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FRAMEWORK OF A VARIANT MANAGEMENT FOR MODULAR PRODUCT ARCHITECTURES

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1. Introduction

The concept of a modular product architecture has become increasingly significant throughout the last decades [Baldwin and Clark 2006]. This is caused by the attempt of companies to reverse the threat of an increasing complexity, resulting from globalization effects, shortened product lifecycles, the growing importance of niche markets and the high demand of customers for individualized products [Lindemann et al. 2009]. Modular product architectures offer a solution to face this threat by more efficiently controlling a company's internal complexity [Baldwin and Clark 2006].
A modular product family is created by decomposing existing products into modules, which are several smaller structural elements that can be managed more easily [Jose and Tollenaere 2005]. The resulting modules are combined to a modular tool kit. Within a modular structure, sellable products are generated by combining existing modules [Weiser et al. 2015]. The efficient handling of complexity by a modular product architecture is attained through the usage of commonalities [Ripperda and Krause 2015]. A modular product family reuses modules across different products [Jose and Tollenaere 2005]. Therefore, the modules require defined interfaces to ensure their combinability [Chen and Liu 2005]. Yet, without considering the modular design rules in a module development and while ensuring an efficient internal complexity, the sustainability of a modular product architecture is at risk.

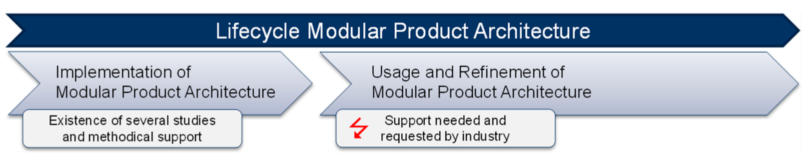

Figure 1. Modular product architecture lifecycle

As shown in Figure 1, the lifetime of a modular product architecture can be segregated in two phases. The first phase is the implementation phase of the modular product architecture. Several studies and methods exist to support companies in this stage [Jose and Tollenaere 2005]. The second phase addresses the usage of the modular structure. The initial modular tooling kit is derived from existing and previously planned products. However, this roadmap planning is limited to a certain timeframe. There will be novel ideas of new technologies and products throughout the lifetime of a modular structure that have not yet been considered. These ideas result in an alteration of the modular product family [Weiser et al. 2015]. This leads to one of the main challenges in the daily work with modular product architectures, the long-time maintenance after its implementation [Beckmann et al. 2014]. However, for the second lifetime phase of a modular product family insufficient support to sustain modularity exists [Bahns et al. 2015]. The objective of this paper is to identify the demand for such a methodical support in the second lifetime phase of a modular product architecture, especially for refinement decisions of a modular structure. Initially, the challenges of refining a modular structure are discussed, in order to derive the requirement for a modular variant management framework in section 2. Thereafter, existing variant management methods are examined in section 3. Based on this literature review, a new concept to evaluate refinement scenarios for the modular product architecture is presented in section 4. Finally, in section 5 the application of the framework in the industry is presented and further discussed in section 6.

2. Need for a variant management framework of modular product architectures

Companies nowadays are facing the threat of a steadily increasing complexity [Lindemann et al. 2009]. Cutting the external variety by consolidating a company's product range is not an equitable option to solve this challenge [Blees et al. 2010]. Particularly in the modern world, differentiation within the own product range and to competitors is indispensable in order to handle the demand for progressively customized products [Lindemann et al. 2009]. A modular product architecture enables companies to handle complexity more effectively, due to its less complex one-to-one mapping of functional elements to physical components and de-coupled interfaces between the components of a product [Ulrich 1995]. The aim of a modular product architecture is to manage the internal complexity of a company in a more efficient way, by breaking a given product family into several smaller modules with defined interfaces and space envelopes. This enables parallel work [Baldwin and Clark 2006] and leads to a decrease in the development time of products, to economies of scale, cost savings in inventory and logistics, flexibility in component commonality and further benefits [Jose and Tollenaere 2005].
Although modular product architectures offer many benefits, there are also costs resulting from modularity [Engel and Reich 2015]. A modular architecture comes with search costs, which are efforts to find the most cost-effective interface breakdown, as well as with bargain costs to negotiate and thereafter design and document the interfaces and moreover, with enforcement costs, which are the costs required to test and reject the interfaces that do not meet the negotiated interfaces [Engel and Reich 2015]. Additionally, modules must encompass all requirements of the products that are using this module. The result is that the design of a modular product requires "expertise, coordination, efforts, time and is more expensive than the design of classical products" [Jose and Tollenaere 2005, p.375]. In order to compensate this initial effort of modular products, the reutilization of modules is an imperative characteristic of modular structures.

