Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 119 (2023) 1078–1083

www.elsevier.com/locate/procedia

33rd CIRP Design Conference

Battery System Optimization Using Format Flexible Pouch Cells – Literature Review and Research Methodology

Philip Müller-Welt[a]*, Katharina Bause[a], Albert Albers[a]

[a]IPEK – Institute of Product Engineering, Karlsruhe Institute of Technology (KIT), Kaiserstr. 10, 76131 Karlsruhe, Germany
* Corresponding author. Tel.: +49-721-608-47254; fax: +49-721-608-45752. *E-mail address:* philip.mueller-welt@kit.edu

Abstract

The development of battery systems using pouch cells is a complex process due to the various system levels and domains to be considered as well as multiple design options such as cell to pack or cell to module designs. Among other things, a combined consideration of the electrical and thermal properties of the system is required in addition to the selection of suitable cells. Also, the packaging of the cells and modules in an existing installation space is a challenge that often represents a limiting factor in the performance of the battery system. Battery cells that can be produced in a flexible format offer potential for better use of existing installation spaces. However, these new degrees of freedom in the design of the battery system also represent an increased complexity and a larger solution space. To handle this complexity, new methods and tools are therefore required to support the developer. Therefore, this paper includes a literature review showing current approaches in battery system development and optimization with special focus on pouch cells. From this, the authors form the hypothesis that battery systems can be further optimized using pouch cells produced in a flexible format and according research questions. Finally, the paper describes a research methodology to answer these questions including the analysis of the state-of-art in battery system optimization, development of an optimization tool and case studies for evaluation of the approach.

Keywords: battery systems; cross-domain, modelling, optimization; methodology

1. Introduction

The change to electric drive systems in the mobility sector is an important aspect of reducing greenhouse gases. The use of battery systems as energy storage systems plays an important role in this context. Cell selection and packaging currently plays a significant role in the development of battery systems. The battery system often represents a performance-limiting component of the drive system, since only limited installation space is available for the battery system in the application. In addition, battery cells are usually produced in standardized formats (cylindrical, prismatic, pouch), with which sensible packaging must be carried out taking into account the temperature control system and interconnection concept [1]. Whereby according to [2], the trend in the automotive sector is toward the use of pouch cells und secondly prismatic cells.

A battery cell consists of multiple layers of anodes, cathodes and separators that are either coiled or stacked to a cell. A representation of a cell and its layers is given in Fig. 1.

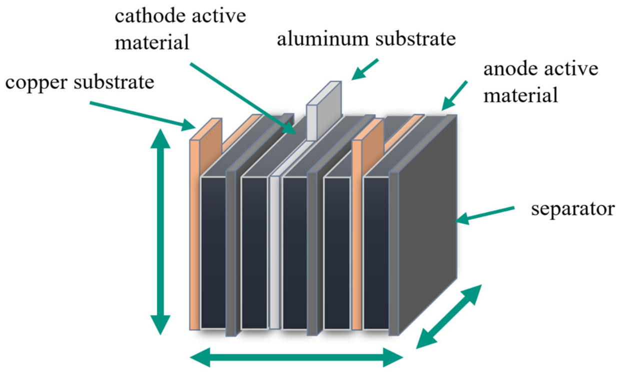

Fig. 1. Schematic representation of pouch cell layers

10.1016/j.procir.2023.02.181

For pouch cells the number of layers as well as their length and width can be defined. Especially the usage of pouch bags in contrast to casings makes the variable definition of these parameters and the production of the cells comparably easy.

To make ideal use of the installation space available for a battery system, it is advantageous to have a battery cell which, unlike standard formats, can be produced in variable sizes and shapes [3]. The flexibility in the format of the cell results in degrees of freedom and thus a large number of possible arrangements and interconnections of the cells.

Similarly, the flexibility gained by the cells results in a rising number of interactions and challenges in the holistic development of the battery system. For example, this creates challenges in the uniform discharge of the cells that can be caused by uneven sizes and therefore capacities and must be considered in the design process.

The development process of battery systems usually starts with the definition of requirements for the entire system such as the necessary voltage level and capacity. Based on these initial requirements the choice of a cell type and format and the necessary number of cells can be conducted. Subsequently the development of modules with multiple cells and then the battery pack can be conducted. [4]

While using cells of different formats within one battery system multiple challenges arise during the development process.

