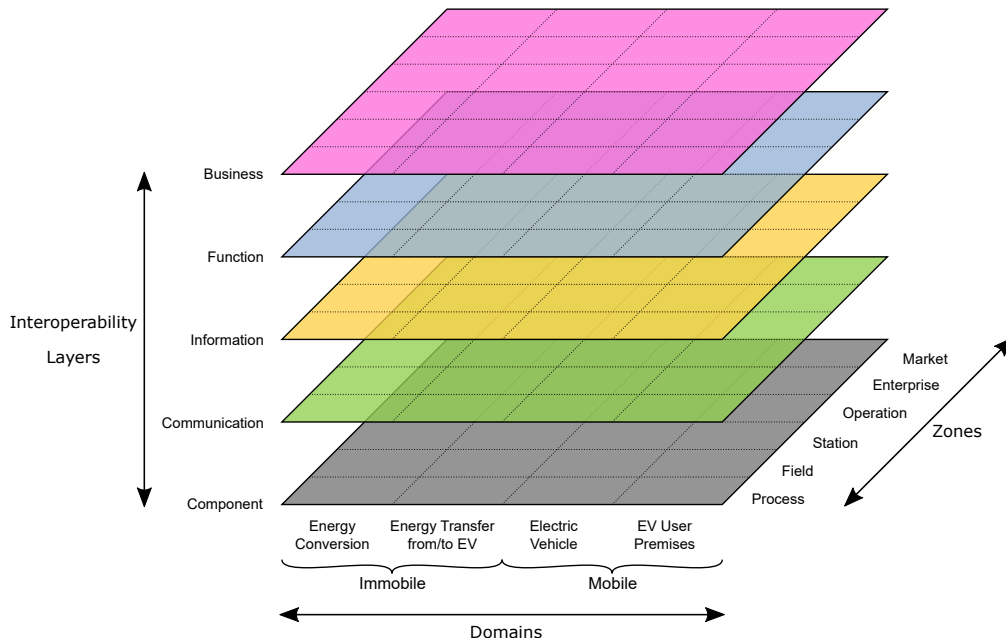


Figure 3. The E-Mobility Systems Architecture (EMSA) Model [10].

In order to engineer an interoperable reservation system, the EMSA allows for separation of concerns through the utilization of architecture viewpoints represented by the layers. Additionally, it ensures interoperability during the design and development phases on multiple layers. The EMSA-based system model consists of the logical architecture (Business and Function layer) and the physical system architecture (Component, Information and, Communication layers).

4.1.1. Logical Architecture

A capable system is required to implement high-level use case *HLUC.01: Charging Station Reservation*, which was derived from the business analysis (see Figure 1). The logical architecture of this CS reservation system is composed of four major functional building blocks (see Figure 4a). Within *Function.01*, the EV user requests relevant CS information from its EMSP via a reservation service. The EMSP returns this data and shows reservable charging stations to the user in the reservation service front-end (e.g., mobile app). The EV user selects a CS connector for reservation and the request is forwarded (optionally via charging roaming) from the EMSP to the CS operator, which then reserves the respective connector (*Function.02*). In case of a successful reservation, the CS operator notifies the EMSP, which then forwards the acknowledgment to the EV user via the mobile app. If the reservation failed or was denied, the EV user also gets notified. When the EV user arrives at the reserved CS, he/she authenticates (with the user id), accesses the CS connector, and starts to charge (*Function.03*). Payment is excluded from this logical architecture. Optionally, grid operators can directly read and interfere with reserved charging sessions in order to enable smart charging approaches and execute demand-side management (*Function.04*). Since some steps of the sequential flow might be omitted in certain scenarios, we grouped and modeled them as separate self-contained functions.

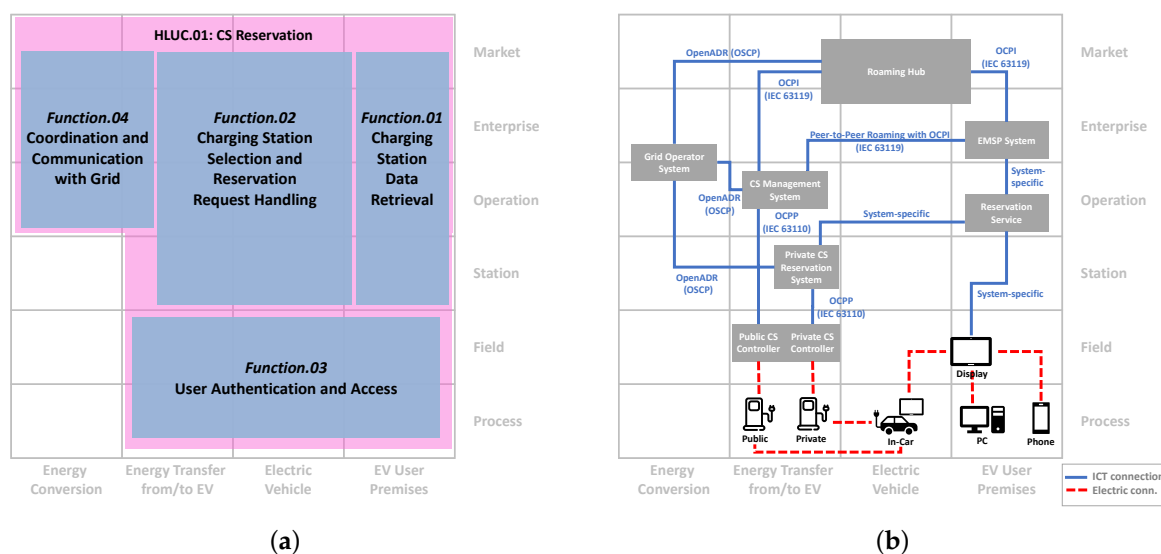


Figure 4. Reference architecture for reservation consisting of logical (to the left) and physical (to the right) parts. (a) Reservation Reference System: Logical Architecture (Business and Function Layer); (b) Reservation reference system: physical architecture (Component, Communication, and Information Layer).

