INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

INTEGRATION OF DESIGN METHODS FOR THE PRODUCT GENERATION DEVELOPMENT OF ELECTRIC ENERGY STORAGE SYSTEMS

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Keywords: C&C²-A, SysML, topology optimization, electric energy storage system

1. Introduction

The electric energy storage system (EESS) is one of the key components for the electrification of drive trains. Upcoming legislation leads to increasing efforts to realize functional improvements (e.g. safety or range), to reduce system weight and to increase the overall energy density. The EESS is a complex system (including thermal management, mechanics, electrical contacting and battery management) which conducts in extensive development activities. In the first generations of plug-in hybrid and battery electric vehicles some experience was gained regarding the integration in the vehicles, safety, service, performance and user behavior. The industry demands methods to cope with the complexity of the product itself, include the experience with previous product generations and to find new concepts on this basis. Therefore, the objective is the application and interconnection of design methods in the specific context of electric energy storage systems in order to facilitate the identification of new concepts for lightweight system design and embodiment. For this purpose, a case study involving the enhancement of crash safe design and an automation of space analysis for the embodiment of the system structure is presented.

2. Theoretical background

2.1 Contact and Channel Approach C&C²-A

The description of products and systems from the perspective of designers and engineers is based on defined geometries such as CAD models or engineering drawings [Albers and Matthiesen 2002]. The development of mechatronical systems begins with the definition of several requirements and by sketches of principle solutions in many cases based on predecessor systems [Albers and Braun 2011]. These visualize geometrical shapes of the components that fulfill functions. A complete description of every function is not necessarily given. The Contact and Channel Approach C&C²-A relates a system's physical structure to its functionality [Albers and Sadowski 2013] and uses pairs of two connected Working Surfaces (WS), the Channel and Support Structure (CSS) and the Connector (C). The modeling elements in the Contact and Channel Models are defined as follows [Albers and Sadowski 2013]:

- Channel and Support Structures (CSS), which denote permanently or occasionally interacting physical structures of solid bodies, liquids, gases or fields,
- Working Surface Pairs (WSP), which represent interfaces between these physical structures, and

- Connector (C) modeling elements, which represent the effect and the state properties of the environment that is relevant for the function of a system.

ALINK utilizes the Connector in order to specify the interaction of the system with its environment [Alink 2010]. This virtual element comprises and represents relevant influences, constraints or parameters, which are linked to the Working Surfaces (WS) at the system boundary. These modeling elements can represent every technical system. The smallest conceivable system that can still satisfy a (partial) function consists of two pairs of Working Surface Pairs (WSP) and a Channel and Support Structure (CSS), which connects them [Albers et al. 2004].

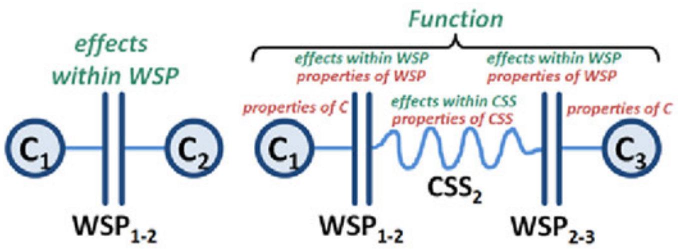

Figure 1. "Effect" and "Function" in the C&C²-Model based on the C&C²-A [Zingel et al. 2012]

The second hypothesis of [Zingel et al. 2012] defines, that "… functions are represented by at least two WSPs, the connecting CSS and at least two Connectors which embedded the model into the environment. The properties of WSPs and CSSs are determining for the fulfillment of the function." (see figure 1). Properties of the CSS characterize the transformation of the incoming object flow to the outgoing object flow in the CSS. An output object flow value can be calculated for a given input object flow value using the information, which is defined and provided by the C&C²-Model.

2.2 Model-based Systems Engineering using SysML

The Model-based Systems Engineering (MBSE) is according to the *Systems Engineering Vision 2020* [INCOSE 2009] "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases". MBSE therefore is used in disciplines like mechanical, software and electrical engineering. Hence, the model-centric approach should replace the document-centric procedures of previous systems engineering practice [INCOSE 2009]. Thereby the specification and design quality may improve as well as the possibility to reuse design artifacts and facilitate communications [Friedenthal et al. 2011].

