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The Complex Reality of Modularization – Towards an Approach for a Business-Driven Modularization of Smart Products

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Abstract. The main objective of this article is to structure and clarify the transdisciplinary reality of modularization as a foundation for handling business-driven modularization of smart products. Lately, the complexity has increased in the industry due to global manufacturing, different customer requirements, legal requirements, digitalization, new business models, and the evolvement of smart products. The increasingly complex reality has been acknowledged on an enterprise engineering level where complexity is one part of different grand challenges for enterprises. This complexity needs to be handled both horizontally (in the whole value chain) and vertically (on all management levels). It is therefore essential to clarify the modularization landscape by bringing together the business domain, and the engineering domain to cater for the future of modularization. The main contribution of this paper is to suggest a conceptualization of the modularization domain through a meta-model that covers essential aspects of business-driven modularization of smart products.

Keywords. Modularization, business model, meta-model, value chain, smart products

Introduction

The concept of modularization is far from new but modularization approaches are still undergoing refinement and redesign to improve the profitability of the industry. The need for improvement has lately been even more evident since contemporary modularization must include more than the physical product family, its parts and modules, to also cover the business side [1], manufacturing [2] and new kinds of products, such as smart products that integrate physical products with software and services, to provide and exploit capabilities for harvesting data in real-time [3]. This creates complexity in the modularization landscape that companies have to be able to handle.

The development towards increased complexity has also been acknowledged on a more general enterprise engineering level [4] where four grand challenges are identified as a consequence of the increased complexity: narrowness of scope, problems due to complexity, sustainability and viability, and modes of survival of systems. Many times, the approach chosen in practice is to reduce complexity as the most natural way to managing complex situations. In the context of modularization, it will be a balancing act between both reducing complexity and the necessity to also be able to handle the complexity in a structured and coherent way.

The current competitive business environment with an increasing complexity of product and services makes it challenging to manage an enterprise. One of the grand challenges to making an enterprise manageable is to reduce the complexity in design [4]. However, a reduction of complexity is not enough to increase the value created in an enterprise [4]. It is also essential to include other aspects to cover the complete value chain [2], starting with the definition of company goals and strategies to the set-up of manufacturing, services, and products as services [3]. Modularization has been proposed as a way to reduce variability and complexity in design [5], [6]. However, reducing the product complexity, is not enough, and Hvam et al. [7] state that it is both the organization, its working processes, and the product itself that create complexity.

This paper compares and extends 6 existing modularization frameworks to clarify their key constructs and working methods, as well as methods used in industry practice. This information is mapped in concept models, structuring, and describing the constituents and their relations, and integrating both, the business domain and the engineering domain. It brings the two domains together into a cohesive whole. The result of this activity is a meta-models on two levels, overall level and detailed level, that clarifies the relations between different enterprise activities and methods that constitute a complete modularization initiative.

The research is guided by the question - *How can industrial modularization be supported to master business-driven modularization of smart products?*

The purpose of this paper is therefore to present the first step in an ongoing research project to develop method- and tool support for business-driven modularization of smart products. The focus and main contribution of this paper is to present a two-level meta-model that will serve as a foundation for our future development of method- and tool support for business-driven modularization of smart products.

1. Research Methodology

In this paper, we have structured and conceptualized experiences from modularization work over several years, two recent modularization case studies, contemporary modularization frameworks, and the modularization literature. This means that we have performed a number of activities to develop a conceptual model covering the business-driven modularization of smart products, see **Figure 1** below. The research has been performed in a number of steps where some of these steps also have been iterative.

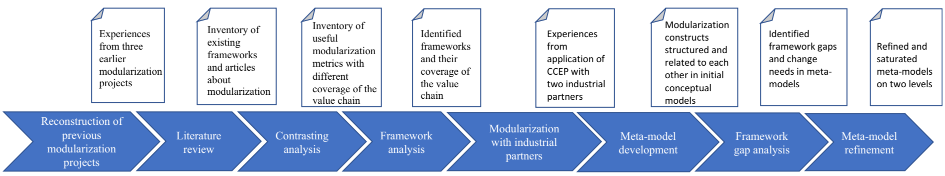

Figure 1. Research steps (blue flow symbols) and their results (white document symbols).