On the one hand, the available installation space must be utilized in the best possible way in order to increase both the energy content and the potential performance of the battery system. Cells of different formats offer potential, especially in complexly shaped installation spaces. In this context, technical feasibility must be considered on both the product and production sides, and a reasonable degree of flexibility must be found. In particular, the interaction of the cell and module shape with the potentially required temperature control system must already be taken into account during the design space optimization, as well as being integrated into the cross-domain optimization of the overall system. In addition, battery systems are nowadays important structural elements in vehicle stability

For the resulting possible cell arrangements, an electrothermal analysis of the system properties is also necessary. In addition, potential interconnection possibilities in different parallel and series connections of the cells can be considered. Furthermore, differences in the cell properties resulting from the different cell formats must be considered, resulting in restrictions in the interconnection options due to different state of charge and temperature developments.

The necessary parameterization of the electrical and thermal cell properties poses a challenge, since an experimental determination of the cell properties for the entire solution space of the potentially usable formats represents a large expenditure of resources. Scaling cell properties of one format to other formats is a potential solution for this.

Furthermore, this approach results in security aspects like unequal discharge and heat distribution that have to be taken into account and represent a potential limitation in the use of different cell formats.

In addition, manufacturing restrictions such as minimal and maximal dimensions of the cells or layer thicknesses and the resulting production costs must be considered as further constraints. Taking such a new and flexible production system of battery cells into consideration during the development process of battery systems can be seen as an aspect of a Product-Production-CoDesign approach [5].

Summarizing this approach of using pouch cells of flexible format within one battery system results on the one hand in multiple interactions and challenges that have to be considered but on the other hand also in new degrees of freedom and therefore potentials in the development of battery systems. To help the developer some sort of automated placement of battery cells and cross-domain evaluation of potential arrangements to optimize the battery system is required because of the increased solution space.

2. State of Research

The development process of battery systems consists of multiple steps. For example Cicconi et al. [6] are describing a process for thermal analysis and simulation of a Li-ion battery pack. The input of the process is an initial specification of the battery system, its operating conditions and the type and size of cells to be used. The process is divided in the main steps of electrical and thermal characterization of the cell properties, the definition of a geometrical layout and three-dimensional simulation of the cell and pack. The resulting geometrical layout and cooling parameters are finally implemented in a physical prototype and tested in an application.

The literature review for this paper focuses on optimization of battery systems with focus on simulation-based design and evaluation of the system. It is conducted in the main areas of interest of battery development: Battery modelling, combination of domains, model parameterization and optimization approaches. In addition, the considered system level as well as the degrees of freedom are investigated.

In terms of electrical modelling of batteries, common approaches are to use equivalent circuit models, mathematical models, or electrochemical structure models as described by Keil and Jossen [7]. The most widely used form is represented by electrical equivalent circuit models, which reproduce the physical behavior of a battery. These are described, among others, by Li et al. [8], Zhang et al. [9] und Meng et al. [10]. Mathematical models can bring advantages of fast parameterization. This is used, for example, by Schröder et al. [11] to quickly implement different battery types and configurations in a real-time test environment. Another common form of modelling are models describing the spatial variations of electrochemical fields in porous electrode microstructures, as described by Garcia et al. [12].

In terms of thermal modelling of batteries on cell level Pals and Newman [13] are presenting two models to predict the thermal behavior. Thermal models of cells are often used to evaluate different cooling systems. Examples are Chen et al. [14] or Kokkula et al. [15].

A combined FE based consideration of electrical and thermal aspects is a common approach for investigation of temperature and heat generation distributions within one cell.

For example Xie et al. [16] and Goutam et al. [17] are using this approach for a temperature distribution analysis in pouch cells and their tabs.

Especially regarding safety aspects FE based mechanical models of battery cells are often used. Lian et al. [18] are investigating the deformation behavior of pouch cells under in-plane loads. Also Kermani and Sahraei [19] are looking into dynamic impact behavior of pouch an elliptical cells. Another important safety aspect is the behavior of cells during a nail penetration where a combined consideration of electrical, thermal an mechanical aspects in one model is necessary as shown by Liu et al. [20].

