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Design Automation for Battery System Variants of Electric Vehicles with Integrated Product and Process Evaluation

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Abstract

From the absence of standardization regarding components of battery systems for electric vehicles results a large number of theoretically applicable battery configurations for a given application. This leads to decision making problems and expenditure of time during development processes. This paper presents a method that automates the electrical and mechanical design process of battery systems to identify applicable battery variants. The design automation is coupled to an evaluation tool that allows variant selection regarding product and process characteristics such as power, energy or ease of assembly. The paper closes with a use case of a medium sized electric vehicle.

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Keywords: Design for Assembly; Design Automation; Variant Design; Battery; Electric Vehicle; Decision Making Problem

1. Motivation for the topic

Product developers have to run through several decision making steps especially during the first phases of the product development process. The number and variety of choices that have to be made rely on different factors: The accuracy of initial boundary conditions, the amount of possible technical solutions that fulfill these requirements as well as the number of conflicting goals that have to be achieved. The more accurate and complete the list of requirements, the fewer technical solutions might occur during the conceptual design phase. In some cases, even precisely documented requirements cannot reduce the amount of technical solutions that fulfill the targets, because many technically identical solutions exist for the specific set of requirements. Therefore, each decision has to be made wisely as it influences downstream cost development within purchasing, manufacturing and service phase [1]. Furthermore, making decisions, especially in large companies and organizations with interdisciplinary teams, might end up in time consuming (coordination-) processes and thus stretch the time span of the development process. This correlation becomes even more evident if companies enter new markets with cost extensive product types and design products from scratch with a low level of experience. In this case the validation of the quality of decisions is not proven until first prototypes are manufactured and tested. High energy storage systems especially for mobile applications such as electric vehicles are a perfect example for the challenges described before. Due to a missing standardization regarding geometrical properties, many shapes and sizes for the different components of the battery system are available and these are (in principal) interchangeable. If a certain principle design for the components of the system has been identified, there might still be an unmanageable number of solutions for the mechanical package of components due to packing problems. Herein each solution might fulfill the initial energetic boundary conditions but differs regarding volumetric and gravimetric characteristics or the assemblability of the system.

To overcome these problems, the authors automated the process of creating the mechanical package of the battery system with respect to the electrical boundary conditions, coupled it with a battery specific evaluation methodology for decision support that incorporates product and assembly specific characteristics and linked a common CAD system to the concept generation.

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2. Technical Background and Related Work

2.1. Lithium Ion Battery Systems

Lithium-Ion battery systems have to fulfill the efficient, reliable and safe usage within a given application such as electric vehicles, marine applications and stationary battery systems. According to [2] battery systems are composed of several hundred / several thousand parts like the battery cells, the interconnection of cells, thermal management systems, parts for mechanical integrity and electronic components for supervision and energy management of the system. The principle design can be subdivided into two types: Block design and modular design. The block design describes an assembly in which all necessary battery cells and peripheral components are assembled to a single unit which is designed for a specific design space or field of application. Modular battery systems, as the name implies, are subdivided into smaller but interchangeable sub units, that make up the system. Following the concept of modularization battery systems of electric vehicles are typically subdivided into three levels with the lithium-ion battery cell representing the smallest unit, the interconnection of battery cells to an interchangeable module of the battery system presents the second level and the interconnection of modules represents the third level, a pack or system [3]. Figure 1 shows a principle design and the three product levels of a generic battery system

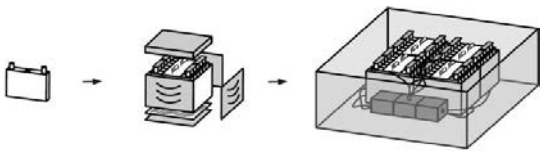

Fig. 1: Generic battery system design (cell, module, system)

2.2. Methodological approach and related work

Several different approaches regarding the automation of the principle as well as the detailed design process have been published. The number of publications rises steadily with the development of computing power and global networking. The presented work relates to approaches that couple the detailed design with decision making methodologies, to approaches that incorporate CAD part and product templates for the automation of variant design and to approaches that incorporate product as well as process characteristics to shorten the overall product development time (simultaneous engineering). Selected publications are presented in the following section that are closely related this work.

