

A MODULARIZATION METHOD IN THE EARLY PHASE OF PRODUCT DEVELOPMENT

A. Albers, N. Burkardt, C. Sauter and K. Sedchaicharn

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1. Introduction

1.1 Structure of paper

The first section of this paper presents an overview of modular product characteristics, modularization and of the Contact & Channel Model (C&CM). The state of the art in modularization and the objectives of this research are illustrated in section 2. In section 3, the modularization method used in this research will be explained. This method includes the evaluation of the interactions between Channel and Support Structures (I_{CSS}) and a measure for the degree of modularization. An implementation and the result of the method are shown in section 4. A conclusion and a proposal for future work are contents of the final section.

1.2 Modular products and modularization

A product architecture is a hierarchical architecture that illustrates how the product parts and product assemblies are fitted together. A modular product architecture is one type of product architectures and it generally consists of various detachable groups of components. Modular products can be recognized through the types of mapping from the physical architecture to the functional architecture. There are three types of mapping; one-to-many, many-to-one and one-to-one [Ulrich 1995]. One-to-many and many-to-one mapping lead to an integration of the product architecture. Conversely, the one-to-one mapping leads to a product which has a form of a modular architecture. The more one-to-one mappings a product contains, the more modular it will be. Another way to characterize a modular product is to consider interactions between the physical components. In this case, a matrix is normally applied as an analyzing tool to recognize the groups of physical components that have more internal than external interactions and which are so called "modules". It is essential that each module in a product be easily detachable. It would have less benefit in case that the product is modularly constructed without being able to be detached. As a conclusion, a module in a modular product should:

- perform a function by itself,
- have more internal than external interactions and
- be detachable.

A personal computer (PC) and a notebook will be used to compare between two different product architectures. Both products have the same basic functions but their architectures are different. The architecture of a PC can be classified as a modular architecture since it contains various operational modules which can be easily detached. Examples for modules include monitor, mouse, keyboard and modules in a deeper level, for instance, main board, sound card and VGA card. Unlike a PC, a notebook is designed in an integral manner. As a result, many aspects including performance per

weight and mobility have been improved substantially. It is ambiguous to decide which product architecture is better since both architectures possess their own advantages. The question which product architecture can meet the requirements under the specified constraints and target system more efficiently frequently arises. It is of great importance to determine how modular the product architecture should be. These constraints and a target system relate together the product requirements (i.e. weight, dimension) and the process conditions (i.e. assignment of tasks, production, and manufacturing).

A process to make a product more modular can be called “modularization”. Nevertheless, modularization is not a process to turn a “non-modular” into a “completely modular” product but it can be applied to increase the degree of modularity [Rapp 1999]. In most cases, it is reasonable to consider whether a function of a product should be handled in a modular or integral way [Ulrich 1995]. Despite many advantages achieved by the modular method, it is misleading to expect that modularization can solve all problems. Many disadvantages like a rising unit cost due to overdimensioning [Rapp 1999] and an easing of illegal product piracy can emerge. Modular products are normally larger, heavier and less energy efficient than integral products.

1.3 Contact and Channel Model (C&CM)

C&CM is an elementary design model which has been developed by the Institute of Product Development (IPEK) since 1999. Technical products have been conventionally modeled with defined geometries grouped into sub-systems. The C&CM approach models the products by using two basic elements - Working Surface Pairs (WSP) and Channel and Support Structures (CSS). They are defined as followed [Albers 2005];

- “WSP” are all pairwise interfaces between components and its environment. This can be solid surfaces of a body or a boundary, surfaces of liquids, gases or fields which come into permanent or occasional contact with the Working Surface (WS). They take part in the interchange of energy, material or information within the technical system.
- “CSS” are physical components, a volume of liquid, gas or space containing field which link exactly two WSPs. They do not only participate in a transfer of energy, material and information from one WSP to another but they can also store them (e.g. the mass inertia).

These elements represent both the geometrical as well as the functional description of a system. C&CM bridges both descriptions without the need to switch between two different, non-connected descriptions of the same system [Albers 2005].

2. State of the art and the research objective

As explained earlier, even though a modular product architecture possesses many advantages required as one of the development goals but the availability of the literature and supporting tools is limited. Most of the modularization methods focus on the redesign of existing products, in which a matrix representation is often used as a tool for an integration analysis, for example a modularization of an automotive climate control system [Pimmler 1994].

