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EXAMINATION OF MODULARIZATION METRICS IN INDUSTRY

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ABSTRACT

It is the aim of this paper to examine applicability of modularization metrics in industry. For this purpose, two studies were designed. The first study collects requirements in industry for the application of modularization metrics. The second study mirrors modularization metrics from literature to main application requirements from industry. It has been revealed that efficient calculation of modularization metrics is a main requirement of industry. However, there is a gap between information needed to calculate existing metrics and product architecture relevant information that is available in standard IT-Systems like PDM- or ERP-Systems. Thus, only few existing metrics meet the main requirement of efficient calculation. This gap can be closed by developing modularization metrics that either have a diligently selected information content or by introducing product architecture relevant information into standard information systems of companies.

Keywords: modularization, product architecture, product family design, platform design, system design

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1 INTRODUCTION

If companies want to stay profitable in today's highly competitive markets, they have to find the right means how to profitably fulfill agreed customer requirements with low internal complexity. From the perspective of engineering design, it is claimed that this endeavor can be supported by designing modular product architectures.

The large volume of publications on product architecture design covers diverse supportive means for modularization. Central to product architecture design and modularization is the assessment of product architectures (Heilemann et al., 2012). For this reason, various metrics measuring the performance of product architectures on different levels of abstraction can be found in literature.

Even though, the identified metrics consider relevant factors that are used to establish product architectures, it has not yet been examined whether the metrics are actually applicable for introducing them into daily practice in industry.

Thus, it is the purpose of this paper to examine modularization metrics in the context of their suitability for implementation in industry.

This paper has been divided into three major parts. It starts with the review of modularization metrics from literature. It then presents requirements for modularization metrics from a survey in industry. Finally, as the survey in industry showed that it is very important that product architecture assessment does not load additional effort on engineers, a second study examines how applicable existing metrics are in daily practice.

2 MODULARIZATION METRICS IN LITERATURE

The benefits of modularization can be seen technically, in the whole value chain and on the financial side. In detail, the targets pursued with modularization are manifold. For example, modularity is related to fast time to market, high product variety, cost reduction, or end-of-life impact of the products (Fixson and Clark, 2002). For this reason, researchers have developed metrics not only to measure the degree of modularity of products or product families but also to measure the expected benefits and drawbacks that are related to certain types of product architectures (Holtta-Otto et al., 2012).

2.1 Metrics measuring the degree of modularity

The degree of modularity of a product architecture can be measured by considering product functions and the interactions between a product architecture's elements. Compared to the analysis of interactions, the consideration of functional product properties seems quite rare. For example, Holtta and Otto (2005) use functional product structures in their metric for architectural assessment. The relation of functional elements to physical elements of the product (to assess functional independency of modules) is measured and compressed into a modularity metric by Mattson and Magleby (2001).

A considerable amount of literature about modularity metrics has been published on the analysis of interactions and interfaces between components. Screening literature databases for modularity metrics identified 18 metrics. The metrics consider interfaces, interactions and dependencies between components in order to get high interaction levels inside a module instead of between modules. These include for example, the Singular Value Modularity Index (Holtta-Otto and De Weck, 2007), Degree Modularity (Sosa et al., 2005)and the Modularization Function (Mikkola, 2006). A selected set of these metrics have been reviewed in recent years by Van Eikema Hommes (2008) on similarities and differences and by Holtta-Otto et al. (2012) with a focus on bus modularity.

2.2 Metrics measuring the results of product architecture design

Metrics developed by researchers to measure the effects of a certain degree of modularity assess certain objectives that are related to modularization. These can be characterized as commonality and variety, or strategic and financial objectives and are summarized below:

Commonality and variety effects

Thevenot and Simpson (2006) review six metrics to assess product architectures concerning commonality. More recent commonality indices can be found in Blecker and Abdelkafi (2007) and Johnson and Kirchain (2010). As commonality has always to be balanced with the objective of diversity, the assessment of product variety is introduced and usually combined with commonality

assessment (Thevenot et al., 2007; Möller et al., 2011; Döpke et al., 2009; Beisheim and Stotz, 2013; Rapp, 1999). Martin and Ishii (2002) develop a generational variety index (GVI) which measures the ability of a product architecture to adopt for future requirement changes. Keese et al. (2006) develop a change
mode and effect analysis (CMEA) to measure the flexibility of a product architecture concerning planned and unknown design changes.

