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Modularity: New Trends for Product Platform Strategy Support in Concurrent Engineering

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Abstract. Modularity intersects technical aspects with the business aspects. This paper analyzes modularity from this intersection point of view. It involves design for modularity as well management of modularity. Methods for supporting modular design are analyzed in relationship with technologies and tools for modular design. The current trend is toward usage and integration of different technologies such as advanced CAD systems, product configurators, agent-based systems and PDM systems. Development of intelligent models and intelligent tools as well as the development of intelligent modular products (i.e. intelligent system: model-tool-product), which can communicate and cooperate, demands the design of more intelligent organizations of modular design. Development of intelligent model-tool-product systems needs the development of holistic and concurrent engineering approaches. These approaches can offer the possibility of the design of intelligent self-sustainable models and intelligent self-sustainable products.

Keywords. Modularity, Modular Design, Product Variety, Mass Customisation, Product Platform, Product Configurator.

Introduction

Through the development of concepts and a body of knowledge, modularity has become an area worthy of study in its own right. It can be considered that the roots of modularity can be derived from human cognitive abilities [1]. The definition of product modularity is related to the criteria of component separability and component combinability in the domain of tangible assembled artifacts. Autonomy or independence towards external, dependence towards the internal is an important characteristic of modules. In context of concurrent engineering, modularity combines technical aspects with business aspects, both from a qualitative and a quantitative viewpoint.

Technically, products can be understood as a network of components that share technical interfaces (or connections) in order to function as a whole. Component modularity is defined based on the lack of connectivity between components. Modules are thus encapsulated groups of similar interconnected physical components which

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operate a flow of energy, material or information to perform a set of functional requirements. Minimization of interactions with external components and maximization of interactions between the components within the module are thus principles for finding modules. Technically, it can be expressed with three measures: *(a) how components share direct interfaces with adjacent components, (b) how design interfaces may propagate to nonadjacent components in the product, and (c) how components may act as bridges among other components through their interfaces*.

From the business point of view, modularization has three purposes: *(a) to make complexity manageable*, *(b) to enable parallel work,* and *(c) to accommodate future uncertainty* [2]. The impact of modularity to the financial and organizational structure of an industry can be described with three aspects: *(1) Modularity is a financial force that can change the structure of an industry; (2) The value and costs associated with constructing and exploiting a modular design are explored; (3) The ways in which modularity shapes organizations and the risks that it poses for particular enterprises are examined.* Modularization in enterprise leads, thus, to the disaggregation of the traditional form of hierarchical governance. The enterprise is decomposed into relatively small autonomous organizational units (modules) to reduce complexity and to integrate strongly interdependent tasks while the interdependencies between the modules are weak. The dissemination of modular organizational forms yields a strong process orientation: the complete service-provision process of the business is split up into partial processes, which can then be handled autonomously by cross-functional teams within organizational subunits.

Modularity can thus be considered as a powerful concurrent engineering concept intersecting technical and business aspects, in the one hand, and qualitative and a quantitative viewpoints, on the other. This paper analyzes the modularity following this intersecting concept. It involves the designs for modularity as well the management of modularity (section 1). The methods for supporting the modular design are analyzed (section 2) in relationship with the technologies and tools for modular design (section 3). Two industrial applications (plant design, aerospace) are also analyzed (section 4) in relationship with technologies. The paper proposes some new trends for modularity (section 5) and concludes with respect to the future of modularity from a CE perspective (section 6).

1. Modularity: Design and Management

From our point of view, modularity is a concept which intersects design and management.

1.1. Modular Design

Modular design considers functions, properties and interfaces of product constituents. Standard interfaces make parts interchangeable, thereby reducing the expenditure for the combination of different product constituents. Modular design usually involves the following processes: (1) *the identification of product architecture and reusable components (building blocks) from existing products*, (2) the *agglomeration and adaptation of singular building blocks into modules to derive a new design,* and (3) *assessment of product performance and cost*. Modular product architecture is generated by deriving a rule base (scheme) for the mapping of product functions to physical components. For the utilization of modules comprehensive interfaces become crucial. Three basic types of modular architecture are defined, namely slot, bus and sectional, according to the interfaces between components [3]. Platforms as a special expression of a modular design are of particular relevance for an industrial practice. A platform is a standardized base product with fundamental functions and properties of the total product, on which a variety of similar products can be efficiently built by using subsystems, modules and components. In the platform the architecture and the interfaces to optional elements are included, which are used for differentiation of the end products.

