Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 109 (2022) 31–36

www.elsevier.com/locate/procedia

32nd CIRP Design Conference

Why to design modular products?

Jarkko Pakkanen[a,*], Tero Juuti[a], Timo Lehtonen[a], Janne Mämmelä[b]

[a]Tampere University, Kalevantie 4, Tampere FI-33014, Finland
[b]University of Oulu, Pentti Kaiteran katu 1, Oulu FI-90014, Finland

* Corresponding author. Tel.: +358503433751 . *E-mail address:* pakkanen.jarkko.t@gmail.com

Abstract

This paper is based on the development project of productivity by applying principles of product modularity and design reuse. The focus is on companies operating in manufacturing industry and specializing in large investment project deliveries. Analyzing the business impact of modularity is one method and tool used in modularization projects. The analysis is made to ensure that the investment in the development of modular products and the supporting way to operate is justified and supports the company's strategic business objectives. Preliminary business impact analyzes are usually carried out before the actual technical modularization project starts to justify starting the project. Analyzes are made also during the modularization project at different stages, for example to compare alternative concepts or module partitioning types. To support the business impact analysis of modularization, several possible benefits and value creation mechanisms have been identified in previous publications. These mechanisms can be linked to many stages of the product life cycle. This paper first reviews the main mechanisms of modularization through a literature review. In addition to this, based on an ongoing modularization project in a case study with investment product deliveries, we present as new information the latest findings on different potential benefits of modularization to reinforce the previous literature.

Keywords: Modularity; modularisation

1. Introduction

This paper discusses the potential benefits that can lead to the development of modular products. Our focus is on investment products. Modularity can be studied, for example, from the perspective of the company, the user and sustainability. The modularity of products affects the operations and efficiency of a company that manufactures products in many ways. Modularization aims to increase commonality within products without sacrificing variability. Modularity can also be beneficial to the customer, for example as easier repairability, refurbishing, technology upgrading, and finally, longer product lifetime.

Modularization should focus on areas that can be developed to achieve business benefits [1]. Modularization typically focuses on developing a unified modular architecture for the product portfolio [2]. Sections that are independent of other parts are encapsulated into their own modules [3]. The interchangeability of module variants is ensured, for example, by standardized interfaces [4] and space reservations between the product range [5]. Only product variants consisting of modules that are technically compatible with each other are sold to customers [6]. In this case, the description and management of the configuration rules and constraints of the product variant also are relevant [7]. Thus, modularization is a product development tactic that aims to make product modification, and through it, the entire company's operations more efficient in the sales-delivery process and in the later stages such as maintenance and product management.

From product management viewpoint, the modular system is managed as a whole, so that individual technical development projects per module variant do not destroy the value creation of the modular product portfolio for the company and the customer. All engineering change requests

10.1016/j.procir.2022.05.210

are assessed separately to see what they mean for the modular system. For example, the technical development work considers what the individual module variant is related to and what restrictions the environment of the module places on it.

In modularization, development measures must be targeted at areas where they have the potential to add value. Therefore, before starting a technical modularization project, it would be good to have at least some idea of what the modularization could enable and in which areas the modularization could be beneficial. Hence, this paper provides exemplary reasons why modularization could be taken. The contribution of the paper presents a list of different benefits that can be affected by the modularization. We have grouped the identified opportunities according to the typical functions and life cycle stages in the manufacturing industry based on a single case study. The list we present complements the existing literature on the value creation mechanisms of modularity, such as [8–10].

In the next section, literature review on modularization is presented. Then, research method is introduced in Section 3. After that, results are presented in Section 4 and discussion conclusions in Sections 5 and 6.

2. Literature review

Olesen [11] recognizes cost, throughput time, quality, efficiency, flexibility, risk, and environment as seven universal virtues that can be found in development projects. He explains that typically the focus is on some particular measure, but the other virtues are not completely neglected. Although the above-mentioned seven universal virtues can be associated with most development projects, more detailed virtues, or benefits in our context, related to modularization have been presented in the literature. Typically, these can be linked not only to these virtues but also to the typical life cycle stages of manufactured products. The following presents a brief overview of benefits and mechanisms related to modularization.