2.1 Necessity of a support for refinement decisions of modular product architectures

When a company has made a decision for a modular product architecture, it must initially implement this architecture. This preliminary step is marked as uncritical in Figure 2, as a broad variety of methods exist that a company can choose from [Jose and Tollenaere 2005]. The result is the initial modular building set that reflects existing and planned future products. In the usage phase, a company can benefit from the initial efforts by easily constructing novel products through combining existing modules.

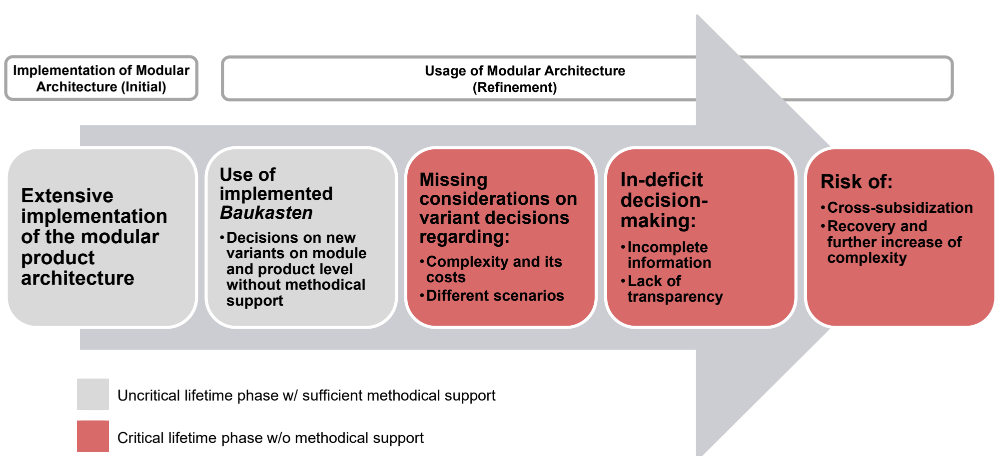

Figure 2. Challenges when refining modular product architectures

However, at a certain time the existing modules will not capture all functional wishes of the market anymore. Besides an increase in the customers' value, quality issues or productivity improvements are similarly a trigger for new variants and technical changes [Gemmerich 1995]. A refinement of the modular product family is required and a decision on new modules and module variants has to be made. Yet, for such a refinement, no adequate methodical support exists [Bahns et al. 2015]. Bosch Thermotechnik has derived the need for support during this phase and thus, reflected upon the consequences of the missing methodical support. These consequences are presented in Figure 2 and are subsequently explicated.
To support refinement decisions of modular product architectures, the effects of complexity and its costs are a good way to succor companies. Beckmann et al. 2014 determined that a company aims to evaluate and quantify the complexity reduction by a modular product architecture in terms of costs. Although the biggest complexity reduction step has been made when implementing the modular product architecture, changes on this and the commonalities can influence the internal complexity in an advantageous or disadvantageous way [Bahns et al. 2015]. This implies that a company will not only need an evaluation of complexity to decide on an appropriate modular concept [Ripperda and Krause 2015], yet also to refine the existing modular product family. Furthermore, various possible scenarios on how to satisfy requested innovations within the modular structure are not assessed adequately on variant decisions.
This leads to an inadequate decision making process, as decisions are made based on incomplete information, resulting from scenarios that have not been considered. A lack of transparency will be prevailing in the company. The reason for this is the unknown complexity effect, created by the refinement of the modular product architecture. Decisions on variants without consideration of complexity costs might lead to an unwanted cross-subsidization [Schuh 2005], thereby causing a recovery of the reduced complexity. If a company refines its modular structure based on these deficient decisions, the risk of failure of the modular product architecture is high.
Companies implementing a modular product architecture not only need support in the implementation phase of the modular product architecture, yet also need to be supported when maintaining the modular product family. At Bosch Thermotechnik the necessity for methodical support concentrating on variant decisions of a modular product architecture has amplified and is subject of this paper.

