ASSESSING MODULARISATION TRANSITION WITH METRICS

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Abstract

Modularisation is a major area of interest within the field of engineering design. In order to support engineers in establishing modular product architectures, researchers have published a wide variety of modularisation metrics.
However, no research has been found that surveyed the implementation of modularisation metrics in companies transitioning from single product development toward modular system development.
For this reason, this paper seeks to close this gap by providing a set of six coherent metrics for modularisation transition.
The metrics were developed in close collaboration with industry and tested and applied in a company transitioning toward modularisation.
The metrics assess three different levels. First, the business level is assessed for senior managers that have a focus on the overall modular system. Second, result-oriented metrics provide support for engineering managers and senior engineers. Third, product architecture metrics support design engineers on detailed product level already during early design phase.
Validation of the metrics in industry showed that the metrics are applicable in industry and support companies in modularisation transition.

Keywords: Product architecture, Complexity, Product families, Platform strategies, Systems engineering (SE)

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1 INTRODUCTION

Diverse, dynamic and fluctuating market needs push companies to provide an increasing range of products more quickly than ever before. This leads to high-mix and low-volume product portfolios which are more costly for companies to develop, produce and deliver than mass-produced products. Especially modular product architectures are seen as appropriate means to provide high variety of product functionality while reducing internal effort for designing, producing and delivering products (Pahl et al., 2007).

No matter if modularisation is seen as improvement initiative, project or process, it requires many different aspects to be considered. In general, it is essential for a company to carefully monitor and analyse projects, processes and improvement initiatives (Slack et al., 2006). This is also true for modularisation (Heilemann et al., 2012). An appropriate means for such evaluations are metrics (Kreimeyer and Lindemann, 2011).

Although extensive research has been carried out on modularisation metrics in academia, there remains a paucity of information on how modularisation is measured in industry. Moreover, only scarce resources exist which examine metrics that monitor the transition of a company from single product development toward modular system development.

In order to close this gap, it is the aim of this paper to provide a coherent set of validated metrics with the purpose to assess modularisation transition in industry. Instead of coming up with totally new modularisation metrics, it is rather the purpose of this research to show how metrics have been adopted and tailored to daily needs in industry. Thus, the key research questions addressed by this work are as follows: What are existing metrics related to modularisation in literature? What are requirements for metrics assessing modularisation transition in industry? Which metrics are proposed to assess modularisation transition in industry?

In order to answer these research questions, this paper has been divided into five parts. Chapter 1 introduces this work. Chapter 2 briefly guides through existing literature. The third chapter is concerned with requirements for metrics assessing transition toward modularisation. Chapter 4 is the main contribution of this work and presents metrics to assess modularisation transition. Finally, chapter 5 concludes this work.

2 LITERATURE REVIEW

2.1 Definitions

The characteristics of complexity can be defined as a) diversity of elements (Franke et al., 2002; Malik, 2003), b) intensity and diversity of interactions between elements (Ehrlenspiel, 2007; Franke et al., 2002; Gomez and Probst, 1997; Malik, 2003) and c) system dynamics (Gomez and Probst, 1997). It is a main goal of modular product architectures to reduce complexity.

All products possess an architecture, which means the organisation of parts and components into assemblies. However, product architecture design is not only seen as decomposition activity but mainly as a starting activity of development (Erens and Verhulst, 1997). In order to acknowledge the impact of product architectures, the definition can be extended from "composition of a product from a number of component products" (Erens and Verhulst, 1997) to "(1) the arrangement of functional elements, or the function structure; (2) the mapping from functional elements to physical components; and (3) the specification of the interfaces between interacting components" (Ulrich, 1995).

According to the definition of Ulrich (1995), a modular architecture embodies a one-to-one mapping between functional and physical elements. This means that a certain product function is realized by one defined module. In an integrated architecture, a certain product function is realized by several different physical elements or vice versa. Thus, there is no one-to-one mapping in an integral product architecture. Another characteristic of modular product architectures is that the interfaces are de-coupled. This means that a design change within one module does not require a design change in another module - provided that the product still works as intended (Ulrich, 1995).

In practice, products may possess a certain degree of modularity, which means that the product is neither fully integral nor fully modular (Salvador, 2007).

In order to improve commonality between different products, the architecture can also be defined on the level of a whole product portfolio. This extended architecture makes different products having (a) the same functionality embodied by the same elements, (b) common arrangement between elements and (c) standardised interfaces between elements (Martin and Ishii, 2002).

