Brownfield Process: A method for modular product family development aiming for product configuration

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Modularisation, product platforms, product families and product configuration are efficient product structuring tactics in mass customisation. Industry needs descriptions of how the engineering should be done in this context. We suggest that key engineering concepts in this field are partitioning logic, set of modules, interfaces, architecture and configuration knowledge. A literature review reveals that methods consider these concepts partly or with different combinations, but considering all of them is rare. Therefore, a design method known as the Brownfield Process is presented. The method is applied to an industrial case in which the aim was rationalisation of existing product variety towards a modular product family that enables product configuration. We suggest that the method is valuable in cases with similar goals.

Keywords: design method, design process, engineering design, product design, product development

End users of products can be segmented into different market groups based on the same kind of expectations related to the products (Liu, Kiang, & Brusco, 2012). There are companies which are competing for the share of a single or several market segments. When a company has to consider customer segments with changing requirements towards products, the cost effectiveness of offering product variants is one challenge. This paper studies this kind of environment. Our research background is familiar with studying companies that operate in projecting business and produce products in small series (the size of a series can be just one). In these surroundings, the costs of engineering are relatively high in comparison with the cost of producing the product. The case discussed in Section 2 considers similar context. Product variety describes the number of different versions of a product offered by a firm at a single point in time (Randall & Ulrich, 2001). Companies should be able to respond to different customer needs while keeping their operations profitable. For this challenge, modularisation, product platforms, product families and product configuration are suggested

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product development tactics, which are considered as part of the mass customisation paradigm (Pine, 1993).

Linking modularisation, product platform and product family development approaches with product configuration aspects is unusual in design methods, although these tactics and their importance are highlighted separately for supporting design reuse and enabling several benefits in the business environment of companies. Consequently, there is a need to study how to structure the key engineering concepts in this field and how these concepts could be synthesised in order to support a design situation in which existing product variety should be rationalised towards a modular product family that supports product configuration. The focus is on the existing product variety because for example Oja (2010) describes that the designing of a completely new product is rare in the manufacturing industry because of the risks.

The paper presents a more advanced method description of our approach to modular product family development compared to the earlier publication (Lehtonen, Pakkanen, Järvenpää, Lanz, & Tuokko, 2011). Considering the research method, the current situation was analysed first. The original method description did not consider the most relevant modularisation aspects, though they were considered in the same industrial case discussed in this paper. This conclusion was supported by the literature review and also empirical findings from other projects on modularisation prior to and following the case. As an outcome of the review, an improved design method for modular product family development was described. Validation of the results is based on existing research and academic publications, in which many of the suggested tools and approaches have been presented separately and demonstrating the use of method in a case. The case experiments were originally performed during 2010−2011.

The background of the research context was discussed briefly in this section, but the literature review is continued in Section 1. A modular product family development method for configurable products is presented in Section 2. In Section 3, the conclusions are discussed.

1 Background and motivation

This section focuses on existing research on product family development and product configuration based on standardisation and modularisation.

1.1 Standardisation and modularisation

Standardisation is an important enabler of design reuse and refers to a situation in which several components are replaced by one component that can perform the functions of all of them (Perera, Nagarur, & Tabucanon, 1999). Pahl and Beitz (1996) emphasise that designers should always use readily available standard, repeat or bought out parts instead of specially manufactured parts because of cost reasons. Unfortunately, this is not always possible because of varying customer needs. Victor and Boynton (1998) suggest modularisation as a product development technique for responding to changing customer needs which cause pressure in terms of product variety. Ulrich and Tung (1991) and Pine (1993) present types of modularity including component-sharing, component-swapping, cut-to-fit, bus, sectional and mix modularity. Andreasen (2011) explains that modularisation includes the defining of a modular architecture with module and interface definitions in order to reduce the complexity in operations of a company. Interfaces can be perceived differently (Parslov & Mortensen, 2015) and effective creation of variants is enabled by standardised interfaces between varying modules (Cai, Nee, & Lu, 2009). There are different levels of standardisation related to the interfaces as well as to components, as Fujimoto (2007) presents. He separates model specific, company specific and industry standard components and interfaces. The categorisation of interfaces to open standard, closed standard, non-standard and also to frozen or unstable is also presented (Cabigiosu, Zirpoli, & Camuffo, 2013).

1.2 Product families and product platforms

The designing of product families and product platforms is an often discussed topic when the objective is to increase design reuse and enable product variants. Robertson and Ulrich (1998) and Kristjansson, Jensen, and Hildre (2004) summarise that a platform is a collection of core assets that are reused to achieve a competitive advantage. Meyer and Lehnerd (1997) define a product platform as a common product structure for a series of derivative products. They emphasise that product family development based on product platforms has the potential for reducing different components. This enables lower development costs of derivative products as well as reducing the number of different production lines as an example. Developing product platforms requires research and development experiences in order to create product releases utilising a certain platform (Ulrich & Eppinger, 2008). Lehtonen, Juuti, Pulkkinen, and Riitahuhta (2003) define that a product family corresponds to certain market needs now and in the predictable future.

1.3 Product configuration and configurable products

The designing of a modular product family does not facilitate the making of product specifications for the customised products alone. Product configuration has been introduced for this issue. As an activity, it includes choosing compatible components from predefined entities in order to satisfy the customer needs (Brown, 1998). The development and maintaining of configurable products requires the modelling of configuration rules and restrictions (Tiihonen et al., 1999). In many publications, this is considered as configuration knowledge and includes the mapping of product elements with customer needs. For example, the Unified Modelling Language (UML) and matrix-based approaches are presented for this task (Bongulielmi, Henseler, Puls, & Meier, 2001; Felfernig, Friedrich, Jannach, & Zanker, 2002). Configuration knowledge related to the technical and sales points of view can be used in the IT systems of a company (Forza & Salvador, 2002). Haug, Hvam, and Mortensen (2012) explain that the benefits of using an IT-based configurator include, for example, shorter lead times, improved quality of product specifications and preservation of knowledge. Hence, product configuration can bring several benefits if the engineering of a modular product family succeeds.

1.4 Engineering perspective with configurable products

Our aim is to specify such key engineering concepts that provide improved focus for the engineering work and are essential in designing a modular product family that supports product configuration from the product structuring perspective. Identification of the key engineering concepts is mainly based on the research performed by Juuti (2008). Product structuring considers identification of the building blocks in the modular product family, which can be standard, configurable, partly-configurable or one of a kind. From this perspective, the reasoning aspects for the modular product family structure should be highlighted. In this paper, the first key engineering concept is partitioning logic, which describes why a certain design is or should be partitioned in a specific way. Customer needs and market considerations contribute to this element, but the reasons for a certain partitioning may arise from the supply network or from de facto standards in a certain business environment.

We extract the second, third and fourth key engineering concepts as set of modules, interfaces and architecture. Set of modules includes the definition of building blocks for creating product variants. We consider that the platform viewpoints are considered in this concept by defining the type of a building block: whether a block or a module is used in the every variant or not. Standardised interfaces are highlighted as the major enabler of efficient defining of product variants as discussed in Section 1.1. Therefore, we suggest interfaces as the third key engineering concept. It is also noticed that the consideration of a modular architecture is beneficial in defining the overall content of a modular product family (Bruun, Mortensen, & Harlou, 2013; Eilmus, Gebhardt, Rettberg, & Krause, 2012; Harlou, 2006). Architecture aims to describe how the modules interact with each other and considers the interface and layout aspects.

The previous section revealed that focus on product configuration aspects is important for companies that offer product variants for customers. Considering the configuration viewpoint as an integrated part of modularisation, product platform and product family development methods, is exceptional though. We treat configuration knowledge as the fifth key engineering concept because it facilitates the specification of a product variant for the customer, and this knowledge is reusable for the delivery network.

1.5 Support of existing methods against the business perspective

Several publications review methods in this field. Jensen and Hildre (2004) present that most of the modularisation and platform development methods consider functionality and technological feasibility. Jose and Tollenaere (2005) categorise product family development into clustering methods, graph and matrix methods, mathematical methods, artificial intelligence methods and genetic algorithms and other heuristic methods. Simpson (2006) suggests that optimisation approaches are seen in module-based and scale-based family designing. Jiao, Simpson, and Siddique (2007) explain that product family development methods are usually platform-based, scale-based or module-based (configurative) including algorithms and mathematical models. Salvador (2007) studies the definitions of modularity based on the perspectives of component commonality, component combinality, function binding, interface standardisation and loose coupling. Gershenson, Khadke, and Lai (2007) highlight the role of modules and interfaces, drivers for modularity, considering the life-cycle perspective and analysis of possible benefits in modularisation and product family designing. Nomaguchi, Askhøj, Madsen, Akai, and Fujita (2012) present the Design Method Selection Matrix that considers mainly index-based methods. Okudan Kremer and Gupta (2013) found that applying different methods resulted in a different number of modules.

