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# Modularisation Metrics - Contrasting Industrial Practice and State-of-Research

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**Abstract**
In many industrial sectors, modularization of products and services is considered as an important contribution to increased efficiency and competitiveness. Research has developed many modularization approaches, however, there is a gap between industrial practice in modularization and state-of-research in this field, which partly is due to shortcomings in "measuring" the value and state of modularization. This papers contribution is an analysis of industrial real-world cases to contrast practice and research, and a compilation of metrics in the context of modular product design from research.

*Keywords: modularisation, performance indicators, case study, product families, product development*

## 1. Introduction

In many industrial sectors, modularization of products and services is considered as an important contribution to increased efficiency and competitiveness. Among the many reasons are the potential for mass customisation, reduction of development costs, or suitability for loosely coupled production networks (Bonvoisin et al., 2016). Importance of modularization seems to grow in times of cyber-physical systems (Baheti & Gill), 2011) and quantified products (Sandkuhl et al., 2022) as the possibility of controlling behaviour of physical products by embedded and connected control units allows an even greater variability in physical products.
Research has recognized the importance and developed many approaches supposed to meet industrial modularization requirements, including design with modules, identification of modules, design of modules (Liang and Huang 2002), modular architectures (Baldwin and Clarke 2000) and economic perspectives on modularity in design for configuration (see section 2 for a detailed analysis). However, research on diffusion of innovation (Mustonen-Ollila & Lyytinen, 2003) and adoption of technology innovations (Baker, 2012) indicates that many context factors affect the adoption of innovations, one of them being the possibility to quantify and qualify the added-value of new approaches. Based on own experiences in modularization projects, our conjecture is that there is a gap between industrial practice in modularization and state-of-research in this field, which partly is due to shortcomings in "measuring" the value and state of modularization. Our observation is that metrics as such are not sufficiently connected to the strategies and economic effects enterprises expect them to support and express. "Environmentally friendly" or "maintainable" modular product design, to take two examples, can be operationalized by indicators from modularization metrics, which have been proposed by earlier research. But how this operationalization has to be done is based on the actual enterprise context and the application domain.
For this paper, we focus in particular on identification and design of modules and the support by metrics. Thus, the main research question is:
RQ: How can industrial modularisation processes be supported by modularisation metrics?

The paper is part of a research program aiming for the development of method and tools support for data-driven product modularization with metrics-supports as key feature. The intended contributions of this paper are (a) an analysis of industrial real-world cases to capture commonly used practices and requirements, (b) a compilation of metrics in the context of modular product design from research, (c) identification of gaps in industrial and research view on metrics with focus on modularization strategy and economic effects.
The paper is structured as follows: section 2 summarizes and discusses related work in fields relevant for the above research question. Section 3 briefly summarizes the research methodology used for the overall work. Section 4 investigates industrial cases of modularization and identifies practices for modularization processes and the use of metrics in the processes. Section 5 contrasts modularization metrics observed in industrial practice with metrics visible in scientific work for strategy aspects and economic effects. Section 6 gives an outlook on future work.

## 2. Related work within modularisation metrics

Modul Modularisation metrics is an area that´s been pointed out for the need of further development (Bonvoisin et al. 2016). Standardisation and definitions need to be improved in terms of key performance indexes (KPI) to facilitate calculations to measure and handle the complexity in product development (Shamsuzzoha et al. 2020). Standardisation and definitions need to be improved in terms of key performance indexes (KPI) to facilitate calculations to measure and handle the complexity in product development (Shamsuzzoha et al. 2020). There are several publications that address modularisation and interfaces, but metrics doesn't seem to be equally elaborated in the literature (c.f. Otto et al. 2016). There is however an example where quality cost is driven from the demand side. In this case customer data is used for analysis for a new modular structure (Aguwa et al. 2012).

