A Domain-Specific Modeling Language for Electric Vehicle Batteries

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Abstract. Electric vehicle batteries (EVBs) are crucial components of electric vehicles (EVs). They also account for a major share of the initial prices of EVs, inhibiting the diffusion of green mobility solutions. After having been removed from the vehicles due to an increased internal resistance or an insufficient capacity to store energy, EVBs may be recycled, refabricated, or reused to comply with legal regulations and to generate additional business returns. Making an informed decision on the further application of a used EVB presupposes in-depth product data, operating instructions, and status data on the battery. In this paper, a domain-specific modeling language is designed to specify the data structures required to describe EVBs. In the spirit of design research, the modeling language's validity and utility are demonstrated by modeling a typical EVB. In future research, the modeling language's meta-model can be extended and made configurable to inform various afterlife scenarios.

Keywords: Electric Vehicle Battery, Traction Battery, Electric Mobility, Meta-Model, Domain-Specific Modeling Language

1 Motivation

As an emerging technology electric mobility comprises manifold services, components, and resources and aims at a systemic integration of these items [1]. However, electric vehicles (EVs) are still facing technical and economic shortcomings, such that their market penetration is inhibited by low customer acceptance rates [1]. Most of these shortcomings refer to limitations of the electric vehicle battery (EVB), which is the crucial device for storing energy to propel the EV's electromotor. The range of EVs mainly depends on the EVB's performance, indicated by the state of health (SOH) [2], which is described as the ratio of an EVB's remaining capacity to its initial capacity [3]. Due to the continuous degradation of EVBs over time [4], their end of (first) life is reached when their SOH drops below 80% [5].

Considering the huge value of used EVBs [1], their subsequent use in second life applications seems to become a worthwhile business [6]. Manufacturers [7] and researchers [6], [8] propose the three main dispositions refabrication, reuse, and recycling for coping with the growing amount of used EVBs that are expected to enter the

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market in the next years [9]. In order to select and carry out these dispositions on an industrial scale, IT artifacts need to be designed and implemented.

To decide which dispositions should be selected and implemented, in-depth data on individual EVBs must be recorded and made available in the decision process. Since conceptual modeling languages for describing EVBs in sufficient detail are unavailable, we set out to design a domain-specific modeling language (DSML) to identify and systematize the required data fields and their relationships. The proposed modeling language enables further design-oriented research, amongst others to develop and implement IT artifacts for assessing an EVB’s status, to select adequate dispositions in a comprehensive decision task, and to implement the selected disposition in an efficient way.

Inspired by the design science research (DSR) publication schema proposed by Gregor and Hevner (2013) [10], the subsequent line of argumentation is structured as follows. In Section 2, we review the common structure of an EVB and present an overview of second life applications for which data on the battery is required. A review of related work reveals that no conceptual modeling languages for EVBs have been designed so far. In Section 3, the approach taken in our design research project is sketched. In Section 4, three design principles, including modularity, a distinction of master data and transaction data, and a level of abstraction to allow for extending and configuring the modeling language, are identified to guide the design of the proposed conceptual modeling language based on the design science research paradigm. In Section 5, the design of the modeling language’s conceptual aspects is presented by developing a meta-model. In Section 6, the representational aspect of the modeling language is developed and a typical EVB is modeled to demonstrate the language’s validity and utility. In Section 7, a discussion of the major results concludes the paper.

2 Related Work

This section opens with providing basic foundations on the structure of EVBs. Then, suitable dispositions for used EVBs and their requirements for EVB data are elucidated. A brief review of existing modeling languages for EVBs concludes this section.

2.1 Structure of Electric Vehicle Batteries

An electric vehicle battery is a high-voltage energy storage device for supplying the electromotor of an electric vehicle with electric current. Despite the fact that there are different areas of automotive application (e.g. hybrid, plug-in hybrid, and full-electric vehicle) EVBs are similarly constituted. Typically, an EVB is a compound structure consisting of four major components [11]: (1) battery pack, (2) battery management system, (3) thermo system, and (4) battery case (Figure 1).

The battery pack is the EVB’s main component as it is the energy storage device accumulating electrochemical energy. A battery pack is composed of a couple of battery modules that in turn consist of battery cells [12]. The internal assembly of connecting battery cells by series connection (increasing total voltage) and battery modules by parallel connection (increasing total amperage) result in several electrotechnical characteristics of the battery pack such as nominal voltage, nominal current, and nominal capacity. Usually and most commonly, an EVB's cell chemistry is based on lithium ion technology and there is a plethora of cell chemistries available such as lithium nickel manganese cobalt oxide, lithium manganese oxide, or lithium iron phosphate [13], [14].