In the course of this work, the elements of a modular architecture that are established across a wider range of products is called a modular system (Pahl et al., 2007). In other words, a modular system is a set of predefined module variants which (a) follow the same designated product architecture specification and (b) have the purpose to derive final product variants of the portfolio.

2.2 Modularisation metrics

Researchers have introduced a wide variety of metrics assessing modularisation. For the purpose of this work, these metrics have been classified according to principles and benefits of modularisation:

2.2.1 Product architecture metrics

Holtta and Otto (2005) use functional product structures to measure the modularity of products. The goal of the metric is to reduce redesign effort by placing complex interfaces inside modules and less intricate interfaces between modules. Other researchers strive to achieve functional independency of modules and therefore derive metrics to measure functional-physical relations (Mattson and Magleby, 2001; Steva et al., 2006). Physical interactions between components are well researched and measured by coupling metrics (Holtta-Otto et al., 2012). It is the goal of coupling metrics to achieve de-coupled modules that are less sensitive to change in other parts of the product. In order to achieve similarity in the architecture of different already existing products, it is the goal of bill of material (BOM) similarity metrics to measure similarity of the architecture of different products (Geng et al., 2008; Romanowski and Nagi, 2005).

2.2.2 Measuring commonality, complexity and variety: Result-oriented metrics

Commonality metrics measure the degree of commonality between products like the degree of common components or common interfaces. Other researchers enrich these commonality metrics by adding information like cost, value, shape, size, material or by adding weighing criteria to measure only commonality that is actually desired (Simpson et al., 2014; Thevenot and Simpson, 2006).

Variety and flexibility as necessary counterparts to commonality are measured by cross-product and generational variety metrics. For instance, Rapp (1999) introduces simple variety metrics that measure the potential to create variety behind a number of products. The future potential of an architecture to create variety is measured by the Generational Variety Index (Martin and Ishii, 2002), or derived by the Change Mode and Effect Analysis (Keese et al., 2006).

2.2.3 Reporting on management level: Business level metrics

Metrics measuring strategic factors

Suitability of a product architecture for post life intent (e.g. recycling, reuse, incineration and land filling) is measured by a metric that compares compatibility of components that are inside a module (Newcomb et al., 1996). This principle is extended to other product life cycle processes by Gershenson et al. (1999). Their metric evaluates to what degree the components inside a module use the same product life cycle processes. Fixson (2005) provides a framework to assess the effects of a product architecture alternative on other supply chain and process domains. Adoptable to nearly all strategic factors that a company pursues with modularisation, Blees et al. (2009) qualitatively measure to what extent a product architecture alternative complies with the goals of a company.

Metrics measuring cost and profit

Above mentioned measurements either have a direct or indirect effect on cost and profit of an organisation. In turn, these effects can be measured indirectly (Martin and Ishii, 1996). In contrary, other researchers directly measure the cost effects of different architecture alternatives (Fixson, 2004; Fixson and Blanchard, 2001). Park and Simpson (2005, 2008) make even more detailed analyses and use an activity-based costing approach in addition to cost for direct material and labour.

2.3 Summary

The literature review shows that existing modularisation metrics tend to focus either on a single step in quite isolated new product development projects, or on the assessment of dissected products. Moreover, complexity of some metrics themselves and difficult data gathering to calculate the metrics might pose a real problem for industrial application. Therefore, it is suggested that if assessment of product architectures shall be applicable for modularisation transition in practice, an adopted approach is needed.

3 REQUIREMENTS FOR MODULARISATION ASSESSMENT FROM INDUSTRY

The requirements that were used to derive modularisation metrics have been collected in two different studies that are described in section 3.1 and 3.2. The fulfilment of these requirements can be seen as success and test criteria for validation (see section 4.4).

3.1 Process and document analysis

Data for this section was collected during participant-observer field-research in industry with a major global manufacturer. The study also included several benchmark partners from nine benchmark organisations of different size, operating in different industries.