1.2. Mass customization, variety and configuration

Under the term “Mass Customization” a business strategy is defined that utilizes modular design for complex offerings of products and services that are configured on demand to achieve the best fit with customer-specific needs [4]. Mass customization joins two concepts that are usually supposed to be opposite: mass production and customization including two approaches: mass and craft (single-piece) production. Mass production manufactures low cost products by reaping the benefits of standardization and scale economies. On the other hand, craft production assumes a high level of individualization since the products are tailored to specific customer requirements.

Product structure of customized products must be thoroughly adjusted for specific customization options by adopting entirely individual components that are specifically created besides of standardized and configurable modules. Generally, a fixed and a variable area of product structure can be identified, in which mandatory and optional spaces are foreseen for individual implementation. Product customization is usually supported by configuration systems. Generic conceptual procedures for designing such system are important for mass customization. These procedures involve analysis and redesign of the business processes, analysis and modeling of the company’s product portfolio, selection of configuration software, programming of the software, and implementation and further development of the configuration system .

1.3. Modularity from a Management Perspective

In general, from a management perspective, modularity can be seen as a business strategy for efficient design and structuring of complex products, procedures and services with the objective to rationalize the enterprise. By now, modularity has become a basic irreplaceable development methodology inside the product strategy for a variety of technical products planning based on market research and correspondent forecast. Modularity seems counter-productive, when selective distinctive features are the reason to buy a product. When customers focus on elements, like styling, haptics, or specific colors, creative freedom is necessary. In such cases modular design is not applicable, because investments in modular design outweigh the efforts to create a user-specific product of which the number is often very small. The integration of different product variants does not come with any monetary benefits if it is not organized through a holistic controlling approach [5]. This approach enables the assessment of modular product families as well as their holistic management based on the new modularity-balanced-score-card (M-BSC). Additionally, the different perspectives from production, development, marketing and sales need to be integrated. Cost schemes of modular products can also be established by decomposing the product family into generic modules to support cost calculation.

2. Modularity: Methods for Modular Design

Modularity is achieved by partitioning information into three categories [3]: *Architecture*, *Interfaces* and *Standards*. Architecture specifies system modules and their functions. Interfaces describe the interaction of modules. Standards test a module's conformity to the design rules and compare performance of competing modules. Common attributes of modular products can be [4]: *commonality of modules*, *combinability of modules*, *function binding*, *interface standardization, loose coupling of components*. There are various methods to support modular design like axiomatic design (AD), functional modeling, design structure matrix (DSM), modular function deployment (MFD) and variant mode and effects analysis (VMEA), which can be also used in combination with an architecture development process [6]. Comparison of methods in several application areas (product variety, product generation and product lifecycle) have shown that the generation of modules depends on both the chosen method and the weighting of different criteria.

3. Modularity: Technologies and Tools for Modular Design

Currently, manifold technologies and tools are offered to foster modular design. They provide optimal functionality by mutual integration and interaction with other systems.

3.1. Product Configurator

A product configurator is a multi-functional, commercial IT tool which serves as interface between sales and delivery in an enterprise. It supports the product configuration process so that all design and configuration rules, as expressed in a product configuration model, are guaranteed to be satisfied. A product configurator implements formalized product logic, which contains all *"If-Then"* configuration rules and constraints. The customer inputs his detailed requirements controlled by the user interface. A product, which meets the customer's requirements in the best way, is then selected. After validity check and cost analysis, the bill of material (BOM), CAD models, and finally, the bid are generated. By force of circumstance, as its function affects multiple core areas of an enterprise, a product configurator has to be integrated deeply with the involved IT systems such as Enterprise Resource Planning (ERP), Product Lifecycle Management (PLM), CAX technologies. However the complexity associated with managing and synchronizing configuration master data across different applications such as ERP, PLM and CAX is an important barrier to the deployment of integrated product configuration.

3.2. Agent-based Approach

Collaboration and fuzziness are integral parts of configurable product modeling [7]. The *agent paradigm* can be applied to handle complex *uncertain problems* where global knowledge is inherently distributed and shared by a number of agents, with the aim to achieve a consensual solution in a collaborative way. Fuzzy agents are proposed to solve distributed fuzzy problems [8] as well as to model the processing of the fuzziness of information, fuzziness of knowledge, and fuzziness of interactions in collaborative and distributed design for configurations [7, 8]. Structural problems of configuration are also formalized with the help of configuration grammars [9] and implemented in a grammar-based multi-agent platform [10]. An agent-based system called *FAPIC* (Fuzzy Agents for Product Integrated Configuration) is developed for product configuration [11]. In FAPIC, each requirement, function, solution and process constraint is a fuzzy agent, with a degree of membership in each community of agents: requirement community, function community, solution community and constraint community. In the first phase, FAPIC builds different societies of fuzzy agents, necessary for the configuration of a product. In the second phase, the fuzzy set of consensual solution agents emerges. First the *fuzzy set of requirements* for a particular customer is defined. In third phase, the optimal configuration emerges from fuzzy consensual solution agents and their affinities. During this phase, the consensual solution agents through their interactions and using their affinities are structured into modules. Maximization of interactions between the consensual solution agents within a module and minimization of interactions of consensual solution agents in-between modules is the objective function to be optimized. Finally, in the fourth phase, the agents seek the consensus. Thus, consensus agents interact with fuzzy solution agents as well as with the fuzzy configuration agents. They can inform the designer about the different coefficients established to measure the consensus that emerged.