In the first step, *reconstruction of previous modularization projects*, we have in an exploratory way [9] reconstructed and captured experiences from three earlier modularization projects [2], train couplers, trucks, and chain conveyers. This activity elucidated four main challenges, 1) lack of business dimensions, 2) transformation of customer requirements to technical solutions, 3) fragmented coverage of the value chain, and 4) a suppression of interfaces between modules. The second step involved a *literature review* to make an inventory of existing frameworks and articles about modularization [2]. In the third step we conducted a *contrasting analysis* where we compared the literature and the reconstructed experiences from the industrial cases. This mainly resulted in an inventory of useful modularization metrics where these metrics represented different parts of a value chain. In the fourth step we then performed a *framework analysis* to identify the frameworks that had an over all coverage of the value chain. Six frameworks where selected since they covered a major part of value chain. In this stage we also added some new relevant articles to the literature review.

Based on the experiences from previous reconstruction of modularization projects, the framework analysis also resulted in a tentative suggestion for a customer-centered engineering process [8] according to **Figure 2** below.

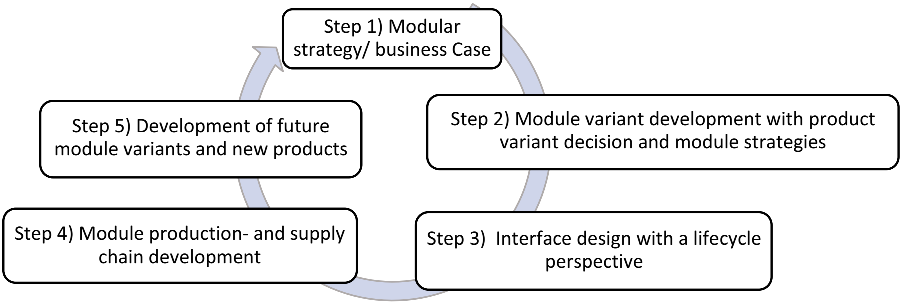

Figure 2. Customer-Centered Engineering Process (CCEP) (adopted from [8]).

In the fifth step, *modularization with industrial partners*, we applied step 1-3 in the Customer-Centered Engineering Process (CCEP) presented in **Figure 2** above. This was mainly done through modularization workshops together with two industrial partners (robotic lawn mowers, industrial brakes) and complementing interviews to validate the work step 1-3 in CCEP.

Based on the previous steps we then were able to do the *meta-model development* where modularization constructs where structured and related to each other in an initial conceptual model. A meta-model is needed when a complex reality is to be described, understood, and used to define “things” and “phenomena” which are in use in practice [10]. The meta-model was validated through interviews with modularization experts at our industrial partners.

Afterwards, the meta-model in combination with the CCEP and the chosen frameworks was used in the step to perform a more detailed *framework analysis* where gaps in these frameworks were identified, see table 1 below. With the CCEP and the evolving gap analysis as a base we could also identify change needs in our meta-model. At this stage we also identified the need to develop the meta-model to cover two levels, an overall level and a detailed level where the constructs in the overall model, see **Figure 3** below, were conceptualized on a detailed level, see **Figure 4** below. The detailed framework analysis was an iterative activity with the next step, *meta-model refinement,* where the meta-model and the gap analysis were feeding each other until we had reached a saturation in both the gap analysis and the refinement of the meta-model.

2. Related frameworks handling multiple aspects of modularization

In this section, we have only considered frameworks that can handle multiple aspects of modularization with respect to coverage of the value chain, i.e., specific modularization tools are not considered relevant.

