35th International Electric Vehicle Symposium and Exhibition (EVS35)
Oslo, Norway, June 11-15, 2022

A Methodology for Application-Specific Concept Definition of Battery Systems Using Pouch Cells Produced in Flexible Format

Philip Müller-Welt[1], Konstantin Nowoseltschenko[1], Katharina Bause[1], Albert Albers[1]

[1]IPEK - Institute of Product Engineering at Karlsruhe Institute of Technology (KIT), Kaiserstr. 10, 76131 Karlsruhe, Germany, philip.mueller-welt@kit.edu

---

Summary

In battery system design the installation space can be a limitation regarding capacity and power. New potentials in design and integration can be achieved by higher flexibility in the embodiment of individual components. Cells produced in variable formats can therefore be advantageous. The flexibility of cell embodiment results in new degrees of freedom and thus a large number of possible arrangements. In addition, the choice of other function-related components is also influenced by the cell format. These aspects lead to an increased solution space and complexity, so that the synthesis under consideration of boundary conditions is supported by the development of a method. This new methodology enables the developer to define application-specific concepts of battery systems with pouch cells of flexible format.

Keywords: battery, BEV (battery electric vehicle), optimization, PHEV (plug in hybrid electric vehicle), vehicle performance

---

1 Introduction

In recent years, electric vehicles have gained importance as a potential solution to economic, environmental and social challenges in the field of individual mobility. Currently, battery electric vehicles are limited in their energy and power because the available space for the battery system is limited or cannot be utilized. One reason for this is the development of electric vehicles based on existing vehicle platforms for which central installation spaces for the battery system are provided in the sense of conversion design. Imagining battery cells manufactured in variable sizes and formats, battery systems can be adapted to existing installation spaces and additional installation space can be utilized efficiently. The improved exploitation of an existing installation space enables higher capacity and installed power. However, on today's production lines for battery cells, it is not possible to produce different formats, materials or even quantities on the same production line. To implement this product idea, a new type of production system is needed that offers both flexibility in the individual design of the cell and modular scalability. Such a production system creates the possibility of producing cells for various fields of application on just one production line, which can be adapted and scaled on a modular basis. At the same time, this opens up new potentials in the development of these products that were previously not feasible with standard formats.

To exploit this potential, it is necessary to consider and develop the product and its production system together. Among other things, the development of products benefiting of a cell produced in a format-flexible manner additionally requires an overall consideration of all new degrees of freedom in the design of individual components as well as their interactions [1]. Thus, new methods are required to support the development in dealing with the increasing complexity due to flexibility. The authors aim to develop a method for synthesis and optimization based on the multitude of potential concepts of a battery system and the interactions resulting from format flexibility.

2 State of Research

In the current development process of battery systems, the first question is the choice of the right cell type for the application. Lithium-ion batteries represent the state of the art for a large number of applications. Common formats are cylindrical, prismatic and pouch cells, whereby all of them offer more or less advantages depending on their application case. Ultimately, the choice of cell type is followed by the further design of individual modules and then of the entire battery system [2]. As a rule, uniform cell types and module sizes are used. This has the advantage that the number of units can be increased by using the same parts. This also results in a small number of possible temperature control concepts or arrangement and interconnection options. The development of battery systems rarely considers a flexible and, above all, cross-application approach. Examples for a selection of a cell type and subsequent flexible arrangement of the modules are presented by WAGNER [3] and FRANK [4].

For the standardization of products and their subsystems, the development and application of construction kits is a common approach. The subsystems of a product can be designed, independent of the system under consideration, either according to the module, the platform or the series design. Thus, it is possible to encounter any combination of the above design types at different system levels of a product. This property can be called the fractal character of design types in the sense of ALBERS [5]. Among others, BURSAC [6] considers this fractal character in the development of construction kits supported by Model Based Systems Engineering (MBSE). In this context, the added value of the MBSE approach for the development of construction kits for technical systems was shown, but also the increasing complexity in the development of construction kits due to the simultaneous consideration of multiple products. A common approach for this is the use of a construction kit to generate alternative product solutions. BURSAC [6] defines a construction kit for the development of technical systems as follows:

A construction kit is the set of all technical subsystems that follow the associated construction kit rules, with the aim of being able to configure technical systems from these subsystems, each with a different set of functions.

A schematic representation of a construction kit as well as a product derived from it can be seen in Figure 1.

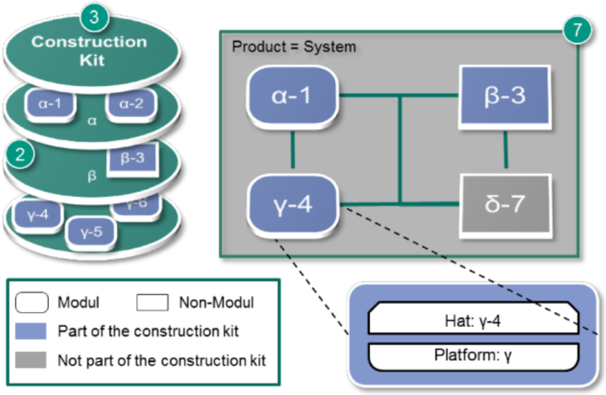


Figure 1: Illustration of construction kit and a derived product [7]

In this context, a construction kit is not understood as a complete product, but rather as an abstract structure that contains the subsystems from which technical systems can ultimately be configured. The system to be developed can consist of several subsystems, which in turn can consist of subsystems [8], [9]. The construction kit set of rules describes the product architecture of the individual subsystems with the aim of ensuring the compatibility of the subsystems. It is particularly important to consider the interfaces and interactions of the subsystems. Thus, the development of a construction kit includes the development of the individual subsystems of the modular system as well as the definition of the construction kit rules. For the configuration of a product, individual subsystems of the construction kit can be selected and combined. These do not represent yet the entire product architecture, but can be supplemented additionally by not included subsystems, which represent further components and can be combined by structure elements.