4.1.2. Physical System Architecture

These four functional building blocks define the potential functionality of the CS reservation reference system. The physical system architecture consists of multiple components on the Component layer (see Figure 4b). The components from the *Field* zone upwards are mainly relevant for the actual software systems: Reservation Service, EMSP System, Roaming Hub, CS Management System, Private CS Reservation System, CS Controllers, and Grid Operator Systems. These are connected via ICT (Information and Communication Technologies) connections (blue line). The charging stations, in-car systems, and the EV users' devices (e.g., mobile phone) have an electric connection (dotted red line) to the other components, controllers, and displays.

The ICT connections define the information exchange between components and their data models (Information layer) as well as communication technologies and protocols used for this respective data exchange (Communication layer). In the current strongly fragmented electric mobility ecosystem, open protocols dominate the information exchange. Standardized data models are rarely used and rather de-facto standards specify the relevant data formats. In the *Market* and *Enterprise* zones of the EV-related domains, protocols for clearing house-based or peer-to-peer information exchange such as the Open Charge Point Interface (OCPI) v2.2 (<https://ocpi-protocol.org/>) dominate. The upcoming standard IEC 63119 is currently under development. For the information exchange of charging stations with back-end systems, the Open Charge Point Protocol (OCPP) (<https://www.openchargealliance.org/protocols/ocpp-20/>) is dominant.

Also, for these domains, a standard is currently being developed, namely IEC 63110, which might substitute the open protocols. For the cross-domain information exchange with grid operator systems, OpenADR (<https://www.openadr.org/>) and OSCP (<https://www.openchargealliance.org/protocols/oscp-10/>) are available. The remaining ICT connections from and to the Reservation Service are system-dependent and not covered by any domain-specific protocols or standards. For specific information objects, the respective data formats from OCPP, OCPI or ISO 15118 could be utilized to comply with interoperability requirements, e.g., e-Mobility Account Identifier (EMAID) for the user ID and Electric Vehicle Supply Equipment ID (EVSEID) for the CS ID are both defined by ISO 15118 [29].

The communication protocols used to realize this information exchange are mostly TCP/IP with HTTP over SSL, making this reference reservation system highly interoperable. A suitable interoperable

roaming hub is the decentralized Open Charging Network (OCN) (<https://shareandcharge.com/open-charging-network/>), curated by the Share&Charge Foundation, which implements an OCPI-based decentralized message bus as a communication infrastructure for data exchange.

4.2. Design Decisions for Reservation System Instances

In this study, we adopted the morphological analysis methodology, also known as the morphological box, to derive parameters relevant for the design and to provide guidelines for implementation decisions. The morphological analysis allows for identifying, structuring, and investigating the total set of possible relationships contained in a given multi-dimensional problem space. Consequently, a solution space and a flexible inference model can be created by defining, linking, and evaluating the different parameters of the corresponding problem space [11].

Table 1 presents the derived design parameters and their corresponding characteristics (i.e., options) within the context of CS reservation. The list of parameters was attained through the extensive literature survey of theoretical and practical contributions. *Enforceability* describes the design decision of whether a placed reservation is actually ensured, or if performing the charging process remains uncertain. The latter indicates the possibility that despite a successful reservation, the EV user upon arrival at the charging station might find the corresponding parking slot/connector occupied. Implementation of enforceable reservations typically requires installation of additional IoT devices, e.g., sensors or barriers. The design parameter *Planning* represents the ability to specify start and end times of the actual charging process with the reservation request. If *planning* is not included, the start time is instantaneous, i.e., the CS is blocked immediately and there is no need to specify the end time. For planned reservations, both start and end times need to be specified. The parameter *Fee* describes the types of costs related to a reservation request. Design option “No” refers to a free-of-charge service, whereas “Fixed” and “Flexible” indicate a paid reservation service with static or dynamic costs. The design parameter *Data Availability* considers whether data are available for the charging stations and connectors. In this context, three options exist: (1) no data are available, (2) only limited data are available (e.g., on current availability status or current charging capacity), and (3) all necessary information for reservation is known (e.g., reservation schedule). *Roaming* is used to specify whether reservation of charging stations is available across multiple operators. As last design parameter, *Scheduling* refers to the order in which reservations are processed. Its design options can be based on (1) policy (e.g., First Come First Served, Last Come First Served, Round Robin, etc.), (2) priorities such as high or low, and (3) auctions through game theoretic mechanism design methods. In this work, we used the FCFS scheduling, as this is the default in the real-life scenarios especially when queues are concerned [30,31].

By considering the design parameters and selecting suitable design options (Table 1), it is possible to aggregate the design decisions and create an instance of a suitable reservation system. For example, a system instance {"Yes"*Enforceability*, "Yes"*Planning*, "Flexible"*Fee*, "Full"*DataAvailability*, "Yes"*Roaming*, "FCFS"*Scheduling*} can be defined in order to design a full-fledged reservation solution and instantiate the respective system implementation. Numerous configurations of potential implementations can be defined with this methodology, not necessarily all of them being useful combinations.

To identify the most relevant design concept, we used a Pugh Matrix analysis [32]. In short, the Pugh Matrix is a criteria-based decision matrix which uses criteria scoring to determine which of several potential solutions or alternatives should be selected. When using three values, 0 means as good as the baseline concept, -1 means worse, and +1 means better than the baseline. Table 2 illustrates the result of the Pugh Matrix analysis by considering as baseline Uncertain Ad-Hoc reservation and comparing it with the other three concepts of Guaranteed Ad-Hoc, Uncertain Planned, and Guaranteed Planned respectively (see Section 3.2). This sample illustration shows that full reservation (e.g., Guaranteed Planned) is a concept that has substantial advantage over the de-facto concept of Uncertain Ad-Hoc one.

