PARAMETER CONTROL ASSISTING MORPHOLOGICAL PRODUCT CONCEPTUALIZATION OF MULTI-TECHNOLOGY-MACHINE-TOOLS

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Abstract

Product conceptualization is an essential part of each product emergence process. A valid and context-sensitive selection and validation of appropriate product concepts in early stages of product development is challenging. The major reference for subsequently synthesizing overall out of individual solutions represents the morphological analysis, for a systematic heuristic generation of product concepts. This paper addresses a multi-stage design process for a holistic and quantitative morphological analysis and synthesis based on relation-oriented functional modelling. General object is to manage complex problems which do not necessarily suffer by combinatorial explosion. A similarity based product conceptualization is carried out by a Euclidian distance measure for the selection of well-balanced and robust overall concepts. Therefore, various target systems including functionality, economic efficiency and innovation potential are considered during assessment for a systematic combination. A validation and evaluation is performed by an integrative sheet metal forming center.

Keywords: Complexity, Conceptual design, Design methods, Functional modelling, Morphological analysis

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1 INTRODUCTION

More than ever, enterprises are confronted to global competition. Especially manufacturing companies' viability and competitiveness depend primarily on their innovative strength (Friedli and Schuh, 2012), (Gausemeier, 2014) and (Pahl and Beitz, 2013). Additional key factors for success are the reduction of innovation cycles and costs by early and integrative product and process development to guarantee a sustainable and future-oriented production in high-wage countries (Brecher, 2011).

In many cases, novel product development processes are characterized by non-quantifiable and insufficient experience. For this purpose, functional analysis and synthesis in early stages of product development are based on conventional and established solutions so far and show a heuristic character. Thus, the results obtained are not satisfying in most cases, do not meet transparency requirements and have a negative impact on the use phase. Simply relying on experience and trial-and-error processes in designing systems frequently lead to failures, cost overruns and missed schedules (Suh, 2016). Even though, principal reasons for this way of proceeding are finite time and capital resources as well as the need for innovation companies are exposed to.

Functional decomposition forms the basis to solve complex tasks efficiently and effectively. One essential part of each product development process represents a valid and reproducible selection and validation of appropriate product concepts. Methodological problem solving provides the opportunity to transfer suitable individual solutions into a robust overall concept. A general procedure getting methodically from a design task to a valid product concept is illustrated in Figure 1.

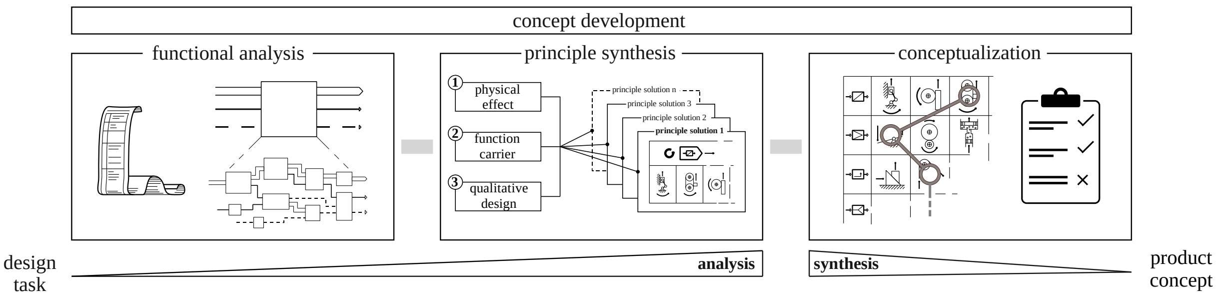

Figure 1. Systematic product conceptualization based on functional decomposition and physical effect catalogues, according to Bernhardt (1981), Koller (1994) and Roth (1994)

Existing synthesis methods within engineering design enable a selective combination and variation of individual solutions. However, creativity as well as product and process expertise are limited. Though, an optimal solution is frequently neglected also due to shortage of resources and time. For this purpose, a method for a cascading development process of morphological analysis and synthesis for product concepts is intended. Therefore, an iterative process of alternating analysis and synthesis in order to meet the requirements in terms of objectivity and quantifiability presents a practical application. The object is to develop a method for integrative modeling of solution principles based on relation-oriented functional modeling. The main emphasis of this contribution is a context-sensitive reduction of the complexity during the investigation of morphological boxes in a timely manner, without risking to exclude an optimal solution inadvertently too soon. The required target is iteratively realized by parameter control.

