Journal of Engineering Design

ISSN: 0954-4828 (Print) 1466-1837 (Online) Journal homepage: http://www.tandfonline.com/loi/cjen20

Identifying and addressing challenges in the engineering design of modular systems – case studies in the manufacturing industry

Jarkko Pakkanen, Tero Juuti & Timo Lehtonen

To cite this article: Jarkko Pakkanen, Tero Juuti & Timo Lehtonen (2018): Identifying and addressing challenges in the engineering design of modular systems – case studies in the manufacturing industry, Journal of Engineering Design, DOI: 10.1080/09544828.2018.1552779

To link to this article: https://doi.org/10.1080/09544828.2018.1552779

JOURNAL OF ENGINEERING DESIGN
https://doi.org/10.1080/09544828.2018.1552779

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

Identifying and addressing challenges in the engineering design of modular systems – case studies in the manufacturing industry

Jarkko Pakkanen, Tero Juuti and Timo Lehtonen

Laboratory of Mechanical Engineering and Industrial Systems, Tampere University of Technology, Tampere, Finland

ABSTRACT
This paper focuses on the engineering design of modular systems in the manufacturing industry, in which companies can benefit from modular and configurable products that fulfil a variety of customer needs. The purpose of this paper is to study the types of challenges faced in the engineering design of modular systems and the types of support needed to address these challenges. The topic is studied via a literature review and seven industrial case studies. The analysis method for the case studies combines engineering and business perspectives. The engineering perspective highlights engineering concepts related to designing modular systems, while the business perspective focuses on related managerial issues. We find that the studied companies emphasised different aspects of modular system development, despite having similar high-level goals related to the benefits of modularity and design reuse. We also identify several challenges, along with the need for support related to the engineering design of modular systems in the manufacturing industry. Current engineering design practices related to modular systems are not sufficient to generate the typical benefits related to modularity and design reuse; organisations must also focus on other aspects of the design process, such as knowledge retrieval.

ARTICLE HISTORY
Received 13 April 2017
Accepted 22 November 2018

KEYWORDS
Design reuse; product variety management; modularity and standardisation; engineering design in industry; knowledge and information management

1. Introduction

Products are manufactured to meet needs and requirements, which continuously change to reflect products' multiple users, alternative usages, restrictions and rules (e.g. legislation), and shifts in societal values. While varying customer needs and product designs based on these needs are major sources of product variety, products also vary based on other product lifecycle phases. For example, maintenance and aftersales can affect product design and functionality. From the design perspective, managing product variety involves several different tasks: modifying existing variety according to new requirements, changing a product's modules and components or designing a new version of a product (ElMaraghy et al. 2013). When a company manufactures different products for different needs, it creates a variety of products (ElMaraghy et al. 2013). Therefore, product variety describes the range

CONTACT Jarkko Pakkanen ✉ jarkko.pakkanen@tut.fi

of products a company can offer within a certain time period in response to market demand (Ulrich and Eppinger 2008). Examples can be seen in the automobile industry, which offers different models and accessories for different markets.

The need for product variety creates challenges for businesses. Variety is a disruptive phenomenon in the mass and serial production manufacturing industry, where standard parts and standard working procedures are the basis for high productivity and cost effectiveness. If a product range is not designed to support efficient customisation from a technical perspective or if a company's sales-delivery process does not support the reuse of product elements that do not need to vary, costs related to product design, production, warehousing, sales and services, and profitability may fall. In the industry, this issue is solved by structuring product families according to the principles of modular design, whereby modules within the modular system are handled as standard elements in the sales-delivery process, and variants are created by combining the modules in different ways. One classic example demonstrating the importance of design reuse is that of Sony Walkman personal stereos (Sanderson and Uzumeri 1995). In the late 1970s, Sony took the first steps towards the personal portable stereo market from cassette recorders used by reporters by studying the use of recorders exclusively for playback and studying headphones in a separate project. Finally, these projects were connected, and the first Walkmans were sold in Japan in 1979. The company maintained its dominance in the global market for over a decade, largely due to systematic and disciplined development and management of a product family and evolution of product platforms. Sony had its own flexible manufacturing system that was optimised for small production runs and easy model changeover, but many of Sony's competitors, such as Matsushita (Panasonic), had similar manufacturing capabilities. Thus, Sony invested in key component technologies and key generational platforms that made it easier to make large numbers of incremental design changes in features, packaging and appearance based on knowledge of the lifestyle-driven needs of consumers in major regional markets. All the variants were built around key modules and just a few platforms, and single distributors were not offered customised models. Sony's official product line was broader than those of competitors. The company's use of platforms also enabled the development of models for marginal market segments with occasional success and little fear of large losses. Aspects of design reuse supported high quality and low cost, enabling the creation of high product variety with good market impact (Sanderson and Uzumeri 1995).

The aim of this paper is to discuss the industrial practises and challenges of designing such modular systems to support product variety management in the manufacturing industry. The engineering design of modular systems refers to the application of product development tactics to find and define reusable elements of a company's existing products. In this paper, modularisation, product family development, product platform development, and product configuration are considered the main tactics supporting the engineering design of modular systems. These tactics are discussed in detail in Section 2. Our research objective includes studying the challenges inherent in the engineering design of modular systems and determining the types of support needed to address these challenges. This study is based on seven industrial case studies, which are discussed in Section 4. These case studies present industrial projects related to the engineering design of modular systems in different manufacturing companies, and they provide evidence of such tactics as reducing engineering hours and costs and increasing commonalities among products in the same family. We also discuss the generic benefits of design reuse in Section 2. However, the main focus of this paper is not to review these benefits in detail, but to draw together a unified view of the challenges in modularisation after considering a number of modularisation projects. The seven case studies pursued the benefits of modular systems from different approaches, but each approach was related to the main building blocks of modular systems. We consider the building blocks of modular systems to consist of partitioning logic, set of modules, interfaces, architecture, and configuration rules and constraints. To clarify the terminology in this paper, partitioning logic refers to the reasons architecture, set of modules, and interfaces exist in the forms they do. An individual module belongs to a set of modules, which is one of the main building blocks of the modular system. A module complies with certain interfaces and has a position in the architecture. Configuration rules and constraints specify the situation in which a module is used in a product variant for a customer. These building blocks are discussed in Section 3, which also discusses the analysis approach adopted in this study.

While this study presents some of the same case studies as the previous publication by Pakkanen et al. (2016), it also presents new case studies, and the method of analysing the cases and findings is explained in greater detail. The companies in question have been anonymised to protect sensitive information. This qualitative study used a mixed research methods approach including two research methods: An action research approach (Baskerville and Trevor Wood-Harper 1996), in which researchers contributed to the modularisation project in each company, was used in case studies A, B, C, D, and G, and the case study method (Yin 2009) was used in case studies E and F. The first mentioned approach included two data collection methods because one of the authors worked in company G for ten years, whereas time and depth of participation in case studies A, B, C, and D was shorter and lesser. All the case studies were done in different companies. Data from the case studies were obtained by participating in the modularisation projects as researchers and consultants (case studies A, B, C, and D), listening to presentations given by the companies' employees and interviewing key personnel (case studies E and F), and working in company for longer period (case study G).

To summarise the structure of the paper, Section 2 includes a literature review that provides background on the engineering design of modular systems from the perspectives of design reuse and knowledge management, as well as a background on the main product development tactics used to support design reuse from the perspective of product variety management. Section 3 presents the approach for analysing the case studies, which are presented in Section 4. The findings and results, including how they relate to our research objectives, are presented in Section 5. Finally, Sections 6 and 7 present a discussion and conclusions.

2. Engineering design of modular systems

Design reuse and knowledge management are important topics in the management of product variety and the engineering design of modular systems. We first discuss the motivations behind design reuse and knowledge management, as well as both the related benefits and the drawbacks and challenges. We then introduce the various approaches to developing product variety and the engineering design of modular systems, including those based on modularisation, product family development, product platform development, and product configuration.

2.1. Design reuse and knowledge management

Design reuse is a process of reusing existing (previously designed) solutions, concepts, components, modules, and interfaces in new products or design situations. Hansen and Andreasen (2004) explained that decision-making during the design process is complex, and the outcomes of these decisions significantly affect the design solution, design process and overall business. Compared to working overtime, hiring more personnel or negotiating longer delivery times, design reuse is considered a sustainable solution to engineering overload (Pulkkinen 2007), and it can reduce both effort and risks, thus preventing errors and uncertainties in development (Busby 1999; Siddique and Repphun 2001). Furthermore, design reuse helps to familiarise production staff with products' designs, and the use of similar elements across products makes it easier for customers to use and maintain new product purchases (Busby 1999; Siddique and Repphun 2001). Through these different mechanisms, design reuse reduces costs, shortens time to market, shortens testing time, and improves quality (Duffy and Ferns 1998).

Many elements can be considered when deciding whether design reuse should be pursued for a particular project. Typically, to justify design reuse, one must consider the whole product lifecycle and all associated costs with and without incorporating design reuse. For example, in research on standardisation, Perera, Nagarur, and Tabucanon (1999) and Wacker and Treleven (1986) emphasised focusing on estimating cost effects of standardisation in specific lifecycle phases. Lifecycle and costs were also emphasised by Fixson (2006), who suggested modelling the relationships between the product architecture characteristics and the costs related to specific lifecycle phases. Similarly, Gershenson, Prasad, and Zhang (2003) discussed the effects of modularity on lifecycle phases, and Ong, Xu, and Nee (2006) suggested that cost effectiveness can be improved by increasing commonality among products. Martin and Ishii (1997) weighed the importance of variety against the cost of variety using commonality and variability indices. Scholars have also proposed generic models of product development that highlight time, quality, efficiency, flexibility, risks, and environment, in addition to costs, when analysing decisions about product development (Olesen 1992; Andreasen 2011); however, costs remain the most commonly discussed element when justifying design reuse. For example, Duffy and Ferns (1998) used the metrics of time, cost, quality, and performance to analyse the benefits of design reuse in a large company making made-to-order products, asking four practising designers about current and potential future impacts of design reuse on the design development process. The analysis of the benefits showed that cost reduction had the largest scope for improvement (compared to quality, time, and performance) when considering foreseeable impacts.

In addition to conducting cost analyses, scholars also frequently discuss the technical performance of a product in the context of design reuse. Kong et al. (2009) suggested that the optimisation of product performance and similarity should be considered in managing product variety. Gonzalez-Zugasti, Otto, and Baker (2000) explained that, in product family development, the technical performance, costs, and risks of the proposed family of products should be compared to those of the original product or to some other product family exhibiting similar variety. Fellini et al. (2002) suggested that a product family may lose performance and that tolerable performance losses compared to the performance of the single optimised product should be clarified. Finally, Halman, Hofer, and van Vuuren (2003) suggested that, compared to single products, product platforms and product families can improve cost and time efficiencies, technological leverage, and market power.