2.2 Requirement of a modular product family on a variant management

A modular product family has to be maintained after implementation [Bahns et al. 2015]. Maintaining a modular product family is often termed sustaining and defined as "managing commonality during the product family lifecycle when the (…) [modular product family] is changed after the product structure concept has been defined" [Bahns et al. 2015, p.1]. If a company is not attentive to their commonalities and adding variants without ensuring reutilization, the modular tooling kit will increase in magnitude and the aim of a controlled internal complexity will be antagonized, albeit the modular design rules are followed. However, modular structures are different than integral products and therefore have different requirements on variant management than conventional, integral products [Avak 2006].
The overall requirement of a modular variant management is the consideration of modules and its variants. Products are created by combining various modules [Feldhusen et al. 2013]. Thus, a modular variant management needs to support decisions on new modules, not on products [Avak 2006]. When evaluating the complexity resulting from new modules and module variants, it is insufficient to solely look at one-time effects, as the recurring complexity effects created by this variant must also be observed. One-time complexity is, for example, the R&D efforts to develop the new variant, while recurring complexity is the quality inspections [Thiebes and Plankert 2014]. To evaluate these recurring complexity efforts, the varying module lifecycles have to be taken into consideration.
In a modular variant management, the reuse of modules must also be deliberated. A new variant might be reasonable when the revenues gained by this variant are significantly higher than the costs of complexity generated [Rathnow 1993]. A module is not merely utilized in one specific product, but within the whole product range. All products that are planning to use this module have to be included.
Additionally, design engineers of a company must ensure that the modular design rules are followed when creating new modules and module variants [Baldwin and Clark 2006]. A modular structure is characterized by defined interfaces [Ulrich 1995]. New modules must comply with these interfaces. A

company can either proclaim that these interfaces are never allowed to be altered, or the modular variant management has to consider the effects of changing these interfaces. Permitting modifications on interfaces will increase the flexibility of a modular structure, yet these variations in the interfaces of a module will most likely also affect one or more other modules; these effects must be evaluated.
Finally, if the requirement for a novel product or feature emerges, various scenarios have to be evaluated [Rathnow 1993]. When considering such a refinement of a modular product family, it can be implemented by adding a new module, or, changing or splitting an existing module [Baldwin and Clark 2006]. Moreover, it is possible to satisfy a specific market demand by a development independent of the modular structure [Dellanoi 2006], as shown in Figure 3. The reason for this could be a very specific demand that can only be integrated into the modular construction kit with high effort. Ultimately, it is also feasible to not fulfill the market request [Dellanoi 2006].

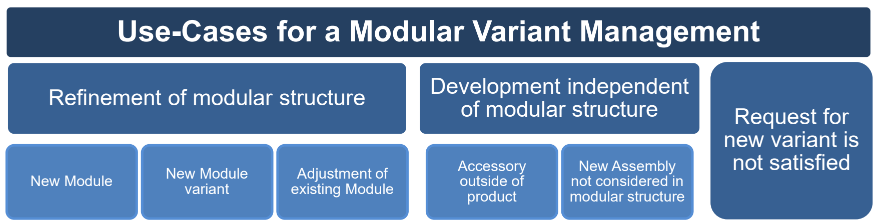

Figure 3. Use-cases of a modular variant management

A modular variant management is required to ensure sustainability of the modular product family after the implementation phase. It has to consider variant decisions on module and module variant level. For each decision, one-time and recurring complexity effects must be contemplated, allowing for the various module lifecycles. Besides the costs of complexity created by the new variant, the benefits also have to be deliberated. Therefore, all products planning to use this module have to be taken into consideration. If such a variant decision affects the interfaces of the modular structure, a detailed evaluation of the effects on other modules has to be executed. Finally, diverse scenarios to refine the modular structure have to be defined and benchmarked, to ensure an optimal modular product structure over time.

