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RESEARCH ARTICLE



Calculation of product service systems in single and small batch production

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Abstract

Single and small batch production is characterized by complex value-added processes and products. The transparent calculation of new offers and change requests is therefore a particular challenge. At the same time, the rising spread of product service systems (PSS) increases the complexity of costing, as additional intangible services have to be calculated precisely. In addition to the challenges posed by such precise calculation of intangible services, companies have to master another complexity driver in the form of PSS. Innovative information and communication technologies (ICT) offer new potential for effective and efficient design of the costing process for the entire life cycle. The rising availability of data along the entire product life cycle significantly increases transparency and, thanks to intelligent analysis algorithms, allows the identification of clear cause-and-effect relationships and forecasting options. The aim of the presented paper is thus to develop a model for calculation of PPS in single and small batch production that exploits the new potential of ICT.

Keywords Production engineering · Single and small batch production · Cost calculation · Product service systems

How this paper addresses the editorial statement

The transparent and accurate calculation of new offers or change requests is a cornerstone of successful pricing management decisions. However, due to the inherent complexity of the related products and processes, target costs can deviate significantly from actual costs. This is further amplified by the adaption of PPS which provide new sources of revenue for manufacturers and an improved offering for the customer, but add challenges to the calculation process. This

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¹ Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen University, Campus-Boulevard 30, 52074 Aachen, North-Rhine Westphalia, Germany paper aims at addressing these challenges through the innovative use of ICT in the calculation process. The theoretical framework provided in this paper is based on the WZL's research into the digitization of manufacturing processes and intends to provide a model for improving the quality of calculation in practice.

Introduction

Accurate, fast and reliable calculation is a key factor for the success of a company (Kessler and Winkelhofer 2004). This is particularly evident in the current business environment, where there is an increasing trend towards individualization as well as the integration of services into traditional product offerings (Uhlmann and Meier 2017). Last-mentioned phenomenon, known as servitization, has led to the emergence of so-called product service systems (PSS) (Mont 2002).

A PSS involves combining tangible products with related services, such as spare parts sales, maintenance and repair. The aim of PSS is to increase sales of the core product, foster stronger customer relationships and generate stable income through service offerings (Frank et al. 2019). However, the inclusion of intangible services has increased the complexity of calculation (Meier et al. 2010). This applies in particular to single and small batch production (SBP), where calculation is already very complex due to the uniqueness of each product, the resulting lack of experience and the low level of automation. The addition of intangible services further increases this complexity, resulting in a very timeconsuming process for order processing and a high risk of budget variances.

In tooling, a characteristic industry for SBP, these challenges are reflected in budget variances between target and actual costs of +70% to -40% (Boos et al. 2016). Overcoming these challenges and ensuring the profitability of the order fulfillment process requires new methods and tools for calculating manufacturing and service costs. One possible solution for these challenges lies in the use of innovative information and communication technologies (ICT) that enable precise costing of PSS throughout the product lifecycle. With the growing access to data, an increase of transparency regarding costs is possible. Furthermore, the implementation of algorithms allow identifying dependencies and potential outcome scenarios (Acácer and Cruz-Machado 2019). Conventional calculation models do not take sufficient account of the use of ICT and are therefore not suitable for the precise calculation of PSS. In view of the significance of these challenges, this paper explores the research question of how an adaptive model for the calculation of PSS in SBP should be designed. The proposed model leverages ICT to gather all cost-relevant data from the entire lifecycle in near-real time and integrate it into a digital shadow. The digital shadow serves as a foundation for the model to continuously perform cost calculation and generate forecasting models. Ultimately, the model aims to improve the quality of the entire calculation process in terms of accuracy, speed, systematization, and automation.

State of the art

Definitions

Calculation

Product calculation determines the cost of manufacturing of a product and incorporates both direct costs, which can be fully attributed to each individual unit, and indirect costs, which can only be divided amongst all products. These primary costs provide a basis for determining both the economic viability and final sales price of the product in combination with individually chosen profit markups as well as strategic decisions (Böge and Böge 2021).