Strategic and financial effects
How different product architectures match different viewpoints of the post life intent is measured by Newcomb et al. (1996). Gershenson et al. (1999) develop a metric to assess similarities and dependencies between parts and related life cycle processes and Blees et al. (2009) assess different product architectures on their fulfillment of company strategic objectives.
Gonzalez-Zugasti et al. (2001) assess the monetary value of different product architecture alternatives. Metrics that assess product architecture cost can be found on different detail level. Martin and Ishii (1996) indirectly measure the effect of the product architecture on indirect cost. More detailed approaches directly measure product architecture related cost (Fixson and Blanchard, 2001; Fixson and Clark, 2002; Siddique and Repphun, 2001; Park and Simpson, 2008).

2.3 Summary
The literature review suggests that a large number of metrics exist that assess product architectures directly as well as the related effects. However, preferences from industry how to assess product architectures are not clear. Moreover, it is also not clear on which level to assess product architectures. Therefore, a study which is described in the next section was set up to bring clarity into this topic.

3 REQUIREMENTS FOR MODULARIZATION METRICS FROM PRACTICE - STUDY A
The aim of this section is to find out the requirements that industrial practitioners have for assessing product architectures, especially (but not limited to) if they embark upon a modularization strategy.

3.1 Research Methodology
In order to get a high reply rate from industry, it was decided that the best method to adopt for this investigation is to use a semi-structured questionnaire approach (Blessing and Chakrabarti, 2009). After screening literature about important factors concerning modularization metrics, questions were collected that can be asked to industrial partners. However, as the amount of potential questions was quite high, it was decided to preliminarily select the most adequate and practical questions. The selection of questions also had the purpose of limiting the minimum duration for completing the mandatory section of the questionnaire to five minutes in order to improve the reply rate. The final questionnaire design and the selection of questions evolved during discussions with industrial practitioners, trying to find out which questions they want to have answered. 49 participants were selected because of their senior engineering and management positions but also because of their involvement in modularization activities and projects. Most of the approached participants were from the same sector of industry (HVAC industry), but they all had totally different backgrounds regarding knowledge about modularization, product variety, organization, location, culture and product development tradition. Five participants were consultants with high expertise in modularization. The reply rate of the participants was 82 %.

3.2 Research Results
The screening of modularization metrics and factors used to establish product architectures in 47 modularization methods suggested that factors to be measured are all product related, and go deep into the functional, physical, and strategic composition of the product.
However, the analysis from the literature review that these questions are most important could NOT be confirmed during the requirement collection in practice and was instead declined. Abstract factors that measure the degree of modularity, for instance, and that seem to have a high value in academia did not seem to have high priority in industry. This is valid for both, consultants and industrial practitioners. Although a number of points emerged, the two leading questions (relating to modularization) that will be dealt with for the purpose of this paper are as follows:

– What to measure during product architecture design and lifecycle?
– How to measure during product architecture design and lifecycle?

As the first overall question about *what* to measure is obvious already from literature, it is surprising in academia that a main question by industry is *how* to measure product architectures and their lifecycle.

3.2.1 Requirements on "what" to measure with modularization metrics

The first group of collected, filtered and selected questions about requirements is about the *object* that shall be assessed.

Figure 1 shows how the participants prioritized the preselected requirements for assessment of modularization. The product-related object (i.e. platform, project, products) that was most frequently prioritized with "High" in 90 % of the cases was the platform . In this paper, the "platform" is a product family with shared modules which are developed in several different development "projects". This means that a "platform" comprises more products than a development "project" (which comprises several products) and logically more products than a single "product". The message is that the participants considered it as less important to assess single products or a relatively small set of products in the course of a certain development project than assessing the whole set of products from a platform.

A surprising result which is also apparent from Figure 1 is that more than 50 % of the participants found it important to appraise the specific engineering processes that are needed to design the modularized technical objects. The assessment of roles that are needed to modularize multiple products compared to single product development was also highly prioritized by the majority of participants. It is remarkable that the assessment of knowledge about modularization within the organization was mentioned by the participants as well. However, knowledge was not highly prioritized, and it was similarly rated like the assessment of single products.

