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Towards an Optimised Value Creation Network for Modular Investment Goods

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Abstract

Companies are under increasing pressure from global competition while at the same they need to offer flexible products to meet individual customer requirements. Therefore, modularised capital goods are designed and manufactured to meet both challenges. This paper presents an approach to identify necessary changes in the production process and summarises the changes in the automotive and aerospace industries due to modularisation. Three key findings are identified: increased outsourcing potential, production in a value creation network with specialised manufacturers and joint investments.

Keywords: *modularisation, production design, value creation network, investment goods, platform strategies*

1. Introduction

The climate change and its effects are becoming increasingly evident in everyday life. In many cities this leads to plans for restricting conventional cars from the streets in favour of zero emission cars like battery electric or H^2 powered ones (Transport Decarbonisation Alliance, 2020). The public road transportation as well as the transport of goods is also affected by this and environmental friendly solutions are created. One field that gets more into the focus now are fast ferries in urban areas (Bouman et al., 2017). Today, they are responsible for an over proportional share of emissions per passenger kilometre in urban environment (Dahle, 2020). In contrast to busses and cars, ferries are not mass-produced but individually developed for each intended use. Utilising the proven one-off procedure and well-known methods is not sufficient to update whole ship fleets into the age of zero emission: the required capacity, the level of adaption and time to market are not met (Eyres and Bruce, 2012).

A possible solution to overcome these limitations is utilising the principle of modularisation for the design and production of future ships. For this paper we consider the design of the ferry modules as given to focus on how to optimise the production of modular investment goods (Lagemann et al. 2021). Therefore, the actual product modularisation is not discussed in this paper. The focus of this paper is on presenting a methodical approach for identifying the effects on the value creation network that result from modularisation.

In this paper a method to identify the target picture of a value creation network that is optimised for modular investment goods is presented using the example of zero emission fast ferries.

In the problem analysis the paper shows up the challenges of building modular investment goods. Similarities and differences to other industries in which modularisation is already common are discussed. To derive a target picture based on the experiences gained in other industries, methods for comparing products as well as methods for description and comparison of value creation networks are presented in the state of the art. Finally, the suggested method for anticipating the target picture of an optimised value creation network for modular investment goods is presented and discussed. This follows the first and second phase of the design research methodology by Blessing and Chakrabarti (2009): Within the scope of this paper, preliminary work is carried out to define the target vision as result of the descriptive study. These results will be used to design a value creation network and improve it with suitable optimisation measures in future work (phases three and four of the DRM).

2. Problem analysis

Challenges of modular ship building

The challenge in the design of a modular ship is the interdependencies between the individual elements due to physical conditions (Erikstad, 2019). These challenges are evident, for example, in a slight change in the planned number of passengers. The additional weight also means that a larger hull is needed, which also changes the handling of the ferry and leads to a higher power demand for propulsion. These problems are even more noticeable with high-speed ferries (Papanikolaou, 2010).
The emission-free operation of a high-speed ferry by means of an electric drive presents further challenges. The increase in the number of passengers at the same distance and speed means that a more powerful battery is needed for the ship, making it larger and, above all, heavier. This also requires an adjustment of the hull to accommodate the battery and to keep the driving resistance as low as possible during the adjustments. This example shows how many adjustments to components of the ferry become necessary due to a slight change in requirements. In addition, for high-speed catamaran ferry the cruising speed has a quadratic influence on the power requirement of the drive (Bertram, 2012).

Investment goods

With an investment good, such as trucks or ships, the goal is to operate profitable in the long therm. To evaluate the cost-effectiveness of an investment good, the Total Cost of Ownership (TCO) is examined (Hilgers and Achenbach, 2021) to cover the total costs during a planned lifetime. The TCO of trucks and ferries (Figure 1) as examples for investment goods in the transport sector show that the largest part of the costs are the personnel costs with around 40 % and the energy costs with 24 %. The investment costs for capital goods account for only 16 % of total costs (Almaas et al., 2021; Williams and Murray, 2020). Furthermore, wide similarities in the cost structure for ferries and trucks can be identified making trucks a meaningful reference for investment goods.