Future topics for the development and research within manufacturing companies, in particular in the machine tool industry, have already been predicted by Moriwaki in 2006. As predicted, current research topics focus on combined multi-functional machine tools for the reasons of reduction in machining time, need for high precision, high flexibility and efficiency (Moriwaki, 2006). However, a systematic and methodological support of the design phase of Multi-Technology-Machine-Tools (MTMT) has been addressed insufficiently so far (Spicer et al., 2002) and (Moriwaki, 2006). MTMT systems are machine systems combining different manufacturing technologies for simultaneous and/or sequential processing. Consequently, the application of this quantified method for product conceptualization using morphological analysis is currently investigated and validated by MTMT demonstrators. After this short introduction, existing approaches concerning morphological analyses form the topic of this paper's second section.

2 MORPHOLOGICAL APPROACH FOR PRODUCT SYNTHESIS

Morphological analysis (*morphé*: Greek for form or shape) refers to the investigation of structural relationships. The morphological approach or design pursues the registration of the totality of all possible solutions, generating an acceptable outcome in combination for the individual application. This approach is based on the fundamental idea of engineering design methodology to decompose comprehensive systems into subsystems with a lower degree of complexity to be able to manage the development task (Pahl and Beitz, 2013). The benefits arising are a universal applicability of solution sets and design catalogues if the granularity of the functional description is generalized and in an adequate quantity (Koller, 1998; Roth, 2000; VDI, 2010).

The major reference for synthesizing overall out of individual solutions in academia represents the morphological box, for a systematic heuristic generation of product concepts. Generally this conceptualization of products is widely addressed in diverse research fields, from engineering design to policy analysis over to creative writing. According to Alvarez and Ritchey (2015) over 80 articles with a particular focus on General Morphological Analysis (GMA) have been published since the 1950's. The research area synectics, which dates back to the inventor William J. J. Gordon in 1961, addresses a similar problem solving approach due to selective combination by means of disassociation and consideration of analogies (Gordon, 1961).

2.1 General Morphological Analyses

The origin of morphological analysis dates back to the late forties of the 19th century (Zwicky, 1947). Author of this systematic examination is Fritz Zwicky, a Swiss physicist and astronomer based at the California Institute of Technology at that time (Zwicky, 1949; Zwicky, 1966). An early application of morphological analysis to engineering design can be found by the Norris brothers in the 1960's. Therefore, during the design of the Bluebird CN7 attempting the world record in the automobile world speed category, different vehicle configurations have been investigated and evaluated, (Norris, 1963) found in (Álvarez, 2014). The opportunity of an algorithmic solvability of design tasks using design catalogues has already been deeply investigated by Franke (1976). He answered the question for which sub-function to investigate the most partial solutions. To guarantee the highest probability to find an optimal overall solution the most partial solutions have to be investigated for the sub-function where the selection criteria are the most uncertain. However, a strict algorithmization is difficult to apply in numerous sectors of the design process. Main reason is the lack of content-related acquisition. Lotter pursued the rational development of an optimal technical principle bridging the gap between function and structure. He focused on the development of a method for combinatorial examination of principle solutions with a computer-aided evaluation of multi-purpose complexes (Lotter, 1978). Birkhofer pursued both analysis and synthesis and described the selection of appropriate solution chains out of the wide variety of possible combinations by justifiable efforts (Birkhofer, 1980). A hierarchical concept generation phase using the morphological matrix methodology has been described by Weber (1989). For this purpose, the theory of coupling based on transmission of energy, material, information, generalized forces and displacements has been taken into account. The key steps therein are: 1. Identification of primary functions 2. Creation of solutions 3. Creation of a primary morphological matrix 4. Selection of compatible synergistic solutions 5. Identification of lower level functions 6. Creation of lower level solutions 7. Creation of lower level morphological matrices 8. Selection of a compatible synergistic solution and 9. Evaluation and iteration. Evbuomwan (1997) demonstrated the effective application of morphological analysis for the generation of conceptual design solutions within the Design Function Deployment. Ritchey gives a historical and theoretical overview of general morphological analyses and the comparison to “soft-OR” methods. A recent application in structuring a complex policy issue is carried out as a validation (Ritchey, 2006). Levin (2007) addresses hierarchical morphological modeling and design on the basis of a morphological clique problem. As a result, design alternatives are generated and illustrated in a hierarchical tree structure. Ostertagova et al. (2011) presented an application of morphological analysis in the selection of useful production system variants in design synthesis research, based on five basic steps which contain formalized mathematical apparatus: 1. Identification of basic functions 2. Creation of variants 3. Identification of every possible combination, according to the three fundamental production system classes introduced 4. Examination of every applicable variant in practice and 5. Final reduction of suitable combinations based on decision analyses. Heller introduced quality measures to categorize morphological boxes and a supporting software demonstrator using optimization algorithms (Heller et al., 2013; Heller et al., 2014).

