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WEIGHT AND COST REDUCTION OF THE THERMAL MANAGEMENT FOR TRACTION BATTERIES BY USING THE DSM METHODOLOGY

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Keywords: design optimization, matrix-based product description, DSM, lightweight design, cost reduction, decision making

1. Introduction

The advancement of electromobilty is based on the discussion of greenhouse gas emissions, the associated climate change and the shortage of oil reserves. After evaluating the requirements regarding energy storages like power and energy density, cost, durability, cycle stability and saftey, the li-ion cell is attested a large potential in the automotive industry for present and future serial applications. With these cells, which are connected parallel and in series to increase the capacity and the voltage, modules are formed and then connected together to the battery to drive electric vehicles. The disadvantage of this technology is the high price of the cells, which is currently about 500 €/kWh [Wallentowitz 2010]. Due to these high costs, the potential of this cell technology has to be exploited optimally and fast cell aging has to be avoided. For accomplishing this, it is essential to operate with a homogeneous temperature distribution and in a temperature range specified by the cell manufacturer. Operation during low temperature applies to a reduction of performance and efficiency. Temperatures above 40°C lead to the loss of Li^+-ions and active materials and therefore to a reduction of capacity and an increase in resistance [Vetter et al. 2005]. So, the optimum operating temperature of li-ion cells is between 15 to 35°C [Schuler 2011]. To achieve these goals, the li-ion cells have to be monitored and if necessary controlled by a thermal management. Therefore, an approach with the focus on the main requirements “cell temperatue”, “cost” and “lightweight design” is proposed in this paper in order to support developers to evolve the complex thermal management for li-ion cells.

1.1 Complexity of the thermal management of li-ion cells

There are various concepts for electric vehicles, which differ in the power convertor, the size of the battery pack and the possibility to drive only with gasoline, with electricity or with both. In the implementation of the drive concepts, it can be selected between three different designs of li-ion cells. There are prismatic, pouch and cylindrical cells, which have different geometrical, mechanical and thermal properties. Due to their specific advantages and disadvantages, these types of cells can be found in various electric vehicles. For these cell types, suitable concepts for the thermal management of li-ion cells have to be developed and thereby the climatic conditions have to be considered. Subsequently, it has to be differentiated between cold regions (e.g. Scandinavia) and hot regions (e.g. Nevada) on the one hand and between the four seasons on the other hand. The differences and variations in the temperature data must be taken into account in the design of the thermal management. Depending on the ambient temperature and on other general requiremts of the OEMs concerning the temperature, a suitable thermal management concept is required. This results in several challenges for the product developer. The following four aspects regarding the cell temperature are particularly important:

- The minimum and maximum temperature of the cell
- The gradient of the temperature in one cell
- The gradient of the temperature between the cells
- The optimal operating temperature

Currently, the quantitative fulfillment of these requirements regarding these temperatures is depending on the manufacturer and varies from cell to cell. Finding the optimal solution for an appropriate thermal management system by taking into consideration the requirements for every combination of drive concept and li-ion cells is very challenging for product developers because there are different factors that influence the temperature of the cell.

1.2 Objectives and overview of the approach

To meet the requirements relating the temperature, the thermal management consists of various components, which perform different functions. Each of these functions has a weight and a cost share of the total thermal management system. To reduce weight and cost of the thermal management in particular, the expensive and heavy functions have to be identified with the help of the value engineering methodology. Thereafter, the identified functions have to be optimized in terms of cost and weight. Prior to the optimization of a function, it is essential to understand which modification of individual characteristics has an effect on properties of the complete system. For this purpose, the matrix-based product description is used in a simplified industrial case study. This makes it possible for the developer to understand and to recognize the numerous, complex dependencies and relationships between all requirements, functions, properties and characteristics. For instance, the developer has the possibilty to change the determing characteristics of the thermal management system in order to reduce the cost and weight without decreasing the performance. By using the matrix-based product description, a basis for a transparent and objective communication among engineers and managers is provided for improving decision making in early design phases.

