Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 23 (2014) 143 – 148

www.elsevier.com/locate/procedia

Conference on Assembly Technologies and Systems

Battery system development - Assembly planning between lightweight design and high volume production

Alexander Tornow[a]*, Annika Raatz[b], Klaus Dröder[a]

[a] *TU Braunschweig, Institute of Machine Tools and Production Technology (IWF), 38106 Braunschweig, Germany*
[b] *Leibnitz Universität Hannover, Institut für Montagetechnik, 30823 Garbsen, Germany*

* Corresponding author. Tel.: +495313912583; *E-mail address:* a.tornow@tu-braunschweig.de

Abstract

Battery systems of electric vehicles suffer from low energy densities as well as high masses and geometrical complexity. The absence of standards for battery cells and peripheral components in combination with large and distributed design spaces within passenger vehicles open up innumerable possibilities to design battery systems. The results are product specific and uneconomical assembly systems.
This paper describes the work of the TU Braunschweig to create a methodology that generates and evaluates modular and easy to assemble battery systems based upon user requirements. This methodology gathers and links requirements between the priorities "lightweight design" and "high volume production" including a partly automated generation of CAD data. The generated concepts are directly used for assembly planning. The presented methodology therefore represents a simultaneous engineering approach that shortens development time and supports design engineers as well as process planners.

Selection and peer-review under responsibility of the International Scientific Committee of 5th CATS 2014 in the person of the Conference Chair Prof. Dr. Matthias Putz matthias.putz@iwu.fraunhofer.de

Keywords: Battery System; Assembly planning; Design for Assembly

Nomenclature

BCG	Battery Concept Generator
BEV	Battery Electric Vehicle
BIW	Body In White
BSAP	Battery System Assembly Planning
CAD	Computer Aided Design
DABA	Design for Automated Battery Assembly
DfL	Design for Lightweighting
ELVA	Advanced Electric Vehicle Architectures
ICE	Internal Combustion Engine
IWF	Institute of Machine Tools and Production Technology
SLC	SuperLightCar
VBA	Visual Basic for Applications

1. Introduction

The reduction of passenger vehicle mass through the use of innovative materials and manufacturing technologies has been subject of research and development for a long period of time. Results of recent EU-funded projects such as the SuperLightCar (SLC) [1] have proven that it is sufficient to reduce the vehicle mass through the utilization of different materials in different components of the body in white (BIW). However the so called multi-material design involves major research regarding component design, manufacturing and joining technologies. This in particular is necessary if materials such as magnesium and fibre reinforced plastics are used.

The SLC project showed that a considerable reduction of the vehicle mass of a passenger car with internal combustion

Selection and peer-review under responsibility of the International Scientific Committee of 5th CATS 2014 in the person of the Conference Chair Prof. Dr. Matthias Putz matthias.putz@iwu.fraunhofer.de
doi:10.1016/j.procir.2014.10.101

engine (ICE) is possible through the use of multi material design. Future battery electric vehicles (BEV) benefit from these results of recent R&D regarding lightweight design of ICE cars. Nonetheless the vehicle design and thus the used materials and associated manufacturing technologies for BEVs can be radically different compared to ICE. This matter of fact makes it necessary to investigate on the key differences between both types of vehicles and the impact on the optimal approach to minimizing weight. Next generation electric vehicles might have different vehicle architectures and weight distributions that will furthermore have an impact onto the crash worthiness of the complete vehicle. Basis for this change of the vehicle architecture is the electric drive train. Especially the battery system, its high volume, distributed arrangement and considerable mass is a driver for the use of new materials, assembly technologies as well as crash energy dissipation load paths within the vehicle structure.

1.1. Motivation for lightweight and assembly oriented battery system design

Battery Electric Vehicles (BEV) suffer from high costs and a low driving range in comparison to ICE cars. Both the costs as well as the driving range are significantly influenced by the battery system of the vehicle. Roland Berger Strategy Consulting Global showed in [2] that the costs for the production of a battery system will decrease from currently 750 $ per kWh of energy to roundabout 280 $ per kWh in the long term. The battery system costs are split into different components. Figure 1 shows the long term development of battery system costs as predicted by Roland Berger.