Simpson (2004) categorises designing product platforms and product families into bottom-up (reactive redesign) and top-down (proactive platform) approaches. Reviewing bottom-up approaches is interesting because of our focus on rationalising existing products by increasing commonality while enabling customer variants. In this context, one of the most famous examples is how Black & Decker redesigned their product line and gained several benefits (Lehnerd, 1987). Another good example is how a manufacturer of food processors redesigned its product line based on consumer perspective with conjoint analysis and product line simulations (Page & Rosenbaum, 1987). Ulrich, Randall, Fisher, and Reibstein (1998) state that successful variety strategies are both market driven and capability driven. Sand, Gu, and Watson (2002) present a method for redesigning an existing product to enhance the product modularity based on considering life cycle, product architecture and functional structures. Farrell and Simpson (2008) present a product platform portfolio optimisation method that aims to maximise commonality within an existing product line focussing on market segmentation grid (Meyer & Lehnerd, 1997). Simpson et al. (2012) present an approach to product family design that integrates several tools with qualitative measures and quantitative data.

Based on the review, we suggest the main categories for modularisation and product family development methods as function-oriented methods, index-based methods, optimisation methods and matrix and clustering based methods.

Functions or function structures in modularisation are considered, for example, by Erixon (1998), Stone, Wood, and Crawford (2000), and Dahmus, Gonzalez-Zugasti, and Otto (2001), and Eilmus et al. (2012). The challenge with these kinds of approaches is that the function-based partitioning logic is not a viable approach from the business perspective in all cases, as Lehtonen (2007) demonstrates.

Index methods are seen in the product platform and product family development publications (Martin & Ishii, 2002; Simpson et al., 2012). Indices are useful in finding parts in which standardisation and modularisation could bring benefits as an example, but a design method should also guide the performing of other tasks in creating the needed information in the modular product family development.

There are modularisation methods in which optimisation approaches are suggested. Fellini, Papalambros, and Weber (2000) developed a method for quantifying and capturing performance trade-offs for products that share components based on functional dependencies. Gonzalez-Zugasti, Otto, and Baker (2000) discuss defining module variants based on a product platform by focussing on performance and cost objectives. In their approach, product platform is defined prior to optimising. Gonzalez-Zugasti, Otto, and Baker (2001) continue with analysing the value of alternative product families. Li and Azarm (2002) present a method including multi-objective optimisation in product variant designing that highlights marketing potential. Rai and Allada (2003) propose a method that is based on creating alternative solutions and eliminating faulty modules. Optimisation approaches encourage systematic designing. According to the studied methods, the industrial applicability of optimisation methods encounters challenges such as computational expenses, mathematical challenges leading to assumptions and simplifications and difficulties in valuing non-quantified objectives. Considering our experiences in companies with low volume and partly-configurable product variants, we have decided to leave optimisation methods outside the scope of the research objective, but these approaches have potential for future studies.

Matrix and clustering approaches are often seen in publications about modularisation. Applying Design Structure Matrix (DSM) (Steward, 1981) is probably the most common in this category. Browning (2001) reviews DSM approaches and considers DSM as a tool for modelling system architectures based on components and/or subsystems and their static relations. Also, Helmer, Yassine, and Meier (2010) suggest a component-based DSM clustering approach for definition of modular product architectures. Component-based DSM is suggested also in the approach by Simpson et al. (2012) as a supporting tool for defining differentiation plan and for studying the interactions of components and sub-systems. Cai et al. (2009) and Rahmani and Thomson (2009) suggest DSM for analysing relations in product decomposition and recognition of interfaces. In general, matrices are easy to use for mapping relations, even though in cases in which the number of elements is high, matrices might become cumbersome to read and modify. Partitioning is often done using algorithms that help to reorganise the matrix in order to make architectural decisions. Matrix-based methods are not comprehensive alone for holistic modularisation as they do not consider strongly how to create the relevant information related to the suggested key engineering concepts. Modular product family development needs a case specific target setting from different perspectives that would explain the reasoning why a product family should be partitioned in a specific way.

To summarise, there is a lack of design methods of modular product families that focus on all the suggested key engineering concepts in a redesign situation. Therefore, objective in the next section is to define a method that considers these aspects.

2 Modular product family development method supporting product configuration

2.1 Overview of Brownfield Process

Figure 1 presents a method for the rationalisation of existing product variety towards a modular product family that supports product configuration, which is named the Brownfield Process (BfP). In our context of product development in the manufacturing industry, brownfield stands for the reusing of available assets, and that there are limitations in designing and solutions because of the existing structures. We suggest that companies which are operating in projecting business in which products are often customised to fit the customer needs and where considering the reuse aspects and common architecture is low, would benefit from applying the method. The first version of BfP was presented by Lehtonen et al. (2011). This paper defines the approach further as highlighted in Figure 1 also.

Selected concepts were presented in Section 1.4, but in the following, other key terms related to BfP are discussed. In designing modular product family concepts, we consider that product structure describes the type of ‘building blocks’ the product family consists of. Examples are given in Figure 7. Architecture describes how the building blocks of product variants are located in the