3. State of the art

The research topics complexity and variant management are frequently discussed in scientific works. However, a brief definition of the term complexity is necessary, as the definitions highly differ between the various authors and disciplines [Lindemann et al. 2009]. The definition for this study has been derived from Lindemann et al. 2009 and describes complexity as a property of a system. Characteristics of complexity are aspects such as the dependencies of the components, as well as the number and variants of components in the system. The complexity of a system can result from internal and external influences, however, only the internal influences can be affected [Lindemann et al. 2009].
In section 2, the demand for a modular variant management has been derived to ensure a controlled internal complexity within the lifetime of a modular product structure. Otherwise, disordered, chaotic change processes and the dominance of marketing increase the internal complexity [Ehrlenspiel et al. 2007]. Controlling instruments to ensure a lean variety are required [Schuh 2005]. Initially, methods to ensure sustainability of a modular product architecture are the focus of the literature review. Thereafter, variant management methods have been examined that assist in limiting the number of components and variants in the system, which is crucial for a controlled internal complexity.
Several methods to support the implementation phase of a modular product architecture exist. Some of these focus on the development of stable concepts to ensure future sustainability. Martin and Ishii 2002 aim at developing a modular structure that can be easily applied to future generations. Erixon 1996 defines modules based on complexity drivers. Examples for these drivers are: "carry-over", “technology push" and "product planning", which take alterations of the modules into consideration. Moreover, Engel and Reich 2005 introduce a design for an adaptability approach for modular product architectures to derive the optimal degree of modularity based on an ideal ratio of the benefits gained by standardized

interfaces to the costs of these interfaces. It is undoubtedly essential to focus on a robust modular structure against future changes, however, support in the lifetime phase is still indispensable.
Methods to supervise a prevailing modular product architecture also exist. Junge 2005 developed a modular balanced scorecard, derived from the traditional balanced scorecard. This tool measures the performance of a modular architecture by twenty-three KPIs and therewith enables the tracking of the status quo of a modular structure; whereas help to achieve a maintained modular structure is not specified. Methodical support for a sustainable modular structure itself rarely exists [Bahns et al. 2015]. The Variant Mode and Effect Analysis by Caesar 1991 is an instrument to structure and thereafter control the variety of a product portfolio. This tool is predominantly sufficient to ensure sustainability from a manufacturing point of view [Avak 2006]. Bahns et al. 2015 have developed a modular product family sustainability process, which helps to ensure a maintained modular product family. Though a detailed methodical support to evaluate variations is not given. The variant management funnel by Avak 2006 helps to decide on new modules and module variants. Initially, effects on the modular structure are evaluated and subsequently, the effects of this new variant are analyzed. However, this method does not explicitly consider different variant scenarios and a monetary evaluation is not given.
In a second step, variant management approaches which evaluate complexity costs have been examined. The inauguration of complexity cost evaluations is in the activity based costing method by Cooper and Kaplan 1991, which is a tool that enables the allocation of activities to the resources they consume. Schuh 2005 enhanced their concept to the resource oriented activity based costing method, thereby enabling, with high effort, the calculation of complexity costs for new variants. To reduce this effort required to evaluate complexity costs, Bayer 2010 developed a new concept by pre-evaluating novel or expiring products and complex assembly variants. This concept is a good starting point, however, bigger adjustments to tailor it to modular structures have to be executed. One concept focusing on complexity costs for modular structures is the cost prognosis by Ripperda and Krause 2015. This concept offers a method to evaluate diverse possible modular structures a company can choose from in the implementation phase of a modular product architecture. With this method, whole concepts are evaluated, as opposed to single variant decisions emerging in the lifetime of a modular structure. No method exists that supports variant decisions of modular product architectures in terms of complexity costs within the lifetime of the modular structure. To close this gap, a framework for a modular variant management is discussed in section 4.

4. Framework of a modular variant management

To ensure that the above mentioned requirements of a modular product architecture on a variant management are considered, a modular variant management framework has been constructed and verified within a case study at Bosch Thermotechnik. The aim of this framework is to support a sustained modular structure of a company by ensuring the preparation of valuable, substantiated variant decisions.