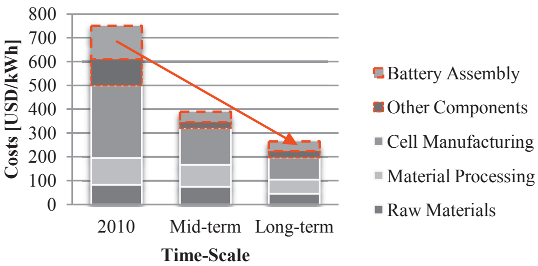

Fig. 1. Development of battery system costs according to [2]

Regarding to this cost projection a 20 kWh battery system will be priced at 15.000 $ in 2010. Two thirds of these costs are related to the raw materials of the cells, the material processing and the cell manufacturing. One third can be traced back to the assembly of the system and the manufacturing of peripheral components. The reduction of these assembly costs is the focused by the IWF within the presented methodology.

According to [3] the gravimetric energy density of lithium ion batteries in comparison to gasoline is still lower by a factor of 100. In order to achieve tolerable energy capacities within battery systems of BEVs it is inevitable to design large systems with high masses.

The lightweight design of the battery system is thus motivated by the relationship between total vehicle mass and energy consumption. This relationship is almost linear within the range of 700 kg to 1700 kg (vehicle mass). Regarding to [4] a reduction of the vehicle mass from 1600 kg to 1280 kg can lead to energy savings of nearly 15 %. This can reduce the required drive power and battery capacity of the vehicle. As a result, both the battery and the mass of the total structure of the vehicle can be reduced. The consequence is an iterative process that reduces the weight of the vehicle in four major steps. Figure 2 illustrates the described relationship.

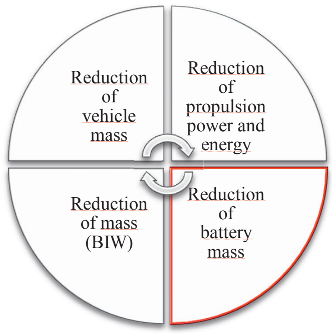

Fig. 2. Lightweight design for EV according to [4]

The following chapter describes the methodology that was developed to gather and link requirements between the priorities "lightweight design" and "high volume production" to create a battery system a typical passenger vehicle.

2. Assembly planning between lightweight design and large scale production

The objective of the work of IWF is to break up the typical design process for the battery system and to answer the question which battery system fulfills the lightweight and assembly requirements best. The main goals are:

- shortening the design phase of the product
- shortening the process planning time
- lowering the costs for the system assembly and
- reducing the weight of the battery.

To fulfill this task a methodology has been created that supports the designer as well as the process engineer. The need for such methodology and the principle is described in [5]. In comparison to the process based approaches presented by [6] or [7] the presented methodology is driven from a design point of view. Figure 3 gives an idea about the procedure that is used to optimize a system. The conceptual basis is the Battery Concept Generator (BCG)-(I). This is the starting point for the iterative optimization of the battery system. It is followed by the steps: Design for Automated Battery Assembly (DABA)-(II), Design for Lightweighting

(DfL)-(III) and Battery System Assembly Planning (BSAP)-(IV).

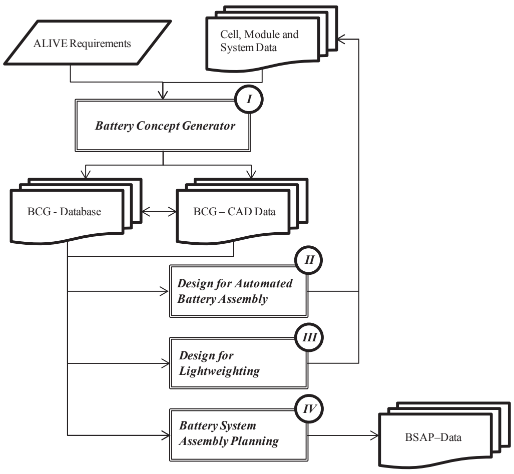

Fig. 3. Flowchart – Methodology for assembly and weight optimized battery systems

2.1. Requirements

The first step is the determination of essential and facultative boundary conditions and requirements for the design and the assembly process planning of a passenger vehicle battery system. These have been derived from expert interviews as well as literature research and will be described shortly.

