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Finding the ideal automotive battery concept

A model-based approach on cell selection, modularization and thermal management

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Abstract
There are many degrees of freedom in the design of a battery concept for electric vehicles. A suitable lithium-ion battery (LIB) must be selected from different cell chemistries, types and sizes. During operation, the LIBs must always be kept in the optimum temperature range, thus a suitable battery thermal management system (BTMS) architecture must be developed. All these decisions have a direct impact on the later characteristics of the battery system and are subject to complex interactions. Therefore, the question arises of an automated method that supports the user in finding the ideal overall battery concept for a given vehicle concept. This paper introduces and discusses such a process. After an analysis of all relevant electrical and thermal influences and previous work on this topic, an approach is derived that allows automatic cell selection, modularization and BTMS development considering all relevant influences up to the vehicle level. The approach considers the electrical and thermal behavior on both the cell and the system level. Furthermore, the BTMS is simulated using a novel approach allowing the configuration of air and liquid cooling with any desired configuration. The complete simulation framework is made available under an open-source license.

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Auf der Suche nach dem optimalen Batteriekonzept für Elektrofahrzeuge

Ein modell-basierter Ansatz zur Zellauswahl, Modularisierung und Thermomanagement eines Batteriesystems

Zusammenfassung

Bei der Entwicklung eines Batteriekonzepts für Elektrofahrzeuge gibt es viele Freiheitsgrade. Eine geeignete Lithium-Ionen-Batterie (LIB) muss aus verschiedenen Zellchemien, -typen und -größen ausgewählt werden. Während des Betriebs müssen die LIBs immer in ihrem optimalen Temperaturbereich gehalten werden, wofür eine geeignete BTMS-Architektur (Batterie-Thermomanagementsystem) notwendig ist. Alle diese Entscheidungen haben einen direkten Einfluss auf die späteren Eigenschaften des Batteriesystems und unterliegen komplexen Wechselwirkungen. Es stellt sich daher die Frage nach einem automatisierten Verfahren, das den Anwender dabei unterstützt, das ideale Gesamtbatteriekonzept für ein bestimmtes Fahrzeugkonzept zu finden. In diesem Paper wird eine solche Herangehensweise vorgestellt und diskutiert. Nach der Analyse aller relevanten elektrischen und thermischen Einflüsse und vorangegangener Arbeiten wird ein Ansatz abgeleitet, der eine automatische Zellauswahl, Modularisierung und BTMS-Entwicklung unter Berücksichtigung aller relevanten Einflüsse bis auf Fahrzeugebene ermöglicht. Der Ansatz berücksichtigt das elektrische und thermische Verhalten sowohl auf der Zell- als auch auf der Systemebene. Darüber hinaus wird das BTMS mit einem neuartigen Ansatz simuliert, der die Konfiguration der Luft- und Flüssigkeitskühlung mit beliebiger Konfiguration ermöglicht. Die komplette Simulationsumgebung wird unter einer Open-Source-Lizenz zur Verfügung gestellt.

Abbreviations

BEV	Battery electric vehicle
BTMS	Battery thermal management system
CCCV	Constant current constant voltage
CFD	Computational fluid dynamics
ECM	Equivalent circuit model
LIB	Lithium-ion battery
PCM	Phase change material
SEI	Solid electrolyte interphase
SOC	State-of-charge

1 Introduction and Scope of the Paper

As battery electric vehicles (BEVs) aim for higher ranges and shorter charging times, the demands on automotive lithium-ion battery (LIB) systems are rising. The need for higher electrical capacities requires the utilization of larger cell sizes or a high number of parallel interconnected cells. The demand for fast-charging leads to higher continuous currents, thus resulting in increased electrical and thermal strain and requiring efficient thermal management [1]. At the same time, the battery system concepts must meet stringent package restrictions, as well as high safety and reliability standards and—as one of the key factors influencing safety and cost of BEVs—have to be designed in a target-oriented, efficient and modular manner.

Due to the broad range of possible solutions, which include e.g. various cell types, sizes and chemistries, electrical interconnection, battery thermal management system (BTMS) architectures and frequently contradictory demands on the different system levels, the development of an automotive battery system concept is a nontrivial task. To obtain an expedient design, it is necessary to consider all relevant electrical and thermal effects [57]. At the same time, however, the design process should allow for a rapid response to innovations like new cell or BTMS technologies, thus not relying upon iterations of existing concepts.

In order to meet these demands, this paper proposes a novel, model-based approach for the holistic concept development of automotive battery systems. Using an iterative approach, various available LIB types are selected, electrically interconnected, modularized, arranged geometrically and complemented by a suitable BTMS concept. The battery system concept is created and verified, depending on range, peak and continuous power demands as well as geometric and weight constraints of the overall vehicle concept. Due to the fully parametric modelling and simulation approach on every system level, the method allows application without necessarily incorporating an existing system design.

The goal of the paper is to investigate whether an overall battery system concept development process is feasible and all influences and interactions between the different system levels can be represented reliably and with reasonable implementation and computational effort. Based on the fully modular implementation, the framework can easily be extended and the level of detail of subsystems considered as particularly relevant can be increased. Due to the open-source release of the framework (Sect. 4.7), the complete source-code and the full parameterization are open to the public to review and to improve. Furthermore, all results presented in this paper can be easily reproduced for further discussion.

The paper is structured into six parts. Following a summary of the theoretical background, the current state of the art of automotive battery concept development is presented and the research gap targeted by this study is identified. Afterwards the proposed design process is explained. The aptitude of the process is evaluated and possible limitations and the integration into the overall automotive battery development process are discussed. Finally, an outlook regarding possible future work and improvements is provided.

2 Automotive Battery Systems

LIBs show a distinctive dynamic behavior in the electrical and thermal domain. The knowledge of these effects and their impact on short- and long-term battery behavior is fundamental for ensuring optimal operation of a battery system throughout its whole service life [6]. This section summarizes the theoretical backgrounds of LIB cells and battery systems. Details about the implementation are provided in Sect. 4.

2.1 Lithium-Ion Batteries

LIBs are available in a multitude of cell chemistries, sizes and shapes, the most common of the latter being cylindrical, prismatic and pouch type. During electric load LIBs show a distinctive dynamic voltage response [23]. A popular way to describe dynamic cell behavior is via equivalent circuit models (ECMs), where the dynamics are described by an electrical circuitry of capacities and resistors [42].