[4] presents a methodology that incorporates decision making processes within an automated conceptual design generation. Herein extended morphological matrices are used to create new conceptual design solutions that can be evaluated according to user defined characteristics. The concept of the morphological box has therefore been automated and linked to functional matrices. The detailed CAD design however is not focused within the presented work.

[5] presents a methodology that incorporated three research efforts: functional structure grammar, configuration design grammar and tree search algorithm for component selection. These efforts are combined to explore the possibility to solve a conceptual design problem through the manipulation of standard graph representations. At the stage of development, the methodology lacked an evaluation methodology and outputs too many solutions (20 trillion). Furthermore, there is no linking to an automated design tool.

A novel method for design automation that links knowledge based engineering with generic high level geometry templates that can be reused by developers to describe complex engineering tasks is presented in [6]. Applications from robotics and aircraft engineering have been successfully investigated and the automation of the geometry generation could be fulfilled sufficiently. However, it was also stated that for a very large engineering task the input parameter density can be excessive and the handling might be affected in a negative way.

[7] describes the automation of the conceptual design phase by implementing a web-based repository of functionally analyzed consumer goods. The repository consists of function component matrices as well as design structure matrices for a large number of products. These have been made accessible through a Matlab GUI and can therefore be used in an intuitive manner for the generation of conceptual design alternatives. However, the actual design process of the part or product has to be fulfilled based upon the functional layout of the conceptual design.

Empirical approaches that quantify the impact of alternative goals for CAD model creation and alteration are presented in [8]. The presented work shows the impact of feature creation and alteration, the useful selection of reference planes and many more. The presented results have been a starting point for the selection of the level of detail and the possibilities on how to modify the product after creation for this work.

[9] describes the automated mold design on the bases of CAD standard parts that have been stored in databases for effective reuse. The GUI that controls the integration of parameters and the placements of parts also creates a bill of materials and list of attribute parts that is dynamically updated during further development. The presented work shows the successful use of part and product templates but does not alter morphology and topology to find potentially better solutions according to user defined key performance indicators.

[10] describes a methodology that is based upon modular, reconfigurable CAD pre-design, that has been optimized for usage within industrial applications. The principle of the methodology checks a predefined assembly regarding modules and mating surfaces. The generated structure of the product is broken down to low level 3D parts with a limited amount of features. The user of the system has than the possibility of changing certain modules within the assembly without needing to change the complete product. Bills of materials as well as rudimentary 2D sketches are created automatically after finishing the process of module design.

The related work has been used to create a sufficient flow of information within the presented methodology. However, features such as the automated variant generation and the coupled decision making tools for variant selection based upon product and assembly process characteristics have been missing within the related work. Furthermore the aspect of battery systems and their design has not been mentioned so far.

3. Principle of the methodology

The primary goal of the presented methodology is to shorten product and process development time through an automation of the mechanical CAD design of battery systems in combination with a battery specific evaluation methodology based upon multiple criteria. For the achievement of this goal and to be independent regarding the specific type of battery system, four major questions had to be answered:

- What are the influencing factors that define the mechanical package of battery systems?
- How can these factors be abstracted to variables and implemented into a software environment to automate the variant development process?
- What effect does the mechanical layout have onto the assemblability?
- What are key performance indicators that can be used to evaluate system variants?

These key questions represent the basic principle and sequence of the methodology, which is presented as follows.

3.1. Influencing parameters for the electrical and mechanical layout of battery systems

As described in [11] the electrical and mechanical design of battery systems for electric vehicles is primarily defined by the vehicle platform (volume and layout of the available design space), the vehicle performance attributes, the drive cycle and the electric range. Additional influences are related to the existing production technology, the production volume as well as specific requirements of the application (water proof, shock resistant, hot/ cold environments, etc.). To identify the exact correlation between mechanical and electrical layout of modular battery systems and the stated influencing factors literature research, disassembly studies and expert interviews have been conducted.

