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DESIGN FOR FUTURE VARIETY TO ENABLE LONG-TERM BENEFITS OF MODULAR PRODUCT FAMILIES

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ABSTRACT

By developing and using modular product families, large savings can be achieved through reuse and combinability along the entire value chain of a company. Since these potentials often have a very long-term character, the lifetime of a modular product family should be as long as possible. Change drivers, such as changing customer and production requirements, however, result in changes having to be made to the initially developed modular product family, which not only causes a great effort but also prevents the long-term benefits from being fully exploited. With the Change Allocation Model, we introduce a tool that makes it possible to align the essential future changes to the product architecture and to identify and redesign the change-critical components taking into account the existing component variety of the product family. This enables future changes in variety to be considered in the product architecture and a future robust modular product family to be developed. The new visualization is illustrated using the example of a product family of pressure regulating valves and is finally discussed with regard to further potentials and challenges.

Keywords: Product families, Design for X (DfX), Product architecture, Modularity, Change

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1 INTRODUCTION

Increasing individualization of buyer markets as well as rising economic dynamics force companies to offer their customers a high variety of different products and services in order to remain competitive. The challenge for companies is to provide a wide range of external diversity while managing the resulting high internal product and process variety. A great leverage for handling the variety can be found in the design of modular product families (Otto et al., 2016). This strategic measure allows many potentials to be tapped along the entire value chain and influences the essential economic targets of a company. The positive effects of modular product families on companies were verified in several studies (Greve et al., 2020). However, it was also found that a large part of the essential advantages only appears after a certain period of time. For example, production costs can often only be reduced in connection with process adjustments (production systems, assembly processes), which can take several years depending on the business environment. Thus, there is often a long period of time between the initial planning and the use of the modular product family.

This long time span entails risks for the success of the initially developed product family. With increasing duration, the probability of changes in the company and market environment increases, which can lead to the fact that the requirements set at the beginning no longer correspond to the new circumstances. The main drivers of change can be found in dynamic customer requirements and in changes in production and procurement (Bauer, 2016). These change drivers not only cause cost-intensive changes to the product architecture, but also result in the fact that the desired advantages cannot be achieved by already standardized and configurable components or modules (Schuh & Riesener, (2018), Greve et al. (2020)).

These dynamics must be taken into account in modular product family design. For this purpose, we are introducing a new tool, the *Change Allocation Model* (CAM), which enables the transfer of the relevant influencing factors to the product architecture and the identification of change-critical components from a dynamic customer and production perspective. With the help of the model, constructive recommendations for a future robust design can be derived and long-term savings can be achieved. The model is illustrated by the example of a product family of pressure regulating valves, where the case-specific applicability is shown. Following the demonstration, we discuss the method and show possible links to further methods of design for variety and modularization. Finally, an outlook on further research is presented.

2 STATE OF THE ART

In the literature, there is a large number of tools and methods for the design of modular product families for handling the variety. Some influential methods in this area include *Modular Function Deployment* according to Erixon (1998), *Structural Complexity Management* according to Lindemann et al. (2009), *Theory of Modular Design* according to Stone (1997) or *Integrated PKT-Approach for the Development of Modular Product Families* according to Krause et al. (2014). The aim of the methods is to influence the modularity of a product architecture in such a way that functional and/or product-strategic advantages result across product variants. The modularity of a product architecture can be understood as a gradual characteristic, which according to Salvador (2007) can be described by the characteristics of decoupling, commonality, combinability, interface standardization and functional binding. Hackl et al. (2020) add the attribute of oversizing to this characteristic. In particular, commonality and combinability are the key levers for saving costs across product variants (Greve et al., 2020).

The alignment of a modular product architecture should always be based on the customer-relevant product characteristics, since their fulfillment provides the benefit for the company (Kipp & Krause, 2008). Customers consciously perceive these product features and include them in their decision process for selecting a product variant. The principle of *Design for Variety* addresses this circumstance and has the goal of obtaining a minimum internal variety at components and processes by the configuration of a fixed external variety of offers (Kipp & Krause, 2008).