Calculation activities separate into pre-calculation, continuous calculation and post-calculation. Pre-calculation takes place before work on a product has begun and serves to determine a price used to make an offer to the customer. Continuous calculation begins as soon as the customer places an order. It continuously accumulates actual costs and compares these to planned costs to monitor the budget, so that corrective action can be taken if necessary. Lastly, post-calculation takes place after the project is finished and provides an overview of actual costs. It is used to assess the project success and relay information for future calculation (Boos et al. 2016).

Product service system

As a commonly cited definition, Goedkoop et al. (1999) defines product service systems (PSS) as "[...] a marketable set of products and services, jointly capable of fulfilling a client's need.". This differs from a conventional product in the way that not only a physical product is sold to the customer, but also a system incorporating adjoining services that expand the usage of that product. Hereby, tool manufacturers can address customer demands to a higher degree and maximize value for the customer (Mont 2002; Maier and Uhlmann 2012). Furthermore, PSS provide an opportunity to expand business models and grow revenues (Annarelli et al. 2016). Providing PSS as a customer-individual solution can help tool and die manufacturers to increase competitiveness through differentiation and improve the offering to the customer with innovative, service-based business models (Schuh et al. 2007; Maier and Uhlmann 2012).

Tool and die manufacturing

Tool and die manufacturing incorporates all activities associated with the creation of tools and dies used for the production of parts in a manufacturing environment. Differentiating these from standard and hand tools is the characteristic that the final geometry of the produced part is fully or partly formed in the tool or die. The focus is thus on so-called hollow tools and dies for shaping. Examples would be injection molds or sheet metal processing tools. (Eversheim and Klocke 2012). The tool and die manufacturers addressed in this paper can either refer to independent companies or an organizational subdivision specialized in these activities.

Digital shadow

A digital shadow is defined by SCHUH as "a set of models and data traces that, in addition to the pure data set, also contain contextual metadata about the respective intended use." (Schuh et al. 2020). It describes a digital image of a production system, either in whole or focused on a specific operation or task. Herein, it comprises all relevant data from a system, ranging from design through manufacturing to the usage of a product or part. An exemplary instance of this can be the real-time process data created by cyber-physically linked machine tools regarding the manufacturing of a part. Using the digital shadows creates transparency within the production process and can therefore contribute to identifying the causes for deviation in production processes. The preliminary goal of its usage is the improvement of processes and quality (Bauernhansl et al. 2016).

Primary to the creation of a digital shadow, its goals and purposes are defined so that data needs can be analyzed. Once a structured overview of the required data and its granularity is available, a comparison is made between required and available data. This then allows for the selection, validation, and implementation of suitable technology for data collection. The technical basis of a digital shadow is a holistic information architecture through which data that is created by the system can be collected. The data initially needs to be tested for consistency and plausibility before the digital shadow can then be fully employed in the intended context. It provides the foundation for the evaluation and analysis of data through specific models and methods (Bauernhansl et al. 2016). Application-specific aggregation, filtering and processing enables autonomous or semi-autonomous usage of data for validated and accurate decision-making. This is particularly critical, as the vast amount of data aggregated within the system can by itself rarely lead to a greater understanding of the process. It is important to note, that the digital shadow itself never influences the system it is referred to. Only adjoining systems that are reacting to data provided by the digital shadow can affect changes within a production system (Schuh et al. 2020).

Theoretical approaches

Several approaches aimed at resolving the shortcomings of current calculation methods mentioned above can be found in scientific literature. Each of these focuses on different aspects of the calculation of PSS in tool and die manufacturing. Three approaches representing the state of the art are briefly outlined in the following paragraph.