2. State of the art and related work

2.1 Value engineering

In [DIN 1325-1], the value engineering is actually defined as an organized and creative approach, which has a function and economic orientated design process with the aim of bringing the appreciation of a value engineering object to the application. The aim of the value engineering procedure is to re-cognize all non necessary costs for the value and/or the function of a product and eliminate them. In 2000, the [VDI 2800] divided the value engineering procedure into six steps. Due to the European standardization, this [VDI 2800] was expanded to ten steps in 2010 [VDI 2011]. However, the approach of the year 2000 is the most widespread, and therefore this one is explained thereafter:

1. Prepare project: First define the task, define target, build team, plan the process
2. Object analysis (actual state): obtain information, describe functions, identify function costs
3. Define target state: check the function performance and the costs
4. Develop solution ideas: search for ideas
5. Define solutions: check the feasibility and the economics
6. Implement solutions: choose, recommend and realize one solution

One focus is the decomposition of the main function into subfunctions with decreasing complexity in comparision to the main function and their assignment to the assemblies and single parts. The costs of the different functions can be estimated from the calculated costs of the single parts. These functional costs, which should be minimized, are the basis for the evaluation of design concepts and alternatives. After connecting the requirements with functional costs, solution ideas can be developed and afterwards checked and realized. To sum up, the six steps emanate from a design, which is analysed in terms of functions to be fulfilled and costs, which are reduced with this approach [Pahl et al. 2007].

A new approach for conceptual lightweight design in early design phases based on target costing and value engineering was presented in [Albers et al. 2013]. To identify the most recommended weight reduction, a functional analysis is necessary. Instead of cost, the mass was mapped to each function in this approach. In this way, it is possible to analyze the functions to be achieved together with their corresponding masses. This allows to search for new solutions of each function to realize weight savings in order to optimize the product regarding lightweight design [Albers et al. 2013].

2.2 Matrix-based product description

The interactions and dependencies between requirements, behaviours, properties, functions, active principles and characteristics within the thermal management system mentioned in chapter 1 can be mapped systematically by using a matrix-based product description. This matrix-based product description is shown in Figure 1 and consists of several Design Strucure Matrices (DSM) which are on the diagonal of the matrix (e.g. requirement matrix) and Domain Mapping Matrices (DMM) which are above/below the diagonal and therefore represent a Multi Domain Matrix (MDM) [Krehmer 2012].
A DSM is a square matrix which shows the dependencies between elements of a product or system in a visual and analytically advantageous description [Browning 2001] and has been used to model many different types of systems [Eppinger et al. 2012]. A DMM is a rectangular (m x n) matrix relating to two DSMs. Thereby, m is the size of one DSM and n is the size of the other DSM. By using the MDM (Figure 1) several analysis can be conducted and these have, inter alia, the following benefits: capturing the dynamics of product development, showing traceability of constraints across domains, providing transparency between domains, synchronizing decisions across domains, cross-verifying of domain models and analysing the complex dependencies and relationsships between elements [Danilovic et al. 2007]. As a result, the matrix-based product description can be filled with information step by step – starting from the customer requirements (RE) – regarding the respective behaviour (B), properties (P), characteristics (C), as well as the function structure (FC) and active structure (AS) of the overall system level (OSL), the subsystem level (SSL) and the component level (CL) [Luft et al. 2013b].