However, design reuse is also associated with several potential drawbacks and challenges. Engineering, cognitive, motivational, organisational, and environmental factors may prevent design reuse (Busby 1999). Engineering factors can include, for example, obscure design rationales in situations in which features perform multiple functions. Busby (1999) offers an example in which a designer understands that a product element has a locating function and reduces the weight of the part to save material costs without compromising this function. However, the designer does not realise that the lightened section also has another function to support orientation-checking that is now compromised because of lightening the element. According to Bracewell et al. (2009) and Gedell and Johannesson (2013), a description of a comprehensive design rationale should include the issues addressed, the options considered, and the pros and cons of changing the design, thereby answering the question of how things currently are and why. If this kind of description is not available, inexperienced designers might not be able to select suitable solutions from among similar pre-existing solutions, which may lead them to design a new solution instead of reusing an existing one. Design reuse might also prevent innovation and lead to design fixation if the reuse strategies are too strict (Sivaloganathan and Shahin 1999).

Aspects of design knowledge management are also important when discussing product variety management. Knowledge capturing, indexing, and retrieval can be considered part of the design process, and research on this topic has explored design rationale and support systems. Information systems should help designers store, represent, search, and use reusable knowledge (Sivaloganathan and Shahin 1999). Derivatives of issue-based information systems (IBIS) (Kunz and Rittel 1970) are probably the most popular solution in this context. Bracewell and Wallace (2003) and Bracewell et al. (2009a) presented two generations of design rationale editor (DRED) tools for formally capturing and communicating issues that have been addressed, options being considered, and arguments for and against each option. In addition to factors inhibiting design reuse, Bracewell et al. (2009) noted that design rationale capture tools have great potential, but must fit naturally with designers' working methods and consider the challenges inherent in large and complex projects to ensure clarity. Other tools, such as Compendium, support the building of shared understanding and structured knowledge (Conklin et al. 2001). Leake and Wilson (2001) discussed the role of concept maps in capturing reusable knowledge to support case-based reasoning. Ontologies, or collections of knowledge that include structured conceptualisations defining specific pieces of knowledge (Chandrasekaran, Josephson, and Richard Benjamins 1999), have also been discussed as ways of representing components and parts to support the reuse of product information (Moon, Simpson, and Kumara 2010).

The success of knowledge retrieval depends on the representation of reusable solutions. Wallace (2006) explained that 30%–50% of designers' information retrieval needs are broad during the concept phase and that these needs are the most difficult to satisfy. Colleagues are a very important source of information, especially when detailed queries using indexes and keyword searches prove difficult (Aurisicchio, Bracewell, and Wallace 2010). Maier, Fadel, and Battisto (2009) reported that affordances are more fundamental than functions in engineering design and form in architecture. They suggested affordance-based design for facilitating knowledge capture and reuse, explaining that such frameworks support an understanding of past design failures and that understanding the affordances of a design may prevent the same failures in the future. Ahmed (2005) suggested creating a visible indexing structure for employees to use when searching for knowledge. For example, if standard catalogue components are going to be used, the main issue is how to find and select the most suitable example component (Sivaloganathan and Shahin 1999).

The concept of shared understanding is also relevant to design reuse and knowledge retrieval (Lehtonen et al. 2015); there must be agreement and a mutual view regarding what elements are designed to be reusable and how and why. If engineers lack a shared terminology and the metadata are not coherent, then the search itself may require more effort than simply redesigning a reusable module option. According to Baxter et al. (2007), reuse requires an understanding of the product, the lifecycle steps and the concepts, as well as the data elements and relationships among these concepts. This presents challenges for explicit representations produced during the engineering design of modular systems. Costa et al. (2012) also highlighted knowledge models in supporting the reuse of design information when designing variety. Kleinsmann, Buijs, and Valkenburg (2005) noted the importance of communication solutions in improving shared understanding at the individual, project, and company levels.

Some researchers have argued that general design methods can be considered design reuse methods because their fundamental principles are reused in every design, although the specific design instances are defined each time (Baxter et al. 2007). In addition to these approaches, Briere-Cote, Rivest, and Desrochers (2010) posited that defining a generic product structure supports an engineer-to-order (ETO) configuration of product variety (combining principles of product configuration with the possibility of designing customer-specific elements). To summarise, systematic and explicit definitions of terms, information, and knowledge representations are essential elements of design reuse.

2.2. Product development tactics related to the engineering design of modular systems

The need for product variety poses challenges for design reuse in general. Therefore, we review the main product development approaches used when a business requires not one standard product, but, rather, a variety of products. Previous discussion has suggested that such tactics as modularisation, product families, product platforms and product configuration may allow customer-specific product variety while still offering the benefits of design reuse (Pine 1993; Victor and Boynton 1998; Pakkanen, Juuti, and Lehtonen 2016). These tactics allow companies to offer product variety without significantly increasing costs (Jiao, Simpson, and Siddique 2007). The following subsections present the main aspects of each of these tactics.

2.2.1. Modularisation

Modularisation is a product development approach for increasing design reuse in businesses when customers require product variety. Modularisation involves defining a modular architecture, including definitions of each module and interface, to reduce the complexity of company operations and realise the business benefits of design reuse (Andreasen 2011; Pakkanen, Juuti, and Lehtonen 2016). In discussing the role of knowledge modularity in supporting design reuse, Meehan, Duffy, and Whitfield (2007) argued that existing modularisation approaches insufficiently formalise and maintain the knowledge behind defined modules. Their approach aims to support the maintenance of modular solutions by highlighting and modelling evolutionary design knowledge. This design knowledge can then be analysed to recognise inherent modularity and to optimise and map design viewpoints. The reuse of modules and the parameters of modules, interfaces, and architectures support the process of effectively designing differentiated products (Dahmus, Gonzalez-Zugasti, and Otto 2001; Harlou 2006; Fujimoto 2007; Ettlie and Kubarek 2008; Schönsleben 2012).

2.2.2. Product platform and product family development

Developing product platforms and product families is also a viable tactic for managing product variety. A platform is a collection of core assets that are reused to achieve competitive advantage (Kristjansson, Jensen, and Hildre 2004). The platform viewpoint offers several possibilities for reuse, such as knowledge, functionalities, designs and design variables, architectural rules, people and relationships, processes, product foundation, technology, interfaces, modules, subsystems, components, elements, and single monolithic parts (Kristjansson, Jensen, and Hildre 2004; Ettlie and Kubarek 2008; Moon, Simpson, and Kumara 2010; Ramani et al. 2010; ElMaraghy et al. 2013). The definition of what can be reused is broad and varies from company to company. Therefore, when applying platform thinking, each company must define the knowledge, elements, and assets it can reuse to bring benefits. Understanding these elements enables managers to set goals for design tasks relating to design reuse.

Product family development can be based on modularisation or on product platforms. Product families reduce the number of different product elements (Meyer and Lehnerd 1997; Dahmus, Gonzalez-Zugasti, and Otto 2001; Harlou 2006; ElMaraghy et al. 2013). Products belonging to the same product family can share, for example, modules and other elements related to product platforms.

Previous research has suggested that product platform and product family tactics are most suitable when market diversity is at a medium level (Krishnan and Gupta 2001). Standardised products are suggested when diversity is low, and niche products are suggested when diversity is high and economies of scale vary from low to medium (Krishnan and Gupta 2001). Defining product variety without utilising the concepts of product families results in redundant data, weak relationships among single variants, an inability to combine existing variety or create new versions of products, and increased delivery risks emerging from unproved product elements (Sawhney 1998; ElMaraghy et al. 2013).

2.2.3. Product configuration

When product elements are designed to be reusable using the tactics mentioned earlier, product variety can be specified more efficiently to address particular customer requirements. We discuss this specifying of variants under the theme of product configuration. Configurable products are based on a set of predesigned elements, rules, and constraints describing how these can be combined into customer-specific versions of a base product (Tiihonen et al. 1999; Forza and Salvador 2002; Heiskala et al. 2009). As an activity, product configuration entails the selection of suitable modules for customers by using configuration knowledge to meet the necessary variability requirements (Tiihonen et al. 1999; Pulkkinen 2007). Variability requirements relate to the need for different module options. Consequently, these requirements must be explicitly defined when various modules and product families are designed to support possibilities for design reuse.

From a market segment perspective, each significant variability requirement should be matched by a certain product variant based on predefined modules and product-structuring principles. This leads to a question concerning the optimal number of modules. Ideally, no module should require project-specific engineering; rather, all modules should be available from among existing complete and reusable design options. However, predesigning every imaginable variety is infeasible, especially in low-volume businesses, as it involves too many risks. Using the principles of product configuration does not require that all modules be completely predesigned before receiving the first order in which they are needed (Pakkanen 2015). At a minimum, however, the modules' structuring principles should be predefined during the engineering design of modular systems. The aim of clarifying the underlying structuring principles of the basic product is that the project-specific elements that are not completely designed will not harm the product family or related business objectives. Such a configure-to-order (CTO) way of operating, based on modular and configurable products, supports design reuse better than ETO. ETO is based on engineering the product when the customer orders the product, and CTO is based on configuring the product mainly from reusable elements (e.g. modules) in the same situation. Engineering the product entails designing new product elements or modifying exiting ones, whereas configuring the product can include selecting predesigned product elements, replacing predesigned product elements with other predesigned elements, or excluding some elements. In sum, product configuration considers both defining configuration knowledge and using configuration knowledge to define customer-specific variants.

2.2.4. *Cost and value of the main product development tactics for the engineering design of modular systems*

This section considers the impacts of applying the tactics discussed above. A variety of studies have presented quantitative models and data and qualitative statements regarding the cost and value of these product development tactics. Figure 1 summarises the aspects discussed in this section.

Several studies have investigated the benefits of product modularity, but few have focused on the costs of developing modular products. Berman (2002) reported that combining modular product design and postponing product differentiation in the Deskjet line of printers enabled Hewlett-Packard (HP) to reduce total costs (manufacturing, shipping, and inventory) by 25% compared to centralised production of all varieties, despite higher manufacturing costs (though the article did not reveal how much higher these costs were) due to postponing product differentiation. Danese and Filippini (2013) concluded that modularity positively affects new product development (NPD) time and product performance because it supports supplier involvement. Engel and Reich (2015) reported that adaptable products and modularity reduce the cost of system lifecycles and upgrade cycle time while increasing the system's lifespan. They also noted that, while defined interfaces support adaptability, there is a cost associated with creating new interfaces. Hansen and Sun (2010) stated that product modularity reduces direct costs, capital binding, and lead times, but not in every case. They also stated that investment requirements are normally significantly higher in modular products than in more integrated products. Finally, Jacobs, Vickery, and Droge (2007) suggested that product modularity has a positive effect on cost, quality, flexibility, cycle time, and performance.