The idea to configurate a modular architecture in the early phase is not new. In this research, the early phase of the design refers to conceptual design and the beginning stage of the embodiment design. In this early phase, a basic solution from the conceptual design will be further applied. The product architecture is formed based on a basic solution which was initially derived from the conceptual phase. The guideline VDI 2221 [VDI-2221 1993] suggests that the task “dividing the basic solution in realizable modules” and “a modular structure” (the result of this phase) should be performed with a CAD system. The use of CAD as a tool is actually not appropriate for the modularization in this phase. This modularization step is described more in detail in guideline VDI 2223. In order to complete the modularization, the following two sub-tasks introduced in this guideline need to be fulfilled. These are “identifying requirements and conditions influencing the form design” and “modularization of the basic solution”.

The modularization in this early phase is important for an efficient distribution of design work among design teams and also for various aspects of “Design for X” (e.g. design for assembly or design for maintenance). This is particularly essential for complex products. Due to the strong effects on the latter development steps, an analysis tool for the modularization in the early phase of development is

needed. However, this tool has not been sufficiently considered so far. A necessary tool for the modularization is the integration analyzing tool concerning the inspection of the degree of integrations of elements as well as interactions between elements. The result should be shown as the suggested groups of elements required to create the product architecture in the latter steps. Because of the lack of a suitable tool, the modularization is nowadays intuitively operated. This process usually requires numbers of experienced designers. Similarly, despite its simplicity, the modularization without a quantitative measurement or an evaluation is considered inefficient [Gershenson 2004]. The objectives of this paper are to further extend a method in VDI 2223 as well as to develop an analyzing tool to support the modularization in the early phase of product development process for a new design.

3. Modularization with Contact & Channel Model (C&CM)

3.1 Function classification

An integration analysis of a modular architecture of a system in the early phase of development is considerably related to the functional analysis. The classification in this paper is taken primarily from the modular product systematic according to Pahl [Pahl et al. 2003]. Four different sub-functions including basic function (BF), auxiliary function (AF), special function (SF) and adaptive functions (ADF) are distinguished and are illustrated in the following figure.

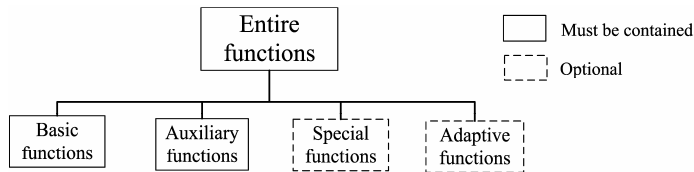


Figure 1. Functional classification in modular product systematic [Pahl et al. 2003]

- Basic functions are fundamental. They are repeated, indispensable and not variable in principle. A technical system always contains this type of function.
- Auxiliary functions required in the product are the functions which are used to connect various components.
- Special functions are specific, additional, task-related sub-functions that must not recur in overall function variants.
- Adaptive functions are an essential function to adapt the product with the other products.

Two function types that must be contained in the product are BF and AF. A BF performs a necessary sub-function for the product which relates to other BF to complete the entire function. The hypothesis for this approach is to synthesize the product architecture with the considered BF and their relations. After the product architecture is found, the components that perform the BF will be connected together by AF. That means the AF is not necessary to decide the product architecture. Since the determination of the product architecture and a single product are focused, the BF is used for defining the product architecture.

3.2 Our modularization approach

Two sub-tasks are introduced in VDI 2223 to divide the system into modules. While trying to complete the tasks for a new design in this step, the following questions and difficulties usually arise:

- Because only the rough form of the product is illustrated for example by the sketch of the basic solution, all functional interactions can no longer be clearly recognized. How can the interactions inside modules be maximized and how can the interactions outside the modules be minimized quantitatively?
- Is there another representative model that helps designers to visualize the rough geometries and the functional interactions simultaneously?

- There is no supporting tool for deciding the product architecture in case there are many aspects to be considered.

Conclusively, several problems are recognized. These include representative model, integration analysis and nomenclature. A dependency matrix and C&CM are applied to solve these problems. The C&CM is used for nomenclature and the functional analysis. By means of C&CM, the system elements are modelled as WSPs and CSSs, in which the hardware perception and understanding of the functional interactions are revealed. The determination of modules can be realized with C&CM, the evaluation of the interactions and the matrix together. Consequently, three more tasks will be added into the modularization procedure from the guideline VDI 2223 as shown in figure 2.

