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METHODOLOGIES TOWARD PRODUCT ARCHITECTURE IMPROVEMENT IN THEORY AND PRACTICE

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1. Introduction

Manufacturing companies are more and more challenged by increasing complexity in all areas. Companies have to offer high variety or even customized products to satisfy the wide range of customer requirements. The resulting variety is increased by a dynamic process of fluctuating demand and fast changing needs. In addition, a common strategy for companies if they want to gain market access, expand their product portfolio or acquire know-how about new technologies is to buy or merge with other companies. The negative effect of this strategy is that engineering, manufacturing and administration processes have to handle an increasing amount of complexity. In order to compete with strong and price-aggressive competitors, companies seek to reduce their internal complexity while increasing the product portfolio they offer. A common strategey to find the right balance between internal and external complexity is product architecture improvement. If companies want to take advantage of improved product architectures, they have to find means to establish and maintain optimized product architectures. For companies who wish to start to embed product architecture decisions into their development process, it is not easy to find an appropriate approach towards product architecture design and management.
To help to support some of these issues the purpose of this paper is to link together critical aspects for modularisation from industry and compare these to the literature and then to cross compare them to modularisation strategies adopted by industrial practicioners.

1.1 Considerations for product architecture improvement

Some initial analysis about the expectations of managers was undertaken, particularly about how to consider product architecture optimization. It was also established that managers were concerned about the overall approach toward product architecture improvement and product complexity reduction, besides focusing on the methodology. This means that in addition to the methodology, other aspects have to be considered as well. For this reason, critical aspects were collected in industrial organizations that seemed to be important to be answered for companies which are contemplating to improve product architectures. This was undertaken in a classical questionnaire manner. In total more than 20 senior engineers in different organizations or organizational units who were approached beforehand and personally interviewed in open-ended interviews contributed to the aspects. 27 questions that were collected in the initial study about expectations were asked to the engineering managers. Among the 27 questions were broad questions like “What has to be considered during modularization, based on your experience?” and more detailed questions like “Which rules, processes, methods do you use fort that?”. The five aspects established are summarised below.

2. The five aspects

The aspects were varied and wide ranging and have been distilled and summarised below to form the basis for the next elements of the paper. The categorization analysis was done in two steps by first brainstorming possible aspects from the interviews and second by clustering the answers into meaningful categories which constitute the five aspects. These are views as seen by practicioners and form a good bench mark for the work reported in the literature.

2.1 Establishing product architectures

Aspect one focuses on how product architectures can be established and improved with an appropriate methodology. This methodological aspect also asks if the methodology also considers other important issues, like product strategy, value stream, product life cycle or market requirements. It is seen as beneficial if the methodology takes regard of other functions and areas in a holistic manner.

2.2 Technical representation of product architectures and support during the design phase

Aspect two addresses the issue as to how the product architecture can be represented technically and how engineers can be supported during the design phase. This question also considers the effort for engineers when handling product architecture processes after they are created. Moreover, it deals with the stability of the product architecture if it is appropriately specified, documented and represented, for instance in existing IT-systems like CAD, PLM Software and ERP.

2.3 Administrating product architectures

Aspect three focuses on the administration of product architectures within an organization. An effective administration of the product architecture should reduce the effort for dealing with architecture related processes. It should also ensure that the defined product architecture is kept stable over time and only changed in a controlled manner. Moreover, if the introduction of new module variants and interfaces is constrained, uncontrolled growth of variety can be prevented.

2.4 Implementing modularisation

Aspect four focuses on the implementation strategy considered by an organisation to establish improved product architectures. This needs to ensure that product architecture processes are well understood and integrated into existing processes in order to keep effort down through additional processes. If a holistic product architecture process is implemented, this point is of special importance. Additionally, the process integration and built-up of know-how shall ensure that product architecture creation and administration is lived actively and therefore contributes to the stability of product architectures. The implementation aspect also contains the point to install additional roles in an organization who are responsible for product architecture creation and management.

2.5 Assessing benefits of architecture and improvements

Finally, aspect five focuses on the benefits and disadvantages of approaching product architecture improvements. The main focus are monetary savings from and the level of investments for the improvement of product architectures. However, direct monetary benefits are often not on hand as they are related to process costs in various kinds of areas and they cannot be harvested immediately but in future. That is why other means of evaluation have to be implemented like process, product or architecture related key figures. If the benefits of architecture improvement can be evaluated and clearly shown to the organization, it is more likely that product architecture improvement measures are lived more actively. Furthermore, product architecture evaluation gives a direct feedback about the result of aspect one to four.

