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DERIVATION OF STARTING SOLUTIONS BASED ON PRODUCT ARCHITECTURE FLEXIBILITY EVALUATION

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Abstract

Manufacturing companies nowadays face growing numbers of heterogeneous customer requirements. Due to that, internal and external complexity lead to an increase in the associated costs. Especially companies with a high Engineer-to-Order business are strongly affected. To reduce external and internal complexity, Starting Solutions are a suitable way to do that. Starting Solutions require on the one hand the evaluation of product flexibility, on the other hand the evaluation of customer requirements. These two requirements are compared to each other and Starting Solutions are thereby derived.

Keywords: starting solutions, product architecture, mass customisation, configuration management

1. Introduction

The growing number of heterogeneous customer requirements is increasing internal and external complexity of manufacturing companies and their customers this increas in complexity is followed by an increase in associated costs. Especially companies with a high Engineer-to-Order business are strongly affected (Schuh, 2012). Product architectures of most manufacturing companies do not meet the flexibility needed to develop highly individual products demanded by the customers. Combined with shorter product lifecycles and time to market this leads to high costs in fulfilling these diverse customer requirements. Although, sales volume increase the operating profit often decreases (Schuh and Riesener, 2017). In order to counteract this effect and remain competitive despite high customer orientation, a modular product architecture is often used within the companies. The modular structure helps to address the mentioned challenges (Schoeneberg, 2014). Therefore, standardized components and assemblies are developed, which are reused as frequently as possible in modules with standardized interfaces in order to achieve economies of scale and decrease complexity along the entire value chain. Furthermore, the manufacturer benefits from this by turning away from standard products on the one hand and individual solutions on the other towards configurable products (Schuh, 2012). In order to not overburden the customer with the selection process of the required modules for the product according to the desired demands, product configurators can help to present the characteristics of the respective features clearly and logically. Product configurators offer the customer the possibility to configure the product as precisely as possible according to the customers' needs (Stormer, 2007). To simplify the configuration process, Starting Solutions are one possibility to reduce complexity of choice. A Starting Solution describes an incomplete pre-configured product for a particular customer group and requires only a fraction of the features for customization, providing simplification for the customer and at best leading to the product with the greatest customer benefit (Hildebrand et al., 2014).

Besides customer benefits, the manufacturer can also decrease complexity to save costs. By offering the customer a preselected configuration, which does fit to the identified customer group, changes to the configuration can be minimized. Therefore, it is possible to increase the amount of standard modules used within a configuration (Schuh, 2012). To implement Starting Solutions, each module of a product must be evaluated regarding its customization flexibility from the product view and to its relevance fulfilling customer requirements. The challenge is to identify a meaningful intersection of product architecture, customer group requirements and Starting Solution. This challenge is addressed within the present work. In particular, the product architecture is focused within this work. The aim of the paper is to present a methodology for the evaluation of the product architecture flexibility in the context of Starting Solutions. The paper structure as follows: After the Introduction within the first section, the second section introduces the theoretical background for Starting Solutions, as well as product architecture. The third section describes the Methodology of the paper and presents the customer requirement key figure as well as product flexibility key figure. The last part of section three describes the derivation of the starting solution by comparing the already introduced key figures. Section four validates the introduced method by the aid of an industry example. Section five gives a conclusion and thoughts about further research.

2. Theoretical background

2.1. Starting solutions

Product configurators are already established in the B2C market, and begin to find application in the B2B market. They enable the customer to configure a product with comprehensible characteristics derived from a given structure within the configurator (International Federation for Information Processing, 2017). According to studies, the complexity of the configuration process can increase to an extent, at which the customer is unable to complete the process and pursuits for a more understandable and intuitive variant of the competition (Babin et al., 1994).

Starting Solutions are one way to decrease complexity during this process (Schuh et al., n.d.). Starting Solutions are preselected configuration solutions of a product, from which the customer can select an initial solution that meets his requirements as closely as possible, and then iteratively modify individual product attributes of the selected solution to meet the requirements (Hildebrand et al., 2014). This is a two-stage preference mapping, in which a variant is first selected from a small number of completely specified initial solutions. Within the second step, individual product characteristics can be changed as required. This method leads to a comparatively higher customer benefit due to lower complexity perceptions of the configuration process than the sole use of default options or an additive option framing in an attribute-based representation of the options (Hildebrand et al., 2014). Similar approaches are used in the B2C context, in which the configuration process is improved through attractive design solutions of previous users that are made available as an initial designs (Franke et al., 2008). A major challenge is to find the right Starting Solutions for the respective customer group and not to patronize the customer with too much pre-configuration or overburden him with too many options in the downstream selection process (Schwartz et al., 2002).