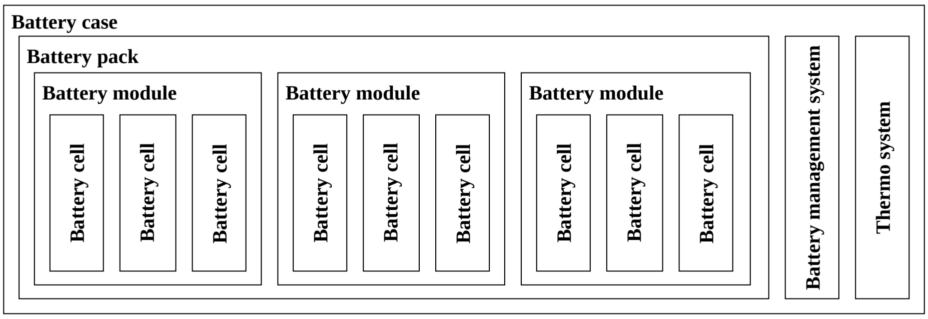

Fig. 1. An EVB's structure on a high level of abstraction [11]

Independently from the applied cell chemistry, a battery cell consists of two electrodes, an anode and a cathode. Based on the redox reaction, ions flow between anode and cathode resulting in electric current. The anode accommodates the lithium ions coming from the cathode upon charging and, depending on the cell's type, usually consists of materials such as carbon (graphite), lithium, or lithium titanate [14]. Furthermore, a battery cell consists of an electrolyte that is the medium for establishing the flow of ions between both electrodes [15] and a separator that is available for separating both electrodes from each other in order to prevent short circuits [15]. For preventing an unsafe cell state regarding the internal pressure, a safety vent is applied to each cell in order to release gas from the inside if necessary. The applied materials such as cobalt, nickel, and especially lithium are financially valuable due to restrictive world deposits [16].

For operating an EVB's equipment and monitoring vital control parameters, an embedded system, the battery management system (BMS), is in place [13]. The BMS controls operating parameters such as voltage, battery cells' and battery modules' temperatures, state of charge (SOC), state of health (SOH), and other parameters in order to safeguard the battery's operations, especially charging and discharging processes, accurately [17]. Furthermore, it is crucial to apply event-based or continuous logging of vital parameters during an EVB's lifecycle in order to assess the EVB's quality at a certain point in time [18], [19].

Additionally, the BMS controls an EVB's periphery such as the thermo system (e.g. cooling fans and heating) to provide optimal and safe climatic conditions for the entire battery pack due to temperature sensitivity of the battery cells [13], [20], [21]. For protecting the EVB's inner components against mechanical loads, moisture, dirt and other undesirable external influences, the components are covered by a solid battery case that usually consists of light-weight metals and plastics.

2.2 Dispositions for Used Electric Vehicle Batteries

Similar to other battery technologies like nickel cadmium or nickel metal hydride, lithium ion secondary batteries also suffer from degradation, resulting in a reduced capacity and a fade of power [4], [22]. Consequently, an EVB's performance and, thus, its utility is limited by calendar ageing and cycle ageing. The aging effects have various causes such as the decomposition of the electrolyte, inaccessible surface areas of anode and cathode materials or contact losses of active material particles and are e.g. enhanced by an operation in high temperatures, high cycling rates, and deep discharges [22], [23]. Due to the degradation, current lifecycle estimations for EVBs state an end of life for the original automotive application after approximately 10 years of usage and a remaining SOH of around 80% [5].

The EVB is the most expensive component of an EV [1] and may cause up to 50% of the vehicle's initial price, due to the sophisticated manufacturing process and the valuable materials contained in EVBs. Lowering costs of EVBs is a crucial challenge that may lead to a higher market penetration of EVs. Consequently, although a used EVB is not suitable for its original automotive application anymore, alternative usages might be possible and a suitable strategy to lower an EV's total cost of ownership, before the battery is recycled. Further arguments for considering a second use of EVBs lie in the positive environmental impact resulting from repurposing [24].

In general, researchers and car manufacturers like Nissan differentiate three options for the disposal of used EVBs [6], [7], [8]. First, a *refabrication* or *remanufacturing* might take place for preparing the used batteries for their reuse in electric vehicles or applications with lower performance requirements. Ramoni and Zhang (2013) define remanufacturing as the process of returning "a used product to like new condition with a warranty for the buyer"[8]. For reaching a 'like new condition', researchers describe several complex and expensive procedures to remove the aging effects from cells and peripheral components [8]. Since battery cells within a single battery pack might age differently [18], the disassembly and reconfiguration of EVBs without recovery measures might be necessary to ensure a homogeneous quality level within a battery pack and guarantee the proper functionality of the used cells as a system.