Modularisation activities of the collaborating organisations were analysed and taken to derive requirements for metrics assessing modularisation transition. These requirements can be briefly summarised as follows:

- Poorly defined customer requirements, poor forecasts and lack of focus on those product features that are profitable made it impossible to create a common and stable reference architecture for the product portfolio. Therefore, a stable reference architecture starts with focused input from product management across all products. "Focused" in this sense means concentration on most efficient product variants. This variance efficiency has to be measured during modularisation transition.
- A common product architecture across a wide product portfolio has positive effects on overall company performance. However, it might compromise cost, functionality or performance of products that were originally developed in single product development projects. Thus, engineers and engineering managers who still have the focus on single projects might try to bypass the reference architecture by creating optimised solutions for their products and not for the overall architecture. Therefore, new assessments have to be in place during transitioning that emphasise the importance of the overall architecture compared to the goals of single products (local optimum vs. global optimum).

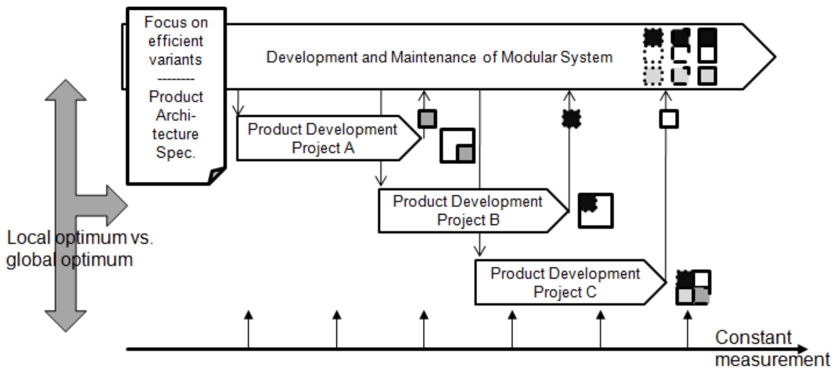

Figure 1: Overall framework for assessment of modularisation transition in industry

3.2 Survey in industry

A study by Heilemann et al. (2013) collected requirements of industrial practitioners for assessment of product architectures during modularisation transition. The requirements of this study which are relevant for this work can be summarised as follows:

- It is more important to assess the architecture of the whole product range derived from the modular system than that of single products or only small product ranges.
- The most important effects of modularisation to assess are external variety, internal complexity and reuse of physical elements. Other modularisation effects were only weakly prioritised during the study.

- Practitioners prefer to have several distinct metrics instead of one condensed metric.
- The metrics must be simple and easy to calculate with information that can be provided by standard IT-systems.

Figure 1 shows how the collected requirements have been condensed into an overall framework with frequent measurement points for assessment of gradual modularisation transition in industry.

4 SUGGESTED MODULARISATION METRICS

It is the purpose of this chapter to provide metrics that fulfil the requirements of the previous chapter and to give industrial practitioners an assessment approach that supports them during modularisation transition.

Following a goal-driven methodology (Park et al., 1996), the metrics were developed based on existing literature and in close collaboration with industry. The process describes how to come to final measurements with the help of business goals, sub-goals, detailed requirements and available input data elements.

Before applying this assessment approach, following premises have to be fulfilled:

- Definition of product portfolio that shall be derived from modular system
- Definition of requirements for product portfolio
- Reference architecture of modular system
- Product architecture specification of modular system

Once these premises are in place (e.g. through a modular system development process), the company can start measuring its progress during modularisation transition. The metrics for this measurement are divided into a business level for senior engineers, result-oriented metrics that shall give guidance for engineering managers and into product architecture related metrics that shall give guidance for engineering designers. Figure 2 shows an overview of the metrics and how they correlate.