In addition to the electrical aspect, LIBs also show a thermal response, comprising reversible and irreversible heat generation [9]. Due to their inner structure of electrode layers LIBs exhibit different heat transport alongside or perpendicular to the electrode layers [58]. This, together with the heat transfer coefficient and distance to the environment which is dependent on the cell size and format [48], influences the heat dissipation from the cell. As an additional complication a cell's heat capacity is not static but rather depends on temperature and state-of-charge (SOC) [30]. As a result, in order to reduce modeling and testing effort, LIBs are commonly regarded as lumped thermal masses possessing a constant heat capacity. This is especially valid for considerations at the system level in the early concept phase [61]. This assumption is applicable if the Biot criterion

$$\mathrm{Bi} = \frac{\alpha_{\mathrm{th}} L}{\lambda_{\perp,\mathrm{cell}}} < 1 \tag{1}$$

is met. In this equation, α_{th} describes the heat transfer coefficient between cell and environment, L is the maximum distance from center to the surface of the cell and $\lambda_{\perp,\mathrm{cell}}$ is the minimum heat conductivity, perpendicular to the electrode layers inside the cell.

On a long-term basis LIBs show varying effects of degradation [6]. Given the time-consuming nature of modelling cell-specific aging [31, 52], this study mainly focuses on compliance with the safe operating conditions that are specified. For safe operation the electrothermal and aging properties of LIBs must be understood thoroughly. Since every cell type, cell chemistry and cell size features different electrical and thermal parameters, the basic properties, namely both the ECM parameters and the thermal properties must be obtained for every cell model being considered for the battery system.

2.2 Electrical Properties of Battery Systems

At a system level, individual LIBs are interconnected in series and parallel. One crucial question—in addition to the cell type to be used—is whether the required battery system capacity will be provided by a few big cells or many small cells connected in parallel.

The selection of the cell type and size will influence the electrical and thermal behavior of the battery system. Relevant effects include the influence of contact resistance [36] and, more challenging, compensating currents in parallel connections [5]. In addition to production fluctuations, compensating currents occur due to non-uniform aging induced by temperature gradients inside the battery system. The compensation effects lead to uneven current distribution and SOCs in the parallel connections and induce further divergences in capacity and the resistance of the individual cells [3]. Therefore, the full capacity potentially resulting from the voltage range of the LIBs cannot be used since doing so might cause overloading or deep discharging and potentially irreversible damage to individual cells [43].

These phenomena imply that the effects inside parallel connections must be considered for a detailed prognosis of battery system behavior [51, 7]. Therefore, the approach presented in this paper utilizes a detailed simulation of the electrical interconnection inside the battery system.

2.3 Thermal Properties of Battery Systems

LIBs must always be operated within safe temperature limits. To assure these demands in extreme ambient temperatures or high-power scenarios, a BTMS is needed [41] for cooling or heating the battery as required [21]. Both the absolute temperatures within the system and the limitation of temperature gradients are important for preventing non-uniform aging [40].

While thermal management may be achieved by natural convection alone, this approach generally is not deemed potent enough for high power applications [25]. Therefore,

this paper focuses on forced convection BTMSs also used in many production vehicles [38]. Furthermore, since fast-charging is the primary stress factor being considered within the scope of this paper, we will focus on the cooling of the battery system.

The performance of BTMSs is influenced by the choice and mass flow of the fluid as well as the type, number and placement of the heat sinks [25, 50]. Common choices for fluids are air, coolant or refrigerant. Also, substances like PCMs have been investigated [20]. Although several studies suggest phase change materials (PCMs) as promising for use in BTMSs [28, 37], they will not be further regarded at this point, because they are only suitable for buffering temperature spikes and not for removing continuous waste heat out of the battery while it is being generated during fast-charging.

The first fluid to be considered is air. Air can be in direct contact with the cells [20, 55] which allows systems of low complexity. However, the low thermal capacity [20] of air necessitates high volume flow [29], so it is considered unsuitable for a high continuous load [20, 24]. Liquid coolants or refrigerants, which have a higher thermal capacity [20], allow for a higher cooling potential [55]. They enable lower flow rates, thus resulting in lower energy consumption and noise. On the downside, they also lead to higher system complexity since they must be sealed against the cells if an electrically conductive or corrosive medium is used [55].

The thermal connection of the cells to the BTMS depends on the type of the cell. Cylindrical cells can be directly cooled. When liquid cooling is used, the cells are often surrounded by thin sealing cylinders [55]. Another possibility for the liquid cooling of cylindrical LIBs are flexible channels between the cells [17]. The direct cooling approach is usually not chosen for prismatic or pouch cells. In this case, plates inside [60] or on the exterior of the modules [35] are used, which either comprise cooling channels [24], or serve as fins for heat transport out of the module [22, 55].

The approach presented can simulate both air- and liquid-based BTMSs. Due to the mutual influence of electrical and thermal properties both aspects must be considered simultaneously [54]. This is achieved by a joint simulation of electrical and thermal system behavior, which is presented in Sect. 4.

2.4 Aging Properties of Battery Systems

The aging of a LIB can be characterized as the change of its electrical and thermal properties over its lifetime. The underlying processes occur in a complex non-linear manner, especially in automotive usage with a highly dynamic electrical and thermal load profile [47]. Even though different cell chemistries induce different aging mechanisms, the stress factors on aging are closely comparable [16]. To decrease aging, LIBs are ideally operated within specific temperature [55] and SOC windows [43]. The main aging effects are the increase of the ohmic resistance and the loss of active lithium, hence capacity decrease, which can be caused by the growth of the solid electrolyte interphase (SEI) layer, lithium plating and decomposition processes [53].

State of the art findings have extensively shown the influence of the electrothermal and mechanical load as well as calendar time on the aging behavior [45, 8]. The electrothermic and mechanical strain can be minimized in the vehicle design phase, whereas the former can also be controlled during operation by the BTMS.

Recent investigations have further revealed the negative effect of current and temperature gradients on LIB degradation on the cell and the system level. On cell level, thermal gradients generally increase with cell size [12, 27]. Due to the higher distance to the case and the higher energy conversion, the dissipation is lower. The thermal gradients directly influence the electrical gradient due to the temperature dependency of the electrolyte conductivity. Electrical gradients can be directly generated through the cell format, e.g. in pouch cells where the current between the connection taps is higher [2]. On system level the gradients are influenced by the arrangement of the cells and the BTMS.