Second, both researchers and car manufacturers propose to *reuse* EVBs. Application scenarios mainly comprise stationary applications such as peak load management for grids [25] or for private households [18] and as buffer storage for green energy generated by photovoltaic installations or wind farms [26]. Since each scenario implies different requirements regarding the battery's performance, selecting a suitable reuse scenario is a challenging task and presupposes detailed information about an EVB's condition and operation parameters.

Third, the end of life of battery cells, modules, and packs is reached when a refabrication for a reuse or a direct reuse is either not possible or not worthwhile anymore. As a consequence, the packs and peripheral components need to be disassembled and *recycled* for retaining valuable materials [13]. For that to happen, various physical and chemical processes are available [13]. In the spirit of closed-loop supply chains, the recycling process' outputs may serve for constructing new products such as EVBs.

2.3 Review of Existing Modeling Languages for Electric Vehicle Batteries

A sound description of an EVB's structure is prerequisite for selecting and realizing a suitable second life scenario. Conceptual modeling languages can be used to specify and depict the structure of physical objects, which has often been demonstrated in product data management and in enterprise resource planning.

To identify and review related work on modeling languages for EVBs, a literature search[1] was conducted by querying the literature databases Scopus (hits: 30; relevant hits: 0), Web of Science (15; 0), and AISEL (3; 0). The search revealed that no conceptual modeling language for EVBs and batteries in general exists that covers all properties of a battery that are essential to select and implement second life applications. Some existing modeling languages enable simulating physical characteristics of batteries or electric devices [27], whereas other languages cover the description and simulation of electric fuel cells [28] and fuel cell powertrains [29], [30]. The search revealed that the most common language for this purpose is the object-oriented modeling language Modelica[2]. However, since there are a few libraries featuring building blocks for battery models that can be used for simulating different objectives, e.g., thermal or aging simulation, Modelica is not suitable to describe EVBs for second life applications. Gao and Musunuri (2006) propose a domain-specific modeling environment for hybrid EVs containing a meta-model and models of HEV components [31]. In this article the battery is depicted as "an internal resistance equivalent circuit model"[31] representing the battery as a voltage source and a resistance, which depends on the SOC and the operating temperature. Kral and Simic (2011) describe purposes and challenges for simulations of EVs [32].

3 Research Method

The research presented in this paper is conducted in the consortium research project [33] EOL-IS that is funded by the German Federal Ministry of Education and Research (BMBF) to develop a decision support system for selecting and implementing optimal second life applications for EVBs that have reached their end of first life. The development of the proposed conceptual modeling language serves to describe different types of EVBs in the system. The overall research project is conducted in the spirit of the design science research paradigm [10], [34], [35], [36], while the proposed domain-specific modeling language is one major IT artifact developed in the project.

Based on the observation that design is a search process, which is subject to iterative cycles of design and evaluation [34], [36], different versions of the modeling language were designed and discussed in interviews[3] with both scientists from battery

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[1] (("battery" OR "energy storage system") AND ("modeling language" OR "modelling language")), conducted on June 12th, 2014

[2] http://www.modelica.org/

[3] At this early stage of research, the interviews were conducted informally, without developing structured interview guidelines or transcripts. In each cycle, the designed modeling lan-

research and engineers from battery manufacturing companies. In addition, document analyses were conducted to evaluate the modeling language with product specifications of common EVBs to verify that no common properties of EVBs were neglected. Since product specifications of EVBs are often treated as trade secrets and, hence, are not accessible, we retrieved the specifications from product data sheets[4] that must be published to enable a safe transport of EVBs as dangerous goods. The iterative cycles of design and evaluation stopped after the design principles were fulfilled and no additional concerns were raised by the involved experts. The activities and outcomes of the design process are summarized in Table 1.