Table 1. Charging station (CS) reservation system design decisions based on a morphological analysis.

Design Parameter	Design Options		
Enforceability Level of charging certainty	No	Yes	
Planning Specified start and end times	No	Yes	
Fee Costs incurring from reservations	No	Fixed	Flexible
Data Availability Availability of relevant information	No	Limited	Full
Roaming Reservation across multiple operators	No	Yes	
Scheduling Order in which reservations are processed	Policy	Priority	Auction

Table 2. Pugh Matrix analysis for the reservation service comparing the three concepts of Guaranteed Ad-Hoc, Uncertain Planned, and Guaranteed Planned with the baseline Uncertain Ad-Hoc concept.

Criteria	Guaranteed Ad-Hoc	Uncertain Planned	Guaranteed Planned
Enforceability	1	0	1
Planning	0	1	1
Fee	0	0	0
Data Availability	0	1	1
Roaming	0	0	0
Scheduling	0	1	1
Sum	1	3	4

5. Demonstration and Evaluation

To demonstrate the usefulness of our system reference architecture, we applied a two-phase evaluation: First, we verified the system's interoperability requirements as specified in Section 3.1.2 by conducting a static quantitative analysis based on the EMSA for a specific system instance. Second, we validated a set of relevant stakeholder requirements as identified in Section 3.1.1 with an agent-based simulation case study.

5.1. EMSA-Based Verification of System Interoperability Requirements

To verify the proposed reference system architecture against the defined requirements, we instantiated one reservation system. The instance considered in this paper was an extension of an OCPP-based uncertain ad-hoc reservation system presented in Appendix A with peer-to-peer roaming based on OCPI, excluding private charging stations and grid operator connections. The system instance {"No"_{Enforceability}, "No"_{Planning}, "No"_{Fee}, "Limited"_{DataAvailability}, "Yes"_{Roaming}, "FCFS"_{Scheduling}} was modeled with a logical and physical architecture in Figure 5 (combining all EMSA layers in one model). Note that the instantiated system does not consider "Enforceability", "Planning", and "Fee". It has limited information (i.e., current status) about the connectors, "Roaming" is enabled, and the scheduling follows "first come, first served" without priorities. In the following, this system instance is quantitatively analyzed regarding interoperability with the model-driven i-Score metric [27,28] based on the EMSA and graph theory.

First, the operational thread of the reservation system instance was modeled as a UML activity diagram (Figure 6). It reflects the whole sequential flow, showing all potential activities of the three

major system functions within the main high-level use case (HLUC.01). The activities were allocated to the system components. Therefore, this assessment exceeds a purely functional analysis, but can be used to analyze the sequential flow along the respective connections. To define the i-Score, each sub-system (actor or component) was assigned an index, represented in the respective swim lane (column) of the activity diagram, e.g., #1 for the EV user and #5 for the charging station. The array T was an ordered set of the sub-systems that handles each step in the operational thread:

$$T = \{4, 3, 2, 1, 2, 3, 4, 5, 4, 3, 2, 1, 5\}$$

The operational thread can be defined as a complete directed multi-graph $D = (V, E)$ with a vertex array $V = \{v_1, v_2, \dots, v_n\}$, being the set of n systems and an edge array $E = \{e_1, e_2, \dots, e_{n \times n}\}$, being the set of all possible directed ICT connections between systems.

The i-Score uses the concept of interoperability spins with $s_{ij} \in \{-1, 0, +1\}$, which reflects the intrinsic interoperability between two systems i and j . For our system instance, only 0 and 1 were considered, as there was no connection with relatively negative interoperability, e.g., human-to-human communication.

Subsequently, an interoperability spin matrix $S = [s_{ij}]_{n \times n}$ with $s_{ij} \in \{0, 1\}$ and $i, j = 1 \dots n$ was developed as a weighted adjacency matrix. It represents all permutations of sub-system pairs and their respective ICT connections considered in the system architecture (see Figure 5). ICT connections with informational interoperability (i.e., an existing standard or open protocol) are represented by a 1, all others by a 0. For instance, the ICT connection e_{15} and e_{51} in Figure 5 is a part of the electric connection between EV and CS (transferring data via a communication pin in the plug). Consequently, in the matrix S , the elements (1,5) and (5,1) have a value of 1. Furthermore, it was implemented with the standard ISO 15118, e_{34} and e_{43} was implemented with OCPI and e_{45} and e_{54} using OCPP. Thus, all of them have an interoperability spin of 1.

The multiplicity matrix $M = [m_{ij}]_{n \times n}$ with $m_{ij} \geq 0$ and $i, j = 1 \dots n$ contains the number of path appearances for each system pair (i, j) in T .

$$T = \{4, 3, 2, 1, 2, 3, 4, 5, 4, 3, 2, 1, 5\}$$

For example (4, 1) has four paths overall: the accumulated number of times where a system #4 activity is followed by a system #1 activity in the operational thread T .

$$M = \begin{bmatrix} 1 & 2 & 2 & 2 & 3 \\ 4 & 3 & 4 & 4 & 5 \\ 4 & 5 & 3 & 4 & 5 \\ 4 & 5 & 5 & 3 & 5 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix}; I = \begin{bmatrix} 1 & 0 & 0 & 0 & 3 \\ 0 & 3 & 0 & 0 & 0 \\ 0 & 0 & 3 & 4 & 0 \\ 0 & 0 & 5 & 3 & 5 \\ 1 & 0 & 0 & 1 & 1 \end{bmatrix}$$

The interoperability matrix I is the result from a pairwise element multiplication of spin matrix S and multiplicity matrix M . It is defined as $I = [m_{ij}s_{ij}]_{n \times n}$.