As a result of our literature review we identified six frameworks that handle multiple aspects of modularization and show different coverage of the value chain; Modular Function Deployment (MFD) [11, 12], Interface Diagram (IFD) [13], Institute PKT approach for developing modular product families [14], Configurable Components [15], a Systematical requirement flow-down model of architecting steps [1] and Customer-Centered Engineering Process (CCEP) [8]. A majority of the selected modularization frameworks share the following content:

- Translation of customer needs to product properties, by methods such as QFD
- Product family layout
- Module system design
- Product family configuration/variant selection
- Introduction of new module variants

In industrial practice, an essential aspect of modularization is the ability to define metrics related to the modular system, to set targets that guide the modularization initiative [2]. Companies have different strategies for how they pursue their value creation. Therefore, the business strategy will be the foundation for the modular strategy expressed in the three pillars *product leadership, customer intimacy*, and *operational efficiency* [16]. Another article describes in this context the importance of digitalization and the nessecity to be able to handle and take advantage of digitalization [17]. Finally, leading KPIs can be defined and smart for the modularization project [2]. In this context, we define a business case as an activity that must consider manufacturing volumes and profitability for different product variants. Otherwise, it will be impossible to design a modular system with the module variants with the highest profitability [18]. Most of the selected frameworks lack this central aspect, except CCEP [8]. In CCEP, the value map method is used [19] which clarifies the indirect costs by activity-based calculation [20].

Moreover, several of the selected frameworks lack the ability to handle interfaces, which is a cornerstone in modularization [21]. Most of the frameworks partly address interfaces but they do so in terms of transfer, energy etc., but they do not specify them or design them in detail [8].

There is also a lack of descriptions of a modular manufacturing system. In our literature analysis, we only found one framework covering this aspect [11]. A module manufacturing strategy is needed to calculate the overall profitability for the modularization initiative and compare it to the initial project goals [2].

Since the modularization frameworks commonly do not consider manufacturing, the resulting modular system is not fully prepared for manufacturing. The total complexity requires an involvement of manufacturing early in the product design, as stated by [22] in a study of the manufacturing strategy in four companies. Other important activities in manufacturing commonly not fully considered in modularization frameworks are make- or buy assessments [23] and low-cost country sourcing [24].

To summarize, the selected frameworks are partly overlapping and there is no complete description of the modularization process. Thus, there is a need to try to close the gaps in different modularization frameworks and create a holistic model of the complex reality of modularization. One example of such a gap related product families is to include secondary aspects affecting the module system, such as different business models (remanufacturing, direct sales, and leasing) and manufacturing strategies.

3. Conceptualization of business-driven modularization of smart products

The overall meta-model was developed using the empirical information from the case studies, interviews, workshops, and literature. The meta-model consists of relevant constructs and their relations to set the conceptual foundation for business-driven modularization of smarts products.