3 Automotive Battery Concept Development

Several proposals for automotive battery concept development or specific aspects thereof have been presented in the literature. This section provides an overview and identifies the research gap that this study aims to address.

3.1 State of the Art

Ever since Pesaran [41] introduced a universal approach for the thermal design of automotive battery systems these principles have been developed further and connected with the electrical aspects of battery system concepts. Gross et al. [15] focused on the thermally induced degradation of battery systems and the impact of different load profiles. As a result, they arrived at the need for a capable BTMS solution. However, they did not consider electrical and thermal system architecture. Fleckenstein et al. [12] further focused on the impact of thermal gradients on cell degradation and the simulation thereof, also without an emphasis on the system level.

Paul et al. [39] extended this view to the system level and carried out lifetime prediction based on the probability of failure of individual LIBs. They used a joint ap-

proach including electrical, thermal and aging simulation while taking parameter spread between individual cells into consideration. Nevertheless, they did not emphasize cell selection and BTMS architectures. Karimi et al. [24] thoroughly analyzed the thermal properties of a battery system using various BTMS configurations and coolants while giving only basic consideration to the electrical side. Similar studies were carried out by Nieto et al. [35] in developing and validating a methodology for thermal management design using detailed models for heat generation, transmission and dissipation, and Hosseinzadeh et al. [19] focusing on pouch cells, again with only a basic contemplation of the electrical side. All studies used a previously fixed overall battery concept, so no dynamic adaption and enhancement of the battery concept based on the simulation results was intended.

An overall approach for the electrical and thermal concept development of battery systems was presented by Zhou [61]. Using a simulation framework depicting the various system levels, overall battery system design can be conducted throughout the different development steps. All relevant cell types and different BTMS architectures can be examined. A similar approach was presented by Xia et al. [55] using a detailed multi-physics-based simulation with a focus on cylindrical cells. However, this and comparable works rely on experience from previous iterations of a battery system, which impedes adaptability to new vehicle concepts, requirements and LIB technologies.

An exception is the holistic method to find the optimal cell size presented by Kerler [26]. The method is adaptable to new vehicle requirements while taking thermal gradients, electrical efficiency, safety and costs of cylindrical and pouch cells into consideration. Again, the focus lies on cell level. Only the electrical efficiency model considers the systems level and only certain predefined cooling topologies can be chosen for the thermal simulation.

3.2 Research Gap

The review of literature in the previous subsection shows the substantial progress which has already been made for the electrical and thermal concept development of automotive battery systems. However, significant limitations do remain.

Most studies focus on partial aspects of the overall concept development process and specialize in certain system levels like the cell level or the electrical or thermal domain. This specialization enables those studies to conduct detailed investigations using simulation models tailored to the respective subject of consideration. While this procedure provides detailed insights into the individual facets, the interactions with other system levels are often not considered. Furthermore, because those approaches rely on detailed system parameters obtained by extensive testing mostly an—at least in parts—already finished battery concept is necessary which excludes the use for fundamental concept development.

Consequently, it can be ascertained that there is currently no conclusive process that incorporates all basic steps of automotive battery concept development. Since the decision of the concept should be reached independently of previous system iterations, the approach must not rely on extensive and long-term test data from physical battery systems. Therefore, simplified simulation models of the underlying system levels are needed. The models must be efficient in parameterization and computation and at the same time offer enough accuracy to find a reliable system concept.

4 Concept Development Process

In this section, the battery system concept development process is presented and explained. First, a summary of the overall process is given. The individual steps of the approach are explained thereafter and illustrated by examples and simulation results. The entire simulation model is freely accessible (Sect. 4.7), allowing other researchers to easily reproduce the results of this paper.

4.1 Overview

The design process follows the basic steps of cell selection, electrical interconnection, modularization, geometric arrangement, and BTMS development. After each step the feasibility of the design in its current level of detail is tested. An overview of the design process is given in Fig. 1. The implementation of the algorithm follows a modular approach, offering the option of reusing or further detailing individual sub-units.

To minimize the danger of overlooking promising configurations, a full-factorial approach is chosen when computation time allows it. The solution space is reduced after each step because the stringency of the requirements the concept must meet increase. This allows further detailing of the simulation leading to higher accuracy and reliability of the system concept.

Typically, for a given cell type and battery system capacity with the additional degrees of freedom from modularization and geometric alignment (Sect. 4.2), over 1000 possibilities for the electrical and geometric configuration must be considered. After the most suitable combinations have been selected, the BTMS concept is developed by gradually increasing the number of cooling channels until the thermal requirements are met. When using the chosen fast-charging load cycle as input for the battery system, the