Based on this interoperability matrix I , the i-Score can be calculated by the summation of interoperability spins x_{ij} between all system pairs:

$$i\text{-Score} = \sum_{i=1}^5 \sum_{j=1}^5 x_{ij} = 30$$

For the current state of standardization in the electric mobility sector, without standardized information exchange for connections (1,2) and (2,3), this is the maximum possible i-Score for this specific system instance. With a potential standardized information exchange in the future between (i) EV user (system #1) and reservation service (system #2), and (ii) reservation service (system #2)

and EMSP system (system #3), their respective interoperability spins would also be 1. The resulting optimal spin matrix S_{opt} and optimal interoperability matrix I_{opt} would be:

$$S_{opt} = \begin{bmatrix} 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 \end{bmatrix}; I_{opt} = \begin{bmatrix} 1 & 2 & 0 & 0 & 3 \\ 4 & 3 & 4 & 0 & 0 \\ 0 & 5 & 3 & 4 & 0 \\ 0 & 0 & 5 & 3 & 5 \\ 1 & 0 & 0 & 1 & 1 \end{bmatrix}$$

Subsequently, also the optimal i-Score for this system instance would be higher:

$$i\text{-Score}_{opt} = \sum_{i=1}^5 \sum_{j=1}^5 x_{ij} = 45$$

This optimal i-Score does not consider any physical or operational constraints of the system. Overall, it only provides an indication for the informational interoperability of this reservation system instance. Further, it helps in identifying interoperability gaps. In this paper, we specify interoperability of sub-systems as the application of open protocols as de-facto standards or as official standards. Next steps in the interoperability assessment would be to consider the normalized i-Score [27], to compare different system instances and to adopt elements of existing standards in order to harmonize proprietary ICT connections.

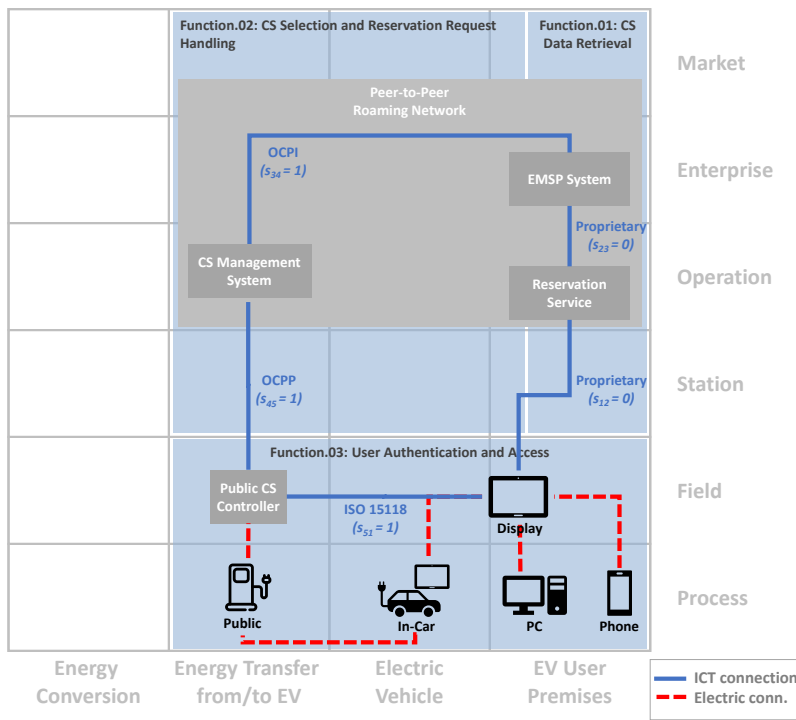


Figure 5. Reservation system instance with roaming, excluding private CS and grid communication.

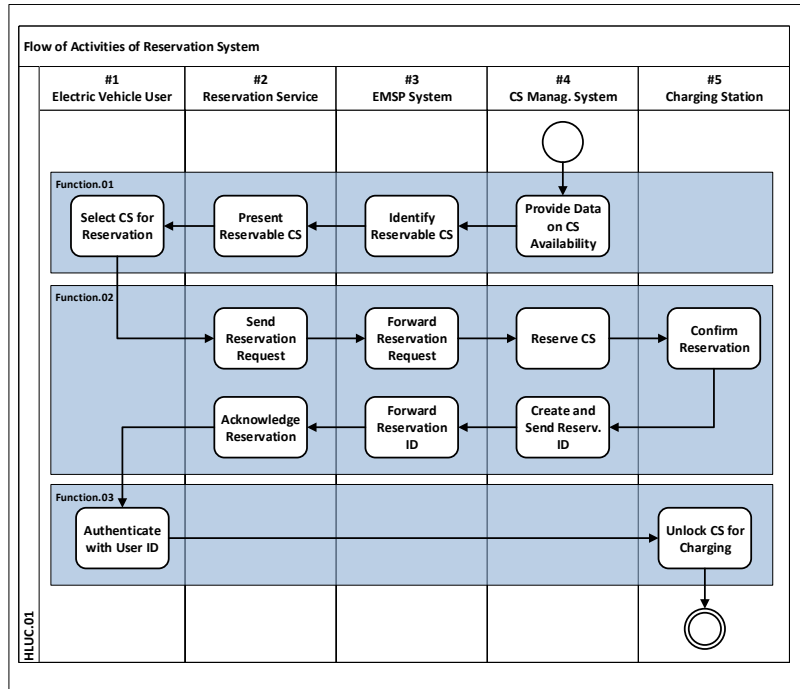


Figure 6. Operational thread of the reservation system instance modeled as a UML activity diagram.