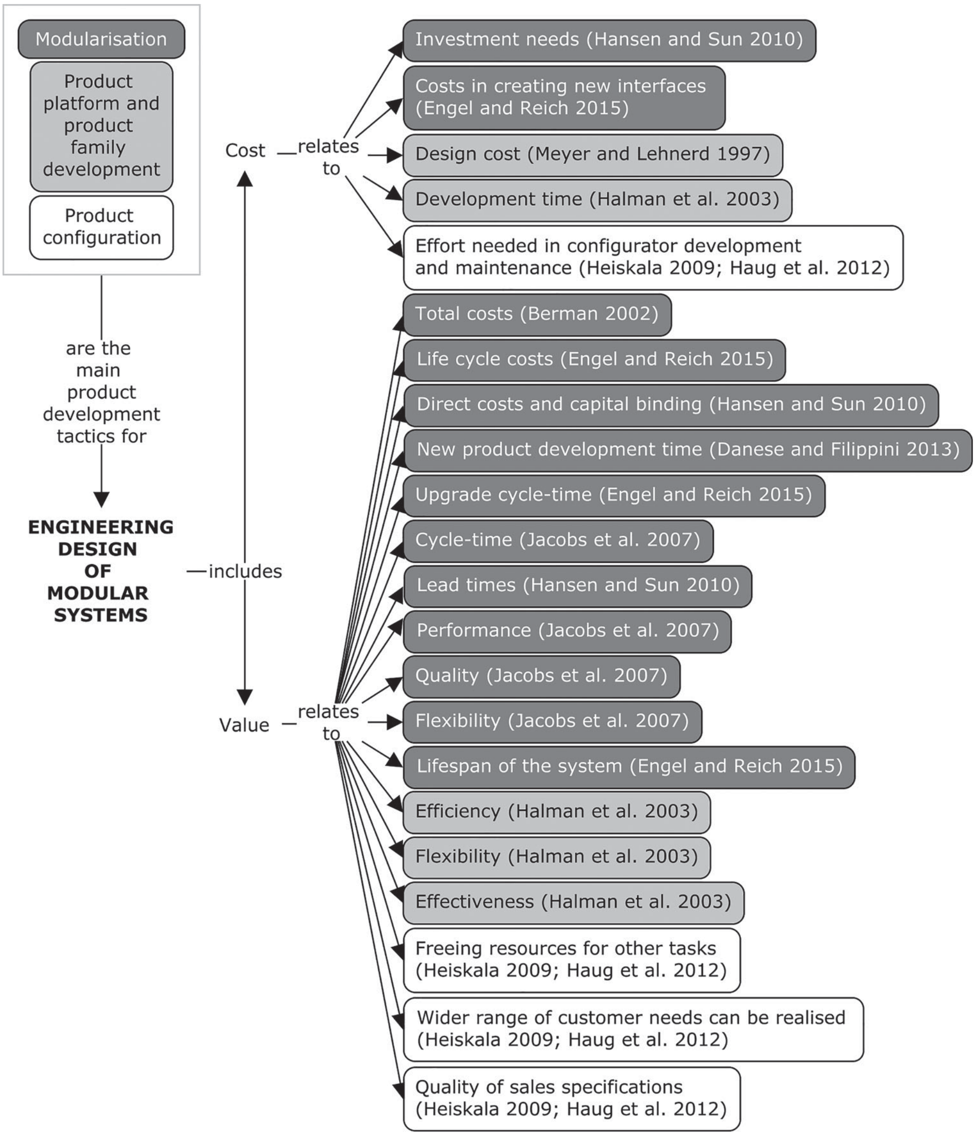

Figure 1. Cost and value of the tactics for the engineering design of modular systems.

Publications investigating the development of product platforms and product families also present insights on cost and value. Halman, Hofer, and van Vuuren (2003) considered efficiency (costs, maintainability, high variety, and time), flexibility (time to market, assembly, styling, and serving of different market segments), and effectiveness (training, learning, brand identity, and ease of explaining products) as the main benefits of product platforms. The cases they studied indicate that designing a product platform is costly and that sufficient development time is required to meet the specifications of all target markets and to integrate existing elements. Meyer and Lehnerd (1997) presented several industrial examples of product platform and product family development. For example, Black

& Decker committed to and invested heavily in platform and product family development, which enabled the efficient introduction of new product variants based on standardisation, modularisation, and automation. Business impacts were particularly related to labour and material costs, and savings of up to 85% were reported.

Heiskala et al. (2009) and Haug, Hvam, and Mortensen (2012) extensively reviewed the benefits and challenges of configurable products and product configurators. They found that the efficiency of fulfilling a wider range of customer needs is one of the most common benefits of configurable products, whereas configurators are beneficial for reducing and eliminating errors in sales specifications, freeing up resources, and preserving knowledge, among other things. Heiskala et al. (2009) also discussed several challenges of configurable products. According to Heiskala et al. (2009) and Haug, Hvam, and Mortensen (2012), determining the appropriate amount of customisation to offer, eliciting customer needs, and defining specifications are among the key challenges of developing configurable products and configurators, and maintenance requires time, effort, and money.

This review is by no means comprehensive, but it provides a more detailed consideration of the engineering design of modular systems than the generic benefits and challenges of design reuse discussed earlier in this paper. Based on the review, it seems that the engineering design of modular systems requires effort and investments and involves risks, but reusability enables various benefits that can be very valuable to a company. It is important to estimate the business potential of applying different product development tactics before fully implementing them to understand whether the benefits and value outweigh the challenges and costs.

3. Analysis approach to understanding the engineering design of modular systems

Section 4 presents seven case studies in which the engineering design of modular systems has been pursued. In the present section, we discuss how these case studies are analysed from the perspective of modularisation. First, we discuss the focus of the analysis. Then, we present the data collection methods. Finally, we describe the criteria used in our data analysis.

3.1. Building blocks of modular systems

The authors (three researchers) of this paper carried out the analysis. We selected five engineering concepts (referred to simply as building blocks) related to the engineering design of modular systems as the main elements for the analysis. Previous research (Pakkanen 2015; Pakkanen, Juuti, and Lehtonen 2016) has identified several key building blocks of modular product families:

- partitioning logic of the modular system (referred to as partitioning logic),
- set of modules,
- interfaces,
- architecture, and
- configuration knowledge (referred to as configuration rules and constraints).

In this paper, the goal is to investigate how the studied companies considered these building blocks of modular systems and utilised them to support design reuse and to manage product variety. The paper further seeks to determine what kinds of challenges the companies faced and what solutions may exist. Some of the above building blocks have already been mentioned in Section 2.2; however, as partitioning logic, in particular, is not a very common concept, these blocks are now discussed in greater detail.

Partitioning logic, or the partitioning of engineering entities, is a critical building block in engineering modular systems (Pakkanen 2015; Pakkanen, Juuti, and Lehtonen 2016). Partitioning logic aims to capture the reasons architecture, modules, and interfaces exist in the form they do. Other building blocks of modular systems (architecture, modules, interfaces, and configuration rules and constraints, according to Pakkanen, Juuti, and Lehtonen 2016) aim to answer the questions of ‘what’ and ‘how’, while partitioning logic aims to answer the question ‘why’. Partitioning involves dividing the modular system into smaller engineering entities based on (1) drivers from the business environment, known as product structuring principles, and (2) variability needs from the customer environment. In our approach, each engineering entity consists of a module or modules. Some may be standard modules required in every configuration, and some may be interchangeable, or may have parametric properties. The module type depends on (1) which product principles are allocated to the particular engineering entity and (2) which variability needs (when relevant) are allocated to each module. The partitioning logic – that is, the reason the modular system has those particular engineering entities and specific modules with specific properties – is modelled during the engineering design effort. The model allocates the variability needs and product structuring principles to particular engineering entities. Once the partitioning is complete, the model permanently documents the allocation of variability needs to modules and interfaces. This enables the company to discuss, validate, and later manage product structuring principles, variability needs, divisions of engineering entities, and the allocations of these to the modules and interfaces. The model also reveals the assumptions and decisions that result in a particular partitioning of the modular system. Capturing partitioning logic (at least partially) in modularisation is important to, for example, prevent the loss of valuable product knowledge due to organisational changes.

Set of modules is required to enable product variety, while interfaces are required to enable module interchangeability and independence, thus supporting reuse by bounding the spreading of variety within a product family. Parslov and Mortensen (2015) provided a good explanation of how interfaces can be understood.

Architecture describes how modules and interfaces are combined to make a product. Consequently, architecture considers the possible layout and other engineering restrictions necessary to maintain reusability. For example, designers may need to define product areas that other module variants cannot affect, known as ‘freezing zones’, to support the reuse of base structures (i.e. the product platform) (Holmqvist 2004).

To support sales teams in reusing modular structures, configuration knowledge must include rules and constraints for suggesting particular set of modules based on specific customer needs. We use ‘configuration rules and constraints’ instead of ‘configuration knowledge’ because the former phrase describes the building block more clearly. Configuration rules and constraints also play an important role in enabling reuse, and they are needed to define information technology (IT)-based product configurators.

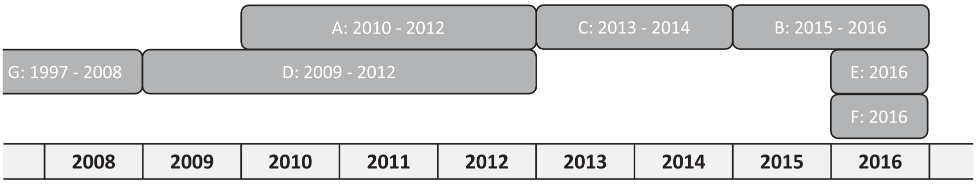

Figure 2. The data collection for the case studies was conducted mainly between 2008 and 2016, with the exception of case study G (1997–2008).

These building blocks are tools for thinking, as they highlight aspects of engineering design that are important for realising benefits from reuse and product variety. Previous research has proposed that successful consideration of these building blocks in the design process opens up possibilities for business benefits if a company needs to rationalise its existing product assortment (Pakkanen 2015; Pakkanen, Juuti, and Lehtonen 2016). The presumption is that this assortment does not enable reuse of product elements or effective configurability of product variants (in the ideal case, the need for delivery-specific engineering should be as low as possible).