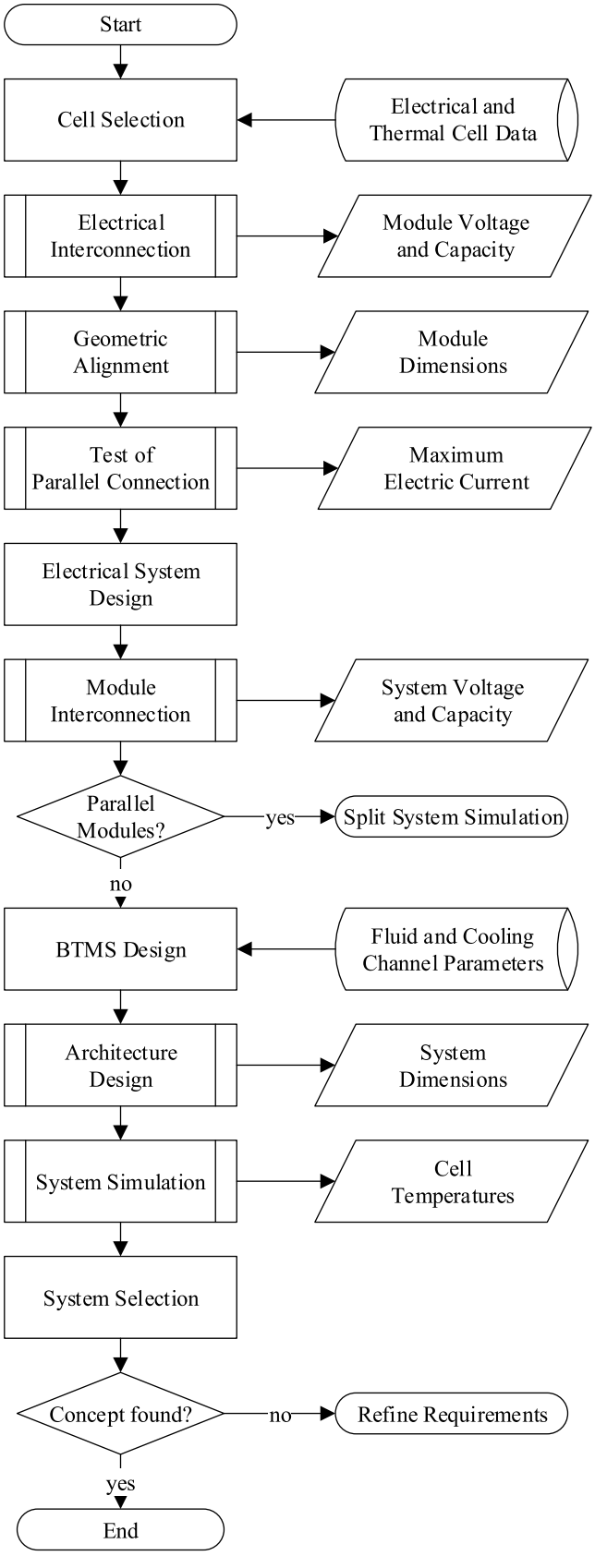

Fig. 1 Sequence and sub-models of the battery system design algorithm

complete configuration process takes around twelve hours on a standard desktop workstation.

4.2 Cell Selection and Battery System Configuration

The first step consists of the selection of feasible cell types. LIBs are electrically interconnected in serial and in parallel at the module level. Every module consists of p parallel and s serial cells. To comply with package restrictions, this step must contain information about the geometric arrangement of the cells. Therefore, the LIBs are arranged in e stacked layers, consisting of pe parallel cells each. This leads to a total count of

$$p = e \ \ pe \tag{2}$$

parallel cells per module. Since the dimensions of the cells are known, the approximate overall length, width and height of the modules can be calculated.

For every cell type considered, a full factorial investigation of e-pe-s combinations is carried out as long as the specifications

- min. capacity (Ah)
- min. charging current (A)
- min. discharging current (A)
- max. voltage (V)
- max. mass (kg)
- min. energy (kWh)
- max. length (m)
- max. width (m)
- max. height (m)

are met. By default, only even numbers for s serially connected cells are considered to decrease the solution space. Combinations fulfilling all specifications are selected for further consideration, as shown in Fig. 2.

In the next step, the modules are electrically interconnected at the battery pack level. Again, only an even number of modules can be connected and only a serial interconnection is supported. If a solution of only serially interconnected modules is not feasible, the battery system must be split into two or more equal parts that are later connected in parallel. These measures lead to a further reduction of the solution space and faster computation of the algorithm. Analogous to the consideration at the module level, the resulting battery systems are reviewed based on electric and geometric criteria.

The battery system is assumed to be rectangular for reason of maximum battery volume and the flexibility this shape offers in vehicle concepts [33]. If other battery shapes are required, the volume has to be approximated with a rectangular shape. Package restrictions on the modules resulting from the shape of the battery system must then be consid-

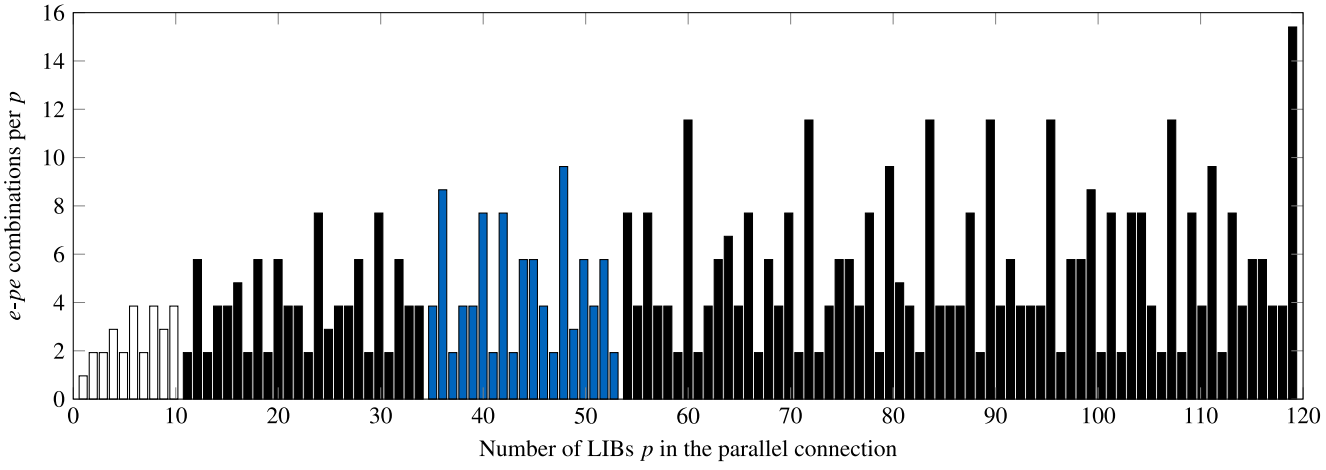

Fig. 2 Selection of feasible e-pe-s cell interconnections (*Black:* All requirements fulfilled. *Blue:* Selected interconnection that fulfill requirements without overdimensioning of one or more criteria. *White:* Minimum current requirement not fulfilled.)

ered in the geometrical restrictions on the module level. All criteria up to this step are part of either the cells' datasheet or part of the system specifications, so no simulation is needed up to this point, allowing the consideration of a still high amount of possible variants.

4.3 Consideration of LIB Parameter Variations

As mentioned in Sect. 2.2, fluctuations in the electric parameters occur between individual LIBs, leading to compensating currents in parallel connections. To ensure no cells are overloaded in the parallel connection, a simulation for maximum current load and different SOCs, under consideration of the statistical deviations of the cell properties, must be carried out. The electrical battery system model used to simulate the electric current distribution inside the battery system is described in detail in [44] and was used for a similar purpose in [43].