2.2 Computer-aided Morphological Analyses

An overview of the latest engineering design automation systems and a selection of appropriate methods, mostly associated to the field of computational design synthesis, have been compiled in general by Rigger (2016). In addition, for the implementation of cluster-analyses computer-aided tools are available (Gausemeier et al., 1996).

Arciszweski introduced a mathematical model of morphological analysis for random solution generation by a nonhomogeneous *Markov chain* (Arciszewski, 1987). Levin described combinatorial modelling of decomposable systems, pointing out some basic combinatorial operations and modifications based on standard multi-criteria decision making problems and a hierarchical solving scheme with weighted interconnection among subsystems (Levin, 1998). Levin also addresses morphological approaches to the design of modular systems. The following methods are described: 1. General morphological analysis 2. Modification of morphological analysis as a method of closeness to the ideal point 3. Reducing of morphological analysis to linear programming 4. Multiple choice problem 5. Quadratic assignment problem 6. Pareto-based morphological analysis, Hierarchical Morphological Multicriteria Design and a Hierarchical Morphological Multicriteria Design approach based on fuzzy estimates (Levin, 2005; Levin, 2012). Tiwari used a genetic algorithm for extracting Pareto optimal solutions from a morphological chart as a combinatorial multi-objective optimization problem (Tiwari et al., 2009). Wünsch also combined morphological boxes with genetic algorithms by using aspects of the Autogenetic Design Theory (Wünsch et al., 2016). The purpose of Vertakova's article is the presentation of methodological tools for the main stages of morphological analysis and synthesis in scientific research areas. Therefore, 29 dissertations devoted to problem solving in various research areas are utilized (Vertakova, 2016).

The central provision of product and process knowledge for MTMT systems in a relational data-base to facilitate an individual combination has already been addressed, (Schmid et al., 2015; Schmid et al., 2016). However, in engineering design methodology there are several not fully and sufficiently answered research questions according to morphological analysis. Essential research issues in early phases of product development, which this contribution addresses, are given below:

- Consideration of a multi-stage design for product conceptualization of MTMT to make complex problems manageable which do not necessarily suffer by combinatorial explosion.
- A general method for a quantified and objective modelling of morphological boxes is still pending, regardless of user expertise, to enable an automatic and objective determination of the compatibility and effort. For this purpose, a parameter control in which direction the box should be iteratively developed for the application scenario MTMT development is aimed.
- Interface issues for partial solutions of the morphological box have not been systematically analyzed yet.
- A quality measure using context information for the entries and interactions in the overall system is missing.