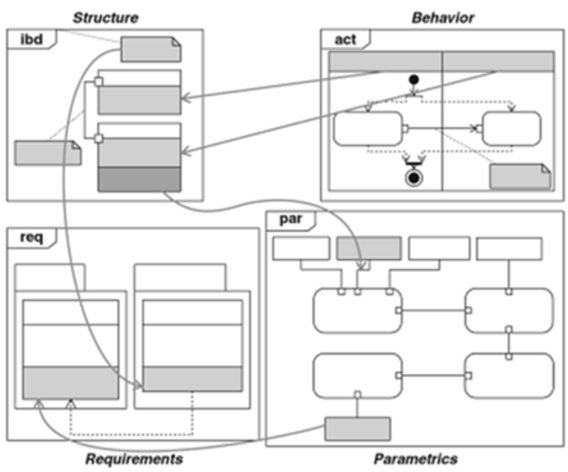

Figure 2. SysML system model [Friedenthal et al. 2011]

One of the common languages is the System Modeling Language (SysML, development of the Object Management Group OMG) based on the Unified Modeling Language (UML). While the UML is

widespread for software systems, SysML is a graphical modeling language to specify, analyze, design and verify complex systems [OMG 2010] and is therefore predestinated for the EESS.
This language makes it possible to model hardware, software, procedures, data etc. of artificial and natural systems. Figure 2 visualizes an interconnected set of diagrams that describe the key aspects of the system model: Structure, Behavior, Requirements and Parametrics. These enable different views on the system focusing for example the allocation of requirements to the components of a system [Friedenthal et al. 2011]. While the model describes the system, a diagram is the visualization of a model in a certain aspect [Weilkiens 2006].
This system model is typically used to design a product that satisfies its requirements. For this purpose, the model includes interfaces, component interactions and performance, associated functions and physical characteristics. Data exchange (engineering analysis or simulation) from the model or automatically generated documentation (e.g. diagrams) are utilized for communication and agreements between system designer (requirements) and component developer (component design that satisfies the requirements). By this procedure, it is possible to integrate and reuse subsystems while maintaining the traceability of interconnections in the system. The diagram taxonomy of SysML includes the following diagrams: package, requirement, behavior (activity, sequence, state machine, use case), parametric, structure (block definition, internal block). [Friedenthal et al. 2011]

2.3 Topology optimization

Topology optimization is one of the processes of structural optimization, in order to identify an optimal material distribution for a given space Ω under various boundary conditions [Hessel 2003]. The result of the post-processing of the topology optimization supports the designer in the early embodiment of a structural component. The input data are the available design space and the mechanical boundary conditions (loads, mounting, etc.) in the finite element model. During the optimization process, each element of the design space is checked whether its existence is necessary to comply with the restrictions and achieving the optimization target [Harzheim 2008]. The result of the topology optimization represents a load-capable raw shape, which serves as a embodiment proposal. In the process of the topology optimization the maximum design space Ω is reduced to the calculated design proposal Ω*. Figure 3 illustrates this by means of a beam under load, where the compliance is minimized, which means a maximization of stiffness, with 30% remaining volume as optimization constraint.

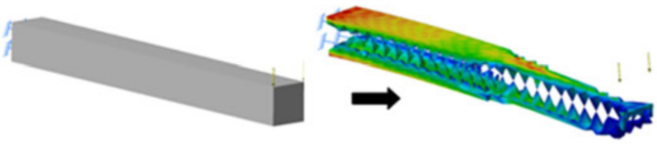

Figure 3. Topology optimization using the example of a simple beam

To describe the material distribution for the topology optimization the following equations are used [Koller 1998]:

$$\rho(\mathrm{x}) = \begin{cases} 1, \mathrm{x} \in \Omega^* \\ 0, \mathrm{x} \in \Omega \end{cases} \tag{1}$$