Due to the dynamics described earlier, it is no longer sufficient to simply master the variety in terms of the past. In fact, the change-induced variety in the future must also be taken into account in order to be able to exploit the advantages of a modular product family in the long term. This can be addressed by the changeability of a product architecture. The objective of this approach is to be able to react to dynamically initiated changes with as little effort as possible. According to Fricke & Schulz (2005), adaptability, robustness, flexibility and agility can be defined as four different aspects of the changeability of a system. For modular product family design, the concepts of robustness and flexibility are particularly promising (Bauer, 2016). When developing a robust design concept, elements that are resistant to changes in the environment should be robustly designed (Cardin, 2014). This enables the elements to be reused across product variants and to achieve long-term economies of scale. In addition, not only the risk of a dynamically caused change is minimized, but also the acceptance of the risk is allowed by reducing or eliminating the negative change effects (Bauer, 2016). The characteristic of the commonal use of change-resistant product architecture elements is to be striven for here. The flexible design of elements, on the other hand, results in increased reactivity, which is required to react quickly and cost-effectively to changing conditions (Cormier et al., 2009). The concept of flexibility makes it possible - despite change-inducing uncertainty due to dynamic influencing factors - to implement subsequent changes with reduced costs and effort (Cormier et al., 2009). For its realization, especially the combinability as a feature of modular product families has to be addressed.

Taking into account the variety induced by future changes can be designated as *Design for Future Variety* to derive *Future Robust Product Families* (Greve & Krause, 2018). The main drivers for changes are customer requirements and production-relevant factors (e.g., change of production process, change of suppliers), see Figure 1. They lead to cost-intensive adjustments to the modular product architecture and to the fact that the long-term potentials (which often occur in production) cannot be fully exploited.

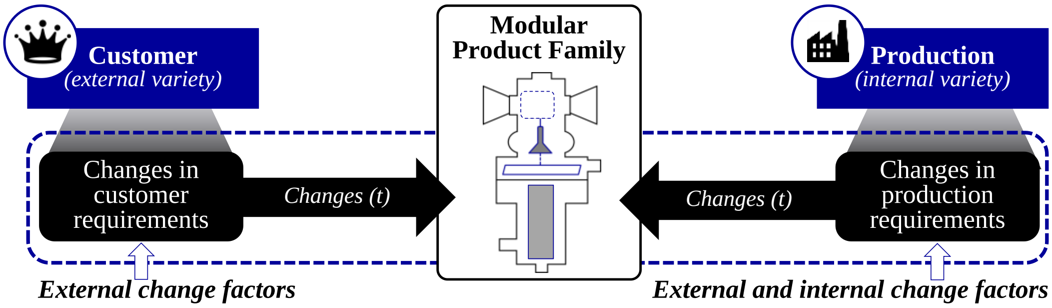

Figure 1. Change drivers considered in the Design for Future Variety

In the literature, there are very few approaches that simultaneously consider changes in customer and production requirements in modular product family design. The focus is mostly on the customer side and is limited to a conceptual design of the module boundaries, as for example in Martin & Ishii (2002) or Bauer (2016). A comprehensive overview of methods and analysis with the present research focus can be found in Greve & Krause (2018). The one-sided view is not sufficient, since the substantial long-term potentials are based on the commonal use as well as configurability and are attainable mainly by a constructional adjustment of the product architecture. In order to close this gap, a new tool is introduced in the following, with which the essential change-critical product structure elements can be pointed out and constructively redesigned with regard to the handling of future variety.

3 INTRODUCTION TO THE CHANGE ALLOCATION MODEL (CAM)

The central element of the developed procedure is represented by the *Change Allocation Model* (CAM). With the help of this model, change-induced variety at different levels can be made visible and compared with existing internal variety. For this purpose, according to Figure 1, the change-critical customer and production requirements are identified and transferred to the existing product architecture. The abstract representation of the model with the different domains is depicted in Figure 2.

The model is based on the different levels of abstraction in product development, whereby the degree of abstraction increases from the inside out. The transfer of the change-critical drivers to the product architecture takes place by technical characteristics, which form concrete starting points for the designer for revision and, thus, the addressing of the change-induced variety. These characteristics are specified as abstractly as possible, describe the product view in its entirety and can be directly influenced by the development engineer. Internal product attributes contain on the level of assemblies or modules the architecture of a product by identifying its elements and their arrangement, on the level of machine elements mainly shape/design, dimensions/dimensions and material properties. In addition, there are also aspects such as surfaces, manufacturing methods and colour. Furthermore, all information should be quantifiable.