A challenge in product and production engineering is that costs over the entire life cycle of the product and production system are determined early in the development process [8]. Customer-specific, individual products lead to high product variance and shorter product life cycles, increasing the number of times development processes are run through and necessitating joint consideration of the product and production system. For example, VDI 2206 [10] describes the need for an integrated view of product and production system development. This approach shows how products can be developed, considering production system requirements and constraints when developing new products.

At present, the state of research does not offer any approaches that offer and exploit the potential of a pouch cell produced in a format-flexible manner to optimize a battery system, considering possible flexibility and restriction of the production system. In addition, under this aspect, a holistic consideration of the different design aspects of a battery system, considering function-relevant interactions and restrictions, represents a new approach. A method in which a free selection and flexible dimensioning of different subsystems for different fields of application is possible does not currently exist in the state of research. Such a method offers the advantage of presenting and using the potential of a flexible design of the cells and subsystems of the battery system.

3 Increased Solution Space and Complexity by the use of Pouch Cells Produced in a Format-Flexible Manner for Various Application Fields

Supporting format flexible cell designs means to deal with cross-domain optimization of battery systems. Also, to develop methods and tools that can be used for various application fields and their associated requirements and that support the developer in the design of the battery system. A schematic representation of the approach followed can be seen in Figure 2.

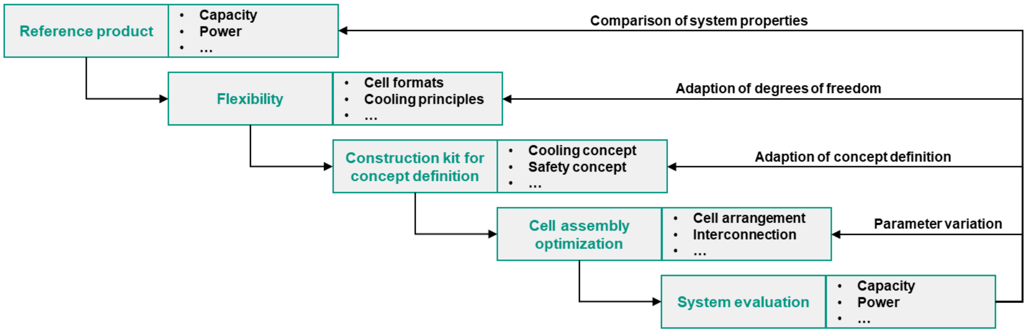


Figure 2: Approach for battery system development

The basic approach consists of several aspects. The starting point is a reference product for which a new battery system is to be developed. Basic requirements arise for this, such as the installation space available for the battery system, the system voltage or, for example, specifications with regard to safety. For the redesign of the battery system, various degrees of freedom are defined, which can be achieved by the flexible cell format but also by other system components. To deal with the resulting variety of solutions, the use of a construction kit for application-specific concept definition is planned. Based on this, a targeted optimization and design of the mechanical, thermal and electrical aspects of the cell network will be carried out. Finally, the system properties resulting from this procedure can be compared with those of the reference product in order to evaluate the improvement of the system properties. In the following, the flexibilization approach pursued will be described in more detail.

Starting with the design of the cells, the first degrees of freedom arise which are to be considered. On the one hand, it should be possible to flexibly design the geometry and thickness of the cell. For example, rectangular, triangular or trapezoidal cells are conceivable. Furthermore, the position of the current conductors of the cells is to be defined, which can be located on the same side of the cell or on opposite sides. In addition, the electrical properties of the cells to be produced on the production system should be able to be defined differently in order to meet both high-capacity and high-power requirements. By varying these, different electrical properties of the battery system can be achieved.

Beside the cell definition, the arrangement and interconnection of the cells to form a cell assembly represents an important factor. 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. Both a modularization of the cells and a free arrangement are conceivable. In particular, the interaction of the cell and module shape with the potentially required temperature control system must already be considered during the arrangement of the cells. For the resulting possible cell arrangements, it is also necessary to consider the interconnection options. These must be evaluated both spatially and electrothermally, since cell properties vary with the cell formats leading to different state-of-charge and temperature behaviour for the interconnection options.

As far as the definition of a temperature control concept is concerned, there are still various options that have to be selected individually for the corresponding application scenario and given requirements. These range from the initial selection of the basic functional principle to the definition of the cooling location and the geometric definition of the potential cooling plates and channels. In particular, the hierarchical character of the overall concept and thus the order of selection must be considered, since certain principles may be mutually exclusive. For example, the use of cooling plates in an implementation using air cooling makes only limited sense. In addition, dependencies resulting from the flexible design of the cells and arrangements must also be considered. One dependency is the choice of the cooling location, which is directly related to the choice of the electrical connection of the cells and, for example, the position of the tabs.