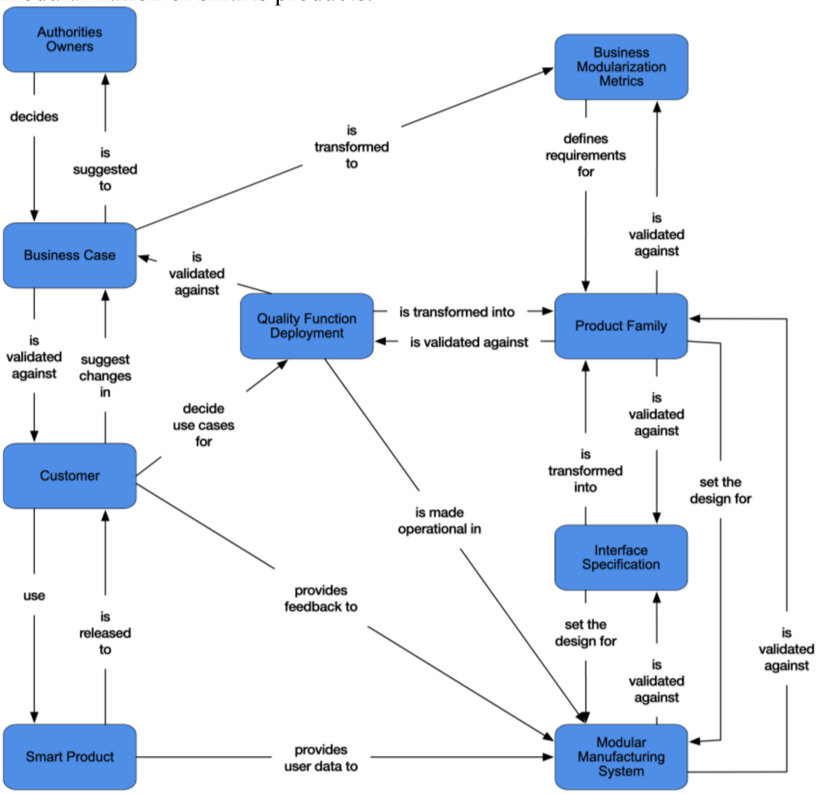

Figure 3. Meta-model for business-driven modularization of smart products.

To describe and explain the model we start with a common start in a modularization initiative. The owners and/or authorities ask for a business case because they have been contacted by different customers and/or new regulations that motivates the revision of an existing or development of a new product architecture. The trigger can be new laws, like environmental regulations, technology breakthroughs, or customized markets. When a business case is in place, it can be transformed into business modularization metrics that cover the value chain and support the modular strategy for the company. Examples of metrics and how they managed can be seen in [2]. Business modularization metrics define requirements for the product family. A product family refers to a set of individual products that share common technology and address related markets [25]. The product family consists of the module system, profitability of the module system, interface specification and performance steps. A performance step is constituted by the product steps needed to satisfy customer requirements and business modular metrics. The customer use cases are then translated into customer requirements, and the product properties are formulated in the Quality Function Deployment (QFD). Finally, the product properties together with defined goal values are transformed into a product family or are made operational in the modular manufacturing system. The interface specification is essential to handle product families and modular manufacturing systems, i.e. the integration of product development and manufacturing. For product families, interface specification is critical because this is the base for the interface design. The interface specification sets the design requirements for the module manufacturing system together with quality function deployment, which are made operational in the modular manufacturing system. The modular manufacturing system consists of business modularization metrics, interface specifications, module and product assembly, equipment for module and product assembly, quality function deployment for manufacturing. Smart products provide real time data to the module manufacturing system, and the customer provides useer feedback to the module manufacturing system. Finally, the smart product is released to and used by a customer. We use the definition of smart products according to [3] where they define smart products as "*complex systems that combine hardware, sensors, data storage, microprocessors, software, and connectivity in myriad ways*".

The constructs that were presented above in the overall meta-model have also been decomposed into detailed conceptual models for each construct. In the figure below we show one of these decompositions: interface specification. Due to page limits, we are only able to present one of these detailed conceptual models.

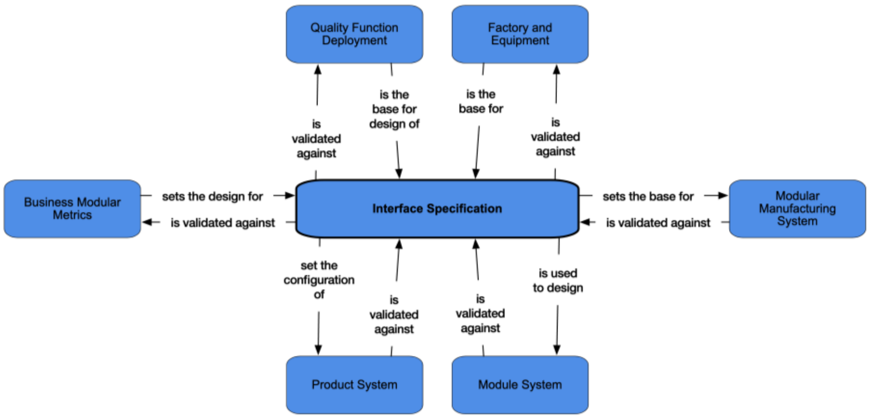

Figure 4. Meta-model för interface specification.

