Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 50 (2016) 719 – 726
www.elsevier.com/locate/procedia

26th CIRP Design Conference

Life Cycle of Multi Technology Machine Tools – Modularization and Integral Design

A. Schmid[a]*, M. Löwer[a], T. Katzwinkel[a], W. Schmidt[a] , J. Siebrecht[a], J. Feldhusen[a]
C. Brecher[b], F. du Bois-Reymond[b], J. Rey[b]

[a]*Lehrstuhl und Institut für Allgemeine Konstruktionstechnik des Maschinenbaus der RWTH Aachen, Steinbachstraße 54B, 52074 Aachen, Germany*
[b]*Werkzeugmaschinenlabor WZL der RWTH Aachen, Steinbachstraße 19, 52074 Aachen, Germany*

* Corresponding author. Tel.: +49-241-8027346 ; fax: +49-241-8022286. *E-mail address:* schmid@ikt.rwth-aachen.de

---

Abstract

For reasons of high flexibility but still maximum productivity, machine tools integrating various production technologies have recently received particular attention. Combining and integrating multiple manufacturing techniques into one single system in early stages of the product emergence process is challenging. To keep the effort for implementation to a minimum, an initiation already in the concept phase is being actively pursued. Design guidelines are currently investigated based on the examination of different technology combinations.
This approach focuses on systematic conceptual design for such hybrid machine technologies. Product architectures are used to describe the modularity and create a specific delimitation for standardization. Reference product architectures for Multi Technology Machine Tools (MTMT) carry high potential for saving expenses in product development. The main emphasis is on technology and system integration. A technological similarity assessment of the single processes involved forms the basis of this approach to assure potential for synergies. Monetary aspects in early stages of product development are considered. Based on the analysis a generic system model is connected with general product architectures for MTMT.
The method introduced is validated by a Multi-Technology Machining Centre with two simultaneously usable workspaces integrating a milling spindle and two laser processing units. The research undertaken is part of the Cluster of Excellence “Integrative Production Technology for High-Wage Countries” and has been funded by German Research Foundation (DFG).

Peer-review under responsibility of the organizing committee of the 26th CIRP Design Conference

Keywords: product architecture design, Multi Technology Machine Tools, modularization, systematic product conceptualization

---

1. Introduction and Motivation

Intelligent production technologies, currently omnipresent under the keyword “Industry 4.0”, mark the transition to interconnected production, addressing the research projects human-machine interaction as well as the holistic digitalization and networking of the individual processing steps, basically shown in Fig. 1. The focus is both on changeability of the company structure and the corresponding manufacturing systems since the forecasting of further market developments is gradually in decline [1,2].

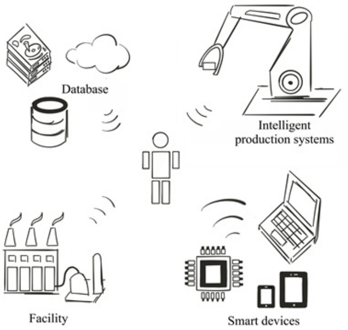

Fig. 1. “Smart Factory” with integrated, cognitive production systems

Peer-review under responsibility of the organizing committee of the 26th CIRP Design Conference
doi:10.1016/j.procir.2016.05.017

Manufacturing industries and consumer behavior call for further flexibility, up to a lot size of one, by simultaneous mass customization [3]. This results in differentiated product structures and has a direct impact on the number of product variants [4,5]. The increasing global competition and the accompanying rising cost pressure result in a augmented complexity in product development and shortened product life-cycles [6,7]. Amendments caused by product modification and technological progress continue to contribute to this development. Due to the fierce competition, products have to cost-efficiently fulfill market needs and provide high quality at the same time. Therefore, a systematic planning is indispensable [8]. A unique possibility to create an added value to competing economies is the ability for innovation of sustainable companies [9]. In addition to ensuring new and sustainable jobs, long-term viability and technological leadership of a company are determined by its innovation [10]. The capacity for innovation is a critical key factor for success. Leading drivers to gain a competitive edge for export and growth markets are a shortened development time and noticeable cost reductions. A stable development and design process form the basis for systematic and effective product development in order to shorten both innovation cycles and time to market intervals [8]. The current focus of production has up to this point been based on the classification between "Economies of Scale" and "Economies of Scope" in order to find the optimal operating point for the manufacturing enterprise. So far the positioning strongly depends on the labor costs [1].