Considering product development and product data management, increased design reuse by modularization reduces the needed design effort per product delivery and may result in cost, quality, and time benefits [12,13]. Design reuse can occur in many levels such as solution [14], interface [2] and component levels [15]. By isolating design parameters from other parts of the design, it is easier to incorporate new solutions later on [3]. Also, possibility of new technologies should be considered in defining modular architecture [16] especially with products whose technology develops fast [14].

Number of mechanisms have been discussed relating sales and offering. In some cases, modularization might contribute to brand management [17,18]. It has also been said that modular products increase responsiveness to market changes [14,16] and fitting products to customer needs [13] and to local legislation and standards [19]. Modular products support product configuration and use of configurators in engineering and sales phases [20]. Using configurators may reduce lead time, increase quality of specifications, enable preservation of knowledge, and reduce the resource need for specifying the product [21]. Thus, part count reduction and use of common components in product variants may reduce product costs [10,15].

The impact of modularization on production, including sourcing of materials and components, prefabrication, logistics, on-site assembly, and commissioning and approval, has been addressed in many publications. Designing modular system off-line improves transparency and predictability of product creation process including production [15]. Increased commonality and availability of parts used may increase economics of parts sourcing and reduce the total cost of production [3]. Well-specified interfaces enable distributed assembly [22]. Modularity may enable transferring production from site to workshop. Existing assembly and operating environment may favor changing the place of manufacturing and assembly [23]. On the other hand, there has also been talk of late point differentiation, which aims at a smaller production inventory [24], keeping the product generic as long as possible, and allocating variation to only one or few parts [14]. Considering cost of transportation, standardized modules and lower number of assortment enable lower administration costs of logistics [14]. Also, architectural decisions define the needed packaging space and product protection requirements [10]. Modularization has impacts to the testing of modules. Separate module testing reduces feedback time compared to testing done after the main assembly [14].

The life cycle of a product often involves service and renewal work. At the end of the product life, the product is decommissioned, allowing the units to be recycled, remanufactured or reused directly [3]. Reuse of designs may improve the reliability of key components over the time because of incremental improvements and learning [15]. Configurability can be linked to product quality management [17]. In maintenance-based modularization, similar lifetimes of modules are recognized and replacing working components is avoided [25]. Modularization can be done in a way that replacing damaged areas is easy to do and down time is reduced [14]. Proper designing enables offering services for reducing the amount of waste by reusing [25] or recycling [14] the modules. Thus, there is possibility to increase the end-of-life value of product by modularization.

This section presented many reasons and benefits that can be achieved with modularization. The advantages and modularization methods discussed in the literature are often associated with mass-customizable products [20,26] where the batch size is usually more than one. The modularization research linked to mass customization deals with very little consideration of delivery-specific requirements and engineering-to-order (ETO). Example products are often fully configurable, consisting solely of pre-defined standard options from which the customer selects the appropriate ones such as motors [27–30], power tools [31–34], and various office items such as printers [25] and staplers [35]. There is little modularization research available for investment commodities where additional delivery-specific engineering is required in addition to applying principles of modularization. This is the main research gap that this paper contributes to. Some studies have been carried out, for example, in the field of construction industry [36], but the number is limited.

3. Research approach

This paper focuses on modularization benefits in engineering-to-order intensive investment products. The research includes two research questions (RQs):

1. What are the potential benefits of modularizing investment goods?
2. What are the modularity benefits of ETO area based on?

The research is based on a single case study. The research was conducted as part of an ongoing modularization project focusing on industrial investment assets. The authors of the paper participate in the company's development project as external experts. For business confidential reasons, we are unable to disclose details of the project such as the name of the company or product in question.

