INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016
Dubrovnik - Croatia, May 16 - 19, 2016.

RECONFIGURABILITY AND MODULARIZATION FOR INTEGRATED MACHINE TOOLS BASED ON FUNCTIONAL ANALYSIS: A SYSTEMATIC APPROACH

A. Schmid, T. Katzwinkel, W. Schmidt, J. Siebrecht, M. Löwer and J. Feldhusen

Keywords: design methodology, reference product architecture, modularization, product conceptualization, functional structuring

1. Introduction

Nowadays manufacturing companies have become increasingly exposed to global competition, in particular high-wage-countries are affected. The capability for innovation has an essential effect on the production site [Schuh 2012b], [Gausemeier 2014]. In this context a solid development and design process is vital, in order to shorten both innovation cycles and the time-to-market factor, especially with regard to the process of globalization [Pahl et al. 2007]. The question arises, how enterprises are still able to position or reorient themselves under these novel constraints to remain competitive. One viable solution is a successful establishment of flexible production systems that enable enterprises to reposition for either customized or mass production [Brecher 2012]. To master this balancing dichotomy between mass production and individualization of production, new products have to fulfill the market needs by providing maximum quality at low cost [Pahl et al. 2007]. Within the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" sustainable production strategies and theories, including the corresponding technologies, are investigated at RWTH Aachen University to respond to this scientific issue. Flexible production systems, so called Multi-Technology-Platforms (MTP), are investigated combining various production technologies in a single machine. For this purpose the survey for design guidelines and methodologies in early stages of product development is a major research assignment.
In engineering design there are several systematic approaches on how to promote the capacity for innovation and to generate concepts for early systematic structuring of the design process. A generic development and design process is illustrated in Figure 1.

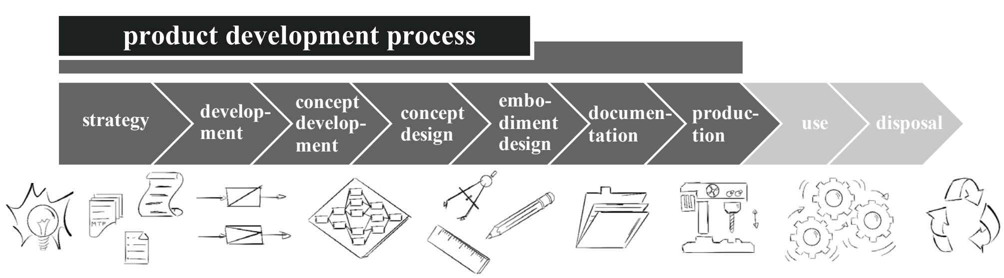

Figure 1. Product development process according to [Pahl et al. 2007]

A universal and systematic approach for the development and design of technical systems and products is presented in VDI guideline 2221, basically split into analysis and synthesis. After clarifying the task, a functional and structural determination is acquired and individual methods for a robust conceptual design are presented. A thorough analysis of the purpose of the aspired system and a subdivision into smaller work packages form the basis for systematic engineering design. For synthesis, individual methods for systematic embodiment design of technical products are proposed. The general procedure during form design is initialized by dividing the basic solution into realizable modules and subsequently dealing with form design of the modules and the entire product [VDI 2221 1993]. However, only a functional decomposition of the main function, according to the purpose of the product, into several subfunctions or even down to the level of elementary functions makes the engineering task manageable, displayed schematically in Figure 2.

