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Concept for the cost prognosis in the industrialization of highly iteratively developed physical products

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Abstract

With the ongoing technological progress and increasing global competition, companies are facing a continuously changing market environment. Due to the volatility of the market, rapid product adjustments and shorter product life cycles are required. Changing customer requirements are rarely taken into account, leading to inventions that do not make the transition to innovations. Highly iterative product development poses a possibility to integrate the customer voice into the development process and thus shorten the time-to-market and enable companies to respond to changes in requirements.

Within the scope of highly iterative product development methods, cost analysis remains one of the main challenges for companies. Since the scope of development is not known at the beginning of a project, neither development nor industrialization costs can be specified. This, however, is essential for product and process development to meet cost-related customer requirements and for forecasting the production and investment budgets. With existing methods, it is either possible to agree to a fixed development budget and target price or to enable the customer to make changes during development.

The concept presented in this paper aims to counteract this challenge. Therefore, existing approaches are analyzed with regard to derived requirements for the transfer from highly iterative and integrated product and process development to agile cost analysis. Influencing factors on product and production process costs are identified based on findings from literature. By aligning the influencing factors and requirements, dependencies between target costs of a product and degrees of freedom of highly iterative product and production process development can be derived and used for the development of a framework for iterative cost analysis. In conclusion, a concept for an agile cost prognosis for the industrialization of highly iterative developed physical products is presented.

Keywords

Highly iterative product development; Process development; Industrialization; Cost analysis; Cost prognosis

1. Introduction

In order to remain successful in a continuously changing market environment, manufacturing companies must be able to react to changing customer requirements and market influences throughout the entire development process. Main reasons for this change are increasing volatility of markets, reduced product life cycles and increasing product complexity. [1] Due to these challenges, the importance of the industrialization regarding the time and cost required for an invention to become an innovation is crucial for the product's success. Thus, companies must not only reduce the time to market but also remain adjustable during product development. [2]

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Highly iterative product development (HIPD) offers the possibility to include changing customer requirements continuously in every project phase. [3,4] The approach is based on the fact that the results of each iteration cycle can be realized as an independent prototype. These prototypes enable a fast integration of customer requirements even in later project phases, an improved product quality and the shortening of the time-to-market. [5] However, the use of HIPD results in high planning uncertainties for downstream production process development due to continuous and late changes. [4] Whereas with HIPD a short time horizon drives development through short-term sprints, production and assembly planning is usually carried out on a long-term basis up to the start of production. [3,6] This excludes the possibility to make early investment decisions in HIPD, which contradicts with production process development since these pose the basis of the development progress. Therefore, an integrated product and production process development for the industrialization of physical products is needed to create a decision-making basis for long-term decisions in an iterative development approach. [4,7]

With the highly iterative and integrated development, cost prognosis poses a main challenge and is difficult to estimate due the uncertainties of development and industrialization costs. The purpose of cost calculation is to allocate all costs that occur in the production process according to their origin. Therefore, different unit-related cost information, purchase prices and manufacturing costs are complied. On this basis, market and internal transfer prices are defined and process decisions such as in-house production, external production and manufacturing processes can be made. [8] Cost forecasting is important to place a new product not only on the market at the right time, but also at market-driven costs. It is crucial to have sufficient transparency in the entire product and production process development as to which costs are associated with the product. A sufficient cost prognosis must be as highly iterative as the considered development process. Current cost prognoses do not meet this challenge, since they are based on definitions and decisions at the beginning of development. [9]

In current cost calculation the development department is of central importance. Even though only 9% of the costs are caused in this development, 70% of the costs are determined in this phase. In contrast, production is one of the main cost drivers, accounting for 28% of the costs incurred. However, during the development phase most of the costs are not considered so that it is not possible to take targeted countermeasures to ensure the market price. [10] To be able to estimate the costs arising during the design phase, calculations are currently based on similarity comparisons with already manufactured and recalculated products. [9] However, changing customer requirements lead to significant cost differences. Apart from purchasing, considerable costs are incurred in the production process during product manufacturing, hence special focus is placed on potential savings. In contrast to development costs, the costs incurred can be allocated directly to the product as direct costs. To identify potential savings, precise cost breakdowns must be available. [10] Therefore, the concept presented in this paper allows the inclusion of the cost prognosis in the highly iterative and integrated product and production process development.