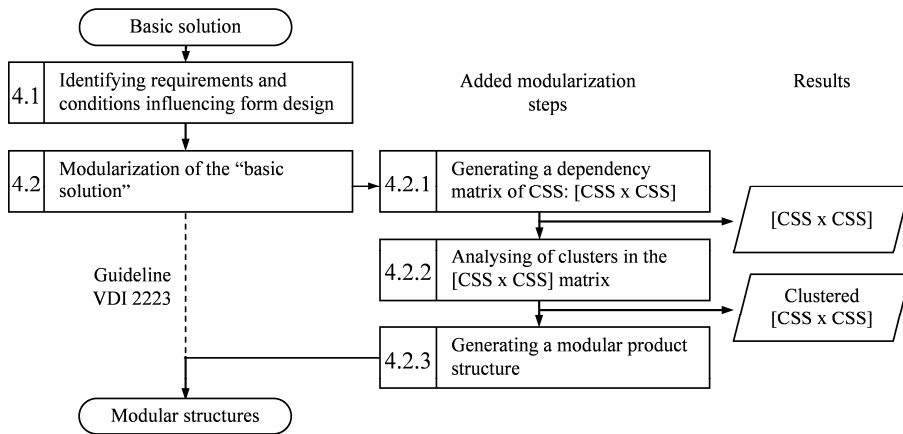


Figure 2. Extended modularization process based on VDI 2223

Step 4.2.1: After identifying the requirements and conditions which influence the form design, a specific function architecture containing only the basic functions is needed. Normally, the function architecture of the product is a combination of the basic and auxiliary functions. In the C&CM, the functions and their interactions are modelled to CSSs and WSPs. A complex technical system is usually composed of numerous CSSs and WSPs. This makes the system representation unorganized. For this reason, another representation is required. A dependency matrix or a design structure matrix is matched to this condition. A C&CM dependency matrix [CSS x CSS] is a diagonal matrix containing CSSs which are all listed on the matrix headers. The CSSs are subsequently mapped to each other through their corresponding WSPs which are entered into the matrix to illustrate this relationship.

Step 4.2.2: In this approach, the [CSS x CSS] matrix with the evaluated interactions (I_{CSS}) is the main integration analysis tool. The interactions are evaluated in terms of functional interactions and suitability values of the modular aspects. The degree of modularity can then be further computed with this matrix (shown in section 3.3.). After the computation, the CSSs in the matrix are clustered and result in a matrix with the maximum degree of modularity.

Step 4.2.3: With this result, an optimal modular product architecture can be established and visualized in the C&CM nomenclature. The following points should be considered:

- Number of the modules of the product
- Functions or CSSs involving in each module
- Boundary of each module and interactions with other modules
- Detachability of each connecting position
- Rough product architecture assisting the design of connecting components.

An example is shown in figure 3a. This simple system has 1 input, 2 outputs and 6 basic functions. All functions and their interactions are transferred to C&CM elements as shown in figure 3b and its [CSS x CSS] matrix in figure 3c respectively.

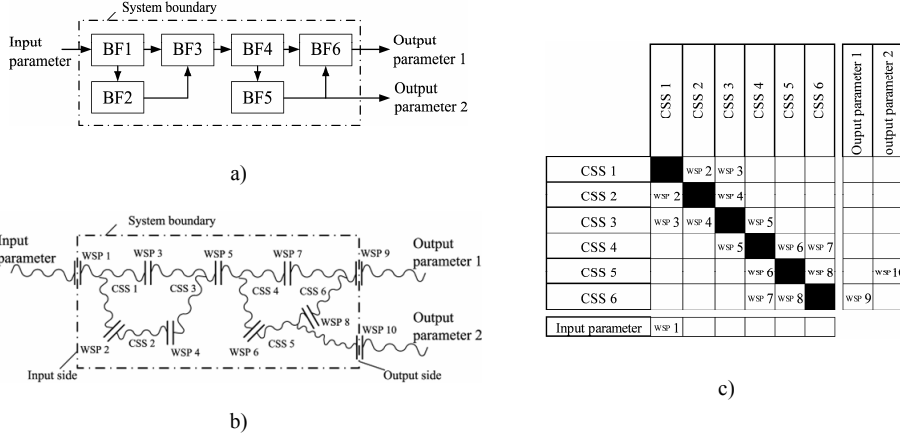
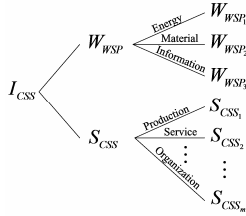