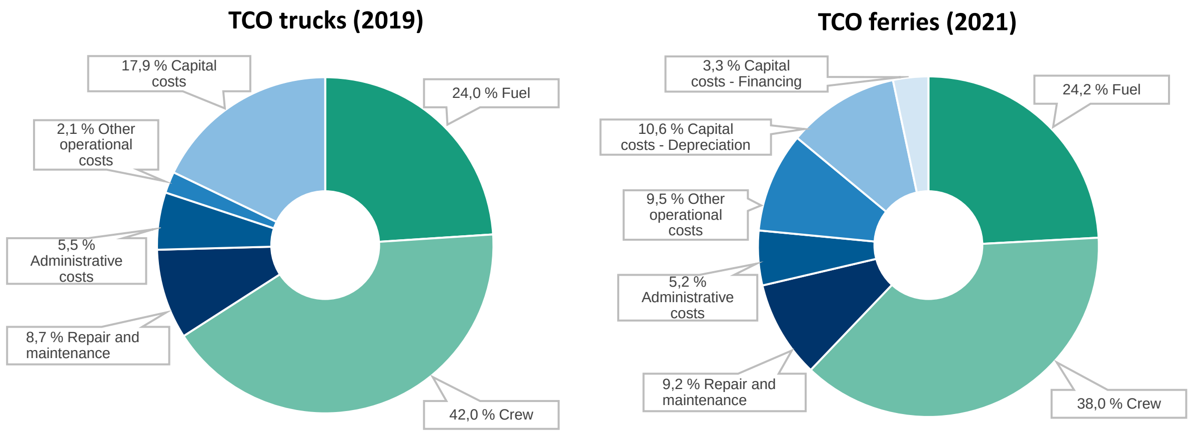

Figure 1. TCO for domestic sea transport by ferries and trucks in the United States of America (Almaas et al., 2021; Williams and Murray, 2020)

Electric ferries offer lower costs when considering the complete live cycle. The Ellen electronic car ferry is an example for this. Due to the size and complexity of the ferry, the investment costs are significantly higher than for conventional ferries. This gets compensated by lower energy costs and savings in the field of maintenance. It was determined that the electric Ellen ferry achieves significant cost savings compared to a conventional ferry (Kortsari et al., 2020).

Globalisation and competition with low wage countries

As shown the production of zero-emission ferries is more cost-intensive than that of conventional ferries (Norwegian Ministry of Climate and Environment, 2019). The production of these ships is associated with increasing competitive pressure from South-East Asian manufacturers, especially for European shipyards, due to global markets. More than 90 % of global ship production takes place in Southeast Asia. This leads to a concentration of shipbuilding know-how in these countries. The associated resources and opportunities are creating increasing cost pressure for European shipyards (Daniel et al., 2018). In addition, the Northern European countries are competing with low-wage countries in Eastern Europe to further reduce production costs.

Conclusion and TrAM project

The problems described show that the European shipping industry must change and adapt to modern standards to remain competitive in Europe. This paper therefore examines other industries that have already undergone a similar transformation to draw conclusions for the coming changes in the shipping industry. For this purpose, this paper analyses value creation networks of two industries which both belong to the transport sector, successfully produce investment goods in Europe and successfully included modular principles in their products: aviation and the automotive sector. The definition of goods from the automotive sector as investment or consumption goods depends on the purpose of use. For private households it is more of a consumption good, while for companies it is an investment good, e.g. in form of trucks and busses. Therefore, the automotive sector is also considered in the context of this paper. The focus of this paper is on how the products in shipbuilding will change and what impact can be anticipated on production and the production network based on the other industries.

The results of this paper were obtained within the EU-funded TrAM project (Transport - Advanced and Modular) and will be further evaluated within the project.

3. State of the art

To identify the effects of modularisation on the value creation network, we need to analyse the changes made in other industries. Consequently, methods to analyse the changes in the product as well as methods to analyse the production network are described in the following chapter. The development and optimisation of a value creation network is not part of the paper but on identifying a target picture.