3.3. PDM Approach

In modern PDM systems, the overall structure of a modular product is mapped in a generalized product structure. Alternative or optional items are initially managed in the database of PDM systems in the same way as all other items, i.e., items as master records with corresponding attributes. Differences to the usual article management arise only in the structuring of the product in the form of bills. Through the use of variants in product structures PDM systems are able to manage order neutral BOMs with varying and optional positions. This approach is beneficial for product development and less for production and accompanied departments because there explicit BOMs are needed for each product variant to be produced. Furthermore, there is a risk that the data management is very complicated, while compromising the performance of the system needs to be tolerated, especially when a large number of product variants needs to be managed. To resolve these conflicts, modern PDM systems are extended by the module "Variant Manager". In the base module all master data (parts, structures and processes) are managed. In case of variants explicit ones are derived by the configuration and clone modules. Various reports can be generated by a reporting module that also contains neutral data when needed.

4. Modularity: Industrial applications

4.1. Plant design

In plant design, machines with more than 10.000 parts are designed which are documented in 3D-CAD and PDM systems. They are customized by the following criteria: market and customer requirements, technical producibility, own business aims and the general possibility to create modules. Thereby, both arbitrary complexity and the reduction of product offering have to be avoided. The right product configuration is generated by a Web based product configurator. Additionally, a convenient product presentation for given configuration is chosen by using KBE.

Even for factory planning with more than 500 machines in one production hall and internet applications, complex models which show every detail cannot be used for performance reasons. Furthermore, no company wants to share its know-how with its competitors through the internet discovering fully detailed CAD models. The key is the separation of complex and simplified CAD models in two different data sets, which, though, are managed by the same status information. The simplified model can be generated in different levels of detail. As an example, the sales discusses the design of the machine hall with the client and configures the design in 3D on site. Thus, the characteristics of the individual machines are written down in the CAD system and the simplified models are used. A prime scale drawing can be printed locally and an offer is generated directly. Moreover, it is possible to add a rendered 3D picture to the offer.

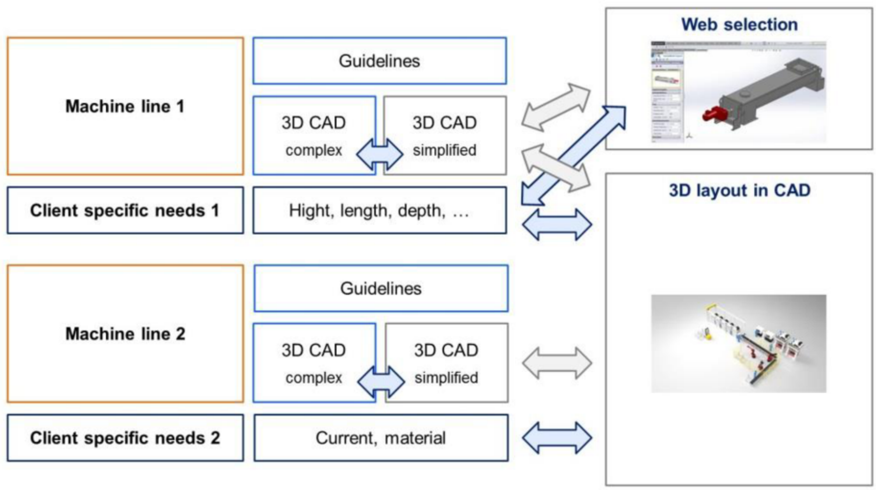

Figure 1. Modular design with product configurator and KBE

In the example of Figure 1 the machine designed by KBE and CAD is able to adapt every of the 50 million possible combinations in the CAD model. According to the client´s choice, the desired variant is adjusted with the product configurator. This variant is checked for doublets at any level of the structure and checked automatically in the PDM system. The parts can be produced directly in the connected sheet bend machine. The variant selection can be conducted by an internet solution with the simplified model and ,hence, can be directly passed to order management. The processing time for one job is reduced from days to hours.