Finally, safety-relevant components and the battery management system (BMS) represent subsystems of the battery system that can be implemented in configurations adapted to the application. Thermal barriers can be used and are available in several designs and interact with the cooling concept. For example, thermal separation of two cells via barriers does not make sense if cooling of these cells at the cell surface is preferred. Similarly, a joint consideration of the functions of the BMS – like temperature monitoring or active balancing of cells – with the electrical topology of the battery system is required.

In summary the approach of format flexible development of battery systems for different applications results in a large amount of new solution principles and degrees of freedom as well as interdependencies which have to be considered during the development process. The fact that a multi-domain approach of mechanical, electrical and thermal aspects is necessary also results in a high complexity for the developer. Therefore, a way to make the large solution space manageable is necessary. One way to achieve this goal is to define specific potential solution principles and degrees of freedom from which concepts can be derived to then optimize the battery system. For an automated optimization approach, they have to be defined in a manner in which optimization tools can use the defined concepts and degrees of freedom. An example for the definition of multiple concepts and degrees of freedom can be seen as an excerpt in Table 1. For a further increase of manageability, the degrees of freedom can also be defined in a defined parameter set with either discrete or completely variable values.

Table 1: Example of subsystem variants and degrees of freedom

Concept definition	Subsystem	Degree of freedom	Values
Concept 1	Thermal barriers between modules	Length/width	[min – max] mm
		Thickness	t1, t2, t3 mm
	Liquid cooling plates within modules	Length/width	[min – max] mm
		Thickness	t1, t2, t3 mm
Concept 2	No Thermal barriers	-	-
		-	-
	Liquid cooling plate at installation space floor	-	-
		Thickness	t1, t2 mm

A schematic representation of the format-flexible approach of the cells and ultimate configuration of the modules and system arrangement is exemplified in Figure 3.

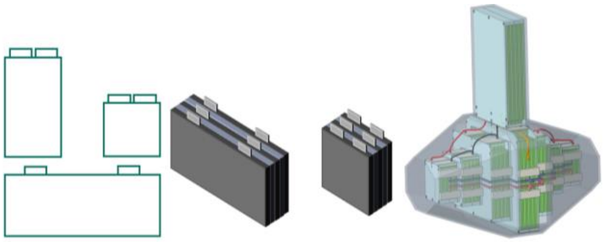


Figure 3: Schematic of flexibility approach

Only if the approach to be developed deals with the described complexity and considers all aspects the engineer will be able to find an optimized solution from the resulting solution space using format-flexible cells. To make this possible, the potential solution principles as well as their interactions must be known. Due to the degrees of freedom in the development of the battery system resulting from the flexible approach, a support of the developer by a method for the selection of suitable solution concepts is necessary.

4 Construction Kit Development to Deal with Solution Diversity and Complexity

The first step is the creation of the construction kit structure and the definition of the individual subsystems as well as the identification of their dependencies within a subsystem. Subsequently, any exclusions of subsystems resulting from the different application scenarios and requirements are included in the construction kit rules. Finally, all dependencies and, if applicable, exclusions between the subsystems of different subsystems are identified by looking at them in pairs.

4.1 Analysis of System Structure and Definition of Alternative Solution Principles

In order to identify the system structure as well as potential solution principles, reference products of different application fields are analyzed. Subsystems that result from the flexibilization of certain product properties are added. A battery system consists of different system levels which are identified in the first step of the approach. The construction kit structure is also defined and built up on the basis of this product structure. The top system level is the battery system itself. This is subdivided into four subsystems, each of which is subdivided again into subsystems. Finally, in the second step, the individual subsystems that are to be available as variants for product configuration in the construction kit are recorded at this system level. Figure 4 and Figure 5 show an exemplary representation of the temperature control system.

The solution principles defined for the temperature control concept include variants in the principle implementation, the choice of the cooling location on the cell, the implementation of the conduction of the cooling medium as well as its geometric implementation and the selection of the cooling medium itself. Within these categories, the solution principles represent alternative variants in each case. The subsystems further identified as relevant for the development of the construction kit are safety components, components related to the electrical design and cell selection, and the battery management system. Analogous to the example shown in Figure 4, subcategories and their respective components were thus defined for each of these three main categories.

The set of rules required for the use of the construction kit includes several aspects that relate to the sequence in which the subsystems are selected, their mutual dependencies and selection conditions with regard to the application scenario under consideration and preferred requirements. These rules as well as potential subsystems of the construction kit have to be identified by the construction kit developer. First, the four main categories are considered individually. The order in which a selection can be made in the subcategories must be defined. For example, a selection of the basic principle is necessary before the selection of a medium. This may already result in exclusions of individual cooling locations and media that are not compatible with the defined basic principle. For this purpose, the construction kit provides for a step-by-step selection of a module in the categories from top to bottom.