The rigidity is described by a density-dependent $\rho(x)$ modulus of elasticity E(x), x at each point:

$$\mathrm{E(x)} = \rho(\mathrm{x}) * \mathrm{E}_0 \tag{2}$$

E_0 is the Young-Modulus of the material. This is an integer problem, which can be solved by the SIMP (Solid Isotropic material with penalization) approach. The SIMP approach is an interpolation of material, in which the density values $\rho(\mathrm{x})$can be between zero and one [Harzheim 2008]:

$$0 < \rho(\mathrm{x}) \leq 1 \tag{3}$$

By this approach the discrete problem is converted into a continuous one. The following relationship is utilized for the relationship of modulus of elasticity:

$$E(x) = \rho(x)^p * E_0 \tag{4}$$

The coefficient p represents the penalty factor that penalizes the intermediate values of the density until a discrete distribution of material is obtained. A value of p ≥ 3 is required in order to obtain reasonable results [Harzheim 2008]. An intermediate value of the density leads to a low value of Young's modulus E, which leads to a significant value for the mass. For this reason, density values of zero or one are preferable for the optimization algorithm, which leads to the desired discrete distribution of material [Häußler and Albers 2005].

3. Application and results

In the Integrated Product Engineering Model (iPeM) [Albers and Braun 2011] the activities *idea detection, modeling of principle solution and embodiment* as well as *validation* are essential for the development of new products. These activities are focused in the presented application by a functional analysis using C&C²-A, the utilization of a SysML model for previously gained simulation data and topology optimization of automatically varied system designs. The connection of these design methods could facilitate the handling of the complex EESS for example by identifying new concepts based on the system model, automatically creating topology proposals for the embodiment and then again validate the results with the requirements stored in the SysML model. In industrial practice, these activities are often distributed and dependent on individual experience and design expertise.

3.1 Applying the C&C²-A to support the modeling process in SysML

In this section, the C&C²-A is applied on a High Voltage System (HVS) representing the battery cell packs and the supporting mechanical structure in the case of a passenger car crash (Pole Side Impact). A vehicle, which is fixed on a movable carriage, is driven with a velocity of 29 km/h against a non-deformable pole with 253 mm diameter. The focus of structural concepts is the protection of the HVS against intrusion of surrounding components and endangering forces [Wagner et al. 2013b]. Figure 4 visualizes the C&C²-M of the HVS and its mounting to the vehicle using the elements "Working Surface Pairs" (WSP), "Channel and Support Structures" (CSS) and the "Connectors" (C).

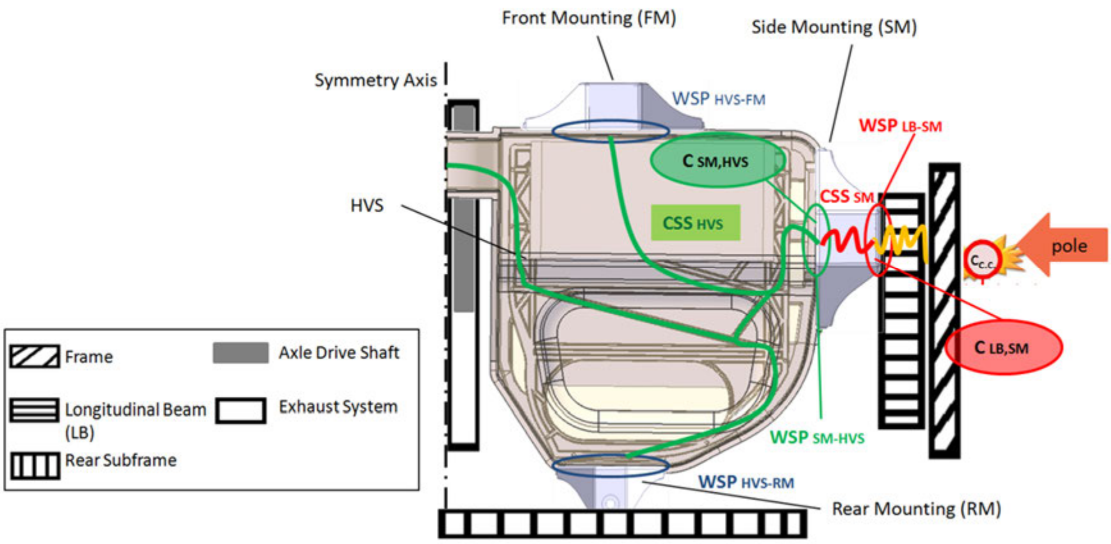

Figure 4. Pole Side Impact on a structural concept of a HVS (C&C²-M)