3.2. Data collection methods

Section 4 presents case studies A through G, each of which involves the engineering design of a modular system. Figure 2 summarises the main data collection period for each case study. The data collection was completed from the modular system information point of view. The research team (authors) used three different data collection methods, which are presented and discussed in the following.

Data collection method 1 was based on field notes, interviews, meetings and workshops held with company personnel while co-creating modular systems. This method was used in companies A, B, C, and D, in which the authors participated in the modularisation projects as researchers and consultants. The data collection focused on the questions presented in Table 1. The research team considered which topics from Table 1 were discussed, including what kinds of information related to modular systems existed or were created and what kinds of challenges were identified.

Data collection method 2 was based on interviews and meetings with company representatives. The companies were asked to show and demonstrate the documentation they had on modular systems in a modularisation workshop organised by the research team. The research team took notes on which modular system areas were covered and in which areas modular system information was missing based on the topics shown in Table 1. The research team was not involved in the modular system design projects. This method was used in companies E and F. In company F, the authors participated in other product development projects as researchers and consultants before the workshop. These projects did not focus on product modularisation and, thus, are not shown in Figure 2.

Data collection method 3 was based on field notes, company documentation on modular systems, and product development processes, tools, and checklists. A member of the research team was employed by company G for ten years in the area of modular system development while simultaneously completing his PhD thesis. This enabled

Table 1. Supporting questions for data collection indicating existing information on modular systems or intentions to create such information and challenges related to building blocks of modular systems.

Building blocks of modular systems	(1) Questions indicating existence or lack of information, (2) Questions indicating challenges
Partitioning logic	(1) Why is the modular system decomposed in such manner? (1) What are the reasons to implement this partitioning? (1) Why are certain modules interchangeable? (1) Why are certain modules standard elements? (1) Why can certain modules have certain configurable parameters? (2) How is the partitioning logic designed? (2) How is the partitioning logic modelled? (2) How is the partitioning logic documented? (2) Where are the documents managed?
Set of modules	(1) Why do these modules exist? (1) How is the module manufactured? (2) How are the modules designed? (2) How are the modules modelled? (2) Where are the modules' documents managed? (2) How is the lifecycle of modules managed?
Interfaces	(1) Why do these interfaces exist? (1) What interfaces are needed? (1) How is the interface implemented? (2) How are the interfaces selected? (2) How are the interfaces designed? (2) Where are the interfaces' documents managed? (2) How is the lifecycle of interfaces managed?
Architecture	(1) What is the architecture? (1) Which layouts are considered? (1) How are the modules, interfaces and space reservations placed? (2) How is the architecture designed? (2) How is the architecture documented? (2) Where are the documents managed? (2) How is the lifecycle of the architecture managed?
Configuration rules and constraints	(1) Which modules are needed for certain customer needs? (1) Which interfaces are needed for certain customer needs? (1) Which modules are needed with this module? (1) Which configurations are possible to manufacture and deliver? (2) How is the configurability designed? (2) How are the configuration rules and constraints modelled? (2) Where is the information managed? (2) How are the changes managed?

reflective practice on both the focus on modular system and the challenges related to the development process and projects. In company G, only data that were relevant to the questions presented in Table 1 were considered in the analysis.

The involvement of one member of the research team in a design process for long period of time and the opportunity for the research team to co-create modular systems in many companies enabled the research team to study the phenomenon from different perspectives and with different levels of involvement. Despite the differences in data collection methods among companies, the research team focused on similar topics, as shown in Table 1. The meanings of the building blocks (partitioning logic, set of modules, interfaces, architecture, configuration rules and constraints) did not change from 2008 to 2016. For each building block, each case offered tangible evidence relating to each question shown in Table 1.

The research team believes that the three different data collection methods support the validity of the research. The co-creation enabled the research team better access to the information and challenges that emerge during the design process. The team members' long-term employment with company G and exposure to company practices and cultures provided insights difficult to capture during interviews or meetings.

Typically, the discussions prompted by the questions shown in Table 1 led to other questions (e.g. how to get enough resources for the project or where to find competent engineers to do the design work). These questions were captured and classified during the analysis phase.

3.3. Assessment criteria for analysing the building blocks of modular systems

This study presents which building blocks were relevant in which companies and which of the companies focused only on certain building blocks. If the information needed to answer the questions presented in Table 1 existed and the company in question had intentions to improve this information, the building block was noted as considered for the company. If the information did not exist and there were intentions to create the information, the building block was also noted as considered. Considering the data collection from this perspective decreased room for interpretation in the case studies by comparing like with like. Building blocks of modular systems form the foundation of the analysis from the engineering viewpoint; however, more detailed categories and criteria within these building blocks are needed in addition to supporting questions used in the data collection to better highlight the differences among the case studies. We therefore created assessment criteria to identify companies' operational maturity level with respect to the management of the above building blocks. The categories and criteria are presented in Table 2. The model is based on research on business process maturity management (BPMM), which focuses on analysing specific organisational capabilities (Harmon 2010; Röglinger, Pöppelbuß, and Becker 2012). Of the different maturity models, we chose Rosemann and vom Brocke's (2010) approach based on research indicating which maturity models have validated connections to business improvement (Tarhan, Turetken, and Reijers 2016). Rosemann and vom Brocke (2010) defined six categories for maturity assessment, as described in Table 2. The criteria in Table 2 describe the perspective from which each modular system building block is analysed.

With regard to the categories and criteria shown in Table 2, one could ask whether the selected IT criteria are too narrow. Rosemann and vom Brocke (2010) explained that IT refers to the software, hardware, and information systems that enable and support process activities. They added that the specific needs of each stage of a process lifecycle must be considered from an IT perspective in business process management. The same authors

Table 2. Categories and criteria for analysing building blocks of modular systems (partitioning logic, set of modules, interfaces, architecture, and configuration rules and constraints) based on BPMM.

Category	Criteria
People	Is the building block defined, agreed upon, and in daily use in the company?
Process	Is the design information related to the building block documented?
IT	Does the design information related to the building block have an identifier (ID), and is it available?
Governance	Does the design information related to the building block have an owner?
Culture	Is the design information related to the building block under change control?
Strategic alignment	Is the building block considered in company strategy?

suggested such evaluation criteria as customisability, appropriateness of automation, integration with other IT solutions, suitability, and accessibility. For this study, we simplified the criteria to focus on identifiers (IDs). An ID could be, for example, a document, an item, a part, or a serial number. Many designed elements, such as modules, receive ID numbers automatically via information systems after they are created. We also sought to highlight the other building blocks of modular systems (i.e. partitioning logic, interfaces, architecture, and configuration rules and constraints) and study how these are considered or should be considered in conjunction with IT to support the design reuse of these elements. For example, if IDs exist for partitioning logic, interfaces, architecture, and configuration rules and constraints, in addition to modules, then we can consider the modular system to be very advanced. We believe that the existence of IDs for information related to different building blocks is evidence of advanced use of IT solutions; however, considering the criteria discussed by Rosemann and vom Brocke (2010), this category could also be studied using other criteria in the future.

Rosemann and vom Brocke (2010) explained that, in this context, culture refers to responsiveness to process changes, process values and beliefs, process attitudes and behaviours, leadership attention to process management, and process management social networks in business process management. This category was also modified to meet our needs. Our criteria considered culture through the existence of change control processes. This is important because many of the companies we worked with on the modularisation projects were previously accustomed to properties of project business, in which explicitly defined, strict, and systematic processes for how and when changes can be made or who can make these changes have not necessarily been defined. Non-managed design changes are harmful from a design reuse viewpoint.

The criteria we use are not exhaustive, but they do serve as indicators. For example, if a building block of a modular system and the related design information are documented, then we have observable proof that the design process exists and produces outcomes. Similarly, if a building block of a modular system has a unique ID, we can conclude that an IT system exists for dealing with the modular system. Considering the challenges identified through the case studies, the data analysis was executed via discussions with the research team on each case. The data were then studied to identify the items with which the companies were struggling in their projects. These items were highlighted by the research team and discussed with the specific companies.

4. Data and analysis of manufacturing industry case studies

This section presents seven case studies from the manufacturing industry in which product variety is necessary and design reuse has been pursued via the engineering design of modular systems. The aim is to investigate what kinds of approaches related to modularisation have been used in each of the companies and what challenges and supporting factors can be identified related to the engineering design of modular systems, thus reinforcing existing literature in this field.

The industrial sectors, manufacturing volumes, and product values of the companies are presented in Table 3. All the studied companies are multinational and large. The companies' names and other detailed information have been withheld due to the sensitive

Table 3. The studied companies (in alphabetical order based on industrial sector).

Case study	Industrial sector	Manufacturing volume in a year	Product value (decade, €)
A	Machinery	50–60	10,000–100,000
B	Machinery	5–10	10,000,000–100,000,000
C	Mobile machinery	200–300	100,000–1,000,000
D	Shipbuilding	1500–4000	100,000–1,000,000
E	Shipbuilding	100–200	1,000,000–10,000,000
F	Shipbuilding	1–2	100,000,000–1,000,000,000
G	Telecommunications	250,000,000–500,000,000	10–1000

nature of the results. Each case study concerns a different company. None of the companies compete with one another. Yearly production volumes vary from low to medium, depending on the company. Some companies deliver only one similar product per year, whereas some companies deliver millions of similar products. We use decades to differentiate product value. In most companies, the product price is not public information, and the case companies asked us not to disclose actual prices. For example, in case study A, a product value of €10,000 to €100,000 means that the product value varies between tens of thousands and hundreds of thousands euros, depending on the product variant selected. Though the information is not detailed, the table helps to differentiate the companies from one another, as significant variations exist among the studied companies. The number of modules in each case study could be another interesting category for comparison, but not all the studied companies disclosed this number. In addition, business environments differ from one another, meaning that the logic behind partitioning product variety into a specific number of modules also differs across companies, even if they were competing against one another.

4.1. Report from case study A: machinery industry

Company A produces manufacturing equipment for global markets. The starting point of this case study was diversified product variety because of the company's operations in the project business. The company undertook a rationalisation project for selected products from 2010 to 2012, focusing on modularisation as a way to increase design reuse. While prior modularisation projects had been carried out, some had not been successful. In addition, the company had never studied its entire product range from the modularisation perspective.

In case study A, the benefits of modularisation drew primarily from an increase in commonality within the product assortment. The first step in the project was to clarify the partitioning logic for the rationalised product range. The reasoning was documented during design workshops held by the participants. Defining a set of modules required redesign work; therefore, this step was costly. However, when the business impacts were estimated, the engineering work was easily justified. Interfaces with external systems were managed systematically, but separate definitions of internal interfaces were not considered necessary. From the architectural viewpoint, space reservation models were made for some product elements, but separate, explicit definitions were not available for the whole product family. Configuration rules and constraints were documented and maintained using simple matrix tools. The importance of explicit configuration rules and constraints was known to the company from previous projects.

