Value Creation Mechanisms of Modularisation in the Engineering Asset Life Cycle

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Abstract: Many companies offering physical assets have to adapt to different market requirements to maintain profitability. Product modularisation is a common solution for this challenge used by suppliers (manufacturers) of engineering assets. Modularisation enables greater product variety and increases commonality between product variants. Modularisation includes defining a set of modules, interfaces, modular architecture and configuration rules and constraints based on case specific partitioning logic. This paper reviews the main value creation mechanisms (VCMs) of product modularisation in the manufacturing industry, and studies what kind of VCMs are related to the main life cycle stages of engineering assets and how companies in case studies have incorporated VCMs. Key VCMs were identified based on the engineering asset life cycle, but other VCMs were considered to be important from a supplier's perspective. Suppliers should consider the whole life cycle when designing engineering assets and clarify which VCMs are the most important guiding principles for their product and make trade-offs when required.

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1 Introduction

Engineering assets, such as equipment and buildings, are managed by engineering asset managers, and are needed to create financial assets, capability value and financial value (Amadi-Echendu et al., 2010). An engineering asset life cycle typically consists of commissioning, operations, maintenance, decommissioning and replacement (Haider, 2007). From the supplier's perspective, engineering assets are considered to be physical equipment, in which case the stages of the asset life cycle become part of the product life cycle. This paper focuses on the supplier's perspective by including additional stages of the product life cycle in the asset life cycle. These other stages common in the manufacturing industry include product development, marketing and sales, production and transportation.

Product modularisation (referred to simply as modularisation) is a common product development approach that enables suppliers to effectively offer product variety. Clarifying the partitioning logic of the module system and defining modular architecture, including the set of modules, interfaces, and configuration rules and constraints, are the key aspects of modularisation (Pakkanen et al., 2016). Modular architecture and defined interfaces support the interchangeability and independence of modules that are the building blocks of product variety. Modularisation is typically aimed at reducing the complexity in the supplier's operations and harvesting positive benefits in certain areas of the business (Andreasen, 2011). Consequently, it is important to clarify the areas and asset life cycle stages where the benefits could be realised.

This paper presents the types of value creation mechanisms (VCMs) that influence modularisation and how VCMs relate to the main life cycle stages of engineering assets. VCMs are helpful for describing aspects of the life cycle that modularisation can affect. As a baseline for studying and linking VCMs, we specifically considered the asset life cycle from the supplier's perspective. The purpose of this kind of comprehensive review of the asset life cycle was to study what motivated suppliers to realise specific asset structures. Throughout the literature review, we focused on the following research questions (RQ):

- RQ1: What are the main VCMs of modularisation in the manufacturing industry?
- RQ2: How did case study companies treat VCMs related to essential life cycle stages of engineering assets in the target setting of a modularisation project?

Section 2 of the paper presents the literature review mainly focusing on Scopus and Google Scholar, which adequately covered many potential sources in this area of research. We used a number of different combinations of search terms and focused on journal articles, books, book chapters and conference papers related to modularisation. Out of hundreds of search results, the titles of papers and abstracts with the highest number of citations were used to narrow down the relevant publications to be studied in greater detail. Nonetheless, there is a risk that valid references were missed during the review because of the page limitation of this paper. Section 3 of the paper presents case studies revealing how companies viewed VCM's in modularisation. Along with further discussion, answers to the RQs are summarised in Section 4.

2 Value creation mechanisms of modularisation

This section presents relevant VCMs of modularisation determined from the literature review. First, generic life cycle stages of the manufacturing industry are discussed, followed by the reasoning for defining the VCMs related to the modularisation of each life cycle stage. At the end of each life cycle subsection is a bulleted summary of the main VCMs related to each stage.

Incremental redesigning or new product development are needed when existing product variety contradicts business goals or the cost of offering product variety is unsustainable. Companies can implement redesigning by developing new products, product families or features, or by updating or correcting designs, changing commercial components or updating technologies. Product development is typically followed by marketing and sales, which relies on technical support and knowledge related to product variety. Production often includes procurement of components and materials, subcontracting, manufacturing, testing of parts and modules, assembly and final testing. Transportation is also an important aspect when considering modularisation because reaching the customer in a profitable way may require different logistics. Products might require commissioning in the operating site before being used. Operations are followed by maintenance, decommissioning and replacement. These are the seven stages of the manufacturing industry life cycle that are discussed in more detail below.

2.1 Product development

Modular design requires investment because of the costs associated with formulating design rules, experimenting, designing modules and testing (Baldwin and Clark, 2000). Consequently, R&D investment is one of the major mechanisms that needs to be considered for modularisation to succeed. Design reuse reduces the engineering effort needed for product design (Pulkkinen, 2007), which results in benefits related to cost, quality and time. Reusing parts, sub-systems, modules or interfaces are some of the possible drivers for modularisation being able to reduce design efforts (Erixon, 1998; Pakkanen et al., 2016). Reusing component designs reduces the development costs of new product variants (Sanchez, 1999). Hence, design reuse can be done at different levels and it is an important VCM of modularisation.