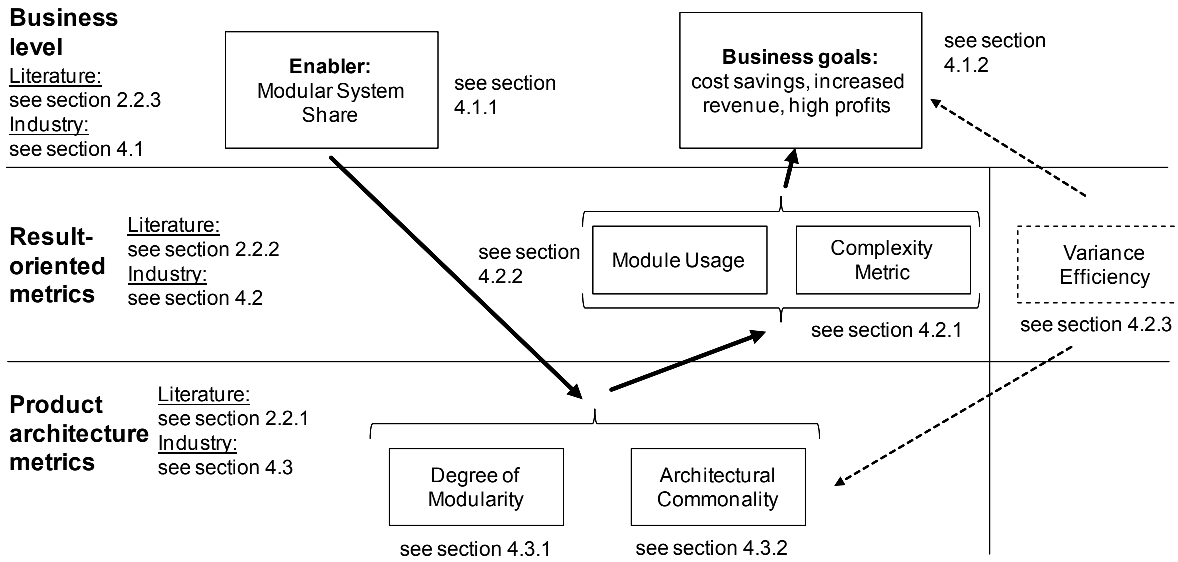

Figure 2: Proposed metrics for assessment of modularisation transition, their interdependencies and their relation to metrics from literature

4.1 Business level metrics

On a high level, it is assumed that the share of products that are directly derived from a modular system influences the company's business goals. Therefore, there is one directly measurable metric to consider on the level of business goals and the business goals themselves:

4.1.1 Share of products derived from modular system (as enabler for business goals)

This metric measures the proportion of revenue of products that are based on the same modular reference architecture in relation to the revenue of all products in scope. For example, "scope" in this sense could mean in car industry that all products with transverse mounting position of the engine are under the same scope. Instead of the sales volume of products, it was decided to take the revenue of the products as it gives more weight to important products.

- **Purpose:** The metric monitors the gradual increase of products that are derived from the modular system. It gives responsibility to a senior product management role to actively contribute to the design of the modular system and to use the modular system whenever specified.
- **Calculation of metric:**

$$\text{Modular System Share} = \frac{\text{Revenue of all products based on modular system}}{\text{Revenue of all products in scope}} \quad (1)$$

- **Hints:** It is important to define the criteria when a product is based on a modular system. For instance, it is possible that only two out of five modules of a product are based on the modular system, especially during transition phase. In this a case, the company has to decide to which category the product is added or if the product is proportionally distributed to both categories.
- **Example:** Following disguised graphs show how this metric can be used for management reports on a corporate level. Even though the figure is exemplified, it has its background in industrial application.

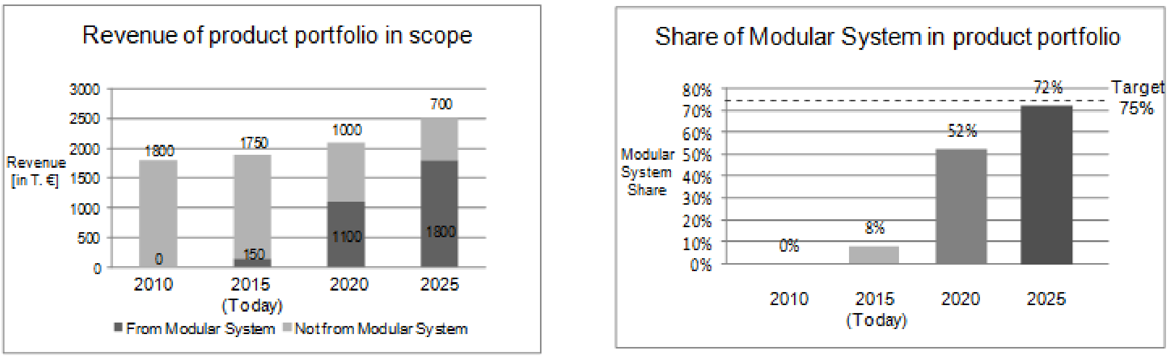

Figure 3: Exemplary calculation and reporting of Modular System Share

4.1.2 Business goals affected by modularisation

Business goals are affected by the modular strategy through benefits from modular system development. Although other goals are not explicitly excluded, it is the aim of this work to focus on cost reduction and profitability improvement through improved complexity. However, there are too many different factors influencing these business goals. That means that they should not be measured in directly if there shall be a relation to modularisation transition. Therefore, these goals have to be further broken down into modularisation result-oriented metrics and product architecture metrics. These more detailed metrics are described in the next sections.