Configurator can communicate bidirectionally with other sections and internal systems (CRM, ERP, PDM) by detached status information from the CAD system. This solution allows building up bottom up relationship knowledge and setting up assembly plans by ERP object lists. Similar concepts, which combine product configuration with KBE are used for the design of automotive components.

Several examples of configurable products have been studied in the literature such as: cars, elevators, computer equipment, computer software, telephone switching systems, telecommunication networks, etc. Automotive OEMs have their own history in the development of configuration technologies and tools. However, often it is found that neither a PLM, nor an ERP-oriented standard application is able to supply the needed functionality for a lifecycle approach to product configuration. PLM systems are product-centered tools, whereas ERP systems consist of operational business tools..

4.2. Small-scaled modular design of aircraft wings [12]

Fostering a differentiation between modularization approaches for conventional products and a new modularization approach for large-scaled products like airplane, the term small-scaled modular design is introduced which describes the possibility to subdivide large components. A methodical approach to determine the ideal module size for large scaled products was developed which is divided into four steps: design, technical feasibility evaluation, analysis of the economic viability, and development of a tool to determine the ideal module size.

The wing of a long-range, wide-body jet airline was selected as a reference product. To identify the best design concept, four variants were evaluated on the basis of the following criteria: manufacturability of the components, easy assembly with a high proportion of preassembly, the use of state of the art technologies, the estimated weight and the comparability to the reference wing. Finally, variant 4 was chosen, especially because this variant shows a high level of comparability to the reference wing and is based on currently available production technologies.

Then the analysis of the application example aircraft yielded that even at the area of the wingtip there is enough installation space to mechanically connect the trailing edge modules with each other. In contrast to the trailing edge, the position with the least installation space for the assembly of the leading edge is not the wing tip. As the pipes of the bleed air system and the generator cables do not lead from the wing tip to the root, the position with the least installation space is just behind the engine mount. In this exemplary assembly situation several hydraulic pipes, a bleed air pipe, several parts of the electric harness and a mechanical drive shaft for the slat system have to be connected with each other. The connection is done via an open segment of the leading edge cover which will be closed after the assembly process is finished.

For a substantial assessment of a small-scaled modular design of an airplane wing the whole aircraft life cycle has to be considered. By an analysis of the whole lifecycle of an aircraft and expert interviews, six groups of 'modularization factors' were identified (see Figure 2 left). Further modularization factors with a lower impact to the lifecycle costs, like ergonomics, the feasibility of retrofitting and a larger product variety, and recycling could be identified, but are not considered. Through this focusing on the most significant modularization factors an application of the developed method in the preliminary design phase is facilitated. The modularization factors include contradictory design targets (Figure 2).

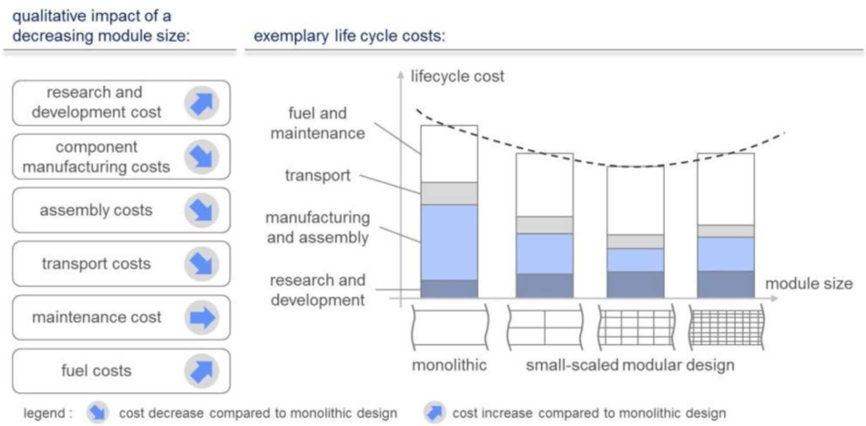

Figure 2. Lifecycle costs as a function of the module size

To facilitate the manufacturing and the logistics, a small module size and, thus, a high number of modules should be realized. There are further modularization factors to reduce the number of modules. For example, fuel consumption raises with an increasing number of modules as each interface between two modules causes additional weight and aerodynamic drag. Thus, the ideal module size was determined based on the predicted lifecycle costs. By minimizing the total life cycle costs not only one design aspect is optimized, but a global optimum is reached.