To use battery models, they must be parameterized using measurement data from existing cells in order to obtain a model that is as close to reality as possible. Examples of parameterization possibilities of electrical models are shown among others by Miniguano et al. [21] and Lenz et al. [22], and for thermal models by Lin et al. [23].

Kim et al. [24] investigate the scalability of cell properties by electrothermal modeling and experimental validation using two different cell sizes. Al Hallaj et al. [25] are investigating temperature profiles on scaled cell models of cylindrical cells. In addition, Kim and Lee [26] are investigating the usage of a lumped cell model with equivalent resistances for the prediction of degradation of different cell sizes. Currently, the transferability of the scalability of cell properties to diverse formats still represents a need for investigation.

Electrical or thermal optimization often takes place at cell or module level. On cell level for example layer thicknesses can be optimized regarding electrical or thermal properties as shown by Xue et al. [27], Changhong and Lin [28], Campbell et al. [29] or Bonanno et al. [30]. On module level an optimization of the cell arrangement and thus flow characteristics of the cooling flow is often carried out under consideration of a cell format Karthik et al. [31], Li et al. [32] and Eisele et al. [33].

In the current state of research, some other approaches for the optimization of battery systems already exist. However, these are often limited to the pure consideration of only one system level consisting of battery system, module or cell. Furthermore, the different design domains of mechanics, thermics and electrics are often considered separately.

Kuchenbuch et al. [34], for example, present a method for the automated conceptual design of battery electric vehicles. The core of the method is the joint representation of the interactions between packaging of the modules of the battery system and vehicle characteristics such as axle load, seat comfort, and vehicle performance in a common mathematical model.

A mechanical consideration of the battery system is also mostly performed at the system level, where a topology optimization of the housing and support structure of the battery system is performed based on generated module arrangements in an existing installation space [35], [36]. In both cases, a consideration of format-flexible cells does not yet exist in the state of the art.

A combined use of different cell types in a battery system is considered by Becker [37], among others. In this context, battery systems can be composed of modules of different cell properties, which in combination can achieve improved electrical properties of a vehicle battery system. However, the available installation space and different cell formats are not considered in this context.

A holistic consideration of mechanical, thermal and electrical aspects as well as costs is carried out, for example, by Frank [38]. The battery system can be designed for a defined installation space for a defined cell format and type and then evaluated with regard to its electrical and thermal properties and costs. Finally, the system is optimized by means of an evolutionary algorithm.

Based on the literature review, some conclusions can be drawn. Among other things, there are already many modeling options for battery cells, each with advantages and disadvantages. They differ in their level of detail and the principle of modeling. In order to select the appropriate approach, for each individual application case an estimation of the required level of detail and resulting accuracy as well as the effort in parameterization has to be done. The use of lithium ion cells in battery systems represents the current state of the art. An exact modelling of the processes occurring within a cell is currently still a subject of research. Simplified models already provide sufficiently accurate results for most development activities. Simulative validation of cooling systems is an important aspect, especially in the early stages of a development process, since physical validation is a cost- and safety-critical option. Therefore, most module and overall system optimizations of overall dimensioning and exact design are carried out simulatively, which requires an accurate representation of the components and their interactions. A consideration of different cell formats represents an area that is hardly ever considered, since standard formats offer an advantage, especially with regard to costs, and these simplify the complex development process. The development process and design optimization of battery systems is difficult due to the complex relations among specifications (e.g., cost, safety, battery capacity, installation space) and design variables/parameters as well as the multiple domains that have to be considered. Therefore, accurate multi-level modeling of the optimization problem is quite challenging for both designer and engineers.

In summary regarding the current gap in research, there are diverse modeling options for battery cells from lumped parameters to detailed 3D models. Regarding battery system optimization, most approaches focus on one system level and on one or a combination of two domains, such as cell layout optimization to improve coolant flow using CFD simulations. A cross-domain consideration of the whole system is done in a few approaches. At the beginning there is always an initial selection of a cell format. Currently, there are no approaches that enable the use of the potential of format-flexible cells by considering new flexibility and restrictions in production. In this context, there are also no approaches that enable cross-domain consideration on several system levels. An application-specific integration of several target variables such as energy, power or costs is also rarely considered. In addition to the lack of approaches to the development of battery systems with format-flexible cells, there is also a lack of approaches to the scaling of cell properties, which are absolutely necessary for this. So that a clear research gap is seen here that promises a major scientific boost.