### 2.1. Value disciplines as strategy for modularisation

One way to define metrics for modularisation is to justify them through three value disciplines; Operational Excellence, Customer Intimacy, and Product Leadership (Treacy and Wiersema 1997). Operational Excellence is defined as delivering a product efficiently at the lowest price. Customer Intimacy is the ability to adapt the product to the needs of individual customers. Finally, product Leadership is to supply a product that is better than the competition.
With a business case as foundation these three disciplines can then serve as a base to define and make different metrics operational within each discipline and as enterprise quality criteria. The three disciplines in the strategy are often unique for each product and provide the base for metrics to use for a specific modularization initiative. The three disciplines can therefore serve as a base to make informed decisions about the modularisation strategy. The potential return on investment (ROI) for the modularisation initiative can then be calculated using the value map method and ROI through using Return on Capital Employed (ROCE). This will provide metrics for the modularization initiative as cost per part number, direct and indirect cost per variant but also process related goals such as order to delivery, increased market share, higher production volumes on articles that reduced development and production costs.

### 2.2. Instrumental support for modularisation

There are several methods, frameworks, and guidelines for modularisation; Modular Function Deployment (MFD) (Erixon 1998), Systematic architecting (Otto et al. 2016), Functional platform modelling (Johannesson et al. 2017), a collection of different modularisation methods (Baldwin and Clark 2000), just to mention a few. In this section we will describe MFD in more detail since this framework was used to a major part in the detailed case study that is described in section 4.2. MFD is a framework that consists of several phases with corresponding instrumental support in each step (Erixon 1998), see figure below:

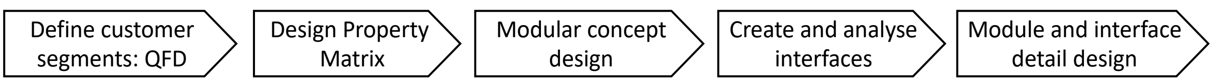


**Figure 1. Phase in modular function deployment**



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The process starts with the definition of customer segments and their needs through a simplified QFD, (Akao and Mizuno 1994). Here, the product properties are defined for the product architecture, and connected to customer requirements. The customer requirements are ranked for different segments in cross-functional workshops.

The next step is to create the Design Property Matrix (DPM), that connects the properties to components and functions. If a component is not fulfilling the suggested goal values for properties, new solutions are needed. Often, a functional tree decomposition (Tjalve 1976) is used for identifying new technical solutions. The results from the DPM are used to formulate the modular concept. Components and functions are transferred to the Modular Indication Matrix and module drivers are used to make sure that the clustering of components into modules are consistent with the total product architecture. Tools such as dendrogram and mind maps can be used to support this process and the result is a module concept with defined properties (goal values) that serve as input to the subsequent detailed design. Interfaces are one of the most important quality attributes in modularization and therefore, in the next step, the interface concept is created and analysed for the whole architecture. In the last step, detailed module and interface specifications are created. This process is iterative, and the project metrics in the form of goal values need to be checked over the entire project that are used as the input for the detail module and interface design.

Metrics from MFD are: the number of modules and module variants (article numbers), number of products, lead time from order to delivery, purchasing volumes, module life length and time to market for new products. These metrics has an important impact on the concept selection process and the profitability of a company, but the business case is missing.

Otto et al. (2016) presents a methodology for modularisation and product architecture in early development phases. Just like MFD, it is a framework of known methods and unique adaptions. It consists of 13 steps ranging from market segments to a selection of architectures. Metrics are not specifically mentioned, but the generational variety index rating and the variety allocation model can be used to guide the modularisation work. Again, the business case is missing.

Other metrics are given in (Shamsuzzoha et al. 2020). They present a way for module division through Design Structure Matrix (DSM) and highlight metrics such as: number of components, number of interfaces, and dependencies of components. In the paper, these are used to assess the complexity of the design but not the impact on the economic results.