The deviations between the LIBs are normally distributed [3]. Therefore, in this step of the concept development process, every electrical LIB parameter subject to deviations is randomly altered according to its statistically anticipated value and its standard deviation. To ensure that no cell interconnection is sorted out because a particularly unfavorable parameter combination was randomly selected, it is expedient to apply an exemplary or worst-case deviation. To maintain comparability between the individual interconnections one deviation is computed and applied to all interconnections of one cell type. For other cell types the deviation is scaled based on the LIBs' different standard deviations.

This allows an initial estimation of the electrical spread of a cell-type interconnection combination. It is recommended that a more in-depth Monte-Carlo analysis of the parallel circuit behavior be carried out during the final concept selection. At this later stage the solution space is small enough to allow this computationally expensive step.

4.4 Thermal Management Design

The design of the BTMS requires a simulation model capable of depicting the thermal effects inside the battery system. As mentioned in Sect. 2.3, the electrical and thermal LIB behavior are tightly interconnected, so the battery system model offers a joint simulation of both aspects. The thermal model supports time-discrete simulation of heat generation as well as heat conduction between the cells [44]. The latter is needed because not all cells may be in direct contact with the BTMS, which results in heat flux across several cells into the coolant.

Since the thermal simulation must be carried out on the battery system level and realistic BEV driving cycles over longer periods of time are considered, stringent demands on the computational efficiency must be met. Additionally, in order to incorporate the different LIB cell types and thermal management strategies into the same code-base, several idealized assumptions regarding the thermal modelling on cell and system level are mandatory. These prevailing circumstances limit the possible depth of the simulation. Since this subsection focuses on the implementation, the necessary simplifications and their implications are summarized and discussed in Sect. 5.1.

To determine the heat transfer from the cells to the cooling system the architecture and fluid parameters of the BTMS must be known. This is achieved by an iterative symmetric placement of cooling channels in the spatial directions length and width. An example containing all possible cooling methods is shown in Fig. 3 for a battery concept using cylindrical cells. For the cylindrical type either cooling of the sheath area by means of cooling channels placed

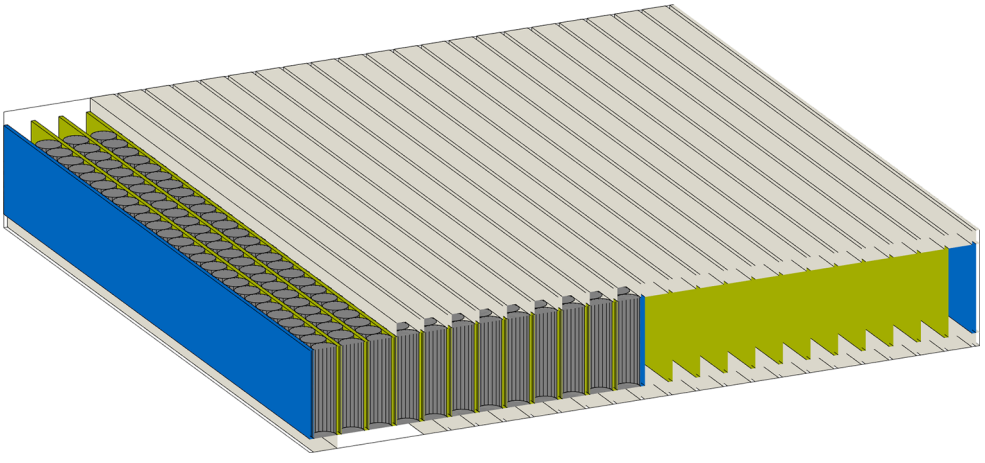

Fig. 3 BTMS concept for a battery concept consisting of cylindrical cells with all possible cooling solutions (*dark grey:* cylindrical cells, *blue:* cooling channel at the outside of modules, *green:* cooling channels inside of the module, *light gray:* axial cooling). All cooling channels can be configured for liquid or air cooling. Hidden axial cooling channels and cells are for emphasis

between the cells or axially on the head and/or bottom of the cells is considered, all included in the example. For prismatic and pouch type LIBs cooling by means of cooling plates is assumed.

To adapt to the different heat dissipation characteristics of the different LIB types, the simulation framework strictly separates the thermal cell and BTMS simulation. The BTMS simulation only considers the heat fluxes entering and exiting the system. The different geometries and the associated thermal characteristics of the LIB types considered, are represented by different thermal resistances and heat transferring cross sections to the BTMS in all three spatial directions. This allows the simulation of thermal BTMS and LIB interaction of different cell types using the same underlying simulation algorithms.

Given the specified cross section of the cooling channels and the total volume flow of the cooling fluid defined by the pump or fan used, the volume flow per cooling channel is known and the heat transfer coefficient can be calculated. As upper limits for the total volume flow $6.25 \times 10^{-2} \frac{\mathrm{m}^3}{\mathrm{s}}$ is assumed for air [29] and $4.5 \times 10^{-3} \frac{\mathrm{m}^3}{\mathrm{s}}$ for liquid cooling [34]. In addition, the number and size of the channels between the cells—together with additional space requirements such as enclosure—determines the final dimensions of the battery system and compliance with package restrictions can be tested in the last step.

In the early concept phase many kinds of information are not available. This impedes the utilization of high-accuracy methods like computational fluid dynamics (CFD). Also, due to the large solution space, fast computation of the thermal model is vital. Therefore, correlation formulas are used to reduce the complexity.

Given the as yet low level of detail of system design, the following assumptions are made:

- one dimensional flow
- isobaric, incompressible and frictionless fluid
- planar channels
- strictly laminar flow ($2200 < \mathrm{Re} < 3600$) [13]

The exclusion of pressure-related effects avoids the incorporation of further assumptions that cannot be made reliably at this stage. The same goes for the assumption of laminar flow. If the condition is not fulfilled, then the heat transfer coefficients between the cells and the cooling system will be underestimated. Therefore, the derived BTMS concepts represent a conservative estimation that can in any case meet the cooling demands.

In all cases the fluid in the BTMS is assumed to flow in planar channels. Probably the farthest away from this assumption is the air cooling of cylindrical cells, which at this level of abstraction is usually modelled using the correlation equations for tube banks [10]. However, even tube banks can be approximated using the scenario of planar channels if the conditions $b < 1.2$, $\frac{b}{a} < 1.0$ and $\mathrm{Re} < 10^4$ are met [14], with a and b being the cross- and longitudinal pitch . If the cooling channels do not fulfill these conditions, the turbulence and heat transfer will be underestimated, so the simulation serves as a conservative estimation.