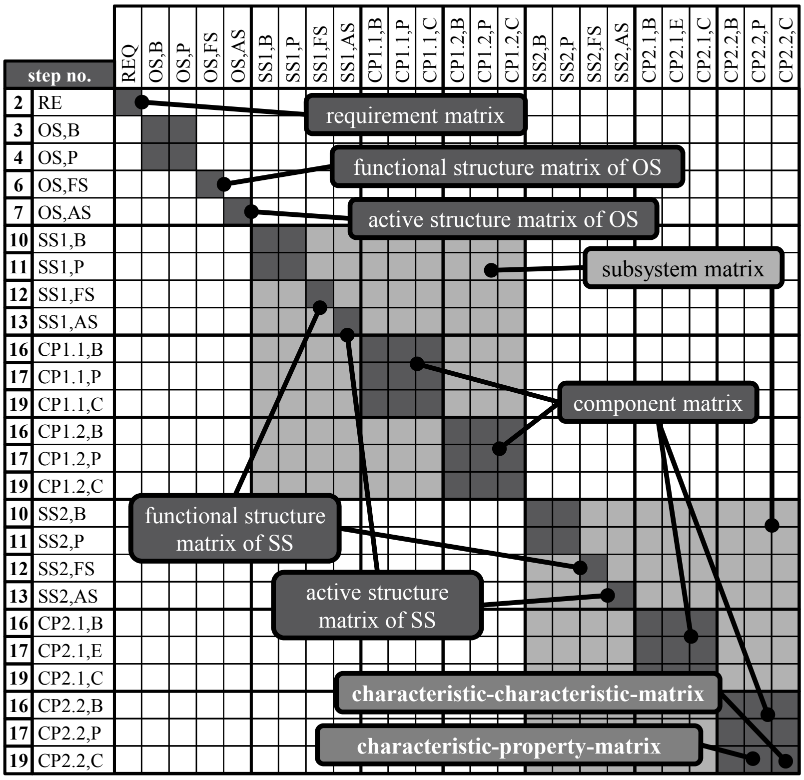

Figure 1. Simplified and schematic overview of the matrix-based product description according to [Krehmer 2012] and [Luft et al. 2013b]

The understanding of the terms “characteristic” and “property” in this work is particularly based on the definitions in [Weber 2005]. The properties of a product cannot be directly determined but are the

result of various characteristics, which are directly determined by developers. Consequently, the characteristics are the direct “setscrews” of product developers for determining the product’s property profile. Thereby, properties can be either quantitatively (e.g. cost, stiffness, weight) or qualitatively measurable (e.g. aesthetics, manufacturability, environmental friendliness). Following this understanding, it can be differentiated between intensive and extensive properties [Roozenburg 2002]. For instance, material characteristics belong to the intensive properties, which are the result of the selection of physic-chemical characteristics (e.g. choice of material). The extensive (or actually realized) properties of a component (e.g. stiffness, weight) arise from the combination of the intensive properties and the geometrical characteristics (e.g. length, width, height). The (structural) dependencies between the (extensive) properties of the components are defined by the determination of structural characteristics (e.g. distance, angle). This leads to the properties of individual product modules, its required functions, which are achieved by appropriate active principles and in a further step to the properties of the entire product. The behaviour of the product, which is relevant for meeting the customers’ requirements, is obtained as a result of the realized product properties by taking into account the actual usage and environmental conditions [Krehmer 2012].
A great advantage of the matrix-based product description is the mapping of multiple dependencies, for example of defined characteristics and resulting properties. By mapping, for instance, the dependencies between characteristics and properties in a characteristic-property-matrix (see Figure 1), it can be analysed, which unintended effects on properties have intended modifications of certain characteristics. Hence, deviations from required properties together with their related causes or effects can be recognized very early in the development process. As a result, better alternatives can be identified as well as their corresponding consequences can be estimated accurately. In addition, it is also possible to reconstruct the impact of changes of certain characteristics on the component, subsystem and overall system level. The matrix-based product description was already evaluated by using the example of a chassis and further developed (e.g. different types of dependencies) in [Luft et al. 2013b].

3. Methodology to reduce cost and weight of thermal management

In the following chapter a new methodological approach is described in order to reduce the cost and weight of the thermal management system of traction batteries. As shown in Figure 2, this approach includes four steps. The first step, the definition of requirements, is not in the focus of this paper and therefore these requirements are assumed to be known (see chapter 1.1). The next three steps are explained in detail in this chapter. The thermal management system consists of a huge number of functions and components, which make it even impossible to present it in its complexity in this paper. In order to demonstrate these steps clearly, only a selection of these funtions and components of the whole thermal management will be discussed in the following. This approach has been successfully used and validated for a thermal management system for traction batteries at an automotive supplier.