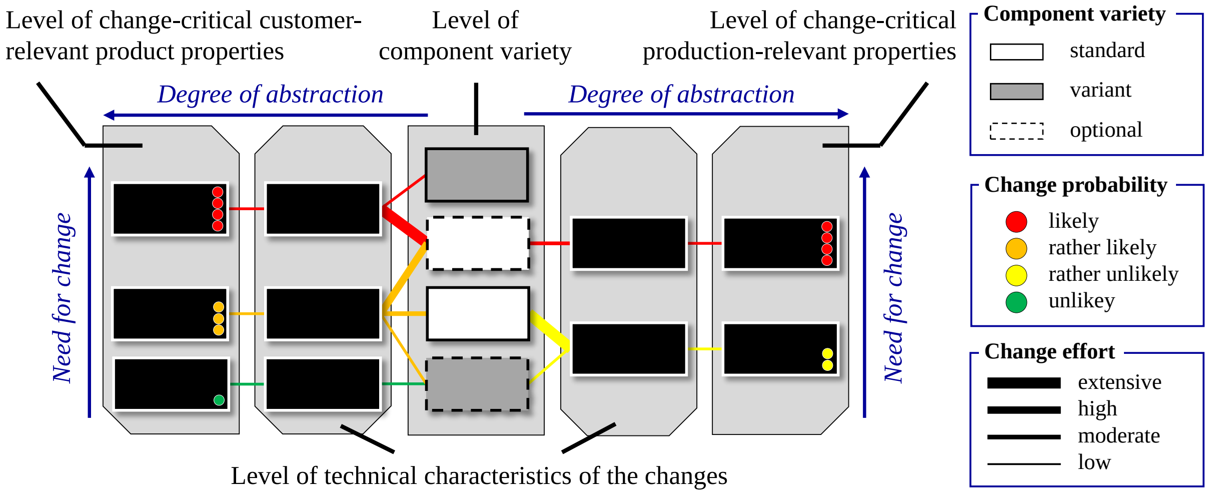

Figure 2. Schematic representation of the change allocation model (CAM)

The resulting CAM documents on different levels the future variety resulting from customer and production changes and maps their causal relationships. The idea behind the model is to highlight just the elements that are critical to future changes. The criticality results thereby from the decision-relevant criteria of the **influenced existing component variety**, the **change probability** as well as the **change effort**. The information is presented visually in the model as shown in Figure 2, allowing a focus on the essential elements. By aligning the levels with the product development process, the CAM can not only make the change-induced variety transparent, but also address it directly through appropriate redesign measures. The tool can therefore be used in the early product planning phase as a support for the creation of concept alternatives. Figure 3 shows the procedure for creating and working with the CAM and is explained below using the example of a pressure regulating valve product family.

Figure 3. Procedure for creating and working with the CAM

3.1 Step 1: Definition of the goals of a redesign

At the beginning of the application the concrete objectives of a future robust product family design must be defined. This is essential because different objectives are addressed by different solution concepts and can be met to different degrees. In order to support the selection of realistic and concrete targets, the *Impact model of modular product structures* can be used as a knowledge base for the definition of relevant target values (Hackl et al., 2020). In addition to potential generic effects, it also contains information on which advantages are particularly significant under which temporal boundary conditions (Greve et al., 2020). In the present case, the variety-induced production and development times are to be reduced in the long term and new production processes should be implemented in the medium term.

3.2 Step 2: Analysis of component variety of the existing product family

To analyze the existing variety, the product architecture of the modular product family is examined with regard to variance. An established tool for visualizing the variety is the *Module Interface Graph* (MIG) according to Kipp & Krause (2008) (see Fig. 4). The MIG hereby represents the entire product family and not individual products. In this case the considered product family consists of 20 variants (PV1-20). The schematic representation is intentional, since it allows, among other things, an interdisciplinary application. The information of the component variety is needed for the middle level of the CAM.

3.3 Step 3: Analysis of Change Drivers

As already mentioned, the probability and the effort of a change are relevant for the determination and transformation of change critical elements. The probability is determined at the level of customer and production-relevant properties, whereas the change effort results from the change-based dependencies at component level.