Given that the channels are regarded as fluid-mechanically equivalent in all cases, the same underlying equations can be applied. The simulation model uses the correlations from Gnielinski [13, 14] for planar channels. The values for Reynolds and Prandtl numbers Re and Pr are calculated as

$$\mathrm{Re} = \frac{2 w_{\mathrm{fl}} S}{\nu_{\mathrm{fl}}} \tag{3}$$

$$\mathrm{Pr} = \frac{\nu_{\mathrm{fl}} \rho_{\mathrm{fl}} c_{p,\mathrm{fl}}}{\lambda_{\mathrm{fl}}} \tag{4}$$

with w_{fl} as fluid speed, ν_{fl} as kinematic viscosity, ρ_{fl} as density, $c_{p,\mathrm{fl}}$ as specific heat capacity, λ_{fl} as heat conductivity and S as pitch on the planar fluid channel. The thermophysical fluid properties are obtained using the open-source framework *CoolProp*[1] [4], which allows an almost unrestricted selection and mixture of different fluids. The

[1] www.coolprop.org.

mean Nusselt number for laminar flow in planar channels Nu_m is given as

$$\mathrm{Nu}_m = \sqrt[3]{\left(\mathrm{Nu}_1^3 + \mathrm{Nu}_2^3\right)} \tag{5}$$

with

$$\mathrm{Nu}_{1,|} = 4.861 \tag{6}$$

for one heat exchanging wall,

$$\mathrm{Nu}_{1,\parallel} = 7.541 \tag{7}$$

if both walls of the channel exchange heat and

$$\mathrm{Nu}_2 = 1841 \sqrt[3]{\mathrm{Re}\,\mathrm{Pr}\,\frac{2S}{l}}\,. \tag{8}$$

From Eq. (5) the mean heat transfer coefficient inside a channel α_{th} can be calculated with

$$\alpha_{\mathrm{th}} = \frac{\mathrm{Nu}_m \lambda_{\mathrm{fl}}}{2S}\,. \tag{9}$$

Inside a cooling channel, the fluid heats up in passing the cells, so cells at the outlet of the channel are cooled less than those at the inlet. To reduce the computational load the vector of outlet temperatures $\vec{T}_{\mathrm{fl,out}}$ of all i cooling channels in the battery system can be approximated from the global inlet temperature $T_{\mathrm{fl,in}}$ using

$$\vec{T}_{\mathrm{fl,out}} = \begin{bmatrix} \frac{\alpha_{\mathrm{th},1} A_1}{\dot{m}_1 c_{p,\mathrm{fl}}} \\ \vdots \\ \frac{\alpha_{\mathrm{th},i} A_i}{\dot{m}_i c_{p,\mathrm{fl}}} \end{bmatrix} \begin{bmatrix} \overline{T}_{\mathrm{cell},1} - T_{\mathrm{fl,in}} \\ \vdots \\ \overline{T}_{\mathrm{cell},i} - T_{\mathrm{fl,in}} \end{bmatrix} + T_{\mathrm{fl,in}} \tag{10}$$

with $\alpha_{\mathrm{th},i}$ as heat transfer coefficient being individually calculated for each channel using Eq. (9). $\dot{m}_i$ is the mass flow inside each channel calculated from its dimensions. A_i is the total heat transferring area inside a channel i calculated by

$$A_i = \sum_{k=1}^{k} A_{k,i} \tag{11}$$

from all k cells in contact with the cooling channel. $\overline{T}_{\mathrm{cell},i}$ is the mean temperature of all cells adjacent to the cooling channel i. It is obtained by

$$\overline{T}_{\mathrm{cell},i} = \frac{\sum_{k=1}^{k} T_{\mathrm{cell},k,i}}{k} \tag{12}$$

from all temperatures $T_{\mathrm{cell},k,i}$ from the k cells adjacent to the channel.

When the inlet and outlet temperatures are known, the fluid temperature distribution inside a cooling channel can be linearly approximated. Afterwards

$$\Delta T_{k,i} = T_{\mathrm{cell},k,i} - T_{\mathrm{fl},k,i} \tag{13}$$

describing the temperate differences between each cell $T_{\mathrm{cell},k,i}$ and cooling fluid $T_{\mathrm{fl},k,i}$ at the location of the cell in the cooling channel can be calculated for every LIB in contact with the BTMS. Following the approach summarized by Stephan [49] using the total thermal resistance $R_{k,i}$ between the cell and the cooling fluid, the heat flux $\dot{Q}_{k,i}$ between the cell and the BTMS can be obtained:

$$\dot{Q}_{k,i} = \frac{\Delta T_{k,i}}{R_{k,i}} \tag{14}$$

Afterwards the temperatures of the recent time-step t, $T_{\mathrm{cell},k,i}$ of the cells adjacent to the BTMS can be calculated by

$$T_{\mathrm{cell},k,i} = T_{\mathrm{cell},k,i;t-1} - \frac{\dot{Q}_{k,i}\,\Delta t}{m_{\mathrm{cell}}\, c_{p,\mathrm{cell}}} \tag{15}$$

using the cells' mass m_{cell}, heat capacity $c_{p,\mathrm{cell}}$, cell temperatures of the last time-step $T_{\mathrm{cell},k,i;t-1}$ and the period since the last time-step Δt. Finally, the final cell temperatures following all heat transport effects within the battery system are calculated by the battery pack model.

An arbitrary and illustrative example for the influence of the cooling channel placement is shown in Fig. 4. In this case, a module consisting of 16 cylindrical cells is cooled by means of two fluid channels between the cells. Additionally, the cells on the outside are equipped with an additional cooling channel for axial heat exchange. It

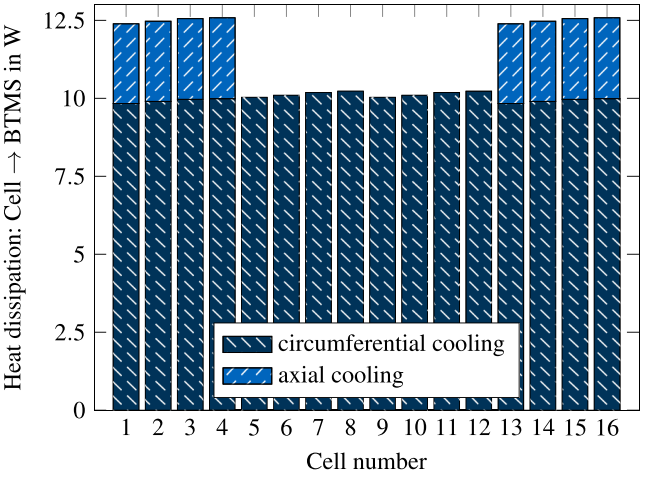

Fig. 4 Influence of cooling channel placement. All cells are circumferentially cooled. Additionally, cells 1–4 and 13–16 are axially cooled

becomes apparent that cells equipped with both cooling solutions can dissipate more heat.