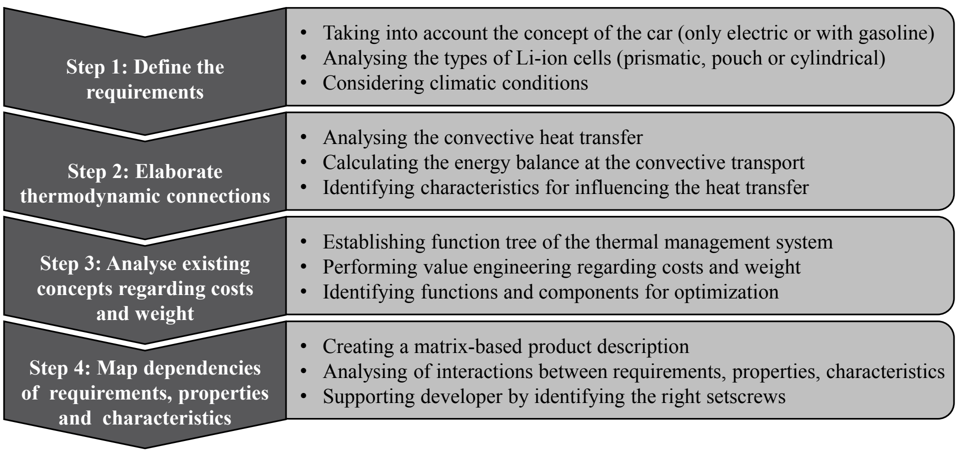

Figure 2. Procedure to reduce cost and weight of the thermal management system

3.1 Elaborate thermodynamic connections

To improve the thermal management system, it is necessary to understand the thermodynamic connections of the system, which is the aim of step 2 in this approach. To regulate the temperature of the cell, it is essential to bring heat into or out of the cell. A important thermodynamic factor for this is the heat transfer and this one will be explained in this chapter exemplary.

Heat transfer is the transfer of energy through a system boundary because of gradients in temperature. The result is a change of entropy in the system. Regarding the total energy, heat is always transfered from the hot to the cold in three different types [Polifke and Kopitz 2009]:

1. Heat conduction: diffusive energy transport in solids or fluids
2. Convection: carriage of heat in flowing liquids or gases
3. Thermal radiation: exchange of heat between bodies at different temperatures by electromagnetic radiation in the wavelength range from 0.1 to 1000 µm (visible light and infrared)

3.1.1 Convective heat transfer

Analyses of heat transfer have shown that convection has a significant influence on the tempering performance of a system and therefore it is considered in the following. Convection means the transfer between a component and a fluid moving relatively to each other. A distinction has to be made between free convection and forced convection. Free convection is caused by body force (e.g. buoyancy force) as a result of distinction in temperature respectively density of the medium. Different to this, at forced convection the flow of the medium is caused from an external power (e.g. pump, air blower). Newton described these thermodynamic relations in equation 1 [Polifke and Kopitz 2009].

$$\dot{Q} = \alpha \cdot A \cdot (\mathrm{T}_{CE} - \mathrm{T}_{TM}) \tag{1}$$

The rate of heat flow $\dot{Q}$ (in W) depends on the heat transfer coefficient α (in W/(m^2·K)), the surface A (in m²), the cell temperature T_{CE} (in K) and the temperature of the tempering medium T_{TM} (in K). All parameters can be measured exactly (except heat transfer coefficient α). The heat transfer coefficient depends on the form of the flowed component, the hydrodynamic and the thermal conditions [Polifke and Kopitz 2009]. The medium and the flow speed as factors of the heat transfer coefficients are shown in table 1. In this table, it is distinguished between free and forced convection and between air and water. Water has a higher heat transfer coefficient than air and as a consequence a higher heat flow. Thereby, the heat transfer coefficient is higher at forced convection (flowing) compared to free convetion (static) and with increasing flow speed the heat transfer coefficient is increasing. As a consequence, the heat flow can be influenced by the selection of a different medium and flow speed.