5. Modularity: Further Development

Design for product variety, design for product configuration, and design for mass customization are considered to be highly collaborative and distributed processes. During these design processes, the amount of information on the products evolves. Uncertainty is thus another characteristic of designs processes for product variety, for product configuration, and for mass customization. *Therefore, from a holistic point of view, there is still much to be desired in order to achieve system-wide solutions for these design processes and platform-based product development, which can consider collaboration and distribution, intensive interaction between distributed actors, heterogeneity, dynamics and evolution of organization, and the uncertainty*.

Product configuration and modularity are inherently related to product architecture. As the product architecture is considered to be the governing force in lifecycle design, the issue of product architecture lacks theoretical foundation. The design of product architecture has been considered rather more as a know-how issue of architects than a scientific-engineering issue. *In what ways a product architecture, accounting nowadays only for the functional and physical aspects of a modular product, integrate all other lifecycle characteristics is an important issue.*

The design of a modular product is considered to resolve a system-based interdependency problem. Traditionally, this issue has been seen as system architect's task. Architects design a functional and physical architecture of a system and their greatest concerns are still with the systems' connections and interfaces. The development of modular designs often requires a redesign of the components themselves resulting in new components. Consequently, an architect should assess the achievable technical performance of systems based on their underlying modular or integral architecture. *Modular design should be the result of a coherent and rationale design process, where the options, modular or integral, are early explored in response to technical constraints and the set of requirements. Finding the relationship between sparseness, modularity, technical constraints and the set of requirements, could allow such assessment early in design process.* A task in modularity assessment is also the issue of increasing the effectiveness of modularity. *Finding the relationship between the level modularity and the effectiveness of modularity is an open-ended issue.*

Actually, the lifecycle of a module is confined to predefined scenarios that depend on its interfaces and its connections. A product with increased adaptability and suitability requires more efforts of design and manufacturing due to increased variety and complexity. *How to design intelligent modules is an important issue related to the design of intelligent products.* The use of open architecture in modular design is a solution to allow the adoption of new technology. The use of existing modules as well as the use of independently developed modules to design new modular systems, while respecting the integrity of these modules, has to do with the suitability for integration of modules. The adaptability and suitability of modules for integration in a wide range of possibly larger systems is an important issue of the design and development of intelligent systems. *The concept of an intelligent product should maximize the design space of architects and system designers.*

The change management of requirements, functions, solutions and process constraints is another question in modular design. The development of intelligent modular products is strongly related to the development of intelligent models and intelligent tools. Thus, development of intelligent multidisciplinary collaborative and distributed platforms can better handle the modularity and variant management problem. *The multi-agent paradigm has the potential to respond to this challenge and to pave the way for the introduction of innovative technologies in a dynamic environment characterized by important changes and evolution.*

Development of intelligent models and intelligent tools on the one hand and the development of intelligent modular products, on the other, which can communicate and cooperate between them, need holistic and concurrent engineering approaches. *These approaches can offer the possibility of the design of self-sustainable models and self-sustainable products.*

To create long-lived modular systems, the foundations of the system have to reflect the corresponding relevant reality. The design of a modular product should exploit this principle thoroughly. More modularity is better in all lifecycle viewpoints. However, except architects, other actors like development project team members and management in general have often limited access to dependency-based system views. *Transfer and sharing of knowledge, from architect to various actors and vice-versa, are essential to be able to support all lifecycle viewpoints in system level project coordination. If collaborative design in this context is to be successful, it must be built on a shared rationale of critical design decisions.*

A key motivation of modularity is the specialization in the design and production of modules. Modular organizations are responsible for modular products. The modular product effectively serves much larger user groups over longer periods of time than a single combined product. Thus the performance of the structure of modular product reflects the performance of actors' coordination in an organization. Should a modular organization in a *dynamic world* reflect the modularity of the product, and, should a modular product reflect the modular organization, are still open questions. *Thus, finding the relationship between the performance of the structure of modular product and the performance of coordination of an organization could allow the assessment of modular product design early in design process.*

6. Conclusions

Modularity is a multidisciplinary and intersecting concept. In the context of concurrent engineering methods, modularity can be defined as the degree to which a product's architecture is composed of modules to respond to a set of requirements, including lifecycle issues and the organization of collaborative and distributed design processes. The current trend of technologies of modular design is to use, combine and integrate different technologies such as advanced CAD systems, product configurators, agent based systems and PDM systems. Development of intelligent models and intelligent tools as well as the development of intelligent modular products (i.e. intelligent system: model-tool-product), which can communicate and cooperate, demands the design of more intelligent organizations of designs processes for product variety, for product configuration, and for mass customization. Development of intelligent model-tool-product systems needs the development of holistic and concurrent engineering approaches. These approaches can offer the possibility of the design of intelligent self-sustainable models and intelligent self-sustainable products.

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