3 QUANTIFIED SPECIFICATION MODEL

According to Heller (2014) morphological analysis within engineering design shows two different specifications: 1. Systematic investigation of the total solution field in order to ensure to find the optimal solution for each individual application (*creativity technique*) and 2. Synthesizing of new product concepts taking into account established or new sub-solutions in order to quickly find a viable solution meeting the requirements. Further restrictions regarding concept synthesis consist in the determined context in which the desired product is going to be developed and produced as well as the varying constraints that have to be fulfilled. For MTMT development and conceptualization a limited solution field (154 currently existing manufacturing technologies) according to DIN 8580 (DIN, 2003) has to be investigated. However, machine tools represent complex systems with approximately over a 1000 individual components and appropriate sub-functions according to Koller (1998). A commonality analysis and parameter control for an efficient generation of system combinations form an integral part of this contribution. According to Suh, in Axiomatic Design uncertainty is a direct measure of complexity for achieving the given set of functional requirements of a design task (Suh, 2016).

Counteracting this development for integrative machine systems a sustainable quality determination based on product and process expertise is forced in early stages of product development.

3.1 Commonality based product configuration for MTMT

Hubka defines similarity as the relation between several systems (objects, processes or statements) due to characteristics of certain units. Therefore, the similarity can be functional or structural (Hubka, 1984). The determination of similarities has the objective of reducing time and effort during synthesis (Lindemann, 2005). For MTMT systems a relation-oriented function modeling seems appropriate as a result of the appearing disturbances (static, dynamic, thermic or tribological), according to Herb (2000) found at Lindemann (2008). Two sub-groups depending on their relation to the remaining system functions can be identified: 1. Functions supporting the purpose and 2. Harmful functions having a negative impact on the purpose, illustrated in Figure 2 on the left.

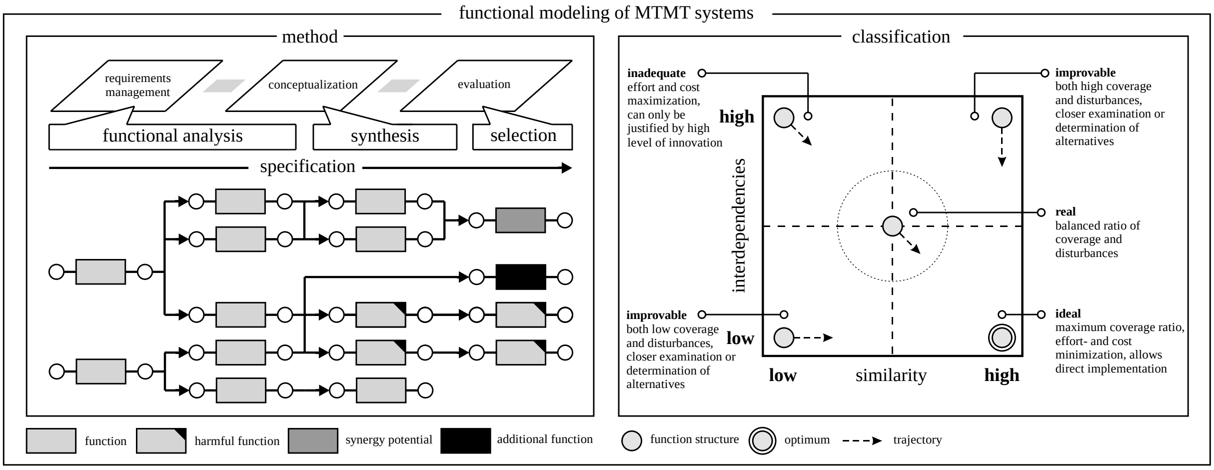

Figure 2. Relation-oriented function modeling (left) and typology for MTMT systems (right)

This approach for functional modeling of MTMT systems is based on the hypothesis that the combination of similar manufacturing technologies is particularly suitable to shorten development cycles and minimize the effort for integration due to low mutual effects (Schmid et al., 2015). The investigation of the total set of possible relationships or configuration options in this specific problem complex is aimed. For differentiation between functional similarities and interdependencies during early stages of product development of MTMT systems a database with characteristic features in relation to the appropriate technologies is the basis for this approach (Schmid et. al, 2015; Schmid et. al, 2016). A classification of these opposing poles can be seen in Figure 2 on the right.