4.1 Design of a framework of a modular variant management

Evaluating the effects of complexity for various variant scenarios is a good way to prepare decisions on new modules and its variants. Existing methods to calculate complexity costs emanate with a high effort for application; consequently, complexity costs should only be calculated if the cost-benefit-ratio is positive. Thus, it must be determined for which variant decisions a complexity cost calculation is beneficial. Additionally, prearranged variant decisions will help to minimize the effort for evaluations. This results in a variant management framework that depicts for which variant decisions the complexity assessment is beneficial and additionally reduces the complexity cost calculation effort by providing predefined input. The various steps to achieve these inputs for the framework are shown in Figure 4.
To design the framework and thus prepare the required inputs for a modular variant management, a workshop with architecture and module responsible individuals, as well as with the management, has to be arranged. The reason for this team formation is that not solely the modular responsible persons, yet also management, understands the impact on various variant decisions on the modular product architecture. They have to coincide on a list of decisions that have a high impact on the modular architecture and that have to be substantiated before a decision can be made.

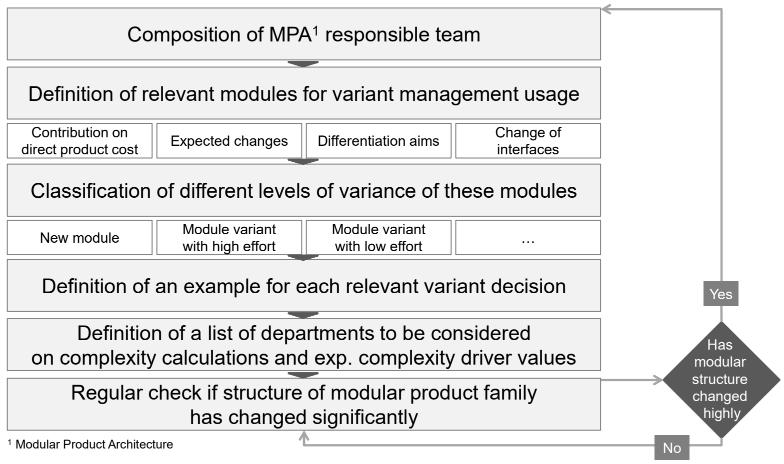

Figure 4. Design of a framework for a modular variant management

Within this workshop, all modules for which the effort for a detailed variant examination is reasonable have to be selected. If a module has a high contribution to the product's costs, the likelihood for new variants that only save direct costs is high, without considering the impact of complexity that might disregard these. Modules that are more inclined to change should also be considered, since the risk of a complexity increase is high, due to new component variants often not replacing existing ones. Modules with the aim of differentiation between the various products, brands and to competitors should not be deliberated, since the variety here is intended. Besides these resulting modules, the evaluation of complexity effects should always be executed in case interfaces need to be modified. The effects on other modules have to be taken into consideration, which most likely results in high complexity costs.

As soon as all relevant modules for the consideration of complexity costs are chosen, the different levels of variance for each module have to be evaluated. The variance level here is defined as the expected resulting complexity by a new module or module variant. The higher the variance level, the higher the resulting complexity accrued by such a new variant is. For each module, it must be demarcated, when a designer is constructing a new module. Moreover, the different possible module variants need to be classified, such as ones with a high, medium or low resulting complexity. To ensure the identical understanding of this classification over time for each variance level of a module, an exemplary variant decision has to be defined. Based on this, it is possible to create consistency from decision to decision.

Finally, a list consisting of all departments that have to be considered in a complexity cost calculation for each module variance level will be generated. This list is an initial input for existing variant management methods such as the resource oriented activity based costing [Schuh 2005]. This tool assesses the activities in the different departments and assigns these to variety. A first indication of the different cost driver values for each module and the corresponding variance levels is auxiliary input for a later complexity cost assessment. Additionally, the duration of the modular lifecycle has to be added, to ensure that recurring complexity costs are calculated for the right timeframe.