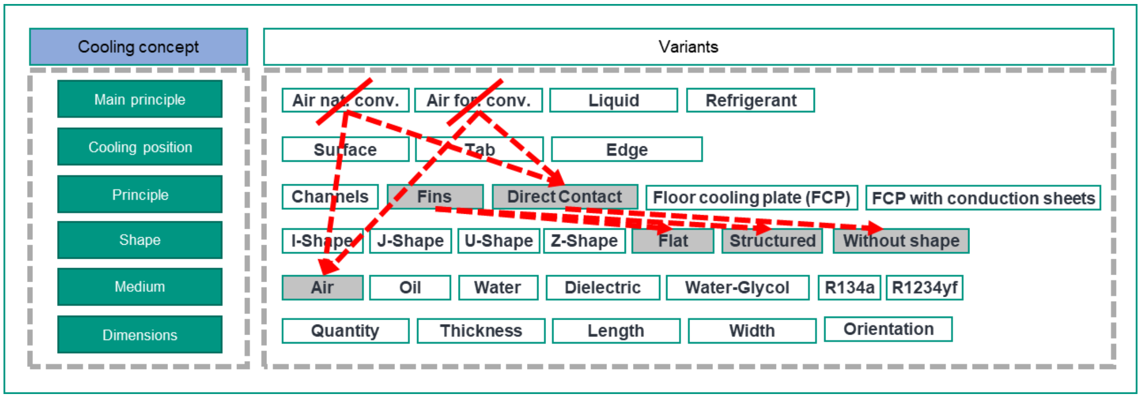


Figure 4: Definition of interdependencies between subsystems

According to the selection of the component of the top category, exclusions are made in the categories below. For example, as can be seen above, the exclusion of air cooling can exclude the use of cooling fins. A similar procedure is followed when a component is selected in the lower categories. This part of the set of rules can thus be used to consider exclusions resulting from the selection of individual subsystems in a subsystem.

4.2 Application- and Requirement-Specific Selection of Solution Principles

For an application-specific concept definition, it can be helpful to narrow down the number of possible combinations. For this reason, a further step in the construction kit rules provides for a preselection based on a defined application scenario. For the selection, an evaluation of all subsystems of the construction kit is required with regard to their suitability for the application scenario. In the process, exclusions that result from their technical or economic feasibility for the application must be defined.

For example, air cooling can be excluded in principle in the case of a plug-in hybrid vehicle. Nevertheless, care must be taken not to restrict the variety of solutions too much, as otherwise the potential of format-flexible development cannot be fully exploited. The resulting preselection can also be seen as an example in Figure 4. In the case of the selection of the application scenario of a plug-in hybrid vehicle, air cooling by natural or forced convection, as basic principles of the temperature control concept, are thus omitted as selectable subsystems of the construction kit.

In the last step, it is also possible to make a preselection based on preferred requirements. For these, an evaluation of the subsystems is also necessary with regard to their suitability in terms of requirements such as performance, costs, safety or installation space.

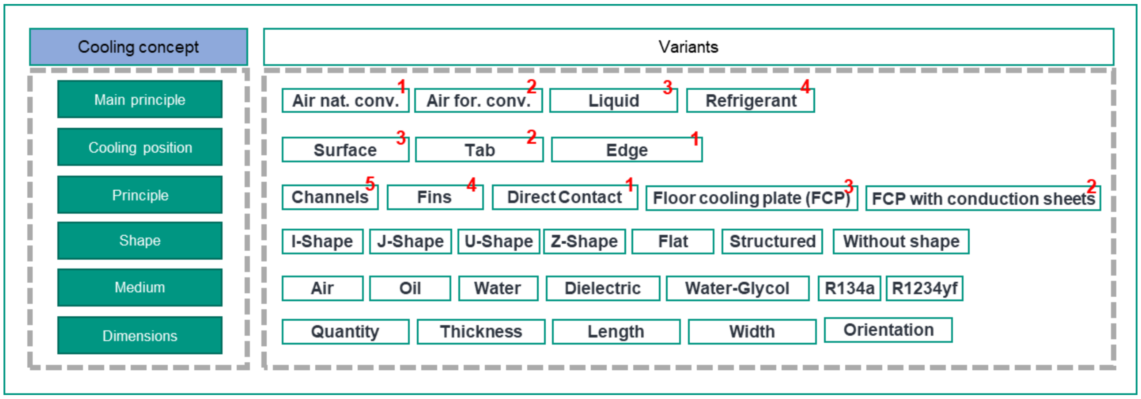


Figure 5: Exemplary ranking of subsystems based on their installation space

Through this procedure, each main category can finally be gone through and step-by-step a module can be selected that is best suited with respect to the requirement. This selection in turn leads, as already mentioned above, to the exclusion of other modules that are no longer suitable for this solution principle. An exemplary representation of the procedure is given in Figure 5, in which the solution to be preferred in terms of installation space, such as air cooling with natural convection, was defined step by step for the categories.

In the end, individual concept definitions can be generated by the described set of rules. One of the objectives was to be able to limit the variety of solutions as desired. This means that ultimately it is up to the developer to what extent he wants to limit the potential concepts of the battery system. This is done on the one hand by selecting any number of applications to be served and on the other hand by selecting any number of requirements on the basis of which preferred solution concepts are to be selected.

