# Approach for an Integrative Technology Assessment Method Combining Product Design and Manufacturing Process

Guenther Schuh, Sebastian Woelk, Daniel Schraknepper, Anders Such



***Abstract*—**The systematic evaluation of manufacturing technologies with regard to the potential for product designing constitutes a major challenge. Until now, conventional evaluation methods primarily consider the costs of manufacturing technologies. Thus, the potential of manufacturing technologies for achieving additional product design features is not completely captured. To compensate this deficit, final evaluations of new technologies are mainly intuitive in practice. Therefore, an additional evaluation dimension is needed which takes the potential of manufacturing technologies for specific realizable product designs into account. In this paper, we present the approach of an evaluation method for selecting manufacturing technologies with regard to their potential for product designing. This research is done within the Fraunhofer innovation cluster »AdaM« (Adaptive Manufacturing) which targets the development of resource efficient and adaptive manufacturing technology processes for complex turbomachinery components.

***Keywords*—**Manufacturing, product design, production, technology assessment, technology management.

## I. Introduction

THE identification of new technologies and their suitability for development and manufacturing of new products are crucial for companies to achieve and maintain a strong competitive position in the market [1]. Therefore key sources for product design innovations are new innovative technologies, which are essential factors for achieving sustainable competitive advantages [2]. Hence, a strategic technology planning is important for analyzing, assessing and planning the development of new innovative technologies [3], [4]. The superior company goal is to increase the efficiency of manufacturing processes while improving the quality and functionality of products to raise customer value [5]. Due to customer demand for an individualized product the manufacturing system needs to be flexible to react to different variations of the product design. To realize this individualized production the most suitable manufacturing technologies for each product design need to be identified [6]-[8]. In addition new manufacturing technologies like Selective-Laser-Melting (SLM) allow additional degrees of freedom in terms of product designing and make innovative product features like lattice structures possible [9]. This added value to the product design needs to be integrated in the assessment of manufacturing technologies to capture the full technology potential. This makes a conjoint analysis of the product design and the manufacturing process necessary. A holistic and integrative approach for considering possible interactions between product design and manufacturing is therefore needed [7], [10]. In this paper we would like to present an approach for the evaluation of manufacturing technologies with respect to the achievable opportunities in product designing. The assessment method also needs to be practical and simple due to the development of new product designs and the usage of new innovative manufacturing technologies. Therefore a systematic and detailed description of the design and technology restrictions is difficult to achieve. [11].

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The Fraunhofer innovation cluster »AdaM« has a running time of three years with a total budget of €10 million. This Innovation Cluster is financially co-supported by the federal State of North Rhine-Westphalia, the Fraunhofer Gesellschaft and the participating companies (grant number PRO/0042).

This research is performed within the Fraunhofer innovation cluster »AdaM« (Adaptive Manufacturing) which targets the development of resource efficient and adaptive manufacturing technology processes for complex turbomachinery components. In the turbomachinery markets - aerospace, energy and automotive - complex technologies regarding product design, manufacturing and material are needed to meet the increasing customer and government requirements in terms of higher efficiencies and less fuel consumption [12]. To achieve this major goal generative and adaptive process chains can be used, which are jointly developed by Fraunhofer ILT and Fraunhofer IPT. Additionally the Institute of Jet Propulsion and Turbomachinery, IST RWTH Aachen, performs a design analysis of a selected demonstrator by reviewing the initial geometry and identifying possible design variations. Goal of the assessment method is the identification of the most suitable technology process chain depending on design requirements of turbomachinery customers.

## II. AdaM Demonstrator

The developed assessment method is tested by applying a complex turbomachinery component. As demonstrator a compressor guide vane of a gas turbine from a turbomachinery OEM of the AdaM consortium is used. This particular guide vane consists of two vanes in tandem arrangement. This special geometry feature is needed to reduce the stall. The tandem arrangement leads to a very small gap between the two tandem vanes. Due to this small tandem vane gap and the size of the guide vane the manufacturing is challenging. The current manufacturing process is performed by milling two blades out of solid which results in a »twin blade«, see Fig. 1 left. This manufacturing method is only possible, if the width of tandem vane gap and the position of the blades allow a virtual cut through the guide vane arrangement without virtually cutting through a blade. Afterwards the tandem gap is formed by assembling the twin blades as a ring in the compressor stage.