2.2. Product architecture

A product architecture can be describes as “the assignment of the functional elements of a product to the physical building blocks of the product” (Ulrich and Eppinger, 2006). Therefore, the product architecture is the combination of functional structure, product structure and their transformational connection (Meier, 2007).

The functional structure describes the functions of a product within a structured form. The derivation of a functional structure is therefore the first step in the development of a product. It is essential to define the customer’s requirements for the product in a solution-neutral way using technical (partial) functions (Pahl et al., 2007).

The product structure consists of physical components and represents the interaction of all individual components. It represents different levels as modules, sub-modules, assemblies as well as individual components and parts (Pahl et al., 2007).

The combined description of functional structure, product structure and transformational relations between them is called product architecture. Those describe ideally not a single product, but all products across the product platform. Nevertheless, standardization and reusability of parts, assemblies, technologies and process steps can be supported by product architectures. Within the modularization, it is important to differentiate functional components between low-variant and high-variant assemblies and to standardize interfaces (Schuh and Riesener, 2017).

During the design process of a product architecture, the relation between the product architecture and customer requirements must be assessed. It is recommended to create standardized modules with standardized interfaces that can be used in as many different products of the portfolio as possible and be adapted without great effort (Bach et al., 2017).

Starting Solutions can be used as a further criterion for evaluating the product architecture. If a pre-defined characteristic is frequently changed by the customer, this can be traced back to incorrect assignment of the characteristic to the respective customer group. The product architecture should be further checked to see whether it is sufficiently precisely designed to meet customer requirements as precisely as possible. It must be evaluated whether it is flexible enough to be adapted accordingly and with little effort.

3. Methodology

The section describes the methodology within this work. A method to derive Starting Solutions based on product architecture flexibility and customer requirements is presented. Furthermore, an approach to form customer groups is described. Finally, the evaluation of customer view and product architecture flexibility, to derive Starting Solutions is described.

3.1. Customer group requirements

Customers can be clustered into different groups based on their requirements. Each customer group has a high differiation from each other, while the customers within a group show high similarity reagarding their requirements (Böttcher et al., 2009). Possible methods to group customers together are analytic hierarchy process (AHP), Two-step-cluster Analysis or the K-means algorithm (Mahdi and Rouhollah, 2016). The here introduced customer requirement key figure describes the demanded flexibility for a certain module by a customer group. Each module is subjected to an analysis. It is determined, how much a single module contributes to the fulfilment of customer requirements of the overall product. The Starting Solutions have to be tailored as closely to the customer's needs in order to reduce the effort on the customer side during the configuration process and even to counteract negative effects such as the "paradox of choice" (Schwartz, 2007). However, different customers also have different preferences with regard to their requirements. To group different requirements that appear together, customer groups are initially formed. This is done by using historical customer data and using cluster algorithms as "Two-Step Cluster Analysis" or "k-means" algorithms. The algorithms determine similarity between different orders and can thereby cluster customers into groups with different product selections and requirements.

Customer groups that have key requirements such as good durability, high performance, low price or low maintenance intensity, can be found in most manufacturing companies. For the calculation of K_j, all requirements must be formulated unidirectional, e.g. either all with a positive or all with a negative result in terms of flexibility or fulfilment of requirements.

The calculation and representation in the shell model is carried out analogously to the flexibility key figure. The requirement key figure is applied from the innermost shell in ascending order from 0 to 1.

Each customer group is additionally assigned a weighting factor g_k. Strategic customer groups or customers with a good product knowledge can thereby be granted more flexibility within the configuration process.

$$K_{k,j} = g_k \cdot \frac{1}{\sum_{r=1}^{m} c_{k,r} \cdot C_{r,j,max}} \cdot \sum_{r=1}^{m} c_{k,r} \cdot C_{r,j} \qquad (1)$$

Equation (1) contains the following variables:

- $K_{k,j}$ = Requirement key figure from the respective customer group view per module j
- g_k = Weighting factor of the customer group k
- m = Number of evaluation criteria
- c_r = Weighting factor of the respective evaluation criterion r
- $C_{r,j,max}$ = Maximum value of the key figures of the module and the respective evaluation criterion l
- $C_{r,j}$ = Key figure of the module and the respective evaluation criterion l