The required vehicle performance and specific requirements of the application primarily influence the choice of active material and the electrode layout (high power / high energy) of the battery cell. The drive cycle and the electric range define the number of battery cells and the way these cells are interconnected. Both cases serial and parallel interconnections of the battery cells are possible whereas a parallelization of cells on module level rather than system level is more favorable. The number of battery cells and choice of a centralized or decentralized management system of the battery influences the extent of voltage, current and temperature sensors as well as their distribution within the system. The environmental influences of the application in combination with the selected active materials and performance requirements push the demands for cooling or heating devices and their attachment to the heat source (battery cell). The principle design (block of modular) is primarily defined by the energy demands (size of the system) and production volumes and technologies. The components that are used for the module setup are primarily defined by the selected cell type, its dimensions, its terminal type and the specific requirements of the application. The analyses of the design of these specific components and their breakdown into functional sub structures as well as the reassignment of these functional structures with novel design solutions has already been presented in [12]. Herein a specific focus has been set onto the influence of multi-material components within battery systems and the partly automated conceptual design of these components through function component matrices and coupled engineering catalogues. The structure of the catalogues is defined by the combination of the different functions of the cell, module or system. Therefore, possible solutions for the integration of functions such as “transfer electric energy” and “protect cells” can be found in a fast way. A special focus has been set onto existing solutions for the integration of different materials by injection molding and impact extrusion because of the wide spread usage of these technologies in the market.

These influencing factors, that primarily define the electrical and mechanical layout of battery systems have been abstracted, formalized and implemented as variables into a software environment to create a universal application for the determination of battery variants. Within this application topological and morphological operations have been used to generate battery system variants.

3.2. Generating battery concepts through topological and morphological operations

Based upon the stated boundary conditions for battery concept generation such as design space, cell type, energy and power demands, two types of operations are conducted through the application on module and system level. Firstly, the topology of battery cells within a battery module is analyzed. According to the predefined cell geometry (prismatic, cylindrical, pouch) the number and arrangement of these cells is varied and it is checked whether the created module fits into the design space. If the number and arrangement of peripheral module components is directly linked to the number and arrangement of cells, these components are varied in topology likewise. This for example is the case for the interconnection of one battery cell to another. Parallel to these topological operations a morphological operation regarding the peripheral components of the module is executed. This operation adapts the dimensions of each component according to the varying cell arrangements. The dimensions of housing components for example are changed if battery cells are added according to the topological operation. The peripheral components of the battery modules are stored as templates in a component database. The maintenance and the update of components within this database have to be fulfilled by the user of the methodology. The following figure illustrates the basic topological operations that are fulfilled on module level as well as the components that are affected by morphological operations.

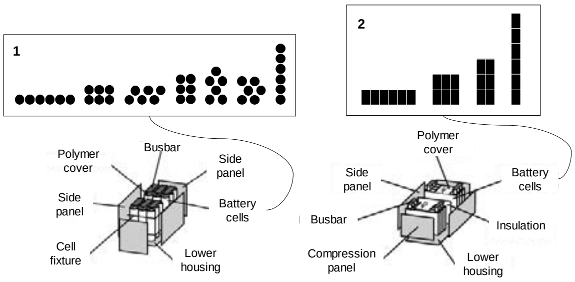

Fig. 2: Principle topological configuration of a 6 cell module with cylindrical cells (1) and prismatic cells (2)

Modules that meet the electrical and mechanical boundary conditions are stored within a database for system generation.

On system level only topological operations are fulfilled. These operations arrange the previously generated battery module types within the given design space(s). Two different strategies for the module selection and arrangement within the design space are applied during system concept generation: variant generation with identical module types regarding the cell number and arrangement within the module and variant generation with mixes module types. In both cases a 2,5 dimensional relative packing sequence to arrange modules has been developed. Figure 3 shows the principle of the packing sequence for 4 modules.