Table 1. Overview of activities performed and outcomes reached in the design process

Activities	*Outcomes*
Inspection of EVBs for electric vehicles and electric busses at two battery manufacturing companies.	List of main components of an EVB, including the physical entities cell, module, pack, thermo system, and case.
Literature analysis on components of EVBs and review of product specifications supplied by manufacturers issued for transporting EVBs.	Additional constructs for modeling EVBs, including non-physical entities such as state parameters that need to be considered as well.
Additional literature analysis and development of design principles that guide and constrain design actions for developing the modeling language.	Three design principles of (a) modularity, (b) master data and transaction data, and (c) level of abstraction to enable extending and configuring the language.
Design of the modeling language as an entity-relationship model (ERM).	Meta-model of the language to be evaluated and refined in further steps.
Review of the modeling language by experts from (a) a battery research center, (b) a battery company, and (c) a battery recycling company.	Cyclic review and update of the modeling constructs and the interdependencies of the constructs in the language's meta-model.
Implementation of the language in a meta-modeling tool and design of the representational language aspect.	Design of graphical representations of all proposed modeling constructs as a hierarchical modeling language.
Design of models of EVBs with the conceptual and representational aspects of the modeling language.	Demonstration of the proposed modeling language's validity and utility to depict common EVBs.

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guage was presented to and discussed with the experts in order to identify if the right modeling constructs and relationships were included in the language. In addition, the model's overall comprehensibility, completeness, and appropriateness were assessed.

[4] http://www.unece.org/fileadmin/DAM/trans/danger/publi/adr/Other_notif/13-0085-Bosch_Battery_Systems_F.pdf, accessed on July 14th, 2014

4 Design Principles for an EVB Modeling Language

Following Sein et al. (2011), design principles are knowledge derived from design research endeavors that can be applied to solve related problems or to design related artifacts [36]. Capturing this knowledge, design principles are justified theoretical statements that define the scope (e.g. goals and constrains) for the design of an IT artifact and facilitate the design process. In the following, three design principles for the development of a conceptual modeling language for EVBs are proposed.

4.1 Design Principle 1: Modularity

EVBs have a complex hierarchical structure, not only consisting of packs, modules, and cells, but also requiring different types of connections between cells and modules (e.g. for series or parallel connection) [11]. Additional components, such as the battery case, the thermo system, and the BMS and their specific functions in the overall battery system (e.g. safety, control, monitoring, and protection), further increase the complexity of modeling EVBs. Additionally, when deciding for or against a specific second life application, the decision must not be solely limited to the battery system. Instead, single components or interrelated subsystems of the entire battery system might be reconfigured or resold for different purposes. Other components of the original system might be stored temporarily or are recycled instantly [6], [18].

Modularity is a common design principle for successfully managing complexity, serving three purposes: Making complexity manageable, enabling parallel work, and providing tolerance for uncertainty, which means that “particular elements of a modular design may be changed *after the fact and in unforeseen ways* as long as the design rules are obeyed”[37].

Accordingly, we propose the design principle of modularity, meaning that the modeling language needs to provide the constructs to decompose the whole battery system into discrete modules (i.e. partial systems) and their particular functionalities, in order to enable both depicting EVBs of different types and providing individual configurations of EVBs for various second life applications.

4.2 Design Principle 2: Master Data and Transaction Data

Making an informed decision for the disposition of a used EVB requires data that can be differentiated into three categories. First, information about the battery system’s structure (e.g. number of modules, cells, peripheral components) and nominal specifications of the included components (e.g. model, nominal capacity, nominal voltage, weight and dimension, operating temperature, charging current, safety instructions) needs to be taken into account. This information is indispensable when it comes to the dismantling and first sight classification of the components and is typically provided by the manufacturer of the components in the form of a product specification [38]. However, especially for the recycling of batteries, more detailed data about utilized materials (e.g. exact cell chemistry including percentage shares or values in weight units for anode and cathode materials) is required to decide for or against specific recycling processes, which are often aimed at recovering particular materials [38]. Following the common terminology in the area of enterprise resource planning (ERP), this data category can be labelled as *master data*, i.e., raw data that is rather static in nature and has a low time reference [39], [40].

Additionally, for making a decision about the actual quality of an EVB's components, data about the current condition of the pack, modules, and cells is required. Since cells degrade over time (calendar life) and are influenced by their charging and discharging profile (cycle life), operating parameters, such as voltage, capacity, and internal resistance and hence maximum discharging current, are likely to be different from the nominal values documented in the product specifications after its first use [22]. This data might be read out from the EVB's BMS or can be documented and analyzed manually (e.g. by test method defined by norm "DIN EN 62660-1. Teil 1").

Finally, especially for estimating the durability of the different components in their second life, data on the transactions experienced by the EVB, including their charging and discharging profiles (deep discharges, charging with too high voltages, and fully charging a lithium ion cell lead to a reduced service life due to stress [41]), operating conditions (best operation at room temperature, higher temperatures cause stress, lower reduce available capacity [1], [13], [17]), and parameters such as the SOC or the SOH, are required. Against the backdrop of common terminology in ERP systems, these data can be labelled as transaction data, i.e., data provided with a time reference that is dynamic in nature [39], [40].