RQ1 is answered as follows. At the beginning of the modularization project, the business impact of the modularization was estimated. Here, a tentative list of potential benefits at different stages of the life cycle made by the authors of the article was utilized. The preliminary list was based on the authors experiences of previous modularization projects in which they had been involved. The initial list of benefits was first reviewed with the core team of the development project. The core team and other participants had previous experience in modularization. This was followed by separate workshops on the specific benefits of different life cycle stages and activities. This was done with a team of experts from each area of the company and authors working as facilitators. In the workshops, the preliminary list was modified based on the comments of the participants and was finally adopted as a starting point for the business impact analysis.

RQ2 focuses on the ETO area, as this has been little addressed in previous research. In our experience, the possibility of delivery-specific design is seen as value-adding (and even obligatory) in many other companies as an addition to the configuration of pre-designed options (modular system is designed offline outside the sales-delivery project and only some section of it is based on ETO). After reviewing the comprehensive benefit list (answer to RQ1), it was discussed in more detail with the participants what the benefits of the ETO area are based on. Mechanisms were identified that support the achievement of those benefits. Most of the factors were related to the existence of a certain style of design information. There were elements familiar to the authors of the article from previous projects, but previously unrecognized mechanisms that would support the achievement of ETO benefits were also highlighted in the discussions.

4. Results

This section presents the answers to the research questions described in the previous sections. Section 4.1 presents the answer to RQ1, and Section 4.2 contains the answer to RQ2.

4.1. Potential benefits of modularizing investment goods

Table 1 presents the identified benefits. We grouped the benefits based on the key life cycle stages and functions of the company. The possible benefits are briefly explained, but for the sake of clarity the table structure is emphasized.

Modularization was considered to provide many benefits in product development and product data management. Many of the individual benefits are related to the formation of a better overall understanding of the effects of design decisions, the reduced need to manage individual items, and the easier integration of new solutions into the modular product portfolio.

From sales and bidding perspective, the sales personnel have more complete design information available earlier. This makes it easier to prepare offers and allow more time, for example, to develop sales arguments and agree on customer and supplier responsibilities.

A lot of potential was expressed regarding ETO for efficiency in terms of time usage, iteration needs, and the number of revisions required, facilitating both design and design management.

Procurement benefits related to, for example, possibility to start the procurement process earlier, economies of scale, and better transparency of delivery times.

Increased number of predefined solutions means that more items can be prefabricated. Predefined solutions enable production development and require less quality control.

From logistics viewpoint, modularization can enable scheduling the transportations more precisely and earlier. In modularization, the most beneficial transportation type can be considered.

Assembly at the site is one of the most critical phases of the sales-delivery process. Modular solutions with predefined and proven solutions can enable several benefits such as cost reductions by transferring the work from site to workshop where possible.

Some modules can be tested separately without being attached to other modules. This enhances commissioning and approvals.

Number of benefits were also recognized regarding service. For instance, defined interfaces support upgradeability and retrofitting. Finally, modular system can be designed in a way that supports reusing and remanufacturing of modules. Thus, end-of-life value of the product can be affected in modularization.

Table 1. Potential benefits of modularizing investment goods

Product development and product data management
Optimization basics are more fact based and transparent
Expensive sub-optimizations are reduced
Enables avoiding expensive solutions (e.g., routing large pipes as directly as possible to decrease the number bends
Easier development of new module variants
Opportunity to predefine solutions for market-specific regulatory requirements (relates also to sales and offering)
Considering industrial design and brand related aspects in a controlled and systematic way as part of all deliveries
A standardized data structure can be introduced for product data management