The side mounting is stimulated by an impulse, caused through the pole side impact between a pole and the chassis of the car (frame and longitudinal beam) at the WSP $_{LB\text{-}SM}$. This impulse is transformed into a force within the CSS_{SM}, which is transmitted via $WSP_{SM\text{-}HVS}$ to the HVS. During the performance of this function the force is transmitted. The force alternates over time and can hence excite vibrations at the HVS itself, and at WSP_{HVS-FM} and WSP_{HVS-RM}. Regarding the third hypothesis of [Albers et al. 2009] ("Functions are the transformation of Input Object Flows to Output Object Flows, using Property Parameters of WSP, CSS and Connectors") Figure 5 visualizes the embodiment of the side mounting.

The main element in this figure is the Input Object flow from the longitudinal beam (specified by Connector C_{LB}), which enters the system at WSP_{LB-SM}. Then it is transformed within an Activity (performed by CSS_{SM}). Finally, it leaves the system at WSP_{SM-HVS} as Output Object Flow towards the neighbor system HVS (specified by Connector C_{HVS}). The effects appearing in WSP_{LB-SM}, CSS_{SM} and WSP_{SM-HVS} are affected by Properties. In this case (figure 5), for example an unmeant effect could be an oxidation because of a material combination (side mounting to longitudinal beam) with a large potential difference. The Property Parameters of the side mounting could subsequently be influenced through topology optimization.

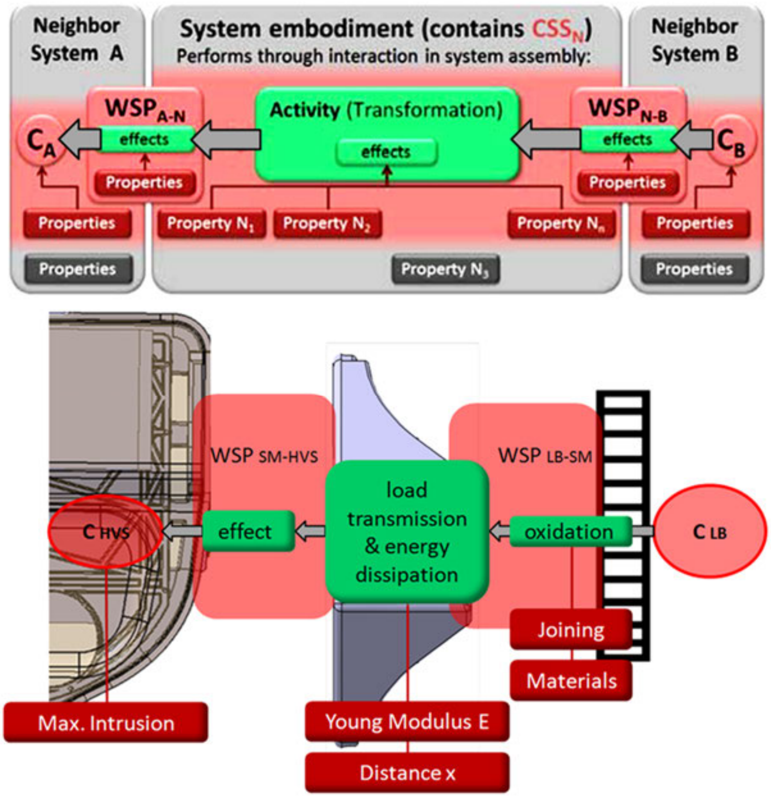

Figure 5. Example of a side mounting in an electric energy storage system

The components (as well as requirements, functions and the use-case of the crash situation) involved in the pole side impact of a predecessor HVS are modeled in SysML and the gained data from vehicle simulations is included. Figure 6 shows a internal block diagram with the ratio of the plastic energy transmission of the pole side impact to the components frame, side rail, longitudinal beam, floor pan, side mounting, HVS, front and rear mounting. The assumed plastic energy that is introduced by the event of a crash into the overall vehicle is 56 kJ. 21,5 % of this energy go into the vehicle frame, 92,5 % of the remaining energy is transformed into the longitudinal beam etc. Accordingly, the shown ratios in Figure 6 are the input parameters of the model and represent the percentage of plastic energy absorption, which passes from one component to the adjacent component.