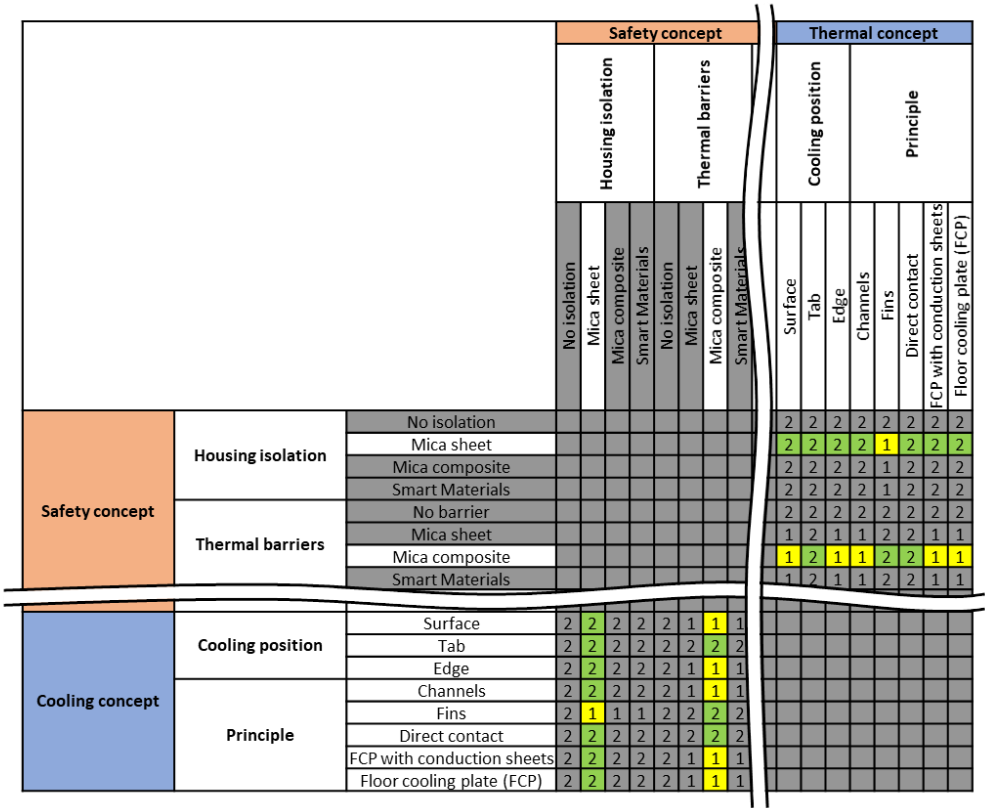
4.3 Identification of Interdependencies Between Solution Principles

In the final step, interactions between the subsystems of the four main categories are identified. There may be interactions between these components which may completely exclude a combination of individual components or only allow it to a limited extent. For example, the selection of a housing material is not dependent on the selected cooling principle. On the other hand, there is a conditional compatibility between the choice of the cooling location and the position of the tabs of the cells. An evaluation in three stages was carried out. A more detailed explanation of the evaluation process during the construction kit definition is given in [11]. A distinction was made between combinations of the subsystems of the categories that are compatible with each other without restriction (green 2), compatible under certain conditions (yellow 1) or not at all compatible (grey 0). The resulting interaction matrix is shown in part in Figure 6 and Figure 7. The resulting matrix for the overall system can finally be used to select subsystems. This defines the product configurations that can be considered in principle, considering the compatibility of the individual subsystems. Ultimately, all subsystems are defined as freely compatible, conditionally compatible or not combinable. In the case of conditionally compatible combinations, an additional definition of conditions is necessary. These conditions ensure the compatibility of the interfaces or dimensions between the subsystems.

Overall, this procedure allows dependencies between modules to be identified for the battery system to be developed. For example, the type of electrical connection and the location of the cooling as well as the position of the tabs are aspects for which there are interactions between the components. Thus, it was possible to identify both mutually exclusive product configurations and, if necessary, conditions that are required in the combination of subsystems. These initially apply independently of the application scenario under consideration.