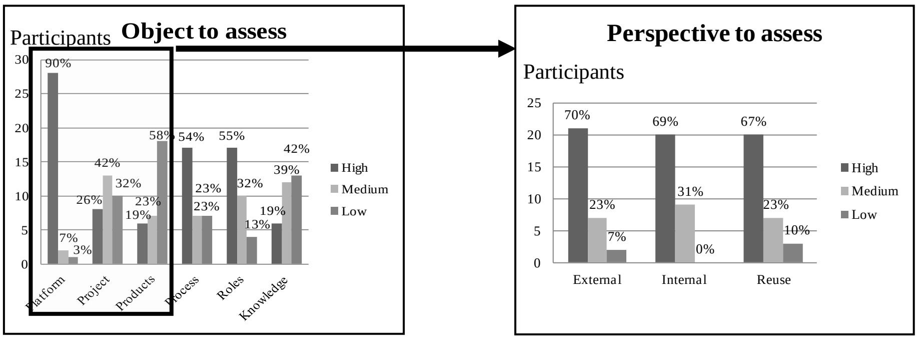


Figure 1: Priority of participants of "What" to access with the metrics

The question however remains what do senior engineers regard as important to assess in detail on the product-related objects "Platform", "Project" and "Product"? Depending on the targets of a company when establishing a certain type of product architecture, many different characteristics of a platform could be assessed. For instance, a company could wish to improve the serviceability or recyclability of its products by establishing a modular product architecture. In this case, the serviceability and recyclability of products should be measured. For other cases, these targets could be irrelevant. It could also be very interesting to know if a certain product architecture improves the complexity of the firm's products. As can be seen from Figure 1 above, the priority of the asked practitioners lies in the assessment of variety that can be offered *externally* to the customer, on *internal* product and process complexity and on the *reuse* of components, modules and processes. External variety can be further specified as the number of distinct product variants offered and the respective sales volume or turnover. Internal product and process complexity means the number of distinct parts, interfaces and processes in direct and indirect areas. This may be achieved by planned and rigorous reuse of modules and standardized interfaces, not only across products but also over different platform and product generations. Other factors that could be assessed were either seen as less important or as a direct effect of another assessed factor. For instance, time to market of a new product is seen as an important factor to assess in the course of product architecture assessment. However, time to market is seen as directly related to the assessed factors reuse and complexity. Thus, it must not be separately assessed by engineering designers.

In summary, these findings show that for practitioners it is more important to assess all products derived from a platform than assessing only a part or single products of a platform. Within the platform, it is most important to assess external variety, internal complexity and reuse of platforms or platform elements. In addition, it was shown that it is also important to assess enabling processes and roles for modularization. Other targets prioritized by some researchers in literature like strategic and lifecycle goals, separate testability, organizational alignment, faster time to market with less resources, postponement of variance creation, and financial objectives were occasionally mentioned but not preselected or significantly prioritized by the given sample size.

3.2.2 Requirements on "how" to measure with modularization metrics

The second category of requirements identified for the implementation of modularization metrics handles the question of how to assess product architectures with metrics. In contrary to the previous section that handles concrete factors to be considered for product architecture assessment, this section covers the assessment procedure as subsequent step to the identification of what to measure.

The results of the requirement collection and prioritization are as follows:

– Modularization is associated with different benefits, limitations and other process, product and overall company factors. Therefore, it is necessary to determine whether to measure one input factor or several input factors. In addition, the decision has to be made whether to compress the input factors into one metric or to use a metric system with separately reflected input factors.

  From Figure 2 can be seen that the practitioners prefer to separately combine several input factors into a metric system. In addition, it is apparent from the figure that the participants prefer measurable quantitative factors instead of qualitative factors. The key results are listed below:

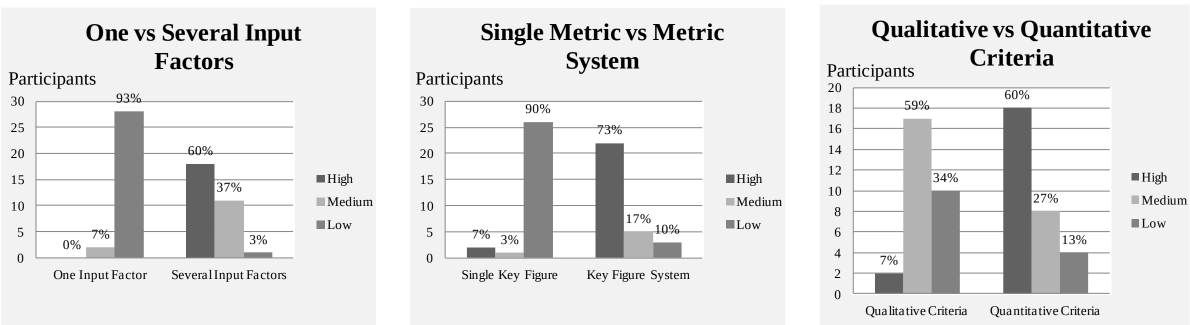
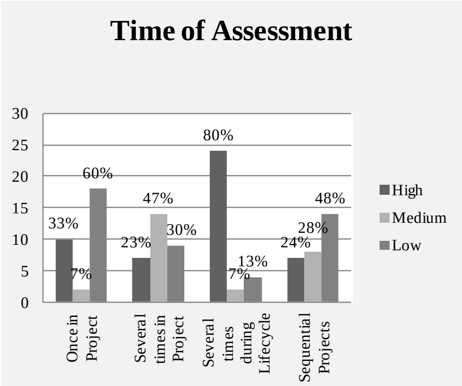


Figure 2: Priorities concerning diversity of factors and criteria

– When pursuing a modularization strategy, it is important to diligently define the number and points in time of measurement. For instance, some existing metrics are intended to guide engineers during the product architecture design process, whereas others are intended to constantly monitor the performance of product architectures during their lifecycle. Figure 3 suggests that the priorities of the participants is on assessment of product architectures several times during the lifecycle instead of assisting engineers with a metric once in the project or comparing sequential projects.

  When implementing modularization metrics into practice, it is important to know how to integrate it and how to conduct the assessment. Practitioners found it as helpful if the metrics are implemented into existing company audits during daily practice, rather than conducting product architecture stand-alone assessment (see Figure 3).

– One of the most important additional requirement that was mentioned or even set as premise for the implementation of product architecture assessment was the statement that a newly introduced metric or metric system must be easy to derive. In the best case it can be automated without bringing inappropriate additional effort for the company. The main statement was that even though product architecture assessment is important, "it should not load any additional effort on my engineers". The participants were not explicitly asked to rate this requirement, but it was expressed as main issue by the participants themselves. To meet this main requirement or concern of the participants, this will be examined further in Section 4.



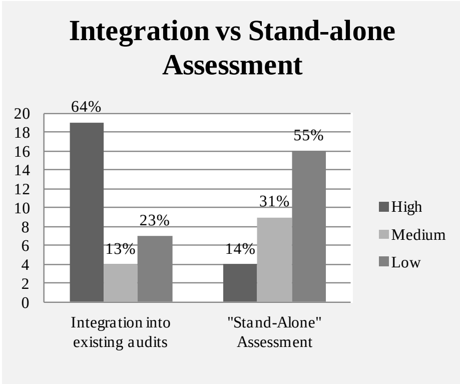


Figure 3: Priorities concerning execution of modularization assessment

3.3 Summary

Study A shows the priorities and requirements of senior engineers in industry concerning assessment of product architectures with modularization metrics. Prioritization of requirements that reflect “what” to evaluate suggests that it is more important to assess whole platforms with a large product range rather than single products and small product ranges. The study also shows that the most important technical properties of platforms to assess are external variety, internal complexity and reuse of elements. Other objectives were only infrequently mentioned and weakly prioritized. It was surprising that practitioners also want to have prerequisites assessed that need to be installed for successful modularization. Another significant finding of Study A is the priority that senior engineers put on the way that product architectures can be assessed which specifically means - how can modularization metrics be introduced and applied in daily practice? The major requirement or even precondition that the assessment procedure should be easily and efficiently applicable will be further examined on existing metrics in the next section.

4 EXAMINATION OF EXISTING MODULARIZATION METRICS FOR APPLICATION IN PRACTICE - STUDY B:

The aim of this study is the examination of existing metrics for easy and efficient application in industry which was identified in Study A as premise for their acceptance by practitioners.