4.2. Report from case study B: machinery industry

Company B manufactures delivery-specific products for global markets with different requirements. The company is familiar with the principles of modularisation for achieving benefits via design reuse, and a modularisation project for the company's whole product range was started in 2013. Before this, the company had developed component-level modularisation.

In case study B, the aim was to reduce operating costs via design reuse. Modular and configurable products were pursued. The company developed its operations simultaneously with product modularisation. During the writing of this article, the project was still ongoing, but positive results had already been reported in some product areas.

Partitioning logic is stored in a support system for the product development process; therefore, the criteria listed in Table 2 are well considered. The same applies to the set of modules. This case study involves no separate interface documentation; this knowledge must come from the company's more experienced engineers. From the architectural perspective, separate space reservation models have not been created because the overall architecture is very traditional, despite varying customer requirements. Separate definitions have also not yet been considered important. Configuration rules and constraints have been defined in detail using separate software.

Strategic alignment was not considered when the modularisation was started; rather, the project's module design was based on the existence of conflicts between cost-efficient manufacturing solutions and existing procurement strategies. However, during the project, more focus was placed on strategic alignment. Several delivery types were recognised for the modular system, and this created pressure to change the procurement and manufacturing strategy.

4.3. Report from case study C: mobile machinery industry

Company C operates globally, producing mobile machines for different product ranges and markets. The company has aimed to increase design reuse by adapting the principles of modularisation since the beginning of the millennium. This case study focuses on a product development project in which the company designed a modular product family based on existing designs in one of its product ranges from 2013 to 2014.

Concerning the building blocks, the partitioning logic of the studied product range was modelled using a tool called the module map, which presented the generic elements of the modular product family, their module variants and the relationships between module variants and the variability needs arising from the use cases of different customers. Therefore, to summarise the fulfilment of the criteria listed in Table 2 from the partitioning logic viewpoint, the company accepted the concept, and the results were documented. The design organisation developed a set of modules, and deliveries were made from this set. The modules were documented, IDs for different versions were defined, and ownership and change control issues were considered. Critical interfaces were documented separately, but IDs were not defined for interfaces. The architecture for the product family was defined based on developing a space reservation model for the module variants. This model also included interfaces. During the analysis period, the architecture model did not include IDs. The modelling of configuration rules and constraints focused on recognising the main customer questions and the answers guiding the selection of a particular set of modules. These main customer questions were also described in the module map describing the partitioning logic of the product family.

4.4. Report from case study D: shipbuilding industry

Company D provides systems globally for companies producing ETO-oriented products. Adaption of systems to changing interfaces is typical in business environments. Before the start of the design project for increased design reuse, the company's products had been adapted to tens of different interface; therefore, the company had offered tens of different solutions. On this basis, the company thought that achieving the advantages of design reuse would be difficult. As in case study C, until a successful redesign was realised, extensive delivery-specific engineering was needed during the product's delivery project. In 2008, the company became acquainted with the principles and benefits of modularisation and configuration. The first deliveries of the redesigned product were made during 2011 and 2012.

Concerning the building blocks, company C made many improvements to its partitioning logic. An understanding of the product structure organisation was achieved and documented, and business estimates were calculated. Later, an engineering configurator that followed the product's partitioning logic was developed and implemented, and the configuration rules and constraints were managed systematically. A set of modules was defined in the configurator, fulfilling the criteria shown in Table 2. Interfaces were not modelled separately, but the engineering configurator includes configuration rules on how to create product variety. Additionally, the architecture of the product assortment was considered via built-in rules in the product configurator to ensure that limited space reservations are not omitted.

The redesign project, which aimed to increase the possibilities for reusing designs, focused on encapsulating the elements that often change due to customer requirements and separating them from the product elements that always remained the same. As discussed, the resulting product architecture could be configured according to customer requirements by using an engineering configurator based on predefined parameters and rules, and delivery-specific engineering became unnecessary.

4.5. Report from case study E: shipbuilding industry

Company E is a subcontractor that produces systems globally for ETO products made by other companies. Company E started its modularisation project in 2009 and 2010. Shifting to this new operating paradigm took four years, according to the company, and required the help of external consultants. After four years, the company considered its own knowledge to exceed that of the consultants and decided that consultants were no longer needed. During the four years, IT systems, such as computer-aided design (CAD) software and product data management (PDM) software, were modified to support modular and configurable products. These systems were previously more focused on unique solutions.

From the partitioning logic viewpoint, this case study is not as straightforward as other cases. Technically, the product is structured into modules, but the description of the logic behind specific product partitioning schemes is very implicit. This knowledge is maintained by a small core team of engineers, whose connections to business units are not as strong as those in other case studies. The project's main focus was on defining modules and their interfaces – and, thus, on the overall architecture and subsequent creation of a product configurator with configuration rules and constraints to support design reuse and product variety.

The starting point in structuring the product family was to define generic product elements on a solution-neutral level. This enabled a defining of the final modules, which included standard, configurable, and project-specific modules.

4.6. Report from case study F: shipbuilding industry

Company F produces ETO-oriented products in low volume. One of the company's main challenges is enabling delivery of the first products for the cost of similar, so-called serial product(s) delivered afterwards. The principles of modularisation have been recognised as important for increasing the design reuse and efficiency of delivery projects and, thus, for managing the cost structure. Although most products consist primarily of project-specific product elements, the company has partly modularised its products' subsystems.

In one product subsystem, the management of knowledge (e.g. partitioning logic) focuses more on personnel than on support systems and explicit models. Therefore, when comparing the partitioning logic to the criteria in Table 2, though the key engineers understood, agreed, and owned this building block, the logic was not explicitly documented, change control aspects were not considered, and partitioning logic was not considered on a strategic level. Therefore, as a whole, we do not believe that company F considers partitioning logic in detail.

The management of interfaces is the most essential element in this case study. In the studied subsystem, principles of modularity have been adapted to support assembly based on the standardisation of interfaces. The studied subsystem included defined space reservations related to interfaces, and the interfaces were considered from the perspectives described in Table 2. Because of the assembly focus, aspects of product variety were not considered. Set of modules and, thus, the overall architecture were not pre-defined, but, rather, relied on project-specific engineering. For this reason, according to the criteria in Table 2, set of modules and architecture were not considered, and configuration rules and constraints based on customer options were not relevant in this case study.

4.7. Report from case study G: telecommunications industry

Company G designs and manufactures consumer electronics for global markets. The variety of customer segments imposes variability needs on the product family. A major challenge is to manage the logistics and delivery of millions of devices globally. Thus, the logic of partitioning the products is strongly guided by logistical requirements. As an example, wireless connectivity was defined for a separate configurable element that was physically a single component that could be configured according to customer requirements using software. The company invests in mechanical and software interface and communication protocol standardisation work, both in-house and through several standardisation bodies. It also focuses on product architecture work, not to standardise the product layout, but to ensure configurability of the key components and the partitioning logic. Configuration rules and constraints are documented, and modules of the whole product family are under strict change control.

The engineering effort was in the range of three million engineering hours and involved several suppliers. There were challenges related to clearly and succinctly sharing the configuration rules and constraints within the development network to prevent misunderstandings. Further, from time to time, the design teams had to react to firefighting in other projects. The key component also had many internal customers with a variety of conflicting requirements. Executing engineering and maintaining schedules in such a setup posed major challenges.

5. Results

This section summarises the case studies presented in the previous section and analyses them from the perspective of creating modular systems and managing business processes, as described in Section 3. The case studies reveal that the different companies approached and executed the engineering design of modular systems differently, as presented in Table 4. In the following subsections, the results are described separately in terms of the building blocks, the challenges, and the support needs of modular systems.

5.1. The building blocks of modular systems

All the case studies focused on partitioning logic, despite taking different approaches and giving this concept different weights. In companies E, F, and G, the role of understanding the partitioning logic was perceived as less important than it was in the other companies. Company E had a small core team of engineers. This allowed the company to build on tacit knowledge, rather than making the knowledge explicit and available. In company F, though the knowledge was not documented, the partitioning logic was perceived as self-evident and self-explanatory; thus, only minor effort was used to capture and share this knowledge. In companies A, B, C, and D, the motivation for capturing the partitioning logic arose from the lifecycle management of the modular systems and the desire to manage these lifecycles with less maintenance effort and fewer human errors. These case studies showed the effort devoted to describing the logic and reasoning of product partitioning. The approaches varied from reasoning models to unstructured documents with textual descriptions. Hence, more systematic methods for capturing design reasoning could be beneficial. This is also an interesting topic for future research.

Although interfaces are typically considered important in modularisation, the case studies revealed that the companies devoted more focus and effort towards module and

Table 4. Summary of case study results concerning the building blocks of modular systems (considered: +; partly considered or not considered in detail +/−; not considered: −).

Building blocks of modular systems	A	B	C	D	E	F	G
Partitioning logic	+	+	+	+	+/−	+/−	+
Set of modules	+	+	+	+	+/−	−	+
Interfaces	+/−	+/−	+/−	+/−	+/−	+	+
Architecture	+	+	+/−	+	+/−	−	+
Configuration rules and constraints	+	+	+	+	+	−	+

architecture descriptions than towards interface descriptions. The modules were largely predefined in companies A, C, D, and G. Company B discussed an approach in which all the modules were not predefined; instead, using its knowledge of modular systems, modules lacking detailed engineering were developed through a DTO approach, rather than a CTO approach, during the order-delivery process. DTO modules require engineering, but follow predefined restrictions and principles of product structuring. While these kinds of DTO modules lean more towards possibilities of effective product variety management, they are not as beneficial as CTO modules, which are based on complete pre-existing designs. This was a feasible approach for company B, however, as the company delivers projects rather than products, and the lead time for delivery allowed this approach.

Six of the seven companies focused on the creation and capture of configuration rules and constraints so that they could provide necessary information to sales personnel. The knowledge was documented and stored in information systems in a very detailed way, and there were defined processes to manage reusable design elements.

5.2. Challenges and need for support in the engineering design of modular systems

The researchers observed the challenges in the engineering design of modular systems in the case studies presented in Section 4 and discussed these with the relevant companies. Then, the challenges were categorised using the BPMM framework shown in Table 2. Table 5 summarises the identified challenges. An additional category – namely, project – was added later, as many challenges were related to the modularisation project itself, rather than to the process, IT, or governance categories. These challenges are discussed in the following subsections.