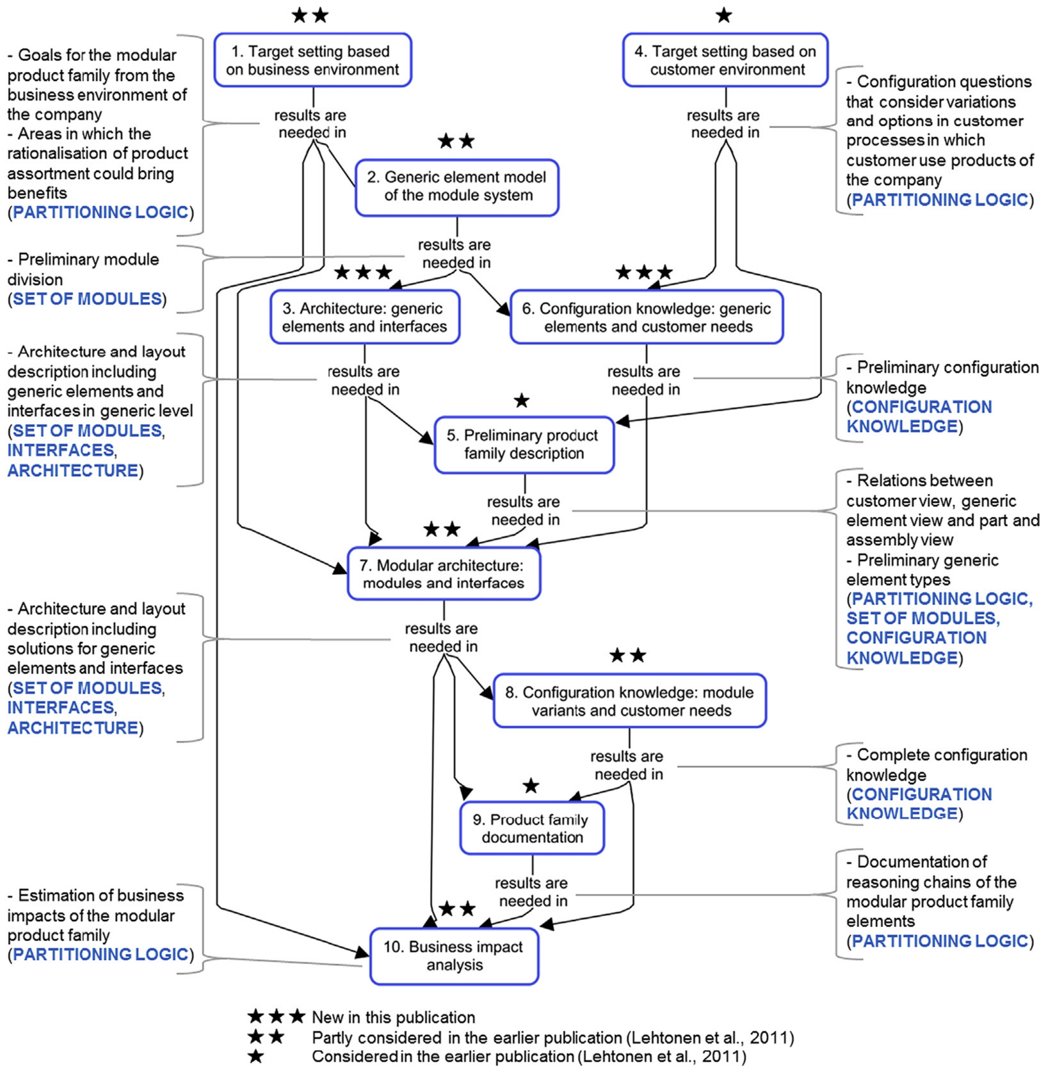

★★
1. Target setting based on business environment
★
4. Target setting based on customer environment
- Goals for the modular product family from the business environment of the company
- Areas in which the rationalisation of product assortment could bring benefits
(PARTITIONING LOGIC)
results are needed in
★★
2. Generic element model of the module system
results are needed in
- Configuration questions that consider variations and options in customer processes in which customer use products of the company
(PARTITIONING LOGIC)
- Preliminary module division
(SET OF MODULES)
results are needed in
★★★
3. Architecture: generic elements and interfaces
★★★
6. Configuration knowledge: generic elements and customer needs
- Architecture and layout description including generic elements and interfaces in generic level
(SET OF MODULES, INTERFACES, ARCHITECTURE)
results are needed in
results are needed in
- Preliminary configuration knowledge
(CONFIGURATION KNOWLEDGE)
★
5. Preliminary product family description
results are needed in
- Relations between customer view, generic element view and part and assembly view
- Preliminary generic element types
(PARTITIONING LOGIC, SET OF MODULES, CONFIGURATION KNOWLEDGE)
★★
7. Modular architecture: modules and interfaces
- Architecture and layout description including solutions for generic elements and interfaces
(SET OF MODULES, INTERFACES, ARCHITECTURE)
results are needed in
★★
8. Configuration knowledge: module variants and customer needs
results are needed in
- Complete configuration knowledge
(CONFIGURATION KNOWLEDGE)
★
9. Product family documentation
results are needed in
- Documentation of reasoning chains of the modular product family elements
(PARTITIONING LOGIC)
- Estimation of business impacts of the modular product family
(PARTITIONING LOGIC)
★★
10. Business impact analysis
★★★ New in this publication
★★ Partly considered in the earlier publication (Lehtonen et al., 2011)
★ Considered in the earlier publication (Lehtonen et al., 2011)

Figure 1 The Brownfield Process (BfP) for rationalisation of existing product variety towards a modular product family that supports product configuration

product family. Compared to product structure, architecture also considers layout, spatial and interface aspects, whereas product structure is more like a hierarchical presentation. We separate building blocks of product variants into generic elements and modules. Considering design hierarchy, generic elements are upper and therefore the abstract level of actual modules. In the modular product family, each generic element includes at least one or a set of alternative solutions which are considered as modules. A module can be also one of a kind. Whether a generic element can be considered as a platform element depends on what kind of solutions can actualise it. If a generic element can be realised with one standard solution that fits all the product variants of a product family, then the generic element is similar to the platform element. Defining generic elements is discussed more in Section 2.4.

BfP includes ten steps and synthesises existing methodological and tool suggestions where applicable. Figure 1 explains the main results of each step and to which key engineering concept (partitioning logic, set of modules, interfaces, architecture and configuration knowledge) the results are related and in which steps the results of each step are beneficial. BfP begins with defining requirements from the business environment against which the selected existing product range should be rationalised (Step 1). After that, a preliminary module division is defined (Step 2). The positioning of preliminary modules, known as generic elements, with each other is also studied (Step 3). Understanding of customer needs is also essential (Step 4). Subsequently, a preliminary product family content is described (Step 5). Configuration knowledge, including the relations of generic elements and customer needs, is defined (Step 6). This step supports the defining of the modular architecture in the next step (Step 7) and the complete configuration knowledge, including actual modules and variety needs (Step 8). After the modules are defined, the design reasoning path of each generic element is documented (Step 9). The final step includes a business impact analysis (Step 10). As an outline for this paper, only the basics of Step 10 are presented. Applying BfP may involve iteration and customisation. For example, Step 4 can be done after Step 1. Step 2 and 3 are very dependent on each other and in some cases Step 3 might be done before Step 2. The methods of BfP are summarised in Table 1. The steps are presented in Sections 2.3–2.12 in greater detail.

2.2 Case description

Alongside the method description, a case in which BfP has been used is discussed. To respect the sensitive nature of the case, all the details cannot be explained at length. The case company produces sheet metal processing equipment comprising loading equipment, portal robots, tables, carriages and conveyors. Over the years, demand had diversified and numerous devices used for material handling had been developed. The amount of different alternatives became a challenge for the company. The company had an excessive number of product solutions which nonetheless fit the sales-delivery process. The quality of production was rational and good solutions and methods of working were familiar to the company. Many designs were projects for specific customers. This led to situations such as the development of certain robot models inevitably going on their own path. Issues were thought about in different devices in similar ways, but for example customer needs had been examined mainly one device at a time. The company had earlier experiences of modularisation, but the entire product range had not been analysed with regard to modularisation and product configuration. Commonalities had been noticed in products, but a

Table 1 Suggested methods in BfP

	Primary methods in BfP	*Alternative methods in BfP*
1. Target setting based on business environment	Manual definition using the Company Strategic Landscape	Manual definition using cause-and-effect diagram of benefits of variety with commonality
2. Generic element model of the module system	Manual planning applying the generic element definitions	
3. Architecture: generic elements and interfaces	Manual definition using MS Powerpoint, Excel or Visio or similar	
4. Target setting based on customer environment	Manual definition considering customer needs from the variety perspective	
5. Preliminary product family description	Manual definition using the modified Product Family Master Plan	
6. Configuration knowledge: generic elements and customer needs	Manual definition using the modified K-Matrix	
7. Modular architecture: modules and interfaces	Manual definition applying the principles of partly configurable product structure, space reservations and interface standardisation	
8. Configuration knowledge: module variants and customer needs	Manual definition using the modified K-Matrix	
9. Product family documentation	Manual description using the Product Structuring Blue Print	
10. Business impact analysis	Manual estimation using the BIA approach	

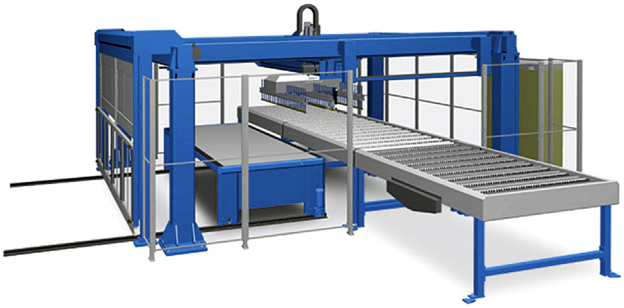


Figure 2 Case product: Prima Power portal robot with a material carriage and a conveyor

supporting method for the rationalisation of the existing product assortment was missing. The company also had several unsuccessful rationalisation projects, which generated learning points and supported the starting of a development project throughout the product range. Figure 2 presents the studied product type.

2.3 Step 1: target setting based on business environment

The first step focuses on clarifying business objectives related to the designing of a modular product family. The main results of this step describe areas of the business environment in which rationalisation of the existing product range could bring benefits and what the targets are. Thus this step contributes mainly to partitioning logic.

Two frameworks are presented: Company Strategic Landscape (CSL) (Lehtonen, 2007) and the cause-and-effect diagram about the benefits of commonality and variability (Juuti, 2008). A generic CSL framework in Figure 3 presents the main elements of a business environment that relate to the product structuring. The aim is that the requirements for rationalisation of product variety are gone through in a workshop in which the areas of the CSL framework are discussed and defined. The target setting done in the workshop benefits from a multi-disciplinary group of participants because the group broadens understanding of the drivers for modularisation, and the voice of different functions can be heard. A specific target might not be relevant to all the participants in the workshop. Despite this, acknowledgement of these aspects and following the workshop on target setting can increase understanding about the overall decision making related to a product range. The studied product range cannot necessarily be optimised from every viewpoint, but trade-offs are often necessary, as, for example, Eilmus et al. (2012) have discovered. The product structuring section is considered as a black box in this step. The goal is to model processes such as product development process, sales-delivery process and other life cycle phases, value chains the company wants to operate in and strategy and organisational aspects that influence product structuring, and to define the targets according to these viewpoints. The targets can arise from several life phases of the product and from the different functions of the company.

The cause-and-effect diagram in Figure 4 is suggested for cases in which the design team has a common understanding of the benefits that are sought after. This diagram can be used in confirming presumptions about the objectives and benefits by presenting explicitly the generic benefits from several viewpoints based on the literature review. This map supports discussion of areas in which the largest benefits could be achieved. Similar work has been undertaken by the others. Ramdas (2003) presents a framework for a company's variety creation and variety implementation decisions, highlighting revenue and cost aspects. Cameron and Crawley (2014) add that commonality enables reduction of risks, including lower technology risks, higher quality production and reduced downtime. In Figure 4, the reduction of risks is shown especially in the possibility to reduce operational waste, time to market and warranty costs.