The framework for die and mold cost estimation using design features and tooling parameters by Nagahanumaiah et al. (2005) provides an integrated method based on the concept of cost drivers and cost modifiers. Following this methodology, first tooling parameters and cost elements are identified and their percentage share of the tool cost is determined. For example, parting plane machining can contribute 10% to the calculated tool cost. After determining a relationship matrix between these elements, these values can be used as cost modifiers for the calculation methodology. These modifiers are adjusted to the specific elements of a new part. Then, they are applied to a reference tool to achieve a parametric, part-based calculation of a new tool. While this approach proves mostly practicable, it does not take into account the adaptive nature of the developed model

as well as the continuous calculation and the service aspects of a PSS.

GAHR modifies the path costing approach originating in the healthcare sector to be used for individualized product development and aims at enabling continuous calculation by assigning paths within the cost structure of individualized products. For this, reference paths based on the degrees of freedom of the customer are first developed that encompass all necessary activities of individualized product development. The order-specific costs are then calculated according to these paths and the resource consumption therein. Hereby, relatively low-effort cost calculation and management can be achieved, however the limited scope of this approach means only a partial fit to the requirements of the developed calculation logic (Gahr 2006).

An approach for the integration of services within the calculation is provided by MöLLER and CASSACK in *Process-oriented Planning and Calculation of (core-)product adjoining Services.* This approach develops activity-based costing further and adapts it to product-related services. For this, a service and core product is identified, defined, and activities and processes related to this are analytically planned. The process model is then adapted and condensed with capacities and costs to be used for planning and calculation of costs (Möller and Cassack 2008). While this approach provides a basis for the calculation of services, it does not take into account the adaptive logic of the developed model.

While these approaches add value in specific parts of the calculation of PSS in tool and die manufacturing, they do not provide an integrated calculation logic as we are intending to create.

Model for adaptive calculation

Figure 1 shows the proposed adaptive model for the costing of tool service systems. The model represents a process model, which is based on the ARIS model according to Scheer (1992).

Based on Scheer, the data layer is represented by the digital shadow, which is a real-time data basis for calculation related tasks. The function layer combines these tasks, namely product-based pre-calculation, continuous calculation and forecasting design of actions, and post-calculation. The control layer comprises the balance sheet shell for the tasks. It is the life cycle of a tool, which consists of the four phases tool making, tool validation, tool usage and tool disposal. The data-based costing represents the performance layer. Finally yet importantly, the consideration of the stakeholders takes place in the organization layer. The stakeholders are the tool manufacturer, its suppliers and the customer. For instance, ownership changes between them during the life cycle of a tool. In the following, the individual layers



Fig. 1 Model for adaptive calculation of PSS in SBP

are explained and the current status of the authors' research is given. Further research will be conducted in these layers.

Tool life cycle

The developed calculation model, divides the lifecycle of tools and dies into four parts, tool making, validation, usage and disposal. In this case, toolmaking encompasses both development and manufacturing of the tool or die.

The life cycle begins with development, at which stage the tool or die is designed and simulated and manufacturing is planned with activities such as procurement of parts and raw materials and programming of machine tools. Following this, the products' components are manufactured and assembled into the final tool or die. During validation, the tool enters a try-out-phase where pre-production parts are manufactured to validate quality and function. Following this, the tool enters the usage phase, where it produces final parts in series production. The disposal phase of the life cycle is reached when the tool is no longer useable or the parts are no longer produced and the tool or die will be disassembled and recycled. While in traditional tool and die manufacturing only the first two or three steps of the life cycle are considered, adjoining services provided by the manufacturer accompany the product through all five parts of its life cycle in PSS. Therefore, the developed calculation model needs to be able to accurately predict costs associated with the PSS in all stages of the life cycle.

In the earlier stages, these costs can range from labor costs for engineering and design of the tool or die to parts and material costs as well as manufacturing costs such as machine operation costs. In latter stages, costs of services



Fig. 2 Life cycle tool costs

such as installation, ramp up support, tool health surveillance, maintenance, or recycling need to be considered.