The results of the workshop have to be stored and will be used on variant decisions of a modular product architecture. These outcomes are valid as long as no severe deviations on the modular structure have been executed. If this is the case another workshop round has to be set up.

4.2 Usage of a modular variant management framework

As soon as the framework of a modular variant management has been designed it can be utilized. The various usage steps are illustrated on the right hand side in Figure 5. The design steps of the framework are listed on the left to elucidate how the outcomes of the workshop are used. When a product or functional request emanates that cannot be captured with the existing modular tool kit, a decision on how to refine the modular structure has to be made. Required input for the modular variant management framework is the definition of the module that is appropriate for the requested function (step zero).

A design engineer has to initially examine whether the functional request refers to one of the listed modules where a detailed complexity assessment has to be applied due to its high impact on the modular structure and overall internal complexity or if interfaces must be adapted for this request. If one or both questions can be answered with yes, a modular variant management has to be executed. An often used method to assess the inter-modular interfaces of a modular structure is a design structure matrix (DSM). This will help to investigate whether interfaces have to be adapted for this market request or not.

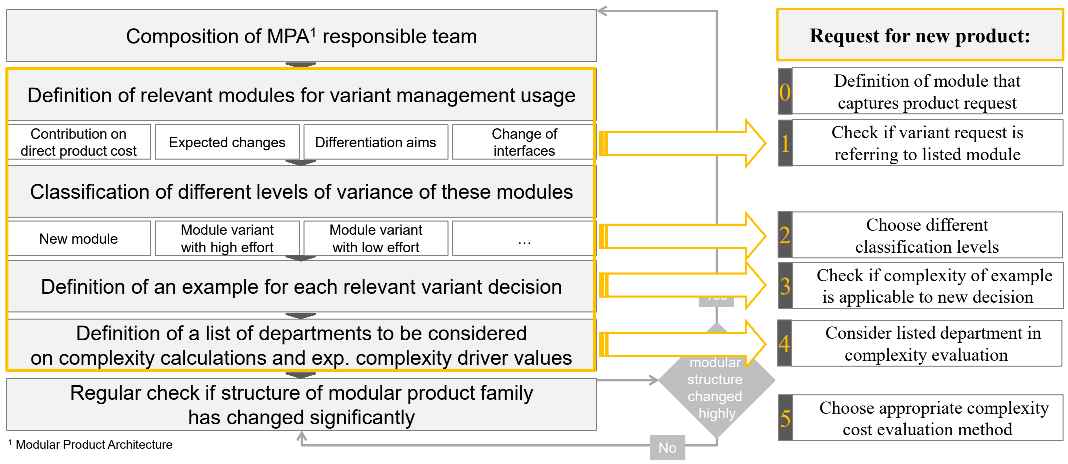

Figure 5. Usage of framework for a modular variant management

Secondly, the design engineer assigns the different possible scenarios to fulfill the market request to the appropriate predefined variance levels. A scenario not formerly listed can be added without an appropriate variance level, as well as the possibility to satisfy the product request independent of the modular structure, or to not satisfy the request. The variance levels are a tool to ensure that the designer considers various options and evaluates these, thereby not confining to a single concept.

Third, the scenarios created to satisfy the product request should be compared with the given examples of the workshop. The aim of these examples is to support the designer in verifying his chosen scenarios.

In a fourth step, the designer should consider the predefined list of departments in which additional complexity will be generated and the corresponding expected cost driver values. Based on this, a first sense of the impact of this decision is attained. This may already enable the elimination of a scenario, as the expected complexity increase may generate an impact too high in comparison to the benefits.

Finally, in step five, the remaining scenarios have to be evaluated based on complexity costs. Existing complexity cost evaluation methods can be used for this (section 3). Input for these are the predefined lists of departments that are affected by the complexity generated by this new variant and the expected cost driver values for the various variance levels prepared. It is imperative to take into consideration the given corresponding module lifecycles to ensure that recurring complexity costs are calculated correctly; one common module or the product lifecycle is not sufficient.