4.2 Result-oriented metrics

Modularisation can positively influence business goals if it reduces complexity of a company without compromising variety offered to the customer. Moreover, modules have to be reused wherever appropriate and it has to be avoided that unnecessary product variety is generated. Following metrics measure the fulfilment of these sub-goals.

4.2.1 Complexity Metric

This metric measures the relation of internal complexity that the company has to handle in relation to external product variety which is offered to the customer. Thus, it reflects the sub-goal of the company to derive required external variety with little internal complexity.

- **Purpose:** It is the purpose of this metric to measure the ability of the modular system to generate high variety with low internal complexity. Therefore, it helps to optimize the modular system concerning flexibility and complexity. A low value of the metric indicates that high variety can be offered to the customer with low internal complexity.
- **Calculation of metric:** (see equation (2) below)

$$\textbf{Complexity Metric} = \frac{\textbf{\# of distinct parts in modular system}}{\textbf{\# of all saleable product variants derived from modular system}} \quad (2)$$

- **Hints:** For large and complex product portfolios it is not straight forward to determine the number of parts in the modular system. For this reason, the company needs a clear definition which parts to include in the calculation and how ordinary BOMs can be used to calculate the number. This metric can be extended by considering distinct interfaces in the numerator as well.
- **Example:** Following disguised graphs show how this metric can be used for management reports on a corporate level, but also for engineering reports during product development projects. Even though the figure is exemplified, it has its background in industrial application.

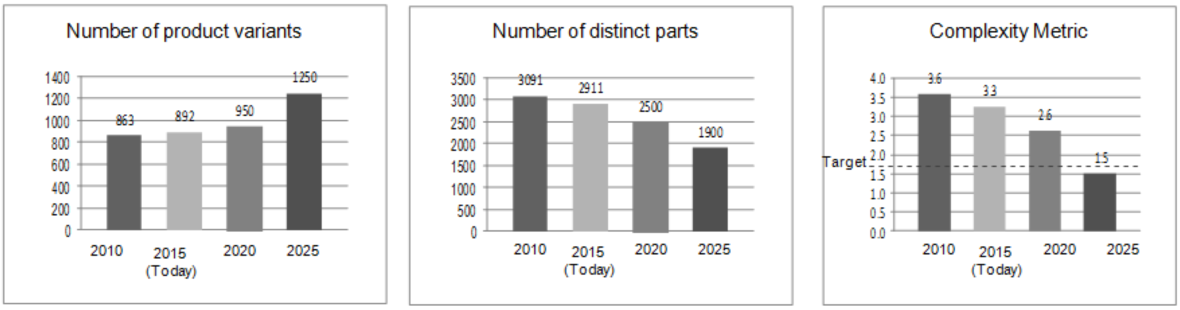

Figure 4: Exemplified calculation and reporting of complexity metric

4.2.2 Module usage

This metric measures how often module variants of a certain module are used within distinct products of the product portfolio in scope.

- **Purpose:** This metric supports the sub-goal of the modular system of lower internal complexity through high reuse of module variants and high commonalities.
- **Calculation of metric:** This metric is calculated separately for each module of the modular system.

$$\textbf{Module Usage} = \frac{\sum_{i=1}^{n} \textbf{usages of module variant i of respective module}}{\textbf{\# module variants from the respective module (=n)}} \quad (3)$$

It is assumed that each module of the modular system comprises n different product variants. Furthermore, it is assumed that the sum of the usages of module variant n equals the number of product variants in which the respective module variants are used. This consideration might ease calculation effort.

- **Hints:** It is not the task of every module to contribute to commonality. Some selected modules have the purpose to generate variety through distinct features. Therefore, it is important to set different target values for different modules. For instance, Alizon et al. (2009) distinguish between "common", "variant" and "unique" modules.
- **Example:** Following disguised graphs show how this metric can be used for management reports on a corporate level, but also for engineering reports during product development projects. Even though the figure is exemplified, it has its background in industrial application.