Technology is another aspect of modularisation that is important. Technological evolution or technology push can set requirements for products whose technology develops fast (Erixon, 1998). Future product elements should be considered in defining product family architecture (Harlou, 2006). Encapsulated technologies are discussed in the modularisation context. Encapsulation of modules makes product management easier (Lehtonen, 2007) and isolating design parameters from other parts of the design makes incorporation of new solutions simpler (Baldwin and Clark, 2000). We summarised these findings in five VCMs related mainly to product development.

- R&D investment
- More capacity for new product development
- Design by reuse (parts, sub-systems, modules, interfaces)
- New technologies
- Encapsulated technologies

2.2 Marketing and sales

Modularisation affects the product cost. Variety can create additional costs for several life phases, unless commonality of the products is considered (Andreasen, 2011). Use of common components (Sanchez, 1999) and part count reduction (Fixson, 2006) are typical cost reduction tools. One factor in analysing the demand for offering variants based on modularity is brand effect (Hopp and Xu, 2005). Enabling configurable products contributes to brand management (Tiihonen et al., 1999), but a modular product family may not be designed very often on a large scale within a company because it requires large investments. While designing a modular product family, the future attractiveness of the products must also be taken into consideration (Harlou, 2006). Styling possibilities can be an important driver for modularisation for products whose purchasing decision strongly relies on trends and fashion (Erixon, 1998). Modularisation supports matching products to customer needs through product configuration which defines product variants based on predefined rules and product elements (Pulkkinen, 2007). Product configuration knowledge and human or software driven configurations have been discussed by several authors as a facilitator of sales, distribution tendering and product variant definition (Soininen, 2000; Haug et al., 2012). Based on these explanations, the following VCMs are connected to marketing and sales.

- Product cost
- Brand impact
- Reactivity to market changes
- Product fit to customer needs, standards and local legislation
- Support for sales and distribution tendering or product variant definition

2.3 Production

Delivery-specific products are more challenging than standard products because there are fewer opportunities to learn lessons from repetition. Designing modular components simplifies and increases the predictability of production (Sanchez, 1999; Baldwin and Clark, 2000). Production includes many stages, such as part procurement. If common parts can be used in a product range, economies of scale in part sourcing may exceedingly reduce the total cost of production (Baldwin and Clark, 2000). Late point product differentiation by allocating variations to only one or a few parts, and keeping the product generic or as “universal chassis” as long as possible, lowers the buffer inventories in production, and thus reduces the complexity of the manufacturing process and overall costs (Lee and Tang, 1997; Erixon, 1998; Sanchez, 1999). The use of universal chassis may reduce the variety of parts to be inventoried and handled in assembly, and thus reduce product costs (Sanchez, 1999). Existing assembly and operating environment reasons can favour distributed production in separate factories (Lehtonen, 2007). Clearly defined building blocks and interfaces support this. Standardised interfaces of modular products enable delivering product modules to a customer site in which the product is to be assembled effectively (Lau Antonio et al., 2007). Separate testing of modules decreases the feedback time about the quality of modules compared to testing done in the main production flow (Erixon, 1998). The reliability of key components can be improved over time because reusing parts enables improvements in materials and processing, which reduces warranty costs (Sanchez, 1999). In product modularisation, companies aim to find proven solutions. Product configuration relates to managing product quality because it focuses on defining product variations based on certain predefined rules, limitations and standardised elements (at least within a company) and therefore, the risk of mistakes is minimised (Tiihonen et al., 1999; Juuti, 2008). These aspects lead to a number of VCMs related to production.

- Improving controllability of production through transparency and predictability
- Component availability and number of supply sources
- Late point differentiation
- Relocating production to more favourable areas or environments
- Decreased ramp-up time and costs with distributed module testing
- Reduction in component quality issues
- Distributing or decentralising assembly
- Reduction in product quality issues

2.4 Transport

Products can be designed to match the relevant type of logistics. Product architectural decisions determine the needed packing space and protection requirements of the product in relation to logistics, including transportation (Fixson, 2006).

Standardised modules with less variety allow for lower logistics costs (Erixon, 1998).

- Decreased transportation costs

2.5 Commissioning

Reductions in components and product quality issues were already discussed in other stages of the asset life cycle, and they are also very relevant in the commissioning stage. Increased commonality enables repetition in operational processes, which makes commissioning more effective (Juuti, 2008).

- Reduction in component quality issues
- Reduction in product quality issues
- Effective commissioning by learning

2.6 Operations

Modularity in product use enables customers to reorganise elements of the final product to match their tastes or needs by making substitutions, augmentations or exclusions (Baldwin and Clark, 2000). Accessibility to different types of interfaces strongly affects the ability to customise the product.

- Ability to reconfigure the product during use

2.7 Maintenance, decommissioning and replacement

Modular structures and standardised interfaces support maintenance. Modularisation can make it easier to replace possible damaged areas (Erixon, 1998). Companies doing maintenance-oriented modularisation should focus on designing the product in a way that ensures the replacement of working components is avoided when maintenance is needed in other components (Umeda et al., 2000). Proper designing can create new business opportunities for companies by providing services that reduce the amount of waste by reusing the modules (Umeda et al., 2000).