Figure 3. a) Function structure, b) C&M representation, c) [CSS x CSS] matrix

3.3 Evaluation of the matrix elements and degree of modularity

Two important calculations for this modularity approach are the evaluation of the interactions between CSS (I_{CSS}) and the determination of the degree of modularity (M). The evaluation of each interaction between CSS requires two sets of values including the influencing values of the WSP (W_{WSP}) and the suitable values for CSS (S_{CSS}). I_{CSS} is the sum of “ S_{CSS_i} ” and “ W_{WSP_i} ”. W_{WSP_i} concerns three functional interactions (force, energy, information) [Pahl et al. 2003]. “ S_{CSS_i} ” illustrates the suitability of two CSS that should be grouped into the same module in different modularity perspectives. For example, the durability of two CSS which is expected to be equal can be grouped appropriately into the same module. This enables the simple process of recycling. This evaluated equation has the maximum value of each I_{CSS} of 1 and can be formulated as shown in equation (1).



$$I_{CSS} = W_{WSP} + S_{CSS}$$

$$I_{CSS} = \sum_{i=1}^3 W_{WSP_i} + \sum_{i=1}^m S_{CSS_i}$$

where:
 W_{WSP} = Weight factor of each functional interaction
 S_{CSS} = Weight factor of each modularization aspect
 m = Number of modularization aspect

$$(1)$$

All I_{CSS} are then entered into [CSS x CSS]. The M value can then be computed from this relation

$$M = \frac{(\sum I_{CSS} / \sum I_{CSS, \max})_{\text{inside module}} - (\sum I_{CSS} / \sum I_{CSS, \max})_{\text{outside module}}}{\text{Numbers of modules}}$$

In case for the CSS dependency matrix, this can be formulated as followed:

$$M = \frac{\sum_{k=1}^{N_m} \frac{\sum_{i=n_k}^{m_k} \sum_{j=n_p}^{m_p} I_{CSS_{ij}}}{(m_k - n_k + 1)^2 - (m_k - n_k)}}{N_m} - 2 \times \sum_{k=1}^{N_m} \sum_{p=k+1}^{N_m} \frac{\sum_{i=n_k}^{m_k} \sum_{j=n_p}^{m_p} I_{CSS_{ij}}}{(m_p - n_p + 1)(m_k - n_k + 1)}$$

(2)

where: n_k, n_p = index of the first CSS in k^{th} module and p^{th} module
 m_k, m_p = index of the last CSS in k^{th} module and p^{th} module
 N_m = total number of modules in the product
 $I_{CSS_{ij}}$ = evaluated value of matrix element (row i and column j in the matrix).

One configuration of the product architecture delivers one value of M . In this research, this value is to be maximized in order to obtain the most optimal modular architecture in the given constraints.

3.4 Searching the maximal degree of modularity

In this step, the determination of architecture delivering a maximum modularity (M_{max}) is the main purpose. This value is the function of numerous variables as appeared in equation (2). Due to the complexity of the calculation, it is not possible to use the analytical way to find out this maximum value. As a result, a simple genetic algorithm (SGA), normally used as searching algorithm, is applied

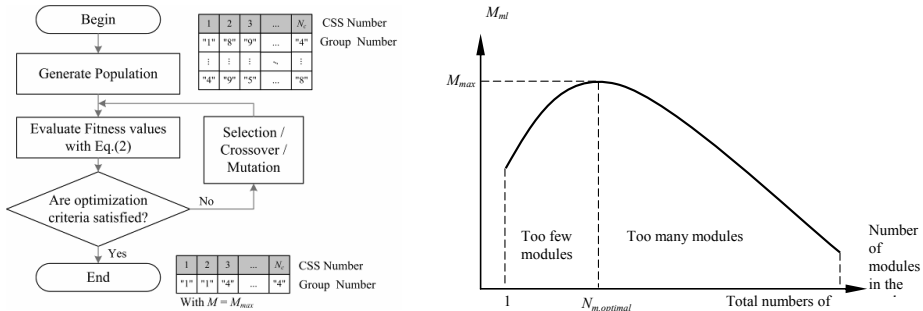


Figure 4. a) Diagram of search algorithm, b) Relation between M_{ml} and N_m

in this step. An integer encoding (figure 4a) is selected to solve the problem. With this algorithm the N_m and all other variables delivering M_{max} can be discovered.

To understand the limitation of M due to N_m , the algorithm has been adjusted to search the maximum value of M with each fixed value of N_m (M_{ml}). This results generally in a curve similar to figure 4b. Only optimal value(s) of N_m can maximize M value. It does NOT mean that the more modules are integrated, the more value of M is delivered. Lastly, a product architecture can be simply created by the conversion of the founded result to the C&CM representation (i.e. from figure 6b to 8b).