4.1 Research Methodology

After analyzing the literature (see Section 2), it became clear that the application and verification of the metrics was undertaken in several ways, dependent on the type of the metric: Analysis of part lists and bills of material (Thevenot and Simpson, 2006), disassembling products (Thevenot and Simpson, 2006), or deriving information from other sources like Design Structure Matrices, interviewing engineers and experts, Drawings, or Service Manuals (Holtta-Otto et al., 2012). The study of a bill of material data is seen as an appropriate way to collect information (Thevenot and Simpson, 2006). However, most of these methods of information gathering have the limitation that they are resource-intensive to apply and therefore contradict the principle of easy and efficient application.

Information can be captured and stored for qualitative and quantitative measurement purposes in a number of different ways (Hicks et al., 2002). For the purpose of this study, it was found to be useful to directly draw upon formal information (textual and structured) from the standard IT-Systems (i.e. ERP and PDM Systems) of a cooperating major global manufacturer. To bring this company into context, it is important to note that the company under study is in the transition phase from single product development to modular system development. It is proposed that using downloadable information from these systems for automated data analysis without human estimation and judgment is the only way to efficiently calculate the metrics. For instance, this means that efficiency reasons in practice do not allow for manually comparing drawings or CAD files in order to calculate the metrics.

The case study approach was chosen to allow direct industrial insights into the applicability of the metrics. For reasons of better generalizability of the case, data availability in the ERP system of the case company was compared and compensated with the sample ERP education company in IDES (International Demonstration and Education System) of SAP. Following criteria were used to appraise the metrics:

- Is it possible to calculate the metrics for modularization from BOM information?
- Is it possible to calculate the metrics from material master data or from formal textual and structured information that is available in the ERP or PDM system?
- Which are the factors that can be computed? / Which are the factors not computable?

4.2 Research Results

Degree of modularity metrics

In total, 20 metrics assessing the degree of modularity of product architectures were analyzed. The most relevant metrics are described in Section 2 and are summarized in the cited review publications. The factors that are needed to calculate the metrics of this category are: number of modules, number of components, interactions between elements, interaction strength, interface/connection information, functional information, similarity and dependency information, and information about new-to-the firm components.

The results are as follows: NON of the metrics could be calculated with formal BOM, PDM or ERP information:

- It was not possible to calculate the metrics from BOM information.
- It was not possible to calculate the metrics from material master data or from other data that is available in the ERP or PDM system.
- Factors that *could* be computed: Number of components, number of modules
  Factors that *could not* be computed: interactions, interaction strength, interfaces/connections, product functions, similarity and dependency information, and information about new-to-the firm components.

The reason for the lack of suitability of these metrics is their need for consideration of information that is only available informally within companies. This type of information cannot yet be efficiently used for calculation and computation. Even though, degree of modularity metrics could be quite useful in practice, they are not efficiently applicable to date.

Commonality and variety metrics

13 metrics have been considered in this category. Section 2 and the review publications cited there shortly describe the most relevant metrics of this category. Table 1 shows that nine of 13 metrics could be easily and efficiently calculated. All of the metrics are understandable and directly related to the effects of product architecture design.

The factors that could (numbers 4, 5), partially (number 3) and could not (numbers 1, 2) be calculated are as follows:

1. Product Line Commonality Index (Kota et al., 2000), Commonality Diversity Index (Thevenot et al., 2007), Comprehensive Metric for Commonality (Thevenot et al., 2007): The first metric could not be calculated because it was not possible to get information about components that should ideally be common regarding size, material and assembly factors. The second metric could not be calculated because components were not classified into common, unique and variant components. The third metric could not be calculated because of its required input geometry, size and assembly scheme.
2. Total Commonality Index (Blecker and Abdelkafi, 2007): In the case company this metric could not be calculated because of its input requirement of a generic BOM. In the IDES system this metric could not be calculated because the information about probabilities of an option was missing.
3. Overall Commonality (Siddique et al., 1998): Common and unique components could be calculated, but information about connections, assembly loading sequence and assembly workstations was not available.
4. Degree of Commonality Index (Collier, 1982), Total Constant Commonality Index (Wacker and Treleven, 1986), Commonality Index (Martin and Ishii, 1997), Component Part Commonality Index (Jiao and Tseng, 2000), Commonality Metrics (Johnson and Kirchain, 2010): The number of parent items on all BOM levels of a component j, and the number of distinct components in the given product range could be calculated. It was the same with component, price, mass, cost and quantity for the Component Part Commonality Index and the commonality metrics of Johnson and Kirchain (2010).
5. Commonality and Variety Metrics by Möller et al. (2011), Döpke et al. (2009), Beisheim and

Stotz (2013) and Rapp (1999): These simple metrics considering commonality and variety could be calculated without exception.