These five aspects (see Figure 1) seem to be relevant for industry when making an organizational shift to product architecture design and improvement. This set of aspects was collected in interviews and categorized. In the next section a literature analysis is undertaken to provide a brief overview how the derived aspects are considered in literature and to show to which extend.

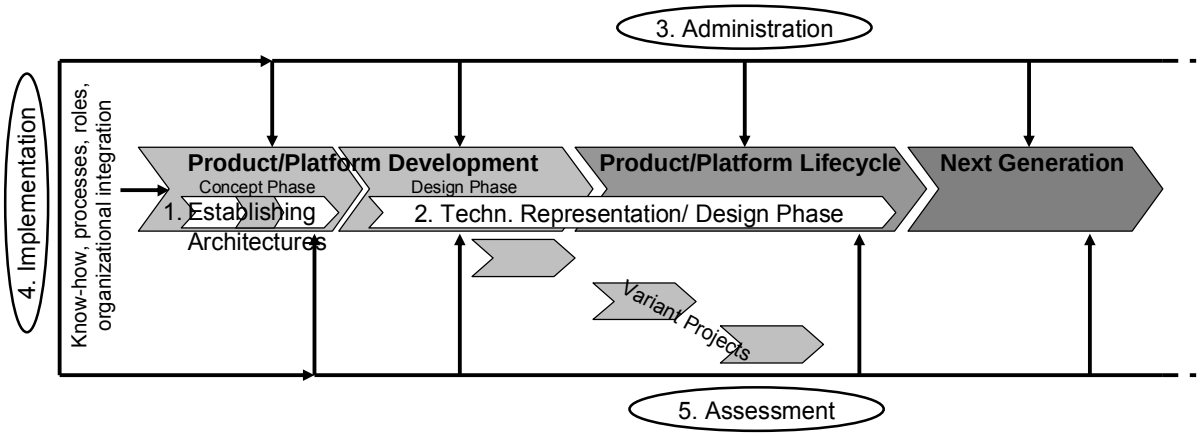

Figure 1. Five important aspects for product architecture support and improvement

3. Product architecture design approaches in literature

It was seen that most authors writing about product architecture really mean the decomposition of the product into modules. Product architecture design literature is mostly related to modular design, which means that integral product architectures are usually not further described because of their intangible nature. Another product related complexity management approach described in literature is platform design. However, the term platform has still an imprecise meaning [Kristjanson et al. 2004] in both, literature and practice. For the purpose of this research, a platform is considered as the base module or the set of base modules which are shared across several products or product families. Therefore this literature review focuses on modularization approaches. Literature on the five aspects was searched in literature reviews about the topic, in university libraries, through tracing and in interdisciplinary engineering databases via Compendex and ISI Web of Knowledge with search terms related to the five aspects. For each publication it was asked whether it is appropriate to answer one or several questions from the initial practical analysis described in section one. What was found in literature is divided into the categories which were derived in the last section.

3.1 Aspect 1: Establishing product architectures

The main purpose of the methodologies is to find product architectures which provide an optimized mix between internal complexity and external variety. All methodologies have in common that they subdivide the product into chunks and try to separate those chunks that can be standardized across products from the chunks which need present and future variety across products. These modularization methodologies were analyzed and the three main ones are briefly described in this section. All in all 105 publications were found to be relevant to answer the questions of this aspect.

Pimmler and Eppinger modularize their products with the Design Structure Matrix (DSM). The DSM is a matrix which shows the relations between components of a product. The aim is to cluster those elements which are highly dependent of each other in modules and to minimize the relations between modules. This helps to provide relatively de-coupled interfaces which facilitate the exchange of modules. Moreover, if modules are independent of each other, a change at one module does not affect the other module. The method of Pimmler and Eppinger only focuses on technical interdependencies like spatial, energy, information and material interaction [Pimmler and Eppinger 1994]. Other aspects than the relation of technical elements are not considered for the modularization process.

