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Cost Valuation Method for Development Concurrent Phase Appropriate Requirement Valuation Using the Example of Load Carrier Development in the Lithium-Ion-Battery Production

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Abstract**—**In the past years electric mobility became part of a public discussion. The trend to fully electrified vehicles instead of vehicles fueled with fossil energy has notably gained momentum. Today nearly every big car manufacturer produces and sells fully electrified vehicles, but electrified vehicles are still not as competitive as conventional powered vehicles. As the traction battery states the largest cost driver, lowering its price is a crucial objective. In addition to improvements in product and production processes a non-negligible, but widely underestimated cost driver of production can be found in logistics, since the production technology is not continuous yet and neither are the logistics systems.

This paper presents an approach to evaluate cost factors on different designs of load carrier systems. Due to numerous interdependencies, the combination of costs factors for a particular scenario is not transparent. This is effecting actions for cost reduction negatively, but still cost reduction is one of the major goals for simultaneous engineering processes. Therefore a concurrent and phase appropriate cost valuation method is necessary to serve cost transparency. In this paper the four phases of this cost valuation method are defined and explained, which based upon a new approach integrating the logistics development process in to the integrated product and process development.

Keywords**—**Research and development, technology and Innovation, lithium-ion-battery production, load carrier development process, cost valuation method.

I. Introduction

As fossil energy reserves shrink and laws in several countries establish CO_2-emission targets for vehicles, car manufacturers face great challenges now and in the future [1]. In order to face these challenges and provide a more sustainable mobility for a growing urban population, car manufacturers have to develop electric powered vehicles to extend their product portfolio and lower fleet consumptions. One of the key components of electric vehicles is the traction battery, as it defines the range and performance of the car. But also from a cost point of view the battery is crucial component. It is the most expensive part in an electric vehicle with a share of about 60% in production costs and about 40% in total costs, respectively [2]. Today sales of electric cars are increasing and so is the demand for lithium-ion batteries [3], [4]. However, despite the trend to an electrified mobility and it necessity, electric vehicles are still not competitive enough on the market compared to vehicles with internal combustion engines [5]. Therefore, potentials to save costs in their production process have to be scrutinized [6]. In order to satisfy the growing demand and lower the costs for battery cells an automated state-of-the-art production is required. However, several problems have to be solved to accomplish this. Among others, these problems are situated in terms of quality and safety, e.g. investigated by [7] and [8]. A crucial issue, researched by the Chair of Production Engineering of E-Mobility Components (PEM) and the Laboratory of Machine Tools and Production Engineering (WZL) at the RWTH Aachen University, is the specialization of equipment suppliers for the battery cell production. Therefore, battery cell manufacturers need to align equipment from many different suppliers by adjusting the interfaces between process steps [9]. Another issue is the batteries cost respectively it's price. A potential to raise the scale of efficiency and minimize costs offers production logistics. Certain processes of the battery cell production have a huge lead time, e.g. formation (1 day) and aging (21-36 days) [10]. Therefore, a significant number of load carriers are needed to store and transport the goods in the production process. Load carriers are a remarkable cost factor [11]. Additionally the development of load carriers is a target of optimization, as in general, 70% of the costs of a product are determined in the development phase [12], [13]. Consequently, the definition of a standardized process of developing logistics processes and load carriers is needed allowing to identify opportunities in reducing costs at an early stage. Therefore a requirement catalogue in form of a matrix was defined by KAMPKER to assess scenarios for a load carrier system at an early stage of the integrated product and process development [14]. Based on this an approach for a standardized load carrier development process by extending the integrated product and process development was introduced. In the course of this, a framework for a cost valuation method, which has to contain all relevant cost factors and attain a practical feasibility was established [15]. This paper uses this framework and introduces the methodology of such a cost valuation method evaluating costs in an early stage.

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II. Background

Concerning the automotive market, lower batch seizes become more common, which, in addition with short product life cycles, lead to the necessity of more ramp-ups in short periods [16]. In order to face this challenge a new thinking of product and process development was established. These new perceptions led to a time wise overlapping product and process development, called the Integrative Product and Process Development (IPPD), shown in Fig. 1 [17].