In conclusion, the imbalance between cost generation and cost causation arises due to the department-specific approach, as opposed to an interdisciplinary approach. In addition, the lack of transparency in product cost accounting evolves due to calculations based on similarity comparisons. Downstream process costs are rarely included in current cost calculation. Production costs are rationalized after the product cost calculation has been completed, thus synergies between product and production costs are not considered. This leads to a lack of transparency in cost prognosis throughout the development progress and is not compatible with highly iterative, customer-oriented approaches.

2. Prior research in cost analysis and prognosis for highly iterative

For an agile cost prognosis based on highly iterative and integrated product and production development, costs need to be regarded completely from the beginning. Therefore, production related costs need to be integrated. For this integration information exchange must be possible throughout the development progress with a responsive and transparent cost prognosis that enables interaction between departments. A literature review was conducted using a forward and backward analysis according to WEBSTER AND WATSON. [11] Since cost calculation is the foundation of this work, this term was used as the origin for this research, which has been extended by agile approaches for cost analysis. In the following, the focus lays on cost prognosis for highly iterative product and production process development.

"Target costing" is a concept for market-oriented target cost management and is applied in the early phases of product development. The aim is to increase competitiveness by means of market-oriented requirements. The focus lays on the derivation of permitted market costs using market prices as the basis. The costs allowed by the market are compared with the production costs, so that target costs can be derived for individual product groups. [12,13] However, the focus lays on determining the maximum production price using a backward calculation. Thus, the calculation is neither complete nor are the production costs integrated. In addition, a fixed market price must exist for a retrograde cost calculation.

"adVANTAGE: A Fair Pricing Model for Agile Software Development Contracting" by BOOK ET AL. provides a pricing model to share the risk of agile software development between customers and suppliers. The development process is divided into four phases, in which requirements are recorded, divided and implemented in successive cycles, as in Scrum approaches. For cost prognosis, the first and last phase are relevant. While in the first phase upcoming costs of each cycle are estimated, in the last phase costs for the development are flexibly adjusted according to the fulfillment of the task within the previously defined resources. If fewer resources are consumed than specified, the charges are reduced by the rate of underspend resources. If the consumption is too high, the charges are reduced by a certain percentage, which disadvantages the supplier. [14] The model and subsequent adjustments are based on previously estimated values, making the entire process highly dependent on the accuracy of the first estimate. Also, it is used in Scrum approaches, so that it is mostly suitable for software development.

"Process costing" is an approach to increase the cost transparency of indirect performance areas. It does not constitute an independent cost accounting system, but complements the traditional systems with an improved allocation of overheads. [15] Resource-oriented cost accounting focuses on indirect costs through variant diversity aiming to improve product and development-related cost information in complex series production. [16] In practice, however, process costing is not used to calculate total costs. The aim is to model only those areas of the company that are directly related to the variety of variants. In addition, it is hardly possible to flexibly react to changes in the product and production process.

"Total cost of ownership (TCO)" approaches are mostly used in the field of mid- and long-term purchasing decisions. [17,18] They are used as a purchasing tool aimed at understanding the actual cost of buying and using a product or service from a supplier. TCO are the sum of purchase, financing, running, and infrastructure costs and highly sensitive to assumptions. Most TCO approaches are used to support the purchasing case in new technology fields with high uncertainties like electro mobility. [19] The high level of customer focus ensures the integration of customer requirements. However, the focus on improving the product from a technical side of view neglects the advantages and requirements of integrating production. Further on, the transparency on costs is missing which is why permanently changing costs cannot be analyzed within a highly iterative development.