The heuristic method introduced by Stone et al. focuses on the functional flow structure of the product. Three heuristic rules can be applied to group functions into modules and hence, divide the product into modules. The first heuristic rule is that functions of dominant flows are grouped into modules. A dominant flow is a flow which enters the product at the system border and leaves the product at the system border without being branched or transformed in between. The second heuristic rule is that parallel function chains which are the result of a branching or which end in a branching are candidates for modules. Finally, the third heuristic rule describes that conversion-transmission functions shall be

taken as module [Stone et al. 2000]. However, other aspects than flow structures are not considered of this method.
A holistic approach drawing upon matrices is described by Ericsson and Erixon. Their methodology builds modules based on module drivers. The methodology modular function deployment (MFD) consists of five steps which all handle different tasks in the product creation process. The design support focuses on transferring customer requirements into components, modules and the system structure. Moreover, all company functions are involved in creating the system structure through the involvement of module drivers, financial evaluations and improvement of modules with DFMA [Ericsson and Erixon 1999]. MFD is a broad methodology which considers company strategic aspects as well as engineering adjacent functions.
To sum up, a whole set of methodologies can be found in literature concerning all conceptual aspects of product architecture creation. After studying the literature in above mentioned scheme, it is clear that the process, methods and tools about modularization are covered by the academic world after intensive research of recent years.

3.2 Aspect 2: Technical representation of product architectures and support during the design phase

If a company moves toward modularization, it was required that the product architecture is represented in the company's information system. Even though literature was found about the representation of conceptual modular systems, no literature was found about the technical specification and documentation of modules and interfaces, like is seen in the computer industry. Nothing was found in literature about the representation and handling of modules and interfaces of a modular system in the design phase. One paper was found how robust interfaces can be designed for modular products [Blackenfelt and Sellgren 2000] and one paper was found how interfaces can be modelled and simulated in modular products [Andersson and Sellgren 2003].
In sum, 23 publications which are considered to answer questions of this aspect were found in the literature survey. The relatively low research concentration on modularization after concept phase in the product development process shows that product architecture is still an abstract construct.

3.3 Aspect 3: Administrating product architectures

If companies want to keep their architecture stable, but constantly develop its modules, interfaces and platforms, companies need processes and responsibilities for the administration of its modular system. One article was found, stressing the need for a manager for the modular system. Arnoscht states that the responsible for the modular system has to take care that the highest possible degree of standardization is kept while providing the necessary product differentiation [Arnoscht 2011].
Another paper stresses the importance to consider later life cycle phases, not only the initial platform development. Alblas and Wortman state that if platforms have to be kept stable without having uncontrolled variety during the platform life cycle and the product life cycle, an efficient change process has to be introduced. Therefore the researchers introduce requirements for the platform maintenance process [Alblas and Wortman 2008]. In total, seven different publications were found to answer the questions from this aspect. This is another under represented area.

3.4 Aspect 4: Implementing modularisation

Interestingly no work was found about implementation strategies when organizations want to implement processes to improve their product architecture. Moreover, nothing was found about how to build up know how, to which hierarchy levels the know-how has to be distributed and to what company functions. In addition, no answer was found how to install roles like the module manager stated in section 3.3. In these terms, the answer was sought to the question on the right effort for product architecture processes. For instance, it was not answered how to find out if it is sufficient to apply a product architecture methodology punctually in the product development process or if a whole set of processes and methodologies has to be implemented into an organization. It would be of considerable practical interest to know more about the organizational implications when implementing product architecture optimization.

3.5 Aspect 5: Assessing benefits of architecture and improvements

Much has been written about concrete metrics and evaluation procedures of how to assess the performance of product architectures. 66 publications which were considered to be relevant to answer the questions of this aspect were identified. Many key figures are on an abstract level. The researchers want to show the degree of modularity of a product architecture with abstract key figures. This is usually done by measuring one-to-one mapping of components to functions and the degree of interaction in modules and between modules [Newcomb et al. 1996] and [Gershenson et al. 1999].
Other researchers focus on key figures which measure the advantage of product architectures. An advantage of modular product architectures is the use of communalities between product lines. Examples for such key figures are the Product-Line-Communality-Index [Kota et al. 2000] and the Communality Index [Martin and Ishii 1996].
The impact of the product architecture for the organization can be measured with a whole set of key figures by, amongst others, Ericsson and Erixon [1999] or Meyer and Lehnerd [1997].
Although there is a huge amount of literature measuring product architectures and describing the benefits of modular systems, it is still difficult for companies to grasp quantitative economical benefits from modularization processes [Hansen and Sung 2010]. Moreover, no examples were found where evaluating product architectures is integrated into organizational processes without loading additional effort on the organization.