5.2. Simulation-Based Validation of Stakeholder Requirements

To evaluate the benefit of different reservation types (see Section 3.2) for EV users and charging providers (i.e., CS operator and EMSP), we used the AgentPolis (<https://github.com/agents4its/agentpolis>) multi-agent simulation framework [33]. AgentPolis is a fully agent-based simulator built upon a discrete-event simulation core. In our use-case, all agents were deterministic in nature (e.g., the same state-of-charge (SoC) level, the same EV user behavior, etc.) and so were all simulation runs for given set of input parameters. In the simulation case study, we spawned multiple EV user agents and CS agents who interact with each other over a 24 h period. CS agents offered charging to the users with different types of reservation in each scenario of the case study, based on a FCFS charging reservation strategy. To reduce the complexity of the modeling, in this simulation, the CS operator concurrently represented the role of the EMSP (in reality this is a common case).

5.2.1. Scenario Description

For our simulation case study, we selected the roadmap of the Netherlands, using open street map data (<https://www.openstreetmap.org>) with 300,000 nodes and 800,000 edges (residential roads were removed). We selected the Netherlands as it has a dense and well-connected highway network and its electric mobility infrastructure is well developed. For charging station locations, we used open charge map data (<https://openchargemap.org>). We clustered these locations to create a set of 150 fast chargers (50 kw), each with one charging slot in most important EV charging centers (see Figure 7). In our experiments, we sampled between 10 and 2000 drivers using the infrastructure. Each simulation spans 24 h. For the vehicles, we assume a 200 km range with a 100 kWh battery and each vehicle starting with at least 30% state-of-charge.

Each driver performs a single trip that will require charging. Drivers use a planner that is a derivation of an A* algorithm that minimizes travel time [34]. Driver origin and destination were sampled from the set of charging locations, whereas the departure time was sampled from Gaussian distribution with mean at 8:00 AM and variance of 1 h.

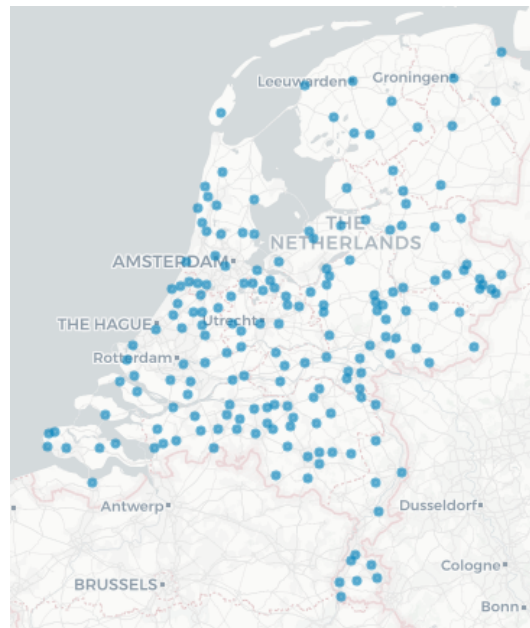


Figure 7. Charging location clusters for simulation case study.

We used two types of drivers in the simulation case study: *naive* and *prudent*. While both try to optimize their trip time, each driver does it in a different way. A naive agent uses his/her EV in a similar way that people use their combustion-engine vehicles, i.e., not planning their trip with refueling in mind. Instead, a naive agent searches for charging stations opportunistically when his/her battery state-of-charge (SoC) drops below 50% (Driver selects the closest charging stations in the direction of his travel and depending on the scenario, sorts them by availability and distance and then travels to the closest, presumably available CS.). The prudent driver uses a driver assistance system (e.g., a mobile or in-car app) in order to plan charging before starting his/her trip, and if the scenario permits, reserves charging stations at the beginning of the trip as well.

For the simulation case study, we selected two feasible reservation types according to the planning capability dimension from Section 3.2 and compared them against the initial scenario with no reservations:

1. No reservations: Users can not reserve charging station, but the current availability status of the connector/charging station is broadcast to drivers.
2. Ad-Hoc reservations: Only one reservation is allowed at a specific connector of a given charging station at any time, as described in Section 3.2. By the morphology in Table 1 from Section 4.2, this instance of reservations can be described as {"Yes"^{Enforceability}, "No"^{Planning}, "No"^{Fee}, "Limited"^{DataAvailability}, "Yes"^{Roaming}, "FCFS"^{Scheduling}}, referring to supporting "Enforceability" and "Roaming", having limited information on connector and not supporting "Planning" and "Fee".
3. Planned reservation: Users can make planned reservations at any time and CS can accept multiple reservations for different periods at the same time. This instance can be defined by the vector {"Yes"^{Enforceability}, "Yes"^{Planning}, "No"^{Fee}, "Full"^{DataAvailability}, "Yes"^{Roaming}, "FCFS"^{Scheduling}}.

We did not explore the reliability of reservations as defined in Section 3.2. First results indicate increased uncertainty to worsen performance of reservations [25].

In the simulation case study, we evaluated the combinations of the two drivers and three reservation types (see Table 3) with the exception of the naive driver—planned reservation scenario, as that is identical to naive driver—ad-hoc reservation in our implementation.

Table 3. Overview of simulated reservation scenarios.

	No Reservations	Ad-Hoc Reservations	Planned Reservations
Naive driver	✓	✓	X
Prudent driver	✓	✓	✓

5.2.2. Evaluation Results

(The waiting time being close to the adjusted duration is not an error, as EVs start with non-zero state-of-charge.)

In the results, we use two main metrics based on the stakeholder requirements of Section 3.1.1 to compare the different scenarios:

1. Mean (Adjusted) trip duration in hours across all users—this includes driving time (including time searching for available CS), waiting time at charging station and charging time. This metric addresses EV user goals G.01 and G.02 from Section 3.1.1.
2. Mean CS utilization—number of hours a CS was in use on average in the simulated period (24 h). This metric addresses charging providers’ goal G.03 from Section 3.1.1.