The ***"functional cost analysis"*** is a method to determine the value of a product's function. Functional costs include all planned or incurred resources that are necessary to provide a function. Functional cost estimates are made at the value creation stage, i.e. before the design or development and realization of the product. It is possible to allocate component or assembly costs to the functions they perform or in the performance of which they are involved. The approach is applicable to physical as well as non-physical products and integrates purchasing, production and sales as well as suppliers and customers are included in the analysis.

[20] However, the approach is not able to react and adapt to constantly changing development, nor is it an approach for a stand-alone total cost accounting.

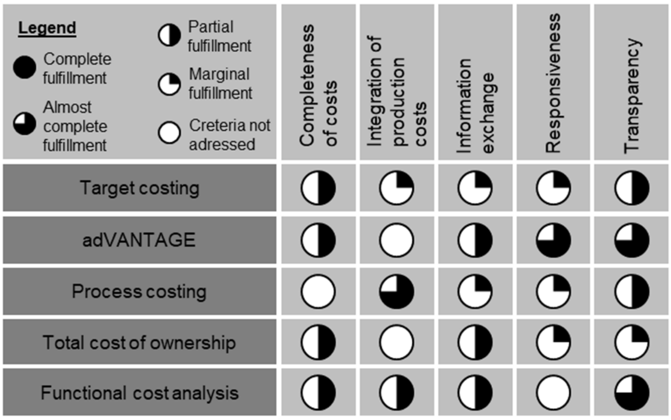

Figure 1: Overview of the evaluated approaches

Conclusion. The evaluation of the different approaches shows that current cost calculations are not able to meet the requirements of integrated product and production process development, as shown in Figure 1. Especially when estimating the total costs at the beginning of the development, the production process costs are usually not considered differentiated. Calculations are not based on the bill of material (BOM) and therefore not product- and process-oriented. Without a complete cost calculation, it is not possible to proactively react to costs that exceed the target costs. Thus, the responsiveness of the calculations to changes within the development process is hardly given, provided that a calculation accompanying the development is possible at all. The transparency of information about the cost development in different departments during the development progress is lacking. During development it cannot be ensured that target costs will be met on the market. The consideration of changing costs during HIPD in relation to an integrated product and production process development is not given. Therefore, an approach for agile cost prognosis for the industrialization of highly iteratively developed physical products is required.

3. Influencing factors and requirements for the transfer from highly iterative and integrated product and process development to agile cost analysis

To overcome the conflict that classical cost analysis poses to highly iterative and integrated development, a concept for an agile cost prognosis is derived. Hence, it is crucial to identify influencing factors for product and production process-related costs to transfer the integrated development approach to an agile cost prognosis. Figure 2 illustrates the integration of HIPD and highly iterative production process development on the left side. The integrated product and production process development is divided into five parallelized phases. Each phase decreases the freedom of the production process and increases the maturity of the product. The central cost drivers of each phase were derived by literature and are allocated on product, production process and integrated side. The derived cost drivers are analyzed and their interdependencies are illustrated on the right side of the figure. The related cost drivers are listed on the different axles. The spanned planes create tables, in which the correlation of two cost drivers is shown. If cost drivers do not influence each other, or the correlation is so low that it is not noteworthy, the cell stays empty. If they do, a "+" marks the influencing correlation.