Based on the complexity cost calculation of the different scenarios, a decision on the refinement of the modular structure can ultimately be made. Therefore, the costs for creating this variant have to be compared with the benefits that can be attained. For the calculation of the benefits, the product family roadmap has to be revised and it has to be examined which products in what quantities would use this module. For the scenario in which the request is not fulfilled, the loss in sales or the costs for alternatively using an existing, over-engineered module, have to be considered.

5. Case study in industry

The presented framework has been verified at Bosch Thermotechnik, which is one of the leading companies offering heating products and hot water solutions in Europe. One exemplary product, the Junkers Cerapur 9000, is shown in Figure 6b. It belongs to the wall-hung heating appliances. A conceptual scheme of a modular boiler is shown in Figure 6a. The conceptual scheme is a highly simplified illustration used to explain the case study. This modular boiler consists of five modules: the expansion vessel, the heat cell, the hydraulic, the electronic and the superstructure of the boiler. Based on these modules, the validation of the framework of a modular variant management is explained.

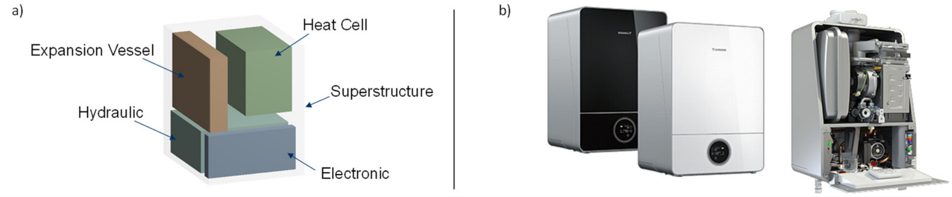

Figure 6. a) Modular boiler b) Junkers Cerapur 9000 (courtesy of Bosch Thermotechnik)

5.1 Validation of the design of a modular variant management

To design the framework of a modular variant management at Bosch Thermotechnik a workshop with all responsible persons of the modular structure was initiated. First, all modules had to be rated based on their relevance for a modular variant management. The heat cell, hydraulic and electronic module were rated as relevant, since these modules contribute a high amount to the overall costs of a product. These modules offer the basic functions of a boiler, modification requests are more probable. Due to the complexity of these modules, change cycles are elongated and differentiation is not an objective of these modules. The modules expansion vessel and superstructure are not relevant for a modular variant management. The expansion vessel is a module with a minor contribution to the overall price and deviations are improbable. The superstructure is the appearance of the boiler itself and therefore intends to differentiate between the products, brands or to competitors; a high variance is thus desired.

In a second step, the levels of variance were defined for the remaining modules. For the electronic module, five levels with a decreasing complexity have been determined. The most complex variant is a new printed circuit board (PCB), which results in a new module. The second level is an assembly variant of a PCB, the third level is a variety in the certified safety core, the fourth level is a language variant and the last level of variance is a variant on the boiler parameters. These variance levels have been derived by regarding the various functions and the corresponding modifications that have to be executed on the module to do so. The different variance levels are ranked by their complexity. On a new variant decision, these predefined levels of variance can always be completed.

In a third step, real, physical examples have been added to the different variance levels of each module. Therefore, existing electronic modules and module variants are linked to the different variance levels. Based on this, the user of the framework can decide more easily if a chosen variance level is appropriate for the decision at hand. Furthermore, other, not yet considered, potential concepts might arise.

Ultimately, for each module's variance level, a list of departments that are affected by this new variety is generated. For example, a new PCB variant of an electronic module has to be created and supervised by the R&D department throughout the lifetime. Furthermore, quality, purchasing, documentation, logistics, manufacturing, marketing are affected by the complexity created by this new variant. Expected complexity driver values for each department are discussed and added for each listed module, variance level and department. This will decrease the complexity cost assessment effort for existing methods.

A regular check whether the structure of the modular product architecture has exceedingly altered has not been verified at Bosch Thermotechnik, since the validation period has not been long enough.

5.2 Validation of the framework of a modular variant management

The outcomes of the workshop were utilized to attain an exemplary refinement decision of the modular product architecture at Bosch Thermotechnik. A market request for a special I/O port for appliances for the UK market has emerged. This request could not be satisfied with the existing modular tool kit and would lead to a refinement of the modular product family if the decision to fulfill this request is made. The framework of a modular variant management has been used as support on this decision.