3.1. Methods to describe and compare a product

To describe and compare the product, we will take a closer look to its architecture but also to the number of product variants. Since the product architecture is the basis for the further process steps, this aspect in particular is relevant for the effects on production. As the number of product variants is not reduced despite the reduced internal complexity, this parameter also captures the effects of modularisation. Product complexity is an often-used value to describe the product changes when implementing modularisation. Therefore, the following paragraphs will also discuss different approaches to measure the complexity of a product.

In the literature there are four types of product architectures which are differentiated depending on the physical and functional characteristics of the system: integral, functional modular, physical modular and full modular. Functional independence exists when a module can perform functions independently of other modules. The possible physical separation of one module from the others by standardised interfaces is defined as physical independence. The greater these two levels of independence, the higher the modularity of a product (Feldhusen et al., 2013).

The term complexity is widely used to describe a high degree of intersystem dependency and is therefore an indicator to use and a challenge for modularisation at the same time. There are different ways to quantify the complexity of a product. Bashir and Thomson measure product complexity based on the solution description. This approach is based on the decomposition of a product in a hierarchy tree, i.e., the product structure. The variable F_j denotes within the tree the number of functions F on the level j and l denotes the tree depth. The product complexity PC is determined with the following formula (Bashir and Thomson, 1999):

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$$PC = \Sigma_{j=1}^{l} F_j \cdot j$$

For this approach a detailed product and function structure is required to calculate product complexity. (Bashir and Thomson, 1999). Another definition of complexity is made by Vickery et. al. (2016). In this definition complexity describes the presence of many different parts, elements or patterns that are connected in ways that make an object or process difficult to understand. In this approach complexity is measured by quantifying the number of items in the bill of materials for the finished product, and the number of distinct manufacturing processes that are required to produce the product (Vickery et al., 2016). In the automotive industry complexity PC is described by Schneider and Rieck (2012) with a function of the actual number of variants n_V, the number of theoretical possible combinations n_C and percentage of rules x that limit the solution space. With 'a' as function of market relevance and dynamic of development the function is described as:

$$PC = a + \left(1 + \frac{n_V}{n_C}\right)^{-x}$$

In summary, many different definitions of complexity exist. It is common understanding that complexity is reduced by the modularisation of a system as following the principle of independency the number of interconnections is reduced. However, to compare the complexity of modular systems with integral systems over different products one would need to use the same method for all cases to have comparable data. In the area of modularisation, there is currently no suitable database for this, which is why the complexity is not considered any further to quantify the changes of the product structure.

The number of variants V is suitable for the quantitative representation of the variant diversity to quantify the complexity of a production. If the number of variants to be controlled increases, the control of manufacturing becomes more complex (Lödding, 2016). However, if no concrete variants are available yet, but the information about the different characteristics and the number of their manifestations, the theoretical maximum of possible variants V_{max} can be determined with the number of expressions n and the number of characteristics m (Buchholz, 2012):

$$V_{max} = n^m$$

If the number of different values of individual characteristics differs, the number of variants is determined from the product of the values. The number is determined from the product of the characteristics. For a product with three characteristics with four, seven, and five expressions, this results in a theoretical number of variants of $4 \cdot 7 \cdot 5 = 140$. However, the calculated theoretical number of variants very rarely corresponds to reality, since some combinations are technical not compatible or economically relevant irrelevant (Buchholz, 2012).

Piran et. al. also names the product engineering efficiency as a key figure to compare products and the impact of modularisation. Due to modularisation the performance of product engineering can be improved since the hours of developing a new product can be reduced (Piran et. al., 2016). Therefore, we also take the time to develop a new product into our approach.

3.2. Methods to describe and compare a production network

To derive the effects of product modularisation on production, different aspects of production must be described and compared with each other. The key factor "production network" in production undergoes several changes due to product modularisation, which must be quantitatively represented and analysed. For this purpose, we evaluated the ABC analysis, the production depth and the R&D quota for suppliers. Due to modularisation the number of suppliers is affected (Brylowski et. al., 2019). In order to be able to evaluate the changes on the suppliers, a supplier ABC analysis is suitable. By the analysis it can be determined, how the supplier number changed by the modularisation and above all whether there are changes with the number of the A-suppliers particularly important for the manufacturers. In order to be able to accomplish an ABC analysis, exact data are necessary over the order volume of the individual suppliers for an enterprise.