In the case, the business environment was well defined prior to application of BfP, and the role of the step was to summarise using Figure 4 why there should be product development. There was sufficient data available related to activities and products prior to this step. The target was defined without the participation of researchers. The main goal was to reduce operating expenses by

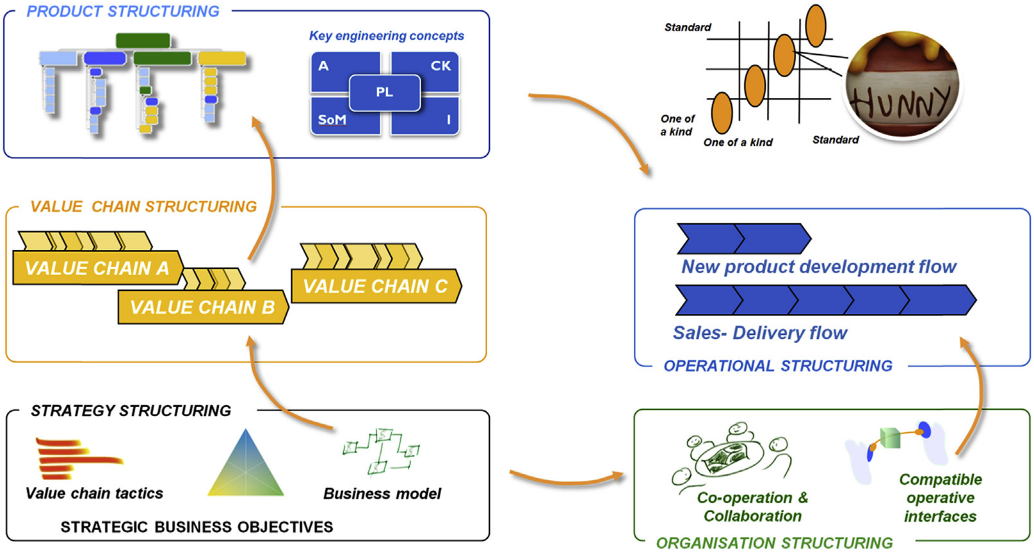


Figure 3 Company Strategic Landscape (CSL) framework (Lehtonen, 2007)

increasing reuse by defining a common architecture (product family) with common modules for the studied product type. The product family should enable use of the same modules in different product variants for customers where possible. Removing of the existing variants which do not add customer value and do not support long-term development or production was also highlighted.

2.4 Step 2: generic element model of the module system

The objective of the step is to define the ideas of generic elements that could be basic building blocks, preliminary modules, for the product family in a solution neutral level based on the existing product variety. Thus, of the five key engineering concepts, this step focuses mainly on the set of modules. A generic element contains all that is required in fulfilling one variation need and it should be possible to realise the element technically as a unit. The aim is that the generic element division divides the product in sections that encapsulate the effect of customer variations.

The defining of generic elements starts with setting up generic (applies to all variants) list of functionalities and requirements e.g. transformations that the customer wishes to achieve with the product. The next step is to consider all the items in the list as technical units (the actual technical realisation is not considered at this phase). Therefore, the generic elements are abstract in this sense. Then the existing product structure is taken under consideration by discussing possibility (in principle) to partition it such way, that there will be technical units corresponding with the generic elements.

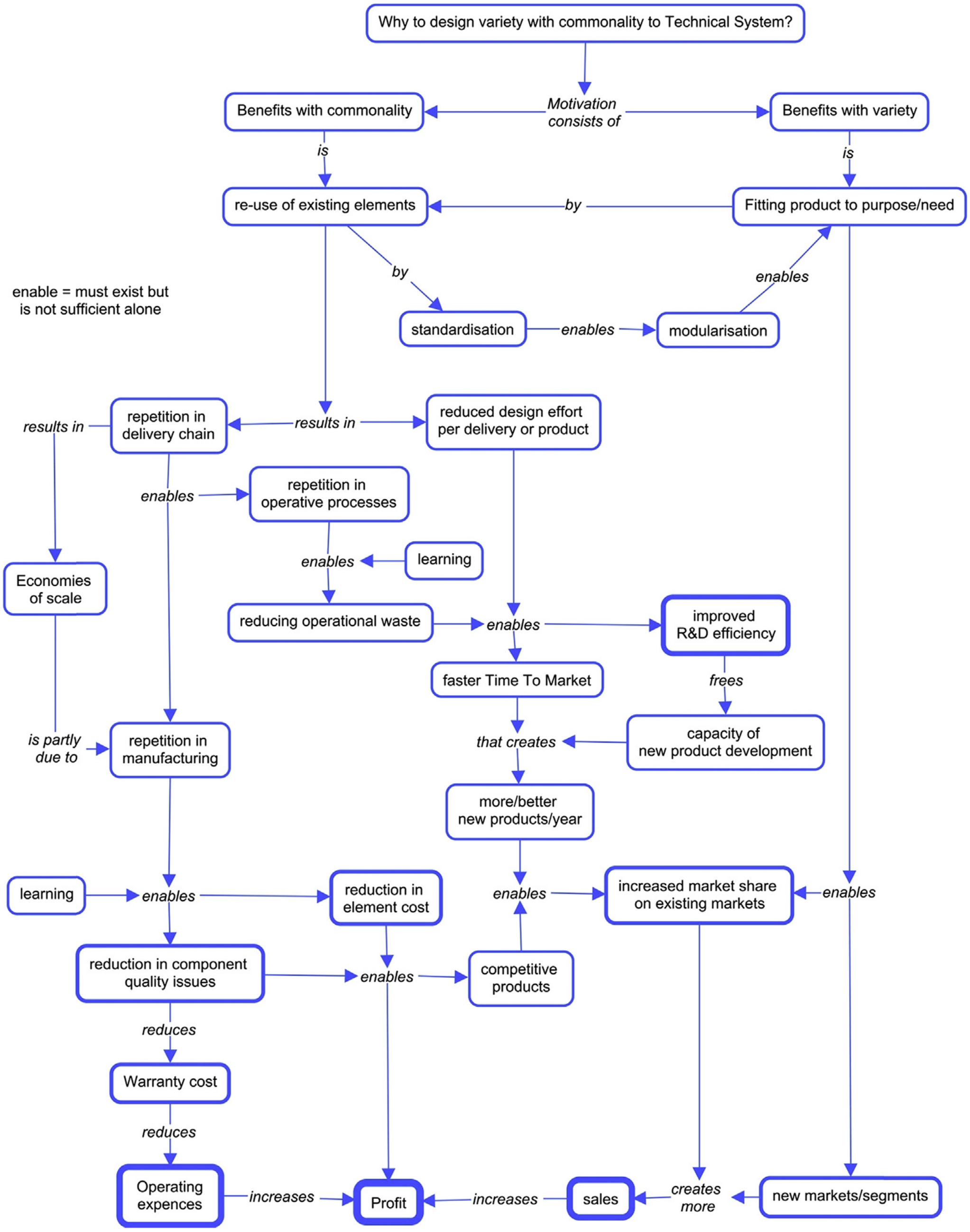

Why to design variety with commonality to Technical System?
Motivation consists of
Benefits with commonality
Benefits with variety
is
is
re-use of existing elements
by
Fitting product to purpose/need
by
enables
enable = must exist but is not sufficient alone
standardisation
enables
modularisation
results in
repetition in delivery chain
results in
reduced design effort per delivery or product
enables
repetition in operative processes
enables
learning
Economies of scale
reducing operational waste
enables
improved R&D efficiency
faster Time To Market
frees
is partly due to
repetition in manufacturing
that creates
capacity of new product development
more/better new products/year
learning
enables
reduction in element cost
enables
increased market share on existing markets
enables
reduction in component quality issues
enables
competitive products
reduces
Warranty cost
reduces
Operating expences
increases
Profit
increases
sales
creates more
new markets/segments

Figure 4 Benefits of variety with commonality (Juuti, 2008)

Figure 5 presents an example from the case in which the old solutions are sorted according to the generic element proposals. Originally the summary of existing solutions was made by the project manager. In the case, the generic elements were defined in a brainstorming session, in which personnel from sales, product development and mechanical, electrical and software engineering participated. The researcher also participated in this step as a facilitator of the single day workshop and as a maker of the synthesis, and hence the hand of the researcher is visible in the results. At first, the participants worked individually to define their suggestions for generic elements. A common session was organised subsequently in which the participants formed pairs and analysed their suggestions and tried to find a common understanding. Five different proposals for a generic element model were defined. These were analysed in a common session by the same group. Distinctions were considered beneficial because the proposals included different views for the same goal. A model, which included all the different elements presented, was drawn on the white board and included 37 generic elements and it was noted that some of the elements, such as software elements, needed further dividing. Eventually, 12 different software elements were recognised. Then it was found that the proposed generic element model could not completely fulfil the business targets and another new suggestion was defined. This suggestion included fewer than 20 elements, and this was found to be too little. Finally, a combined model accepted by all the participants was defined including tens of elements. Some generic elements are listed in Figure 6.

The restrictions of technology may cause that there is no plausible realisation for some generic elements. Then the generic element needs to be defined differently. The generic element model that is defined after iterations is a concept for the modular structure of the product family describing how the partitioning will be realised. Therefore, every generic element is a concept of a module or (as more often) set of modules.

In the defining of generic elements, similarity between the generic elements should be considered. If generic element proposals have many similarities and redundancies related to their realisation, defining of only one generic element should be considered. If generic elements that have much commonality with each other are approved of as separate, there is a risk of unnecessary variation.