Given the plurality of metrics in literature, it is not clear how these can support and guide the modularisation processes from a business perspective. Some metrics are retrospective in the sense that they are calculated after the design is done, and thus cannot drive the work in a strategic and profitable direction. Other metrics, such as complexity, have an impact on the business case performance, but it's unclear how these may be used for creating a modular architecture. It is therefore important to develop better metrics to also support the business case and production phase of modules in a modularisation project.

## 3. Research Methodology

The research approach used is a combination of literature study and case study. Since the literature study showed a gap between industrial practice in modularization and state-of-the-art in research we also conducted case studies (section 4). According to (Yin 2018) the case studies in this paper are exploratory, as they are used to explore modularisation metrics. Based on the case study material and the literature, we derive metrics in the context of modular product design (section 6). One of the authors in this paper has actively been involved in all the cases which means that we have been able to extract and reconstruct empirical data from his experiences and case documentation. In the literature we have searched for and identified relevant articles in Scopus and we have found 60 articles elaborating on different metrics connected to modularisation, see section 5 below.

## 4. Industrial Cases

When investigating the research question presented in Section 2, we analysed several industrial cases summarized in Section 4.1. For brevity reasons, only one of the cases is described in more detail



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and used for illustrating challenges and procedures of industrial modularization and metrics use (section 4.2). Results of the case analysis are presented in Section 4.3.

## 4.1. Summary of the three case studies

From 2001 to 2018, the authors actively participated in several industrial projects that aimed at introducing new modularization architectures or strategies in manufacturing enterprises. Four Three of these projects resulted in material sufficiently rich to be analysed in a scientific paper, see (Table 1) below.

**Table 1. Industrial cases**

| Case | Domain | Modularization focus | Applied techniques |
|---|---|---|---|
| A | Train supplier | Train coupler | Business case + KPI, MFD, Module production |
| B | Industrial equipment | Chain conveyor | Business case + KPI, MFD, External supply chain |
| C | Automotive / trucks | Truck | Variance matrix |

For all case studies, we collected documents, minutes of meetings and interviews with company representatives, field notes taken when working with the companies, models of processes, information structures and business models, and other relevant information. This material concerns the situation before starting the modularization process, the intermediate steps taken and the situation at the end of the project. Due to brevity reasons, we only describe A in more detail. The other 2 cases (B and C) were also analysed for deriving the challenges and requirements for metrics use in modularization.

## 4.2. Modularisation of train coupler

The work procedure that we applied in this case was divided into four general phases; (1) Scoping and business case, (2) Module concept development, (3) Module and interface design and (4) Manufacturing system design. The phases are depicted in figure below.

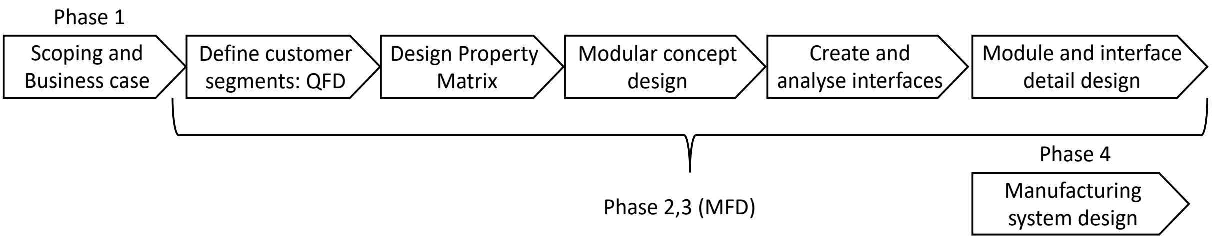


**Figure 2. Phases in train coupler case**

### *4.2.1. Phase 1: Scoping and business case*

The purpose in this phase was to develop an understanding of the financial potential of modularization and to find a suitable strategy based on the three value disciplines in section 2.2, Operational excellence, Customer intimacy and Product leadership. The potential of a modularization initiative was calculated by proposing initial modularisation metrics and project goals, based on reviewing the current product offering, challenges from the field and future development. Conventional economical metrics, such as the return on investment and Return of Investment were derived from the Value Map. Modularisation specific goals were used as an input to the value map, based on company specific requirements. These requirements were manifested through costs for the current product structure, such as cost per part number, number of parts currently in use, number of new parts introduced, production volumes, number of customer and markets etc. For the train coupling case, the goals are described in (Table 2) below.