Module	Module Category	Σ of Usages	# Module Variants	Module Usage	Module Variants				Overview
Cylinder Body (CB)	Standard	4	1	4.0	CB 1 4 usages				Actual Target min. max.
Valve Unit (VU)	Standard	4	2	2.0	VU 1 1 usage	VU 2 3 usages			Actual Target min. max.
Rod Fastening (RF)	Variant	4	3	1.3	RF 1 2 usages	RF 2 1 usage	RF 3 1 usage		min. max.
Mounting (MO)	Variant	4	4	1.0	MO 1 1 usage	MO 2 1 usage	MO 3 1 usage	MO 4 1 usage	min. max.
Cover (CO)	Unique	3	3	1.0	CO 1 1 usage	CO 2 1 usage	CO 3 1 usage		min. max.

Figure 5: Exemplary calculation of Module Usage Metric

4.2.3 Variance efficiency

Even though, it is the aim of a modular system to generate high variety, it is also a requirement of section 3.1 to only focus on variety that is really profitable. This constrain is necessary to ensure stability of the modular system. This is because a modular system can only capture variety within certain boundaries. For this reason, a further auxiliary metric is introduced which has an impact on product architecture commonality as well as the overall business goals (e.g. profitability) of the company. The metric measures the share of sold product variants with a certain volume to the share of all saleable product variants that are derived from the modular system.

- **Purpose:** It is the purpose of this auxiliary metric to prompt product managers to focus on profitable products in order to contribute to the efficiency and stability of the modular system. Moreover, the availability of such a metric makes it clear to everyone that the market analysis has to be done properly and that fixed product management decisions have to be done at the beginning of the project. A poor value of the metric might also give a hint on unprofitable products which have to be removed from the portfolio.
- **Calculation of metric:** This metric is calculated as follows:

$$\textbf{Variance Efficiency} = \frac{\textbf{\# product variants sold with sales volume} > X}{\textbf{\# all final product variants derived from modular system}} \quad (4)$$

  The critical target value X for the sales volume has to be defined for each modular system separately.
- **Hints:**
  - During the concept phase of the project, it can be useful to derive the sales volume of each planned product from the estimated customer demand for each product feature. This is in line with the premise that there has been a dedicated modularisation process (see section 3.1) in place in order to get a sound base for calculation of metrics.
  - It is possible to extend the metric by taking revenues into account instead of sales volumes.
  - It is possible to extend the metric by deriving the critical target value X from an ABC-Analysis. Thus, the critical target value X of the Variance Efficiency can be divided into several categories (see example).
- **Example:** Following disguised graph shows how this metric can be used for management reports on a corporate level, but also for product management reports during product development projects. Even though, the figure is exemplified, it was developed during a pilot project in an industrial project and discussed with partners from other industries.

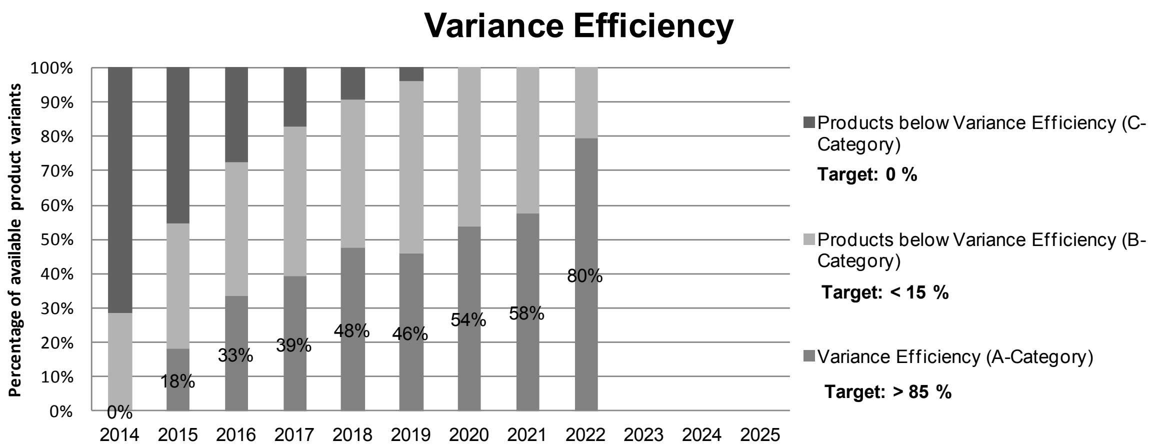

Figure 6: Exemplified calculation and report of Variance Efficiency of product portfolio

4.3 Product architecture related metrics

Even though it is argued that measuring modularity of a product as an end in itself is not important (Gershenson et al., 2004), product architecture metrics are added to this assessment framework for various reasons. First, metrics on business level and result oriented metrics do not directly measure where complexity is created, namely by design engineers on product architecture level. By bringing the product architecture level on board for assessment, it is ensured that deviations from the reference product architecture, which might endanger business goals in consequence, are detected and corrected at a very early stage. The suggested (dependent) metrics are as described in the following sections.