The plastic energy, which is absorbed during the pole side impact by the HVS is composed according to the results of the crash simulation of the predecessor:

$$E\ (HVS) = 56kJ * 0,215 * 0,925 * 0,046 * 4,15 = 2126,1J \quad (5)$$

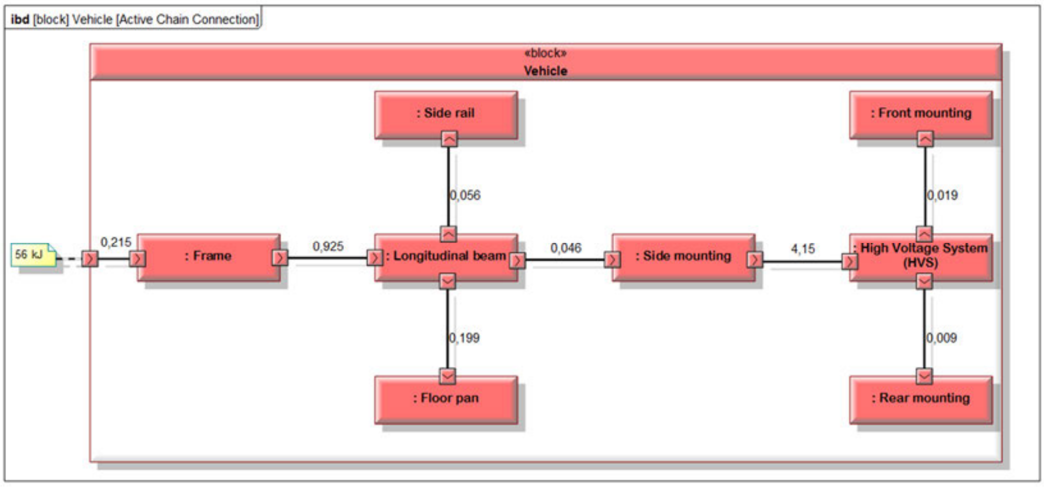

Figure 6. Internal block diagram: Energy transfer of the load path (pole side impact) in a block definition diagram (proportional values added for comprehension) based on a vehicle crash simulation

In the next step, these relationships are utilized to identify ideas for new lightweight concepts respectively to facilitate the dimensioning of the structural components. For this purpose, the system model on the one hand visualizes the current situation of energy absorption and on the other hand indicates the behavior of new concepts. A parametric view and the ParaSolver Plugin for calculation realize the latter:

$$e_n = Z_0 * a * \prod_{i=1}^{n} z_i \qquad (6)$$

- e_n denotes the energy absorption of a component and Z_0 represents the introduced plastic energy (in this case is 56 kJ).
- a specifies the percentage of the transferred energy to the considered subsystem (here 21,5%).
- z_i is the ratio of the absorbed plastic energy of the adjacent components.

As the load on the HVS (especially the contained battery cells) should be minimized, it is useful to calculate a new set of absorption ratios. As an example the incoming energy should be less than 2000J, the new value for the ratio between the side mounting and the longitudinal beam becomes 7,18% (when the other parameters stay constant), see figure 7. This is an extreme simplification of the underlying mechanics, but this approach should demonstrate the basic principle and create initial values for further concept design, rather than random approaches (that tend to be over dimensioned).