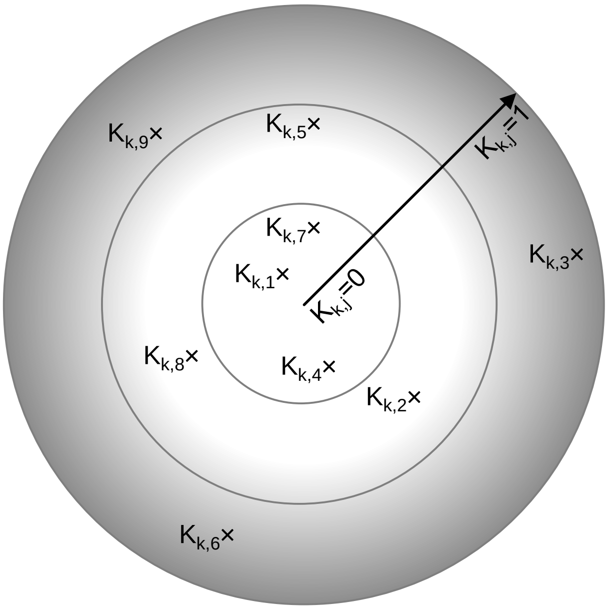

Figure 1. Shell model of the customer requirement key figures

At the beginning, it should be mentioned that the product architecture is only as flexible as its individual modules or components. At first, a procedure for the determination of a module adjustment flexibility key figure is presented. This serves as the basis for the comparison of the requirement prioritization from the customer's point of view in order to be able to derive suitable Starting Solutions for clustered customer groups in the final step.

3.2. Product architecture flexibility

In the following, a procedure for the determination of a module adjustment flexibility key figure is presented. A product architecture is only as flexible as its individual modules or components. Therefore, a procedure for the determination of a module adjustment flexibility key figure is presented.

When developing new product architectures, one possibility to identify relevant features is to use a feature tree analysis of predecessor products. Features are customer-oriented descriptions of the technical product with different characteristics depending on the product differentiation, Product features can be linked to technical features of a product and thereby to module features. Modules nowadays need high flexibility due to heterogeneous customer requirements. A Module is considered as flexible in this context if the required efforts to modify module characteristics are low. Therefore, if further required characteristics of different customers are known, modules can be designed with the right flexibility in advance (Schuh and Riesener, 2017).

Flexibility of a product architecture is necessary to change each module's characteristics at low costs and can only be quantified indirectly by each module's flexibility. It is initially necessary to define the type and scope of the essential drivers and evaluation dimensions. For manufacturing companies, criterias as production and development costs are used for the economic evaluation; individual components can thus be quantified and compared in terms of costs up to the finished product. The costs are used because if changes occure, the resulting costs for these must be passed on to the

customer. The modification of a component often affects further components within the module or product. Therefore, in addition to the costs it is necessary to quantify those indirect efforts caused by changing customer requirements or legal requirements. A sufficiently precise method for determining the degree of interdependence is formulated in the work of Eppinger (Eppinger and Salminen, 2003). Eppinger evaluates a component or a module with regard to the direction of the dependency, the classification based on the input and output variables of the functional structure with the spatial arrangement as additional variable as well as the sensitivity of the interactions.
In order to be able to apply the method presented for different companies, the three rating dimensions production costs, development costs and degree of interdependence can be weighted against each other. This is done in order to allow the company to define the flexibility with regard to their company strategy. E.g. innovation-driven companies could accept higher development costs than a cost-driven manufacturer. By using normalization, comparability is assured between the respective rating dimensions and modules.
To define adjustment flexibility, Equation (1), which is based on prior work to describe flexibility, is introduced (Aleksic, 2015).

$$P_j = 1 - \frac{1}{\sum_{q=1}^{n} b_q \cdot B_{q,j,max}} \cdot \sum_{q=1}^{n} b_q \cdot B_{q,j} \qquad (2)$$

Equation (2) contains the following variables:

- P_j = Product flexibility key figure of module j
- n = Number of evaluation criteria
- b_q = Weighting factor of the respective evaluation criterion q
- $B_{q,j,max}$ = Maximum value for key figures of the module and the respective evaluation criterion i
- $B_{q,j}$ = Key figure of the module and the respective evaluation criterion i