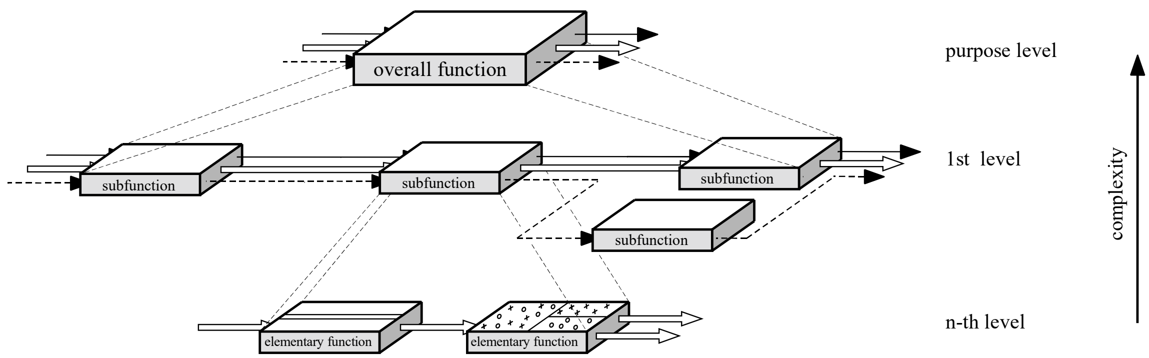

Figure 2. Functional decomposition according to Koller [1998]

Classification schemes such as the morphological box are often used to combine individual solutions for each subfunction needed to build product concepts [Zwicky 1949], [Koller 1998], [Heller 2014]. This widely published procedure basically consists of three steps: a functional decomposition, building of principle solutions often based on design and solution catalogues and finally a systematic combination of the identified solutions [Koller and Kastrup 1998], [Roth 2000], [VDI 2727 2010]. The main issues to be taken into account are a guarantee for compatibility of the individual solutions and a selection of technically and economically preferred combinations. Conceptual design contains in essence the development of working structures and adequate concepts for the specific problem to be addressed. Concept development in general can be structured in the determination of a preliminary product architecture, a range of functionalities and the related interfaces [Pahl et al. 2007].
A different approach is Axiomatic Design by Suh developed in the 1970s, enabling a structured design of systems by mapping suitable solutions with previously determined requirements to deal with complex systems and enhance creativity [Suh 2001].
After this brief introduction product conceptualization of MTP is addressed in the following sections. A structure and classification scheme for product architectures on the basis of functional and physical dependencies of their components is presented in the second section, with a focus on modularization and integral design for next generation machine tools integrating multiple technologies. In addition, an insight into reconfigurable machine tools and existing design methodologies supporting the development process of variable machine tools is given. In section three an early structural approach is introduced for the single manufacturing processes, regarding the integration of different processes into one system. The emphasis is on technological similarity and necessary auxiliary functionalities. The approach is based on the assumption that an investigation on technological similarity of the involved manufacturing technologies of a MTP grant access to untapped potentials for synergies. Reference product architectures are characterized for MTP and validated on a fully functional demonstrator. Industrial applications are able to benefit by a systematic conceptual design and product structuring from the very beginning of the development phase. To conclude, a brief summary and appraisal is made before the paper ends with an outlook about future research.

2. Conceptual design

The complexity of modern products is increasing steadily. As a result of the growing complexity and the constantly rising demand of customers, differentiated product structures are the result and lead to broad effects along the value chain [Franke 2002]. Embodiment design for technical products is complex and intensive, regarding functions, components and manufacturing processes. Consequently, the challenging task has to be subdivided in several smaller units [Göpfert 1998]. In addition, to remain successful in international competition, a high degree of flexibility is in demand [Schuh 2012a]. A systematic design for product architectures enables enterprises to gain a competitive edge [Schuh 2012b].

2.1 Product architecture design

A key performance indicator of manufacturing companies is the underlying architecture of the product [Ulrich 1995]. Ehrlenspiel quotes, the majority of development costs is determined in early stages of product development, this is the time when product architecture is clearly-defined [Ehrlenspiel 2007]. In general, product architectures reflect the relation between market and company perspective. Thus, it is specified which function will be realized by which function carrier, component or assembly. Product architectures are used to describe the modularity and create a specific delimitation for standardization in early stages of product development. The product is addressed from two different perspectives: functional and physical. A decomposition in functional and physical domains is applied and hierarchies are determined. The core task for product structuring comprises in the transformation and interconnection of function structure and product structure [Ponn et al. 2008]. In product architecture design the functional description and characteristics, and the modular structure are defined. Potentials for synergies are facilitated by series concepts and modular systems to master the variety or complexity of MTP [Göpfert 2000], [Ponn et al. 2008]. A robust product architecture increases the profitability and is one key to more efficient structures. Moreover time-to-market intervals can be reduced tremendously [Pahl et al. 2007]. To control the dilemma between enhanced product variety, resulting from diverse customer requests and the corresponding increase in complexity inside the company, a systematic design of product architecture is essential. Figure 3 shows the difference between a modular and an integral product architecture in general.