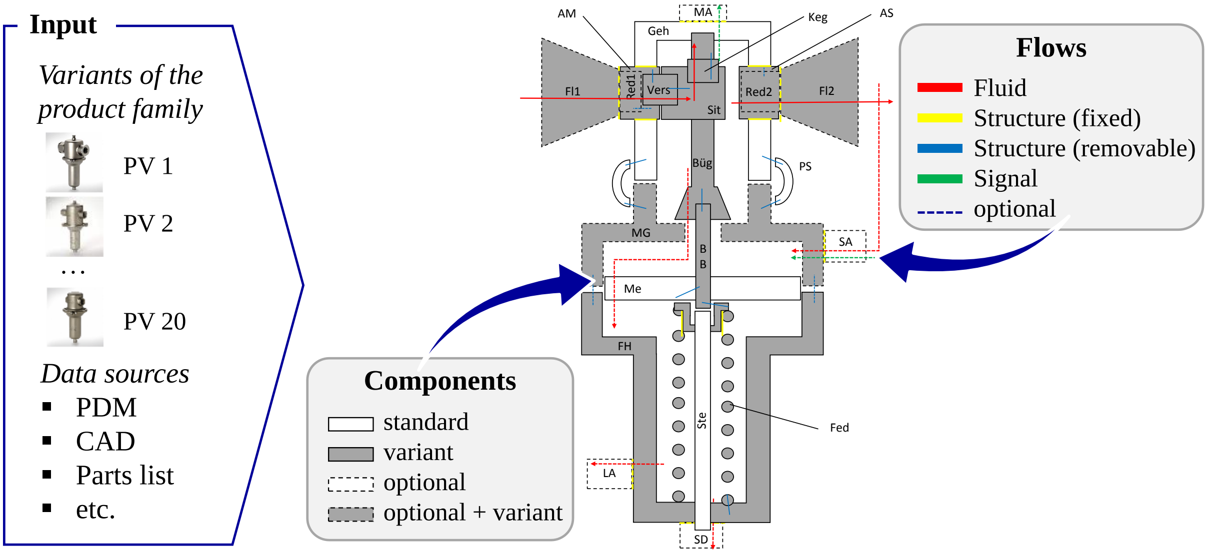

Figure 4. Module Interface Graph (MIG) of the pressure regulating valve family

3.3.1 Assessment of Probability of Change

For the determination of future developments and their probabilities, various approaches exist in the literature, which differ significantly with regard to the horizon, the scope and the required resources. A comprehensive overview of foresight methods can be found in Fink & Siebe (2011). At this point, reference is made to the procedure according to Greve et al. (2019), which uses the Scenario technique and a Monte Carlo simulation to determine the probabilities of changes at the level of customer-relevant product properties. For the representation in the CAM a simplified traffic light system is used, which qualitatively represents the probability in four degrees. A quantitative representation of the values is equally possible. For the application example, the probabilities of change of the customer-relevant product properties are shown in Figure 3. For this purpose, the *Tree of external Variety* (TeV) according to Krause et al. (2014) is used and modified (see Fig. 5).

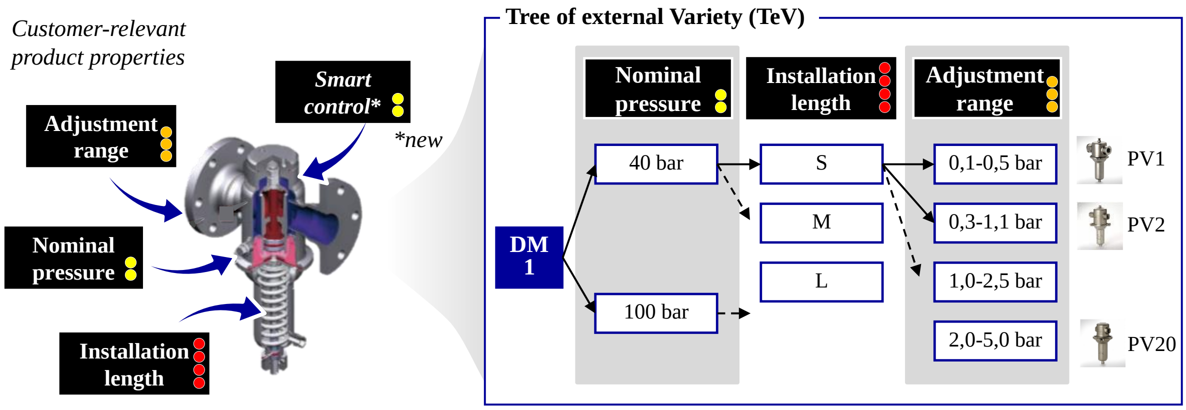

Figure 5. Change probabilities of customer relevant product properties using modified TeV

The adaptation of the TeV is appropriate here, since only product properties and characteristics are mapped that contribute to the creation of variants from the customer's perspective. In the example, the *installation length* has the highest probability of change (red), which is due to market developments in the gas-fired power plant sector. New customer-relevant product features (e.g., *Smart Control*) are not included in the TeV, as these have not yet been sold and must first be examined to determine whether and how they will be taken into account in the redesign.