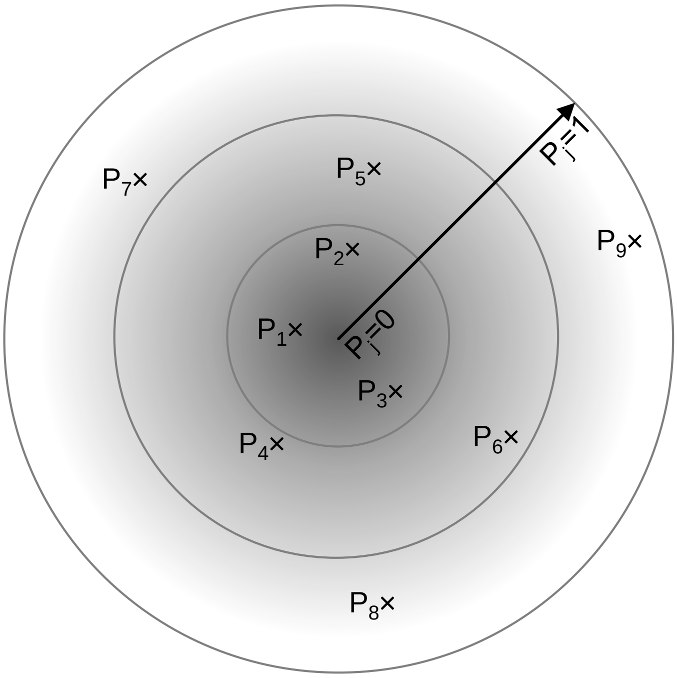

Figure 2. Shell model of the product flexibility key figures

The higher the product flexibility key figure and weightingof a module is, the higher the total effort by changing the module is rated and the higher the subtrahend is respectively. A value of $P_j = 0$ indicates that the module has the lowest adjustment flexibility, a value of $P_j = 1$ the highest flexibility and therefore the lowest costs by changing its attributes. A categorization of the flexibility key figure by splitting into thirds allows a simple division into non-critical and critical modules. For a clearer representation of the flexibility key figure, the shell model is suitable in addition to a tabular listing, which is divided into three concentric circles of equal width and applies the key figures from the core with the lowest flexibility ($P_j = 0$) to the outermost edge with the highest flexibility.

3.3. Starting solution derivation

In order to be able to define a Starting Solution for a customer group, the two key figures P_j and $K_{k,j}$ are brought into relation to each other. The comparison of the two values describes the fit between the demanded flexibility of a customer group for a certain module. The demanded flexibility ($K_{k,j}$) is than compared with the given flexibility of a certain module of the product (P_j). A comparison between the values is done. The optimum is where the product architecture is flexible enough to fulfil high customer interests leads to high values of P_j and $K_{k,j}$. A low Pj for a module with low flexibility is in conflict to a high $K_{k,j}$. It does not provide the needed flexibility to adjust the module to customer requirements with a low effort. Unflexible modules are pre-configured and its customer selections are observed for possibly required changes in product architecture to improve its flexibility. The assignment of the value ranges of P_j and $K_{k,j}$ has to be done company-specific. A first proposal for an initial start evaluation is given following:

- Inflexible modules with ($P_j < 0.33$) have preselected attributes within the Starting Solution and cannot be changed; $K_{k,j}$ is irrelevant. A change by the customer is not possible during the configuration process.
- Modules with a low flexible ($0.66 < P_j > 0.33$) or a medium flexibility but a limited customer importance ($P_j > 0.67$ and $K_{k,j} < 0.33$) are preselected within the Starting Solutions. The chosen attributes are based on the customer group allocation. For those modules, a change by the customer is possible during the configuration process.
- Flexible modules with ($P_j > 0.67$ and $K_{k,j} > 0.33$) do not have a preselected attribute. They are free for configuration by the customer.

The comparison of the two key figures is visualized within Figure 3. The figure contains the combination of P_j on the abscissa and $K_{k,j}$ on the ordinate.