The vision of Integrative Production Technology is to reconcile the bipolarity between "planning-orientation" and "value-orientation" as well as between "Economies of Scale" and "Economies of Scope". In the center of this consideration flexible production systems are accountable for dissolving the discrepancy. The Cluster of Excellence "Integrative Production Technology for High-Wage Countries" funded by German Research Foundation DFG deals with this task at RWTH Aachen University. This initiative emphasizes on the research objectives flexibility, automation and self-optimization. Flexible production systems, so-called Multi Technology Machine Tools (MTMT), integrate supplementary manufacturing technologies in a single machine. MTMT provide the possibility to master this balancing act described above and bridge the gap between customization and process optimization.

This paper focuses on structural and functional integration of Multi Technology Machine Tools to promote a consistent modularization as well as to achieve monetary effects at an early stage of product development. Furthermore, monetary additional expenditures due to the insufficient structure are shown. Following a short introduction, section 1 illustrates the necessity of a life-cycle management and systematic conceptual design within product development for MTMT. Section 2 introduces previous methodological approaches for reconfigurable and flexible machine tools and modular design. The delimitation becomes apparent by implementing product architecture design for an early structuring of MTMT. In section 3 a systematic approach for product conceptualization is presented with an emphasis on functional integration or separation under the premise of saving development costs and effort in early stages. Thus, relevant interdependencies and similarities can be easily detected and conceptual alternatives can be considered. A comprehensive verification by a Multi-Technology Machining Centre which has been produced in the context of the project is carried out. To sum up, a short résumé is presented before the contribution concludes with an outlook on future research.

1.1. Engineering Design Methodology

Methods comprise tools for a better handling of complex issues. In order to take account of already existing solutions, complex problems are decomposed into various individual issues, which are functionally separated to make the engineering task manageable [11]. In Engineering Design there are different approaches and design methodologies for systematic product development, which can also be applied to MTMT. The most significant ones are listed below.

A generic approach to the development and design of technical systems and products is given via VDI guideline 2221 in the form of a phase model, basically split into seven steps with different degrees of concretization [12]. Analysis steps are divided into clarifying and defining the task, followed by a functional examination. Synthesis is equivalent with embodiment design divided into preliminary form design and subsequently detailing in which analysis and synthesis are alternating. The design process has an underlying iterative nature, ending with documentation. This directive focuses primarily on the development of new products.

A similar approach is the "Münchener Vorgehensmodell" which can be abstracted into three main steps: clarifying the problem, looking for alternative solutions and reach a decision with either sequential or simultaneous processing. However, this process does not have to evolve in a linear manner [13].

Another substantial approach for designing systems is Axiomatic Design by Suh, consisting of two axioms: the independence axiom and the information axiom [14].

Furthermore specialized development approaches occur for certain subject areas, e.g. VDI 2206 contains a design methodology for mechatronic systems [15]. A software development framework is characterized by the V-model, structured in various phases [16].

Common to all these approaches is the systematic procedure in order to reduce the complexity and solve the engineering task in an optimal way. The majority of later product costs is already determined in early phases of product development, displayed in Fig. 2.

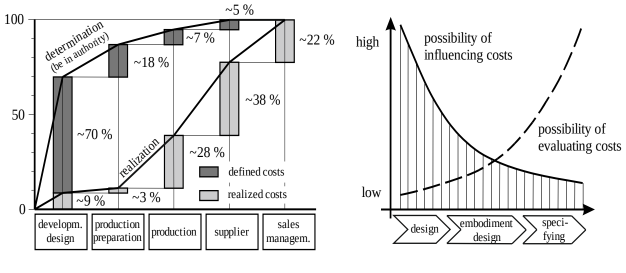

Fig. 2. Cost incurrence and cost control according to [17,8]

Consequently, the possibility of an early intervention is the highest at that time, too. Koren shows that systematic design approaches may deliver substantial cost savings [18]. On the one hand cost benefits by modularization can be achieved, on the other hand increasing development effort has to be accepted once [8].

1.2. Life-Cycle Costing

A modular design of machine tools assumes the development and implementation in different stages of the product during the complete life-cycle [19]. In the approach of Alexopoulos the importance of a universal consideration taking account of uncertainties in current market situations is emphasized [20]. A method for comparing the flexibility performance of manufacturing systems is introduced. Manufacturing system costs are estimated under life-cycle considerations and validated in an industrial case.