The scenario that was set up for this work is a near future electric vehicle ready for large scale production and market introduction in 2020. The production volume is assumed to be between 200.000-300.000 units per year.

The allowable costs for lightweight design have been set to 8 €/kg. According to [4] this is the limit value for an electric vehicle with a driving range of approximately 200 km and a specific energy of the battery system of 200-300 Wh/kg. Further measures for weight reduction would lead to a substantial cost increase which has to be avoided at any case. The above mentioned 8€/kg can lead to a maximum weight reduction of approximately 40 % according to [8].

The energy stored within the battery system shall be sufficient to ensure a driving range of 200-300 km. A modular battery system is assumed, that allows the customer to choose between different battery capacities and corresponded driving ranges.

The design space for the battery integration is set to be between typical BIW components, in this case the firewall, the rockers and the rear wheel axle. In order to ensure a specific deformation in the case of a side impact, a deformation zone of 250 mm between rocker and battery system is assumed. The floor of the finished vehicle is the upper border for the design space. The battery should not be mounted lower than the rockers.

The battery system(s) of the vehicle have to have a voltage of 400 V DC. Due to high voltage safety regulations the voltage of a single module has to be lower than 60 V DC. The capacity of the battery system and module is not restricted.

[9] specifies shapes and dimensions for secondary lithium-ion cells for integration into battery packs and systems used in electrically propelled road vehicles. This specification has been used to for the selection of battery cells for the battery concepts. The capacity of the selected battery cells is negligible since different cells have to be evaluated. The nominal voltage of a single cell is assumed to be at 3,6 V.

3. Battery Concept Generator (BCG)

The battery concept generator (BCG) is a visual basic application (VBA) coupled with the CAD-software CATIA V5. It calculates battery concepts based on user requirements such as design space and geometrical and electrical characteristics of cells, modules and systems. The result of the BCG is a list of possible battery systems with their corresponded CAD Data. In order to generate concepts the requirements described above have been implemented into the BCG.

The first step within the BCG is the subdivision of the available design space into rectangular solids and the allocation of priorities of usage. Based upon a market research regarding floor topologies of subcompact and compact cars a catalogue for design space variants has been created. Figure 4 represents a stylized bottom-view of a typical mid –sized passenger car with the greatest possible design space for battery integration.

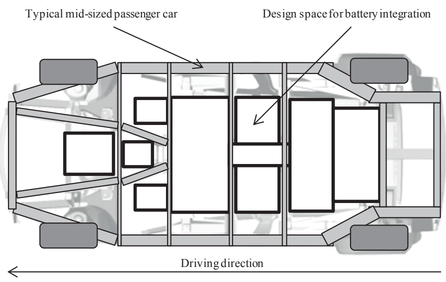

Fig. 4. Available design space for the battery system

Based upon this configuration of design space 12 variants have been derived and implemented into the BCG that differ in topology and volume. Figure 5 shows two examples for these variants. Both variants represent typical topologies for conversion design electrical vehicles whereas the ICE drive train is removed and replaced by an electrical drive train. The vehicle tunnel initially provided for the exhaust system is used for battery integration.

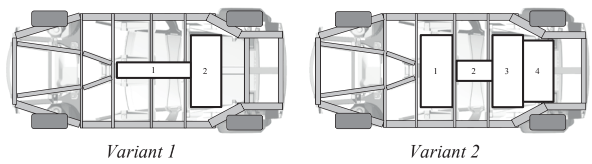

Fig. 5. Example for the subdivision of the design space

The second step is the implementation of cell data into the BCG. As described above the contents of [8] have been used for this purpose. These are:

- Cell shape (prismatic, cylindrical, pouch)
- Dimensions (width, height, depth, diameter)
- Terminal type (threaded, flat, foil)
- Terminal topology (one-sided, opposing)
- Safety elements (overpressure valve)

In addition to the geometrical characteristics of the cell the voltage (min., max. and nominal), capacity, mass and c-rate (charge / discharge) have been implemented.