Table 1. Heat transfer coefficient between a metal wall and air/water [Böge 2013]

		Heat transfer coefficient (W/(m²xK))
Static air		5 - 10
Flowing air	10 m/s	45 - 70
	20 m/s	95 - 120
	40 m/s	150 - 190
	50 m/s	190 - 220
Static water		600
Flowing water ≤ 1 m/s		1700 - 3700

3.1.2 Energy balance at the convective transport

The convective transport describes the transfer of enthalpy in a flowing fluid. Taking into account the mass and energy balance, the whole system is considered in this chapter. The heat flow of the system is described in equation 2 [Polifke and Kopitz 2009].

$$\dot{Q} = \dot{m} \cdot c \cdot (\mathrm{T}_{TM\_EX} - \mathrm{T}_{TM\_EN}) \tag{2}$$

The rate of heat flow $\dot{Q}$ (in W) depends on the mass flow (in kg/s) and the specific heat capacity c (in J/(kg·K)) of the tempering medium. Further, it depends on the difference between the temperature of tempering medium at the entrance T_{TM_EN} (in K) and the temperature of the tempering medium at the exit T_{TM_EX} (in K) of the system. All these parameters are properties of the tempering medium or can be measured exactly. So the heat flow of the complete system can be determined precisely.

3.2 Analysing existing concepts regarding cost and weight

The third step of the approach shown in Figure 2 is to analyse an existing concept using value engineering. Therefore, a simplified function tree is generated, then a tempering plate is explained and finally a value engineering regarding cost and weight is done in this step.

To enable a long service life of the cells and to realize a battery-driven vehicle, the cells must be tempered, which is the main function of the thermal management system. A lot of subfunctions are necessary to fulfill this task. Exemplary, three subfunctions are shown in Figure 3. The first one is to regulate the tempering medium. For this purpose, it is necessary to supply a tempering medium (e.g. water-glycol), to generate a mass flow (e.g. with a pump) and to control the size of the mass flow. The second subfunction is to guarantee the safety. Concerning this, the establishment of the mechanical stability of the thermal management system is necessary as well as the guarantee of the leak tightness, which is important because of the danger of short circuit at any leakage of fluids. The last subfunction is to cool the cell. Therefore, it is required to know the temperature of the cell, to dissipate the heat from the cell and to ensure the thermal contact between the heat dissipating and the cell.

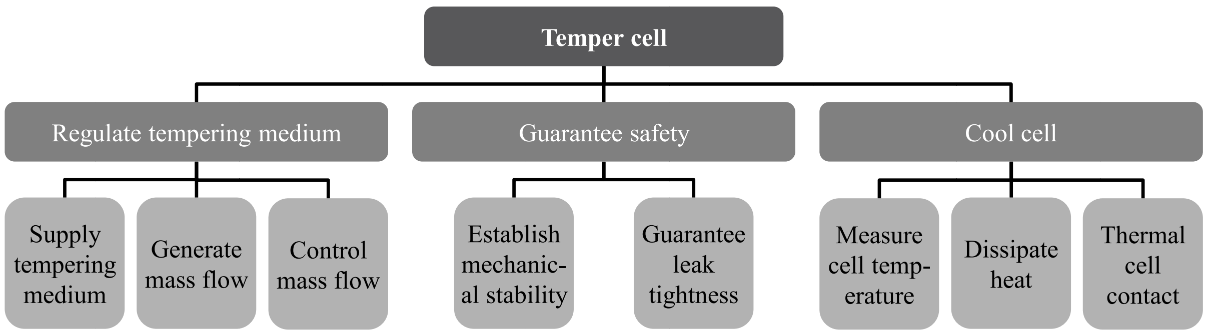

Figure 3. An excerpt of a function tree of the thermal management

As an example a simplified tempering plate of one module is shown in Figure 4. It consists of two plates screwed together and the tempering medium in between. There is a sealing ring between the two plates to guarantee the leak tightness. The sealing plate has the sealing groove for the sealing ring, the clearance hole for the screws and the geometry for the flowing medium. The bottom plate consists of the entrance and the outlet of the flowing medium and the threads for the screws.