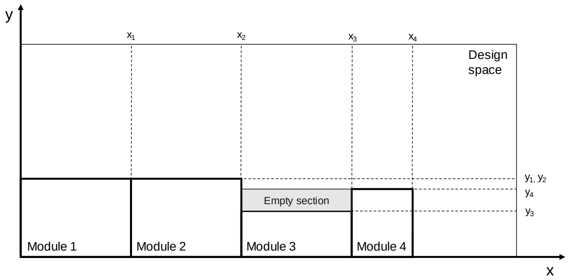

Fig. 3: Packing sequence example with 4 modules

This packing sequence cuts the design space each time a module from the predefined database is loaded. Within the given example modules are implemented along the x-axis. Subsequently to the implementation of module 1, a set of coordinates (x_1, y_1) is created that defines the remaining space for module integration and sets the starting points for the integration of the following module. The given example shows that parts of the design space can remain empty if a certain sequence of modules is loaded into the design space. These empty sections are tolerated for the fact that encapsulated module topologies are to be avoided regarding production and service purposes. The packing sequence is 2,5 dimensional because the z-direction of the design space is cut into planar layers. The presented sequence for module arrangement in x- and y-direction is repeated on each of these layers. The cutting height within z-direction is defined by the dimensions of the implemented modules. These topological and morphological operations in combination with the previously defined boundary conditions offer the possibility of creating the mechanical layout of battery systems. These systems can be visualized in a rudimentary way through a 3D plot in Matlab that shows the orientation of each module within the design space (prismatic blocks). To accelerate the design of battery systems in a CAD environment a linkage to a knowledge base environment within CATIA V5 has been created. Templates of each battery module component have been stored within the CAD system. These templates are loaded through a VBA application which receives a pre-structured bill of components. This contains the information about the components that have to be loaded into the CAD environment, the parameter set that alters the dimensions of the components and the parameters for translation and rotation within the design space. Parallel to that products and sub-products are generated to systemize the structure of the battery system components within CATIA V5. Figure 4 shows the design of these principle component tree structures.

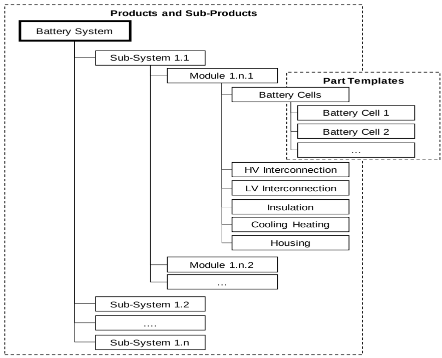

Fig. 4: Tree structure for battery variants within CATIA V5

3.3. Design for battery assembly

To correlate the electrical and mechanical layout of the battery system within development phase with requirements regarding assembly planning, a coupling of the design automation with a battery specific design for assembly (DfBA) evaluation has been suggested. A detailed description of the DfA criteria database has already been described in [13].

The DfBA evaluation tool is directly linked to the concept generation. It evaluates the battery concepts through an analysis of weighted assembly characteristics of the cell (I), the module (II) and the system (III). The evaluation criteria for the cells and module components are derived from state of the art design for assembly methodologies and extended with battery specific characteristics: Cell shape and mass, lock-and-key characteristics, terminal type and topology, cell housing type, additional handling difficulties, number of components within a module, number of identical components and ratio between cells and peripheral components, module variants, single module position & orientation as well as module group position & orientation are the selected criteria for the evaluation regarding the assemblability of the battery concepts. These production oriented characteristics are combined with typical product related characteristics such as the gravimetric energy density, volumetric energy density and performance characteristics to create a decision making environment that incorporates an enlarged spectrum of development target criteria. A dynamic scale in combination with linear, exponential and logarithmical value functions has been selected for the relative evaluation each criterion. The weighting of the characteristics (product and process) can be adapted to the different use cases such as a more product driven approach or a concept with optimal assemblability.

4. Application

The presented methodology has been applied to a medium sized electrical vehicle. Each battery system variant has to fulfill the following basic energy requirements: a system voltage of 360-400 V, a maximum power output of 55 kW and an energy content of at least 20 kWh. The available design space underneath the front passenger seats, within the tunnel of the vehicle and underneath the rear passenger seats have been abstracted to three prismatic bodies and implemented into the system generator. The selected battery cell is an energy optimized prismatic hardcase with 28 Ah and 3,6 V. The principle module design is a 5-piece housing with screw type interconnection system and foil type electrical insulation. No limitations regarding the orientation of cells within the module and modules within the system have been made. The maximum number of cells per module has been limited to 40. This data has been implemented into the application. Figure 5 shows the GUI of the Matlab application including the section for data implementation (1), the concept preview section (2) and the decision making environment (3) wherein different characteristics of the generated battery concepts are plotted according to the user requirements.