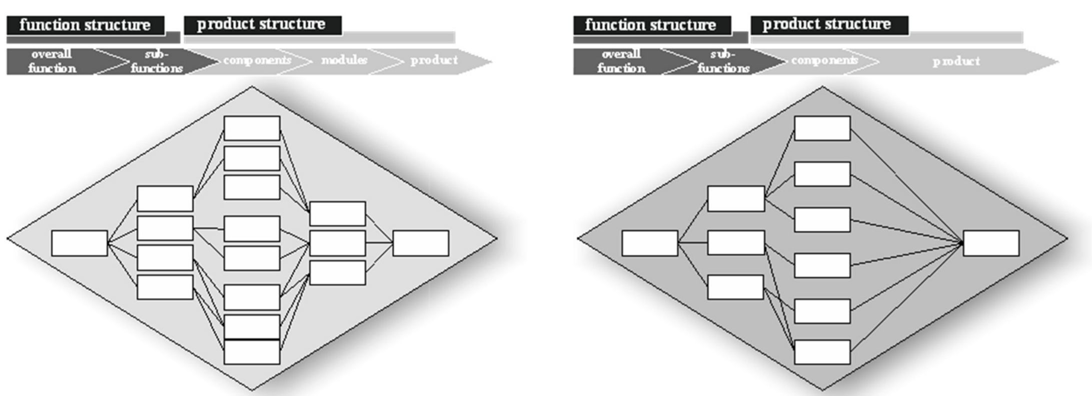

Figure 3. left: modular product architecture / right: integral product architecture

A modular product architecture is characterized by a physical and a functional independence to a large extent. The major advantage of modular product architecture in product development is the decoupling of the different modules. The complexity of the overall system gets divided into smaller packages which are developed largely independently, provided that a consistent interface design is existing. Already developed modules can be reused and the effort for developing future modules for MTP can be minimized. In particular, a solid reconfigurability is guaranteed. Limits of modular structures are the greater risk based on the high reusability of products in case of error and the expensive and heavy design, because no product-specific optimization can be applied [Pahl et al. 2007]. In contrast, an integral product architecture is characterized by a high functional and physical dependency of the components. The functional integration is considerably higher and less components are needed in general. Expensive interfaces between normally physical separated components can be avoided. A complex product architecture is the result, leaving only little opportunity for substitution, monitoring, reusability of components and a difficult expandability. Thus, a standardization for integral product architecture is sustainable only in very rare cases and there is no possibility of an individual combination of components [Pahl et al. 2007]. However, a hybrid form combining modular and integral architecture is permitted to exploit the potential of both designs. Heisel predicts, the key focus of future research is on reconfigurability referring to machine tool conceptualization [Heisel 2004].

2.2 Modularization and integral design

The approach of modular design is to create largely independent modules interacting with each other in the overall system [Göpfert 1998]. The particular benefits of modularization are well defined interfaces, the reusability of already developed modules, an easy replaceability and extensibility. Far more crucial is the possibility of standardization and the combinability in a modular design principle [Pahl et al. 2007]. A classification based on functional and physical autonomy is presented in Figure 4.

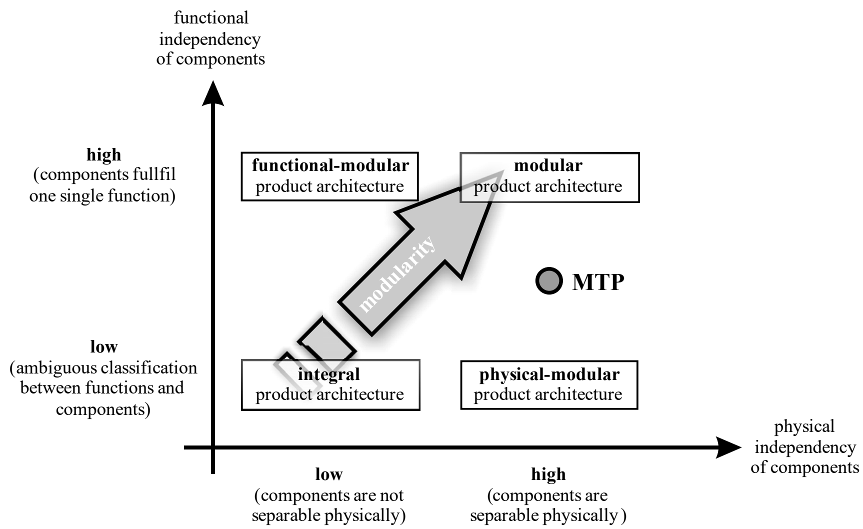

Figure 4. Classification of product architectures according to Göpfert [1998]