Accordingly, we propose to include master data and transaction data on EVBs in the proposed modeling language. The data might be fed from different sources, including the original product specification supplied by the manufacturer, altered specifications from the BMS and manual analyses, and the transaction data provided by the BMS or by a downstream device such as a board computer.

4.3 Design Principle 3: Level of Abstraction for Extension and Configuration

Validity and *completeness* are frequently mentioned as requirements for modeling languages [42], [43], [44]. Validity suggests "that all statements made by the model are correct and relevant to the problem"[42]. Completeness means "that the model contains all the statements about the domain that are correct and relevant"[42]. However, researchers also agree that total validity and completeness cannot be reached [42], [45]. Instead, a *feasible validity* and *feasible completeness* [42] or economic viability [45] are set as objectives to account for "a trade-off between the benefits and drawbacks of achieving a given model quality"[42].

We argue that in immature research areas such as electric mobility, even feasible validity and feasible completeness are difficult to achieve, since a model can only take an abstract snapshot of the reality that might soon become invalid. Consequently, the modeling language has to be constructed flexible enough to react to profound changes in EVB technology.

Furthermore, validity and completeness have been argued to oppose the supportability [46] and simplicity [46] of models. Since feasibility lies in the eyes of the beholder, a modeling language is best defined to be configurable, e.g., by supporting different views. Views allow reducing the complexity of a model by adapting to the specific users, such as second life customers or recycling providers. Whereas customers might be interested in the compatibility of different modules or cells to his application scenario, recycling companies focus on material quotas and safety requirements for handling the battery components.

Accordingly, we identify a high level of abstraction as a design principle for our EVB modeling language, to enable extension and configuration of the language. Therefore, we refrain from including specific values, e.g., to determine parameters for measuring the SOH or specific cell chemistries as predefined constructs.

5 Design of a Modeling Language for Electric Vehicle Batteries

Due to the inherent complexity of EVBs, research in this field needs to involve stakeholders with various academic backgrounds, including engineers, chemists, and computer scientists. Conceptual models have been proven to be valuable artifacts for fostering the communication in interdisciplinary teams [47]. As we assume that this claim also holds true for models of EVBs, we set out to design a DSML. Since the DSML implements the specific terminology and relationships used in the domain of battery experts, our language is expected to better support both ease of use and ease of interpretation than general-purpose modeling languages, such as the ERM, do.

5.1 Linguistic Constructs of Domain-Specific Modeling Languages

A domain-specific modeling language requires three linguistic constructs [48]: an abstract syntax, a concrete syntax, and semantics. While the abstract syntax defines concepts of the language and their interrelationship by rules, the concrete syntax defines the notation of the language by assigning mostly graphical but also textual symbols to the elements of the abstract syntax [49]. Semantics is crucial for constraining the instances derived from the model to be syntactically correct [50]. Defining the abstract syntax requires reconstructing the central concepts of the target domain on an appropriate level of abstraction [51], as specified in a meta-model [52] that was derived based on the three aforementioned design principles (Figure 2).

5.2 Abstract Syntax of the Proposed EVB Modeling Language

The meta-model differentiates the central battery components cell, module, pack, thermo system, BMS, and case by type and instance entities. Type entities of battery components, such as *battery cell type*, *battery module type*, and *battery pack type* and their interrelation are descriptive elements defining existing and allowed configurations. In turn, instance entities of battery components, such as *battery cell*, *battery module*, and *battery pack*, have to refer to existing peculiarities of the defining types. With respect to design principle of modularity, the modeling language specifies that a battery system consists of packs and their subordinate modules and cells. The proposed structures allow for providing information about the specific circuitry for modules and cells (e.g. parallel or series connection), the materials used for the connection, and the type of the connections (e.g. weld, plug socket, glued joint). Finally, the realization of modularity allows to design individual subsystems consisting of additional *peripheral assembly types* and associated *functions*, *manufacturer operating instructions*, and *safety mechanism*.