Finally the electrical boundary conditions have been defined for the battery system (voltage 300-400 V DC, capacity min. 50 Ah) and the modules (voltage max. 60 V DC).

In order to generate modular battery systems it is necessary to implement characteristics regarding the topology of the module. For this purpose the user has to implement geometrical characteristics, material data as well as the topology of the following components:

- the module housing
- the cooling system
- the cell to cell interconnection
- the module controller
- the module fixation

Based upon these boundary conditions the BCG calculates possible system configurations and stores the data within spread sheets. The associated CAD data can be used to get a first visual expression of the system, exclude unrealistic configurations or preselect possible solutions. The diagram within Figure 6 shows the energy capacity and voltage of different battery concepts within design space variant 2 (figure 5). Within these examples a module design based upon frames in which pouch cells are stacked is used.

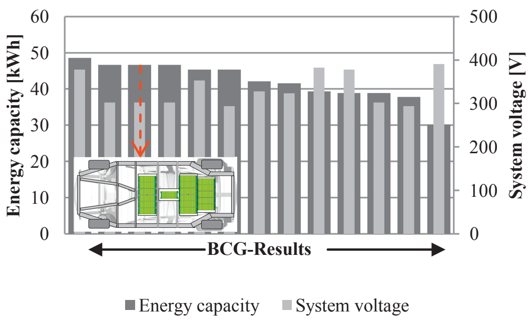

Fig. 6. Selected results of the BCG

The concept marked red has an energy capacity of 46 kWh and a system voltage 302 V (max.). It consists of 18 identical modules that are distributed under the seat of the driver and passenger, the vehicle tunnel and the rear seats. Each module consists of 24 pouch cells stacked in a single row. The other examples within the diagram differ in module length (incorporated cell number), cell stacking order and module topology. In order to identify optimal system topologies for assembly the results are evaluated by the Design for Automated Battery Assembly (DABA) routine.

4. Design for Automated Battery Assembly (DABA)

The DABA evaluation tool is directly linked to the BCG. It evaluates the battery concepts through an analysis of weighted assembly characteristics of (I) the cell, (II) the module and (III) the system. The value necessary for evaluation is either available within the output of the BCG or has to be determined through experiments. A partly dynamic 9-point-scale in combination with linear, exponential and logarithmical value functions has been selected for the evaluation each criterion.

The evaluation of module components in particular battery cells and the evaluation of system designs is described in the following section.

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. The following examples show the cell characteristics and the most influenced assembly characteristics based upon the created criteria catalogue.

A: Cell shape and mass
(rest position, gripping device, gripping force):

Battery cells are available in cylindrical and prismatic shapes, various dimensions and masses. The center of gravity in combination with the shape and orientation of the cell define the static or non-static rest position. This furthermore influences for example the hoisting device. The mass and shape of the cell have a major influence onto the gripping forces and corresponding handling devices.

The characteristics are directly available within the output of the BCG. For example a large cylindrical cell with flat terminals on opposing cell sides is ranked lower within the DABA tool than a prismatic cell with a stiff housing.

B: Lock-and-key characteristics
(detection of rest position, detection of polarity):

The shape of the cell, the type of the positive and negative terminal as well as safety components such as gas ducts generate lock-and-key characteristics that can be used for a fail-safe assembly. In order to automate the evaluation of these characteristics the DABA tool is linked to a battery cell database [9] wherein the named characteristics are pre-evaluated. The lowest value is assigned to a small cylindrical cell with flat terminals on opposing cell sides. The highest value is assigned to a prismatic cell with color- and geometry coded terminals as well as geometry coded gas duct.

C: Terminal type and topology
(part count, joining direction, gripping surfaces):

The terminal type defines the number of additional components for the interconnection between one cell and the next. For example a battery cell with terminals designed with external threads consequently needs threaded nuts as well as an additional element for the cell to cell interconnection.

The topologies of the cell terminals intrinsically define the gripping surfaces and variants of resting positions. A prismatic cell with terminals on opposing sides decreases the possibility of gripping with a two finger gripper from 3 to 2.