5.2.1. People

The identified challenges relating to people dealt mainly with knowledge representation and competence development. A major challenge seems to relate to how individuals

Table 5. Challenges identified in the engineering design of modular systems.

Category	The challenge: How can we . . .
People	Capture and represent the partitioning logic of modular systems? Obtain competence in the engineering design of modular systems?
Process	Identify and use appropriate tools and methods in each phase of the modularisation process? Evaluate the value creation potential or business impacts of a modular system concept? Define acceptance criteria for reusable elements? Evaluate customer satisfaction?
IT	Build an IT system to manage the lifecycle of the modular system? Ensure that information regarding modular systems is valid, up to date, and available?
Governance	Organise the engineering design of modular systems? Organise the management and maintenance of modular systems?
Culture	Manage conflicting cultures between project deliveries and the engineering design of modular systems? Ensure that engineers are dedicated to and allocated only to the modularisation project?
Strategic alignment	Create reliable financial calculations for decision-making? Obtain approval and financing for the engineering design of modular systems? Ensure that organisational priorities are aligned with the engineering design of modular systems?
Project	Scope the CTO section of the product versus the ETO section? Scope the development project or product family? Evaluate the maturity of the modular system?

construct their reasoning in terms of technical systems and how the learning takes place. This is partly due to the lack of ontologies and representational tools in the manufacturing industry and partly due to engineering and cognitive factors. As long as the constructs are personal, the reasoning and logic will differ. This inhibits the creation of a common, shared, and consistent repository of engineering knowledge of the modular systems. This was the case in many companies: A few people possessed the reasoning and rationale of the modular systems as tacit knowledge. Traditionally, an engineer had no incentive to share the reasoning behind a design because reuse of the knowledge was not critical. Now, this knowledge should be made tangible and available to many other people. Companies must support this effort to capture and represent knowledge and to create a common and shared understanding of the design rationale of modular systems. Such tools exist for configuration rules and constraints, but the partitioning logic domain is still a novel area. This also relates directly to the competence requirements of modularisation: Engineers need to create competitive syntheses and be able to share the reasonings for these syntheses.

5.2.2. Process

A well-defined process for engineering design of modular systems would help enable the sharing of the reasoning for the partitioning logic; however, other challenges remain. Operating with the knowledge related to modular systems requires processes other than designing new module variants for the product family. The overall process of engineering design for modular systems must be managed if companies wish to renew their offerings at some point (i.e. when the existing modular systems can no longer be used as a baseline). However, this kind of radical innovation is not as common in industry as incremental innovation or development (Pugh and Clausing 1996; Oja 2010).

The literature presents many methods and tools for use in designing product variety, but there is a lack of support for the selection of such tools or the determination of situations in which to use them. For example, Okudan Kremer and Gupta (2013) showed that using different methods resulted in different product structures. Several product-structuring approaches were suggested, but studies focusing on how to evaluate the fit of product structures to the business environment are also needed. Several publications, such as those by Danese and Filippini (2013) and Jacobs et al. (2011), discuss the benefits of doing this, but methods of doing so are presented less frequently. The case studies reveal that the companies had limited possibilities to explicitly define how the business environment accepted the designing of reusable elements. Thus, this should be considered in greater detail. More support is also needed to evaluate customer satisfaction with modular systems.

5.2.3. IT

None of the companies we studied was at a level at which every modular system building block had separate IDs related to different types of design information. Typically, only modules had IDs, and other building blocks were not managed on the same level; thus, these other building blocks could not be discussed as items in a PDM context. In the case studies presented in this paper, enablers of reuse were relatively well considered; however, some companies also scattered design information across different IT systems, or implicitly stored it in the heads of engineers. In these companies, there is significant potential for improvement. Therefore, there is a need for support systems that can synthesise the scattered modularisation design information and make the design rationale explicit and available to whomever needs it.

5.2.4. *Governance*

In many of the case studies, the engineering design of modular systems was carried out as a project. The project challenges are discussed later; the governance challenges relate to how the modular system is managed and maintained. In companies undertaking projects, there were mental barriers against setting up a separate group (in some companies, with only two or three people) to focus on the management and maintenance of modular systems. These organisations perceived the drawbacks of extra costs with little value.

5.2.5. *Culture*

All the studied companies faced a constant tension between the engineering design of modular systems and other projects, whether they were customer projects or NPD projects. Design reuse as an operational mode was largely resisted and neglected by the existing organisational culture. Cultural change can be difficult for companies that are not accustomed to the principles of design reuse. One could argue that it is irrational to follow an engineer-to-stock approach (similar to the production approach of make-to-stock) because it implies unnecessary hurry. Why should something that does not have a customer order or delivery date be engineered? Keeping to the schedule and budget is important for companies. Thus, if the possibility of reusing engineering design knowledge is considered in addition to other engineering aspects required to produce a solution, a failure to devote more time and resources to engineering may create more challenges. Developing modular systems in delivery projects is a different task than developing them in separate projects dedicated to that purpose. The companies ensured that the selected engineers could focus on the modularisation project by taking the issue to top management and using arguments based on the company strategy (e.g. arguments showing how modular systems would support the company strategy).

5.2.6. *Strategic alignment*

Of the categories shown in Table 2, strategic alignment is the most straightforward. None of the company strategies directly considered the building blocks of modular systems; thus, these were not discussed further in the case studies. There was, however, one exception: case study B. This study considered important strategic aspects that were noted during the design project.

Every company must clarify whether the reuse of certain product elements is beneficial to it and define the scope of its modularisation project. This leads to the need to consider how completely each reusable element is defined during the modular system design project. It might not be reasonable to design everything to be complete, and more generic reusable design guidelines and principles might be sufficient.

Based on our case studies, the engineering design of modular systems requiring large investments was still challenging and laborious, and traditional design processes were of little use. Designing modular systems requires investments in product development because the design task of developing reusable product elements, such as interfaces that are compatible with different module variants, is more complex than developing one-off elements. Additionally, investments are needed to develop other operations to support modularisation. New supporting systems, for instance, are especially relevant from the knowledge retrieval perspective. Some companies revisited the sales process in addition to the purchasing and manufacturing strategies. All the companies exhibited a severe underestimation or neglect of the need for change management (this also relates to the category of culture, as discussed in Section 3) and leadership efforts.

5.2.7. Project

The most typical challenges in modularisation projects involved the project scope and goals. The scope issue deals with questions concerning, for example, which sections of the product offering should be developed as CTO. Especially in project companies, it was evident that the product would never be more than partially configurable. The literature provides very little support for applying this type of analysis to partially configurable products. In some companies where the ETO scope (sections of the modular system and product family requiring delivery-specific engineering) was altered, the changes necessitated a reinvention of the concept of modular systems. This created a certain unpredictability in managing the project in terms of resources and scheduling.

Another challenge was related to the project goals and which parts of the modular system were to be fully predesigned. Despite defining a modular and configurable product family, it might not be reasonable to develop all the varieties of the product family before they are ordered. In these cases, having defined, clear, reusable guidelines and a process for designing module variants during a product sales-delivery process becomes much more efficient than pure ETO operation. This means that partitioning logic, architecture, interfaces, and configuration rules and constraints are fixed, but specific modules still require detailed design. In other words, engineering related to incomplete varieties of the product family can be carried out during product delivery projects, but this does not mean that engineers are given a free hand. The design process should guide engineers via limitations and restrictions and should offer beneficial product structuring principles. The design process should ensure that the module variant to be designed adheres to predefined interfaces with the rest of the existing product family to support possibilities for reusing these new module variants later on. The modules needed for a particular configuration (within the scope of the modular system) were designed by deriving the details from the information contained in the modular system. If the needed configuration fell outside the scope of the modular system, it was either modified to order or ETO. In these cases, the modules occasionally did not comply with partitioning logic or predefined interfaces; thus, there was an increased need for engineering change management.

5.2.8. Summary

Companies must invest in the engineering design of modular systems, including implementing management processes and training personnel to understand the purpose of modular systems, if they are to ensure that the designed modular systems yield benefits and do not deteriorate over time. We identify three managerial implications required by the engineering design of modular systems: managing the effects of modularisation on business, managing the definitions of product variety and scope, and managing the support required for reusing and retrieving existing knowledge related to modular systems. There is a clear need for support regarding the governance, culture, and strategic issues relating to the engineering design of modular systems as an operational mode.

6. Discussion

The discussion is broken into two sections. The first part focuses on the research findings, and the second part focuses on the research process.

6.1. Research findings

The quantitative and qualitative benefits of our case studies have been outlined in this paper and will be part of future studies. Designing modular systems requires investment and competent engineers. The engineers in the studied companies perceived the modularisation process as much more challenging and laborious than the typical product development process. We did not investigate this topic in great detail, but we believe that a reason for this perception is that the engineers were not used to considering product reusability and product varieties in their design tasks. Drejer and Gudmundsson (2003) compared the differences between traditional and multiple product development based on platform and product architecture supporting design reuse. They stated that the product development process for multiple products can be described as interactive and dialectic, whereas the product development process for single products is more linear and consensus-based. They also discussed the organisational perspective and stated that multiple product development is dispersed across an organisation's network, whereas single product development mostly takes place within one organisation. One obvious downside emerging from our case studies was that the most experienced engineers were allocated to the modularisation projects and were not available for other important and urgent engineering tasks. The companies approached the engineering design of modular systems as a long-term investment to support long-term business profitability.

We found that companies face a range of challenges concerning modularisation. The challenges were categorised, and support and methods for addressing each category of challenge were mapped. Most of the literature has focused on the product structure, tools and processes supporting engineering tasks. Only a few studies, such as that by Bruun, Mortensen, and Harlou (2013), focus on the IT systems supporting the engineering design of modular systems; however, this is more common in the field of product configuration. To date, based on our experiences in the manufacturing industry, we are aware of only a few commercial IT systems designed for this purpose in the modularisation context.

An analysis of the other categories, challenges, and research in design science reveals that, with a modular system, there is a clear need for more cross-disciplinary research within the domains of project management, governance, human elements, organisational culture, and strategy. Such research will open new, value-adding tracks to existing research, thus supporting the manufacturing industry and product variety management.

6.2. Novelty, relevance, and validity of the research

The novelty of this research lies in its assessment of case studies based on the building blocks of modular systems. The assessment builds on BPMM, and it enables an evaluation of types of engineering knowledge and the manageability of this knowledge in company settings. This assessment provides new information about why certain building blocks of modular systems are emphasised or neglected. The case studies also reveal challenges with the engineering design of modular systems, such that our study offers a review of a collection of practices from different companies.