4.5 Testing the Complete Battery Concept

The full electrical and thermal system architecture is now finished. The concepts can be tested under consideration of all interdependencies and for any desired load cycles. It is expedient to use a scenario which puts the system under the maximum electric and thermal stress that the concept must withstand within its specification. In the context of this paper; a CCCV fast-charging cycle is chosen. To further increase the demand on the BTMS, different load cycles can be combined, e.g. highway driving with intermediate fast-charging.

For the simulation, the initial values for cell SOC and temperatures as well as the fluid inlet temperature must be specified. Like the electrical load profile these conditions depend on the requirements of the overall vehicle concept. The simulation model allows the specification of initial values for every individual cell, as well as dynamic BTMS inlet temperatures and mass flow. This can be used to test the ability of the BTMS to eliminate thermal gradients.

The simulation, which results from two illustrative concepts (one using air and one using liquid cooling), is presented in Fig. 5 for a constant current constant voltage (CCCV) fast-charge, starting with a completely drained battery and an initial cell and inlet temperature of 20°C. It becomes apparent in this case that liquid cooling can achieve lower overall temperatures.

During the simulation all other electrical and thermal conditions are monitored as well. This ensures the exclusions of concepts which successfully completed the prior steps but no longer meet the requirements due to being negatively influenced by the BTMS.

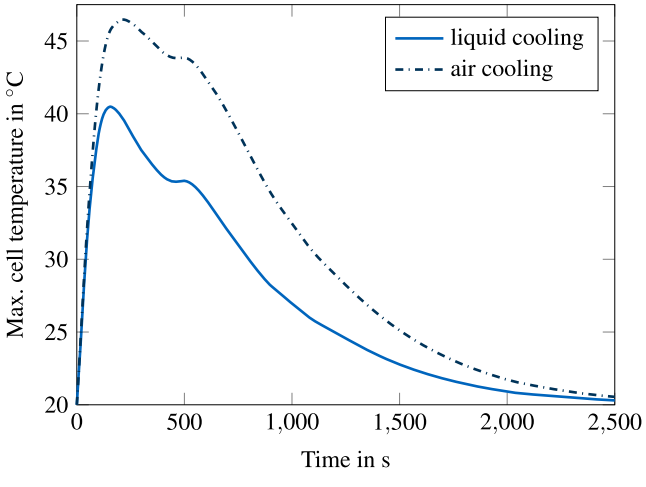

Fig. 5 Maximum system temperatures during fast-charging of a liquid vs. an air cooled concept

4.6 Concept Assessment and Selection

Every system concept that completes the last step has met all specified requirements. This raises the question of how to select the *best* concept from among all of the possibilities. Every system concept is a trade-off between many contradictory demands. The ideal concept is the one with the fewest shortcomings in the areas deemed most important by the user of the approach. This final decision cannot be portrayed by algorithms, so a final evaluation on the part of the user is essential.

The simulation framework presented in this paper fully documents all electrical and thermal properties as well as the dimensions and weight of the battery system. This allows a ranking of the system concepts according to e.g. weight and dimensions as well as respecting more detailed criteria such as the size of the parallel connection or the number and length of cooling channels. If the solution space in this step is still too big, it may be necessary to tighten the requirements on the system. If individual concept choices, e.g. combined axial and circumferential or air cooling, are not considered to be feasible or are too complex, the simulation framework can be adjusted to suppress these specific solutions altogether. By virtue of the full-factorial approach, all concept variants are already finished, so no further simulation is needed. In addition, all variants deemed to be unfeasible are documented together with the reason the design was excluded, which allows analysis of the impact of specific constraints on the system concept.

4.7 Reference Implementation

A reference implementation was done in MATLAB®/Simulink™ using the additional models presented in [43, 44]. The complete simulation framework is available under an open-source license[2].

5 Discussion

This section discusses the method and its simplifications and the resulting limitations presented in the prior sections. Afterwards the approach is placed within the context of the overall battery system design process.

5.1 Simplifications, Limitations and Adaptions

The approach utilizes several simplifications necessary for adapting to the early concept phase and to the demand for a full-factorial system design. Thus, especially for the thermal simulation some assumptions must be made.

[2] https://github.com/TUMFTM/sim_BTMS.

LIBs were considered to be lumped masses, and the thermal gradients inside of them were ignored. Furthermore, in order to use the same algorithms for thermal simulation for all LIB types considered, the simulation framework represents different cell geometries only through different heat transfer capabilities in the three spatial directions. This limits the robustness for large format prismatic cells in particular. Solutions in which only one narrow end of a cell is in contact with the BTMS may be subject to substantial thermal stress not detectable by the simulation framework in its current increment. Consequently, designs using large-format cells must be carefully examined for whether the Biot criterion (Eq. 1) is met in all spatial directions. In case of doubt, a detailed analysis of the cell's internal temperature distribution must be performed.

The temperature distribution in the cooling channels is linearly approximated. Due to the additional computational load for large battery systems with a high amount of cooling channels, it may even be necessary to assume a uniform temperature inside each channel. This will lead to an overestimation of the inlet temperatures. Although this is compatible with the desired worst-case approach, the outlet temperatures are underestimated, and cells at this position might have a higher temperature in reality. Furthermore, the temperature increase of the coolant is calculated using the mean temperature of all adjacent cells. The inaccuracy grows higher as the temperature difference between the inlet and the outlet increases. Therefore, at least for the final evaluation, if the temperature differences become too great, the temperature distribution inside the BTMS must be calculated correctly or at least approximated as being linear.