Efficiency criteria for MTMT with one or two workspaces have already been derived by Tönissen [21,22]. For this purpose, mathematical models based on production, cost and queuing theory have been developed. It has been shown that MTMT should be operated particularly for small output quantities in order to be economically competitive in comparison to conventional machine tools. However, economic effects of the type of manufacturing technologies to be integrated in a MTMT have not been studied in detail so far. The integrated manufacturing technologies strongly influence the accruing costs for the development as well as in the use phase of MTMT. Therefore, it is necessary to pursue a life-cycle oriented approach in order to predict the economic efficiency of different manufacturing technologies in MTMTs. So far, there are a number of already existing approaches which enable a life-cycle oriented cost evaluation of machine tools [23-25]. Most of these studies evaluate machine tools at a high level of abstraction. Only Dervisopoulos enables the derivation of structural optimizations of machine tools based on life-cycle costs by considering the individual components of a machine tool [25]. However, machine structures and operating conditions of MTMTs differ significantly from those of conventional machine tools. As a result, specific requirements for a new life-cycle cost model for MTMTs are essential and a matter of intense research. This also includes modelling of the relationships between the combined technologies and the functional structure of a MTMT. Furthermore methods to derive reference processes for wide product ranges being manufactured on MTMTs for a cost prediction in the use phase have to be developed. On this basis detailed investigations regarding life-cycle oriented cost evaluation of MTMT will be content of future work.

To limit the inner complexity of a company, driven by product portfolio and their characteristics, guidelines and appropriate methods are indispensable in early stages of product development [8].

2. Flexible Production Systems

Market changes reflect customer demands precisely [26]. Flexibility and changeability are vital prerequisites to meet modern market demands [27,28]. To describe the combination and the interactions of production technologies for defined production tasks the systematic selection of a suitable technology chain is presented inter alia in [29]. The definition is based on technical changes that can be achieved on the workpiece. Reconfigurable Machine Systems (RMS) provide a viable solution to adapt to changing circumstances over the use phase efficiently. The reconfigurability is related to the change of functionality. Reconfigurable Manufacturing Systems are mainly designed for mass production, bridging the gap between dedicated and flexible machines. Design principles are essential in the phase of conceptual design of RMS [30].

2.1 Modular and Integral Design

Modular system concepts are finding their way into machine tools for a considerable time. A modular architecture enables a rapid adaptation by removing or adding modules, in case a consistent interface configuration is existing. It will therefore be possible to react quickly and flexibly to market changes. However, designing a universal reconfigurable system is outrageous [31].

To develop a product in the first place, a regulatory framework is needed. As seen in Fig. 2 up to 80 % of product costs are determined during the development phase [17]. This is the time when product architecture design is established. Product functionalities and product varieties are defined and play a decisive part in the economic success of the company [32]. Decisions taken have a major impact on the value-added chain and cost incurrence. In vital enterprises robust product architectures are established, characterized by high profitability and reusability of components. Moreover customers are able to partially configure the product. Due to the nature of the current systems a classification for product architecture design can be carried out by functional and physical autonomy [9,33].

- Modular product architecture:
  Both functional and structural self-contained units are constituted. Per module one function is aimed to guarantee separability.
- Integral product architecture:
  Showing high physical and functional dependencies. No clear assignment is possible.
- Functional-modular product architecture:
  High functional autonomy combined with physical dependency is predominant. Simple separability on component level is ensured.
- Physical-modular product architecture:
  High functional dependency combined with physical autonomy is prevalent. It can be realized with just a few components based on the premise of hard separability.

Benefits that may arise for conceptualization of MTMT are a cost-effective establishment of product functionalities, a limitation of the effort in product development through the use of approved and standardized components [8]. A further differentiation of the different types of modularity can be performed, basically visualized in Fig. 3.

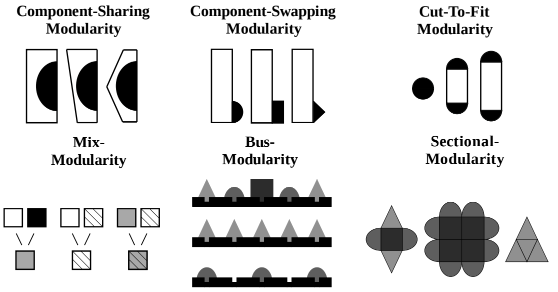

Fig. 3. Different types of modularity for product architectures according to [9]

For instance, a hybrid form consisting of modular and integral product architecture is feasible to benefit from the best aspects of both architectures. Several of the characteristic properties of the diverse modularities are listed below [9].

- Component-Sharing Modularity:
  Reusability of components in different products. Potential cost reduction as a result of economies of scale.
- Component-Swapping Modularity:
  Non-variable parts are either installed as standard or optional components.
- Cut-To-Fit Modularity:
  Product structure, number of components and interfaces are independent. The difference lies in dimensioning.
- Mix-Modularity:
  Applicable to products consisting of different components, regardless of their interfaces.
- Bus-Modularity:
  Precondition is an underlying basic structure. Attachment parts are added through standardized interfaces.
- Sectional-Modularity:
  Combination of components with standardized interfaces to a previously undefined product.