A summary of these results is given in Table 1: It has to be noted that "✓" means that the metric could be calculated, "X" means that the metric could not be calculated and "n.a." means that it was not necessary to draw upon this source of information. It has to be noted that the variety metrics of Martin and Ishii (2002) and of Keese et al. (2006) have not been considered as they are derived in a workshop-like method. Thus, they also failed this calculation approach.

Strategic and financial metrics

Similarly to the degree of modularity metrics, the analysis of modularization metrics assessing strategic effects of product architectures and monetary effects (see Section 2 for brief explanations on identified metrics from this section) failed in ALL the cases of the literature due to a lack of available formal and structured information. Factors that must be known for this metric category include life cycle information, strategic information (e.g. supply strategy, service strategy), information from activity based costing systems, or the cause-effect relationship between all of the mentioned factors.

Table 1: Overview of computability of commonality and variety metrics

	Collier (1982)	Wacker and Treleven (1986)	Kota et al. (2000)	Siddique et al. (1998)	Martin and Ishii (1997)	Jiao and Tseng (2000)	Blecker and Abdelkafi (2007)	Thevenot and Simpson (2007)	Johnson and Kirchain (2010)	Möller et al. (2011)	Döpke et al. (2009)	Beisheim and Stotz (2013)	Rapp (1999)
Computable with BOM information	✓	✓	X	X	✓	✓	X	X	✓	✓	✓	✓	✓
Computable with ERP/PDM information	n.a.	n.a.	X	X	n.a.	✓	X	X	✓	✓	✓	✓	✓

4.3 Summary

Study B reveals a clear gap between industry and academia in the field of metrics to assess product architectures. The reason for this is that academia usually does not consider applicability and implementation into daily practice with all its obstacles that are entailed by limited information availability and cumbersome calculation and data gathering. In the industrial context it must be possible to calculate the metrics for products with several hundred components per product and for a range of several hundred product families as well. In addition, understandability for transfer of research results from academia to industry is also a neglected topic.

It has to be noted that the study only analyzes applicability of the metrics and no other qualitative judgment. Nevertheless, it has to be kept in mind that metrics that are seen as not applicable might be very interesting, but not useful yet from an industrial perspective.

5 CONCLUSIONS

This paper investigates the suitability of modularization metrics for implementation in practice. For this investigation, two studies were designed and executed.

There are many metrics which are useful because of their information content and their suitability to concisely indicate either the degree of modularity inherent in a product architecture or the resulting effects of that degree of modularity on different performance levels (e.g. complexity, commonality, variety, recyclability, cost, profit, quality, performance).

The first finding of this paper from requirement collection in Study A is that besides deciding *what* to measure with the metrics, it is also very important *how* to apply the metrics. The second finding is that it is less important for practitioners to determine the abstract level of modularity (e.g. number and strength of interactions inside and outside of modules) of a product or of a set of products. It is rather more important for practitioners to assess the results of modularization. It was found out that the results of modularization should be measured with "hard facts" like external variety or internal technical complexity. However, it was also revealed that it might not be always possible to date to directly link modularization to performance, cost or profit due to a current lack of direct cause-effect knowledge in this area. It is also notable that many practitioners found it important to assess the prerequisites (i.e. processes, roles, knowledge) for successful modularization of multiple products. This was not apparent from the study of literature.

Study B shows that the focus of current research is more on the coverage of modularization relevant factors than on applicability. Therefore, this paper shows that there is a weakness of available metrics concerning their applicability and understandability. Industry requires clear and simple metrics that are easy to derive with available information to assess the architecture of their products.

For further research, it would be interesting to see how metrics and other assessment methods can be adopted to the findings of this study. This could comprise more practical metrics measuring product architectures which are easy to calculate from available data and which could possibly supported by tools. Another future measure could include easy retrieval of product architecture relevant information in IT-systems of companies and to support industry to make important information automatically available. It is also recommended that future research supports engineering organizations in designing and assessing product architectures by making sure that appropriate architecture relevant responsibilities, competencies, processes and organizational structures are in place. By doing this, information that is required for a broader calculation would be available.

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