The second design principle motivates the integration of master data and transaction data into the EVB models. For depicting master data, each type entity is either generalized to *battery assembly type* or *peripheral assembly type*. Both battery and peripheral assembly types are further generalized to an *assembly type*. The reason for this abstraction is model reduction and the assignment of additional master data on this abstract level. An *assembly type* such as a battery cell is a composition of different *component types*, such as anodes, cathodes, electrolytes, and separators, each consisting of different *materials* such as lithium, nickel, and cobalt. Beside the *manufacturer operating instructions* that are determined on the type level and provide information about operating parameters (e.g. discharge rate, temperature ranges), according *updated operating instructions* have to be provided for every assembly instance, as each component ages individually. For BMS types, further master data is available about the applied storage devices (e.g. hard disk, flash memory, and memory sizes of these devices) and interfaces (e.g. CAN bus, RS-232) for establishing an encrypted or plain data stream in order to exchange data with external devices.

The instance entities *battery cell*, *battery module*, and *battery pack* are generalized to *battery assembly* for model reduction. For generating data about the state of the battery assembly instances, either manually by *lab metering*, or automatically by *monitoring* with a BMS, *state parameters* and measuring characteristics have to be defined. With respect to the operation of the BMS and the existence of different BMS topologies (e.g. hierarchical structure with master and slave BMS), the *monitoring* entity allows to store configurations of *battery assembly* (e.g. cells, modules, and pack) and monitored *state parameters* individually for each BMS instance. The accordingly monitored state parameters are recorded within the *measured data* entity. The lab metering entity allows to document state parameter configurations for manual recording. Further transaction data is available about BMS instances, since occurring errors of BMS's operations are logged with a timestamp.

Finally, for fulfilling the third design principle, an adequate level of abstraction has been selected. Although a description solely on an assembly level would foster the integration of new concepts, modeling EVBs on the component level supports the understandability of the meta-model for domain-unrelated stakeholders and researchers and allows the explication of the domain-specific concepts and knowledge. Additionally, expandability is achieved by defining all generalizations to be partially complete. Since the research on modeling EVBs is still work in progress, the modeling language requests for contingency that is offered in the meta-model by generalizing the main battery system components. The component level - as the selected level of abstraction - enables configuring the modeling language with requirements raised by various use cases, such as refabrication (focus on reassembling of homogeneous components), reuse (focus on condition and suitability of the components), and recycling (focus on component structures and recovery of materials).