3. Aim of Research and Research Questions

Based on the state of research and identified research needs the research objective and research questions are derived.

The main research objective is the provision of a methodology that enables the development of an electrically, thermally, mechanically and cost-optimized battery system design from application-specific target variables using pouch cells produced in a flexible format. For this purpose, methods and tools are to be developed that enable a partially automated, cross-domain design of the battery system, considering possible degrees of freedom and restrictions in cell production.

The addressed research questions (RQ) are:

- RQ1: **Which domains** have to be **considered in which form** in the **modeling** of the overall battery system and which target variables can be integrated to enable an **overall optimization**?
- RQ2: How can the individual **models** be **linked** into an overall optimization, and in which **design parameters** is **flexibility** and optimization useful?
- RQ3: How can electrical and thermal cell **properties** be **scaled to other pouch cell formats**?
- RQ4: Can the application-specific defined **target values** be **improved by** using **format-flexibly produced pouch cells**?

4. Research Methodology

In order to achieve the objectives and to answer the research questions, the methodology is structured according to Design Support Development [39] by Marxen starting with an initial research clarification (RC). The development path of design support according to Marxen and its correlation to the research questions is shown in Fig. 2.

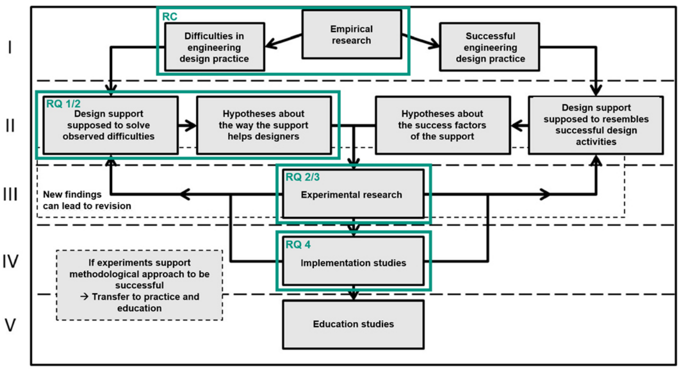

Fig. 2. Development path of design support [39]

According to Marxen the initialization (I) results from observation of real-world design processes and identification of difficulties in practice. This leads to development of support to reduce those difficulties (II). Afterwards the support needs to be evaluated initially in an experimental environment (III) and afterwards in actual implementation studies (IV).

The main parts of the methodology are shown in Fig. 3 and will be further explained in the following subchapters.

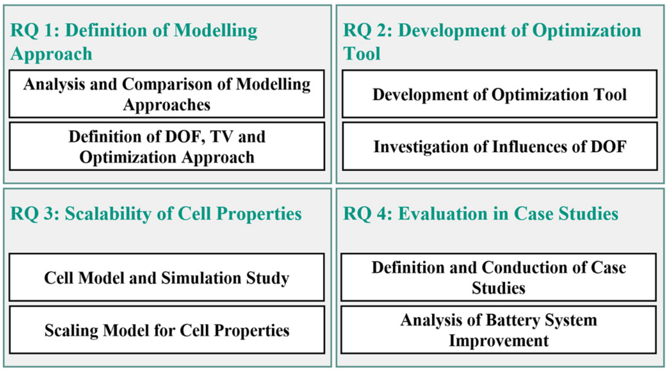

Fig. 3. Main parts of research methodology

It should be noted that the RQ are by no means addressed chronologically, but are answered in a partly parallel or even iterative process.

The usage of the methodology can be seen as part of the early phase of product generation engineering (PGE) [40]. The starting point for the usage of the approach is a reference system consisting of the installation space available in a reference product for the battery system as well as elements such as the cooling system or safety concept to be used. Also included are parts of the reference product such as its system voltage, a reference cell and its properties, and the manufacturing system of the format-flexible pouch cells including its restrictions. Based on this, different variants can be generated, by variation and iteration of design parameters or solution principles, from which an ideal solution can be selected. The selection is based on simple evaluation criteria. In further steps of the PGE, the configured battery systems can then be transferred into detailed virtual or physical models to further validate their functions.