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**Table 2. Business strategy and modularization goals and metrics**

| Strategy | Metrics | Goal coupler |
|---|---|---|
| Operational excellence | Shorter Time to Customer | Four weeks |
| | Increased reuse of development resources | 70 % reduction of development hours |
| Product leadership | New technologies | Double acting damper<br>Internet in cables |
| | Increased reuse of components | 50 % reduction of article number |
| Customer intimacy | More product variants | 4000 New products |
| | Increased customer satisfaction | No problems in the field |

The number of modules and their life span was related to the reduction of article numbers and, to no problems in the field in the way that the modules were consistent in quality. The lead time from order to deliver and purchasing volumes, were depending on the reduction of article numbers.

### *4.2.2. Phase 2: Module concept development*

This step was executed according to the MFD framework that consists of several methods, that were used depending on the specific needs of the company. The starting point was to define customer segments and their needs through a simplified QFD. Using QFD, the desired product properties were defined for the product architecture and connected to the customer requirements in a matrix. This cross-functional approach involved different roles, such as product management, R&D, purchasing, production and quality departments.

The next activity was to create a Design Property Matrix that connected components and functions to product properties. When new technologies were introduced, the required functions were identified through a function driven decomposition, and for mature technologies, the component functions were already known. At this stage, previous problems from the field were also addressed to increase the product quality.

The modules were then integrated into a product architecture by combining technical solutions into modules in the Module Indicator Matrix and the dendrogram. In this phase it was important to consider the characteristics of each module, e.g. to identify the interaction relations between modules. As an example, it was important to avoid combining module drivers that pull in opposite directions such as combining a common unit in a module requiring high variability. A common unit was reused as a carry-over to new projects.

To continue the modularisation, we then moved on to the Design Property Matrix and Module Indicator Matrix. The result of the Design Property Matrix and the Module Indicator Matrix was a proposed modular concept for architecture that was iteratively refined in concert with detailed design and interface design. Now, the number of articles, module and product variants could be calculated together with the corresponding inventory level to compare this with the current situation and to the project goals. Moreover, the properties for all modules, including new technologies, were suggested as an input to detailed design and to be negotiated during the design process. The properties were quantified in order to be measurable and possible to use in the detailed design.

As an example, the goal "no problems in the field" was solved by a major re-design. In this case, the project risks were handled by keeping the same/compatible interfaces and reusing the old solution as a back-up. Part of the modular concept, the centre section, with goal values and interfaces are presented in (Figure 3) below.



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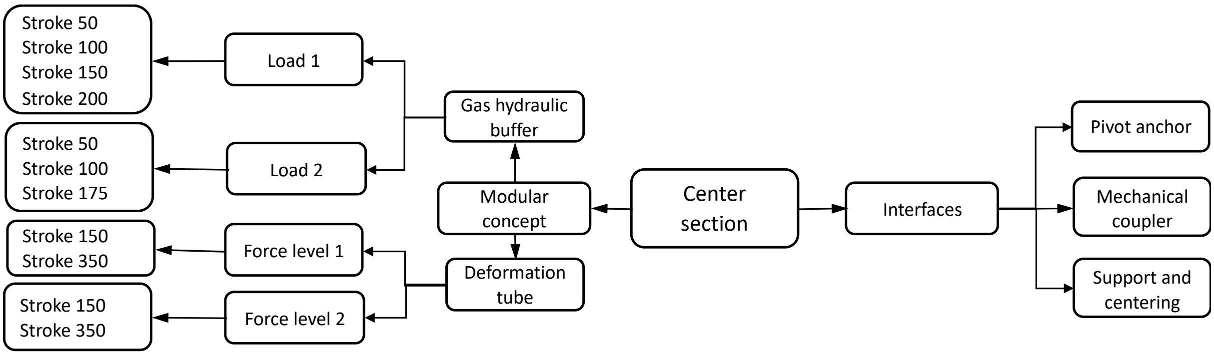