Riesener (2015) shows the determination of a product configuration based on commonality analysis of existing product variants, taking into account costs and benefits. A similar approach can be utilized for comparability in early stages of product development of MTMT systems to overcome mutually contradictory conditions on functional level. Moreover a vector-notation enables mathematical analyzability. Depending on the specific application a proximity measure (measure for similarity: the higher the more similar) or distance measure (measure for dissimilarity: the higher the more dissimilar, identical means zero distance) can be applied (Backhaus et al., 2011). However, the selection of the proximity measure influences the similarity of the research objects.

The quantification is carried out by pair-wise comparison and a subsequent transfer in a square matrix for similarity. Therefore, a *weighted square Euclidian distance measure* is used according to Backhaus et al. (2011) taking into account individual perspectives, see Equation 1. The distance matrix directly results from the data matrix of MTMT systems, containing the product and process knowledge.

$$\mathrm{d_{ij}} = \sqrt{\sum_{k=1}^{n} w_k \cdot \left(y_{ik} - y_{jk}\right)^2} \quad \text{for } \mathrm{i, j} = 1, \ldots, \mathrm{n, i} < \mathrm{j} \qquad (1)$$

with
d_{ij} Weighted distance between the objects i and j.
w_k Weight factor.
y_{ik} Value of object i.
y_{jk} Value of object j.
n Quantity of characteristics that have to be investigated.

The weight factor is introduced for individual impact; otherwise relevant characteristics would be weighted equally. Absolute precondition for this approach represents a database with product and process know-how. The overall evaluation is performed by an arithmetic average of the weighted distances as can be seen in Equation 2.

$$\overline{d_{ij}} = \frac{1}{n} \cdot \sum_{i=1}^{n} d_{ij} \quad (2)$$

3.2 Parameter Control

Target systems can be diverse within the development environment. Consequently, different target systems concerning the type of design (*new development*, *customized design* or *variant design*) and the objective target should be taken into consideration. Figure 3 presents influencing factors and dependencies machine tool manufacturers of MTMT systems are exposed to, basically divided in *functionality*, *economic efficiency* and *innovation*. Context sensitivity with regard to the aspired design task and an identification and investigation of boundary conditions for the individual application is required.

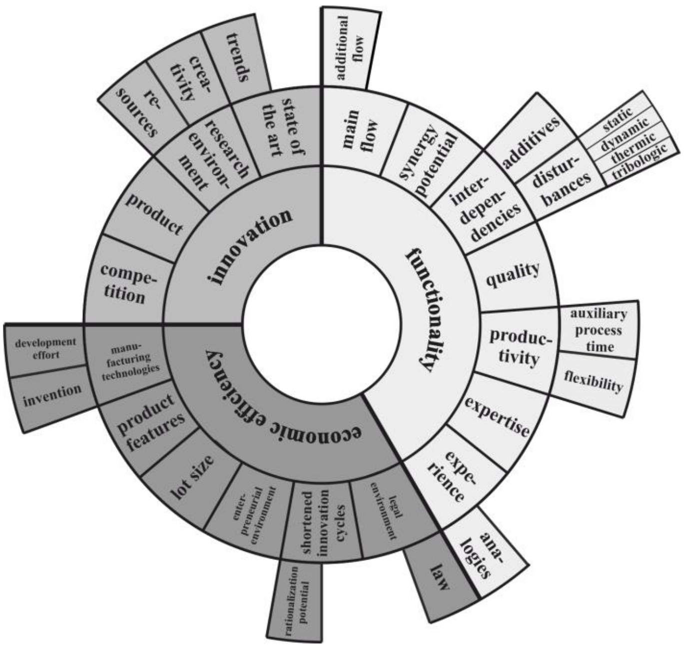

Figure 3. Influence diagram for MTMT development affecting the development phase

An increased reliability within product conceptualization counteracts uncertainty for novel designs and heuristic approaches. The modification of morphological analysis as a method of closeness to the ideal point is used. However, the optimal MTMT is not known and an individual survey for each specific application has to be carried out. Thus, a key performance indicator including several influence factors is a promising approach. Long-term objective is the explicit mathematical descriptiveness of these individual sections to derive cost and effort models.