4.1. Definition of Modelling Approach

After an in-depth literature review to iteratively sharpen the research objective regarding the needs, potentials and challenges in battery system development using format-flexibly produced pouch cells RQ1 addresses the overall modelling and optimization approach. After an analysis of available modelling approaches of battery systems in different domains a comparison of these approaches is conducted. Special focus is lying on level of detail and resulting modelling effort as well as the combinability of the different domains such as an electrical, thermal, mechanical and cost model.

Additionally, potential degrees of freedom (DOF) on cell, module and system level as cell dimensions, number of cells per module are defined that can be used to optimize the battery system. Also target values like the battery systems capacity and power or cost that can be used for the optimization will be identified and a suitable optimization approach will be determined.

4.2. Development of Optimization Tool

RQ2 deals with the development of a design method and corresponding tool for the holistic and partially automated optimization of the battery system. This tool allows the definition of an installation space that is available in a specific application case for a partially automated optimization of arrangements of cells and modules of the battery system based on defined requirements and restrictions. In addition, a consideration of the various domains like electrical and thermal characteristics or cost of the battery system will be included. To achieve a fast characterization of the system properties results from RQ3, to be exact the scaling approaches of cell properties to different formats, will be included into the optimization tool.

To identify in which degrees of freedom an optimization results in improved characteristics of the battery system the influences of individual degrees of freedom, such as cell format or cell thickness, on the properties of the battery system will first be determined by means of a simulative sensitivity analysis. These results will be used to define which degree of flexibility in which part of the battery system is useful.

4.3. Scalability of Cell Properties

RQ3 is dedicated to the scaling of cell properties. Based on literature research, possibilities for deriving regression models of the respective cell properties for scaling between different formats will be evaluated. Characteristics of the individual cells are required to characterize the battery system. When using different cells, this is associated with an increased effort. Characterization of the various possible cell formats via physical tests is not possible in the targeted solution space. For this reason, a cell model is to be constructed, which must be parameterized once and can then be used to determine cell properties for other formats. With the help of this model, correlations between the defined degrees of freedom such as cell length, width or thickness and the respective cell properties such as capacity or internal resistance are then determined. These will ultimately be used to enable rapid determination of the properties of the entire battery system without further experimental effort.

4.4. Evaluation in Case Studies

Finally, to answer RQ4 the developed approach is to be evaluated in different case studies. For this purpose, exemplary application cases with reference products are defined. For each application case the available installation space for the battery system as well initial requirements like the system voltage level and boundary conditions like the according cooling concept are defined. Based on these initial inputs an optimized battery system with pouch cells of different formats is derived using the optimization tool. To evaluate the benefit of these cells as well as the developed approach the characteristics of the new battery system like the capacity are compared to characteristics of the reference product with standardized cells.

The described aspects of the overall methodology show different interdependencies. For example, an estimation and comparison of the selected modeling approach with respect to effort and accuracy but also the combinability of the different domains is necessary to derive a scaling method of the cell properties. Likewise, the limits of the scalability of the cell properties have to be considered when choosing the modeling approach. Under aspects such as these, a sufficient representation of the diverse interactions of the subsystems must additionally be made possible in order to ultimately enable an optimization of the overall system.

The presented methodology offers a possibility for generation and evaluation of battery system configurations. The focus lies on simple parameterization and a quick comparison of different configurations based on a few criteria, such as capacity and performance as well as costs of the battery system. Part of the methodology is therefore a geometric representation of the format-flexible cells and modules in an installation space, considering the cooling concept. Various degrees of freedom are used for optimization, which opens up a previously unavailable large solution space. On the other hand, electrical and thermal properties of the system are considered with lumped models, which does not allow a detailed consideration of the local load distribution. The cell formats considered are limited to certain formats in order to ensure feasibility in terms of production technology and also to enable simple estimation of the cell properties. Basic properties are used to evaluate the battery system in order to enable a quick assessment of the generated configurations and an initial comparison with an existing system with standard formats. A more detailed modelling and evaluation in further development steps is still required afterwards.