To determine the changes and their probabilities on the production side, internal foresight tools such as (production-) roadmaps are used and the changes from the areas of production processes, suppliers, new technologies or laws are determined. This is done analogous to the analysis of the internal change drivers. In this case, the main change drivers are the transition to a *casting process*, *automatic robot welding* and *in-house production* of the *spring*. The results of this step are transferred to the outer layers of the CAM.

3.3.2 *Estimation of Change Effort*

A further criterion for the determination of change-critical components represents the expected change effort. This extends over the entire product life cycle and is difficult to quantify. A common technique for relative determination is the change propagation approach. Here the assumption is pursued that the components, which are most interconnected, produce also the largest change expenditure (Clarkson et al., 2004). The determination can be supported by *Design Structure Matrices* (DSM), in which the change-based dependencies are recorded and quantified in the form of active and passive sums. Within the framework of the presented method, different types of changes are considered, since different changes also cause different effects (e.g., material vs. geometric changes). The occurring types can be derived from the changes of the technical characteristics with the help of the CAM. The sums are transferred into a criticality portfolio and the change effort is determined according to the defined ranges for the components with the respective change type. These areas are to be selected on a case-specific basis. An example of the geometric change analysis of the DSM and the criticality portfolio is shown in Figure 6.

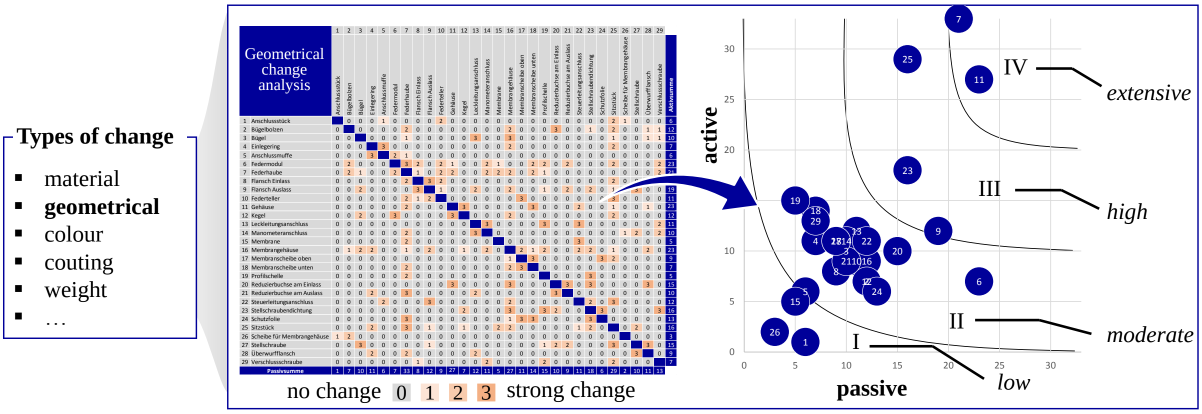

Figure 6. Determination of change effort using the example of geometrical changes

In particular the *housing* (11) exhibits a very high expenditure with geometrical changes, since it has many dependencies to other components. The representation of the change effort is done in the CAM by means of the arrow strength at the transition from technical features to components.

3.4 Step 4: Identification of change critical components using the CAM

The results of the previous steps are transferred to the CAM and the correlations between the change drivers and the product architecture are entered (see Fig. 7). The resulting visualization condenses the future emerging variety and allows to identify the elements that are critical with regard to relevant future changes.