By decomposing the functional and physical characterization of a product, two structures are the result describing the product from different points of view, basically shown in Fig. 4. Product architectures represent the relationship between the function structure of a product shown on the left and its physical structure on the right [34]. Features and attributes are realized by the product. A Decomposition of product functions down to the lowest level creates the precondition to identify components. This perspective corresponds with the development point of view. In product structure, components are combined to assemblies up to the overall product. Physical and functional interfaces and conflicting requirements become clear by the connections. Furthermore technical alternatives regarding design - here marked with A, B and C - are enabled and can be compared and evaluated with each other [33].

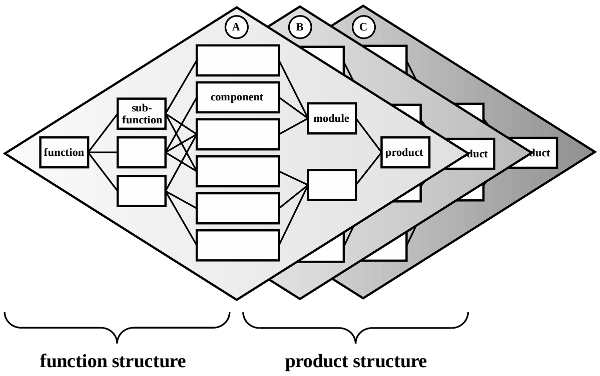

Fig. 4. Product architecture according to [33]

Economic benefits which may arise are shorter delivery times, the necessity of order-related design effort only in the case of functional extension and a subsequently expansion. Exchange opportunities will be significantly improved. Modules can be developed, manufactured and examined independently as well as quality improvement can be achieved. The degree of aspired modularity depends on the specific application.

For MTMT conceptualization a bus-modularity according to Fig. 3 is aspired to utilize a basic structure without reference to the process combinations. Another issue focuses on the reusability of components. The objective is to develop components and modules with standardized interfaces and a low interaction in the relationship structure. A sustainable standardization is facilitated. Due to its modular structure high potentials in expandability and combinability are guaranteed. Already existing interface modules can be used to reduce the effort for implementation and development. Risks in product usage phases are also minimized [9]. The crucial point consists in the connection of function structure and product structure. By building the interconnections between these both structures, development and synergy potentials for the conceptualization of MTMT can be revealed.

2.2. Reconfigurable and Flexible Machine Tools

Reconfigurability is by definition the functional adaption to current conditions based on modular hardware and software in equal parts. The limits set by functional modification and expandability are still narrow [35]. This is due to a change in demand in competitive markets. Reconfigurable machine tools provide the opportunity to adapt efficiently to a short-lived market situation. The main characteristics of RMS are: modularity, integrability, customization, scalability, convertibility and diagnosability [27].

Successful and sustainable implementation and establishment of reconfigurable manufacturing systems in the product emergence process of MTMT requires robust concepts and design methodologies. An excerpt of relevant approaches and research projects referring to this topic are listed below.

For Pasek there are five major challenges in the design of RMS: defining part families, the mechanical design process, control system design, system integration and finally reconfiguration and calibration. Besides the benefits RMS offer, a profound understanding of technology is required [36].

According to Cochran, a decomposition of functional design parameters for an efficient manufacturing system design is required. The interactions among the different elements of system design are also taken into account. The approach is based on Axiomatic Design [37].

Spicer claims there is a demand in system design guidelines, principles and metrics for conceptual design of RMS to find the right configuration. No systematic design methodology selecting the optimal configuration is existing yet [38].

Koren postulates that each time a new product is introduced an appropriate manufacturing system has to be designed [18]. With decreasing product life-cycles Koren's approach becomes marginal. The delimitations mentioned are taken up in this contribution.

Managing variants is a major research topic for manufacturing industries. In ElMaraghy an index for design reconfiguration is determined [39]. ElMaraghy also claims a basic design principle for MTMT consists in minimizing complexity of future machine design. The advancing degree of complexity is only acceptable if an additional competitive edge is gained [40]. An order-related reconfiguration of machine tools is only possible to a limited extent with currently existing processing systems and with large expenditure of time [31].

Flexibility is an important aspect of manufacturing system's design according to Mourtzis [5]. For quantifiable terms the "Penalty of Change" method is used to measure the benefits, both on technological and economical side. Alternative technology solutions under different sets of market requirements with a focus on a punching department have been studied. No hybrid solutions are investigated in this approach.