5 Application of Methodology for Battery Concept Definition

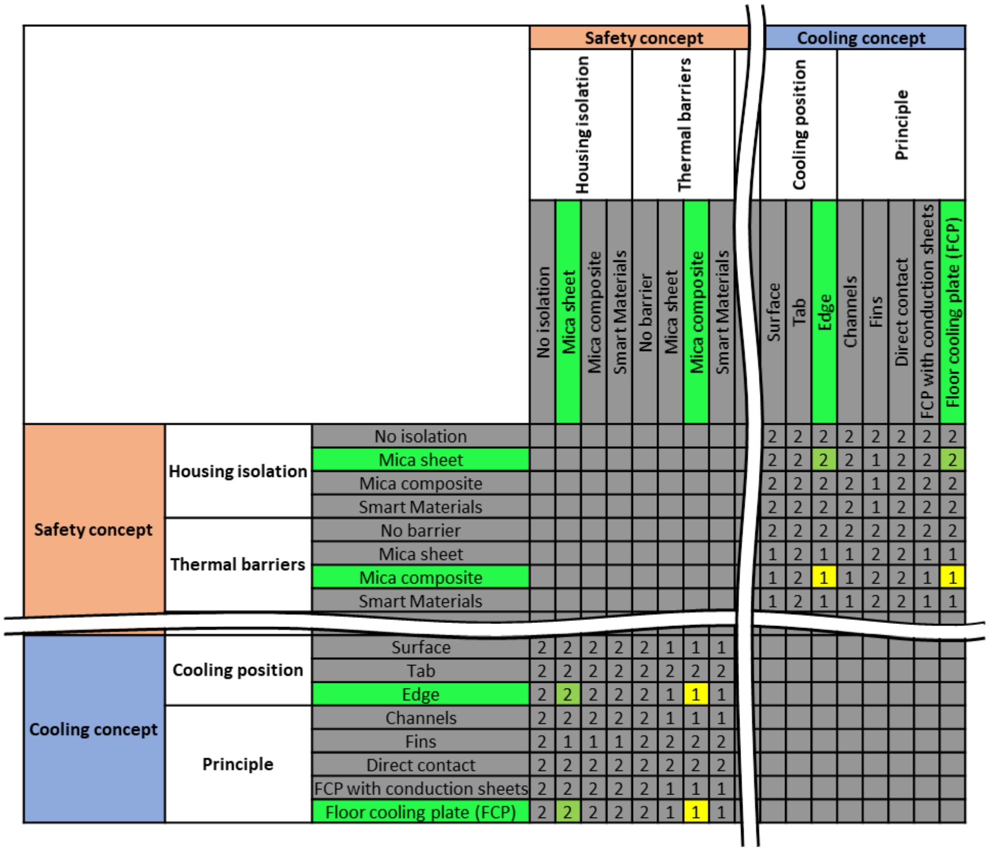
Finally, the application and the concept definitions of the battery system resulting from the developed construction kit and its rules are to be demonstrated. The example chosen for this purpose is a plug-in hybrid vehicle whose battery system subsystems are to be selected on the basis of their installation space requirements. The starting point is the construction kit developed in chapter 4 in the form of the interaction matrix and the rules it contains for selecting and excluding subsystems. Due to the high number of possible product configurations as well as their initial design a semi-automated approach for the concept definition is suggested. This offers the benefit of a faster definition of product concepts by programmed execution of the defined rules within the construction kit as well as an easy transfer of parameters to further optimization steps. If, in a first step, the developer defines the application scenario of a plug-in hybrid vehicle to be considered, the rules defined in step 4 of the construction kit development automatically result in the exclusions of subsystems shown in Figure 6.



			Safety concept								Thermal concept							
			Housing isolation				Thermal barriers				Cooling position			Principle				
			No isolation	Mica sheet	Mica composite	Smart Materials	No isolation	Mica sheet	Mica composite	Smart Materials	Surface	Tab	Edge	Channels	Fins	Direct contact	FCP with conduction sheets	Floor cooling plate (FCP)
Safety concept	Housing isolation	No isolation									2	2	2	2	2	2	2	2
		Mica sheet									2	2	2	2	1	2	2	2
		Mica composite									2	2	2	2	1	2	2	2
		Smart Materials									2	2	2	2	1	2	2	2
	Thermal barriers	No barrier									2	2	2	2	2	2	2	2
		Mica sheet									1	2	1	1	2	2	1	1
		Mica composite									1	2	1	1	2	2	1	1
		Smart Materials									1	2	1	1	2	2	1	1
Cooling concept	Cooling position	Surface	2	2	2	2	2	1	1	1								
		Tab	2	2	2	2	2	2	2	2								
		Edge	2	2	2	2	2	1	1	1								
	Principle	Channels	2	2	2	2	2	1	1	1								
		Fins	2	1	1	1	2	2	2	2								
		Direct contact	2	2	2	2	2	2	2	2								
		FCP with conduction sheets	2	2	2	2	2	1	1	1								
		Floor cooling plate (FCP)	2	2	2	2	2	1	1	1								

Figure 6: Excerpt of exclusions of subsystems based on plug-in-hybrid vehicle application scenario

The resulting exclusions are greyed out in the construction kit and are omitted as product configurations that are considered. In a further step, the developer can select one or more preferred requirements to further narrow down the combinations of subsystems to be considered. These result from the rankings defined in step 5 of the construction kit development and the exclusions of subsystems resulting from step 3. In Figure 7, the subsystems to be preferred on the basis of their installation space requirements are shown in green. In addition, there are components that are omitted, which are highlighted in grey in the construction kit.



			Safety concept								Cooling concept							
			Housing isolation				Thermal barriers				Cooling position			Principle				
			No isolation	Mica sheet	Mica composite	Smart Materials	No barrier	Mica sheet	Mica composite	Smart Materials	Surface	Tab	Edge	Channels	Fins	Direct contact	FCP with conduction sheets	Floor cooling plate (FCP)
Safety concept	Housing isolation	No isolation									2	2	2	2	2	2	2	2
		Mica sheet									2	2	2	2	1	2	2	2
		Mica composite									2	2	2	2	1	2	2	2
		Smart Materials									2	2	2	2	1	2	2	2
	Thermal barriers	No barrier									2	2	2	2	2	2	2	2
		Mica sheet									1	2	1	1	2	2	1	1
		Mica composite									1	2	1	1	2	2	1	1
		Smart Materials									1	2	1	1	2	2	1	1
Cooling concept	Cooling position	Surface	2	2	2	2	2	1	1	1								
		Tab	2	2	2	2	2	2	2	2								
		Edge	2	2	2	2	2	1	1	1								
	Principle	Channels	2	2	2	2	2	1	1	1								
		Fins	2	1	1	1	2	2	2	2								
		Direct contact	2	2	2	2	2	2	2	2								
		FCP with conduction sheets	2	2	2	2	2	1	1	1								
		Floor cooling plate (FCP)	2	2	2	2	2	1	1	1								