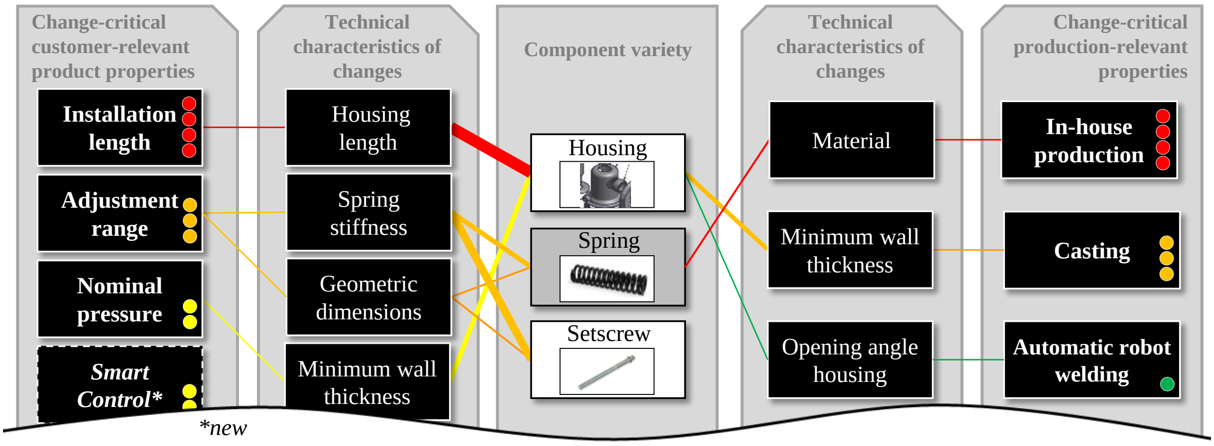

Figure 7. Change Allocation Model for the pressure regulating valve family

It becomes apparent that especially the *housing* is affected by many probable changes and that this results in high change efforts (e.g., due to the *housing length* or *minimum wall thickness*). In addition, the *housing* is currently built into all product variants of the product family as standard, so that a later change can lead to the fact that not only cost-intensive adjustments become necessary, but also savings effects cannot be fully exploited due to reuse. The future robustness is not optimal here, so that there is a need for action to revise it. The same applies to the *setscrew*, which is affected by the customer's change of the *adjustment range*. Also, here dependencies arise, which have to be solved. Ideally, the identification and redesign of the areas critical to change should take place within the framework of a workshop and in consideration of the objectives that have been set. In the following the redesign measures with the focus on the presented emphasis of the two change-critical components are pointed out and exemplarily used.

3.5 Step 5: Redesign using future robust design measures

Concrete measures are being defined to redesign the modular product family in the context of future variety. These are applied on the different levels of abstraction of the CAM and have different impacts.

3.5.1 Search for solutions at component level

The search for solutions on the middle level creates the basis for a future robust concept, which is realized by an adaptive design. The aim is to redesign the change-critical components in such a way that they have as little dependencies as possible on technical features with high change probabilities and the change effort involved. For this purpose, the design measures **differentiation**, **integration**, **oversizing** and **decoupling** of change-critical components are applied. Using the example of the *housing*, these measures are shown schematically in the CAM (see Fig. 8).