**Figure 3. Module concept and interface concept for centre section**

### *4.2.3. Phase 3: Module and interface design*

In a modular design, its mandatory to create both detailed design of the artefact and interface design. For the module socket joint both the attachment, interface design and module design were done in parallel. The interfaces were documented separately, which was important to facilitate sufficient reuse of modules to reach the modularization goals. In the analysis of all interfaces, it had to be clear what modules that were reused and what modules that were new. Here, it was important to consider if a new module was presenting any risks and if an old solution had to be kept as a back-up. In this case, the interfaces had to be compatible between both designs.

A separate Interface requirement specification was used in this project to describe geometric interface design, tolerances and non-geometric properties such as the required tension in the fasteners and the properties that was used for detailed design. In this case it was the torque, bending moment and buff load that the interface must handle. The socket joint is modularized in two performance levels that handle different force levels. A part of the interface and detail design requirements are shown in the figure below.

**Force level 1**

☐ The interface shall be capable of taking a buff load of __ kN and a draft load of __ kN.
☐ The interface shall be capable of taking a moment of __Nm in vertical direction.
☐ The interface shall be capable of taking a moment of __Nm in horisontal direction.
☐ The interface shall be capable of taking a rotational moment of __Nm.
☐ The interface is highly exposed for fatigue loads.

**Force level 2**

☐ The interface shall be capable of taking a buff load of __ kN and a draft load of __ kN.
☐ The interface shall be capable of taking a moment of __Nm in vertical direction.
☐ The interface shall be capable of taking a moment of __Nm in horisontal direction.
☐ The interface shall be capable of taking a rotational moment of __Nm.
☐ The interface is highly exposed for fatigue loads.

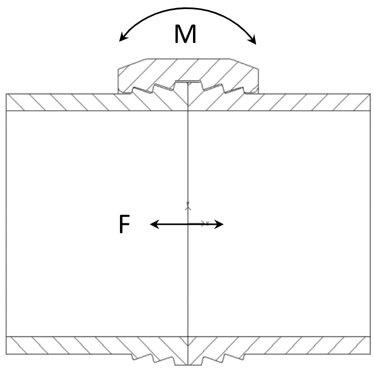


**Figure 4. Excerpt interface design of centre section in coupler**

Metrics in the form of number of products, number of module variants and number of articles were carried over from the module concept, but it was depending on the result from the detailed design. A redesign may be done to achieve the modularization goals. This shifts the focus from an Engineer to Order to a Configure to Order strategy. Thereby most modules are configurable, combined with design of new modules to fit each customer.

### *4.2.4. Phase 4: Manufacturing system design*

For an internal supply chain, a modular production was designed. The vision was to create a production/supply chain where modules were manufactured in parallel to reduce lead-time and by making them arrive in time for final assembly. This reduces lead-time made it possible to test each module before assembly and enabled a late customer order point.

Production metrics were not defined in the initial business case, since they were dependent on the module concept and couldnt be prepared until this was ready. Module production was prepared based on the module concept and was iterated in in collaboration with detailed design.



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Production preparation started with QFD, based on stakeholder requirements, defining properties for production system connected in the QFD. Production properties including goal values were used as metrics for developing the production system. These properties were: tied-up capital reduction, Lack of quality cost, Delivery precision etc. Stakeholders were (environment, production, safety etc.), production management, quality and maintenance. In some cases, the customer wanted to audit the development of the production system.