4. Application

The design of the forearm of the humanoid robot ARMAR III of the collaborative research center (SFB) 588 ‘‘Humanoid Robots’’ [Albers 2007] is taken as an exemplary application of this research. The forearm fulfils 22 basic functions with 28 functional interactions (shown in figure 5). A requirements list, a function structure and a conceptional solution of this forearm were initially completed before the modularization step. One side of the forearm is attached to the elbow while the other side is connected to the hand. Information and Energy are exchanged between forearm and hand.

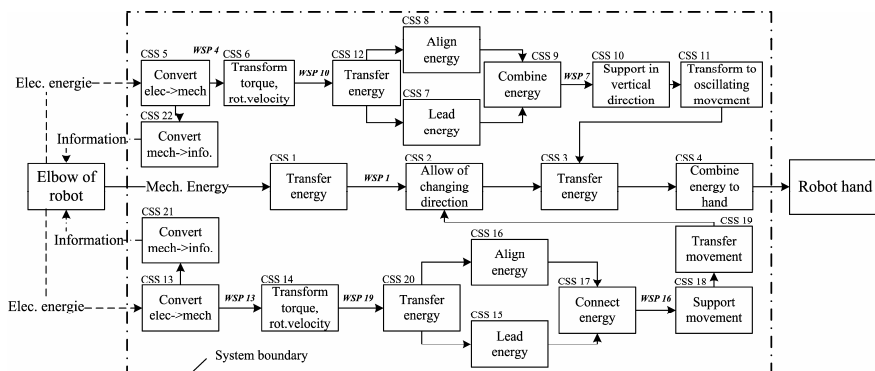


Figure 5. Function structure with number of CSS of a robot forearm

The main function of this forearm is to realize the motion of the hand which resembles the actual human wrist. In this example, energy interaction as well as service and upgradeable aspects are essential. The importance factor equal to 0.5 for both aspects is given. After the beginning of C&CM modelling, the [CSS x CSS] matrix is created. Afterward, all CSS interactions are quantitatively

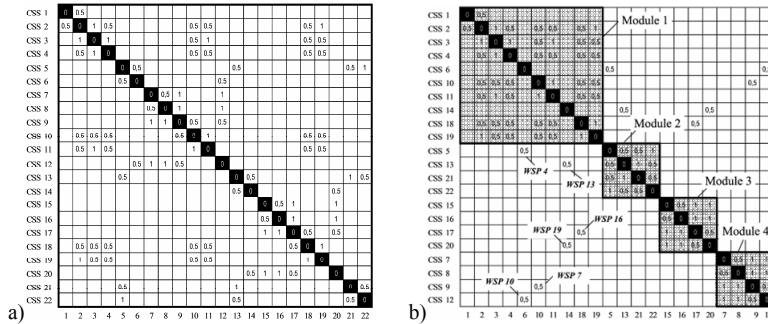


Figure 6. a) [CSS x CSS] before clustering; $M = 0.128$, b) after clustering $M_{max} = 0.47$

evaluated in order to prepare the matrix for the cluster analysis as shown in figure 6a. In this initial stage, the value of M is $\frac{62}{22 \times 22}$ or 0.128. The optimal product architecture can then be searched with the genetic algorithm to maximize the M value. The result of $M_{max} = 0.47$ by $N_m = 4$ is found as in figure 6b, which can be calculated from equation (2) as $\frac{1}{4} \times \left(\left(\frac{28}{100} + \frac{8}{16} + \frac{10}{16} + \frac{10}{16} \right) - 2 \times \left(\frac{1}{40} + \frac{1}{40} + \frac{1}{40} \right) \right)$.