The consideration of logistic processes as subsystems of the production process [18]-[20] does not fit with the overall importance of logistic processes, as e.g. load carriers consume a remarkable amount of invest and have a crucial influence on the efficiency of production processes. Pivotal, in terms of efficiency, is the low level of standardization in production equipment over various process steps. Therefore, different load carriers have to be developed and produced to fit one product design over numerous process steps. This leads to interface losses and inefficiencies in the production process caused by the logistic process [12]. Nowadays the load carrier development starts too late in the IDDP. As numerous heterogeneous components and processes have to be coordinated to act as a functional system, the risk is high, that a late start of the load carrier development leads to a late start of production[6], influencing the costs and the performance of the company.

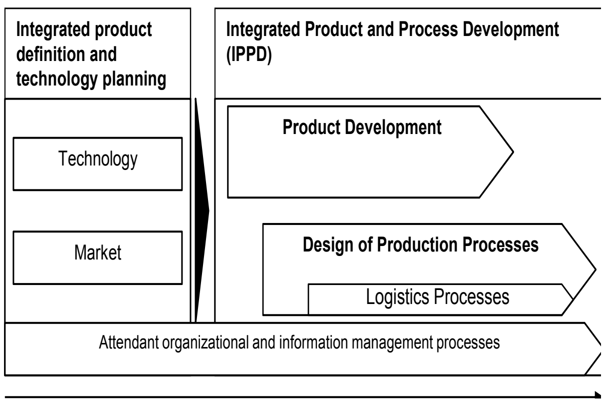

Fig. 1 Framework of Integrated Product and Process Development [14], [21], [22]

Additionally there is no standardized load carrier development process. This lack of feedback leads also to cost inefficiencies, so a tool guaranteeing cost transparency would help to identify and profit from potentials in cost reduction. All in all this leads to the necessity to integrate the load carrier development (LDP) into the IPPD as a third independent process starting simultaneously with the product development. This issue is addressed in a pervious paper by [15], minimizing risks concerning the delay of the SOP and pursuing the most cost efficient solution. As development processes need defined targets and specifications, a design process for load carriers need requirements, which the load carrier has to satisfy. These requirements are determinate not only by the product features, but also by the process features of the battery cell production process. These ten requirements categories are explained in detail in [14] by KAMPKER. For determining costs these requirement categories are crucial as they define the load carrier.

III. Purpose

Costs are a measure for the efficiency of logistic processes and are related to the profit and the return on investment [23]. As process equipment suppliers have specialized only in just a few process steps, the battery cell manufacturer has to align equipment from many different suppliers by adjusting the interfaces between process steps, in order to establish a production line, which leads to interface losses between each process step [9] As some process steps have a huge lead time, a huge number of load carriers are bound by these processes, leading to a substantial capital commitment [10]. These issues combined lead to cost inefficiencies in the logistic process of the battery cell production. A cost valuation method used in combination witch an LDP integrated in the IDDP addresses these issues early in the development process. By which cost inefficiencies can be identified and cost potential exploited. In each development stage the maturity of cost information is different, it advance within the progressing process. In the first phase, the maturity of cost information is relatively low. As the design and specification become more detailed the cost information is getting more precise. In order to address the advancing maturity of cost information, the cost valuation method should be phase adequate regarding the development process of the load carrier. This allows the user to put the cost information or prediction of the model into the right context. The cost valuation method is designed to be a tool for the developer, which is used to make decisions on different load carrier designs. The load carrier is defined by requirements sorted in categories. By changing the specifications of these requirements the developer can find the optimal design for the production system. The cost valuation method uses these changes in requirements to give him a prediction of the costs as well as the maturity of the cost information displayed by the cost transparency. The information about the costs should be divided in to three categories, direct costs, indirect costs and usage costs [15]. An independent standardized load carrier design process is necessary in order to utilize the advantages in schedule adherence and cost efficiency of already used IDDP. This inevitably leads to the necessity of a cost valuation method as a tool to monitor costs and identify as well as exploit potentials in cost for more cost efficiency in the development of load carriers for battery cell production.

IV. Methodology

This chapter defines a methodical approach to evaluate costs and increase cost transparency in an early stage of the load carrier development. In passage ‘Structure Cost Valuation Method’, the phases of the cost valuation method are introduced. This is followed by a more detailed description of each phase in paragraph ‘Cost Valuation Method Phases’.