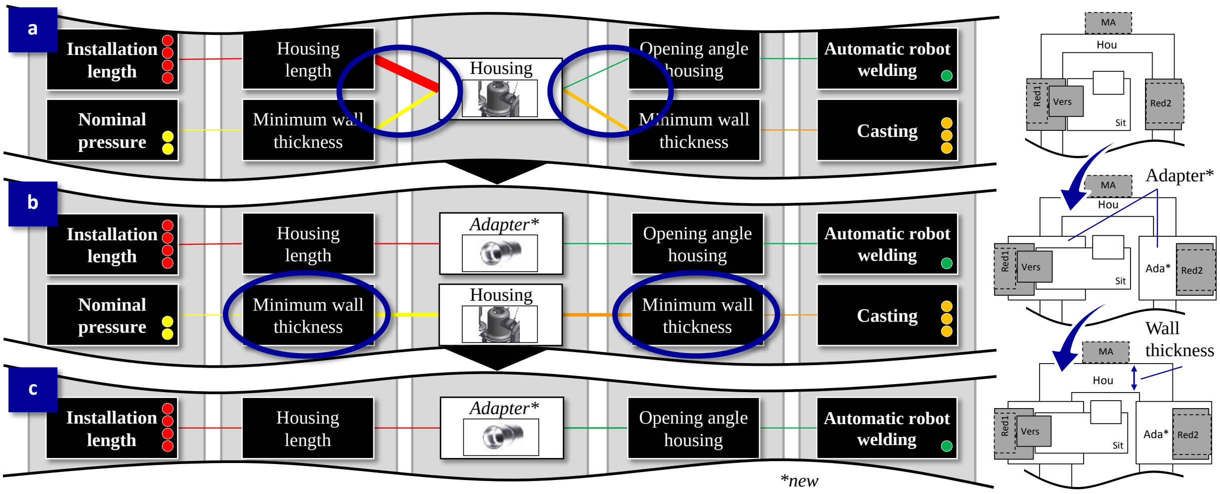

Figure 8. Redesign at component level using the CAM

As already stated, the standardized *housing* in the application example is influenced by various changes (a). In order to solve these dependencies to different changes of technical characteristics, the component is differentiated and the geometrical changes of the *length* and *opening angle* are outsourced in form of an *adapter* (b). In addition, the *housing* and *adapter* are decoupled from each other by means of a standardized interface, which significantly reduces the amount of work involved in making changes when the overall length is changed (see line width between (a) and (b)). These measures result in synergies at the level of the technical characteristics of internal and external change drivers (b). Here it becomes evident that both the *nominal pressure* and the change in the manufacturing principle (*casting process*) result in the same changes in the *minimum wall thickness* and lead to changes in the *housing*. In order to come closer to the ideal of a future robust product architecture, the *wall thickness* is oversized and, thus, both change dependencies are eliminated. This results in the standard component of the *housing* no longer appearing in the CAM (c). Although a new component was created with the *adapter*, the long-term standardized *housing* offers great potential for savings in production through automated manufacturing processes.

3.5.2 Search for solutions on the level of technical characteristics

Redesign on the level of technical characteristics is usually accompanied by more profound measures. In order to increase future robustness, **alternative or innovative operating principles** can be developed, changes in the **hardware can be outsourced to the software** or **substitutional changes can be pre-implemented**. The implementation of these measures is again illustrated by the CAM application example (see Fig. 9).

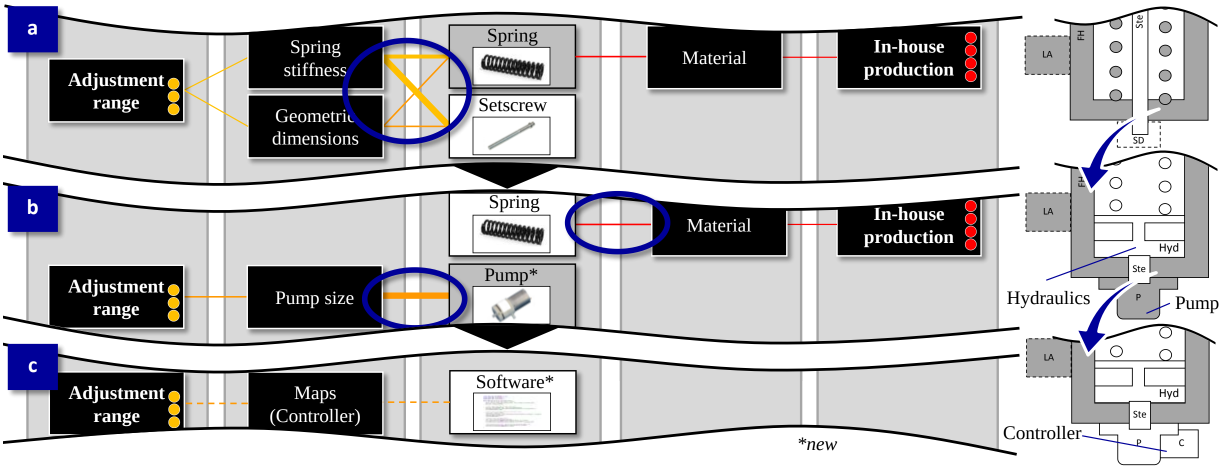

Figure 9. Redesign on the level of technical characteristics using the CAM

The change-critical customer-relevant product property of the *adjustment range* has several modification effects on the *spring* and *setscrew* (a). In order to reduce the manifold effects of change, an alternative functional principle in the form of a *hydraulic pump* is being developed. With this principle, the future changes of the *adjustment range* are realized via different *pump sizes*, which means that no *setscrew* is required and the *spring* can be installed as standard (b). This now calls for consideration of the change on the production side. Here it is planned to cancel the spring supplier due to long delivery times and to produce the component *in-house*. Since this change is very likely and can be influenced by the company itself, it is decided here to pre-empt the change and produce the *spring* directly in-house. This causes the new standard component to disappear from the CAM (c). In addition, the change in *size* of the *pump* can be represented by an adaptable programming of a control system. This eliminates the need for physical changes and can be outsourced to *software*. This is symbolized by the dotted line. In this case, the existing component variety can also be reduced by a targeted redesign, which brings additional advantages.