## 4.3. Analysis of case studies

All analysed cases show the systematic use of metrics within the industrial modularization processes, which indicates the industrial relevance of the topic. The analysis of the industrial cases aimed at creating a better understanding of industrial practices, challenges, and requirements in the field of modularization and metrics use in this field. For this purpose, we focused on modularization strategies and economic aspects, and the indicators used in these phases. Again, we will use the train coupler case study to illustrate our analysis.

The case company produces components for the train industry according to an Engineer to Order strategy. The industrial goal was to be more competitive by reducing product and production costs, and to enable the introduction of new technologies in a new product family. Moreover, the goal was to increases the number of variants in the offering and reduce costly quality issues. Below is a summary of the development metrics developed in the case. It presents the initial state, the modularization goals and the results.

**Table 3. Modularisation metrics**

| Strategy | Metrics broken down from strategy | Current | Modularisation goal | Modularisation results |
|---|---|---|---|---|
| Operational excellence | Shorter Time to Customer | 40 weeks | 4 weeks | 12 weeks |
| | Increased reuse of development resources | 100% development hours | 30% (70 % reduction of development hours) | 50% |
| Product leadership | New technologies | - | Double acting damper Internet in cables | New technology implemented |
| | Increased reuse of components | 100% | 50 % reduction of article number | 50% |
| Customer intimacy | More product variants | 300 products | 4000 New products | 5000 new products |
| | Increased customer satisfaction | Vital quality problem in the field | No problems in the field | 80 % reduction in quality costs |

The results indicate that all goals were not met. The shorter time to customer and reuse of development resources was not met during the project since some module variants were not developed until required by customers. When a need for a new module variant comes, it is developed using the already defined/designed interface as a basis and the full potential for reducing design hours are not achieved until all modules are designed. The goal was to have 20% Engineer to Order in the final stage. Furthermore, the new situation with a 10-fold increase in products made the manual configuration time consuming since there were no working methods to handle/configurate a catalogue of so many combinations. For the production, the economic results are shown in (Table 4) below.

**Table 4. Production metrics**

| Metrics from production properties | MSEK/Year | Metrics from production properties | MSEK/ Year |
|---|---|---|---|
| Tied-up capital reduction | 3,0 | Blue collar workers | 1,0 |
| Lack of quality cost | 7,2 | Less cost for contract manufacturing | 10-15 |
| Delivery precision | 2,5 | | |



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Based on modularization strategy and economic aspects, we extracted the metrics most prominently used in the work of the train coupler case and the other three cases:

**Table 5. Metrics summary**

| | Metrics | Train | Conveyer | Truck | | Metrics | Train | Conveyer | Truck |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Shorter Time to Customer for new product variants | x | x | | 7 | Increased customer satisfaction | x | x | x |
| 2 | Increased reuse of development resources | x | | | 8 | Interface design | x | x | x |
| 3 | Increased efficiency in the value chain | | x | | 9 | Interface knowledge developed through product life-cycle | x | x | x |
| 4 | Shorter TTM for new technologies | x | x | | 10 | Organizational knowledge development | x | x | x |
| 5 | Increased reuse of components | x | x | x | 11 | Late point of differentiation | x | | |
| 6 | More product variants | x | x | x | | | | | |

Some of these metrics obviously are straightforward to operationalize (e.g., part number reduction), others are composed of several indicators (e.g., shorter time to customer new variants) and again others are quite general and difficult to capture and implement (e.g., organisational knowledge development). For the general ones, refinement of the metrics for use in modularization will be necessary. To take an example, "organisational knowledge development" could be refined into (number of) entries in organisational knowledge base on inter-dependencies, characteristics and technical details of interfaces.

## 5. Contrasting modularisation metrics in research and practice

Based on the observations from the industrial cases presented in (Table 5), we see a need for additional research on modularisation metrics:

- Industry uses techniques, such as QFD and E-FD, that can be supported by metrics visible in research on modularization metrics. However, there seems to be no established practice what metrics to apply in what step of the modularization process to support the task at hand.
- Research offers a rich body of knowledge on modularization and relevant metrics, but industry only uses a fraction of theses metrics. Based on discussions with practitioners, our conjecture is that many metrics are considered as either difficult to implement or difficult to interpret as they are too fine-granular, i.e., their meaning only shows in the context of other metrics.
- the metrics applied by industry (see section 4.3) are a selection of what was proposed by research but lack operationalisation and consistent implementation.