In Terkaj's approach to support system design an ontology on flexibility is introduced to classify different types of manufacturing flexibility [41]. The ontology has been validated by analyzing real production systems. With regard to Mourtzis [5] Terkaj also claims, there is no standardized measurement unit for the measurement of flexibility. Methodologies to systems with predefined levels of flexibility are still almost missing. A further approach of Terkaj contains, to design new manufacturing system architectures with a proper balance between productivity and flexibility. One of the key issues are short product life-cycles impacting the production systems. This approach focuses on the production problem evaluation, whereas existing design approaches focus mainly on the definition of the required flexibility levels. The decision between reconfigurability or extra-flexibility is proportional to the investment costs. Quantitative terms to measure the flexibility are also missing [42].

3. Systematic Conceptual Design for MTMT

Functional and physical relations and direct effects on the architecture have to be taken into account to differentiate between functional integration and separation. Designers have to face the following challenges:

- Aiming at a homogenous structure regardless of the technologies involved.
- Achieving a maximum level for standardization for next generation MTMT and a reduction of the number of required interfaces.
- Minimization of required modules.
- Reaching a self-sufficient module design.
- Consistent interface design, hardware- and software-based.

So far a fundamental design methodology for a persistent and effective conceptualization of MTMT is still missing at an early stage.

3.1. Generic System Model for MTMT

According to VDI 2221 to set up a robust product architecture, development may be initiated with analysis. Referring to functional analysis of the potential products, functional costs can be identified. They are an essential approach of value analysis. Functional costs of the individual sub-functions and the related components can be specified through product architecture design. Functional costs are the relevant costs by function for technical realization. A direct comparison of alternative solutions at functional level is provided not exclusively on the basis of parts and modules. A systematic combination for cost minimization and cost estimation in conceptual design on an abstract level is possible [8,16].

A maximum synergetic degree of standardization is pursued in product conceptualization of MTMT independently of the manufacturing processes involved. In addition to the components, modular designed machine tools have to consider interdependencies as well. To set up a product architecture for MTMT the following aspects among other things have to be considered:

- Standardized platform strategy for short cycle times and an easy compatibility is required to enable the application of rationalization potentials [8].
- Uniform definition of system boundaries.
- Definition of process modules.
- Production changes have to be considered for future modification and therefore standardized interfaces have to be intended.
- Homogenous modular architecture including basic modules with basic functionalities and additional modules for auxiliary functions.
- Main functionalities each MTMT has to fulfill are control and safety aspects, workpiece or tool handling and fixation, media supply, process monitoring and diagnostic devices, process preparation before the next manufacturing step starts, quality assurance measures and disposal.

For validation a Multi-Technology Machining Centre developed within the Cluster of Excellence is used. The hybrid machining centre is serving for research to increase the level of automation and to facilitate the transition as industrial application. The major research issue is an increase of controllability of MTMT to master the complexity. The scanner-based machining centre integrates a conventional milling spindle and wire-based laser deposition welding. The basic structure of the machining centre consists of two equivalent working spaces with rotary-tilt tables for workpiece movement. This constitutes a unique selling proposition in comparison to other competitors. An increase in the depth of its production is reached through a complete machining in one clamping. Moreover, an articulated six-axis industrial robot for time-concurrent processing is arranged concentrically to reach both working spaces equally, surrounded by a cylindrical housing. For post-processing operations micro structuring and deburring are integrated as laser assisted technologies. Both manufacturing technologies are driven by computerized numerical control associated with several sensors and actuators to monitor the process. Through spatial and functional integration of the subsystems the complexity is increased tremendously compared to conventional machine tools [1]. According to Tönissen the MTMT introduced can only be used for economic purposes for small batches and prototyping, particularly in the context of two equivalent working chambers [19]. Due to the high laser output, safety devices are essential when operating. Technical challenges to ensure functional integrity from mechanical point of view are the implementation of the industrial robot and the close interaction of the different processes increasing the risk of collision. Additional processes are planned for future integration, e.g. cooperative processing of robot and spindle. Unexploited potentials or unnecessary expenses become evident by means of a heuristic approach in the development phase before 2008.

Depending on the application a functional integration or separation is recommended. A higher demand of valuable resources in terms of time and money is required for an initial development compared to dedicated machine tools. In this use phase a separation or doubling of the work spaces has been carried out for the reasons stated. The approach is to perform a functional integration into modules to create a clearer structure, where possible. The numerical control has to be adapted to the specific machine configuration to avoid collisions in the first place.

3.2. Case Study for a Multi-Technology Machining Centre

For the addressed MTMT high investment costs have been required, at the time of its formation. The previous method to develop this machine was to procure individual parts of production and to integrate in the next step by individual adaptation to the given constraints. There is no opportunity to refer on the extensive fund of expertise and experience from previous projects due to the new development.

The possibility to reconfigure or extend the existing MTMT is given, but will not only result in high financial expenditure. After a potential modification an examination and final review is essential. This adjustment should be counteracted by an adequate structuring. A simplified product architecture of the hybrid machine tool discussed in section 3.1 is given in Fig. 5, with functional correlations on the left and physical components on the right.