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The increasing role of module suppliers production P_{ex} is also having an impact on the company's internal production P_{in}. Therefore, our approach examines the depth of production of manufacturers P_d (Djabarian, 2002):

$$P_d = \frac{P_{in}}{P_{in} + P_{ex}}$$

Experts linked the phenomenon of decreasing production depth with the concept of modular sourcing in 2015. Prior to that, a 2006 study still considered the two trends independently of each other (Göpfert et al. 2016).

The depth of development has also changed in recent years due to the involvement of different partners. In order to make the suppliers R&D quota (SRD) comparable for the analysis, the dimensions of quantity, time and cost can be used. Since in practice the development costs are of great importance and the data is usually available, the development depth is determined on the basis of the costs. For this purpose, the SRD is defined by combining the supplier R&D costs until market launch for all product variants (${C_{R\&D}}^{ML}$) and the total research and development costs (${C_{R\&D}}^{T}$) (Junge, 2005):

$$SRD = \frac{\Sigma_v {C_{R\&D}}^{ML}}{\Sigma_v {C_{R\&D}}^{T}}, 0 < SRD \leq 1$$

The higher the key figure value, the greater the share of external development services. With this formula, not only the external services of the suppliers can be considered, but also those of the development service providers.

To derive the impact of modularisation of investment goods, the methods and key figures presented are applied to other industries. Based on the changes that occur in other industries, the consequences for production in, for example, ship manufacturing can be derived.

4. Suggested procedure

The challenges described show that the organisation of production and partner networks in the shipbuilding sector must change to remain competitive in the future. To derive concrete measures for the upcoming changes in shipbuilding, the effects of modularisation on value creation networks of comparable industries are examined. Based on the systematic literature review the following factors are considered: Variant diversity, efficiency of product engineering, production depth, R&D quota, the supplier and production network structure. The conclusions that can be drawn for shipbuilding will be derived from this. Based on the factors, a statement is to be made on how modularisation affects the structure of the production network. To achieve this goal, a procedure consisting of four steps is proposed (Figure 3), which draws on proven methods and metrics from Chapter 3. The procedure is suitable for researchers seeking to analyse what changes in a production network will result from the introduction of modularisation. After running the procedure model, predicted changes are available, which can then be used for further research to design and optimise a production network producing modular investment goods.

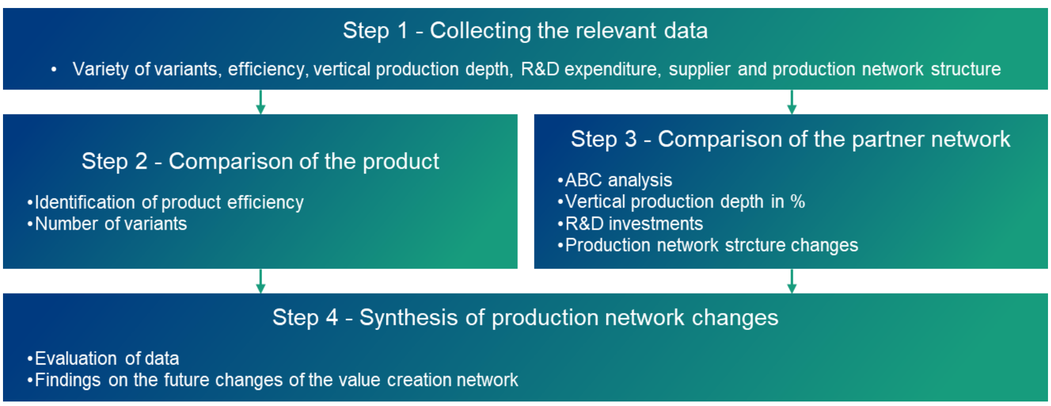

Figure 2. Overview of the proposed procedure

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In the first step, information is collected from comparable industries on the topics of development of variant diversity, efficiency, production depth, R&D expenditures, the supplier and production network structure. In the second step, the product development process is analysed to what extent specifications are made in product development that have an impact on the design of the production network. In the third step, the impact of modularisation on the partner network is analysed. Finally, in the collected findings are summarised in `the fourth step to derive requirements for a production method.