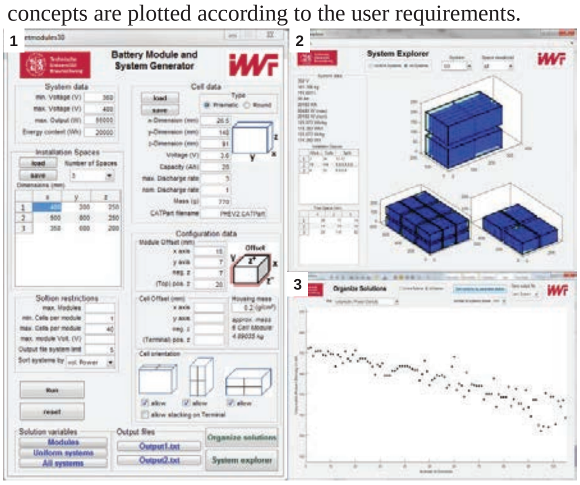

Fig. 5: Matlab GUI (1), system explorer (2) and decision support (3)

These characteristics are volumetric power and energy density, specific power and energy, system voltage, energy content, mass, unused volume of the design space, module distribution and average cells per module.

Based upon the implemented boundary conditions 151 module variants have been identified as suitable for the application. These 151 modules can be arranged in 105 different battery system variants. One of these variants contains only a single module variant. The following figure 6 shows the disorderness of the system and a selected system variant with a high degree of disorder. This characteristic is a constructed value that represents the difficulty of the assemblability of battery systems. It is derived from the unused design space in combination with volumetric power densities of the system. Within the given plot the disorderness has been sorted ascending. Due to the fact that each system variant that has been generated fulfills the initial boundary conditions regarding energy and power demands, it is now possible to identify variants that have a positive (or negative) effect onto the production phase (assembly).

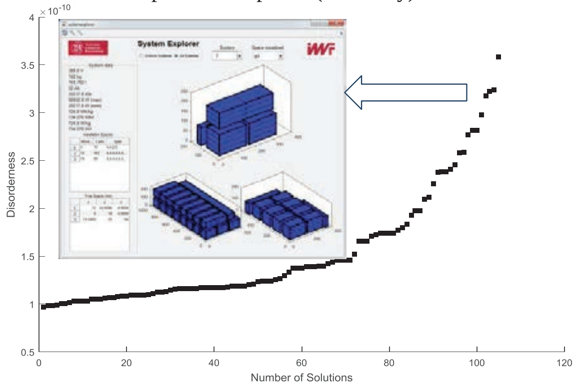

Fig. 6: Plot of the disorder of systems and selected system variant with a high level of disorder

If a certain variant of the generated battery systems has been identified by the user of the methodology according to a set of evaluation criteria, it is possible to generate CAD data from the concept generator. As described a bill of components is generated from the application and read through a CATIA V5 VBA application that loads a predefined set of part templates. Figure 7 shows the results of the CAD generation and the initial view of the variants within the concept explorer.

This state of the design can now be used for the accelerated detailed design of the battery system. If deviations regarding the design space or the module design are experienced, an iterative optimization of the concepts through the system generator is suggested.

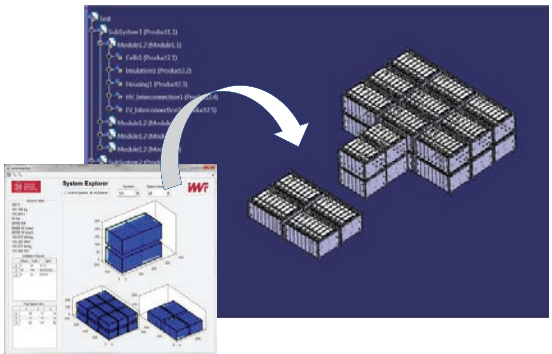

Fig. 7: CAD data generation from the concept explorer

5. Conclusion and Future Work

The presented methodology represents a way of generating battery system variants based upon user requirements that is not only coupled to a CAD environment for accelerated detailed design but offers the possibility to evaluate variants regarding product and assembly characteristics. This makes it possible to compare several hundred variants within seconds of computing time. Furthermore it is possible to derivate optimal configurations of modules and optimal modularization aspects regarding a user defined number of applications. Due to the abstraction of parameters that influence the mechanical and electrical layout of the system it is also possible to use the application for any kind of battery system, e.g. power tools or stationary battery systems.

It has to be remarked that several simplifications have been implemented into the concept generation to accelerate the computing time. The freedom regarding the arrangement for example has been reduced to rather simple patterns. This implies that for example triangular arrangements are not taken into account during concept generation. Furthermore, the detailed design module fixtures, module to module interconnections and piping is not taken into account within CAD design. This is still part of the creative design processes.

The next step within this methodology is the implementation of assembly planning and the adjustment of input parameters for the refinement of the generated concepts.

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