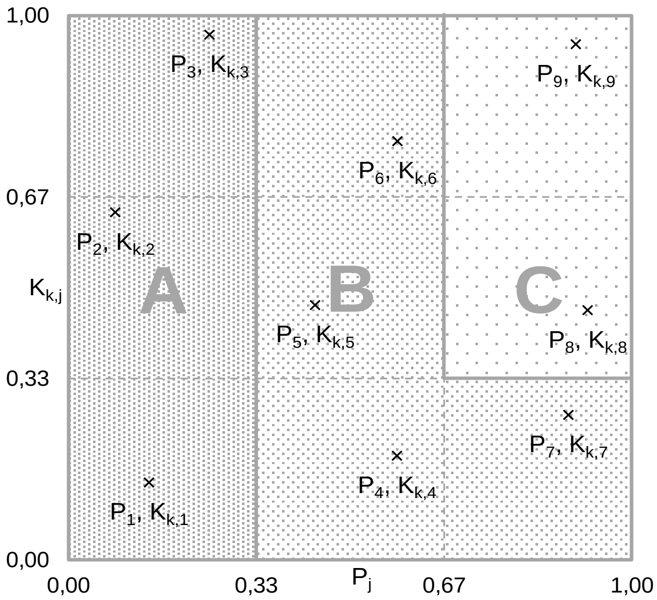

Figure 3. Comparison between the product flexibility and the customer requirement key figures

The comparison of both key figures finally results in the classification for the configuration process. Preconfigured and unchangeable modules are located within section A. Preconfigured but changeable modules are located within section B. Modules without any preselected attributes and free for configuration are located within section C.

4. Validation

Within this section, the above presented method is used on an example of a milling machine. The customer groups are already known in this case whereas the validation focuses on the description of the product architecture flexibility. Furthermore, the Starting Solution is derived.

The manufacturer is willing to incur higher development costs, so the weighting factors are production costs (PC) with gPC = 0.6, development costs (DC) gDC = 0.1 and degree of interdependency (ID) with gID = 0.3. The following Table 1 shows the results of the internal evaluation of each module with regard to the respective evaluation criterion between 1 (low effort) and 9 (high effort) as well as the calculated product flexibility ratios Pj according to Equation (2).

Table 1. Evaluation criteria and customer requirement key figures of the modules

Evaluation criterion r	LS	PF	PR			
(for g_1 = 1.0) $c_{1,r}$	0,7	0,2	0,1			
(for g_2 = 0.4) $c_{2,r}$	0,7	0,2	0,1			
(for g_3 = 0.8) $c_{3,r}$	0,1	0,1	0,8			
Base frame BFR	5	1	1	0,12	0,17	0,42
Drive system DRS	5	7	9	0,75	0,26	0,64
Media supply MDA	5	7	5	0,46	0,24	0,60
Tooling system TOS	9	5	5	0,48	0,35	0,87
Tool changing system TCS	5	9	5	0,48	0,26	0,64
Control system CTR	1	7	7	0,57	0,12	0,31
Safety system SFY	1	3	7	0,53	0,09	0,22
Power supply PWR	3	3	5	0,41	0,14	0,36
Module j				$K_{3,j}$	$K_{2,j}$	$K_{1,j}$

As a result of Table 1, the tool changing system (TOS) and control system (CTR) are identified to be the modules with the lowest adaption flexibility. The base frame (BFR) and power supply (PWR) have the highest adaption flexibility. After calculating the adaption flexibility, the next step is to determine the customer requirement key figures.

To calculate the customer requirement key figure, the relevant evaluation criteria for the product are lifespan (LS), performance (PF), and price (PR). The evaluation by the customers and the thereby derived customer requirement key figures are shown within Table 2.

Table 2. Evaluation criteria and product flexibility key figures of the modules

Evaluation criterion q	PC	DC	ID	
Weight factor b_q	0,6	0,1	0,3	
Base frame BFR	1	5	3	0,78
Drive system DRS	7	9	5	0,27
Media supply MDA	3	3	7	0,53
Tooling system TOS	3	7	1	0,69
Tool changing system TCS	9	7	9	0,02
Control system CTR	7	5	9	0,18
Safety system SFY	7	5	3	0,38
Power supply PWR	1	1	1	0,89
Module j				P_j

Figure 4 shows that for customer group 1, which has the highest customer group weight and the focus on lifespan, the modules TOS, BFR and PWR are defined as free for configuration within the configuration process. All other modules are preconfigured within the Starting Solutions. The modules TCS, DRS and CRT are also fixed, and therefore can not be changed at all. Customer group 2 has the same requirement prioritization as customer group 1 but a lower importance tot he manufacturer. Therefore, only the TOS module is remaining for free configuration. The modules TCS, DRS and CRT are also fixed based on their low flexibility evaluation. All other modules are preselected within the Starting Solution, but changeable by the customer. Customer group 3, which is focused on a low price, can freely configure the modules TOS and PWR. The modules TCS, DRS and CRT are fixed again based on the low flexibility evaluation. All other modules are preselected within the Starting Solution, but up for change by the customer if needed.