4.3.1 Degree of modularity

This metric heavily depends on the assumption that a) the product architecture is the composition of a product of component products on a lower level, b) a module is an organisational construct with a certain strategic purpose and c) a module is not the same as an assembly. If an integral and a modular product architecture are the two architectural extremes, this metric measures how modular a product is.

- **Purpose:** It is the purpose of this metric to quantify the degree of modularity of a single product or of a set of products. Using this metric on product level, deviations from the target degree of modularity of small product ranges can be detected early on during modularisation transition.
- **Calculation of metric:** This metric can either be calculated separately for each product of the modular system or for a series of products if their BOMs are joined. The company has to carefully define what it considers as "item" in the formula. It could only be "physical items" like components or a combination of physical items and "virtual" items like assemblies and modules.

$$\textbf{Degree of Modularity} = \frac{\textbf{\# items in first level module variants}}{\textbf{\# items of product}} \quad (5)$$

- **Hints:**
  - The metric can be used to calculate the modularity on system, product or module level. It only considers the modularity of the considered item, not the modularity of a higher or lower level. For instance, if this metric is applied on product level, it does not consider the degree of modularity of the contained modules themselves. For such considerations, the metric has to be applied on the module itself.
  - This metric is meaningless if it is applied for itself. For full information extraction (global optimum vs. local optimum), it has to be applied together with the metric in the next section.

4.3.2 Architectural commonality

The previous metric calculates the degree of modularity of a single product or of a set of products. However, if a product is modular, it does not mean that it is necessarily derived from a modular system, i.e. that it is based on the same reference product architecture as a wide range of other products. Moreover, it might not always be the target to move toward complete modularity - even for a company that is transitioning toward modularisation. For instance, it could be the decision of a car company to derive everything but the design parts of a car from a common modular system.

For these reasons, a further metric is needed that measures the compliance of one or more products with the designated reference product architecture that was designed during modular system concept phase. Only if the modules of a product are designed to meet overall architecture specifications, they can be systematically reused in other variant and future products.

- **Purpose:** It is the purpose of this metric to calculate the compliance of the modular part of a product's architecture with the overall reference architecture of the modular system. Moreover, it shows the "character" of the modular part of the product by providing figures about module variants.
- **Calculation of metric:** This metric can either be calculated separately for each product of the modular system or for a series of products if their BOMs are joined.

$$\textbf{Architectural Commonality} = \frac{\textbf{\# module variants in line with reference product architecture}}{\textbf{\# module variants of product}} \quad (6)$$

- **Hints:** It has to be noted that this metric only measures the modular part of the product architecture. In order to fully utilize the potential of a modular system, it should be the goal of the company to achieve complete architectural commonality across the products in scope (even if the ultimate goal is not complete modularity of products).

4.3.3 Exemplified calculation of product architecture related metrics

It is possible to use these metrics as guide and reporting support for engineers during modularisation projects. However, the metrics of this example were calculated on already existing products and evolved during discussions with engineers about how modular their products are and how common their product architectures are in relation to the reference architecture.

Sample Product 1:

This product is partly modular with 78% Degree of Modularity as the majority of its components are organised into modules. The modular part of the product could be beneficial for maintainability, or upgradeability of the single product. However, it is not built from a modular system because there is only poor architectural commonality with the company's reference architecture. This negatively influences exchangeability of modules with other products of the company and, thus, commonality. In the example, only one module can be systematically exchanged with other products of the company.

$$\text{Degree of Modularity} = \frac{194}{250} = 78\ \% \qquad \text{Architectural Commonality} = \frac{1}{19} = 5\ \%$$

In this specific example, the engineers insisted on the opinion that they have a modular product already and that there is no need to participate in modularisation transition. However, the quantification with help of the metrics revealed that this is only half the truth as it is necessary to design products based on a common reference architecture in order to fully benefit from modularisation.