To further qualify the research need, we analysed presence of the industrially used metrics in existing publications in the field of modularization. The purpose of the analysis was to identify candidates for integrative conceptual models suitable as basis for more consistent operationalization in industry. The table in (Figure 5) below present an excerpt from the complete literature analysis. The columns marked 1 to 11 refer to the metrics listed in section 4.3. In the cells of the table, we use

- X: the use of this metrics is explicitly mentioned or visible in the article
- (x): the use of this metrics is assumed, but this can only be deducted from the context of the application (implicitly contained)

The analysis shows that there is no publication explicitly covering all metrics, which also implies that there seems to be no conceptual or ontological model in use covering all metrics with mutual interdependencies or semantic relations. Some papers contain 8 or 9 of the 10 metrics in a combination of explicit and implicit use, which indicates that the combination of the metrics identified in our case studies does not only make sense in industry but also seems to be reasonable from a research perspective.



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The majority of papers focuses only on the use of a small part of the discovered metrics for specific purpose.

Not surprisingly the combination of metrics often used in the publications is directly related to product architectures or modularization design, whereas the more context-related metrics are less visible. Context-related refers here to secondary value creation tasks inside the enterprise but with relation to modularization and external factors. This gap between modularization-dependent and context-oriented metrics might be an explanation why there is no conceptual model covering all metrics.