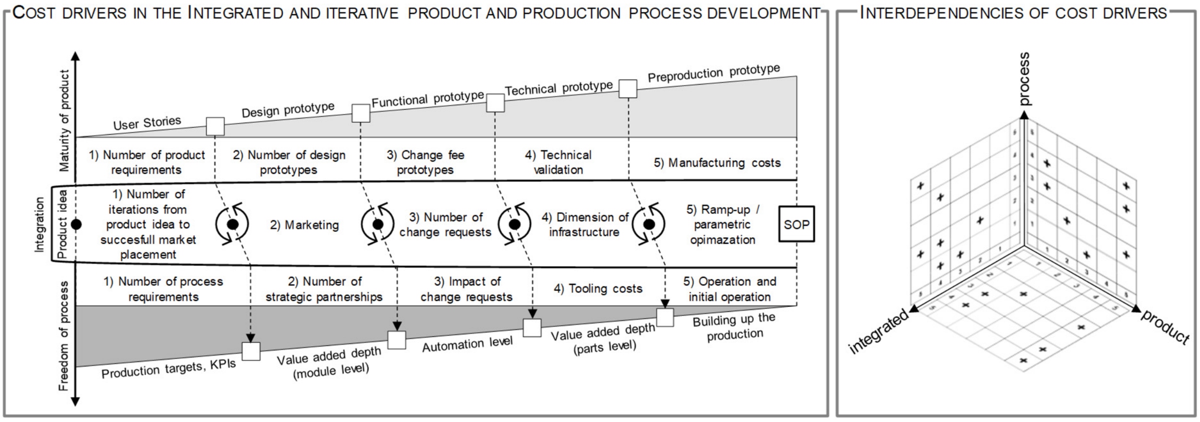

Figure 2: Cost drivers and their interdependencies

In the ***first development phase*** the user stories, the production targets and the key performance indicators are defined. User stories are short descriptions regarding product functions in specific use cases. The main cost drivers in this section are the *number of requirements*, which need to be defined on product and production process development side, since complex systems cannot be handled by existing requirement engineering methods and up to 50 % of all errors are based on incorrect requirements. [21] Therefore, it is urgent to combine the traditional and agile way of handling requirements – reducing the number of requirement errors and detecting errors immediately. [22] The cost driver regarding the integration of product and production process development is *the number of development steps from the product idea to the successful placement of the product on the market* to have a full overview on the end-to-end-process. This includes processes such as homologation and certification, which are cost-intensive but are not considered in current cost accounting approaches.

In the ***second phase*** design prototypes are developed on product side while in process development the value-added depth on module level is defined. Cost drivers are the *number of prototypes* on product side, the *number of strategic partnerships* on production process side and *marketing* on an integrated perspective. Marketing is necessary to get in contact with possible partners. The cost drivers influence each other, because the number of needed strategic partnerships affect the amount of necessary marketing activity, which influences the number and kind of design prototypes that are needed.

In the ***third phase*** functional prototypes are developed and the automation level is specified. Main cost drivers are *the change fees* of already manufactured prototypes as well as the *number and impact of the change requests*. The number of change requests is influenced by the requirements. The less requirements exist and the better these are defined, the less change requests will occur. Likewise the change fees and the impact of the change requests are effected by the number of requirements. [23]

In the ***fourth phase*** technical prototypes and the value-added depth on parts level are defined. The *technical validation* is a main cost driver because it can include complex testing scenarios that take a long time and can destruct one or more technical prototypes. The dimension of the *infrastructure* includes i.e. the investment in new buildings and factories and is effected by the number of process and product requirements, the number of strategic partnerships on module and on parts level. *Tooling costs* are a critical investment and affected by product requirements.

In the ***fifth phase*** preproduction prototypes are manufactured and production is set up. Cost drivers are *manufacturing costs, the ramp-up and the initial operation*, which are strongly correlated. The ramp-up is effected by the number of strategic partnerships, since the risk of a supply shortfall increases with a smaller number of partnerships. [24] Also, the manufacturing costs are dependent on the infrastructure and the tooling costs and the number of strategic partnerships. The initial operation has beside the named ones mostly correlations to other process cost drivers.