In the overal meta-model, interface specification has proven to be a critical part. We have also observed in the literature that the conceptualization of "interface" hasn't been elaborated enough. In the overal meta-model the interface specification for product families and module manufacturing systems are described, in the detailed interface specification also other areas are in focus for interface specification. First is the interface to business modular metrics that set the design for interface specification and is used for interface specification validation. The quality function deployment (QFD) is then the base for design of the interface specification and it is also validated against the QFD. Factory and equiment must also be taken into account in the base for interface specification and the interface specification is validated against factory and equipment. The interface specification set the configuration of product system and it is also used to the design the module system. Moreover, both product system and module system is then validated against the interface specification. Finally, the interface specification set the base for the module manufacturing system which in the end is validated against the interface specification.

4. Analysis of selected frameworks

The constructs in the overall meta-model and the detailed meta-models have been used for the gap analysis of the selected frameworks according to the table below. It is based on the activities in the frameworks and modularization projects. The constructs from the overall meta-model are represented in the category Constructs in the overall meta-model. The constructs from the detailed meta-models are then represented in the sub-category Activities/Roles .

Table 1. Framework gap analysis.

		Selected Frameworks					
Constructs	**Activities/Roles**	Krause et al 2012 PKT	Otto et al 2016 A systematical requirement flow-down model of architecting steps	Erixon 1998 MFD	Brunn et al 2012 IFD	Michaelis et al 2015 C.Comp,	Lennartsson et al 2022 CCEP
Stakeholders	Owner of the company		x	x			x
	Athorities	x	x	x		x	x
Customer	Internal departments by customer	x	x				x
	Quality/Inspection	x	x			x	x
Business case	CE-Strategy resiliance						
	Business modular strategy						x
	The potential return on investment (ROI)						x
	Business model						
Quality Function Deployment	QFD product	x	x	x	x		x
	QFD manufacturing						x
	QFD service				x		x
Performance Steps	Use cases		x		x		
	Product steps						
Modular System	Product family layout	x	x	x	x		x
	Module system design	x	x	x	x	x	x
	Determination of interfaces	x	x	x	x	x	x
	Interface design						x
	Product system configuration	x	x	x	x	x	x
	Product system profitability	x			x	x	x
	New module variants	x	x	x	x	x	x
Interface Specification	Quality function deployment			x	x		x
	Business modular metrics						x
	Module system	x	x	x	x	x	x
	Product System	x	x	x	x	x	x
	Module manufacturing system			x		x	
	Factory and eqiupment						
Modular Manufacturing System	Module and product assembly			x			x
	Module manufacturing test strategy					x	x
	Make or buy/Low-cost country						
	Equipment for module and product assembly						x
	Interface specification						x
	Lead-time analysis					x	x
Smart Product	Access to product	x	x				x
	Product service concept	x	x		x	x	x
	Quantified product						
	Intellectual property						x

In the table above, the marking “x” means that the activity or role is covered in the specific framework. To summarize, there are a number of clear gaps in the literature and in the presentation of the selected frameworks. One of these gaps concerns how to include the business dimension during modularization, especially to ensure that the business model is manifested into the modularization initiative. Another aspect is the manufacturing aspects and how this aspect is suppressed in several of the modularization frameworks. Furthermore, there are two additional areas that need more attention; module manufacturing system and smart products. There are also other essential parts missing the interface design [8] and the product platform profitability [26]. Finally, module test strategy [27] and business model [28] are also missing in some of the frameworks. The business dimension and especially business models will be an important dimension to manage for the evolving circular economy [28] which is a growing demand on the industry.

An important conclusion from this framework analysis is that there is a need for a more comprehensive framework that covers all the constructs and their relations which have been identified in the conceptual analysis of business-driven modularization of smart products. The CCEP framework has the most complete coverage on a meta-level but the work still remains to develop useful method- and tool support for practitioners who work with business-driven modularization of smart products.