2.5 *Step 3: architecture: generic elements and interfaces*

Architecture is understood as a layout scheme of generic elements and their interfaces. The defining of architecture is started by thinking how the generic elements are positioned in a typical product. Generic elements that have interfaces with each other have to be identified, because this is a starting point for defining standardised interfaces within modules. Because accurately designed modules describing the final structure of the modular product family not likely to be available at this step, traditional office software such as Microsoft PowerPoint, Visio or Excel can be used for visualising the architecture. An example is given in Figure 9.

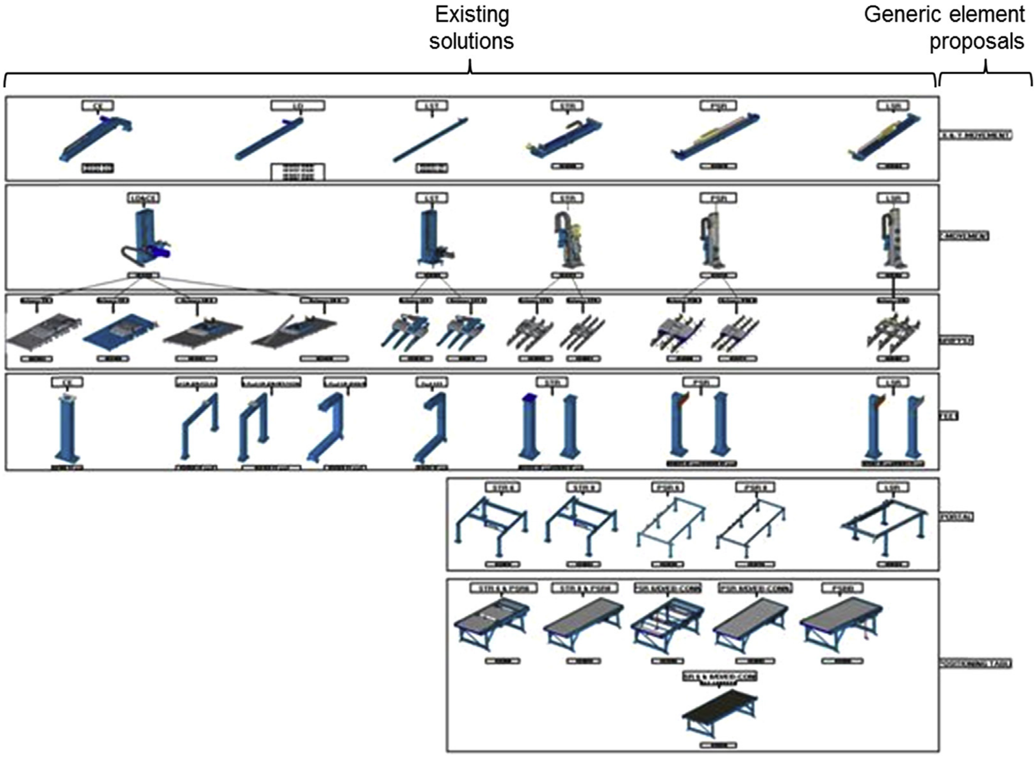


Figure 5 Analysis of the existing product range in order to identify generic elements

In the case, the architecture was illustrated using a two-dimensional layout figure whose purpose was to clarify the same understanding of the elements and their relations for the design group. This was done by the project manager in the company. When considering the five key engineering concepts, this step considers architecture, set of modules and interfaces on a generic level.

2.6 Step 4: target setting based on customer environment

Analysing the customer environment is important if the company wants to change its operating mode from project-specific solutions to configurable product delivery with predefined modular solutions. Formalised customer needs are required in the defining of configuration knowledge, which explains what kind of product will be delivered to the customer with certain needs. If all the needs cannot be described formally, the part which these requirements relate to can be left outside the configuration activity, which is based on the predefined modules. When designing a product family based on existing products, these products have been delivered against specific customer needs. We presume that the basic requirements that the products must fulfil are known within the company and thus the focus should be on clarifying the reasons which cause pressure on variants.

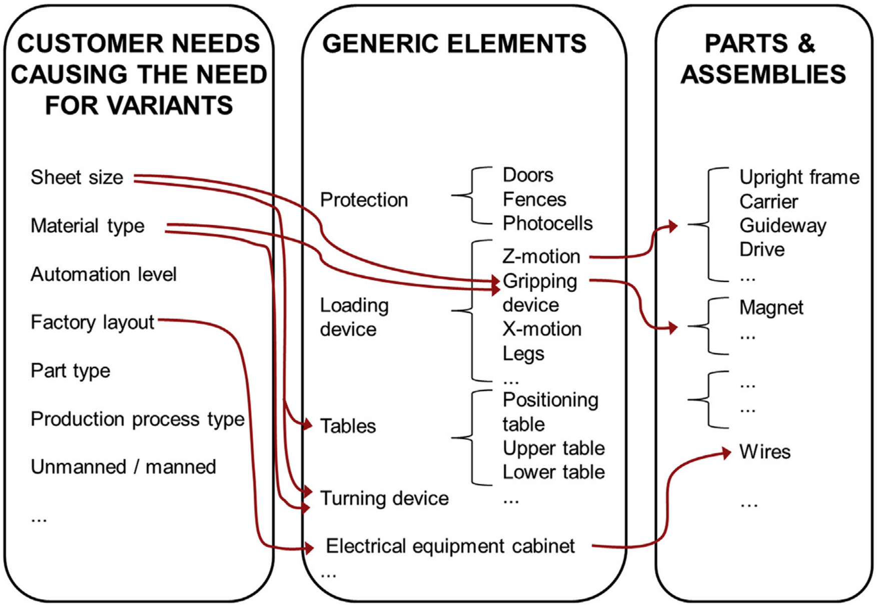


Figure 6 Sample of the preliminary product family description and reasoning

Customer needs are clarified by using an approach that has a background in defining a product structure for a truck by configuring (Lehtonen, 2007). In the sales material of a truck, it is seen how a configurable product can be presented to a customer. Product options are well defined and their suggested use case examples are stated. This kind of product philosophical approach is adapted in this step and therefore is not a unique approach. The need for variants is discussed from the customer viewpoint; what he/she wants to do with a product. The idea is to define by answering from which configuration questions from the customer perspective the most suitable options for a product variant can be selected.

In the case, the customer environment was studied in a one day workshop, which was facilitated by the researcher. The participants were challenged to define the main questions that through answering help to define a product variant for the customer. The contribution of sales was significant. The main customer requirement groups and more detailed optional requirements and ways of working were also identified. In the truck case, we noticed that the main configuration questions related to the rate of use, capacity, use environment and preference topics. Although the case is different to the truck example, the main topics of the identified configuration questions were similar to a high degree. The configuration questions related, for example, to options of sheet size, material type to be handled, automation level, factory layout and production process type, as shown in Figure 6.

This step contributes mainly to the partitioning logic because the results of this step are essential in the decision making related to the content of the modular product family. The purpose is to define a minimum number of modules which fulfil the variety needs in later steps of BfP.

2.7 Step 5: preliminary product family description

The aim of the step is to make a preliminary description of the product family by applying a modified version of the Product Family Master Plan (PFMP) (Harlou, 2006) as a guiding framework. PFMP provides an object-oriented modelling formalism for product families and highlights customer, engineering and part views. Research on Generic Bill of Materials (Callahan, 2006; Hegge & Wortmann, 1991; Jiao, Tseng, Ma, & Zou, 2014) is closely related to PFMP. These approaches aim to enable the defining of variants with a minimum number of data in IT systems. Compared to PFMP, the studied Generic Bill of Materials approaches highlight product structure issues in the models but the presenting of reasoning chains for the source of variation is often missing and consequently we adapt PFMP in this step. Such a detailed approach as in the original PFMP is not used in BfP. We utilise the idea of studying customer, engineering and part views and the relations between these as a base for defining preliminary product family structure in a workshop environment. In BfP, the engineering view includes generic elements (results of Step 2), the customer view includes customer needs producing the need for variants (results of Step 4), and the part view includes parts and assemblies. The application of these views is discussed using our case. Similarities are found also in the Domain Theory (Andreasen, 2011) in which activity, organ and part domains are analysed in order to support reasoning backwards from the wanted behaviour to a concrete structure of a product. Different types of generic elements and possibilities for standardisation are discussed in this step. This step contributes mainly to partitioning logic, set of modules and configuration knowledge of the five key engineering concepts.

In the case, the preliminary product family description was drawn on the white board in the single day workshop held at the company. The workshop was facilitated by the researcher. During the day, the result was defined to an acceptable extent and it enabled moving to the next phase. Figure 6 presents a sample of the case. First, generic elements were listed in the middle of the white board and customer needs on the left hand side. The right hand side was reserved for parts and assemblies related to the generic elements. Relations between the customer needs and the generic elements were discussed as well as relations between the generic elements and the parts and assemblies. The red arrows (in the web version) stand for examples of the relations between the different views in Figure 6. The number of parts can multiply quickly in this view. Therefore, not all of them were described in the model during the workshop, but making the description supported discussions on the preliminary formalisation of the product family. The description done in the workshop facilitated recognition and the stating of uncertainties related to the product family and finding ideas for the rationalisation. The design team mapped out concrete solutions which related to specific generic elements. Also, an overall picture of the generic elements and the existing concrete solutions and their 3D drawings were studied. This facilitated discussion on the necessary variants and potential for the standardisation of the parts and assemblies.