Figure 7: Excerpt of exclusions of subsystems based on installation space requirement

For the final generation of solution concepts for the battery system, combinations can be formed from all components that were not excluded by a preselection. These are highlighted in green or white in the graphical representation. It is important to note any conditional combinability between individual components that is marked with a one in the matrix-based implementation. Through the procedure described in chapter 4, an aluminium housing with thermal barriers as well as liquid cooling by means of a floor cooling plate and a BMS configuration with active cell balancing were selected for this example by the construction kit rules. The cooling medium and cell type have not been selected based on the pre-selection and thus represent a choice of product configurations that can be considered in the further design process.

Finally, for a further design, additional parameters of the selected subsystems as well as their conditions to each other have to be quantified. In order to be able to define these parameters, knowledge about, for example, restrictions in production is necessary. In addition, these final parameters depend on the further design of the system. For example, the cell dimensions are defined in a subsequent development step based on given requirements [12]. Figure 8 shows a schematic of further development steps of the battery system with format flexible pouch cells with the defined concept possibilities from the construction kit as an input.

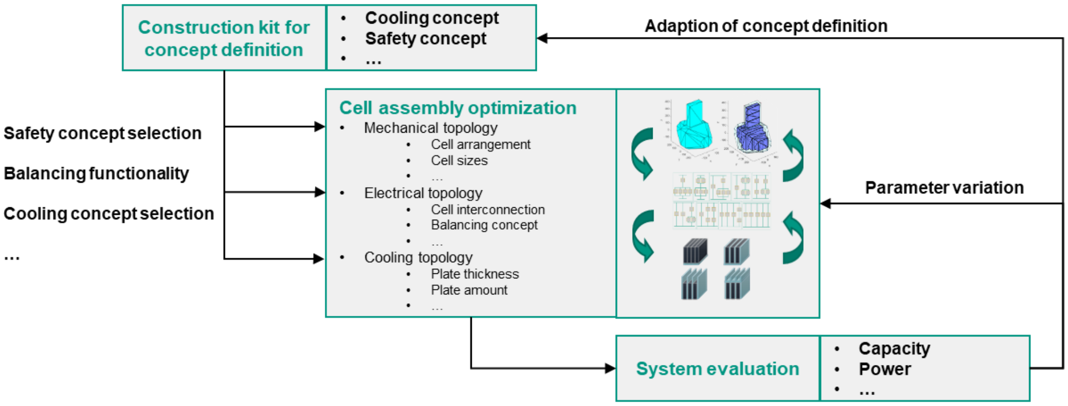


Figure 8: Schematic representation of further development steps

For an execution of the further optimization steps of the battery system as the installation space optimization the defined concepts and their included selected subsystems of the construction kit have to passed on in given parameter sets. For example, the desired cooling concept and its potential geometry are considered within an installation space optimization where also the cell and module dimensions are defined. Also, the balancing functionality can be considered during an optimization of the cell and module dimensions and therefore their resulting capacities. Coming back to the chosen example in this chapter for example the amount and thickness or the orientation of the cooling plates as well as thermal barriers have to be defined in a parameter set. The sets include information about the necessity of installation space that has to be considered at the floor of the installation space for a cooling plate or between modules for thermal barriers. Also, these parameters can be given in the form of single values or a range of values which range from a minimum to maximum amount or thickness and are directly included in the construction kit and can be passed to the other optimization tools. The parameter sets can therefore be seen as discrete degrees of freedom that are still open for the optimization of the battery system. Other parameters such as the cell length and width are not included in the construction kit since they should be freely variable within the installation space optimization and only restricted by potential production restrictions.

As can be seen in the examples, some degrees of freedom as well as solution principles represent variants which do not have to be finally quantitatively defined within the construction kit. These can be transferred into detailed models for the further development process. In addition, the design of the battery system and concept definition can be seen as an iterative process that is conducted several times. For example, it is conceivable to iterate all of the degrees of freedom defined in the construction kit within a concept definition in order to achieve an optimization of the battery system. Furthermore, a further iteration of other concept definitions is conceivable, such as an additional use of heat conduction sheets, which may have been left open by the developer during the use of the construction kit.

6 Summary and Outlook

The method presented in this thesis for the concept definition of a battery system offers a possibility for the application- and requirement-specific selection of subsystems of a battery system from a construction kit. For this purpose, both the structure and the subsystems of the construction kit were defined and a set of rules for the construction kit was derived, which enables the selection of the subsystems, considering compatibility between the subsystems and application-dependent exclusions. In addition, there is the possibility of further selection based on preferences in requirements fulfilment.

By using the presented method, the developer is now able to manage the large solution variety and complexity within the solution selection. It is possible to design the degree of solution selection individually and to generate both a complete concept selection and a variety of potential concepts. The possibility of adaption to different application scenarios of a battery system is to be emphasized. The developed construction kit could be used for electric applications of different kind.