Figure 2, shown below, further underlines the importance of a holistic consideration of costs along the complete life cycle of a tool. Manufacturers of tools and dies can mainly affect the first step of the life cycle as they assume cost responsibility for the tool making stage. These costs traditionally serve as a basis for the acquisition of tools and dies by customers, but as they only amount for 45% of the life cycle costs, total cost of operation of the tool is not sufficiently considered. As is shown in Fig. 2, total cost of ownership (TCO) can be mainly attributed to the last two phases, where cost responsibility shifts from tool and die manufacturers to customers. This separation of cost responsibility and generation establishes a need for a comprehensive calculation model which takes all life cycle costs related to the tool into account.

The digital shadow of the tool or die collects, stores, filters, and processes data collected throughout the complete life cycle of the product. This data is fed back to the calculations system and used to gauge the compliance with budgets or cost goals, so countermeasures can be applied used to provide a continuous calculation, which is detailed further below. This data also enhances the accuracy of calculation for current and future PSS by constantly updating the database for the calculations logic. For these reasons, the digital shadow needs to interact with the complete life cycle of a tool or die and it must be fully taken into account within the developed calculations logic.

Product-based pre-calculation

Before development or manufacturing of a tool or die can begin, costs of the PSS for the tool and die manufacturer need to be determined to set a price for a competitive offer to the customer. For this pre-calculation, the developed logic uses a product-based approach, where characteristics of the product that is to be produced by the tool or die serve as an input factor for the automized calculation. This data-driven approach, which takes the complete product life cycle into account, enables an improvement in the accuracy of calculation as well as increased transparency and speed of the pre-calculation. The creation of the product-based pre-calculation model consists of four steps, beginning with data-selection, where comprehensive datasets from previous projects including product-, tool-, cost- and usage information are first imported from various sources. Each of the datasets is combined into a database and assigned to a set of features pertaining to the product and the tool made to produce it. These features could include, for example, geometric parameters of the product or tool, construction parameters or information about the services correlated with the project.

In the following pre-processing step, the database is cleaned of redundant, inconsistent, or missing entries, and textual data is translated to numerical data to be processed in the following steps.

In the training stage, specific data sets are used to train the calculation logic with diverse parameters to the accurate calculation of PSS, which is then validated through sets of test data. This allows system errors to be identified and corrected by calculating the deviation of the results of the calculation logic from the verified actual costs.

Lastly, once the model has been verified, it can be deployed for use in the developed calculation logic to accurately forecast costs for PSS based on product specifications. Notably, this accuracy is largely dependent on the size and quality of the database used to create the calculations logic. As it is implemented and continually updated through constant data-based cost recording in each step of the product life cycle, the accuracy is set to improve. As shown next, the digital shadows of various PPS creates the database for future product-based pre-calculation.

Digital shadow and data-based cost recording

Complementing the definition above, the digital shadow for use specific use case sufficiently accurate comprises "mapping of processes in production, development and adjacent areas with the aim of creating a timely evaluation basis for all relevant data" (Bauernhansl et al. 2016). In the context of this work, the objective of the digital shadow is to capture all relevant data for calculating the costs of a PSS over the entire tool life cycle.

To achieve this, the initial step is to identify the cost drivers of the individual lifecycle phases. These include, for example, material, labor and energy costs in the development and manufacturing phase, maintenance and repair costs in tool use and recycling costs during tool retirement. Subsequently, all data relevant for the determination of these costs, including product, machine, simulation, process and usage data must be gathered.

In the following step the technologies used for the collection of this data are selected. While some data can be acquired through access to already established application software such as computer-aided design (CAD), production data acquisition (PDA), computer-aided quality (CAQ) or manufacturing execution systems (MES), the acquisition of other data, such as machine data from older machines, requires retrofitting through the use of sensor technology (Wulfsberg et al. 2019). A challenge in this process lies in the diversity of machine controls and the required interface management to access the event data relevant to the calculation. In the context of multimodal data acquisition, a decision is made individually for each data point as to which technologies are to be used. So-called sensor networks can be used to combine the advantages of individual sensor technologies. Technologies already in use are also to be examined regarding their suitability.