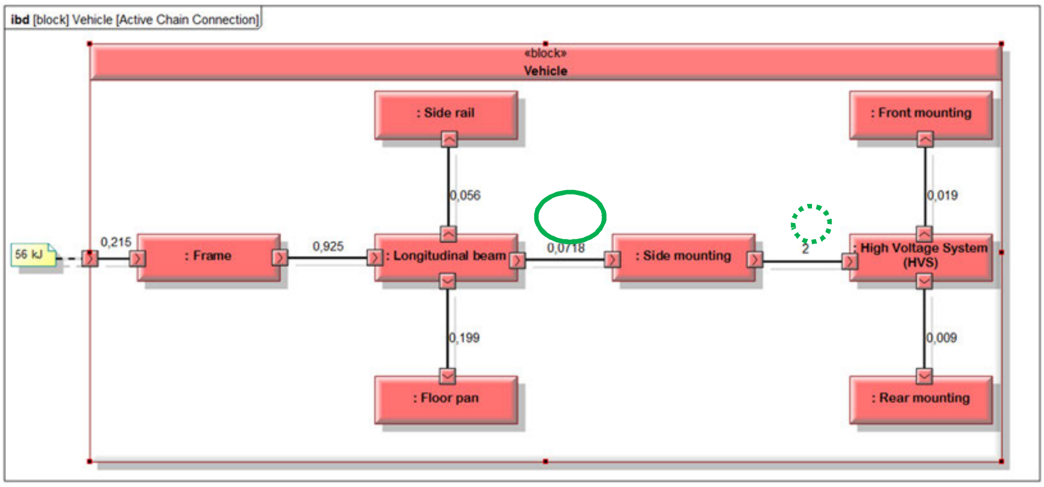

Figure 7. Internal block diagram: New energy absorption ratios calculated for a new design concept (parametric solver) (values added to the figure for comprehension)

Using these calculated ratios, the proposed plastic energy absorption of the side mounting results to:

$$e_{\text{side mounting}} = 56\text{kJ} * 0{,}215 * 0{,}925 * 0{,}0718 = 800\text{ J} \tag{7}$$

This is an estimation of the energy, the side mounting should absorb to protect the HVS for absorbing more than 2000J by keeping the other parameters constant. Another possibility would be to create new paths of energy transmission between the surrounding components in order to bypass the HVS.

3.2 Initial values for topology optimization

Subsequently these values are the basis for the conceptual design of a new side mounting. The previous estimation of the needed plastic energy absorption of the side mounting and further model information (e.g. design space, loads, mounting position, vehicle weight) is used to prepare the boundary conditions of a topology optimization.

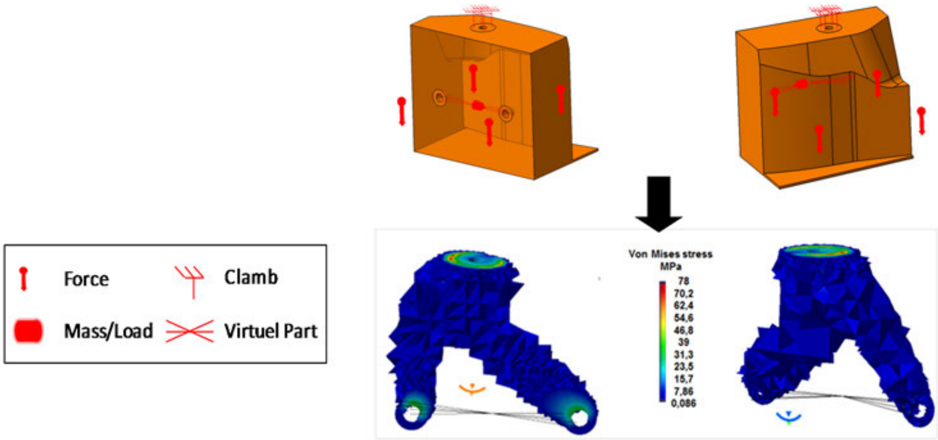

Figure 8. Result in post-processing of the topology optimization mounting design space with a load in x- , y -and z- direction

In the considered case of a side pole crash, especially the kinetic energy of the vehicle E_{kin} and the components, which are involved in the crash are important. For the pole side impact, the kinetic energy, neglecting friction losses, is converted into deformation W_{Def}:

$$E_{kin} = W_{Def} = W_{Def,plast} + W_{Def,elast} \tag{8}$$

This consists of a plastic and an elastic part, while the deformation work W_{Def} can be determined simplified from the multiplication of the deformation s and mean force F_m. At the topology optimization the force or acceleration are considered as mechanical constraints. The available design space or distance to the intruding component are considered as geometrical conditions. The values from the SysML model (e.g. 800 J) are utilized for the dimensioning of the mounting. Figure 8 shows the result of the topology optimization of the side mounting, derived from the available space under operating load conditions. The development of a new set of mounting based on this optimization proofed to be more efficient than a usual iterative process because the subsequent time- and cost consuming vehicle simulations could be reduced. The gained resources are invested in further weight reductions by shape optimization and reduction of security overheads regarding the structural design.
This is a possible connection of the SysML modeling (including calculations) and the topology optimization in order to identify new concepts for the components of the HVS and to facilitate a reasonable embodiment.