- Reduced down time and maintenance costs by using replaceable modules
- Increased end-of-life value by reusing modules

3 VCMs in case studies in the machinery industry

Table 1 presents the VCMs that three companies highlighted during target setting of a modularisation project. Large Companies A, B and C operate globally in the machinery industry, but do not compete with each other. Names of the companies were kept anonymous to respect the sensitive nature of their business. The data was collected from 2010–16 by authors who participated as facilitators and consultants in design projects (Companies A and C) or interviewed key company personnel (Company B). During the projects, companies were not shown the list of VCMs, but authors analysed retrospectively these case studies according to their observations and notes. Therefore, the results could have been different if companies would have been asked to select VCMs they considered important to their business. When considering the key life cycle stages of engineering assets (commissioning, operations, maintenance, decommissioning and replacement) (Haider, 2007), Company A highlighted that the ability to replace modules and to reuse specific modules when making new products would be valuable. Company A managed to reduce the number of items and different technologies for similar functions without losing flexibility in the commissioning phase to adapt to different customer environments. Rationalised items allowed the company to be more consistent with its product offerings because it could reuse the same items in different product variants. They reported a 25% cost savings in some variants. Company B had a different focus. They strived for quality improvements by using modularisation and thought it would be valuable if products could be reconfigured during operational changes. Company B argued positively that after a modular product family has been designed and a new operational model is fully implemented, the investment costs decrease every year; they did highlight that this whole process could take many years until achieving its full potential in cost savings, such as site works related to commissioning. Company C noted that modularisation could decrease product quality problems through proven and predefined solutions (defined outside delivery project). This project is ongoing and results are not available yet. These case studies show that the companies had different motivations for the way the physical assets were structured and that suppliers/producers of assets deal with multiple sub-goals that usually lead to making trade-offs.

Table 1 VCMs in a target setting of modularisation (x: considered)

Life Cycle Stages and VCMs	Company A	Company B	Company C
Product development			
Research and development investment	x	x	x
More capacity for new product development	x	x	x
Design by reuse (parts, sub-systems, modules, interfaces, other)	x	x	x
New technologies	x	x	x
Encapsulated technologies			
Marketing and sales			
Product cost	x		
Brand impact			
Reactivity to market changes	x		
Product fit to customer needs, standards and local legislation	x	x	x
Support for sales and distribution tendering or product variant definition	x	x	x

Production			
Improving controllability of production through transparency and predictability	x	x	
Component availability and number of supply sources			
Late point differentiation	x		
Relocating production to more favourable areas or environments			
Reduction in component quality issues		x	
Decreased ramp-up time and costs with distributed module testing and learning		x	
Distributing or decentralising assembly			
Reduction in product quality issues			x
Transport			
Decreased cost of transportation			
Commissioning			
Reduction in component quality issues		x	
Reduction in product quality issue		x	x
Effective commissioning by learning		x	
Operation			
Ability to reconfigure product during use		x	
Maintenance, decommissioning and replacement			
Reduced down time and maintenance costs by replaceable modules	x		
Increased end-of-life value by reusing modules	x		

4 Discussion

The purpose of the paper was to study (RQ1) the main VCMs of modularisation in the manufacturing industry, and (RQ2) how case study companies related VCMs to essential life cycle stages of their engineering assets in a target setting of a modularisation project. VCMs presented in Section 2 and the same VCMs shown in the first column in Table 1 are the answers to RQ1. The VCMs of modularisation describe possible objectives, phenomena and problems that can arise from modularisation. These VCMs derived from the studied literature consider the whole engineering asset life cycle. The answers to RQ2 show that case study companies consider VCMs differently. All companies in the case studies had a strong focus on VCMs related to product development and marketing and sales, but not all VCMs were relevant. Further differences could be found when considering life cycle stages from production to end-of-life. The case studies show that different objectives may affect modularisation and the resulting asset structure. For example, modularisation can be done in a way that it a) supports asset suppliers by improving asset quality, b) enables reconfiguring of assets, c) facilitates maintenance, and d) increases possibilities to reuse some elements of the assets when the asset as a whole reaches the end of the life cycle. However, one must remember that modularisation, like product development in general, is about making trade-offs and typically all the desired properties for different stages of the life cycle cannot be assigned to a single asset or even a family of assets.

Our hypothesis for future research is that the recognized VCMs support understanding, communicating and estimating potential business impacts and rationale of modularisation. The VCMs derived from the literature review present guiding principles whose importance needs to be defined by the suppliers of engineering assets to find a reasonable structure for asset development. Similar work has been done by Fixson (2006) in product architecture costing, but the engineering dimensions in that approach only highlighted function-component allocation schemes and interface characteristics; from a modularisation point of view, partitioning logic, modules, architecture and configuration rules and constraints should be considered to get a more comprehensive perspective. Our goal is to connect the VCMs to these key elements of a module system (partitioning logic, set of modules, interfaces, architecture and configuration rules and constraints) and develop more systematic tools for estimating the impacts of modularisation, such as comparing different module concepts. For future research topics, VCMs need to be connected to quantitative values to increase their usefulness for management.

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