Structure Cost Valuation Method

The task of a cost model is to transform information about the product into cost information. It describes a logic or mathematical correlation between different input factors, which are the features of the product, and output, which is the cost information about the product [24]. In order to calculate the cost of a product, it has to be described with a set of features. This set has to be limited to features, which are variable for the group of product. Features, which are constant through the entire group, are not relevant for comparing the cost of different designs of the product [24]. Cost models have different purposes in terms of calculation (e.g. calculating the price, make-or-buy-decision or comparative costing). The purpose defines of which type of costs information should be cumulated. As the purpose of this cost valuation method is to compare different designs of load carriers differentiated by the requirements they have to satisfy, it is a type of comparative costing [24]. The method allows an early awareness of the requirements and lead the product development process during its various stages. The framework of the approach presented in this paper is based on two scientific disciplines, in particular the model theory and systems thinking. Systems thinking provides tools and approaches to understand and process complex problems emerging in systems. It describes principles in order to design and control systems [25]. A system is understood as a set of independent components interacting as a integrated whole [26]. The theory of systems thinking defines a general process model at which the cost valuation method, presented in this paper, is oriented. This process model states four basic principles. The first principle defines, that the study area is to be restricted from the general to the detailed, in order to continuously specify the problem and the solution space. In general numerous alternative solutions can be find for one problem. Therefore the second principle states to create variations, identify and structure solutions for the problem. By reducing the number of solutions continuously the relevant solutions are being left over. The third principle suggests to structure the approach into phases, which chronological arranges the solution process into content-related steps. The solution process's general framework is stated in the last principle as a problem independent process going from target selection, to identifying solutions, to solution selection to defining a conclusion [25]. The framework and process of this model is oriented at the four principles of systems thinking, especially phase structuring. Model theory, as the second scientific discipline used, displays the reality in models with a different granularity and forms depending on the purpose and type of the model. Therefore there are different types of models, in particular descriptive models, explanatory models, forecasting models and decision models [27].

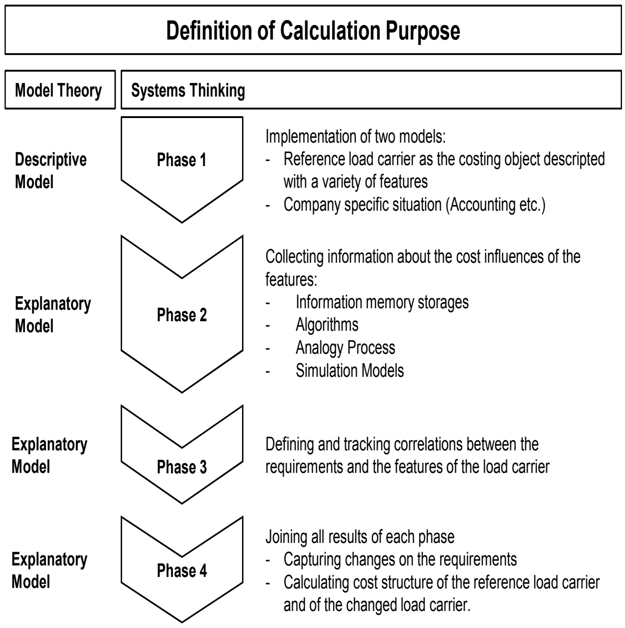

Fig. 2 Structure and phases of the cost valuation method

Each phase of the cost valuation method presented in this paper uses a particular type of model. The connection between both, systems thinking and model theory, constructs the approach of a model, displaying a system with functions and structures abstracted from the reality [28] This allows to generate cost information from features of the load carrier. In order to structure the problem of evaluating costs at an early stage of the load carrier development the approach is segmented into four phases, see Fig. 2. Regarding mode.l theory each phase uses one type of model. The first phase defines two descriptive models. First a reference load carrier as the costing object is described with a variety of features. Additionally the company specific situation is captured in a descriptive model as well. After that, in the second phase, information about the cost influences of the features are being collected. The load carrier development process defines a variety of requirements. To fulfill different tasks or circumstances of production environments, these requirements can be changed by the design engineer. In order to capture the changes' cost influences, in the third phase the correlations between the requirements and the features of the load carrier are defined and tracked. The last phase joins all results of each phase, compiles the changes of the requirements and allows calculating the cost structure of the reference load carrier as well as the cost structure of the changed load carrier.

V. Cost Valuation Method Phases

The cost valuation method is structured into four phases, shown in Fig. 2. In the following each phase is described and tools used presented. The cost valuation method uses a set of typical load carrier requirements and their dimensions (introduced in [14]). This set is changed by manual data input from the developer. The results are various cost overviews, which show the cost elements in respect to their data maturity [15].