3.6 Overview of the comparison

The result of the literature analysis shows a picture of the focus of the academic world in the field of product architecture improvement and evaluation. Management literature focuses on providing examples for product architectures and describes the general benefits of modular product architectures. Practical advice for the improvement and evaluation of product architecture comes from engineering literature as well as from management literature. Only little support is provided from academia for the implementation strategy, management and administration of product architectures, technical support issues and support for the design phase for product architectures. Table 1 gives an overview of the degree of coverage of the important aspects from section 2 in literature. The purpose of the next section is to find out how industry is proceeding in the field of product architecture improvement.

Table 1. Coverage of important product architecture aspects in literature

Aspect	Methodology	Design/Tech Support	Administration	Implementation	Evaluation
Literature					

4. Approaches toward product architecture improvement in practice

A study was then conducted to find out which important aspects of modularization are actually dealt with by organizations. During half a year, a series of site visits, process observations, open-ended interviews, informal discussions and studies of presentations were carried out.
The benchmark partners were either companies manufacturing consumer, building or automation equipment or consulting companies working with customers from all kind of industries. The partners interviewed consisted of senior personnel involved in major engineering decisions. The interview and site visit partners were selected because of their reputation concerning complexity management in industry. In total nine different approaches toward product modularity were studied. The total number of samples was 22, however as different organizations followed similar approaches, consultants applied their approaches in several different organizations or a company followed the same approach in different organizational units, it was possible to divide the studied approaches into the following nine organizational main streams. The nine different approaches are presented in the following paragraphs with a brief description what they do in the fields of methodology, technical support, architecture administration, implementation strategy and architecture evaluation.

4.1 Organization A

The research department develops electronic components for industry and applies a product line approach to take advantage of synergies in product lines and between product lines.
The product line approach of the department is applied to increase the number of shared components within product lines. This is done by setting up a reference product architecture based on product strategy, by administrating components developed for reuse and by managing the reuse. However, this approach does not consider technical support, implementation strategy and evaluation.

4.2 Organization B

The medium-sized consultancy has a strong academic backbone and sets up modular product architectures with a holistic approach. Therefore, matrices are used to translate custumer needs into modules and the system structure. Moreover, the methodology also considers company strategic aspects like module drivers, target costs and complexity costs and other company functions like manufacturing or purchasing.
The consultancy applies a methodology to technically support engineers during the design phase. The purpose of this design methodology is to make the modular system configurable in other systems like CAD and product life cycle management systems. Moreover, the consultants also support engineers during the design phase that the principles of modularity that are brought into the product are kept sustainably.
To administrate modules and interfaces, the consultancy establishes a position which is responsible for the modules. These module keepers have to check and coordinate changes to the modules.
The consultants first measure the readiness of the organization for modularization. Based on this, they derive the requirements for the implementation plan. To successfully implement modularization, building up know-how is proposed which shall make the organization ready for organizational and process integration of the modular toolset.
The benefits of the modular system are calculated with the complexity driven activity reduction and the economies of scale which can be achieved by standardizing modules. The evaluation of the modular system are done with a set of key figures, but the main key figure of the consultancy is the relation of part numbers to the configurable product variants of the modular system.
To conclude, the approach of Organization B covers all aspects which were found to be important in section one.

4.3 Organization C

Organization C is a consulting organization with a focus on production planning. The organization works on the reduction of product complexity as a precondition for efficient manufacturing.
The methodology of Organization C does not explicitly optimize the product architecture, but it optimizes the variety of parts and modules by standardizing them according to customer needs.
The parameters for each component are specified in a design rulebook which is administrated by an engineer in charge for the design specifications. The product architecture is evaluated by measuring the part number count across the product family.
The approach of Organization C has a focus on method, evaluation and administration without advising in the fields of technical support, implementation strategy and benefits.

4.4 Organization D

Organization D is a big consulting company with a strong academic background. Their holistic approach focuses on product complexity reduction in combination with product architecture optimization.
The product architecture methodology of Organization D transforms product strategy, customer requirements and company strategy into the modular system under consideration of the right type of product architecture. To connect all the different aspects, the consultancy applies QFD-like matrices.
The approach of Organization D does not consider technical aspects or support for engineers during the design phase.