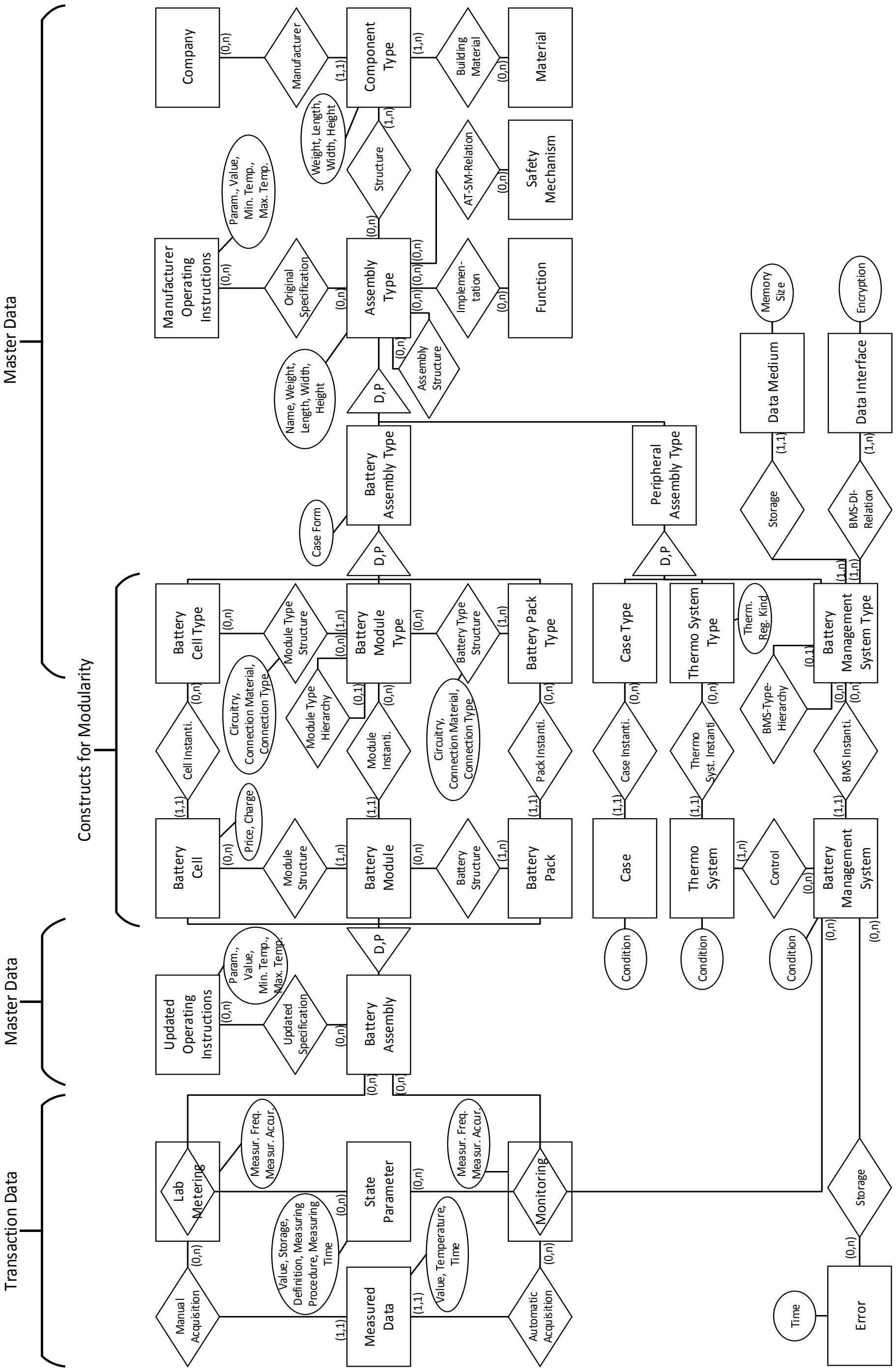

Fig. 2. Meta-model of the proposed modeling language for EVBs

5.3 Concrete Syntax of the Proposed EVB Modeling Language

A concrete syntax (Figure 3) was designed for the proposed domain-specific modeling language by assigning individual graphical and textual symbols to the abstract syntax elements in the meta-modeling tool H2 [53].