D: Housing type
(gripping technology, gripping device, gripping force, gripping surface):

Battery cell housings can differ in material type and corresponding manufacturing technologies. The different types influence the assembly process in terms of gripping principle, gripping type, gripper topology and gripping force. Pouch cells are of special significance for the assembly process because of their flexible and easily damageable housing type which is made from multi layer foils with an aluminum vapor barrier. These housings have to be handled with care. The DABA tool incorporates an automated gripper selection depending on the choice of the cell and its characteristics.

E: Additional handling difficulties
(flexible, adhesive, abrasive, sharp edges, slippery, easily damageable, interlocking):

Apart from the cell characteristics typical properties that complicate the handling of components during the assembly process have been collected from existing methodologies such as [10] and implemented within the DABA tool. If any of these properties are true for the considered component penalty points will be assigned to the total evaluation.

Figures 8 shows an example of the evaluation of a small cylindrical cell in comparison to a prismatic cell with steel housing and threaded terminals as well as a pouch cell (figure 7). The different cell types are evaluated according to the criteria described above (*A* to *E*). The evaluation is based upon a 9-point scale in which a score of 9 represents the best fulfillment of the criteria. In this specific case the DABA tool suggests the prismatic cell type because of its robust gripping surfaces, unambiguous assignment of lock-and-key characteristics, stiff housing type and the absence of additional handling difficulties.

The results are added to the corresponding battery concept within the spread sheet list of the BCG. The next step is the evaluation of the battery module.

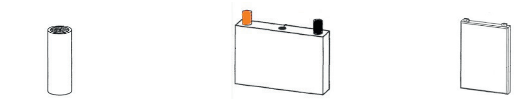

Fig. 7. Example of cell types

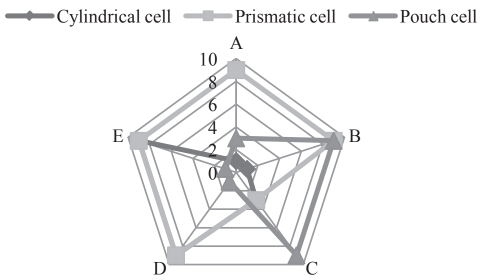

Fig. 8. Assembly evaluation of three battery cells

The components of the modules extracted from the BCG are evaluated in the same way. Additional evaluation criteria are added and grouped as *Module components*. Herein the overall number of components within a module, the number of identical components and the ratio between cells and peripheral components is evaluated.

As a further example the evaluation of the topology of battery modules within the design space is presented on the basis of the concept depicted in figure 9.

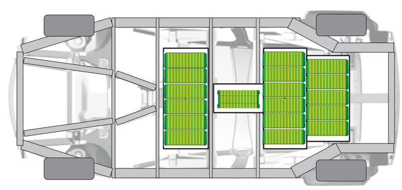

Fig. 9 Battery concept with module topology

Module variants

The number of different module variants consequently enlarges the assembly effort because different components with different quantities have to be assembled at (possibly) different locations within the assembly line. The depicted battery system is build up from identical modules which leads to a high value for the criteria *module variants*.

Single module position & orientation

The position and orientation of a single module influences the number of additional supports for fixation. Within the given example the module can only be fixed without additional support if the terminals are directed in positive z-direction within the vehicle coordinate system. This is only the case for the module inside the vehicle tunnel. Furthermore if a module is placed between two other modules and the mounting direction is top down only one sequence for module mounting is possibly. This is the case for all three groups of modules. Consequently a low value for these criteria is given through the DABA tool.

Module group position & orientation

Groups of modules are rated with a high value if they are aligned in rectangular grids. Offsets in x-, y- or z-direction as well as tilts require additional mounting supports and complicate the assembly process. This will reduce the value for this criteria group. The given example shows rectangular patterns to a great extend. However the part of the system that is placed underneath the rear seats consists of two groups of modules that are arranged with an offset. This reduces the maximum value for the arrangement of module groups.