Decrease of item number
Decrease in management need of items
Enabler of systematic product portfolio development
Better opportunities for simultaneous development
Product development resources can be distinguished from delivery project engineering resources
Cost information is more accurate and impact of changes on costs is understood better
Easier to train new employees when design rules, product structuring principles, and calculation principles exist
Sales and offering
Enabling and supporting additional sales during use phase
Material for the offer is more readily available and more standard
Opportunities to use structural documentation (specifications, graphs, pricing)
Options of pre-designed solutions instead of concepts can be presented during the sales
Cost information is more accurate and better understanding on the impact of changes on costs
More time to refine the arguments for the standard options offered. Once modular deliveries have been made for some time, one can state that the solutions are known and tried
Bidding requires less work and competence
A better shared understanding of the content of delivery is formed with the customer
Less and easier iteration rounds with the customer
Decreased variety of technical solutions enables building a brand image on a product
Brand impact
Ability to demonstrate serviceability
Sales teams have information about the benefits of modularity if modularity is communicated to customers
The cost and savings of modules are known earlier (earlier design freeze)
Creating value for the customer (more precise completion / delivery time known, earlier product use opportunity, lower construction costs, lower supervising costs, better safety, and less risks in the site vs. 100% ETO projects)
What is expected of customer (site works) can be informed more accurately
Enables an earlier request for information and guidance of entities integrated into the product provided by the customer
Engineering-to-order (ETO)
Basic engineering becomes easier
Basic design material will be provided complete for delivery project
Concept design changes from engineering task to selection task
Detail design can be started earlier
Errors of detail design decrease because of more complete starting data
Detail design task is easier
Detail design material will be provided complete for the delivery project
Less needs for iteration in engineering
Less drawing revisions
The time required by the engineering design is reduced or removed from the critical path of the delivery schedule
Engineering design management gets easier
Procurement of materials and components
Earlier start of procurement due to the earlier availability of design information
More accurate procurement enabled by the more complete and finished design information
No need to be prepared for changes in material procurements
More precise quantity of purchases known due to planned architecture, considering adequate working allowance (no need for extras)
Procurements can be made with the most advantageous method of acquisition as a single mass
Elimination of expensive express deliveries and subsequent deliveries because of unfinished engineering
More time to choose suppliers
Opportunity for annual contracts resulting in less need for competitive procurement
Managing delivery times becomes more transparent
Investing in manufacturing tools such as jigs becomes profitable as product variety decreases and management of variations improves
As order volumes increase and predictability improves, a transition to use more efficient manufacturing methods can be made
Prefabrication of predefined components and sections
Better opportunity to prepare for manufacturing work
Earlier start of manufacturing - better chance of finding a suitable fabrication schedule
Production documentation earlier to supplier (or supplier already has it if the solution is pre-designed)
Development of manufacturing work enabled by the increased similarity of product deliveries
Less negotiations, reviews and inspections
Development of manufacturing quality by methods of continuous improvement
Savings based on economies of scale (increasing order volumes)
Logistics
Improvement in scheduling site deliveries
Elimination deficiencies of site deliveries
Making transportable parts to fit typical container sizes (the effect may also be negative when the increase in the prefabrication rate produces larger and more difficult to transport parts)
Reduced (or increased) need for storage space at the installation site
Assembly at the site
Effect of ready-made plans on planning installation work and managing contracting
Benefits of better design of space reservations
Modules can be designed in a way that large scaffolding is not required
The transfer of work from the installation site to factory conditions enables cost reductions
The transfer of work from the installation site to factory conditions enables quality defect reductions
Use of prefabricated piping instead of single pipes: reduction of welding at the site
Supports development of systematic installation plans
Reduction of the site-days because of the transfer of work from the installation site to previous stages
Supports development of easier installation work by emphasizing clear routing and use of reserved channels
Increased similarity of installation work enables optimizing the correct installation order