The results presented here are relevant for design science, as holistic descriptions of how to design modular systems, what kinds of processes are needed, and how typical pitfalls can be avoided are lacking. Based on the results, we can see similarities between NPD projects and modularisation projects, but we also highlight the differences between these projects. It is relevant for design science to address in more detail the challenges in designing modular systems, rather than relying on a generalised understanding of NPD project management.

The research was carried out using mixed methods, combining action research and case study research. To increase the validity of the results, the case studies were selected to represent both project businesses and consumer goods, different business areas and different time frames. The results were derived from the data and aligned through comparison to other research in the field. In terms of future research, the assessment method will be developed further, and it is possible that some aspects of the engineering design of modular systems remain unidentified. The categorisation of challenges by BPMM did not originally offer space, for instance, for project-related challenges, and we had to add the project category after analysing the case studies. This was natural, as the BPMM focuses on processes, rather than projects. Our plan is to study project management frameworks suitable for this purpose.

7. Conclusions

This paper studied the process of designing modular systems from the perspectives of engineering design and process management in the manufacturing industry and research in design science. We found that companies face a range of challenges when designing modular systems to enable product variety that benefits from design reuse. Although the engineering design of modular systems is discussed and used in the industry, most of the benefits lie in operations related to retrieving and reusing captured knowledge; thus, it is relevant to further study the industry's challenges and best practices in this area using a more cross-disciplinary approach. To experience the full benefits of modular systems, companies must use operating processes that support them.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Ahmed, Saeema. 2005. "Encouraging Reuse of Design Knowledge: A Method to Index Knowledge." *Design Studies* 26: 565–592. doi:10.1016/j.destud.2005.02.005.

Andreasen, Mogens Myrup. 2011. "45 Years with Design Methodology." *Journal of Engineering Design* 22 (5): 293–332. doi:10.1080/09544828.2010.538040.

Aurisicchio, Marco, Rob Bracewell, and Ken Wallace. 2010. "Understanding How the Information Requests of Aerospace Engineering Designers Influence Information- Seeking Behaviour." *Journal of Engineering Design* 21 (6): 707–730. doi:10.1080/09544820902877583.

Baskerville, Richard L., and A. Trevor Wood-Harper. 1996. “A Critical Perspective on Action Research as a Method for Information Systems Research.” *Journal of Information Technology* 11 (3). Cham: Springer International Publishing: 235–246. doi:10.1080/026839696345289.

Baxter, David, James Gao, Keith Case, Jenny Harding, Bob Young, Sean Cochrane, and Shilpa Dani. 2007. “An Engineering Design Knowledge Reuse Methodology Using Process Modelling.” *Research in Engineering Design* 18 (1): 37–48. doi:10.1007/s00163-007-0028-8.

Berman, Barry. 2002. “Should Your Firm Adopt a Mass Customization Strategy?” *Business Horizons* 45 (4): 51–60. doi:10.1016/S0007-6813(02)00227-6.

Bracewell, R., M. Gourtovaia, M. Moss, D. Knott, K. Wallace, and P. J. Clarkson. 2009a. “DRED 2.0: A Method and Tool for Capture and Communication of Design Knowledge Deliberated in the Creation of Technical Products.” In DS 58-6: Proceedings of ICED 09, the 17th International Conference on engineering design, 6:223–234.

Bracewell, R. H., and K. M. Wallace. 2003. “A Tool for Capturing Design Rationale.” In *DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design*. Vol. 10., edited by A. Folkeson, K. Gralen, M. Norell, and U. Sellgren. Stockholm: The Design Society. https://www.designsociety.org/publication/24055/A+TOOL+FOR+CAPTURING+DESIGN+RATIONALE.

Bracewell, Rob, Ken Wallace, Michael Moss, and David Knott. 2009. “Capturing Design Rationale.” *CAD Computer Aided Design* 41 (3). Elsevier Ltd: 173–186. doi:10.1016/j.cad.2008.10.005.

Briere-Cote, Antoine, Louis Rivest, and Alain Desrochers. 2010. “Adaptive Generic Product Structure Modelling for Design Reuse in Engineer-to-Order Products.” *Computers in Industry* 61 (1): 53–65. doi:10.1016/j.compind.2009.07.005.

Bruun, Hans Peter Lomholt, Niels Henrik Mortensen, and Ulf Harlou. 2013. “PLM Support for Development of Modular Product Families.” In Proceedings of International Conference on Engineering Design, ICED13, Seoul, Korea, Sungkyunkwan University, Aug 19-22, 2013.

Busby, Jeremy S. 1999. “The Problem with Design Reuse: An Investigation into Outcomes and Antecedents.” *Journal of Engineering Design* 10 (3): 277–296. doi:10.1080/095448299261335.

Chandrasekaran, Bruce, John R. Josephson, and V. Richard Benjamins. 1999. “What Are Ontologies, and Why Do We Need Them?” *IEEE Intelligent Systems* 14 (1): 20–26. doi:10.1109/5254.747902.

Conklin, Jeff, Albert Selvin, Simon Buckingham Shum, and Maarten Sierhuis. 2001. “Facilitated Hypertext for Collective Sensemaking: 15 Years on from GIBIS.” *In Proceedings of the ACM Conference on Hypertext*, 123–124. doi:10.1145/504216.504246.

Costa, Carlos Alberto, Marcos Alexandre Luciano, Celson Pantoja Lima, and Robert I. M. Young. 2012. “Assessment of a Product Range Model Concept to Support Design Reuse Using Rule Based Systems and Case Based Reasoning.” *Advanced Engineering Informatics* 26 (2). Elsevier Ltd: 292–305. doi:10.1016/j.aei.2011.11.001.

Dahmus, Jeffrey B., Javier P. Gonzalez-Zugasti, and Kevin N Otto. 2001. “Modular Product Architecture.” *Design Studies* 22 (5): 409–424. doi:10.1016/S0142-694X(01)00004-7.

Danese, Pamela, and Roberto Filippini. 2013. “Direct and Mediated Effects of Product Modularity on Development Time and Product Performance.” *IEEE Transactions on Engineering Management* 60 (2): 260–271. doi:10.1109/TEM.2012.2208268.

Drejer, Anders, and Agnar Gudmundsson. 2003. “Exploring the Concept of Multiple Product Development via an Action Research Project.” *Integrated Manufacturing Systems* 14 (3): 208–220. doi:10.1108/09576060310463163.

Duffy, Alex H. B., and A. F. Ferns. 1998. “An Analysis of Design Reuse Benefits.” In Proceedings of the 12th International Conference on Engineering Design (ICED ‘99), 799–804.

ElMaraghy, Hoda, Günther Schuh, W. H. Elmaraghy, Frank T. Piller, Paul Schönsleben, Mitchell Tseng, and Alain Bernard. 2013. “Product Variety Management.” *CIRP Annals - Manufacturing Technology* 62 (2). CIRP: 629–652. doi:10.1016/j.cirp.2013.05.007.

Engel, Avner, and Yoram Reich. 2015. “Advancing Architecture Options Theory: Six Industrial Case Studies.” *Systems Engineering* 18 (4): 396–414. doi:10.1002/sys.21312.

Ettlie, John E., and Matthew Kubarek. 2008. “Design Reuse in Manufacturing and Services.” *Journal of Product Innovation Management* 25 (5): 457–472. doi:10.1111/j.1540-5885.2008.00314.x.

Fellini, Ryan, Michael Kokkolaras, Panos Y. Papalambros, and Alexis Perez-Duarte. 2002. “Platform Selection Under Performance Loss Constraints in Optimal Design of Product Families.” In Volume 2: 28th design automation Conference 2002:613. ASME. doi:10.1115/DETC2002/DAC-34099.

Fixson, Sebastian K. 2006. “A Roadmap for Product Architecture Costing.” In *Product Platform and Product Family Design*, edited by R. J. Simpson, T. W. Siddique & Z. Jiao, 305–334. New York: Springer Science+Business Media, LLC. doi:10.1007/0-387-29197-0_13.

Forza, Cipriano, and Fabrizio Salvador. 2002. “Managing for Variety in the Order Acquisition and Fulfilment Process: The Contribution of Product Configuration Systems.” *International Journal of Production Economics* 76 (1): 87–98. doi:10.1016/S0925-5273(01)00157-8.

Fujimoto, Takahiro. 2007. *Competing to Be Really, Really Good – The Behind-the-Scenes Drama of Capability Building Competition in the Automobile Industry*. Tokyo: International House of Japan.

Gedell, Stellan, and Hans Johannesson. 2013. “Design Rationale and System Description Aspects in Product Platform Design: Focusing Reuse in the Design Lifecycle Phase.” *Concurrent Engineering Research and Applications* 21 (1): 39–53. doi:10.1177/1063293X12469216.

Gershenson, J. K., G. J. Prasad, and Y. Zhang. 2003. “Product Modularity: Definitions and Benefits.” *Journal of Engineering Design* 14 (3). Taylor & Francis Group: 295–313. doi:10.1080/0954482031000091068.

Gonzalez-Zugasti, Javier P., Kevin N. Otto, and John D. Baker. 2000. “A Method for Architecting Product Platforms.” *Research in Engineering Design* 12 (2): 61–72. doi:10.1007/s001630050024.

Halman, Johannes I.M., Adrian P. Hofer, and Wim van Vuuren. 2003. “Platform-Driven Development of Product Families: Linking Theory with Practice.” *Journal of Product Innovation Management* 20 (2): 149–162. doi:10.1111/1540-5885.2002007.

Hansen, Claus Thorp, and Mogens Myrup Andreasen. 2004. “A Mapping of Design Desicion-Making.” In DS 32: Proceedings of DESIGN 2004, the 8th International design Conference, 3:1409–1418, Dubrovnik, Croatia.

Hansen, Poul H. Kyvsgård, and Hongyi Sun. 2010. “A Comprehensive View on Benefits From Product Modularization.” In *Proceedings of DESIGN 2010, the 11th International Design Conference*, edited by D. Marjanovic, M. Storga, N. Pavkovic, and N Bojcetic, 233–245. Dubrovnik: The Design Society. https://www.designsociety.org/publication/29369/A+COMPREHENSIVE+VIEW+ON+BENEFITS+FROM+PRODUCT+MODULARIZATION.

Harlou, Ulf. 2006. *Developing Product Families Based on Architectures - Contribution to a Theory of Product Families*. Lyngby: Technical University of Denmark.

Harmon, Paul. 2010. “The Scope and Evolution of Business Process Management.” In *Handbook on Business Process Management 1*, 37–81. Berlin: Springer Berlin Heidelberg. doi:10.1007/978-3-642-00416-2_3.