In modular systems the relationship between the subsystems is less strong in comparison to integrated systems. The complexity in the development and manufacturing process becomes manageable, because the partial tasks can be operated separately. There has been no classification regarding the underlying product architecture of MTP in the field of tension of physical and functional independency yet. A feasible positioning for MTP can be seen in Figure 4. The most prominent differences to traditional, sequential manufacturing in different stations are appearing interactions and mutual influences between the different processes. Consequently, existing design methodologies have to be adapted to these novel machine systems. A modular product architecture with both functional and structural autonomy is aimed to guarantee separability. The goal of future research is to integrate functions and components appearing equally in the manufacturing processes to be combined and to modularize process-specific characteristics to support reconfigurability and flexibility. The interactions of the different technologies have to be considered as well to create a clear separation for either modularization or integral design depending on the use case.

2.3 Reconfigurable manufacturing systems

Technological reconfigurability is the ability to change the current status with minimum effort by integrating or disintegrating specific production technologies [Wiendahl et al. 2007]. Autonomous and standardized function units or modules form the basic framework of reconfigurable systems [Tönshoff 1994]. The coincidence of functional and physical system boundaries facilitate a defined separation of the single modules. The simple opportunity for modification by adding or removing modules is the logical consequence. Therefore, a necessary condition represents the capability for reconfiguration both hardware and software based. Reconfigurable manufacturing systems (RMS) are suitable to adapt to changing requirements and uncertainties [Bi et al. 2007]. The main characteristics to describe RMS are the modularity, integrability, customization, scalability, convertibility and diagnosability of such systems [Wiendahl et al. 2007].

Different methods for the development of RMS are addressed in literature. Koren postulates, that RMS are the basis for an efficient and economic adjustment regarding structure, capacity, technology and their function [Koren 2006]. Besides, a mathematical model for designing RMS is also introduced by Koren. He postulates furthermore, that a new manufacturing system should be designed each time a new product is introduced. A more efficient approach is to consider the evolution of manufacturing systems [Koren 2011]. RMS are designed for a specific, customized range of operation requirements and may be cost-effectively converted when the requirements change [Landers 2001]. In addition to other investigations, Abele developed a multi-technology platform-based prototype for RMS (METEOR) integrating different machining technologies in one machine workspace [Abele 2005]. According to Wiendahl, the following aspects have implications for attaining changeability in the design phase: universality, scalability, modularity, mobility and compatibility. Completely reconfigurable machine systems do not exist yet. Functional requirements and design parameters are represented in a manufacturing system architecture linked by a linear system of equations [Suh 1998]. A major focus in research is on hardware and machine control aspects [Wiendahl et al. 2007]. A cost-efficient development for RMS is identified only for few machines [Bi et al. 2007].

Due to the complexity of RMS there are just a few design methodologies known for reconfigurable manufacturing systems [Koren et al. 1999]. Furthermore no design methodologies are on the advance in commercial parallel kinematic machines [Bi et al. 2007]. In ElMaraghy the increase in complexity is to be minimized in design and only justifiable by improving system capabilities and performance [ElMaraghy et al. 2012]. According to Hyatt, there are no broadly reconfigurable machine tools available yet, except prototypes [Hyatt 2005]. Spicer claims, there is a need for engineering design guidelines and methodologies for the configuration of manufacturing systems. No systematic design methodology for the optimal configuration is known so far [Spicer 2002]. According to Bi, design methodologies for conceptualization depend on the complexity of RMS [Bi et al. 2007]. A holistic approach is presented in Schuh for the development of modular product architectures in three steps: identification of requirements for modular architectures, definition of standards, modularity and at least interface design [Schuh 2014]. A systematic method for machine tool configuration regarding functional analysis and a decomposition into optimal subfunctions is still missing [Perez 2004], [Moon 2006]. Hence, there are no existing approaches for MTP either.