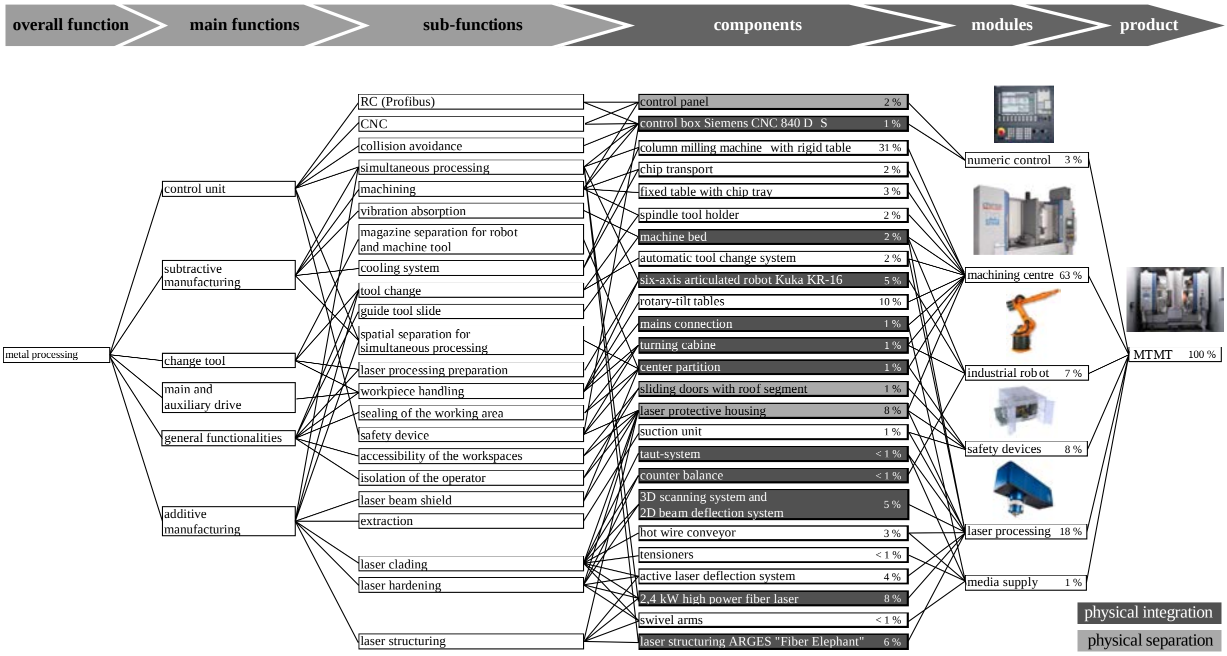

Fig. 5. Simplified product architecture of a Multi-Technology Machining Centre. Illustrations taken from [1].

The percentages for each component refer to the investment costs including installation and start-up. The figures are rounded to two decimal places. Components currently either physical integrated or separated are presented in different colors in an exemplary manner. Interdependencies between functions and physical components are clarified by linear associations. These considerations demonstrate that a clear allocation and separability therefore does not exist. A detailed breakdown of the investment costs to the point of commissioning on a percentage basis has been performed. Disaggregating the cost data enables a precise declaration about the validity and robustness of the initial concept developed and the level of elaboration. Since there is no new design of the MTMT but an existing solution has been modified, the conceptualization becomes even more complicated. A one to one assignment of the costs is failing because of the strong functional integration and the simplified representation of the product architecture. Additional costs resulting by a modification of the original concept have been approximately 12-13 percent of the whole investment. This is due to a series of factors: special designs and engineering work for adaption, assembling and set-up and the corresponding working hours for modification. Particularly exposed to the processes induced by modification work were the following points: changes in the control unit, proper integration of the handling robot and laser processing units combined with special designs, safety devices and for instance modifications like water-cooling or different performance data of the taut-system engine. In this case there was a delay of the assembly or bringing the machine into service. The basic requirement for a reconfigurability of MTMT is the initiation of an early structuring to provide the option for modularization. Different kinds of reconfigurability and flexibility need to be developed for MTMT depending on the use case. Interdependencies between different technologies, the effects on the machine system and the product to be produced have to be investigated precisely. However, the risks accompanying with the flexibility have to be considered.

Developments of MTMT should in general proceed from left to right according to Fig. 4 and Fig. 5, starting with analysis of necessary functionalities and their interdependencies between the individual components. The development is configured with high granularity of the field of solutions. The option to synthesize overall solutions is significantly enhanced.