3.3 Automated space analysis and optimization preparation

Complementing the design of surrounding components to improve the system weight another option is to enhance the package of the battery cells inside the EESS. To improve the gravimetric energy density, the number of battery cells in the available design space has to be maximized and the surrounding supporting structure minimized at high stiffness and low weight. The common design practice is that a developer arranges the initial package based on his expertise. A new tool automates the arrangement (packaging) of cell modules in a defined geometry of the available design space. The goal is to find unconventional settings and to reduce the duration of the iterations. The packaging script is programmed in Python. The design space is scanned for possible cell module positions and combinations with a specified number of cell modules are generated. If there is no collision within the cell modules, a valid arrangement is indentified (Figure 9). The cell modules are build up parametric, so the cell types and amount of cells is variable. In addition, the integration of further hardware components (e.g. battery management unit) in the design volume is possible. The data input (e.g. dimensions, design space, energy requirement) is stored in the SysML model, but the design space needs to be simplified. The abstracted definition of the design space is realized with two piecewise defined functions for the y- and the z-coordinate (medium complex design spaces).

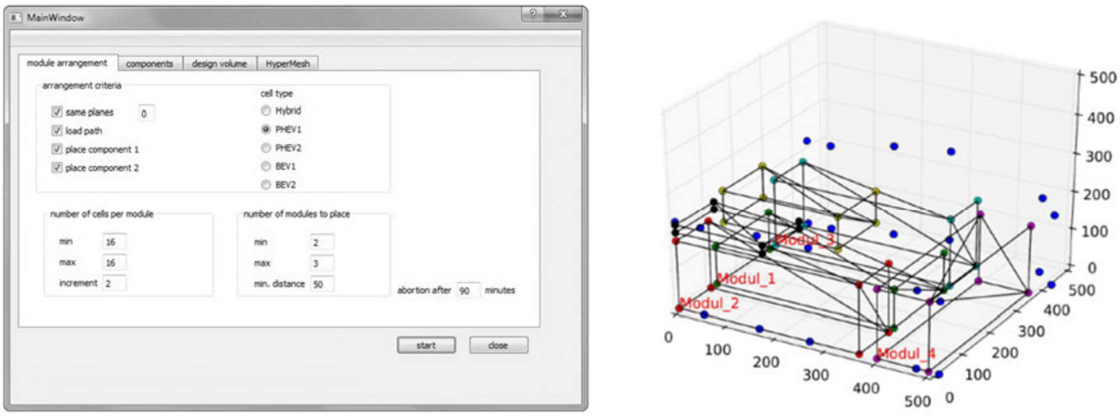

Figure 9. Graphical user interface and exemplary package result

To evaluate and compare the determined arrangements with regard to a following topology optimization, two criteria have been developed. The first criterion represents whether the surfaces of the cell modules match the same planes to reach a well-designed positioning. The second criterion evaluates the positions of the cell modules with respect to the load path between the mounting points of the HVS. Both criteria create an internal ranking of possible arrangement solutions. A graphical user interface (GUI, Figure 9) leads through the possible settings. The definition of the parameters is done once manually but is intended to be realized by a interface to the SysML model (e.g. the design space, weight and measurements of the cells).