The starting point for this investigation is based on the systematic examination of functional aspects. There is no basic methodology existing for elementary conceptualization of MTP, regardless which processes are combined. A basic structure for next generation machine tools integrating various technologies for product conceptualization is introduced in the next chapter. A functional similarity analysis is presented, shared functions and required auxiliary functions are examined more closely. At functional level, auxiliary functions become necessary after the integration of diverse production technologies. An additional value can be achieved by functional integration of an equally occurring functional range. A scheme for a reference product architecture is introduced at its core. The priority aims are to obtain a homogenous structure and to minimize interfaces and modules for next generation machine tools to optimize the integration and reconfigurability. Finally, a comprehensive validation is carried out by a Multi-Technology Machining Center.

3. Product architecture design for MTP

In order to support engineering design within the conceptual phase of product development projects in an efficient way, an advanced scheme for product architecture design of MTP is presented and validated. A closely examination of the functional dependencies and direct effects on the component level are investigated precocious. Structural and functional relations for a necessary and sufficient integration are taken into account.

3.1 Functional description

Developing optimal and generally valid product architectures for individual application is often performed as an iterative process. On account of the interdependencies and numerous configuration options finding the best suited structure becomes a multidimensional optimization problem. But only seldom a purely analytical solution is possible. More appropriate is a design of alternative product architectures, which can be evaluated systematically and optimized iteratively [Pahl et al. 2007].
Overcoming the complexity and diversity of product design there are several approaches for standardization. By functional and physical seclusion of the single modules, product conceptualization of MTP becomes manageable. The potential for reducing costs and effort in early stages of product development is enabled by reference product architecture for MTP. With the analysis, potentials for standardization of assemblies, their components and the interface design take a precedence. A uniform structure leads to a robust concept. A transparent presentation of data acquisition and capture by various sources is facilitated. A generalized consideration is presented in Figure 5.