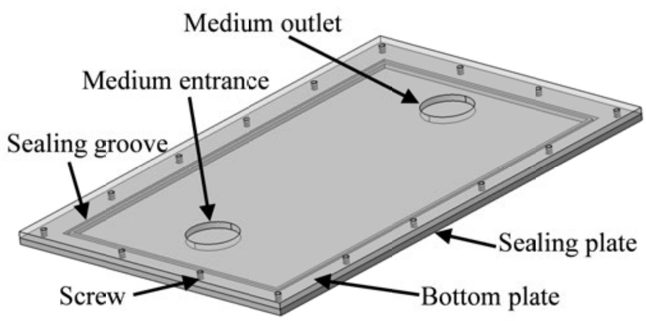

Figure 4. Temper plate of a cell module

The temper plate can partially be described with the functions above. These functions are to dissipate the heat from the cells, the thermal cell contact, to generate the mass flow, to guarantee leak tightness and the mechanical stability. Herefore, different components are indispensable, like the single

components of the tempering plate, a thermal conductive foil and a pump. For the the first two functions listed above and the corresponding components described, the value engineering (see chapter 2.1) is applied exemplarily with the aim to identify functions and components for cost and weight reduction.
Therefore, in Figure 5, the actual costs and weights of each component get assigned. It has to be noted, that the costs get estimated in this case study, because they depend on various factors such as for example the specific number of pieces. The weight of each component is determined by using a CAD program. To establish a connection between the components and the funtions, each component gets a correlation (*s* = strength) with each function, whereby "0" means no correlation and "3" represents a strong correlation. After normalizing (*n*) the strengths, every component (*c*) gets a functional cost (*fc*) and a function weight (*fw*) assigned. With that, it is possible to show which proportion of the cost and the weight of each component can be assigned to each function. Due the summation of each *fc* respectively *fs* of each component, the actual functional costs and weights are determined.

Costs of components (in €)	Weights of components (in g)	Functions / Components	Dissipate heat				Thermal cell contact			
			s	n	fc / c	fw / c	s	n	fc / c	fw / c
400	688	Sealing plate	3	0.3	133.3	229.3	1	0.1	44.4	76.4
300	998	Bottom plate	3	0.3	90	299.4	2	0.2	60	199.6
1	32	Screws	0	0	0	0	0	0	0	0
7	9	Sealing ring	0	0	0	0	0	0	0	0
250	263	Pump	3	0.5	125	131.5	0	0.5	5	0
5	76	Thermal conductive foil	0	0	0	0	3	1	0	76
Σ = 963	Σ = 2066				Σ_{fc} = 348.3 €	Σ_{fw} = 660.2 g			Σ_{fc} = 109.4 €	Σ_{fw} = 352 g

Figure 5. Object analyse (actual state)

In Figure 6, the targets for costs and weights get defined and each function gets its share assigned. For defining the target of costs and weights, it is possible to use target costing and target weighting. Objective in this case study is to reduce the mass and the cost by 20 percent. For that, first the requirements get weighted. A selection of requirements is listed in Figure 6 whereby the weighting is depending on the concept of the car. After specifying and normalizing (*n*) the strength (*s*), the relevance of each function (*rf*) matching the requirements can be calculated. Multiplying these calculated relevance of every function with the target costing and weighting results in the target costs and weight of any function. Subsequently, it is possible to compare these targets with the actual state of Figure 5 to identify the functions for reducing costs and the weight.

Requirements	Functions / Weighting	Dissipate heat			Thermal cell contact		
		s	n	rf / requirement	s	n	rf / requirement
Minimum & maximum temperature cell	0.15	3	0.4	0.06	1	0.1	0.02
Spec. gradient temperature in one cell	0.1	3	0.3	0.03	3	0.3	0.03
Spec. gradient temp. between the cells	0.15	3	0.3	0.05	3	0.3	0.05
Optimal operation temperature	0.1	3	0.4	0.04	1	0.1	0.01
Optimal safety	0.5	0	0	0	0	0	0
				Σ_{rf} = 0.19			Σ_{rf} = 0.12
Target costing [€]	770.4	Target costing function		146.7 €			91.7 €
Target weighting [g]	1652.8	Target weighting function		314.8 g			196.8 g

Figure 6. Define target state

One result of this analysis is that function "dissipate heat" must be reduced from 348.3 € to 146.7 € (58 percent) and from 660.2 g to 314.8 g (52 percent). To achieve these aims without reducing the performance of the thermal management at the same time it is essential for the developer to modify the right "setscrews". In the following this is exemplary shown at the sealing plate, which has a high part at the function "dissipate heat", concerning the costs and the weight.