Finally, the battery model only considers thermal interaction between the cells and with respect to the BTMS. Heat dissipation out of the battery by natural convection or thermal radiation is not considered. Thus, temperatures will be overestimated. The effects which are predominant in this respect and the underestimation due to the simplifications regarding the cooling channels will depend on the design of the battery system and the overall vehicle concept. The possible sources of error must therefore be re-evaluated for each new battery and vehicle concept.

On the electrical side the approach only supports a serial connection of battery modules. If modules are to be connected in parallel, then the battery must be split into equal sub-parts. This limitation was introduced by choice in order to limit the solution space. If the algorithm cannot find a concept or the modules dimensions are too large, the concept must be iterated to incorporate parallel-connected modules and the process starts again. In all cases, the algorithm assumes that the battery system is connected to a single power electronics unit as used in most powertrain concepts. A parallel operation of powered battery modules as presented in [32] is not supported.

The geometric orientation of the cells is always the same relative to the length, width and height of the battery system. If the orientation of the cells in the battery should be changed, then the values for length, width and height must be swapped accordingly.

As a design objective, the approach uses CCCV fast-charging at a specified current rate. Influences regarding the optimal charging protocol [59] or temperature [56] are ignored. The BTMS always runs at maximum power. However, the simulation framework supports dynamic current profiles and inlet temperatures, so a more thorough analysis of promising designs can be carried out with no additional modeling effort.

5.2 Reducing the Solution Space

Many of the simplifications of the simulation framework were necessary to reduce the computational demand of the model due to the large solution space of possible battery system and BTMS configurations. Because the simulation framework only supports manual constraints of the system parameters regarded, e.g. number, placement and cross-section of cooling channels, and the feasibility of a configuration is not checked before simulation, a full-factorial approach was chosen for concept development. This leads to a large number of simulations and the aforementioned necessity of efficient computation.

An interesting possibility to decrease the number of configurations to simulate is the utilization of constraint-based configuration and recommender systems [11]. These systems have been successfully used for interactive product configuration with arithmetic constraints and interactive generation of new constraints as a result of configuration decisions [46]. This approach would allow the detection and exclusion of unfeasible BTMS configurations before simulation and therefore decrease the computational effort. Another possibility would be a constraint-based incremental reconfiguration [18] of the BTMS concept replacing the current full-factorial approach and again strongly decreasing the number of necessary simulations.

Because this approach requires full knowledge about the interrelations of the free parameters defining the BTMS concept and their impact on system behavior, this strategy is currently not implemented in the simulation framework. Until the parameter sensitivities of the BTMS concept are not fully understood, the chosen full-factorial approach is the only feasible approach to ensure no promising configurations are missed.

5.3 Validity of the Simulation Framework

By design, the simulation framework aims to cover as many different LIB types and BTMS configurations as possible.

To ensure global validity a high number of tests conducted with different cell types, battery system geometries and thermal management solutions is required. In respect to the scope of the simulation for model validation a full electrical and thermal examination on at least the module level of a physical battery system and BTMS concept is necessary. Because of the high number of possible variants, this makes the validation of the model a tedious and time consuming task.

A conceivable alternative for reducing the testing effort is the use of validation results from the publications of other authors. However, to recreate the battery system and BTMS concepts examined in other publications, all dynamic cell parameters and the complete thermal properties of the system in consideration must be known. Since most authors focus on certain system levels and therefore do not cover the full scope of the simulation framework presented in this paper, they do not share the design characteristics and parameters of their battery systems. Consequently, a recreation of the results of other papers would require the estimation of crucial system parameters which is not suitable to prove the general validity of the simulation framework.

With the open-source release of the full simulation framework including its parameterization (Sect. 4.7) the authors hope other researchers will aid to collaboratively benchmark and improve upon the model, sharing the substantial infrastructure and time demands for full model validation.

5.4 Classification within the Overall Design Process

The approach aims to guide the battery system development in the early concept phase. All critical electrical and thermal aspects of battery system development are considered. Previous works discussed in Sect. 3 require at least an established basic battery and/or BTMS concept as a starting point. This limitation allows those studies to go into greater detail as would have been possible had the system concept itself needed to be developed.

This paper therefore cannot completely replace other, more detailed simulative approaches. However, it does allow robust conclusions for full battery systems in the early concept phase. Regarding further definite system design the concepts derived from this approach must be further developed using simulation methods such as CFD and coupled with an aging simulation.

6 Conclusion and Outlook

This paper presented an approach for the overall concept development of automotive battery system concepts. In contrast to most other publications the concept is developed without the need for iteration of previous concepts, therefore allowing a fully target-oriented design and immediate adaption to new LIB and BTMS technologies. The influences on the system concept considered include the choice of battery cells, the electrical interconnection, and the geometric arrangement as well as the thermal properties and BTMS architecture. The theoretical background of electrical and thermal influences was analyzed, and a review of comparable approaches was conducted in order to identify the research gap.

The concept development algorithm utilizes a full-factorial cell selection and electrical interconnection and gradually evolves the system design through the individual steps. While many existing approaches disregard individual cell behavior and electrical system level effects for BTMS design, the method presented here directly incorporates all relevant cell-level interactions with the BTMS for concept development. The system design is benchmarked against the requirements after each step. In the end, the approach provides a variety of battery system concepts that meet the specified demands.

To achieve fast computation the approach uses an efficient solution for a joint simulation of electrical and thermal battery system behavior, offering high accuracy while requiring limited parameterization effort. The theory and implementation of the simulation framework were comprehensively elaborated. Possible inaccuracies of the simulation model were discussed, and advice was given on how to apply the method and on how to overcome its limitations.

In future work the approach will help in analyzing the influence of different cell types, load cycles, environmental conditions and package restrictions on battery systems design. Furthermore, it is planned to extend the simulation framework to include electrothermal gradients, to incorporate more BTMS technologies and extend its applicability further into the design process. By the virtue of the open-source license and the modular approach the simulation framework is available to and extensible for the public (https://github.com/TUMFTM/sim_BTMS).

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X.L. reviewed the paper and gave advice on the impact of different cell types and sizes and researched and wrote the parts considering aging and thermal gradients inside cells.

L.-E.S. carried out the literature review on electrical and thermal LIB behavior and implemented the simulation framework.

M.L. made an essential contribution to the conception of the research project. He revised the paper critically for important intellectual content. M.L. gave final approval of the version to be published and agrees to all aspects of the work. As a guarantor, he accepts responsibility for the overall integrity of the paper.

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