Utilizing ready-made fasteners for parts
Enables use of more pre-installed equipment with elements transported to the installation site
Decrease in the need for consultation/negotiations, reviews and supervision
Extra work at the site is reduced or eliminated
Benefits from prior testing of prefabricated entities
Reduced need for crane due to defined lifting order and better liftability of parts
Higher quality material for negotiations
Decrease in construction waste
Decrease in delivery car traffic to the site (broader and pre-defined deliverables, traffic focused on the workshop)
Larger delivery sizes reduce noise and disruption at the site
Pre-built entities can be made with a more precise space reservation
Safety at the site improves because there is less site-intensive work
Commissioning and approvals
Impact of pre-made tests on commissioning
In prefabricated work, there is less need for repair than in the full installation in the site
Possible impact of using proven solutions
Enough time for "tuning" the product because of more precise scheduling
Automation deployment becomes more standardized
Service
Opportunity to develop more product systems and elements to be systematically replaced
With standard solutions, maintenance work becomes more standardized
Product development and service activities: for example, replacing partitions with new designs as planned
Upgradeability and retro fitting
Increased reliability due to component reuse
Reduction of faults due to the reuse of components
Learning due to the reuse of components and improvement of operations in service and repair
Service needs can be considered in design information structure
Health, safety, and environment: consideration of service and repair work
Renewal, decommissioning and reuse
Benefits of a more standard structure in renewals
Reuse of partitions made possible by a more standard structure

4.2. Mechanisms to support achieving modularity benefits in ETO

When discussing the benefits of the ETO phase, it was identified that those are because certain type of engineering design information has been developed and is available. In summary, the benefits were seen to be based on the availability and use of the following information:

- Bill-of-materials
- System and functional descriptions
- Work breakdown structure: supports activity-based costing
- Partitioning logic [37]: design reasoning of the modular system
- Design reasoning model: decision making sequence and deliverables
- Architecture of modular system: predefined layouts and design areas
- Technology catalogue: agreed solutions and principles to be reused in ETO sections
- Interfaces
- Configuration rules and constraints

5. Discussion

This article focused on the benefits of modularization. It should be noted, however, that there are also many challenges and points of vigilance associated with modularization. Developing a modular system is more difficult and expensive than developing a single functional product [3] but as a result, there are many benefits to be gained. The identified benefits could also be classified in the future in terms of whether they are, for example, medium-term or long-term benefits. In some cases, modularization has been done by first developing, for example, general boundaries for modular product family and then taking a single smaller entity from start to finish to gain the benefits and positive experiences of modularization more quickly. There might be conflicting cultural issues between project deliveries and the engineering design of modular systems among other challenges [37]. There are no correct answers for defining, for instance, reusable elements. For example, Holtta and Salonen studied the effects of the design method on the outcome of modularization [38]. Modular system causes new requirements for ICT systems because new kind of design information, such as interface documentations, emerges. There are many costs and challenges involved in product configuration [21].

The previous section presented the answers to RQs. The ETO aspect of the benefits of modularization was addressed in a more detail. Research could be continued by linking benefit-supporting mechanisms in more detail for all the benefits presented in the paper. The benefits could also be classified differently. For example, the division presented in Section 2 by Olesen [11], could be considered. Going through the list of benefit examples together with the participants in the case study, according to our observations, increased the understanding of the possibilities of modularization. The list of relevant benefits is probably different for different products and companies.

6. Conclusions

Considering modularity in products is not limited to mass-customizable products. The benefits supported by modularity are also of interest to companies whose products contain a lot of delivery-specific engineering. In this case, the challenge should be to find a suitable combination to increase commonality without losing the flexibility to customize where it provides significant value to the customer.

Based on the modularization project of an individual investment asset, the paper presented a list of potential benefits that modularization may allow. The potential benefits were comprehensively identified. Future research should focus on considering how the identified qualitative impact mechanisms could be developed into, for example, quantitative assessment tools to support modularization. As the background of the case company is in ETO business, the article briefly introduced the mechanisms supporting the modularization benefits of the ETO section. These are mainly related to the development of particular design information related to the modular system.