3.3 Mapping dependencies of requirements, properties and characteristics

Using this matrix-based product description in an industrial case study, all the dependencies and interactions within the product can be mapped systematicaly in the development process. For instance, developers have to create characteristic-property-matrices for all components (e.g. sealing plate) since properties can be realized only through the determination of characteristics (i.e. setscrews). Afterwards, all required characteristics (e.g. lenght, material) are defined for the individual components (e.g. sealing plate) in characteristic-characteristic-matrices. A simplified sealing plate is shown in the following technical drawing (Figure 7) with its appropriate characteristics. It is important to note that the benefits of these matrix-based product description become only apparent in more complex products.

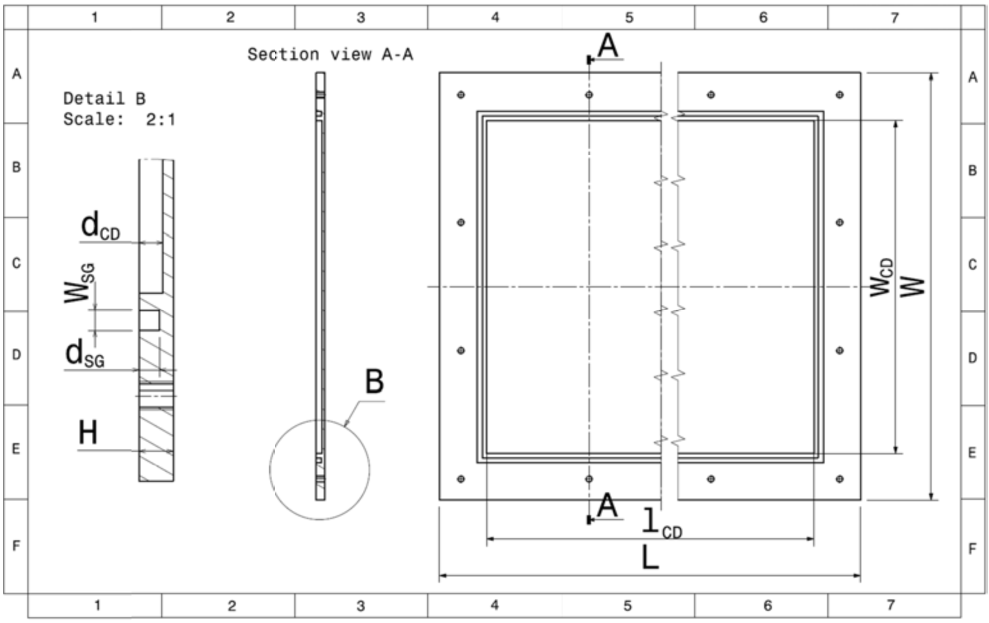

Figure 7. Simplified technical drawing of a sealing plate

Thereby, the effects of characteristic changes on product properties become visible and traceable as well as the differential requirements are set into relationship with the properties and characteristics of the product. The interaction of dependencies between requirements, characteristics, and the resulting properties is shown in this paper through the matrix-based product description using the example of an extraction of the thermal management system. This simplified extraction is shown in the figure below (Figure 8). In this figure, seven requirements (RE) can be found, which are only fixed requirements (FR). In additon, there are characteristics and/or properties of the cell (CE), the pump (PU), the sealing plate (SP), the cooling duct (CD), the sealing groove (SG) and the tempering medium (TM). Furthermore, the figure includes two resulting flow (RE) properties and two resulting heat transfer (RH) properties, which all cannot be mapped only to one of the aforementioned “aspects” of the thermal management system (e.g the mass flow could be mapped to the TM but also to the PU).