The consultants stress the importance of setting up a product architecture organization. This means that roles and responsibilities are defined. For instance, platform managers have to keep care that the variety of the platform does not increase uncontrolled after implementing the platform. Moreover, change processes are defined to consider the impact of change before the change is implemented.
Implementation strategy is an important aspect in the consultancy's philosophy. Managers and engineers are trained to get an understanding about the methods and tools applied and to raise awareness about product complexity. Then the methods and tools are integrated into the organization and into existing processes, while defining new processes where necessary.
The product architecture is constantly evaluated with the help of metrics. Moreover, product architecture alternatives are also assessed with the help of variant trees showing the complexity of the whole product portfolio. The benefits of product architecture alternatives are evaluated with the help of complexity costs for part numbers.
To sum up, company D has a huge approach covering the methodology, the product architecture administration, the implementation strategy and the evaluation and benefits of modularization. However, the approach does not consider technical aspects for the support during the design phase.

4.5 Organization E

Organization E is a medium-sized consulting company which is specialized in product architectures and software to support the product architecture creation process. The product architecture is build upon a methodology which has the focus on visualizing elements which are important for the product architecture process. Therefore, different product architecture concepts are derived and evaluated based on the functional and geometric independency of their components.
The approach offers technical support for engineers in the design phase. The software that the consultants use for the conceptual product architecture creation process has interfaces to common PLM and ERP software systems. This means that the generic product structure of the product family will be the same for all products in the IT-systems.
The product architecture is evaluated and the benefits are calculated in technical factors like the share of common parts and modules, target cost achievement, function encapsulation in one module or the function complexity.
To summarize, the consultants focus on product architecture methodology, technical support and evaluation of the product architecture without covering the apects administration and implementation.

4.6 Organization F

Organization F is a consultancy with a strong academic background. Their approach focuses on improving product complexity by optimizing the structure of the product with matrices.
The applied methodology improves geometric, functional and feature dependencies of a product with the help of software algorithms.
The approach of Organization F focuses on the creation of an optimized product architecture based on several views on the product. However, the approach does not contain any activities from the categories technical and design aspects, architecture administration, implementation strategy and evaluation of the architecture.

4.7 Organization G

Organization G is a leading manufacturer for consumer goods which constantly has to face mergers and buyouts in an international environment. The modules of Organization G evolved from the past and therefore the organization does not have a systematic methodology to design the product architecture of its product portfolios.
The emphasis of the company is on module administration. Organization G modularized its development organization, hence there are responsibilities for modules instead of responsibilities for sites or for functions. Engineers in charge for a certain module also have to plan the lifecycle of the modules and control changes to modules and interfaces. Thereby responsible module keepers can control changes to modules and protect platform relevant dimensions from uncontrolled changes. For

this reason, the organization implemented regular meetings, roles and exchange of experts to discuss different module concepts and to bring life into the module organization.
To sum up, Organization G does not consider product architecture methodologies but the administration of modules to keep established modules stable. Therefore, the organization had to consider how to implement such a module organization. The organization does not cover technical aspects as well as architecture evaluation.

4.8 Organization H

Organization H is a specialized manufacturer for made-to-order industrial equipment. The company focuses on product configuration, not only for fast internal processes, but also for fighting product complexity. Although this configuration approach is no product architecture approach, there are many similarities between the approaches.
The approach of Organization H focuses on the methodology to make products configurable in combination with the implementation of the configuration system. The organization reported that during the process of configuration preparation, different parts with the same function are identified. Because modules and parts are predefined and stored in the configuration system, no uncontrolled changes are made to the system structure. Moreover, by giving the product a configurable and predefined architecture, the configuration system prevents that engineers start to generate a similar but different solution for a product function that has already delivered before. Therefore, this approach also considers administration aspects. This approach does not consider technical aspects and design aspects for the setup of the product architecture as well as the evaluation and measurement of the product architecture.

4.9 Organization I

Organization I is an internationally positioned manufacturer for electronic consumer equipment. The approach of this organization focuses on evaluating product architectures and on cross-platform responsibilities.
The company does not apply a dedicated methodology which is explicitly documented to derive its product architectures. Architecture administration, technical support and design support are not considered by this organization.
Organization I focuses on measuring complexity. The company applies several metrics which measure the number of parts in products, in platforms and across platforms. The set of key figures and the visual representations are controlled by engineering managers and are measured during the stage gate process. To ensure that the overall goal of company-wide complexity reduction is pursued and not only the goal of single development projects, the organization has a keeper of the overall project performance. This person in charge balances the performance and complexity of a single project with the complexity goals of the company.
The approach of Organization I focuses on measurement of its product architecture combined with cross platform responsibilities. Therefore, the organization had to focus on the implementation of evaluation processes and persons in charge for the measurement. The organization does not cover other aspects like methodology, design support or administration.