5. Discussion and conclusions

The main contribution of this paper is conceptual models on two levels, overall level and detailed level, that will serve a foundation to develop method- and tool support for business-driven modularization of smart products. The conceptual models are anchored and justified through six existing modularization frameworks, literature and experiences from case studies. The focal point is the CCEP modularization framework which is elaborated from the MFD framework as a base and some parts from the other selected frameworks. Each activity is generated from the different parts of the conceptual models and clustered into elements that constitute the meta-model for a complete modularization process. For every element, there is methodological support, such as QFD.

The model can be used to clarify which activities have to be performed in a complete modularization process, to arrive at a profitable modular architecture.

Scholars advocate that modularization should be an integrated part of an enterprise. Some methods are quite complicated to use by partitioners and require substantial knowledge of different methods and tools. The proposed meta-models provide a map to clarify the relations between different elements and the order of activities.

Our conclusion is that both the product, the working process and the type of organization create complexity. This total complexity needs to be described in order to be able to both reduce complexity and to be able to handle a required level of complexity.

We aim to extend existing frameworks for modularization that handle multiple aspects in the whole value chain to support the industry with method- and tools support. Furthermore, is a prerequisite to calculate and act upon different business scenarios in order to enable a profitable future circular economy.

The suggested constructs used in the meta-model can be replaced with another choice of methods for different activities, such as customer needs identification. The customer needs can be identified in alternative ways than through the QFD, for example using the variant allocation model [6], as long as they produce equivalent results.

6. Future work

The presented concept models has to be evaluated in different types of industrial settings with different type of challenges. Specifically, the service concept and smart products needs to be elaborated into the product to verify the model. More effort is also required for development of characteristics for each construct and to clarify the links in the conceptual models connecting the activities in the product design process to the manufacturing development process in order better describe the fuzzy front [22] end of a module manufacturing process.

The next step will be the application of the meta-model in an upcoming research project, where circular economy aspects will be modelled in detail, including the business model, modularization strategy, interface design, and management levels. The project will include four companies, manufacturing robotic lawn movers, ground source heat pumps, train brakes and train buffers, developing smart products [3] that collect data in real-time during operation.

An important part in the future work will be to secure a multi-disciplinary setup and environment for modularization where we have a suitable representation for and integration of both product development and production.

In future work we have also planned to develop a new master course in one of our master programs which will focus on theory, methods, tools and the practice to achieve business-driven modularization of smart products.

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References

[1] K. Otto, K. Holta-Otto, T.W. Simpson, D. Krause, S. Ripped and S. Ki Moon, Global views on modular design research: linking alternative methods to support modular product family concept development. *Journal of Mechanical Design*, 2016, Vol. 138(7), 071101.

[2] D. Lennartsson, D. Raudberget, K. Sandkuhl and U. Seigerroth, Modularization Metrics– Industrial Practice and State-of-Research. *Proceedings of the Design Society*, 2022, Vol. 2, 2483-2492.

[3] M. Porter and J. Heppelmann, How smart, connected products are transforming competition, *Harvard Business Review*, 2014, Vol. 92(11), pp. 64-88.

[4] P. Bernus, T. Goranson, J. Gøtze, A. Jensen-Waud, H. Kandjani, A. Molina, O. Noran, R.J. Rabelo, D. Romero, P. Saha and P. Turner, Enterprise engineering and management at the crossroads. *Computers in Industry*, 2016, Vol. 79, pp. 87-102.

[5] M. Blackenfelt, *Managing complexity by product modularization*, Doctoral dissertation, Maskinkonstruktion, KTH, Stockholm, Sweden, 2001.

[6] D. Krause and S. Eilmus, Methodical support for the development of modular product families. In: H. Birkhofer (ed.) *The future of design methodology*, Springer, London, 2011, pp. 35-45.

[7] L. Hvam, N.H. Mortensen and J. Riis, *Product customization*. Springer Science & Business Media, Berlin London, 2008.

[8] D. Lennartsson, D. Raudberget, U. Seigerroth, K. Sandkuhl, An Approach Towards Operationalization of Modularization Interfaces for Industrial Product Development*, Advances in Transdisciplinary Engineering*, 2022, Vol. 28, pp. 3-12.