In the first phase, descriptive models are used to describe the reference load carrier as well as the accounting conditions of the company. The load carrier is captures by its features and their manifestations. In order to describe random objects, an infinite number of features have to be identified. Clearly, it is impossible to find a functional connection to cost for an infinite number of features. Therefore, the variety of objects has to be limited and the load carriers should be described with only a few variable features and mainly with constant features describing the whole group. The variable features are those, which are determined by the requirements categories named earlier in this paper. The constant features of the load carriers are taken into account by the mathematical context. However, an exact separation of the features is impossible. There can always be an influence between all features, which leads to calculation failures, which cannot be ruled out and have to be taken into account. The framework given by the condition of the company and its accounting has to be described in variable and constant features as well. Which cost parameters are necessary in order to get the needed cost information depends on the purpose of the cost mod l [24].

The second phase uses explanatory models to define the feature's impact on costs. This phase is dedicated identify the correlation between features and costs and to gather the needed information. These goals can be achieved by using information memory storages, by rigid connecting existing information or by interactive connection of outgoing information or hypotheses. Combining these approaches four basic procedures can be identified [24]. Cost information, like production costs, can be a storage for various input information, like the form or shape of the load carrier. The current issue can be solved by using this information and applying it on this new case. Therefore, the entire knowledge about the connection between costs and features has to be stored. The precision of the resulting cost information depends on the resemblance between inquiry and solution storage. This approach can be characterized as search, compare, and estimate. The success obviously depends on the size of the information storage [24] Another procedure uses algorithms in order to connect information. Therefore, the influence of the load carrier's features on costs is described by algorithms. These algorithms, also known as cost estimation relationship, must not satisfy any requirement or rule as long as they are sufficient enough. The relationship can be influenced by different parameters, like physical, geometric, production or organizational influences. Usually the relationship is estimated statically out of data from already produced products (top-down-estimation [24]. The third procedure is called analogy process. The load carrier's production is reconstructed limited to the most important characteristics like costs. This approach is similar to using algorithms, as input information is connected with output information. The difference between both lays in reconstructing the tangible production process. It is obvious, that this procedure is very complex and needs a lot of effort to be executed. This model can be derived in general from the procedure of pre-calculation (bottom-up-estimation) or partially calculated with statistical methods oriented on production parameters. By using this detailed method, the overall problem is divided into smaller issues. However the higher effort is recompensed by a higher forecast precision [24]. If it is impossible to find an arithmetic expression of the correlation between input information and output information, simulation models can be used. An example for this is the calculation of output information out of input information via a successively numerical analysis [24].

Phase three is dedicated to identify and model the influences of the requirements on the load carrier's features. This allows adjusting the requirements regarding the production system and therefore calculating the cost information of the load carrier via the cost impact of its features [24].

The last phase collects all results of the previous phases, in order to determine the cost structure of the reference load carrier, the object of comparison, and the load carrier, resulting out of the requirements changed by the developer. This comparison is used by the developer in order to derive alternatives of action. In the fourth phase all changes on the requirements are gathered and applied on the correlations between requirements and features, which lead to the demanded cost information. The cost information is displayed as a cost structure in form of a pie chart [24]. There, costs are differentiated in indirect, direct and usage costs. Direct cost represent manufacturing and material costs, whereas indirect costs resume e.g. developing costs and costs dedicated to the setup of a production line. Usage costs are defined by the use of the load carrier [15]. Furthermore the cost structures indicate the maturity level of cost information (cost transparency). It is an indicator on how plausible a result appears. In [15] a general formula is presented, which allows calculating this indicator. All this information allows the identification of cost drivers, the identification of relationships between costs and deriving a guideline of action on fields with low data maturity [15].