3.3 Method for gradual and context-sensitive morphological analyses

The general procedure of the method introduced for MTMT systems is illustrated in Figure 4. By means of controlling the configuration process an iterative and solution-wide optimization of the solution space is achieved. Result of the individual combination is a quality criterion (*key performance indicator*). The pair-wise comparison is clarified in a triangular matrix representation.

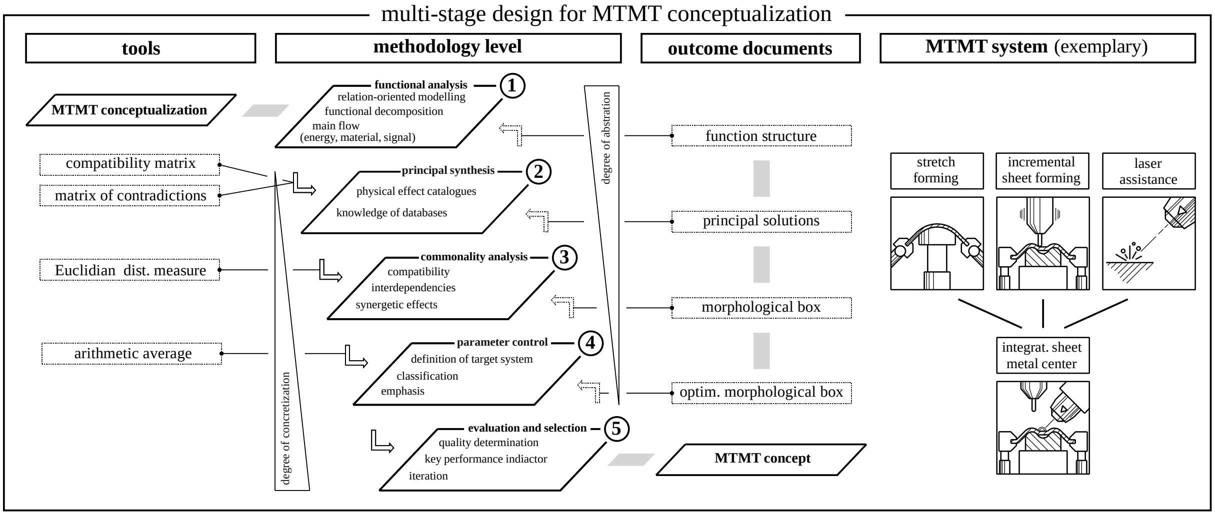

Figure 4. Cascading design methodology for a holistic and objective evaluable morphological analysis of MTMT systems

Initially, a functional analysis is performed (1). The design task for developing MTMT systems can be diverse, e.g. machining, forming or casting processes. A robust requirements management and relational-oriented modeling in advance guarantees functional safety for generating a morphological box. By functional decomposition subsections with similar or identical characteristics can be identified for the combination of different manufacturing technologies. This is followed by a synthesis step for principle solutions according to Pahl and Beitz (2013) (2). Thus, physical effect catalogues according to Koller (1994) and Roth (1994) become applicable. Then the degree of compatibility is investigated by commonality-based analysis (3). For this purpose, the individual evaluation taking into account different boundary conditions (e. g. system boundary, interdependencies, synergy potentials, technical maturity) according to Figure 3 results in a row vector for the individual principle solutions. After the individual target systems have been defined a parameter control is performed through a weighted Euclidian distance measure (4). The result of this pair-wise comparison is illustrated in a triangular matrix and transferred in a key performance indicator for the overall concept (5). The presented process has an iterative character. In order to achieve the intended quality previous steps may be repeated. The consistent sequence of this procedure enables the determination of acceptable MTMT concepts for individual applications. In addition, effort estimation for product development can be performed. By adjusting the parameter assessment alternative solutions can be determined and compared quantitatively (*optimization problem*).