Summarized the DABA tool evaluates each battery system concept that was calculated by the BCG and adds an assembly ranking which is translated to a percentage value. Afterwards this value is compared with a percentage value that reflects the electrical characteristics of the battery systems such as energy capacity and system voltage. The comparison of both characteristics results in a trade-off relationship: A high degree of design space utilization results in a high energy capacity but corresponded high assembly complexity. The analysis of different battery concepts with regard to high energy capacity and low costs resulted in the following system topology:

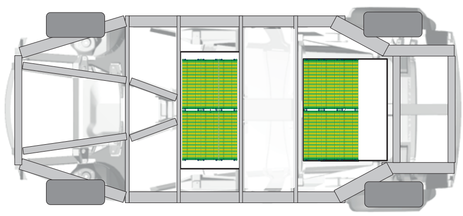

Fig. 10. Assembly optimized battery system concept

Herein 12 identical modules are separated into 2 identical subsystems with identical electrical characteristics. Each subsystem has a high degree of identical components. Each module can be assembled in z-direction and no specific order.

5. Battery System Assembly Planning (BSAP)

The methodology finishes with the planning of the assembly system based on the detailed product and physical demonstrator. Apart from the geometrical and gravimetrical characteristics of the components of the battery system the assembly priority plan is directly available from the BCG. Through the use of the DABA tool single components such as gripping systems for the cells and module components are preselected. Potential bottlenecks within the assembly levels module, subsystem and system can be identified through a graphical analysis of the material flow. The next steps within the methodology will be the investigation of critical assembly steps through with physical demonstrators.

6. Summary and Conclusion

A methodology has been presented that generates and evaluates modular and easy to assemble battery systems in a short period of time. Based upon user requirements regarding electrical and geometrical boundary conditions of battery systems system topologies for different design spaces are calculated. The design engineer that uses this methodology is supported by the Design for Automated Battery Assembly tool in order to select system concepts that guarantee an easy assembly. The DABA tool is split into different evaluation levels (cell, module, system). If necessary the secondary lightweight potential of battery concepts can be integrated into the overall evaluation to identify optimized system concepts between the priorities “lightweight design” and “high volume production”. Through the iterative procedure a continuous refinement of the battery system design is possible.

Through the use of the methodology it is possible to identify optimal system configurations for specific design spaces, identify optimization potentials regarding module and cell designs and locate bottlenecks within the system assembly. However a refinement of the single parts of the methodology is necessary. In particular an experimental analysis of key assembly steps to consolidate the DABA criteria is necessary.

References

[1] Innovative Developments for Lightweight Vehicle Structures, Conference Proceedings, Volkswagen AG, 2009, Wolfsburg, Germany

[2] Roland Berger Strategy Consultants, Powertrain 2020, The Li-Ion Battery Value Chain – Trends and implications, 2011, Stuttgart

[3] Schätzler, Katharina, Chancen der Energiewende : wissenschaftliche Beiträge des KIT zur 1. Jahrestagung des KIT-Zentrums Energie, 2012

[4] Eckstein, L.; Schmitt, F.; Hartmann, B.: Leichtbau bei Elektrofahrzeugen. In ATZ elektronik, 2010, 112; S. 788–795.

[5] A. Tornow and A. Raatz, “Conceptual DFA method for electric vehicle battery systems”, Proceedings of the 4th CIRP conference on assembly technologies and systems, 2012, Ann Arbor, MI

[6] Designing Productive Assembly System Configurations Based on Hierarchical Subassembly Decomposition with Application to Automotive Battery Packs, Sha Li, 2012, Dissertation, University of Michigan

[7] Planning and simulation of high-voltage energy storage assembly for automotive industry – from scalable product concepts via assembly planning and material flow simulation through to web-based assembly information, Jochen Bönig, Christian Fischer, Markus Brandmeier. Thorsten Mersdorf, Thomas Braun, Claudia Mrugalla, 2013, Advanced Materials Research Vol. 769 (2013) pp 42-49, Erlangen

[8] Hofer, J.; Wilhelm E.; Schenler, W.: Optimal Lightweighting in Battery Electric Vehicles, EVS26, Los Angeles, California, 2012

[9] ISO/IEC PAS 16898:2012, Electrically propelled road vehicles -- Dimensions and designation of secondary lithium-ion cells, 2012

[10] Product Design for Manufacture and Assembly, Geoffrey Boothroyd, Peter Dewhurst, Winston A. Knight, CRC Press, 2010