Based on the literature review, it appears that many of the benefits are consistent across investment goods and mass-customized products. Despite this, it seems worthwhile to continue focusing on partially configurable product structures that include both predefined and ETO-based elements. According to our findings, the approval of ETO as part of the development of the modular system and modular way to operate is necessary for many companies. As a hypothesis for the future, paradigm change from ETO to modular ETO (METO) is a well-known practice in the industry.

References

[1] Andreasen MM. 45 Years with design methodology. J Eng Des 2011;22:293–332. https://doi.org/10.1080/09544828.2010.538040.

[2] Fujimoto T. Competing to be really, really good – The behind-the-scenes drama of capability building competition in the automobile industry. Tokyo: International House of Japan; 2007.

[3] Baldwin CY, Clark KB. Design Rules: The power of modularity. The MIT Press; 2000.

[4] Parslov JF, Mortensen NH. Interface definitions in literature: A reality check. Concurr Eng 2015;23:183–98. https://doi.org/10.1177/1063293X15580136.

[5] Holmqvist T. Managing Product Variety through Product Architecture. Chalmers University of Technology, 2004.

[6] Bongulielmi L, Hensler P. The K- & V- Matrix Method - An Approach in Analysis and Description of Variant Products. Proc. 13th Int. Conf. Eng. Des. ICED´01, Glas. UK, 21-23 August 2001, Glasgow: Design Society; 2001, p. 5.

[7] Pakkanen J, Juuti T, Lehtonen T. Brownfield Process: A method for modular product family development aiming for product configuration. Des Stud 2016;45:210–41. https://doi.org/10.1016/j.destud.2016.04.004.

[8] Pakkanen J, Juuti T, Lehtonen T. Value Creation Mechanisms in Product Variety Development. DS 92 Proc. Des. 2018 15th Int. Des. Conf., The Design Society; 2018, p. 623–32. https://doi.org/https://doi.org/10.21278/idc.2018.0240.

[9] Pakkanen J, Huhtala P, Juuti T, Lehtonen T. Achieving Benefits with Design Reuse in Manufacturing Industry. Procedia CIRP 2016;50:8–13. https://doi.org/10.1016/j.procir.2016.04.173.

[10] Fixson SK. A Roadmap for Product Architecture Costing. In: Simpson, T.W., Siddique, Z. & Jiao RJ, editor. Prod. Platf. Prod. Fam. Des., New York: Springer Science+Business Media, LLC; 2006, p. 305–34. https://doi.org/10.1007/0-387-29197-0_13.

[11] Olesen J. Concurrent Development in Manufacturing - Based on Dispositional Mechanisms. Institute for Engineering Design, The Technical University of Denmark, 1992.

[12] Duffy AHB, Ferns AF. An analysis of design reuse benefits. 12th Int. Conf. Eng. Des., Design Society; 1998, p. 799–804.

[13] Juuti T. Design Management of Products with Variability and Commonality - Contribution to the Design Science by elaborating the fit needed between Product Structure, Design Process, Design Goals, and Design Organisation for Improved R&D Efficiency. Tampere University of Technology, 2008.

[14] Erixon G. Modular Function Deployment - A Method for Product Modularisation. Stockholm, Sweden: The Royal Institute of Technology; 1998.

[15] Sanchez R 1999. Modular Architectures in the Marketing Process. J Mark 1999;63:92–111. https://doi.org/10.2307/1252104.

[16] Harlou U. Developing product families based on architectures - Contribution to a theory of product families. Technical University of Denmark, 2006.

[17] Tiihonen J, Lehtonen T, Soininen T, Pulkkinen A, Sulonen R, Riitahuhta A. Modelling configurable product families. Proc. 12th Int. Conf. Eng. Des. ICED99, vol 2, Munich, Germany: 1999.

[18] Hopp WJ, Xu X. Product Line Selection and Pricing with Modularity in Design. Manuf Serv Oper Manag 2005;7:172–87. https://doi.org/10.1287/msom.1050.0077.

[19] Pahl G, Beitz W. Engineering Design: A Systematic Approach. vol. 11. Springer Science & Business Media; 2013.