Initially, it was examined whether the referring module is marked as relevant for a modular variant management. The I/O port belongs to the listed electronic module and thus, the modular variant management is applicable. Additionally, a DSM matrix has been examined to see if inter-modular interfaces need to be adapted or if the changes on the I/Os only alter intra-modular interfaces. During this design phase, the designers can already agree that no interfaces have to be adapted, and consequently, the effort for interface changes does not have to be considered.

In a second step, a designer choses the appropriate levels of variance for the example at hand. In this case, the creation of a new PCB and thus, the development of a new module or the option of altering an existing PCB by an assembly variant development of a new module variant, has been chosen. Moreover, the options to either satisfy this request by developing a special built assembly that no longer fits into the modular structure or to not fulfill this market request was given. Additionally, the designers compared the chosen levels of variance for the market request with the real examples that exist for each variance level. Based thereupon, the design engineer could verify and possibly amplify potential concepts to fulfill the market request.
To evaluate the different refinement scenarios, the resource oriented activity based costing [Schuh 2005] was used. The input was the predefined list of departments that had to be considered on an activity based costing method. Expected values of the cost drivers for concepts based on existing variance levels helped to decrease the complexity cost assessment effort. For the recurring complexity costs, the defined electronic module lifecycle was used. Based on these calculations a decision could ultimately be made.
The framework for a modular variant management offered a structured way to evaluate a market request for a modular product architecture. The first step to a sustainable modular structure at Bosch Thermotechnik has been concluded by ensuring that the company considers the defined interfaces of a modular product architecture and by keeping a lean modular tool kit. Herewith it is ensured, that the various interfaces concentrated in a DSM are considered on variant decisions. The specification of the modules for which a detailed variant management assessment is useful, helped to ensure efficiency. Only modules and its variants that have a high impact on the internal complexity or concepts that come with an alteration of the inter-modular interfaces substantiate a detailed complexity assessment. The evaluation of complexity costs of the various scenarios and the linkage of these costs with the expected benefits created by this new variant, was a good foundation for the management to easily decide on the right scenario. Preliminary listed departments and expected complexity driver values helped to decrease the complexity cost calculation effort of existing methods.

6. Conclusion and outlook

The concept of a modular product architecture to control the internal variety of a company has become increasingly pertinent. After an extensive implementation of the modular structure, companies are aiming to benefit from a lower internal complexity and thus, from lower costs. Within the lifetime of a modular structure, new market requests and ideas for innovations appear, that have not been considered beforehand and therefore, a refinement of the modular structure is required. The risk that the modular tool kit will inflate or modular design rules are not complied, thereby increasing the internal complexity, is high. Methods to support a sustainable modular structure and decisions on the refinement are rare.
The presented framework of a modular variant management provides support for a sustained modular product architecture. The framework considers the characteristics of a modular structure, which is seldom the case in existing variant management methods. Moreover, it facilitates a company to ensure that the modular design rules are considered as defined interfaces and a productive internal / external complexity ratio is given. Preparatory input, such as a list of departments affected by a new variant, as well as expected complexity driver values for various module variance levels and departments, will reduce the efforts for existing variant management methods. The presented approach has been tested at Bosch Thermotechnik. Designers and modular architecture personnel agreed on the usefulness of the framework and appreciated the structured way to prepare variant decisions of a modular structure. The principle, which variant decisions are applicable for a detailed variant management and the provided input for complexity cost methods, helps to reduce the overall effort for refinement decisions on a modular structure and increases the likelihood of a sustained modular product family over time.
A major drawback is the extensive calculation of complexity costs for the various scenarios with existing methods. Although the input resulting from the workshop provides preliminary work, further research should focus on a simplified way to calculate complexity costs of the different variance options of modular product architectures. Moreover, the framework has been verified only at Bosch Thermotechnik; to further test the transferability and scalability of this framework a validation should be executed in other industry branches or at least for other modular product families. Finally, the

consideration of other aspects on variant decisions besides complexity costs has to be discussed and a consolidation of complexity costs with other aspects has to be prepared.

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