5. Conclusion

In summary the literature review shows that currently there are some approaches for an overall optimization of battery systems. Nonetheless most optimization approaches are focusing on either single system levels or are not including multiple domains during modelling of the battery system. Also, the potential of cells of flexible format is currently not investigated and supported by a methodology. Therefore, the developer needs new methods and tools to master the complexity and large solution space during optimization and design of a battery system using format flexible pouch cells. The described research methodology intends to make the potential benefit of format flexible pouch cells in battery systems usable by identifying degrees of freedom and developing a tool for optimization. In further research the benefits of this approach will be evaluated by case studies in different application fields.

Acknowledgements

This work was funded by the Baden-Württemberg Ministry of Science, Research and the Arts within the project “AgiloBat” as part of the Innovation Campus Mobility of the Future.

References

[1] Tschöke, H., Editor, 2015. Die Elektrifizierung des Antriebsstrangs. Springer Fachmedien Wiesbaden.
[2] Hettesheimer, T., Wietschel, M., Neef, C., 2021. Batteriestandort auf Klimakurs: Perspektiven einer klimaneutralen Batterieproduktion für Elektromobilität in Deutschland.
[3] Ruhland, J., Storz, T., Kößler, F., Ebel, A. et al., 2022. Development of a Parallel Product-Production Co-design for an Agile Battery Cell Production System, in Towards Sustainable Customization: Bridging Smart Products and Manufacturing Systems, Springer International Publishing, Cham, p. 96.
[4] Lensch-Franzen, C., Gohl, M., Schmalz, M., Doguer, T. Von der Zelle zum Batteriesystem - Verschiedene Zellformate und ihre Systemintegration, p. 70.
[5] Albers, A., Lanza, G., Klippert, M., Schäfer, L., Frey, A., Hellweg, F., Müller-Welt, P., Schöck, M., Krahe, C., Nowoseltschenko, K., Rapp, S., Editors, 2022. Product-Production-CoDesign: An Approach on Integrated Product and Production Engineering Across Generations and Life Cycles. Procedia 32nd CIRP Design Conference.
[6] Cicconi, P., Landi, D., Germani, M. Thermal analysis and simulation of a Li-ion battery pack for a lightweight commercial EV, p. 159.
[7] Keil, P., Jossen, A. Aufbau und Parametrierung von Batteriemodellen.
[8] Li, S., Ke, B. Study of battery modeling using mathematical and circuit oriented approaches, p. 1.
[9] Zhang, C., Li, K., Mcloone, S., Yang, Z. Battery modelling methods for electric vehicles - A review, p. 2673.
[10] Meng, J., Luo, G., Ricco, M., Swierczynski, M. et al. Overview of Lithium-Ion Battery Modeling Methods for State-of-Charge Estimation in Electrical Vehicles, p. 659.
[11] Schroeder, T., Gwosch, T., Matthiesen, S., 2020. Comparison of Parameterization Methods for Real-Time Battery Simulation Used in Mechatronic Powertrain Test Benches 8, p. 87517.
[12] García, R.E., Chiang, Y.-M., Craig Carter, W., Limthongkul, P. et al. Microstructural Modeling and Design of Rechargeable Lithium-Ion Batteries, A255.
[13] Pals, C.R., Newman, J. Thermal Modeling of the Lithium/Polymer Battery: I Discharge Behavior of a Single Cell, p. 3274.
[14] Chen, D., Jiang, J., Kim, G.-H., Yang, C. et al. Comparison of different cooling methods for lithium ion battery cells, p. 846.
[15] Kokkula, M., Chakraborty, C., Roy, S., Dinda, S. et al. Parametric investigation to optimize the thermal management of pouch type lithium-ion batteries with mini-channel cold plates, p. 120568.
[16] Xie, Y., He, X., Li, W., Zhang, Y. et al. A novel electro‐thermal coupled model of lithium‐ion pouch battery covering heat generation distribution and tab thermal behaviours, p. 11725.
[17] Goutam, S., Nikolian, A., Jaguemont, J., Smekens, J. et al. Three-dimensional electro-thermal model of li-ion pouch cell: Analysis and comparison of cell design factors and model assumptions, p. 796.