With the identified cost drivers and their interdependencies, the foundation is built for a concept for an agile cost prognosis. To transfer the characteristics of highly iterative and integrated product and process development to agile cost analysis, requirements are derived. The continuous integration of the customer is crucial to ensure the target orientation of the development task. Bidirectional information asymmetries that occur with an integrated development approach need to be overcome with a complete cost calculation from the beginning of the development. Through the collaboration of the development tasks synergies in both directions are identified and proactively addressed to either optimize the costs or to ensure that the target costs are not surpassed. The cost prognosis needs to be based on interdisciplinary teams that involve the production and related departments from the beginning. Especially including all emerging cost in an end-to-end consideration of the processes needs to be ensured. With this, the customer focus is integrated in the cost prognosis. To be able to track the cost status quo continuously in the development progress the costs need to be defined completely based on the BOM in the beginning.

4. Concept

To successfully place a new product on the market, the speed with which an invention is developed into an innovation and its target costs on the market are decisive. [7] To do so, a concept for an agile cost prognosis using data based and integrated collaboration in the development is derived. During the integrated development of the product and production process a continuous cost tracking poses a central lever to enable the highly iterative development approach including the customer. Using the infrastructure of the Internet of Production (IoP) the databased collaboration between the user, development and production cycle is enabled. [25] In the user cycle customer requirements are continuously identified and translated into User Stories. With these, target costs are derived using the product structure that states the input for the development cycle. The total costs are defined highly iteratively in a loop with the production cycle in which process, procurement and plant regarding costs are specified in an end-to-end consideration. Therefore, a holistic but also agile cost calculation approach is enabled. Changing customer requirements and product specifications are continuously included through the infrastructure of the IoP. Complex and bidirectional information asymmetries coming from the collaboration of the parallel product and production process development can be cured and transparency of the cost analysis is ensured.

In the following, the concept for an agile cost prognosis is presented as a framework within the integrated and highly iterative product and production process development, as shown in Figure 3.

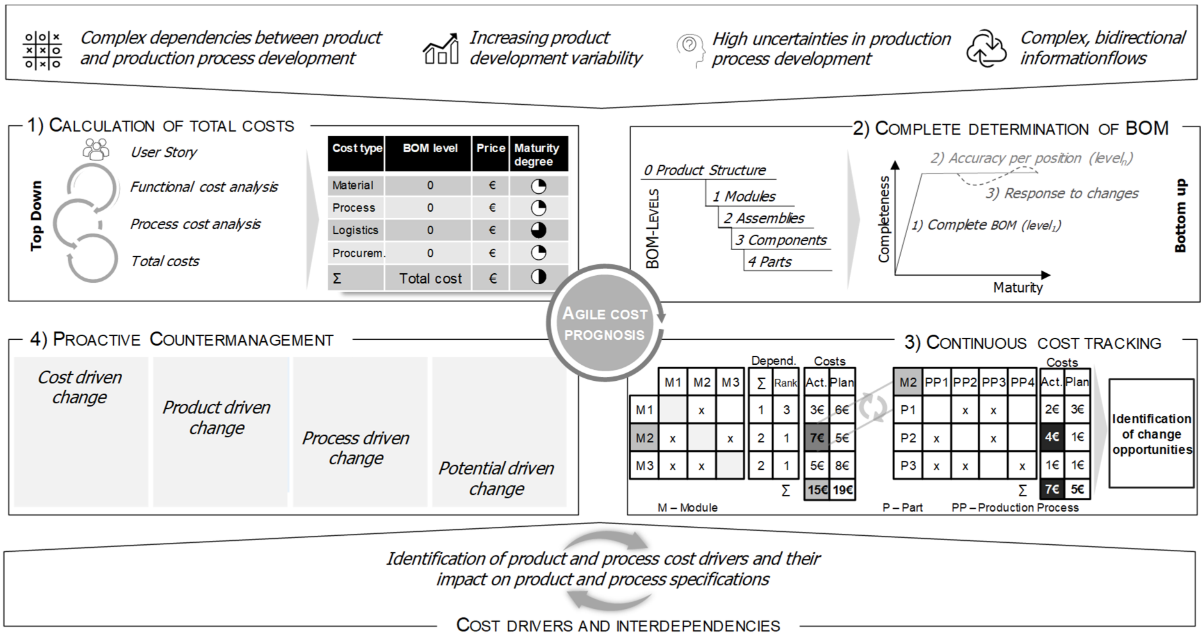

Figure 3: Concept for an agile cost prognosis in the industrialization of highly iteratively developed physical products