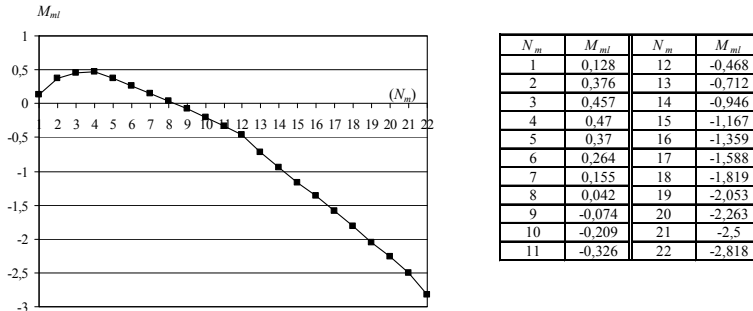


Figure 7. Relation between M_{ml} and N_m

The value M_{ml} equals to 0.128 in case of the integral architecture ($N_m=1$). It will be increased when the product architecture is divided into from two to seven modules. By more than seven modules, M_{ml} will be nearly to zero and decreased almost linearly with the minimum value of -2.818 shown in figure 7. The result of the modularly analyzed forearm has shown several important points which are useful in the embodiment design phase. This forearm should have four modules which contain CSSs as shown in figure 8b. The detachability of the connecting surface of the modules (WSs of WSP 4, 7, 10, 13, 16 and 19) has to be concerned. The auxiliary connecting elements involving these WSPs should be detachable in these WSs. The internal architecture of each module can be constructed in the integral manner. This suggestion of product architecture will be further designed in CAD system as shown in figure 8c.

5. Conclusion and future work

In this paper, the modularization procedure of the new design process and the implementing problems are presented. Even though its advantages have been long noticed, but the suitable supporting tool has

not been found. Clustering analysis with C&CM suggested in this paper as a problem solving tool is used to deliver the product architecture. This contains a maximum degree of modularity of a CSS dependency matrix. An application of a modularization in the early phase of the robot forearm shows the result of a architecture that provides a modular architecture. This is optimized from the functional as well as the service and upgradeability aspects. It provides an assist to a designer in order to present the superficial architecture of the product which benefits the further embodiment design process. The future work of the research is to apply this knowledge to the modularization of a redesign process. Additionally, the development of an easy-to-use tool with an efficient searching algorithm has to be further carried on.

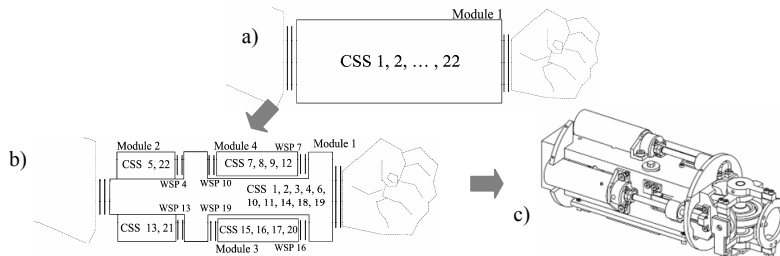


Figure 8. a) Integral architecture, b) Suggesting modular architecture and c) CAD Model

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References

- Albers, A., Burkardt, N., Ohmer, M., "Approaches for the synthesis of technical systems within the ontact and channel model C&CM", ICED 05 International Conference on Engineering Design, Melbourne Australia, 2005
- Albers, A., Burkardt, N., Ohner, M., "How C&CM can help the designer to find the Right Principles", Proceedings of CIRP Design Seminar, New Trends in Engineering Design, 2005
- Albers, A., Brudniok, S., Otnad, J., Sauter, C., Sedchaicharn K., "Design of Armar III – A new humanoid robot", Proceedings of 16th Int. Workshop on Robotics in Alpe-Adria-Danube, RAAD, 2007
- Pimmler, T., Eppinger, S., "Integration Analysis of Product Decompositions", ASME Design Theory and Methodology Conference, Minneapolis USA, 1994
- Gershenson, J. K., Prasad, G. J., Zhang, Y., "Product Modularity: Measures and design methods", Journal of Engineering Design. Vol.15, No.2., 2004, pp 33-51
- Pahl, G., Beitz, W., Feldhusen J., Grote K. H., "Engineering Design. A Systematic Approach", Springer Verlag Berlin Germany, 2003
- Rapp, T., "Produktstrukturierung", University St. Gallen, Gabler Verlag Wiesbaden Germany, 1999
- Ulrich, K., "The role of product architecture in the manufacturing firm", research policy, Cambridge USA, 1995, pp 419-440
- VDI-Richtlinie 2221, "Systematic approach to the development and design of technical systems and products", The Association of German Engineers (VDI), 1993
- VDI-Richtlinie 2223, "Systematic embodiment design of technical products", The Association of German Engineers (VDI), 2004

Prof. Dr. – Ing. Dr. h.c. Albert Albers
 Institute of Product Development (IPEK)/University of Karlsruhe, Mechanical Engineering Department
 Kaiserstr.10, 76131, Karlsruhe, Germany
 Tel.: +49 721 608 2371
 Fax.: +49 721 608 6051
 Email: albers@ipek.uni-karlsruhe.de
 URL: <http://www.ipek.uni-karlsruhe.de>