| | **Publications** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | ## | ## |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Function and process modeling for integrated product and manufacturing sytems plattforms Marcel T. Michaelisa,∗, Hans Johannessona, Hoda A. ElMaraghyb( 2015) | | x | (x) | x | | | | | | | |
| 2 | Voice of the customer: Customer satisfaction ratio based analysis Celestine C. Aguwa ⇑, Leslie Monplaisir, Ozgu Turgut( 2012) | (x) | (x) | | (x) | | | x | (x) | | | |
| 3 | Modularisation in two Global Product Developing Companies-Current state and Future Outlook Dag Raudberget1, Samuel André1, Fredrik Elgh1( 2018) | (x) | x | | x | | | (x) | x | | (x) | (x) |
| 4 | The Design Structure System: A Method for Managing the Design of complex system DONALD V. STEWARD (1981) | | x | | (x) | | | x | | | | |
| 5 | Product family design and platform-based product development: a state-of-the-art review Jianxin (Roger) Jiao · Timothy W. Simpson Zahed Siddique (2007) | (x) | x | (x) | x | (x) | (x) | x | | x | x | (x) |
| 6 | Developing Flexible Modules- a Pragmatic Way to Organize and Reuse Engineering assets D. Raudberget1, K. Hörnmark, B. Younadam | | x | | (x) | | | (x) | | | | (x) |
| 7 | Co-platforming of products and assembly systems Mohamed Abbas, Hoda ElMaraghy ( 2018) | (x) | x | (x) | x | (x) | (x) | | | (X) | | |
| 8 | Global Views on Modular Design Research Alterative Research : Methods to Support Modular Product Family Concept Development Kevin Otto, Katja Hölttä-Otto, Timothy W. Simpson, Dieter Krause,Sebastian Ripperda, Seung Ki Moon (2016) | | x | (x) | x | | (x) | x | (x) | | | |
| 9 | Concurrent Design of Product Families and Reconfigurable assambly systems April Bryan, Hui Wang, Jeffrey Abell( 2013) | | x | (x) | x | | (x) | | | (x) | | |
| 10 | Integrated product-process modelling for platform based co-development Thomas Ditlev Brunoe, Ann-Louise Andersen, Daniel G.H. Sorensen, Kjeld Nielsen & Mads Bejlegaard( 2020) | x | x | | x | | | (x) | | (x) | | |
| 11 | Enterprise Knowledge Based Database for New Product Development process K. M. Tham, S. A. Sharif and B. Kayis 2006 | x | x | (x) | x | | (x) | | | | | x |
| 12 | DEVELOPMENT OF MODULAR PRODUCT FAMILIES Christoph Blees, Henry Jonas and Dieter Krause 2010 | x | x | (x) | x | | (x) | (x) | (x) | | | |
| 13 | An integrated method for flexible platform modular architecture design Zhongkai Li , Zhihong Cheng a , Yixiong Feng & Jinyong Yang 2013 | x | x | (x) | x | | | (x) | (x) | (x) | x | |
| 14 | A Strategy for Managing Customer-oriented Product Design Ming-Chyuan Lin, Chen-Cheng Wang and Tzu-Chang Chen 2006 | (x) | x | | x | | | x | (x) | x | x | |
| 15 | A QFD-based optimization method for a scalable product plattform Xinggang Luo , Jiafu Tang & C. K. Kwong 2013 | (x) | x | | | | | x | (x) | | | |
| 16 | A product module identification approach based on axiomatic design and design structure matrix Qiang Cheng, Guojun Zhang, Peihua Gu and Xinyu Shao 2012 | | x | | | | | | (x) | | | |
| 17 | A Methodology of Integrating Marketing with Engineering for Defining Design Specifications of New Products Kwong, Chen, Chan( 2011) | | | x | (x) | | x | x | | | | |
| 18 | A methodology for developing product platforms in the specific setting of the housebuilding industri Vanessa S. Veenstra Æ Johannes I. M. Halman Æ Johannes T. Voordijk 2006 | x | x | | (x) | | x | x | | | | |
| 19 | A high-definition design structure matrix ( HDDSM) for the quantative assessment of product architecture Andrew Harold Tilstra , Carolyn Conner Seepersad & Kristin L. Wood 2012 | (x) | x | (x) | (x) | | | | | x | (x) | |
| 20 | A cost calculation model for the optimal design of size ranges David Mueller 2010 | (x) | x | x | | | x | | | | | |
| ⋮ | | | | | | | | | | | | |
| 60 | A Modeling Approach for Correlation's Evolution of Modular Product Family. Yue Yang and Xibin Wang. (2009) | (x) | x | (x) | x | | | x | | (x) | | |
| 61 | Research on product innovation design of modularization based on theory of TRIZ and axiomatic design. (Zhong-hang Bai et.al 2018) | x | x | x | x | | x | | | x | | |
| 62 | A Pragmatic View of Knowledge and Boundaries: Boundary objects within New Product Development Paul R. Carlile (2002) | | | | | | | | | | (x) | x |

**Figure 5. Excerpt from literature analysis**



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## 6. Future research

Based on the results of the case study analysis and the comparison of modularization metrics in research and practice (section 5), the most important future work will be to develop integrative conceptual models suitable as basis for more consistent operationalization in industry. This model would have to include the "traditional" modularization metrics and the context-oriented ones. In this context, we propose to consider the pragmatics and intended semantics of the metrics more as "higher-level" quality attributes that reflect how well the modularization strategy and the economic effects are supported. These quality attributes would have to use the established metrics as underpinnings but allow for company-specific interpretations and configurations. The results in the case study also indicate to the importance of starting a modularisation initiative with a busines case. Our conjecture is that it will be important to have a business case as a foundation and that the business case should be the driving force to guide all the phases that are described in (Figure 2) above. This will be part of future research and integrate a review of existing work on value creation mechanisms of modularisation (Pakkanen et al. 2016).

One of the biggest shortcomings of our work is that we base our findings only on three industrial cases and observations from these cases. Future work will have to address this shortcoming by widening the empirical base, for example with an interview study among a larger number of enterprises to confirm the importance of the identified metrics for strategy and economic aspects.

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