[9] R.K Yin, *Case study research and applications*, Sage, Thousand Oaks, 2018.
[10] K. Sandkuhl, J. Stirna, A. Persson and M. Wißotzki, *Enterprise modeling*. Springer, Heidelberg, 2014.
[11] G. Erixon, *MFD–modular function deployment: a systematic method and procedure for company supportive product modularisation*. ISRN KTH/MSM/R-98/1-SE, 1998.
[12] F. Börjesson, Modular function deployment applied to a cordless handheld vacuum. In: T.W. Simpson et al. (eds.) *Advances in Product Family and Product Platform Design*, Springer, New York, 2014, pp. 605-623.
[13] H.P.L. Bruun and N. H. Mortensen, (2012). Modelling and using product architectures in mechatronic product development. In *DS 71: Proceedings of NordDesign 2012, the 9th NordDesign conference*, Aarlborg University, Denmark. 22-24.08. 2012.
[14] D. Krause and S. Eilmus, A methodical approach for developing modular product families. In *DS 68-4: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 4: Product and Systems Design*, Lyngby/Copenhagen, Denmark, 15.-19.08. 2011, pp. 299-308.
[15] M.T. Michaelis, H. Johannesson and H.A. ElMaraghy, Function and process modeling for integrated product and manufacturing system platforms. *Journal of Manufacturing Systems*, 2015, Vol. 36, pp. 203-215.
[16] M. Treacy and F. Wiersema, *The discipline of market leaders: choose your customers, narrow your focus, Dominate Your Market*. Addison-Wesley, Reading, 1997.
[17] P. Pfenning and M. Eigner, A novel procedure model for developing individualized digitalization strategies. In *Proceedings of the Design Society: DESIGN Vol. 1*, 2020, pp. 667-676.
[18] B.J. Pine and S. Davis, *Mass customization: the new frontier in business competition*, Harvard Business Press, Boston, 1993.
[19] T. Larsson and J. Åslund, ValueMap™-a Method for Understanding the Economical Potential of Product Modularisation and Cost of Variety. In Asko Riitahuhta et al. (eds.) *Design for Configuration*, Springer, Berlin, Heidelberg. 2001, pp. 215-222.
[20] F. Elgh, Automated engineer-to-order systems - A task-oriented approach to enable traceability of design rationale, *International Journal of Agile Systems and Management*, 2014, 7(3-4), pp. 324–347.
[21] K. Ulrich, The role of product architecture in the manufacturing firm. *Research Policy*, 1995, Vol. 24(3), pp. 419-440.
[22] J. Trolle, B. Fagerström and C. Rösiö, Challenges in the fuzzy front end of the production development process. *Advances in Transdisciplinary Engineering*, 2020, Vol. 13, pp. 311-322.
[23] L.E. Cánez, K.W. Platts and D.R. Probert, Developing a framework for make-or-buy decisions. *International Journal of Operations & Production Management*, 2000, Vol. 20(11), pp. 1313-1330.
[24] K. Kusaba, R. Moser and A.M. Rodrigues, Low-cost country sourcing competence: A conceptual framework and empirical analysis. *Journal of Supply Chain Management*, 2011, Vol. 47(4), pp. 73-93.
[25] R.B. Stake and M. Blackenfelt, Modularity in use-experiences from five companies. In *the 4th WDK Workshop on Product Structuring*, Delft, 1998, pp. 11-26.
[26] M.H. Meyer and A.P. Lehnerd, *The power of product platforms*. Simon and Schuster, New York, 1997.
[27] P. Kenger, G. Erixon and S. Lennartsson, Module Property Verification: A Conceptual Framework to Perform Product Verifications at Module level. In *The 14th International Conference on Engineering Design*, Stockholm, August 19-21, 2003.
[28] A. Rashid, F.M. Asif, P. Krajnik and C.M. Nicolescu, Resource conservative manufacturing: An essential change in business and technology paradigm for sustainable manufacturing. *Journal of Cleaner Production*, 2013, Vol. 57, pp. 166-177.