By a novel approach based on functional analysis modules can be rearranged to simplify the separation and configuration. Currently explored benefits are a rising learning curve and the associated progress in terms of productivity. Procedural features explicitly occur once in a MTMT should be separated in a single module. Some components are considered separately.

The laser protective housing has been physically separated. The housing has to be closed every time the laser processing units are working. Caused by technology integration collisions between the industrial robot and the milling spindle can currently not be excluded. To solve this issue an intensive work is carried out on an adapted machine control. Both technologies should be divided into autonomously modules. Conversely functional costs are currently overlapping because no modular design is existing and characteristics influence each other. Furthermore there is no possibility for distributing of the costs incurred to individual functionalities. The effort for integration is excessive because no consistent or no existing interface design to combine these different manufacturing technologies is available. One challenge is to clearly define module limits depending on the function package the customer needs. A basic module structure supports assembly operations and exchangeability. Reference models for life-cycle engineering have to be applied to promote reusability [43]. Finally, interface design has to be scrutinized and standardized.

4. Conclusion and Outlook

To conclude, by a preventive structuring based on product architecture design, product conceptualization for MTMT becomes manageable. By generating functional modules in the first place, costs and effort can be saved for future generation of MTMT. However, the effort for first-time implementation can be classified higher. An estimation and comparison on modular level is made possible by the fact of functional costs. The objective is to establish a basic structure for context-sensitive product development to minimize the effort by standardization. In general a systematic development and design process is superior to heuristic methods referring to the level of complexity of MTMT.

For future research designers should consider the possibility to account for effects on the processing accuracy caused by the combination of different technologies in one machine in an early design stage. Moreover a determination of standardized interfaces and more concrete product architectures depending on the manufacturing technologies to be integrated are investigated gradually. A complete understanding of the single technologies of the multi-technology platform and their effects is essential, e.g. the macroscopic laser beam path has to be describable. Future plans include an examination of effects on the machining accuracy caused by the integration of a laser processing unit into a machine tool. Furthermore experimental and simulative investigations have to be connected to receive a matched machine model. Furthermore, no standard methodology to define characteristics of a production problem taking into account the evolution over time is existing [42].

Acknowledgements

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”.

References

[1] Brecher C. Integrative Production Technology for High-Wage Countries. Heidelberg: Springer; 2012.

[2] Landers R G, Min B K, Koren Y. Reconfigurable Machine Tools. In: CIRP Annals Vol. 50 (1); 2001. p. 269-274.

[3] Schuh G, Wiendahl H P. Komplexität und Agilität. Berlin: Springer; 1998.

[4] Franke H J, Hesselbach J, Huch B, Firchau N L. Variantenmanagement in der Einzel- und Kleinserienfertigung. München: Carl Hanser; 2002.

[5] Mourtzis D, Alexopoulos K, Chryssolouris G. Flexibility consideration in the design of manufacturing systems: An industrial case study. In: CIRP Journal of Manufacturing Science and Technology, 5 (4); 2012. p. 276-283.

[6] Schuh G, Friedli T. Wettbewerbsfähigkeit der Produktion an Hochlohnländern. 2nd ed. Berlin: Springer; 2012.

[7] Schuh G, Schmidt C. Produktionsmanagement. 2nd ed. Berlin: Springer; 2014.

[8] Pahl G, Beitz W, Feldhusen J, Grote K H. Engineering Design: A Systematic Approach. 3rd ed. London: Springer; 2007.

[9] Schuh G. Innovationsmanagement. 2nd ed. Berlin: Springer; 2012.

[10] Gausemeier J, Plass C. Zukunftsorientierte Unternehmensgestaltung. 2nd ed. München: Hanser; 2014.

[11] Koller R. Konstruktionslehre für den Maschinenbau: Grundlagen zur Neu- und Weiterentwicklung technischer Produkte. Berlin: Springer; 1998.

[12] VDI 2221. Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte: Berlin: Beuth; 1993.

[13] Lindemann U. Methodische Entwicklung technischer Produkte. Berlin: Springer; 2005.

[14] Suh N P. Axiomatic Design. New York: Oxford University Press; 2001.

[15] VDI 2206. Design methodology for mechatronic systems. Berlin: Beuth; 2004.

[16] Bröhle A P, Dröschl W. Das V-Modell: Der Standard für die Softwareentwicklung mit Praxisleitfaden. München: Oldenburg Verlag; 1993.

[17] Ehrlenspiel K, Kiwert A, Lindemann U. Kostengünstig Entwickeln und Konstruieren. Kostenmanagement bei der integrierten Produktentwicklung. 6th ed. Berlin: Springer; 2007.