3.5.3 Search for solutions on the level of change-critical properties

At property level, the future robustness of a product family can be influenced differently. In most cases, the company has no influence on the external drivers of change, where the market and its customers determine the direction. One way to start at the left side of the CAM is that identified changes are already included in the product family. For this purpose, measures of product design suitable for **upgrading** can be applied, e.g. according to Mörtl (2002). Future customer requirements, such as *Smart Control*, are implemented in such a way that interfaces are already defined and can then be easily adapted later. Again, the CAM supports the representation of possible dependencies in the design of a selected technical implementation (e.g. *sensor integration*).

On the right side, the company has a greater influence on changes in production-relevant properties, as these are mostly internal. Here, with the help of **flexible production systems** (e.g. according to Morales, 2003), the most critical change drivers can be eliminated so that they have no effect on the product architecture (e.g. through *adaptable welding processes*). In this case, an interdisciplinary dialogue with the responsible persons of the respective departments is always necessary.

3.6 Step 6: Evaluation and selection of future robust product structure alternatives

The result of the previous application of the method are various product architecure alternatives, which are compared with each other in terms of future robustness. The comparison is also carried out here with the help of the CAM. For this purpose, no key performance indicator is deliberately generated from the relevant criteria for determining future robustness, but a visual decision support for a relative comparison is provided. The less dependencies to probable changes and components are contained in the CAM, the more optimal is the future robustness of the product architecture. Here also in particular the present component variety is of relevance. Especially standard components should, if possible, have as few dependencies on changes as possible and ideally not appear in the CAM at all. In this way, long-term potentials can be achieved and the effort for change can be kept low. The result of the method is a selected future robust modular concept of a product family, which provides the basis for further elaboration or modularization.

4 DISCUSSION

The exclusive addressing of future potentials by a suitable modular product structuring is not always appropriate for manufacturing companies. In addition to the possibility of future benefits, current, variant-induced problems must also be solved - ideally simultaneously and by exploiting synergies between short, medium and long-term benefits. Here a simultaneous optimization regarding the existing variety is conceivable for example by a symbiosis with methods of Design for Variety and object of current research. In this context, further criteria must also be taken into account when selecting a suitable product architecture alternative. Since the measures carried out are aimed at future potentials, the opportunities opened up by this must be balanced with the resources used for this purpose. Here the direct costs as well as the variety-induced complexity costs are relevant.

In contrast to existing methods, our approach does not rely on a KPI-based determination of change-critical product architecture elements, but shows the change-induced diversity qualitatively and graphically. On the one hand, this enables increased transparency and creates the basis for the decision for or against a product architecture alternative. This is particularly important in cooperative decision-making processes, where various stakeholders with different backgrounds are involved. This situation is typical for concept decisions of modular product architecture concepts (Windheim, 2020). On the other hand, the simplified representation of the probability of change does not suggest the false precision that is always present in decisions under uncertainty. Here, the quality of results is strongly linked to the input of the experts. However, it is possible to add quantified values to determine the probabilities of change and integrate them into the method (e.g. in the form of percentages). The same applies to the change efforts, which are also only represented in the model in a simplified form by the propagation of changes. A more precise determination is also conceivable here and can be integrated into the model.

The presented tool is deliberately kept simple and limited to the essential decision-relevant criteria so that it can also be applied in an industrial context. In addition to the application example presented, further case studies have already been conducted, the results of which indicate a high level of acceptance among users. This must be conclusively confirmed in a comprehensive evaluation study.

5 SUMMARY AND OUTLOOK

In this paper we introduced an approach that helps to redesign modular product families so that they are as robust as possible against future changes in a dynamic customer and production environment. The central element of this procedure is the tool of the Change Allocation Model, which makes it possible to visually identify and redesign the change-critical elements of the product family based on decision-relevant criteria (existing product variety, change effort, need for change). The aim was to redesign especially the standard parts of the product family so that they are robust against future changes, as this allows the long-term potential of modular product families to be exploited. To support this, various design measures were introduced, which were illustrated using the CAM and demonstrated by an example of a product family of pressure regulating valves.

However, the constructive redesign is only the first step in a comprehensive modular product family design. The module boundaries must also be defined and the module process in the company must be designed. For this purpose, the information from the CAM can be used to form flexible clusters with change-critical components as well as robust clusters with non-change-critical standard components as module drivers. The development of a methodical support for modularization with regard to future robustness is subject of further research.

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