VI. Validation

In the following the cost valuation method is executed by using the example of a load carrier designed to store battery cells during the formation process. It is crucial step during the cell assembly, in which the battery cells are being charged for the first time and being stored in order to change chemically. The formation process has a lead-time of 24 hours, which consequently lead to a substantial capital commitment concerning the load carriers. The load carriers considered in the validation will be used in the PEM's Centre for Electric Vehicle Production (ZEP). They provide four slots for one battery cell each, see Fig. 3. Each slot is a depression in an inlay, which is made out of ABS. All four inlays are held together by a frame, made out of a sheet metal, in order to form the load carrier. Each inlay provides two small depressions, where the cell's contacts (cathode and anode) are placed and a larger depression storing the cell's body. The cost valuation method is applied to this load carrier. The changes in requirements considered here address the traceability of the load carrier, meaning to track the load carrier and it's status throughout the whole production process of the battery cell. This approach allows the load carrier, as a smart object, to support the factories logistics directly. First, in phase one, the load carrier has to be described by a set of features and their specifications. These features are divided into two types, variable and constant features. The constant features, defined for this load carrier, are basic geometrical measurements of the load carrier itself and the inlay's depressions. The load carrier has to fit into the equipment used for the formation process. The inlays have to be big enough to store the battery cell produced. Here a crucial measurement is the depression for the cell contacts, as they have to match exactly the battery cell contacts size in every variation of the load carrier. The depression storing the cell's body is not as strict proportioned, as the cell's body can be smaller than the actual depression. Variable features of the load carrier were defined as the materials of which the inlays and the frame are made of. Also features allowing to track the load carrier throughout the production process were considered. In means of simplification the company's specific situation (e.g. the accounting) was not modeled in this validation, but was taken into account implicitly during the validation.

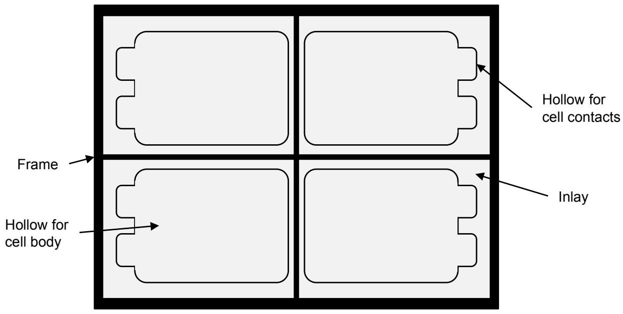

Fig. 3 Load carrier layout

In phase two the feature's influences on costs where identified. This was largely be done by using information memory storages. This approach allows comparing current cost issues with already solved issues. By using those comparable cost information, current issue can be solved. In phase three the correlation between the requirements, which the load carrier is facing, and its features were tracked. In this case the requirement under special consideration is the traceability defined by KAMPKER [14]. Defining a correlation between the features and the requirement leads to the possibility of applying a RFID-Chip to the load carrier's frame. In phase four this change in requirements is examined cost wise. In order to compare the costs and to make a statement on the cost impact of traceability, two variations of the load carrier (with and without RFID-Chip) were modeled and their cost structures were compiled. The result shows that the load carrier without the RFID-Chip accumulates € 120 of direct costs and € 5.000 of tool costs (divided among all produced load carriers), in order to manufacture the inlays, captured as indirect costs. Applying an RFID-Chip to the load carrier adds € 1 of direct cost and about € 800 (antenna, reading devices etc.) of indirect cost. Four costs structures were compiled, a direct and an indirect cost structure for each load carrier. For further information about the composition of cost structures see the paper published by KAMPKER [15].

VII. Summary

The major objective of the extended IPPD is cost reduction, in order to achieve this goal a supporting cost valuation method was developed in this paper serving a high level of cost transparency. Based on a catalog of requirements, costs for different scenarios in developing a load carrier can be calculated. The cost valuation method is based on four phases. First, a reference load carrier is described by a set of features, after which, information about the cost influences of the features are being collected. By changing the requirements, the different scenarios can be confected. Therefore, in the third phase, the correlations between the requirements and the features of the load carrier are defined and tracked. The fourth phase collects and joins all results of each phase, captures the changes of the requirements and allows calculating the cost structure of the reference load carrier as well as the cost structure of the changed load carrier. Those are displayed in a pie chart differentiated by direct, indirect and usage costs. In order to benefit from these potentials, the effect of certain product attributes on the load carrier design that have to be taken into consideration early. The cost valuation method has been validated by calculating the costs of two different variations of a load carrier, used by the PEM, and comparing both. The next steps, for further research, include detailing the general framework of the extended IPPD and defining different stages of maturity. Furthermore, the requirements need a value, which is approved by experts and serves as a standard value for the cost valuation method. Once this has been accomplished, the cost valuation method to receive a higher level of usability. Additionally a model of one ore more reference load carrier has to be built and described by features. Last but nor least the cost valuation method must be converted into a tool, which can be modified in a simple way by the user.

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