[18] Lian, J., Koch, M., Li, W., Wierzbicki, T. et al. Mechanical Deformation of Lithium-Ion Pouch Cells under in-plane Loads—Part II: Computational Modeling, p. 90556.
[19] Golriz, K., Elham, S. Dynamic impact response of lithium-ion batteries, constitutive properties and failure model, p. 2464.
[20] Liu, B., Yin, S., Xu, J. Integrated computation model of lithium-ion battery subject to nail penetration, p. 278.
[21] Miniguano, H., Raga, C., Barrado, A., Lazaro, A. et al. A comparative study and parameterization of electrical battery models applied to hybrid electric vehicles, p. 1.
[22] Lenz, M., Jöst, D., Thiel, F., Pischinger, S. et al. Identification of load dependent cell voltage model parameters from sparse input data using the Mixed Integer Distributed Ant Colony Optimization solver, p. 226880.
[23] Lin, X., Perez, H.E., Mohan, S., Siegel, J.B. et al. A lumped-parameter electro-thermal model for cylindrical batteries, p. 1.
[24] Kim, U.S., Shin, C.B., Kim, C.-S. Modeling for the scale-up of a lithium-ion polymer battery, p. 841.
[25] Al Hallaj, S., Maleki, H., Hong, J.S., Selman, J.R. Thermal modeling and design considerations of lithium-ion batteries, p. 1.
[26] Kim, H.-K., Lee, K.-J. Scale-Up of Physics-Based Models for Predicting Degradation of Large Lithium Ion Batteries, p. 8544.
[27] Xue, N., Du, W., Greszler, T.A., Shyy, W. et al. Design of a lithium-ion battery pack for PHEV using a hybrid optimization method, p. 591.
[28] Changhong, L., Lin, L. Optimal Design of Li-Ion Batteries through Multi-Physics Modeling and Multi-Objective Optimization, E3254-E3264.
[29] Campbell, I.D., Gopalakrishnan, K., Marinescu, M., Torchio, M. et al. Optimising lithium-ion cell design for plug-in hybrid and battery electric vehicles, p. 228.
[30] Bonanno, F., Capizzi, G., Coco, S., Laudani, A. et al. A coupled design optimization methodology for Li-ion batteries in electric vehicle applications based on FEM and neural networks, p. 146.
[31] Karthik, A., Kalita, P., Garg, A., Gao, L. et al. A Novel MOGA approach for power saving strategy and optimization of maximum temperature and maximum pressure for liquid cooling type battery thermal management system, p. 80.
[32] Li, Y., Zhou, Z., Wu, W.-T. Three-dimensional thermal modeling of Li-ion battery cell and 50 V Li-ion battery pack cooled by mini-channel cold plate, p. 829.
[33] Eisele, M., Werner, D., Ott, S., 2018. Evaluation of a validation process for a battery cooling system: direct cooling of cylindrical battery cells, in International Electric Vehicle Symposium & Exhibition.
[34] Kuchenbuch, K., Vietor, T., Stieg, J., 2011. Optimierungsalgorithmen für den Entwurf von Elektrofahrzeugen 113, p. 548.
[35] Albers, A., Wagner, D., Hammami, W., Spadinger, M., Höfler, T., Editors, 2014. INTEGRATION OF DESIGN METHODS FOR THE DEVELOPMENT OF ELECTRIC ENERGY STORAGE SYSTEMS: Proceedings of DESIGN 2014.
[36] Wagner, D., 2015. Methodengestützte Entwicklung eines elektrischen Energiespeichers zur Erschließung von Leichtbaupotenzialen als Beitrag zur Produktgenerationsentwicklung, Karlsruhe.
[37] Becker, J.N., 2017. Flexible Dimensionierung und Optimierung hybrider Lithium-Ionenbatteriespeichersysteme mit verschiedenen Auslegungszielen, Aachen.
[38] Frank, F., 2018. Optimierter Hochvoltbatterieentwurf hinsichtlich mechanischer, thermischer und elektrischer Randbedingungen unter Berücksichtigung der Produktionskosten, Duisburg.
[39] Marxen, L., 2014. A Framework for Design Support Development based on the integrated Product Engineering Model iPeM. Dissertation, in Forschungsberichte des IPEK ‐ Institut für Produktentwicklung. ISSN: 1615-8113, Karlsruhe.
[40] Albers, A., Rapp, S., Birk, C., Bursac, N., 2017. Die Frühe Phase der PGE – Produktgenerationsentwicklung, in Stuttgarter Symposium für Produktentwicklung SSP 2017, Fraunhofer-Institut für Arbeitswirtschaft und Organisation IAO, Stuttgart, o. S.