Haug, Anders, Lars Hvam, and Niels Henrik Mortensen. 2012. “Definition and Evaluation of Product Configurator Development Strategies.” *Computers in Industry* 63 (5): 471–481. doi:0.1016/j.compind.2012.02.001.

Heiskala, Mikko, Juha Tiihonen, Kaija-Stiina Paloheimo, and Timo Soininen. 2009. “Mass Customization with Configurable Products and Configurators: A Review of Benefits and Challenges.” In *Mass Customization Information Systems in Business*, edited by Thorsten Blecker and Gerhard Friedrich, 1–32. London: IGI Global.

Holmqvist, Tobias. 2004. *Managing Product Variety Through Product Architecture*. Gothenburg: Chalmers University of Technology.

Jacobs, Mark, Cornelia Droge, Shawnee K. Vickery, and Roger Calantone. 2011. “Product and Process Modularity’s Effects on Manufacturing Agility and Firm Growth Performance.” *Journal of Product Innovation Management* 28 (1): 123–137. doi:10.1111/j.1540-5885.2010.00785.x.

Jacobs, Mark, Shawnee K. Vickery, and Cornelia Droge. 2007. “The Effects of Product Modularity on Competitive Performance.” *International Journal of Operations & Production Management* 27 (10). Emerald Group Publishing Limited: 1046–1068. doi:10.1108/01443570710820620.

Jiao, Jianxin, Timothy W. Simpson, and Zahed Siddique. 2007. “Product Family Design and Platform-Based Product Development: A State-of-the-Art Review.” *Journal of Intelligent Manufacturing* 18: 5–29. doi:10.1007/s10845-007-0003-2.

Kleinsmann, Maaike, Jan Buijs, and Rianne Valkenburg. 2005. “Managing Shared Understanding in Collaborative Design Projects.” In *DS 35: Proceedings ICED 05, the 15th International Conference on Engineering Design*, edited by A. Samuel, and W. Lewis, 14. Melbourne: The Design Society. https://www.designsociety.org/publication/23029/MANAGING+SHARED+UNDERSTANDING+IN+COLLABORATIVE+DESIGN+PROJECTS.

Kong, F. B., X. G. Ming, L. Wang, X. H. Wang, and P. P. Wang. 2009. “On Modular Products Development.” *Concurrent Engineering* 17 (4): 291–300. doi:10.1177/1063293X09353974.

Krishnan, Viswanathan, and Saurabh Gupta. 2001. “Appropriateness and Impact of Platform-Based Product Development.” *Management Science* 47 (1): 52–68. doi:10.1287/mnsc.47.1.52.10665.

Kristjansson, Arnar H., T. Jensen, and Hans Petter Hildre. 2004. “The Term Platform in the Context of a Product Developing Company.” In *Proceedings of DESIGN 2004, the 8th International Design Conference*, edited by D. Marjanovic, 325–330. Dubrovnik: The Design Society.

Kunz, Werner, and Horst W J Rittel. 1970. *Issues as Elements of Information Systems*.

Leake, David B., and David C. Wilson. 2001. “A Case-Based Framework for Interactive Capture and Reuse of Design Knowledge.” *Applied Intelligence* 14 (1): 77–94. doi:10.1023/A:1008307108914.

Lehtonen, Timo, Nillo Halonen, Jarkko Pakkanen, Tero Juuti, and Petri Huhtala. 2015. “Challenges and Opportunities in Capturing Design Knowledge.” In Proceedings of 10th World Congress on engineering Asset management – WCEAM 2015, 1–8.

Maier, Jonathan R.A., Georges M. Fadel, and Dina G. Battisto. 2009. “An Affordance-Based Approach to Architectural Theory, Design, and Practice.” *Design Studies* 30 (4). Elsevier Ltd: 393–414. doi:10.1016/j.destud.2009.01.002.

Martin, Mark V., and Kosuke Ishii. 1997. “Design for Variety: Development of Complexity Indices and Design Charts.” In Proceedings of 1997 ASME design engineering technical Conferences, 9. Springer-Verlag.

Meehan, Joanne S., Alex H. B. Duffy, and Robert Ian Whitfield. 2007. “Supporting ‘Design for Re-Use’ with Modular Design.” *Concurrent Engineering* 15 (2): 141–155. doi:10.1177/1063293X07079319.

Meyer, Marc H., and Alvin P. Lehnerd. 1997. *The Power of Product Platforms: Building Value and Cost Leadershop*. New York: The Free Press.

Moon, Seung Ki, Timothy W. Simpson, and Soundar R T Kumara. 2010. “A Methodology for Knowledge Discovery to Support Product Family Design.” *Annals of Operations Research* 174 (1): 201–218. doi:10.1007/s10479-008-0349-7.

Oja, Hannu. 2010. *Incremental Innovation Method for Technical Concept Development with Multi-Disciplinary Products*. Tampere: Tampere University of Technology.

Okudan Kremer, Gül E., and Saraj Gupta. 2013. “Analysis of Modularity Implementation Methods from an Assembly and Variety Viewpoints.” *The International Journal of Advanced Manufacturing Technology* 66 (9–12): 1959–1976. doi:10.1007/s00170-012-4473-9.

Olesen, Jesper. 1992. *Concurrent Development in Manufacturing - Based on Dispositional Mechanisms*. Copenhagen: Institute for Engineering Design, The Technical University of Denmark.

Ong, S. K., Q. L. Xu, and A. Y. C. Nee. 2006. “Design Reuse Methodology for Product Family Design.” *CIRP Annals - Manufacturing Technology* 55 (1): 161–164. doi:10.1016/S0007-8506(07)60389-8.

Pakkanen, Jarkko. 2015. *Brownfield Process: A Method for the Rationalisation of Existing Product Variety Towards a Modular Product Family*. Tampere: Tampere University of Technology.

Pakkanen, Jarkko, Petri Huhtala, Tero Juuti, and Timo Lehtonen. 2016. “Achieving Benefits with Design Reuse in Manufacturing Industry.” *Procedia CIRP* 50: 8–13. doi:10.1016/j.procir.2016.04.173.

Pakkanen, Jarkko, Tero Juuti, and Timo Lehtonen. 2016. “Brownfield Process: A Method for Modular Product Family Development Aiming for Product Configuration.” *Design Studies* 45. Elsevier Ltd: 210–241. doi:10.1016/j.destud.2016.04.004.

Parslov, Jakob Filippson, and Niels Henrik Mortensen. 2015. “Interface Definitions in Literature: A Reality Check.” *Concurrent Engineering* 23 (3): 183–198. doi:10.1177/1063293X15580136.

Perera, H.S.C, Nagen Nagarur, and Mario T Tabucanon. 1999. “Component Part Standardization: A Way to Reduce the Life-Cycle Costs of Products.” *International Journal of Production Economics* 60–61 (April): 109–116. doi:10.1016/S0925-5273(98)00179-0.

Pine, B. Joseph. 1993. *Mass Customization: The New Frontier in Business Competition*. Boston, MA: Harvard Business School Press.

Pugh, Stuart, and Don Clausing. 1996. *Creating Innovative Products Using Total Design: The Living Legacy of Stuart Pugh*. Boston: Addison-Wesley Longman Publishing Co., Inc.

Pulkkinen, Antti. 2007. *Product Configuration in Projecting Company: The Meeting of Configurable Product Families and Sales-Delivery Process*. Tampere: Tampere University of Technology.

Ramani, Karthik, Devarajan Ramanujan, William Z. Bernstein, Fu Zhao, John Sutherland, Carol Handwerker, Jun-Ki Choi, Harrison Kim, and Deborah Thurston. 2010. "Integrated Sustainable Life Cycle Design: A Review." *Journal of Mechanical Design, Transactions of the ASME* 132 (9): 0910041–09100415. doi:10.1115/1.4002308.

Röglinger, Maximilian, Jens Pöppelbuß, and Jörg Becker. 2012. "Maturity Models in Business Process Management." *Business Process Management Journal* 18 (2): 328–346. doi:10.1108/14637151211225225.

Rosemann, Michael, and Jan vom Brocke. 2010. "The Six Core Elements of Business Process Management." In *Handbook on Business Process Management 1*, 107–122. Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-00416-2_5.

Sanderson, Susan Walsh, and Mustafa V. Uzumeri. 1995. "Managing Product Families: The Case of the Sony Walkman." *Research Policy* 24 (5): 761–782. doi:10.1016/0048-7333(94)00797-B.

Sawhney, Mohanbir S. 1998. "Leveraged High-Variety Strategies: From Portfolio Thinking to Platform Thinking." *Journal of the Academy of Marketing Science* 26 (1): 54–61. doi:10.1177/0092070398261006.

Schönsleben, Paul. 2012. "Methods and Tools That Support a Fast and Efficient Design-to-Order Process for Parameterized Product Families." *CIRP Annals - Manufacturing Technology* 61 (1): 179–182. doi:10.1016/j.cirp.2012.03.071.

Siddique, Zahed, and Bill Repphun. 2001. "Estimating Cost Savings When Implementing a Product Platform Approach." *Concurrent Engineering: Research and Applications* 9 (4): 285–294. doi:10.1177/1063293X0100900405.

Sivaloganathan, Sangarappillai, and T. M. M. Shahin. 1999. "Design Reuse: An Overview." *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 213 (7): 641–654. doi:10.1243/0954405991517092.

Tarhan, Ayca, Oktay Turetken, and Hajo A. Reijers. 2016. "Business Process Maturity Models: A Systematic Literature Review." *Information and Software Technology* 75: 122–134. doi:10.1016/j.infsof.2016.01.010.

Tiihonen, Juha, Timo Lehtonen, Timo Soininen, Antti Pulkkinen, Reijo Sulonen, and Asko Riitahuhta. 1999. "Modelling Configurable Product Families." In Proceedings of the 12th International Conference on engineering design, ICED99, Vol *2*. Munich, Germany.

Ulrich, Karl T., and Steven D. Eppinger. 2008. *Product Design and Development*. New York: McGraw-Hill.

Victor, Bart, and Andrew C. Boynton. 1998. Invented Here: Maximizing Your Organization's Internal Growth and Profitability.

Wacker, John G., and Mark Treleven. 1986. "Component Part Standardization: An Analysis of Commonality Sources and Indices." *Journal of Operations Management* 6 (2): 219–244. doi:10.1016/0272-6963(86)90026-4.

Wallace, Ken. 2006. "How Engineering Designers Retrieve Information." In Design methods for practice - 5th International Seminar and workshop of engineering design integrated product development, 171–177, Zielona Gora, Poland.

Yin, Robert K. 2009. *Case Study Research: Design and Methods*. *Applied Social Research Methods*. Vol. 5. Thousand Oaks, CA: Sage Publications.