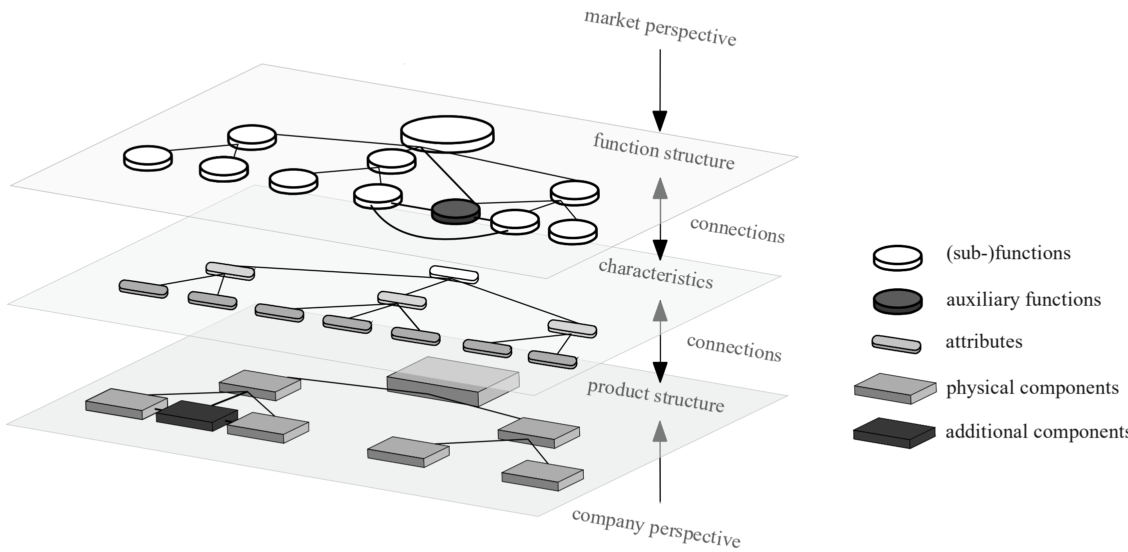

Figure 5. Advanced product architecture

A systematic identification of potentials for sustainable cost reduction is aimed. All perspectives, both inside and outside the company are shown. Customer requests and requirements reflect the functional view on top, internal structures and processes on component side are described below. Certain functionalities and components are needed only after the combination of different manufacturing processes, e.g. specific safety measures or extra components for extraction, cooling or workpiece handling. Thus, functional similarities and additional auxiliary functions can be identified when combining various, sophisticated technologies. This fact does not merely increase the costs for development, but also provide an opportunity setting up a clear structure. Depending on the combination, diverse auxiliary functions are needed to guarantee a functional MTP. Previous approaches have to be extended by potential functional interactions. Consequently, on component level further elements become essential to secure the efficiency of the MTP. The increasing functionality equally results in a rising complexity of MTP. Cost-optimized synergy effects can be exploited providing an early structuring. The investigation focuses on the interaction between the functions as well as the related components. A clear distinction of the interfaces is essential, both on the hardware and software side. One possible representation of the functional structure is illustrated in Figure 6 based on DIN 8580, including all existing manufacturing technologies [DIN 8580 2003].

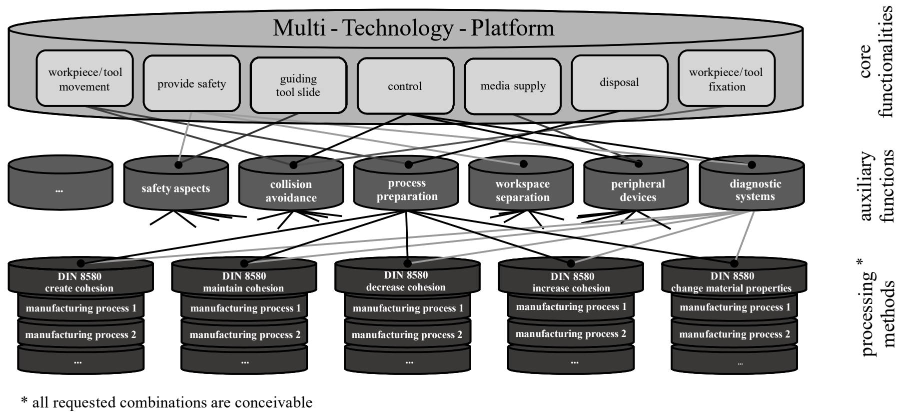

Figure 6. Reference architecture for MTP focusing on functional aspects

Besides, recent developments caused by customer requirements can be integrated more easily within a modular concept with adjustable functionality. Furthermore additional components are necessary at the lowest level resulting from the auxiliary functions. Due to the interdependencies between the processes, the workpiece has to be prepared before the next process starts, e.g. for laser processing the chips have to be removed in advance and a sufficient cooling time has to be complied. Interfaces need to be intended interacting with the overall system. The assignment of attributes, e.g. production or development costs, provides the opportunity to specify the product architecture and to support the product emergence process. Different concepts can be evaluated and compared to each other by the assignment of attributes. Thus, MTP development expenses and the fulfilling of its different functions can be pre-assessed already in the concept phase. The determination and selection of standard components, optional components and the assignment of individual customer modules are enabled. Combining dissimilar technologies, conceptual design has to deal with obstacles finding a reference architecture for each application.

As a result, of the partial separation consistent and self-contained units can be realized independently of the combination. The dependencies and connections between the core functionalities, additional auxiliary functions which are caused by the combination of various processes and the processing methods are illustrated in general. The manufacturing processes according to DIN 8580 are divided into create, maintain, decrease and increase cohesion and the change of material properties. By a reasonable division of the modules, the complexity is kept manageable and the reproducibility for future developments is increased significantly. The main characteristics of RMS modularity, integrability, customization, and convertibility are addressed with this basic structure. The foundation is constituted by the connection of the manufacturing technologies to be integrated. By A future itemisation it is intended to describe the process in detail. With a homogeneous structure it is predictable to react instantly to market changes. Thus, a functional integration or separation can be identified more easily. The flexibility and productivity is considerably improved and an upgrading becomes possible. A general procedure initiating product architecture for MTP is presented in Figure 7.