In this context, the battery system concepts that can be generated by the construction kit do not represent fully developed products, but rather a part of the early phase of product generation engineering. The early phase, according to the PGE - Product Generation Engineering model, is a phase in the development process of a new product generation that begins with the initiation of a project and ends with the evaluation of a product specification. The product specification contains, among other things, information regarding the technologies and subsystems used [13]. The derived concepts of the battery system thus represent a starting point for the further development and validation process.

For the further design of the battery system, a consideration of the identified dependencies between the selected components is necessary. Among other things, potential geometric dependencies must be considered. For a further design using the potentials resulting from the flexible approach, a holistic consideration of the different design aspects is required. The aim is to optimize the cell geometries for the available installation space, which interacts with the installation space required for cooling and safety components, and to optimize the electrical and thermal properties of the cell assembly, which will evaluate both the internal cell properties and the interconnection and cooling aspects.

Acknowledgments

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] J. Ruhland *et al.,* “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*, A.-L. Andersen et al., Eds., Cham: Springer International Publishing, 2022, pp. 96–104. [Online]. Available: https://doi.org/10.1007/978-3-030-90700-6_10

[2] M. Schmalz, C. Lensch-Franzen, M. Kronstedt, and M. Wittemann, “Skalenübergreifende Batteriesystembetrachtung zur effizienten Entwicklung und Optimierung elektrischer Antriebe,” in *Experten-Forum Powertrain: Simulation und Test 2019*, J. Liebl, Ed., Wiesbaden: Springer Fachmedien Wiesbaden, 2020, pp. 15–24.

[3] D. Wagner, “Methodengestützte Entwicklung eines elektrischen Energiespeichers zur Erschließung von Leichtbaupotenzialen als Beitrag zur Produktgenerationsentwicklung,” Dissertation, Institut für Produktentwicklung (IPEK), Karlsruher Institut für Technologie (KIT), Karlsruhe, 2015.

[4] F. Frank, “Optimierter Hochvoltbatterieentwurf hinsichtlich mechanischer, thermischer und elektrischer Randbedingungen unter Berücksichtigung der Produktionskosten,” Dissertation, Universität Duisburg-Essen, Duisburg, 2018.

[5] A. Albers, A. Braun, and S. Muschik, “Uniqueness and the Multiple Fractal Character of Product Engineering Processes,” in *1st International Conference on Modelling and Management Engineering Processes*, Cambridge, London, 2010, pp. 15–26.

[6] N. Bursac, *Model Based Systems Engineering zur Unterstützung der Baukastenentwicklung im Kontext der Frühen Phase der Produktgenerationsentwicklung*. Dissertation. Karlsruhe: IPEK - Institut für Produktentwicklung am Karlsruher Institut für Technologie (KIT), 2016.

[7] A. Albers, H. Scherer, N. Bursac, and G. Rachenkova, “Model Based Systems Engineering in Construction Kit Development – Two Case Studies,” in *CIRP 25th Design Conference: Innovative*

Product Creation, Haifa, Israel, 2015, pp. 129–134. [Online]. Available: https://doi.org/10.1016/j.procir.2015.01.044

[8] K. Ehrlenspiel, *Integrierte Produktentwicklung – Denkabläufe, Methodeneinsatz, Zusammenarbeit*. München: Carl Hanser, 2009.

[9] G. Ropohl, *Allgemeine Technologie: eine Systemtheorie der Technik*. s.l.: KIT Scientific Publishing, 2009.

[10] *Entwicklungsmethodik für mechatronische Systeme,* VDI 2206, Berlin, Jun. 2004.

[11] P. Müller-Welt, K. Nowoseltschenko, K. Bause, and A. Albers, "Methode zur anwendungsspezifischen Konzeptdefinition eines Batteriesystems unter Verwendung formatflexibel produzierter Pouch-Zellen," in *KIT Scientific Working Papers,* 182nd ed., 2022.

[12] P. Müller-Welt, K. Nowoseltschenko, C. Garot, K. Bause, and A. Albers, "Automated Optimization of a Cell Assembly Using Format-Flexibly Produced Pouch Cells," in *22. Internationales Stuttgarter Symposium*, M. Bargende, H.-C. Reuss, and A. Wagner, Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2022, pp. 569–581.

[13] A. Albers, S. Rapp, C. Birk, and N. Bursac, "Die Frühe Phase der PGE – Produktgenerationsentwicklung," in *Stuttgarter Symposium für Produktentwicklung SSP 2017*, Stuttgart, 2017, o. S.

Authors

Philip Müller-Welt

Philip Müller-Welt, M.Sc. is a scientific researcher of the research group drive systems of the IPEK-Institute of Product Engineering. The research group focuses on systems, methods and processes in the development and validation of conventional, electrified and electric drive systems.

Konstantin Nowoseltschenko

Konstantin Nowoseltschenko, M.Sc. is a scientific researcher of the research group drive systems of the IPEK-Institute of Product Engineering. The research group focuses on systems, methods and processes in the development and validation of conventional, electrified and electric drive systems.

Katharina Bause

Dipl.-Ing. Katharina Bause is chief engineer and head of the research department drive systems and clutch and tribology systems of the Institute of Product Engineering at the Karlsruhe Institute of Technology.

Albert Albers

Univ.-Prof. Dr.-Ing. Dr. h. c. Albert Albers is head of the Institute of Product Engineering at Karlsruhe Institute of Technology