In our results, the mean trip duration of naive drivers is about twice the trip duration of prudent drivers. Because the naive drivers look for charging at any time their state-of-charge drops below a threshold, they tend to arrive at their destination with much higher state-of-charge than the prudent drivers who plan their trips with much smaller margins. This means that naive drivers and prudent drivers are not comparable in terms of absolute trip duration. To make the two driver types comparable, we use the *adjusted* versions of these variables obtained by subtracting time that was required to charge this leftover energy from the total trip time and CS utilization.

We ran all simulation scenarios with different numbers of drivers (see Figure 8 for values). We found that the driver type and reservation method have a strong influence on the number of drivers that reach their destination successfully. More precisely, a driver fails if he/she runs out of charge en-route or if he/she takes more than one day to finish the trip. By observing the results in Figure 8, we have decided to use the scenario with 200 drivers for comparison of four reservation types, as (1) vast majority of all drivers finishes their trips, and (2) the demand is high enough for reservations to make sense. In our experiments, it is apparent that the greater the demand, the bigger the benefit of reservations.

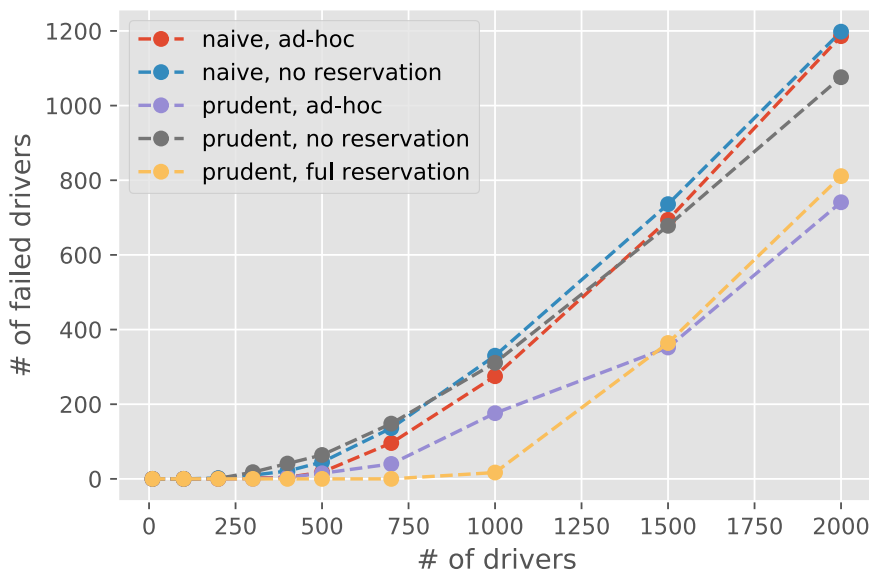


Figure 8. Number of failed drivers as demand increases for different reservation types.

Note that in our experiments, we consider only fixed value of battery capacity and charging speed. The relative results of different methods in Figure 9a,b would not change if we considered different battery capacity or charging speed. This is because we select the scenario for comparisons as the case with saturated supply as per Figure 8.

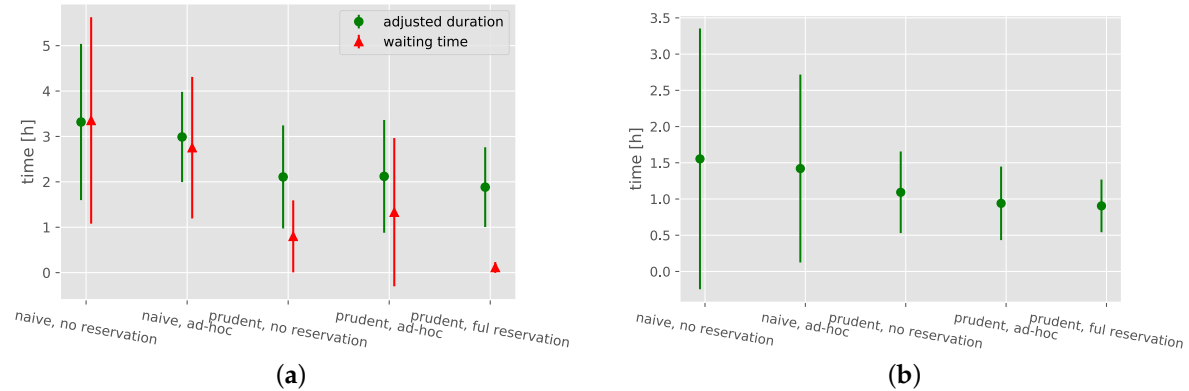


Figure 9. Simulation results illustrating the mean waiting time of electric vehicle (EV) users (to the left) and mean utilization of the charging station. (a) Mean and std of *waiting times* and *adjusted trip times* in the population of drivers, in different scenarios. These results correspond to the EV user goals G.01 and G.02; (b) Mean and std of *adjusted CS utilization* in the set of all CS, in different scenarios (scenarios lasting 24 h). These results correspond to the charging provider goal G.03.

Additionally, note that the error bars in Figure 9a,b are not confidence intervals as the results are from a single deterministic simulation run. Instead, they show the mean and standard deviation in the population of EV drivers, respectively, from the CSs used in the simulation run. Sensitivity to different driver origin/destinations and departure times is addressed in a separate sensitivity analysis.

In addition to this main experiment, we ran two additional types of experiments:

1. *Sensitivity analysis experiment* where we evaluated all scenarios with 10 different samples of driver origin destination pairs to test sensitivity of our results to geographical changes in demand. The sensitivity analysis suggest that the relative results in Figure 9a,b are preserved when the demand is sampled differently.
2. *Baseline experiment* where we set all CS capacity to infinity to create a baseline for our main results. For comparison with the main experiment, in the baseline, the adjusted trip duration of naive driver is 12 min (0.2 h) longer than that of the prudent driver.