[20] Victor B, Boynton AC. Invented Here: Maximizing Your Organization's Internal Growth and Profitability. 1998.

[21] Haug A, Shafiee S, Hvam L. The costs and benefits of product configuration projects in engineer-to-order companies. Comput Ind 2019;105:133–42. https://doi.org/10.1016/j.compind.2018.11.005.

[22] Lau Antonio KW, Yam RCM, Tang E. The impacts of product modularity on competitive capabilities and performance: An empirical study. Int J Prod Econ 2007;105:1–20. https://doi.org/10.1016/j.ijpe.2006.02.002.

[23] Lehtonen T. Designing Modular Product Architecture in the New Product Development. Tampere University of Technology, 2007.

[24] Lee HL, Tang CS. Modelling the Costs and Benefits of Delayed Product Differentiation. Manage Sci 1997;43:40–53. https://doi.org/10.1287/mnsc.43.1.40.

[25] Umeda Y, Nonomura A, Tomiyama T. Study on life-cycle design for the post mass production paradigm. AI EDAM 2000;14:149–61. https://doi.org/10.1017/S0890060400142040.

[26] Pine BJ. Mass Customization: The New Frontier in Business Competition. Boston, MA: Harvard Business School Press; 1993.

[27] Huang, C.-C. & Kusiak A. Modularity in design of products and systems. IEEE Trans Syst Man, Cybern - Part A Syst Humans 1998;28:66–77. https://doi.org/10.1109/3468.650323.

[28] Dai Z, Scott MJ. Product platform design through sensitivity analysis and cluster analysis. J Intell Manuf 2007;18:97–113. https://doi.org/10.1007/s10845-007-0011-2.

[29] Jiao J, Zhang Y, Wang Y. A generic genetic algorithm for product family design. J Intell Manuf 2007;18:233–47. https://doi.org/10.1007/s10845-007-0019-7.

[30] Kumar D, Chen W, Simpson TW. A market-driven approach to product family design. Int J Prod Res 2009;47:71–104. https://doi.org/10.1080/00207540701393171.

[31] Cai YL, Nee AYC, Lu W-F. Optimal Design of Hierarchic Components Platform under Hybrid Modular Architecture. Concurr Eng 2009;17:267–77. https://doi.org/10.1177/1063293X09352122.

[32] Dahmus JB, Gonzalez-Zugasti JP, Otto KN. Modular product architecture. Des Stud 2001;22:409–24. https://doi.org/10.1016/S0142-694X(01)00004-7.

[33] Stone RB, Wood KL, Crawford RH. A heuristic method for identifying modules for product architectures. Des Stud 2000;21:5–31. https://doi.org/10.1016/S0142-694X(99)00003-4.

[34] Alizon F, Shooter SB, Simpson TW. Assessing and improving commonality and diversity within a product family. Res Eng Des 2009;20:241–53. https://doi.org/10.1007/s00163-009-0066-5.

[35] Thevenot H, Nanda J, Simpson T. Redesigning Product Families using Heuristics and Shared Ontological Component Information. 2006 IEEE Int. Conf. Inf. Reuse Integr., IEEE; 2006, p. 330–5. https://doi.org/10.1109/IRI.2006.252435.

[36] O'Connor JT, O'Brien WJ, Choi JO. Critical success factors and enablers for optimum and maximum industrial modularization. J Constr Eng Manag 2014;140:1–11. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000842.

[37] Pakkanen J, Juuti T, Lehtonen T. Identifying and addressing challenges in the engineering design of modular systems – case studies in the manufacturing industry. J Eng Des 2019;30:32–61. https://doi.org/10.1080/09544828.2018.1552779.

[38] Holtta KMM, Salonen MP. Comparing Three Different Modularity Methods. ASME 2003, American Society of Mechanical Engineers; 2003, p. 533. https://doi.org/10.1115/DETC2003/DTM-48649