The next tool functionality supports further structural studies utilizing the topology optimization (see Figure 10). Therefore, the analysis model of the energy storage for the optimization will be provided automatically in two steps. In the first step, in HyperMesh, the finite element model of the cell modules and the two-dimensional pre-meshed hull geometry of the design space will be imported by an automatically generated command file. Subsequently, the design space between the cell modules and the hull mesh is meshed with tetrahedron elements. Finally, the analysis model is exported to an Abaqus input file. Due to the many possibilities of arranging the cell modules, it is not possible to define the contacts between the cell modules and the design space in an automated way in HyperMesh. Therefore, the second step, the definition of the contact sets and tie contact definitions directly in the input file, is also realized within the programmed Python script. This script searches for the cell module related nodes, which can be identified by a pre-existing node set. Because of the chosen meshing technique, nodes with identical coordinates exist in the design space and can be identified easily and added to a new node set for every placed cell module.

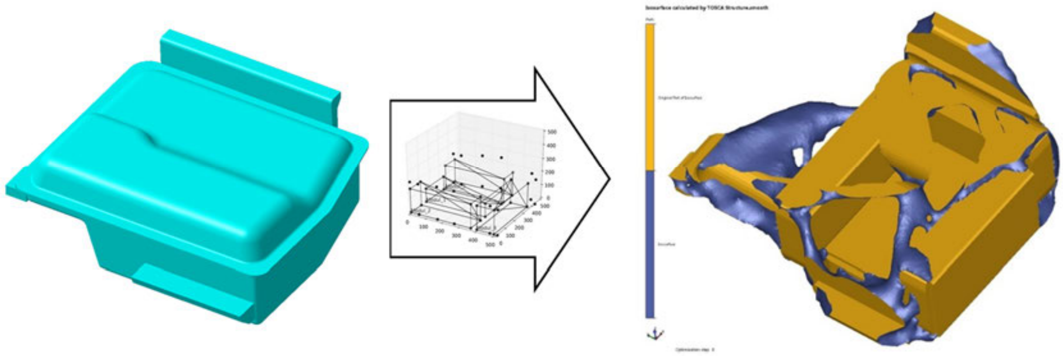

Figure 10. Sequence of the presented method

The results of the packaging and the optimization could add information about the expected structural quality of possible cell module arrangements to the SysML model. The system model and the included requirements and previous solutions help to evaluate the found system designs. Therefore, this approach improves the efficiency of early concept design and allows suggestions in the embodiment activity. For further automated evaluation of the structural designs it is possible to find system specific criteria like the movement of the vulnerable battery cells [Wagner et al. 2013a]. The gathered structures in this case study were compared to conventional housing solutions and revealed a weight reduction potential of 15%.

4. Conclusion and outlook

This paper presents the application and interconnection of design methods in the specific context of the product generation development of electric energy storage devises. For this purpose, a reference product system was analyzed using the Contact and Channel Approach and modeled in SysML. This model also includes the components of the EESS, surrounding systems and their requirements. The model is utilized to store gained simulation data and to calculate simplified assumptions for the impact between the components of the EESS within the vehicle. This is the basis for the identification of weight potentials regarding improved structural components. The calculation results in values that are used to create an initial topology optimization, by defining the geometrical and mechanical conditions. In order to efficiently enhance the HVS design , the authors present a tool to automate the package and automatically prepare a subsequent structure optimization. In summary, the model-based approach using SysML helped the designers to connect and discuss different information gained from the functional analysis and crash simulations regarding the identification of new concepts and their embodiment. Therefore, the tool automates different steps of the embodiment process and enables a broad concept gathering. The integration of these methods in the Integrated Product Engineering Model (iPeM) [Albers and Braun 2011] regarding the activities *idea detection, modeling of principle solution and embodiment* as well as *validation* creates an efficient approach based on the storage of experience (previous product generation) in a SysML model. The presented results could indicate possible interconnections of design methods by the simplified application within the EESS. The model-based data is useful to create efficient procedures and to support the development of product generations as the comparison with conventional solutions revealed significant weight potentials while reducing the development duration.

More criteria need to be integrated in further work in order to improve the tool regarding automated evaluation: for example the integration of thermal dependencies, the electrical connection between the cell modules or restrictions from production. This will help to create results that get closer in overall quality instead of just focusing on lightweight structures. Moreover it is necessary to integrate this approach in existing development processes, especially to build up a consistent system model including all relevant and up to date information. Further applications need to validate there results in different contexts and increase the benefit of the integration while reducing inaccuracies that result from simplifications (e.g. calculation of energy, abstraction of design space).

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