Figure 9a shows the mean of the adjusted trip duration in the different scenarios. Most important difference is between the driver types. According to our results, planning of trip routes has the much bigger impact than the choice of reservation types.

Surprisingly, ad-hoc reservations improve the trip time for naive driver, but not for the prudent driver (however, the prudent driver still performs better than the naive driver in all scenarios). In fact, ad-hoc reservations worsen the trip times of prudent drivers. This is because many prudent agents end up re-planning to the same charging stations when available slots open up and slow each other down. Notably, the prudent agents with planned reservations offer the lowest waiting times.

For utilization of charging stations, reservations and driver type seem to have no significant effect on the total (adjusted) utilization of charging infrastructure (Figure 9b) at the same demand level as previous figures. Without the adjustment, in the scenario with naive drivers, charging stations are utilized significantly higher than in the scenarios with the prudent agents as they arrive to their destination with significantly higher state-of-charge.

6. Conclusions

Electric mobility provides excellent alternative transportation technology for our modern society with less environmental impacts compared to traditional combustion-engine vehicles. In spite of their advantages, electric vehicles are not yet widely accepted due to challenges such as (1) insufficient charging infrastructure, and (2) proportionally long charging times. Those challenges lead to dissatisfaction of the EV users as well as inefficient utilization of the charging infrastructure.

Reservation systems for EV charging stations as proposed in this paper are a promising approach to tackle the above-mentioned two challenges of electric mobility. Despite the advantages that they bring to the involved stakeholders, in existing literature their generic requirements have not yet been identified and analyzed from a coherent perspective. Since such systems involve a lot of heterogeneous infrastructure and communication technologies, they need to consider and satisfy interoperability requirements.

Extending on the state-of-the-art approaches, in this study, we designed and developed the corresponding generic reference architecture for interoperable reservation of charging stations. Interoperability is ensured by adopting the EMSA framework, whereas generality is guaranteed by considering the most relevant stakeholders' requirements during the design and implementation phase. In order to derive system instances of the proposed reference architecture, we provide guidelines based on a morphological analysis methodology. We instantiated one instance (i.e., customized solutions) of the reference architecture to evaluate our solution by verifying system requirements and validating stakeholder requirements. The former was carried out with a quantitative analysis using the i-Score metric, whereas the latter was executed with an agent-based simulation case study for potential scenarios in the Netherlands.

Results of the simulations show that full-fledged planned reservations are a promising way to reduce trip duration and waiting times on top of improved EV user-side planning in high demand-to-supply ratios. This is not the case for limited ad-hoc reservations, which are supported by most of the current charging infrastructure. In fact, ad-hoc reservations may lead to longer trip and waiting times. The aggregated utilization of the CS infrastructure remains mostly unaffected by the choice of the reservation method as the total amount of required energy in the system is not significantly impacted by any reservation scheme. Overall, the users planning their trips has a much bigger impact than the reservation system used. However, this does not imply that reservations are useless for charging providers, as our simulation case study does not capture the effects of a potential competitive advantage of reservations being deployed against providers not providing reservations.

Future research will focus on the different aspects (e.g., focus on DSO requirements) and demonstrate the usefulness of our solution approach for other instances and in other customized configurations (e.g., with focus on the "reliability" dimension). For the simulation, future work would include the calculation of how many additional CSs would be needed to achieve the same quality of service without reservations. As a further and more complex extension, pricing considerations the most important omission in our model. Our research results are of high relevance for practical applications and tackle critical issues and challenges in electric mobility.

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Abbreviations

The following abbreviations are used in this manuscript:

BC	business cases
CS	charging station
CSO	charging station operator
DSO	distribution system operator
EMAID	electric mobility account identifier
EMSA	e-mobility system architecture
EMSP	e-mobility service provider
EV	electric vehicle
EVSEID	electric vehicle supply equipment identifier
FCFS	first come first served
G	goal
HLUC	high level use case
HTTP	hypertext transfer protocol
ICT	information and communication technologies
IEC	international electrotechnical commission
IP	internet protocol
OCN	open charging network
OCPI	open charge point interface
OCPP	open charge point protocol
OpenADR	open automated demand response
OSCP	open smart charging protocol
PoC	proof-of-concept
SSL	secure sockets layer
TCP	transmission control protocol

Appendix A. Proof-of-Concept for Ad-hoc Reservation Type

In this section, we present the proof-of-concept (PoC) in implementing an *ad-hoc* type of reservations by considering CSs operated by e-Wald (<https://e-wald.eu/en/>) in the region of Bavaria in Germany. It is worthwhile to mention that such an implementation is achieved by instantiating the reference architecture as: {"No"_{Enforceability}, "No"_{Planning}, "No"_{Fee}, "Limited"_{DataAvailability}, "No"_{Roaming}, "FCFS"_{Scheduling}}. To realize such a system, the software solution is divided into front- and back-end. For the latter, the following hardware characteristics are considered:

- Processor: multi-core CPU with 4 cores
- Memory: 24 GB RAM
- Storage: 100 GB hard disk
- Network: 100 Mbps
- Operating system: Ubuntu Server 16.04

Appendix A.1. Front-End

The main objective of the front-end for the reservation PoC is oriented towards providing the EV users with the availability information about a given charging connector and its quick reservation process. To achieve this, the front-end (e.g., mobile app) is designed such that the map displays only the available charging station(s). Figure A1a demonstrates the realized front-end such that the blue-marked icon of the CS indicates that the corresponding connector is available. Upon selection of the corresponding CS, a new dialog box pops up (see Figure A1b) demonstrating the CS relevant information such as the connector types that can be reserved. The EV user has the option of canceling the reservation, or in the other case receives a confirmation that the corresponding CS has been reserved successfully (see Figure A1c). In case the reservation is not successful, the front-end will display an

error message, leaving the user with the opportunity of selecting another connector, CS or skipping the reservation process.