Sample Product 2:

Figure 7 shows a simplified example of the calculation of the "Degree of Modularity" metric which is done on single product level. The "Architectural Commonality" which is also done on single product level could be extended to generate a single metric that gives a statement about the whole product portfolio.

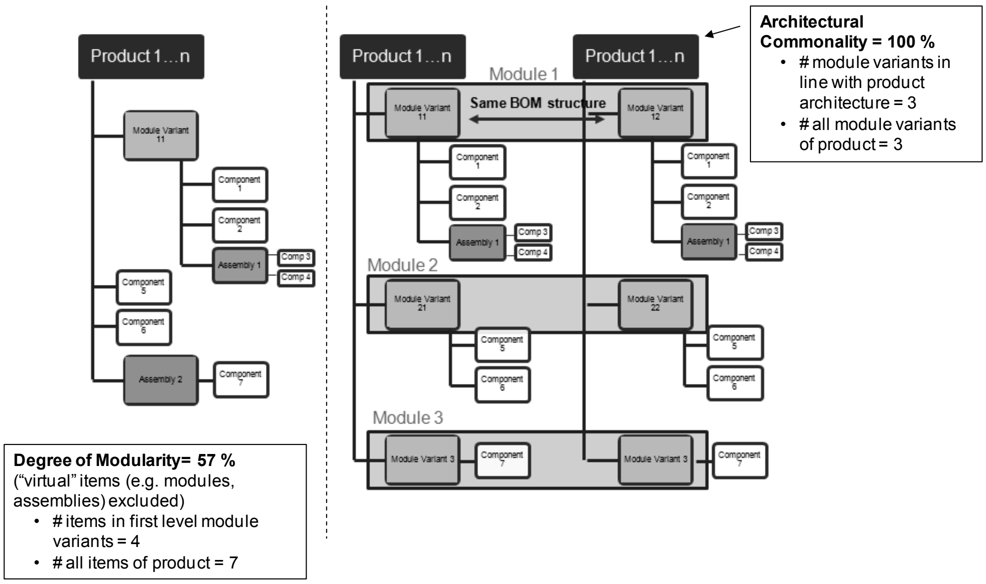

Figure 7: Example for calculation of "Degree of Modularity" (on the left) and "Architectural Commonality" (on the right)

4.4 Validation of metrics

Confidentiality agreements made it not possible to show detailed results of validation in industry. Therefore, exemplified results were given in previous sections. However, the content behind the examples is well-founded and substantiated with industrial application. The presented metrics evolved in close collaboration with industrial practitioners. In detail, these examples have their source in a) benchmark studies, b) discussions within academia and industry, c) sample calculations, d) selecting decision process to implement the metrics in industry and e) regular industrial application. Thus, it can be concluded that the metrics are sufficiently validated against applicability in practice and against the requirements from chapter 3.

5 CONCLUSION

In sum, this study provides six diligently derived metrics which were tested in industry and partially implemented as metric dashboard at a major global manufacturer. Therefore, this study makes an important contribution for engineering companies with the strategy to transit toward modularisation.
In contrary to most studies found in literature where the metrics help to improve single products, this study shows how companies can assess their overall transition progress toward modularisation. After few amendments, the presented category of metrics on business level and the result-oriented category are quite close to what can be found in literature. However, the main difference to literature for this sort of metrics is that the presented metrics could be easily derived with standard IT-systems. Moreover, this work shows what kind of metrics are the most promising ones out of the massive bulk of available metrics for gradually transitioning companies. In this sense, this work serves as support for companies that want to reduce complexity, first, with concentration on their most efficient products and, second, with products that are derived from modular systems that strive for a global instead of a local optimum.
More theoretical "product architecture metrics" have their value in early detection of deviations from architecture goals and for well-reasoned discussions with engineers about how their product contributes to modularisation transition and how their products can be improved to contribute to the global "performance" of the portfolio. The presented metrics of this category constitute a new approach and show a significant difference to what was found in literature. This difference is mainly caused by different input factors that are easier to derive in industry.
Detailed issues like controlling factors for the metrics (e.g. "How can be proceeded if a module is outsourced?", "How to proceed with untidy BOMs?", "Shall assemblies be counted as parts or are they virtual items?") and how data was gathered were excluded from this report, although these are important topics. Thus, it should be a topic of future research how product architecture information for efficient calculation of modularisation metrics can be provided within companies.

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