The concept is derived to be used in the scope of the integrated and iterative product and production process development, which is characterized by complex dependencies and bidirectional information flows between both development strands. At the same time the voice of the customer is of particular impact to become successful on the market. This is linked to high uncertainties within the development of products including their industrialization. Therefore, the continuous cost analysis and prognosis is crucial in order to create transparency on the possibilities and decide on changes within development. The previous identification of product and production process cost drivers as well as their interdependencies is a supporting tool throughout the progress within the concept.

In the ***first step*** the total costs are calculated. Therefore, user stories are created using the data from the user cycle. In these, the required functions coming from the market are determined. To be able to place the innovation successful on the market, the price the customer is willing to pay needs to be calculated. Therefore, the target costs are calculated using the functional cost analysis top down in the first place. The functions relate to the functional structure of the product and enable the product and production development to think in new structures. This is especially relevant when developing high technology innovations that are accompanied by uncertainties. Thus, the functional structure of a product is directly linked to the product structure (cf. step 2).

Through the highly iterative and integrated product and production process development functions can change throughout the development process depending on changing customer requirements or production processes. Therefore, the functional cost analysis is specified in each iteration by getting deeper in the product structure including all production process related costs. After the first prognosis of the target costs is carried out, the target costs for the product are completely calculated. Further on, it is necessary to continuously prognosticate all cost that occur, not only focusing on functional costs. For this, an end-to-end approach using process cost accounting and TCO analysis is executed. Hence, all emerging processes, i.e. certifications of processes and products or testing of products, can be integrated from the beginning of the analysis. The total cost table is completely filled in each iteration at different levels of maturity. The target costs are extended with all process relevant costs as well as use-related costs. At any time the total cost table needs to be filled out completely in every position. In order to continuously monitor the degree of maturity of the cost prognosis and thus make decisions for or against changes, each cost estimate is linked to a Harvey Ball evaluation. An empty ball represents a simple estimate, a quarter ball is a researched value from a desktop study. Half a ball gets cost statements, which could be obtained by an indicative price offer, a three-quarter ball by a customer specified offer. A full ball is attainable at a negotiated or paid price.

The full cost table is specified with each iteration and is dependent on the ***second step***, the complete determination of the BOM. Starting with the product structure that is derived by the functional structure (cf. step 1), the highest level of the BOM is determined. To enable the integrated development, the progress relies on a hypothesis-based approach. [7] In this step only the currently prioritized BOM is considered. It is crucial to first ensure the completeness of the BOM on a high level than specify parts that are not relevant in this early stage of development. Therefore, all integrated functions in the user story need to be fulfilled by the product structure. Having a complete product structure that is fully priced (cf. step 1), the foundation for the target driven development is defined. After the completeness on a high level is achieved, all positions are specified within the development progress. To do so, the product structure needs to be broken down into modules, assemblies, components and parts and developed bottom up. Since from the beginning of development the BOM is completed on level 0 and combined with the total cost calculation from step 1, a complete priced BOM represents the reference for the further development. After this, all changes are treated as deviations (cf. step 3).

Having the reference BOM that is complete and priced at all times with different maturity degrees, the actual costs during the complete development task can be tracked and compared with the planned costs in the ***third step***. The continuous cost tracking makes the bidirectional connections between product and production process development transparent. These connections occur due to the integrated development. [7] Affected product parts are identified in the event of changes and linked to the respective production processes.