Generic elements which have no relation to any customer needs related to variability are a potential for standardisation, whereas generic elements to which several customer needs are related are a challenge for modularisation. Considering the relations between different views can be an eye-opener if current products do not include lots of commonalities and there are many solutions for almost the same need. This leads to a discussion on different types of solutions for the generic elements. Generic elements can include, for example, standard solutions (without options), configurable solutions (with predefined standardised options), one of a kind solutions (unique options) and combinations of these, as illustrated in Figure 7 by Juuti (2008).

2.8 *Step 6: configuration knowledge: generic elements and customer needs*

The main purpose of configuration knowledge is to support sales by describing which modules are selected when certain customer needs exist. Steps 6 and 8 consider defining the configuration knowledge in a more systematic way than the previous step. This step is a starting point for defining the configuration knowledge including generic elements and customer needs.

The K-Matrix (Bongulielmi et al., 2001) is applied in Steps 6 and 8. The original K-Matrix is a configuration matrix in which relations between the technical view and the customer view are studied using *yes* and *no* types of relations. Because the technical view is not defined yet in detail in this step, we suggest using the following four types of relations listed below instead of *yes* and *no* types of relations. Thus, our approach is slightly modified from the original K-Matrix and considers the relations differently because of the early phase of designing.

- Customer need requires generic element
- Customer need excludes generic element
- Customer need might affect generic element
- Customer need does not affect generic element

In our case, matrix presentation of the preliminary configuration knowledge was not made because earlier considerations of relations between the customer

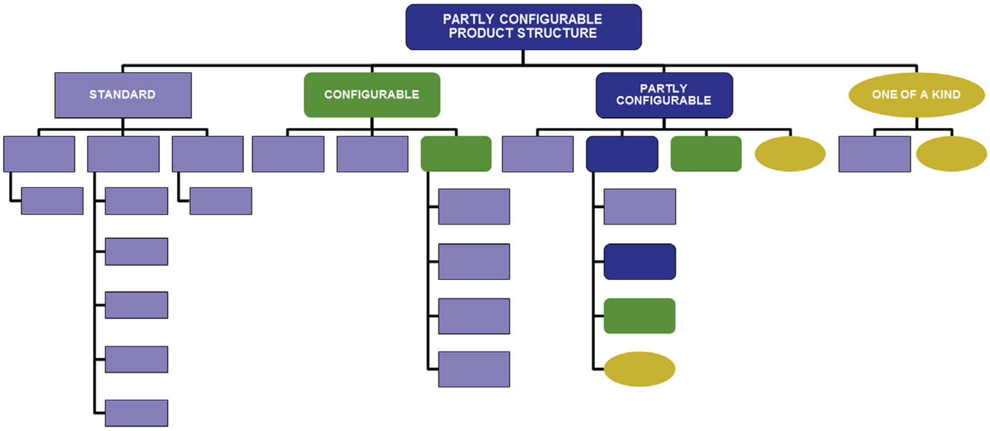


Figure 7 Partly configurable product structure (Juuti, 2008)

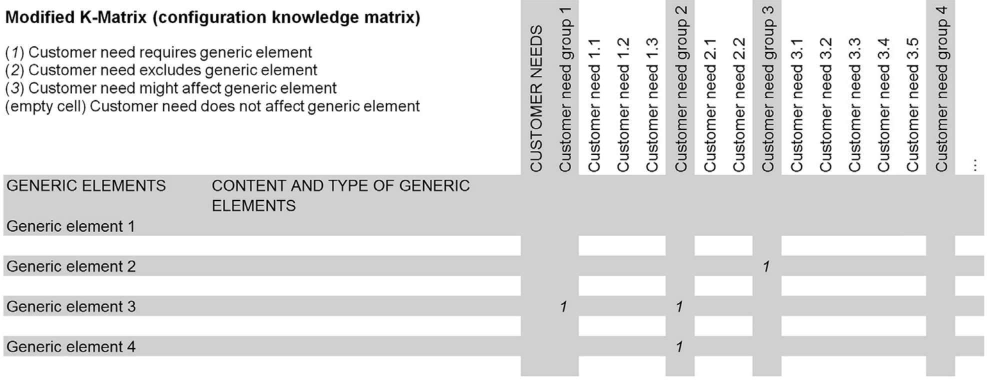
needs and the generic elements done in Step 5 were considered sufficient. A more systematic defining of configuration knowledge was done later in Step 8. Therefore, Figure 8 presents a generic example of the configuration matrix. Generic elements are listed in the rows of the matrix, and customer needs are added to the columns. The matrix includes areas that are not considered in this step yet. Content and type of generic elements are discussed in Step 7. The relations between the elements and the customer options are defined by using the suggested relation types. Because the content and type of generic elements are not yet defined in detail, it is sufficient to analyse the relations between the generic elements and customer need groups.

2.9 Step 7: modular architecture: modules and interfaces

This step aims to define the content of the generic elements in greater detail by focussing on the following topics, as illustrated also in Figure 9:

- Defining the standard section of the product family
- Defining the variable section of the product family
- Defining part sets for generic elements
- Clarifying the overall architecture of the modular product family and defining the interfaces

This step is described mainly using our case. The generic target is to define only a minimum number of modules for creating the needed variety for reasons of cost (Andreasen, 2011). In the case, the step included several brainstorming sessions in which participants from the organisational functions such as product design, procurement and production were participating to define the concept of modular product family. This step was the most time-consuming and took up most of the calendar time in this project. The researchers did not participate in every session, but reviewed some of them. In the sessions,



Modified K-Matrix (configuration knowledge matrix)

(*1*) Customer need requires generic element
(*2*) Customer need excludes generic element
(*3*) Customer need might affect generic element
(empty cell) Customer need does not affect generic element

GENERIC ELEMENTS	CONTENT AND TYPE OF GENERIC ELEMENTS	CUSTOMER NEEDS	Customer need group 1	Customer need 1.1	Customer need 1.2	Customer need 1.3	Customer need group 2	Customer need 2.1	Customer need 2.2	Customer need group 3	Customer need 3.1	Customer need 3.2	Customer need 3.3	Customer need 3.4	Customer need 3.5	Customer need group 4	...
Generic element 1																	
Generic element 2										*1*							
Generic element 3			*1*				*1*										
Generic element 4							*1*										

Figure 8 Generic example of a matrix for defining preliminary configuration knowledge

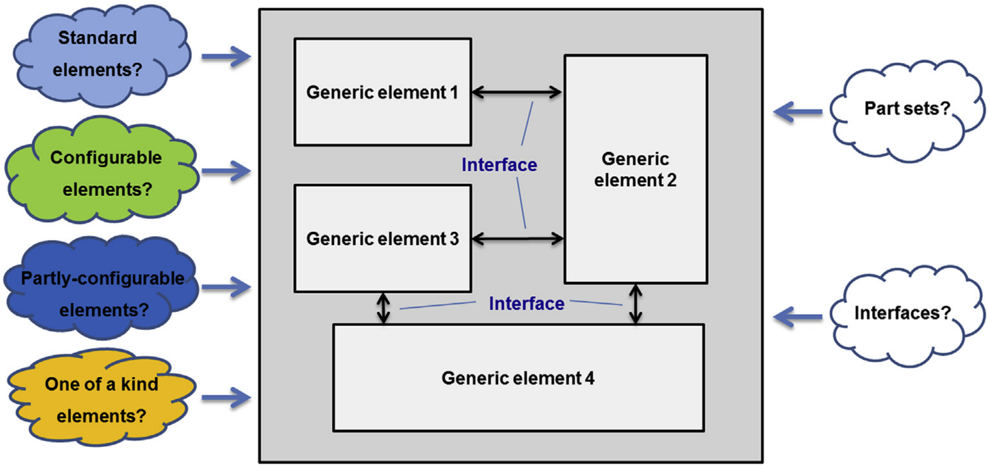


Figure 9 Generic element types, solutions for generic elements and interfaces are considered in defining modular architecture

ideas regarding how to realise the solutions for the generic elements were concretised. Common sessions brought out detailed issues that were solved in specific meetings. In these meetings, areas such as cost effects and economies of scale issues of solution alternatives and suitable part structures and preliminary solutions were discussed and designed on a more detailed level. When defining modules for the generic elements, questions related to the possible number of modules to be offered were asked. Decision making related to the needed number of modules was based on the experience of the participants. For this issue, the method did not provide detailed guidance. In the sessions on designing and ideation, it was found that five product structuring principles for solutions regarding generic elements are relevant:

- Standard parts that can be used in all deliveries (standard elements)

- Interchangeable modular solutions with standardised layout with no changes for dimensioning or design (configurable elements)
- Interchangeable modular solutions with layout alternatives (configurable elements)
- Parametric solutions including one of a kind defining (one of a kind elements)
- Solutions that require free layout designing (one of a kind elements)

Product structuring types and solution principles were suggested for each generic element. History data from the earlier product deliveries was used in analysing the types of delivered solutions. In this step, a reasonable size for the product sections to be standardised was defined based on the variants with the most considerable sales volumes. Possibilities for using only one solution for different variants were recognised for certain elements which had earlier been considered as two or more product elements.