4.1. Colleting the relevant data

In the first step, different data are collected based on the factors described. One key factor is the number of production variants of one product and the development of *efficiency* in comparable industries. *Efficiency* is a term for combining e.g. commercial and engineering lead time, number of parts and number of reported problems and customer complaints which therefore also need to be gathered (Piran et al, 2016). In addition, the supplier list, the production depth, the R&D quota and individual information on the production network are collected for the third step.

The references used in the following chapter are based on the results of the literature review carried out in this step of the method. It shall be noted that there are difficulties when trying to analyse developments in these areas as not enough data could be collected for a sufficient period of time using uniform methods or because different scientists publish contradictory research results.

4.2. Comparison of the product architectures

In this step, it is examined which changes in production result from product modularisation in product development. First, general differences are explained and then illustrated by means of numerical examples.

Table 1 lists various characteristics that distinguish modular and integral product architecture. The results show that the focus of each architecture is different. The modular approach is designed for reuse and the clear demarcation of individual components and thus enables parallel working and the outsourcing of individual modules.

Table 1. Characteristics of modular and integral product architecture (Bonvoisin et al., 2016; Mikkola, 2006; Koppenhagen, 2014; Krause and Gebhardt, 2018)

factor	Modular product architecture	Integral product architecture
Redesign to Architecture	without modification	with modification
Development mechanism	parallel development	sequential development
Communication mechanisms	weak	intensive
Product variants	high	low
Complexity	low	high
Component outsourcing	easy	difficult

The individual characteristics are examined in the following by means of the respective key figures. The factors "redesign to architecture", "development mechanism" and "communication mechanisms" are difficult to consider separately by means of a key figure because they partly influence each other. Therefore, these three factors are analysed together by the efficiency of product engineering. In this paper, the efficiency of Piran et al. (2016) is used as the basis for the investigation. As part of a study, the development of efficiency at a bus manufacturer was examined before and after modularisation. Piran et al. (2016) figured that modularisation led to a statistically significant increase in efficiency in the production process.

This chapter also examines the diversity of product variants. Modularisation offers the possibility to constructively create and pre-conceive a multitude of variants. The pre-conceived variants have an effect on production because it must be able to map a multitude of production possibilities. In the automotive industry, the number of variants have multiplied in the context of modularisation. Audi AG produced 10 models in three model series at the end of the 1980s. In 2015, they have produced 59 models in 12 model series (Hirschberg, 2015). Similar results can be seen at BMW AG (Renner, 2007).

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Another characteristic of modularisation is reducing complexity. In the state of the art, it has already been described that no uniform definition of complexity exists and contradictory information is available from comparable industries. Therefore, complexity is not directly evaluated in this model, however several components of different complexity definitions are considered individually.
A modular product architecture offers the advantage that different components can be outsourced. This offers a number of possibilities for production in a production network. The associated advantages and likely changes in production are analysed in the following chapter.

4.3. Comparison of the partner network

Modularisation also offers the possibility to manufacture the product in a production network and to produce it in a distributed production through the physical independent modules. The effects of modularisation on the partner network are therefore analysed in this step. First, general differences are worked out and then illustrated by means of numerical examples in three areas: suppliers, production depth and R&D expenditure.
The transformation of the production network from an integral product architecture to a modular design leads to numerous changes. Based on a study from automotive suppliers, modularisation leads to distributed flexible production in order to be able to produce many different variants (Table 2). Factories are located close to the market and consist of specialised companies that also share production resources within the production network. Bruch et al. (2020) additionally address which requirements the company that is responsible for final assembly should fulfil.