4.10 Overview of the comparison

The comparison of Organizations A-I shows that each of the important aspects (see Section 2) which a company has to consider when it wants to sustainably improve its product architecture is weighted differently from organization to organization. There is no overall mainstream recognizable. However, Table 2 shows that all aspects are covered in industry.

Table 2. Coverage of important product architecture aspects in practice

Aspect	Methodology	Design/Tech Support	Administration	Implementation	Evaluation
Organization A	**X**		**X**		
Organization B	X	X	X	X	X
Organization C	X		X		X
Organization D	X		X	X	X
Organization E	X	X			X
Organization F	X				
Organization G			X	X	
Organization H	X		X		
Organization I				X	X

Analyzing the 22 samples which were used to identify the mainstream approaches of organizations A-I shows the same picture. A holistic methodology covering strategic aspects seems to be the central point in product architecture optimization. However, Figure 2 shows that implementation, evaluation, administration and design aspects are also covered to support the optimized product architectures.

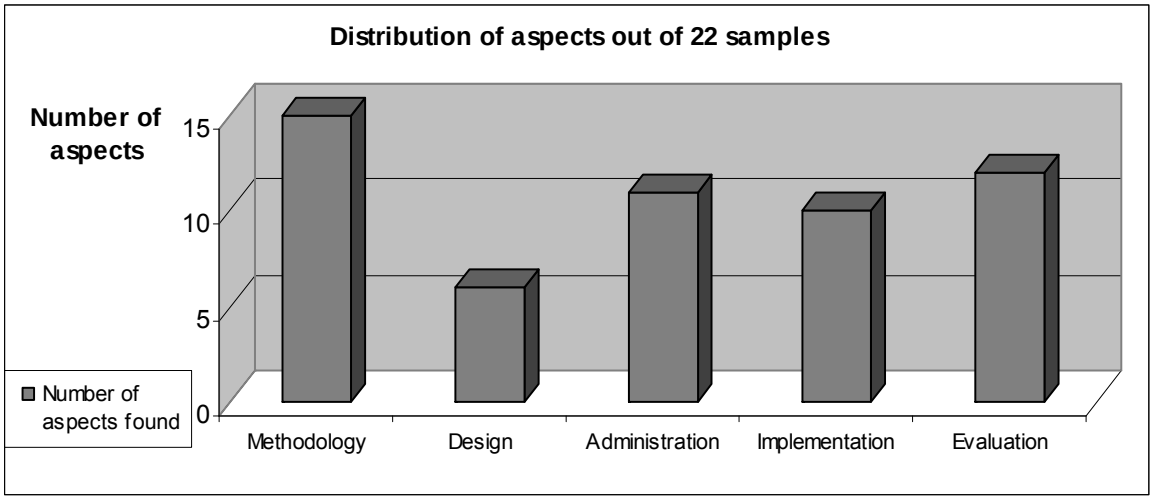

Figure 2. Distribution of important aspects in practice

5. Conclusions

The study that has been summarised in this paper has 3 elements. The first element is opinion from industry which is then compared to the literature. This is then compared with actual practice from 22 industry sources. It has shown that important aspects relating to product architecture support and improvement are broader in industry than in the literature. When support for engineering design in general and product architecture improvement is dealt with in the literature, the focus seems to be on methodology and the abstract evaluation of product architectures.

The study in industry has shown that it is important that other measures like technical design support, architecture administration, implementation strategy and practical evaluation have to be considered

alongside the focus on a holistic methodology. The reason for this is that companies have to invest to improve product architectures and therefore they want to have sustainable product architectures which harvest benefits of the initial efforts in future. Because of this, measures to support product architecture design have to support the sustainable stability of the product architecture as well.
A broad and strategic methodology considering all present and future market trends as well as needs of other company functions can assist to create product architectures which are less likely to change over time. It is important to consider all aspects when an organization wants to achieve sustainable results by product architecture improvement. However, which aspects to consider depends on the effort the organization wants to put in, the benefits it wants to achieve and how good the organization is already in the different areas.

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