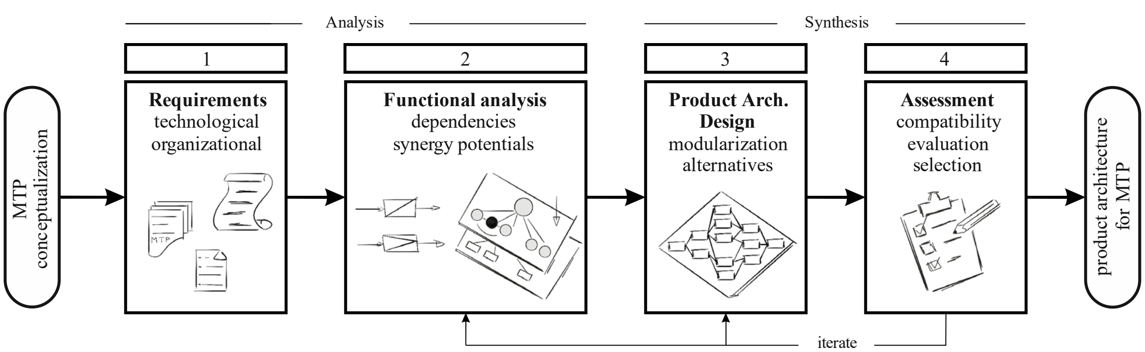

Figure 7. Proposed method for a systematic and holistic conceptualization of MTP

3.2 Validation at a Multi-Technology Machining Center

Within the Cluster of Excellence demonstrators have been designed and built for research application. A Multi-Technology Machining Center with two simultaneously usable workspaces integrating a milling spindle and two laser processing units serves the purpose of verification of the introduced reference architecture on functional side. The basic structure is formed by a five-axis milling center "Mill 2000" from CHIRON-WERKE GmbH & Co. KG. Wire based laser deposition welding and for post-processing-operations micro structuring and deburring are integrated as laser assisted technologies. The machine is equipped with two equally and simultaneously usable rotary swivel tables surrounded by a laser protective enclosure. A six-axis industrial robot "Kuka KR-16" for workpiece handling is a component part of the machine [Brecher 2012]. Unexploited potentials are disclosed structurally because of the use of a heuristic approach in the emergent phase of the demonstrator before 2008. The purpose of this MTP is to combine additive and subtractive manufacturing technologies for metal processing in a highly flexible manner to be able to respond to current demands of the market. Designing robust concepts of MTP in the first place is challenging. These challenges are widely caused by the systems‘ differences to be integrated. The functional intersection forms a basis, on which the analyzed combination is built. A simplified product architecture representing the main and essential functions and components of the existing Multi-Technology-Platform is illustrated in Figure 8.