Table 2. Changes in production network structure due to modularisation (Lampón and Rivo-López, 2021; Pashaei and Olhager, 2019; MacDuffie, 2013)

factor	Modular product production network	Integral product production network
Network structure	Dispersed production network with loose coupling and high level of supplier integration	Concentrated production network with tight coupling
Coordination mechanisms	Intensive coordination mechanisms to share manufacturing resources among plants	Weak coordination with autonomous plants
Plant focus	focus on flexibility and economics-of-scope to be able to configure many variants	focus on economies-of-scale to achieve high volumes in a narrow range
location	Plants located in close proximity to the markets	Large distance between plant and market
capabilities	Many suppliers with specialised manufacturing capabilities	-

In the following, some of the general results are examined through key figures. First, the network structure is examined through an ABC analysis in comparable industries such as the automotive industry and aviation. The number of direct suppliers in the German automotive industry has decreased over the last 20 years, while the module share has increased significantly. In the same period, the number of components from these suppliers has increased significantly (Göpfert et al., 2016). A similar trend can be seen in the aerospace industry (Frigant and Talbot, 2005).
The analysis of the production depth of OEMs shows a similar picture as in the German automotive industry it has fallen from 37% in 1980 to about 21% in 2007 (Verband der deutschen Automobilindustrie, 2008; Göpfert et al., 2016). In the aerospace industry, the share of in-house production is higher but is being reduced at both Airbus and Boeing (Bloed, 2013).
Finally, R&D expenditure is examined. Adjusted for inflation, these have quintupled in the German automotive industry since 1990 (Verband der deutschen Automobilindustrie, 2008; Angenendt et al., 2019). It can be assumed that a large part of the R&D expenditure is invested by the supplier industry. MacDuffie studied the supplier structure at Hyundai and found that only 30-40% of developers work at Hyundai and the majority work for suppliers (MacDuffie, 2013). Similar findings were made by the Oliver Wyman Group (2007), who studied the entire automotive industry and assumed an increasing share of suppliers in development spending. Similar findings apply to the aviation industry (Frigant and Talbot, 2005).

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4.4. Final comparison and interpretation of the results

Finally, the results from the second and third steps are analysed in more detail. Overall, it can be anticipated that an increasingly complex supplier network is emerging with the modularisation of products in which the processes must be accurately coordinated. The selection of suppliers and the reliability of individual suppliers are thus becoming more important. In the long term, modularisation in shipbuilding will lead to a production network in which shipyards increasingly focus on assembly and outsource the production of individual modules to specialised suppliers.

Manufacturing will have to be change in order to handle the increasing number of variants and will require intensive coordination mechanisms. Furthermore, it can be assumed that the flexibility in production will be significantly increased by the joint investments of cooperating companies in production equipment to be able to map the diversity of variants. In contrast to the automotive industry, it is found that centrally controlled production networks cannot be transferred to shipbuilding because the degree of specialisation of the companies in this industry is very high and some components can only be produced by one or two companies worldwide. As a result, the companies in the production network have a similar position of power.

In conclusion, the four-step approach has shown that it is possible to use data from comparable industries to derive statements about the changes that will occur in shipbuilding as a result of the introduction of modularisation. Nevertheless, there is a need for further research in order to develop a production methodology that translates the findings into an implementation method.

5. Conclusion and outlook

To date, there has been little research on how modularisation affects production or the production network in shipbuilding. Part of this research gap is filled by this paper. In this paper, we analyse what changes might occur in the shipping industry as a result of the transformation towards a modularised product architecture. For this purpose, comparable industries (such as the automotive industry and aviation) are analysed and central changes in these areas are elaborated.

As first key finding it can be summarised that modularisation offers the advantage of outsourcing certain production steps to suppliers with specialised equipment and thus realising cost and quality advantages. Secondly, increased production in a production network is possible with distributed locations, but with a high degree of supplier integration. Furthermore, company resources (such as machinery and equipment) are used across companies. For this purpose, intensive coordination mechanisms are used within these networks to coordinate the production of the individual companies.

Further research should therefore be conducted in the future on how such a production network can be implemented and which special features of shipbuilding in particular should be taken into account in this production network. At this point, it is important to emphasise what a strong change this type of production would represent for shipbuilding, as the current production processes relay on traditional supply chains. In addition, further data sources should be analysed to further validate the results presented here.

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