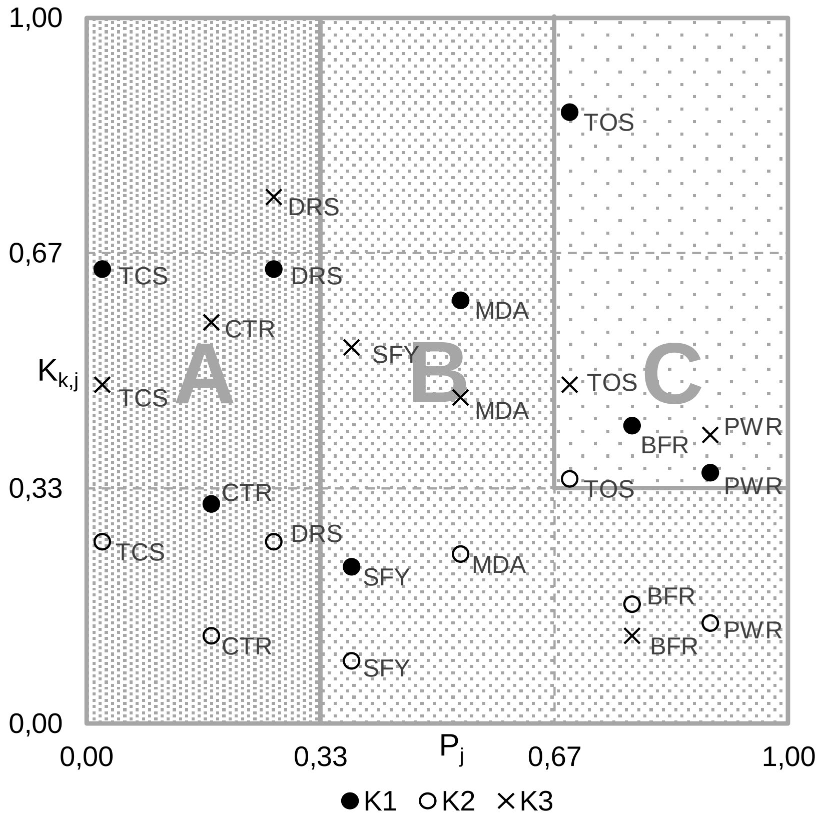

Figure 4. Comparison between the product flexibility key figures and the customer requirement key figures of the milling machine's modules

As a result of the validation, the different degrees of freedom for different customer groups is shown. Customer groups with a high customer group weight do have higher flexibility. Nevertheless, there are modules with low flexibility cannot be changed by any customer group, as seen here by TCS, DRS and CRT. Those modules are fixed for all customer groups. A differentiation between free configuration and a preselection of the Starting Solutions is only done, if the flexibility rating of a module is above 0.67. Since for all these modules, changes are possible for the customer, the preselection of this features is mainly done to decrease the complexity of choice for the customer.

5. Conclusion and further research

Manufacturing companies nowadays face increasing internal and external complexity. Most product architectures do not meet the requirements needed to enable highly individual products demanded by the customer. To reduce both, internal and external complexity, Starting Solutions have been presented as a suitable solution. To use Starting Solutions, two different key figures are necessary: First, the flexibility evaluation of modules is needed to define the efforts needed for changes of each module within the whole product architecture. Second, a key figure to determine the customer focus is needed. By using a comparison between those key figures, the configuration logic for Starting Solutions can be derived. Within this work, a method evaluate product architecture flexibility through module flexibility is introduced. Furthermore, a guideline to derive Starting Solutions based on flexibility and customer requirement is presented. An exemplary milling machine is used for the validation of the methodology.

Within the next steps, the success of Starting Solutions should be evaluated. Even though, theoretically the concept has proofed itself within the Business-to-Customer market, research about the effects within the Business-to-Business market is still needed. Nevertheless, further research should also focus on methods, to gather additional information for product architecture adaptions based on decision made during the configuration process by the customer. E.g., features, which are changed very often during the configuration process should be analysed. The focus of further research should the improvement of product architecture with regard to customer requirements and product flexibility.

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