In addition, the evolving structure is continuously evaluated with regard to change effort. It is assumed that a product consists of several modules (M) and individual parts (P), which are manufactured in production processes (PP). With regard to prospective digitalization, the dependencies are represented by matrices. First, the dependencies between the modules need to be determined and marked with an "x" in the matrix. The number of dependencies is a measure for the possible change effort. The more dependencies a module has, the higher the potential change effort. A change of the module can lead to the compatibility to other modules no longer being given, which leads to additional changes. Furthermore, the planned and actual costs are assigned to the individual modules from the total cost table (cf. step 1). The use of colors indicates whether there is a need for change or not. In Figure 3, the total actual costs are lower than the total planned costs. This implies that, fundamentally, there is no need for change. However, the current total costs are displayed in light grey, which shows that at least one module is more expensive than planned. To find the cause the next matrix shows which parts the module consists of and with which production processes it is planned to be manufactured. Actual and planned costs are assigned to the individual parts dependent on BOM levels and cost maturities from the first two steps. Since the entire module exceeds the plan costs, the total actual costs are colored black. It also shows that P2 is responsible for the cost overrun (colored black). On this basis, it can be decided whether the geometry of P2 has to be changed, alternative production processes have to be used or the part has to be purchased from an external supplier. This decision is supported by the cost drivers on product, production process and integrated side (cf. Figure 2). By analyzing the interactions of the cost drivers assigned to specific development cycles, it is possible to identify previously unrecognized cost reduction potentials. Therefore, through the continuous cost tracking, the actual costs of all product and production process related costs are monitored and compared to the target costs that the customer is willing to pay.

Having identified the opportunities for changes, a proactive counter management process is included as the ***fourth step***. If target costs are exceeded or cost potentials are identified due to the improved transparency, changes must be initiated in a different way. The opportunities of change are therefore clustered in four different management processes with different responsibilities. According to the continuous cost tracking, opportunities for *cost driven changes* are identified. These need to be simulated within the four steps to validate if with the planned change the target costs can be achieved. If not another hypothesis-based product or production process related BOM needs to be considered. Changes that allow target costs to be achieved must be approved by the respective process owner. The process owner is dependent on the maturity of the product and the freedom of the process. In the first phases in which the product maturity is low and the process freedom high, the engineering department represents the process owner to decide on the changes. This is due to the high freedoms in the production process development. After a certain maturity degree of the product is reached and the minimum viable product is defined by the functions, the process owner shifts to the production department. Therefore, all change requests need to be negotiated between the inquiring entity and the process owner. The change requests are permitted if either the target costs or the customer benefit is improved, i.e. with lower TCO. If the actual costs surpass the target costs, this concept enables an active counter management. With the continuous tracking a specific i.e. module, part or production process that is too high in cost is shown and can be directly linked to the BOM and functional structure that is the foundation of the target cost calculation. Therefore, the process owner knows which change has to be done in order to fulfill the customer requirements at any time. Besides the cost driven change opportunities, *product or process driven changes* can occur. These change requests origin in the interdisciplinary development approach, which integrated the product and production process development. Since all dependencies are transparent and connected to the cost drivers, also *potential driven changes* can occur. These changes indicate proactive improvements in costs, even if the target costs have not been exceeded. This is the result of interdisciplinary cooperation from the integrated development approach.

5. Summary and outlook

In highly iterative product and production process development, continuous changes are used to adapt the product to the changing requirements of the customer. For an efficient implementation of these changes, an agile cost prognosis is necessary. To integrate an agile cost prognosis concept into the highly iterative and integrated product and production process development, cost drivers were derived and their interdependencies analyzed. This is the foundation for the developed concept presented in this paper. Through a complete and fully priced BOM the actual costs are continuously monitored. With this, changes are identified proactively to achieve the customer driven target prices. This concept is applied at the moment for the industrialization of a fuel cell range extender regarding the commercial proof of concept. The BOM is completed on level 3 and fully priced with different maturity degrees of costs. The agile cost tracking enables the integrated development to identify changes that need to be considered quickly to ensure the right direction of development even though high uncertainties characterize the development progress. Further research will be needed to specify the concept and to develop methods for the data based implementation.

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Biography

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