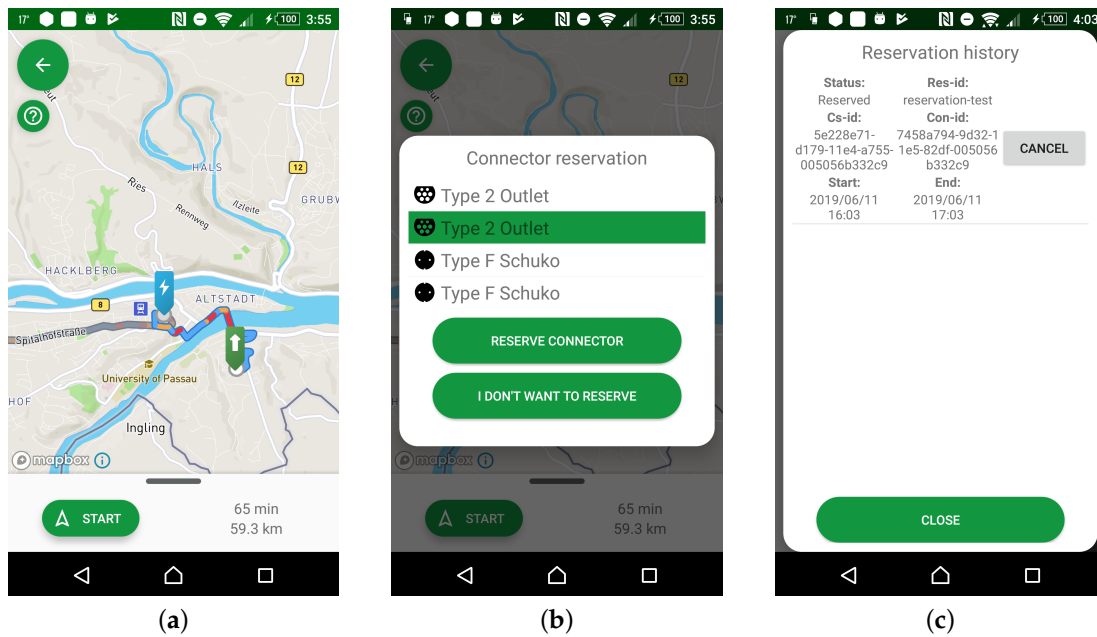
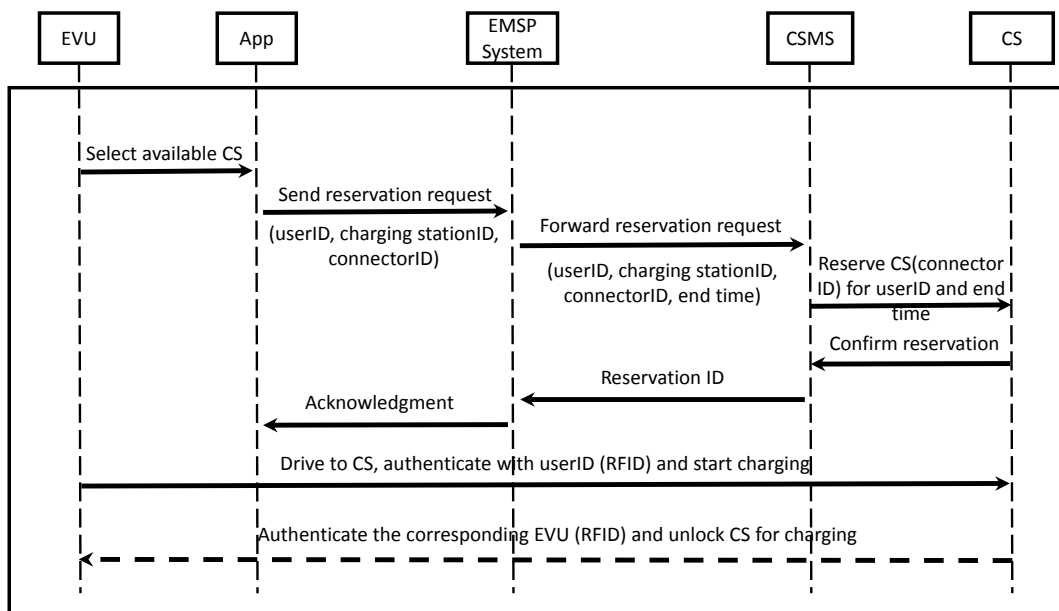


Figure A1. The different dialog boxes from the front-end perspective to reserve a connector of a given charging station. (a) Availability information of the charging stations; (b) Dialog box for reserving the corresponding charging station; (c) Dialog box for showing the summary of the carried reservation.

Appendix A.2. Back-End

The main objective of this part is to provide the software solution from the back-end perspective. To achieve this, the back-end needs to communicate with the charging station management system (CSMS), which is in its turn also a software solution. To realize the corresponding reservation, CSMS sends the request to the physical hardware (e.g., charging station) by means of the OCPP protocol. The exchange of the most relevant messages between the different involved entities is illustrated in Figure A2a. Finally, once the reservation is carried out by the back-end system successfully, a message is shown on the screen of the charging station denoting that the corresponding charging box is reserved (see Figure A2b).



(a)



(b)

Figure A2. The sequence diagram as well as the message showing on the charging station for the reservation. (a) The sequence of exchanged messages between different entities for the sake of reserving a given charging station; (b) The message showing on the monitor of the charging station that it has been reserved.

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