4 CASE STUDY FOR AN INTEGRATIVE SHEET METAL FORMING CENTER

The presented approach is carried out by a simplified example. Figure 5 represents an excerpt from a morphological box of an integrative sheet metal forming center and illustrates two different product concepts. The focus of this consideration is on the main functionalities of the MTMT system in order to maintain clarity and validate the introduced method. First of all every partial solution has to be evaluated by means of the different perspectives, in this case functionality, economic efficiency and potential for innovation. The scale is from 1 (completely fulfilled) to 5 (insufficient degree of fulfillment). Taking full account of relevant influencing factors enables a holistic evaluation. General objective is the minimization of the entries due to the proximity measure defined in section 3.1 to maximize the key performance indicator. Sub-functions to be fulfilled are (from left to right): machining process (a), preform generation (b), form itemization (c), improving formability (d) and control aspects (e). The two concepts have been selected due to the respective target systems.

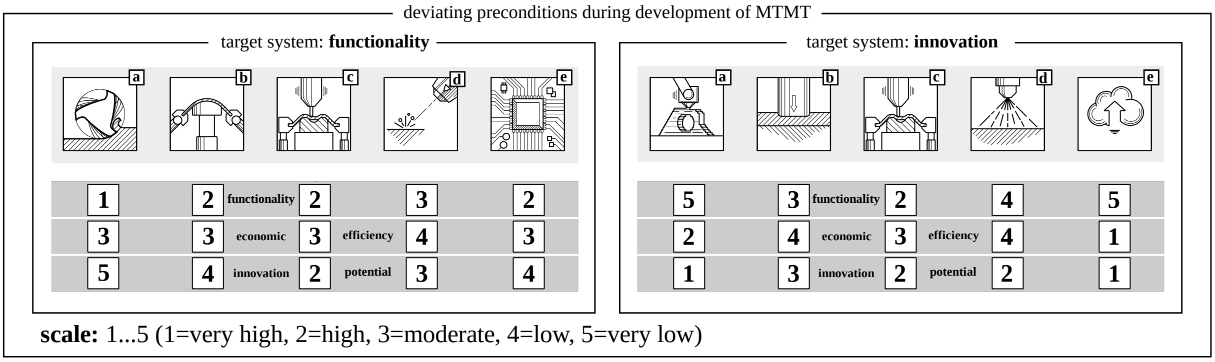

Figure 5. Simplified MTMT product configuration with a focus on functionality (left) and innovation potential (right)

The main emphasis combining these solution principles in Figure 5 varies. The two different validation scenarios are as follows: On the left, an existing integrative sheet metal forming center which has been designed for research application at RWTH Aachen University is listed (Araghi et al., 2011). Established solutions have been combined and extended by laser assistance. This demonstrator is based on a portal milling machine which has been extended by four modules for stretch forming. After the stretch forming process is finished a hemispherical forming tool forms the desired contour gradually out of the material. Furthermore, a laser processing unit facilitates the forming process and enables cutting blanks. Moreover, in the same clamping process patrices can be manufactured. This multi-functional demonstrator is operated by computerized numerical control.

An alternative with equal functional orientation but various function carriers is illustrated on the right with a particular focus on novel technology combinations. Instead of milling to generate the preform, generative manufacturing methods (e. g. 3D-printers) are selected. To increase the formability of metal, the blanks are coated beforehand. The preform generation is performed in this case by a pressing process to realize the rough embodiment design. The itemization of the contour is also performed by incremental sheet forming similar to the left concept. Furthermore, the machine control is outsourced through a cloud application to address the idea of *Industry 4.0*. The next step will include the pair-wise comparison of these two concepts introduced to estimate the similarity as can be seen in Figure 6. The evaluation according to Figure 5 is the basis for the triangular matrices.