Alternative realisation techniques and manufacturing methods were also considered in the brainstorming sessions. BfP does not suggest any specific innovation tools, but tools for finding new ideas can be found, for example, in the publication by Pahl and Beitz (1996).

All of the solution suggestions for the generic elements could not be standardised within the company. Thus, there was a need to divide these generic elements into smaller elements and to define configurable structures for those including standard and variable sections. Also, 'cut to fit' properties (Pine, 1993) had to be enabled for certain solutions. Figure 10 presents a generic example of how the modular architecture might look after this step. Interface between two or more generic elements should always be standard, at least within a product family, although generic elements would include module options or unique elements with different space reservation needs. In the ideal situation, all the interfaces and space reservations for solutions are recognised and defined in modular architecture. Space reservations and layout aspects are also discussed by Holmqvist (2004). Interfaces are typically categorised into spatial, structural, geometry, material, energy, signal and information (Avak, 2006; Rahmani & Thomson, 2009; Sosa, Eppinger, & Rowles, 2007). DSM methods can be used for the recognition of interfaces between modules, but the results of DSM analysis are not sufficient. Interfaces have to be defined according to real part geometries and solutions, and therefore it is not an abstract design task because we are dealing with brownfield products with existing solutions. The designer has to study existing product documentation. In the case, interfaces related to how solutions are attached to each other. Generic fastening solutions were defined for this issue. During the brainstorming sessions, background information consisting of reasoning for the suggested solutions was documented.

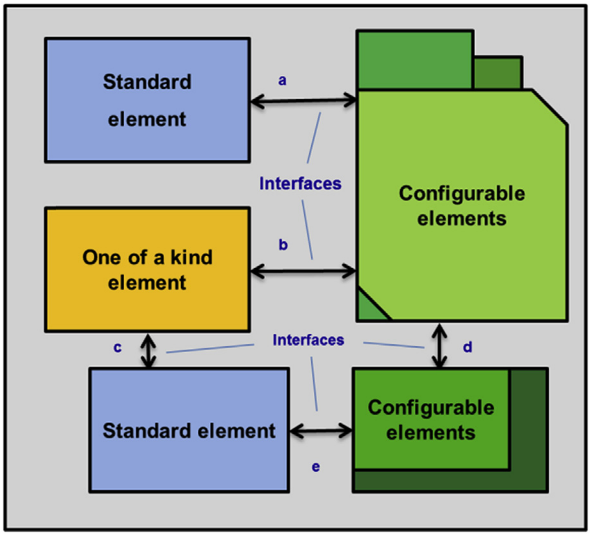


Figure 10 Example of an architecture description of a modular product family

2.10 Step 8: configuration knowledge: module variants and customer needs

The complete configuration knowledge is defined by adding the solutions for the generic elements to the matrix presented in Step 6 and defining the relations with the customer needs using similar notation.

Figure 11 presents an overview of the configuration knowledge matrix defined in the case. This step required two workshop days in which the researchers also participated as facilitators. Colour coding was used in the cells of the matrix instead of numbers. The modelling of the configuration knowledge was already begun parallel to the previous step. Results of the previous step were also summarised in the configuration matrix. The column 'Solution principles for product variation' includes the solution principle options of the each generic element and also explains related product structuring principle as defined in Step 7. Similar matrix tools can be used for defining compatible customer needs and compatible solutions in the early phase of configurator development. A well-made configurator guides the customer or sales personnel in choosing only technically compatible options.

2.11 Step 9: product family documentation

After defining the modules and the configuration knowledge, the design reasoning path of each generic element is described using the graph known as the Product Structuring Blue Print (PSBP) (Lehtonen et al., 2011). PSBP describes the name of the product family in question, the generic elements it includes, the solution principles for each generic element and type of each

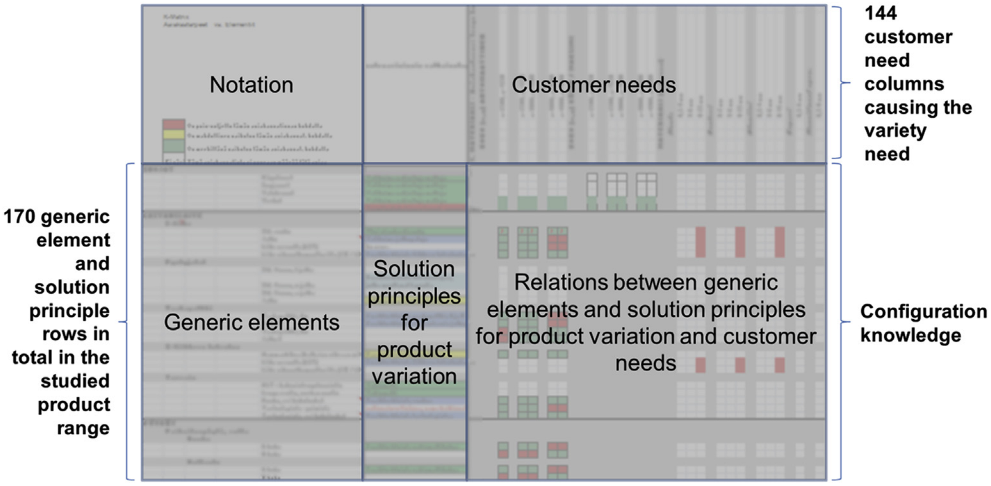

Notation
Customer needs
144 customer need columns causing the variety need
170 generic element and solution principle rows in total in the studied product range
Generic elements
Solution principles for product variation
Relations between generic elements and solution principles for product variation and customer needs
Configuration knowledge

Figure 11 Configuration knowledge supports reuse of existing solutions

solution and variation needs. A generic example of PSBP is shown in Figure 12. Compared to the defining of configuration knowledge, this step highlights visually the hierarchy and reasoning chains of each solution. Therefore, the step contributes mainly to the partitioning logic.

Figure 13 shows an overview of PSBP examples done in the case. This step included a one day workshop that the researchers facilitated. PSBP figures were drawn by the researchers. These models include detailed knowledge about the reasoning for the products, and therefore they are not presented in greater detail. The aim of the documentation is to support in understanding and discussing the structure of the product family and to support future updating of the modular product family in a company. If the solutions have to be modified, for example because of changed customer need, it could be seen from PSBP where the changes have effects. Ultimately the company defined their own convention to present the product family.

2.12 Step 10: business impact analysis

Analysing the results of the product development is important for clarifying the rationality of the chosen partitioning logic. Only fundamentals of the business impact analysis (BIA) are presented in this paper. In many publications, Activity Based Costing (ABC) is adapted to estimate the cost savings of product platforms (Park & Simpson, 2006; Siddique & Repphun, 2001; Zhang & Tseng, 2007). The studied ABC approaches typically consider production perspectives in bottom-up cases. Also, other approaches such as process-based cost modelling focussing on the effects of component sharing (Johnson & Kirchain, 2010) and considering market segment perspectives related to commonality decisions (Kim & Chhajed, 2000) have been presented. The purpose of BIA is not to