Next, the operational design for the selected technology concept must be carried out. This includes, for example, planning the location and mounting of transmitters and receivers as well as clarifying the reusability of the sensor technology. The type, quantity as well as the location of the sensor technologies determine the quality of the captured data, making the optimal design one of the most important steps in the creation of the digital shadow.

The captured data is stored in a so-called middleware. A middleware is an application-neutral program that is used to store and mediate data. Redundant data recorded during data acquisition is now linked in the so-called sensor fusion to create a uniform database, which ensures the completeness as well as the correctness of the data. The implementation of a consistency and plausibility check ensures the required quality level of the data (Bauernhansl et al. 2016).

In the next step, the digital shadow is created by accessing the middleware data and bringing together all raw and processed data relevant for the calculation of the PSS. The restriction to relevant, non-redundant data results in a smaller database than that of the middleware. The merging and integration of the data in the digital shadows, as well as the data collection in the middleware, is done continuously and automatically, resulting in a real-time updated database (Wulfsberg et al. 2019; Bauernhansl et al. 2016, Schuh et al. 2016).

A costing-relevant digital shadow must be created for each PSS, both current and completed. The resulting set of digital shadows forms the basis for the preliminary costing of future PSS.

Continuous calculation and forecast based design of actions

The objective of the continuous calculation is to create a forecast model capable of identifying potential cost overruns at an early stage and proposing suitable countermeasures. With the infrastructure of the optimization of the tool calculation, a target image was developed in which the creation of the forecast model is made possible by the



Fig. 3 Infrastructure of the optimization of the tool calculation

holistic networking of machines, resources and processes with the help of ICT and the developed digital shadow (Cf. Fig. 3).

In a first step, the costing model of the preliminary costing is updated in real time with the data of the digital shadow. This enables the calculation of current actual costs and deviations from target costs. Subsequently, a forecast model is developed, which aims at extrapolating possible future scenarios from current data as well as their probability of occurrence. This allows for the identification of potential future cost deviations. When a current or future cost deviation is detected, the system proposes appropriate countermeasures. These measures can vary and depend on the type of tool and the life cycle phase. Possible measures include identifying and addressing bottlenecks in the production line, adjusting production schedules to reduce downtime and implementing cost reduction measures. Examples of cost reduction measures include choosing a cheaper supplier and using a machine with a lower hourly rate. These measures are then evaluated by a specialist, who determines and initiates the most suitable action. The near-real-time updating of the forecasts enables very early initiation of measures, minimizing the impact of the variance on overall costs. In the future, the costing model will be further developed to evaluate countermeasures and initiate appropriate actions autonomously.

At the end of the tools life cycle, a post-calculation is performed. This process involves determining the actual total costs and comparing them to the value of the preliminary costing, from which the actual profit margin is calculated. The profit margin as well as findings on cost overruns, such as the reasons and timing as well as the implementation and effectiveness of countermeasures taken, are used to improve the costing model. This knowledge feedback enables the continuous improvement of the costing model.

Conclusion

Individualization and the so-called servitization lead to an increase of PPS, which builds a decisive measure to stay competitive in many industries. The success of a PPS depends on its calculation. However, the inclusion of intangible services has increased the complexity of calculation significantly. This applies in particular to single- and small-batch production, where calculation is already very complex especially due to the uniqueness of each product. The presented paper aims to answer to research question how a model for adaptive calculation of PSS in SBP needs to be composed. In order to answer this question, the presented paper introduces a process model based on ARIS. The model focuses on the calculation of tools and dies as an illustrative example for SBP. It furthermore regards the possibilities of the growing amount of data in production and usage environment and the benefit as well as the transparency, which this data can potentially create. While the model structures the relationship and interdependencies between different layers necessary for calculation, further research on each specific layer has to be carried out in the future.

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