In this matrix-based product description (see Figure 8) in which the columns influence the rows (e.g. volume of the SP (V) influence the max. weight), different types of dependencies or interactions can be distinguished from each other. Influences or dependencies between two requirements, characteristics or properties are marked with an “X”. As a consequence, it is not possible to indicate the direction of the dependencies. So it is not possible in these cases to distinguish whether, for example, the characteristic A is dependent on characteristic B or if characteristic B is dependent on characteristic A (e.g. the temperature of the CE influences the rate of heat flow). In contrast to “X”, the direction of the dependency can be specified by a plus sign “+1” or a minus sign “-1”. For instance, a negative directed dependency (“-1”) exits when the value of a dimensional characteristic increases and, as a result of this, the value of a (e.g. geometrical) property decreases (e.g depth of CD influences, the flow velocity). Therefore, the product developers will be assisted in the collection and analysis of the dependencies and interaction between characteristics, properties and requirements. For instance, a larger depth of the cooling duct CD results in a larger volume of the CD and in a slower flow velocity (v). Due to a larger volume of CD, the weight of the thermal management system is reduced, which is generally be assessed positively. In addition, the flow velocity affects the heat coefficient positive. Using the matrix-based product description, the product developer can understand what affects characteristic modifications have. These setscrews can have effects which can be intended and unintended as well as evaluated positive and negative. With the help of the equations given in chapter 3.1, the dependencies can also be quantified or determined more accurately. This gives the product developers a very good understanding of the thermal management system during the early conceptual design phase.

Column influences row			RE							CE	PU	SP					CD				SG				TM					RF		RH	
			FR							P	C	P	C				P	C			P	C			P			C		P		P	
			1	2	3	4	5	6	7	T_{CE}	VF_{PU}	V	L	W	H	M	v_{CD}	l_{CD}	w_{CD}	d_{CD}	v_{SG}	l_{SG}	w_{SG}	d_{SG}	ρ_{TM}	c_{TM}	T_{TM_O}	T_{TM_E}	t_{TM}	m	v	α	Q
RE	FR	1 Max. costs		-1	X											X													X				
		2 Max. weight										+1				X	-1				-1												
		3 Optimal safety																											X				
		4 Min. and max. temp. CE																															X
		5 Spec. gradient temp. in one CE																															X
		6 Spec. gradient temp. between CE																															X
		7 Optimal operating temperature																															X
CE	P	Temperature of CE T_{CE}																															
PU	C	Volume flow VF_{PU}																															
SP	P	Volume of SP V											+1	+1	+1																		
	C	Length of SP L																															
		Width of SP W																															
		Height of SP H																															
		Material of SP M																															
CD	P	Volume of CD v_{CD}																+1	+1	+1													
	C	Length of CD l_{CD}																															
		Width of CD w_{CD}																															
		Depth of CD d_{CD}																															
SG	P	Volume of SG v_{SG}																				+1	+1	+1									
	C	Length of SG l_{SG}																															
		Width of SG w_{SG}																															
		Depth of SG d_{SG}																															
TM	P	Density of the TM ρ_{TM}																											X				
		Specific heat capacity of TM c_{TM}																											X				
		Temp. of TM at SP outlet T_{TM_O}																															+1
	C	Temp. of TM at PU exit T_{TM_E}																															
		TM type t_{TM}																															
RF	P	Mass flow m									+1														+1								
		Flow velocity v									+1								-1	-1													
RH	P	Heat transfer coefficient α														X		X							X	X					+1		
		Rate of heat flow Q								X																	X	X		+1		+1	

Figure 8. An extraction of the matrix-based product description

4. Summary and future work

A methodology for reducing weight and cost of a thermal management system for traction batteries was presented in this paper. Due to the complexity of developing this thermal management system, the rate of heat was intensively discussed and the analytic equations were presented. Based on a sealing plate of one cell module, a value engineering procedure was performed in order to identify functions and components for reducing weight and cost. To increase the understanding of the thermal management system and to get a starting point for the optimization of the identified component, a matrix-based product description was developed. Using characteristics and properties, the flowing properties and the thermodynamic correlations were elaborated. This allowed to show the dependencies between the characteristics, the properties and the requirements, which were defined regarding the weight, the cost, the safety and the temperature of the cells. This procedure supports product developers in their optimization task of components and functions regarding weights and costs.

Future research work will not only deal with the further application of this methodological procedure, but also use and validate computer-aided tools especially for the matrix-based product description (e.g. Loomeo) since its creation is very time-consumig. For a better support of developers, the significant characteristics and properties have to be identified more easily. Therefore, a test stand will be built up, the different characteristics will be varied and subsequently the effects are to be interpreted. In future work, the matrix-based product descrioption will be linked to the steps of development process, the development organization and the so-called knowledge and information objects [Luft et al. 2013a].

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