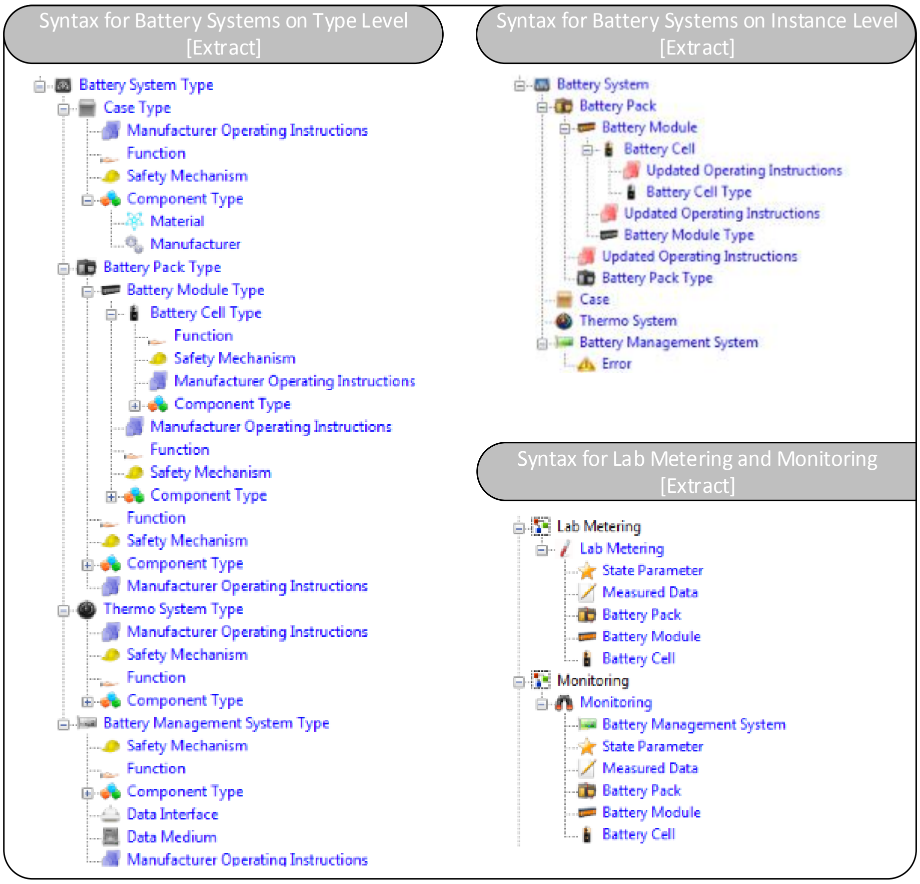

Fig. 3. Concrete syntax of the DSML

6 Demonstration of the DSML

In the spirit of DSR, utility is shown by instantiating and demonstrating the designed artifact [34]. For that to happen, an existing EVB is modeled using the proposed modeling language (Figure 4). Since there is no transaction data available, the model instance only contains master data provided by a product data sheet. Following this description, each battery pack is consisting of 8 battery modules. In total, the exemplary battery pack type consists of 96 battery cells since each battery module consists of 12 battery cells.[5] Furthermore, it is possible to add in-depth information about the EVB's inner components such as anode, cathode, and electrolyte each containing of several materials (e.g. lithium, manganese, copper). The battery pack's information are completed by functional aspects (e.g. power unit, energy storage), safety mechanisms (e.g. bleed-operated safety vent), and manufacturer's operating instructions. Another battery system's component is the applied BMS containing an RS-232 interface and 1024 kilobytes of non-volatile onboard memory. The exemplary battery system is completed by the thermo system and a battery case.

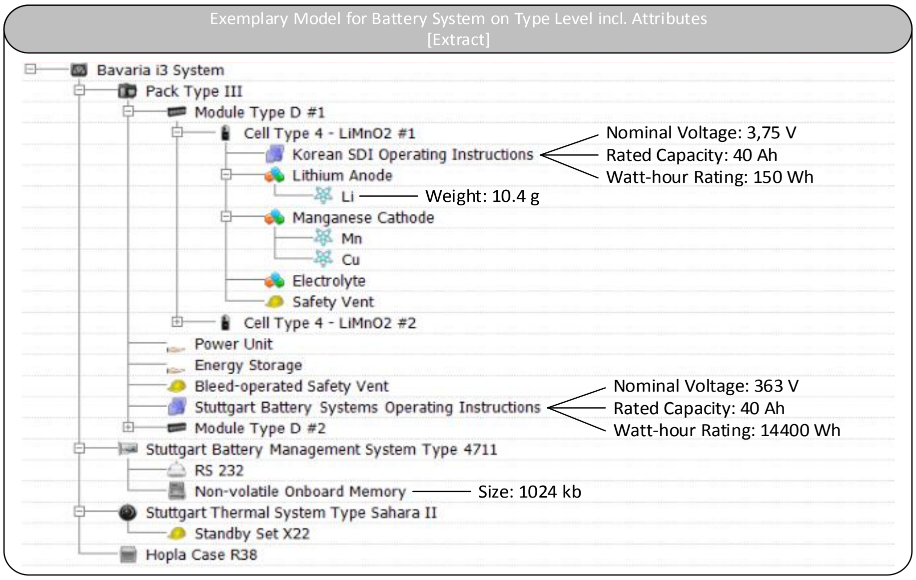

Fig. 4. Model instance for the exemplary EVB

7 Discussion and Conclusion

The main contribution offered in this paper is the design of a DSML for EVBs. A review of the existing body of knowledge revealed that such a language was not available before. The design of this language was guided by three design principles, comprising (a) modularity for coping with the complexity of EVBs, (b) master data and transaction data to capture the product data of the battery and the transactions carried out in the battery's lifecycle, and (c) a high level of abstraction that allows for extending and modifying the language. The language's validity and utility were demonstrated with sample EVB data.

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[5] The model instance contains only one exemplary module and cell for meeting the page length requirement of this article. For illustration purposes, the model is supplemented with exemplary characteristics (e.g. weight, size, nominal voltage) that are usually hidden.

A limitation is that a constraint language for defining the semantics of the language [50], was not developed so far. Moreover, the language needs to be evaluated, e.g., with respect to its representational fidelity, representational efficiency, interpretational fidelity, and interpretational efficiency [54], to validate the language's ability for modeling the right constructs and its usefulness for its stakeholders. This approach might let the "situated implementation of artifact"[10], manifest in the proposed instantiation, evolve into a "well-developed design theory about embedded phenomena"[10].

The proposed DSML can offer a contribution to various applications that require data on the structure and operation of EVBs. Against the backdrop of reusing EVBs, some of these application scenarios include assessing the status and value of an EVB, decision-making on the treatment of the battery, refabricating the battery by recombining battery modules, and recycling the battery to retain valuable materials such as cobalt and lithium. Future research may design processes for conducting these operations, such that the data featured by the proposed modeling language can be brought to bear on the activities to be performed. On the other hand, specifying these processes might raise the need to extent or refine the DSML, which can be done by adapting the proposed abstract and concrete syntax presented in this paper. Moreover, a thorough evaluation of the proposed modeling language that goes beyond demonstrating its appropriateness by modeling a particular EVB instance, as done in this paper, is required in order to validate the utility of the modeling language in practice.

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