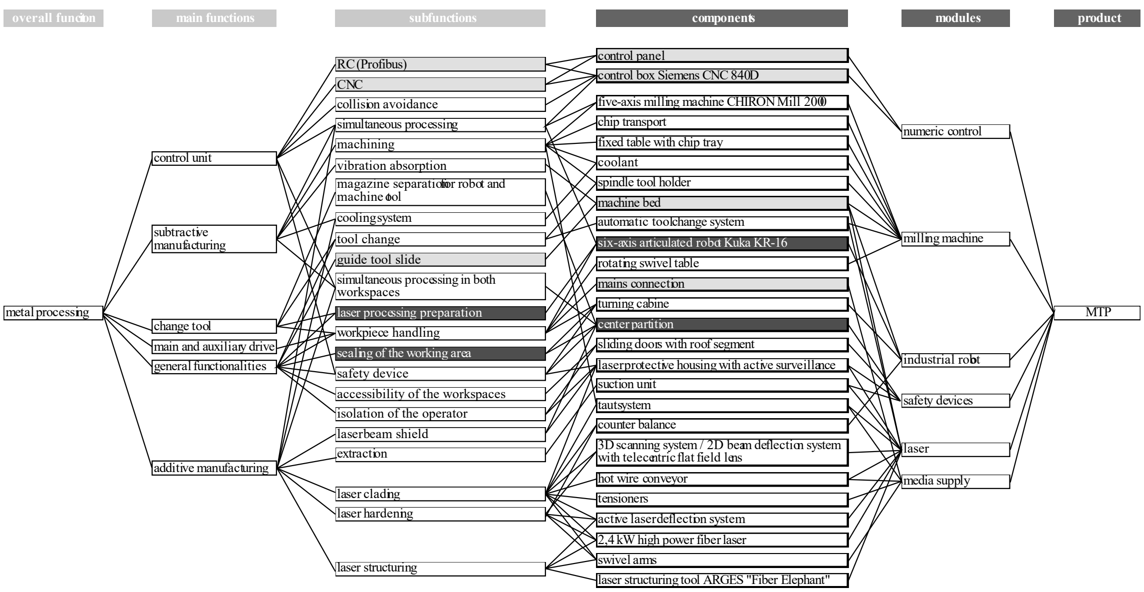

Figure 8. Simplified product architecture for a Multi-Technology Machining Center

Resulting from an early structuring on the one hand functional similarities can be identified, presented in light grey. Both the milling spindle and the robot require a rigid machine bed to ensure the accuracy of the manufacturing processes, to absorb vibrations, to minimize interdependencies and to increase the production accuracy. Furthermore both systems are driven by a computerized numerical control including several sensors and actors to provide a precise movement. To avoid any collisions of the various systems it is indispensable for the control system to communicate effectively. For both features a Profibus-interface fulfills this demand. For collision avoidance a suitable control algorithm is currently under development. A preventive structuring could have resolved the situation in a preliminary stage by spatial separation or different arrangement of the processing units.

On the other hand functions have to be modularized to build up self-contained units, presented in dark grey. The functional description has a direct impact on how the system components are integrated into the overall structure of the machine. For example two swivel tilt tables have been implemented especially to reduce auxiliary process time to a minimum by separating work spaces. Preparing the laser process chips and cooling fluid have to be removed, which is both inside the working area and on the surface of the workpiece. The inert gases used for laser processing have to be extracted from the working

area as a consequence as well. The difference in waste products results in the fact that the MTP uses two separate working areas, which are sealed by a center partition. This is one requirement to combine the two processes in one machine. Furthermore the laser protection enclosure is oversized, a functional integration is considered and currently research projects are carried out.
A strict separation between the core functionalities and the process-specific functionalities is aimed in a long term objective to guarantee an easy reconfigurability and does not need to initiate the essential development process each time. To sum up, the structure of the analyzed MTP has been adapted to the given constraints for this individual application and the development is still in process. There is a possibility of reconfigurability of the MTP, but the effort is significant. No universal interface is integrated, an exchange or extend has to be specified for the machine.

4. Conclusion and outlook

In essence, downsizing the complexity of MTP can be achieved by an early systematic structure. Although, the initial effort is higher due to the varying interactions of manufacturing technologies, however for similar MTP the consisting architecture can be used as a basic structure. Further extension, reconfigurability and modularization are facilitated. Concept generation of MTP has been addressed with this precocious structuring. MTP conceptualization and modularization have been examined via early recognition of the functional connections. The functional integration or separation can be measured by the average number of modules for each function. A synergetic degree for unification has to be determined from a technological and economic point of view. The basic process of product architecture establishment is transferable on MTP without limitation. Variant management and an assessment procedure for product conceptualization are still pending. However, from a functional point of view additional expense for the development of such systems is required. Due to the interactions of the processes, a higher dependency of the function structure and thus of the product structure of MTP have to be taken into account. Thus, modularization and reconfigurability of MTP become more demanding. Various, more concrete reference product architectures depending on the processes involved are conceivable. Therefore a universal interface design is appropriate. An identification of the required component and module combinations regarding the manufacturing processes involved has to be considered. In addition, morphological analysis and the selection of suitable solutions can benefit by the investigation of the functional dependencies of the components.

Acknowledgement

The authors would like to thank the German Research Foundation DFG for the support of the depicted research within the Cluster of Excellence "Integrative Production Technology for High-Wage Countries".

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Alexander Schmid, M.Sc.
RWTH Aachen University, Institute for Engineering Design
Steinbachstr. 54B, 52074 Aachen, Germany
Email: schmid@ikt.rwth-aachen.de