[18] Koren Y, Shpitalni M. Design of reconfigurable manufacturing systems. In: Journal of Manufacturing Systems Vol. 29 (4); 2011. P. 130-141.

[19] Gostimirovic M, Kovac P, Radovanovic M, Madic M, Krajny Z. Modular Design of unconventional cutting machine tools. In: Journal of Production Engeineering JPE Vol. 18 (1); 2015. p. 27-30.

[20] Alexopoulos K, Papakostas N, Mourtzis D, Chryssolouris G. A method for comparing flexibility performance for the lifecycle of manufacturing systems under capacity planning constraints. In: International Journal of Production Research, 49 (11); 2011. p. 3307-3317.

[21] Tönissen S. Economic Efficiency of Manufacturing Technology Integration. Aachen: Apprimus; 2014.

[22] Tönissen S, Rey J, Klocke F. Economic efficiency of manufacturing technology integration. In: J Manuf Syst 37:1; 2015.

[23] Trender L. Entwicklungsintegrierte Kalkulation auf Basis der ressourcenorientierten Prozesskostenrechnung. Karlsruhe: 2000.

[24] Nesges D. Prognose operationeller Verfügbarkeiten von Werkzeugmaschinen unter Berücksichtigung von Serviceleistungen. Karlsruhe: 2005.

[25] Dervisopoulos M. Methode zur lebenszyklusbezogenen Optimierung von Werkzeugmaschinen. Aachen: Shaker; 2011.

[26] Molina A, Rodriguez C A, Ahuett H, Cortés J A, Ramírez M, Jiménez G, Martinzez S. Next-generation manufacturing systems: key research issues in developing and integrating reconfigurable and intelligent machines: In: International Journal of Computer Integrated Manufacturing, Vol. 18 Vol. 7; 2005. p. 525-536.

[27] Gupta Y P, Goyal S. Flexibility of manufacturing systems: Concepts and measurement. In: European Journal of Operational Research 43; 1989. p. 119-135.

[28] Wiendahl H P, ElMaraghy H A, Nyhuis P, Zäh M F, Wiendahl H H, Brieke M. Changeable Manufacturing – Classification, Design and Operation. In: Annals of the CIRP Vol. 56/2; 2007.

[29] Schuh G, Knoch K. Systematisch zur besseren Technologiekette. In: wt Werkstattstechnik online Jahrgang 95; 2005. p. 259-263.

[30] Katz R. Design principles of reconfigurable machines. In: International Journal of Advanced Manufacturing Technology 34; 2007. p.430-439.

[31] Bi Z M, Lang S Y T, Verner M, Orban P. Development of reconfigurable machines. In: International Journal of Advanced Manufacturing Technology 39; 2008, p. 1227-1251.

[32] Ulrich K. The role of product architecture in the manufacturing firm. 1995.

[33] Göpfert J. Modulare Produktentwicklung. DUV:Wiesbaden; 1998.

[34] Ponn J, Lindemann U. Konzeptentwicklung und Gestaltung technischer Produkte. Berlin: Springer; 2008.

[35] Wurst K H, Heisel U, Kircher C. (Re-)konfigurierbare Werkzeugmaschinen – notwendige Grundlage für eine flexible Produktion. In: wt Werkstattstechnik online Jahrgang 96; 2006. p. 257-265.

[36] Dashchenko A. Reconfigurable Manufacturing Systems and transformable Factories. Springer: Berlin; 2006.

[37] Cochran D S, Arinez J F, Duda J W, Linck J. A Decomposition Approach for Manufacturing System Design. 2002.

[38] Spicer P, Koren Y, Shpitalni M, Yip-Hoi D. Design Principles for Machining System Configurations. 2002.

[39] ElMaraghy H, Azab A, Schuh G, Pulz C. Managing variations in products, processes and manufacturing systems. In: CIRP Annals – Manufacturing Technology 58; 2009. p. 441–446.

[40] ElMaraghy W, ElMaraghy H, Tomiyama T, Monostori L. Complexity in engineering design and manufacturing. In: CIRP Annals – Manufacturing Technology 61, 2012. p. 793-814.

[41] Terkaj W, Tolio T, Valente A. Focused flexibility in production systems. In: Changeable and Reconfigurable Manufacturing Systems; 2009. p. 47-66.

[42] Terkaj W, Tolio T, Valente A. Designing Manufacturing Flexibility in Dynamic Production Contexts. In: Tolio T (ed) Design of Flexible Production Systems. Springer; 2009. p. 1-18.

[43] Feldhusen J, Bungert F, Macke N, Löwer, M. An integrated feature-based reference model to manage multi-life products. In: Interaction of Science, Technology and Engineering: Proceedings of ICCPR2007; International Conference on Comprehensive Product Realization; 2007.