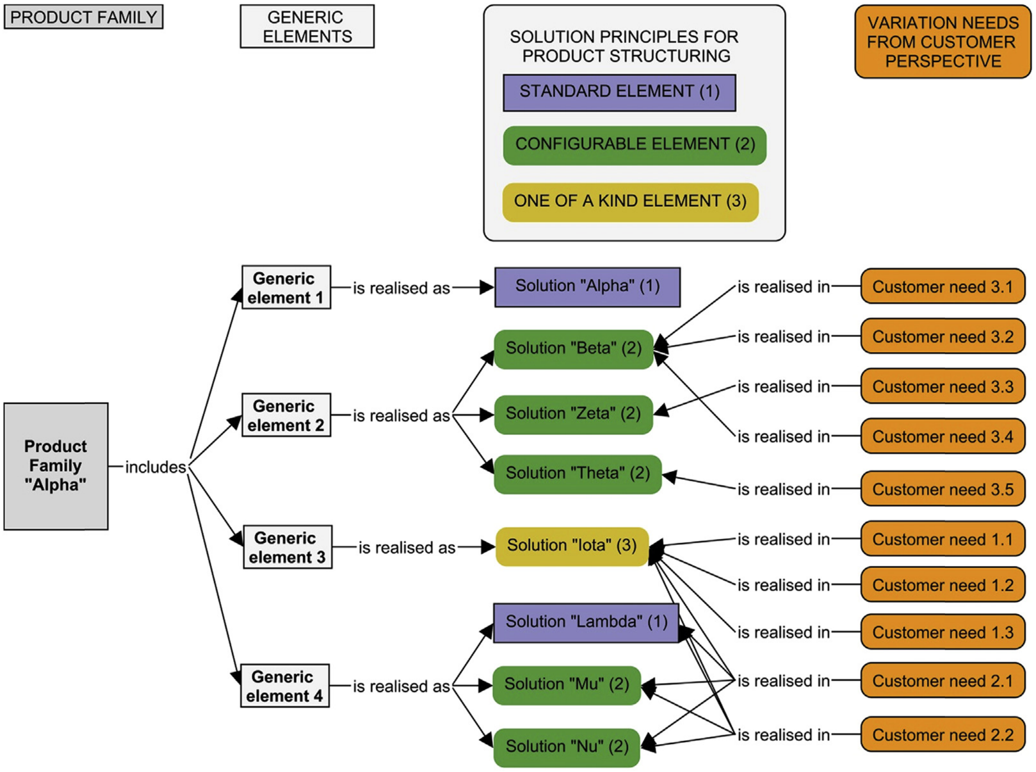


Figure 12 Product Structuring Blue Print for product family documentation

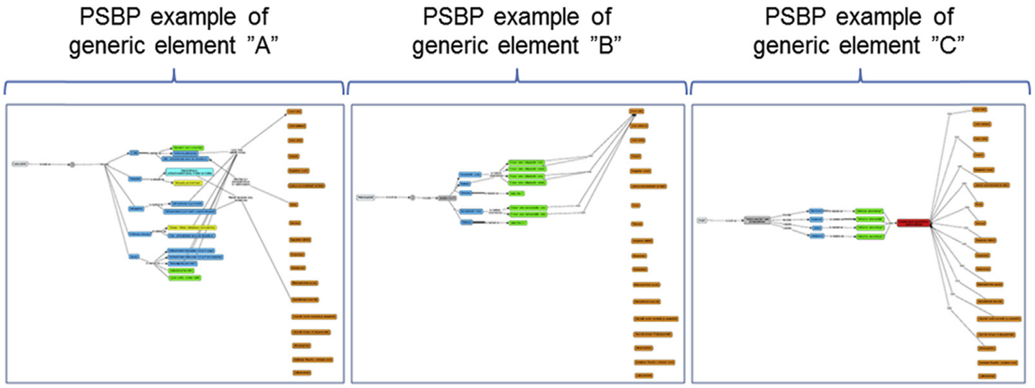

PSBP example of generic element "A"
PSBP example of generic element "B"
PSBP example of generic element "C"

Figure 13 PSBP documenting examples in the case

replace detailed cost analysis done with ABC approaches, but rather aims to work as an easy and fast approach to give a rough estimate about profit in a workshop environment. BIA is supported by a model that describes relations between key engineering concepts, encouraging guiding principles and mechanisms for rationalisation of the product variety and generic steps of manufacturing industry. The basic structure of the BIA framework is shown in Figure 14.

The guiding principles have similarities with the module drivers (Erixon, 1998) and the mechanisms (Fixson, 2006). The idea is that BIA includes a questionnaire-based supporting tool. Answers are given by focussing on decades of money (thousands, tens of thousands, etc.) because analysis with definitive values is difficult if there is no accurate information available. In the case, BIA was made with a prototype tool in the one day workshop with the managers. Estimated savings on materials and components were moderate. The impacts were higher in operational costs for the company. In certain cost topics, it was evaluated that the costs could even be reduced by 40%. The repayment time for the product family development project was also calculated and this was seen as positive, and therefore the project was continued towards the realisation.

3 Conclusions

BfP includes ten steps that support the defining of design information related to the key engineering concepts in the rationalising of the existing product variety of a company towards a modular product family that supports product configuration. We claim that the key engineering concepts include partitioning logic of a modular product family, set of modules, interfaces, architecture, and configuration knowledge. If design information related to these concepts does not exist or information is not created in the design work, it is possible that a modular product family that would support product configuration will not be realised. Therefore, commitment, determination and investments in product development are important to reach the goal. The literature review revealed that the number of approaches and methods suggested for modularisation and product family development and product configuration is high and they focus on different aspects. In BfP, new architecture is created based on the analysis of business and customer environments and the old solutions. Therefore, it is not a pure bottom-up approach because also strategic aspects related to design reuse and standard elements within a product family are defined. Considering the bottom-up approaches, the novelty of our study is to consider the key engineering concepts in rationalising existing products towards a modular product family and to describe a method that considers these concepts. Design methods in which all the suggested key engineering concepts are considered are rare. The importance of these concepts has often been recognised separately or in smaller sets. This paper also presents examples of how BfP can be applied in a company.

BfP has a presumption that the design team understands its business, customer environment and products. This is required in decision making related to the viewpoints that are not described in the BfP. Nevertheless, we state that BfP

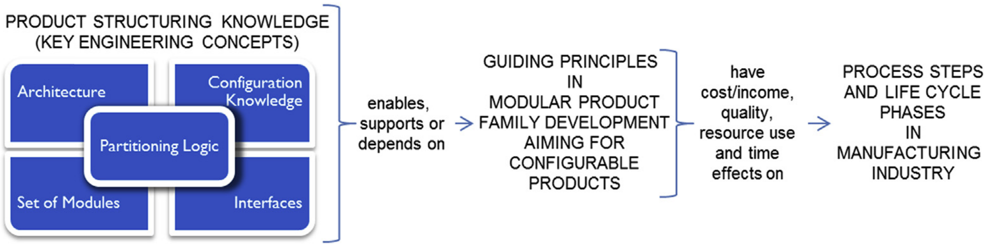

PRODUCT STRUCTURING KNOWLEDGE
(KEY ENGINEERING CONCEPTS)
Architecture
Configuration Knowledge
Partitioning Logic
Set of Modules
Interfaces
enables, supports or depends on
GUIDING PRINCIPLES IN MODULAR PRODUCT FAMILY DEVELOPMENT AIMING FOR CONFIGURABLE PRODUCTS
have cost/income, quality, resource use and time effects on
PROCESS STEPS AND LIFE CYCLE PHASES IN MANUFACTURING INDUSTRY

Figure 14 Main structure of the business impact analysis framework

follows the method-like characteristics presented by Newell (1983). BfP in itself cannot define the best solution in a design situation, but it aims to provide suggestions and guidance about what should be defined in each step. The method aims to present a specific way to proceed, including different steps. The goal of these steps is to define design information that relates to the suggested key engineering concepts in designing of a modular product family that supports product configuration. The aim of BfP is that by following the steps, the possibilities to succeed increase. BfP includes generic sub-goals and subplans. The method does not define exactly how these sub-goals can be achieved in every case, but it aims at offering generic suggestions that may help in the realisation of these sub-goals. The aim in the method description has been to define the results of each step, including what these results look like and to which other steps the results of a specific step relate. A method can be a strictly algorithmic or strictly regulated procedure, heuristic instruction (relatively flexible procedure) or a quite free procedure where only main principles work as guidance (Hubka & Eder, 1996). BfP includes characteristics of heuristic and fuzzy instructions and it cannot be considered as a strict procedure. Gericke and Blessing (2012) explain that design processes do not represent the creative process sufficiently. This is one of the potential weaknesses of BfP. BfP does not remove the need for trial and error which is a typical property of traditional design processes.

In the case, the benefits of the modularisation were based mainly on the increasing of commonality, which resulted in operative benefits and efficiency. The proposal for this collaborative development project came from the company. Although the starting point was challenging because of the backlog in production, the company was motivated to try development with a method originating outside the company because of unsuccessful initiatives with their own approaches. The researchers did not need to motivate anyone to start the modularisation project. The researchers made non-disclosure agreements with the company and this made it easier to get familiar with the products and the company. The main task of the researchers was to act as interpreters of modularisation and to guide consideration of the modularity aspects forward.

Universal durations needed for modularisation are difficult to present because cases are always different. In our case, most of the calendar time was used for developing the solutions in Step 7. The principles of BfP were adopted by the middle management. We have also seen a case in which the middle management of another company considered that the method was not compatible with their processes. In the beginning, the desired language of the results was English, but later on it was discovered that also Finnish (the company is located in Finland) was needed in defining the main terminology. The company's attendance at the workshops was good. There were always people responsible for the project and other experts (director of product development and CEO participated also) available who could answer questions and ensure that the tasks would be done. There was no need for the researchers to manage the company personnel. As a method, BfP gained acceptance within the company and the company began another project for the existing product range, in which the researchers were not needed as facilitators anymore. Therefore, it can be stated that by going through these method-like steps of BfP, common understanding increased about the issues that should be considered in modularisation.

Future work will focus on further defining business impact analysis and describing a tool made according to it. Succeeding in designing configurable technical systems is not enough to realise all the benefits of modularisation, but the operations of a company also need to be adapted to get the most out of the new paradigm. Consequently, studying the transition from engineer-to-order to configure-to-order from the organisation's viewpoint is an interesting topic. Also, defining the optimal number of modules is one of the major challenges of modularity because of the different business and customer environments in each case.

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