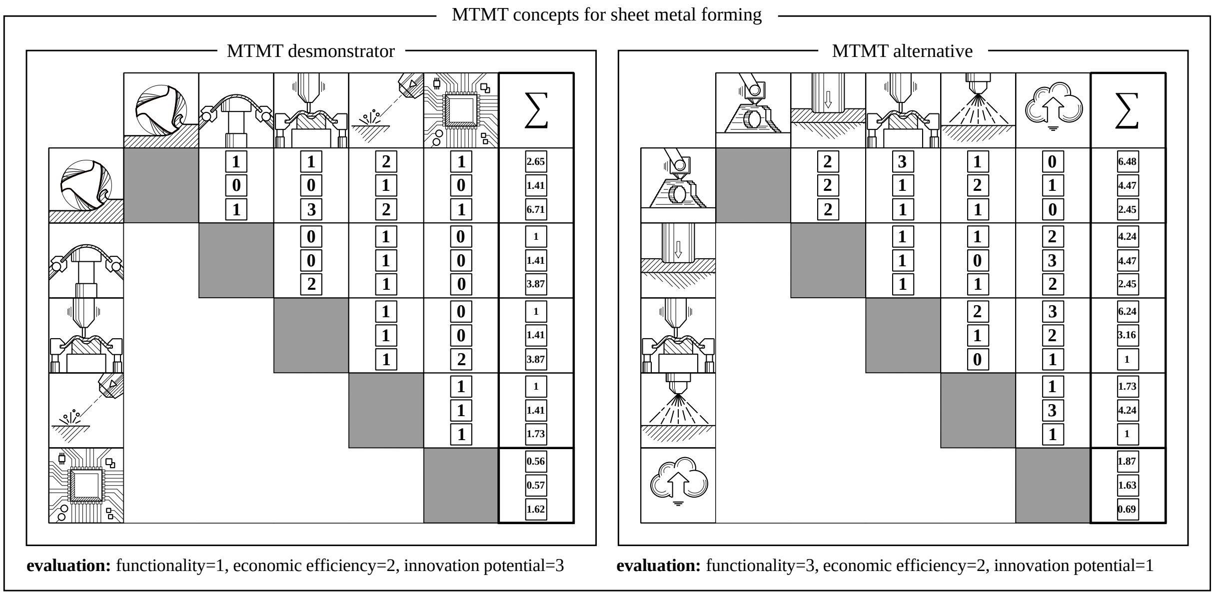

Figure 6. Evaluation of diverge product concepts in matrix representation (absolute value)

On the basis of this approach well-balanced product concepts can be determined considering the target system. The average weighted assessment per row and the overall assessment are illustrated in the last column. Furthermore, it is possible to vary the entries with the highest distances. The disturbances of the MTMT demonstrator on the left are incidental: the milling process is upstream and the thermal factor of the laser processing unit is secondary because the integration was carried out consciously for process improvement. Consequently, the functional assessment of these solution principles results in a low overall evaluation. However, the innovation potential is quite low due to the combination of conventional technologies. The MTMT alternative on the right shows a strongly contrasting behaviour. Generative manufacturing is not yet ready for series production and the control unit implemented as a cloud application needs appropriate infrastructure and know-how for realization. Further interdependencies (e. g. various material flows) influence the assessment. The different weight factors in Figure 6 prioritize the influencing factors according to the specific development objective. According to Tönissen the economic viability of MTMT systems is satisfied in particular for low quantities (Tönissen, 2014). The economic evaluation performed becomes clear in this context. The factor for economic efficiency has a minor importance and is identical for both product concepts.

5 CONCLUSION AND OUTLOOK

The introduced approach including commonality analyses during product synthesis of morphological boxes enables a context-sensitive fulfilment (achievement of required goals, monetary expenditures) of the introduced key performance indicator during product development of MTMT. Consequently, disturbances during the use phase can be predicted and excluded by a robust conceptual phase. One important result is the selection of well-balanced overall systems for MTMT conceptualization regarding the particular target system using the weighted square Euclidian distance measure.

Computer-assisted evaluation methods (e. g. multi-criteria optimization) are going to be included in the next iteration step. Furthermore, the usage of fuzzy set approaches and artificial intelligence techniques to overcome uncertainties represents a possible extension for MTMT development (Ritchey, 2006; Levin, 2007). Further examination of the applicability for rationalization methods and different types of proximity measures during product conceptualization (e. g. Design of Experiments) are aimed for future research. In addition, a specific analysis which functions can be described mathematically for computerized syntheses according to Koller's approach of elementary functions is considered (Koller, 1994). Finally, a further objectivation of the evaluation process and an application in industry is aimed for.

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