Despite the easier manufacturing of the twin blade the manufacturing of a guide vane cluster is attractive, see Fig. 1 right. Advantages of the integral structure are an easier and faster assembly as well as an optimized positioning.

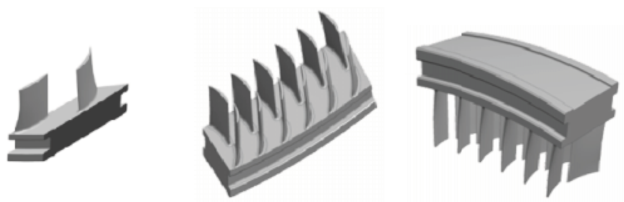

Fig. 1 AdaM demonstrator: twin blade and cluster

In Table I the dimensions of the guide vane cluster are shown.

TABLE I
DIMENSIONS OF THE GUIDE VANE CLUSTER

| Cluster length | Vane height | Tandem gap width |
|---|---|---|
| 65 mm | 15 mm | 2 mm |

mm = Millimeter

For the research the materials Inconel 718 and X22CrMoV12-1 are evaluated to address different requirements in the turbomachinery markets.

## III. LITERATURE REVIEW

The common assessment methods are usually limited to the sole consideration of the product or the production side. Therefore, a method is needed that realizes the combination of those two dimensions [13]. The majority of the assessment methods aim at an early cost-related analysis and assessment of the product or design approach [14]. In the short run this seems logical due to mainly cost driven purchase reasons of customers. However, there are hardly any methods that allow the evaluation of manufacturing processes regarding the improvement or worsening of the product functionality. Thus, the potential of the production technologies for new design variants is not fully captured. Furthermore, the selection of a manufacturing procedure is nowadays often not included in the product development. This often leads to production decisions from the gut without a methodological explanation why a decision for specific product design option was chosen. In the early phases of the product development process, information about potential manufacturing technologies and processes should be provided to identify design potentials [8], [11], [15], [16]. Current approaches mostly integrate the technology planning and its technology assessment at the late of the product design process. But in order to exploit all potentials, the technology planning must be integrated in the early construction phase to support finding the entire solution space of the product functions. Otherwise influencing the product functions by specific manufacturing technologies is not possible [15]. By this integration in the early design process the product designers gain a better understanding of technology performance restrictions. Likewise the needs and trends of product designing are known by production specialists.

Besides the assessment of manufacturing technologies regarding new product designs a systematic illustration of the correlation between product design and manufacturing process is needed. Existing methods mostly focus on the market view comprising the market position and the technology potential [17]. An evaluation and explanation for the need of a new product design in combination with the required innovative manufacturing process is therefore not possible.

In the following important existing methods for technology assessment and portfolio analysis are introduced.

### *A. Combination of Product Design and Manufacturing Process*

By FALLBOEHMER an integrated technology planning method is introduced which integrates the knowledge about the potential of new materials and production technologies in the product design process [11]. The requirement is systematic information exchange between the product development and the production planning by dividing the product development process in a rough and a detail design phase. This way it is possible to identify alternative manufacturing process chains. This can be achieved by a feature based correlation between the product and the manufacturing technologies. For this correlation a deep analysis and a detailed description of the characteristics is needed. The method is therefore very complex. A comparison of the production process regarding economic, ecological and quality aspects is not part of the method. TROMMER expands FALLBOEHMERS method aspects to a fabric location planning method by considering those economic, ecological and quality [16]. Evaluating the most suitable combination of product design and manufacturing process is not in the focus of the assessment method.

Another approach for integrating the technology knowledge in the product development is the method of BORSDORF [15]. In contrast to FALLBOEHMER the integration process can be described as control loop system using the manufacturing technologies as regulator. This way market pull and technology push can be considered as inputs of the loop system. In this integrated method the product design is divided into sub functions which are transformed to technology characteristics which are then realized by different manufacturing processes. Detailed information about the description of the product and technology characteristics are needed which makes this method also complex.

HEITSCH describes a method for a multi-criterial assessment of production processes for an investment planning [18]. Thereby an assessment regarding economic, ecological, quality as well as strategic aspects is possible which results in a ranking of the production processes. Identifying the potential for new product designs as well as assessing the product designs is not part of the method.

KROELL introduces an assessment method which is derived from the Quality Function Deployment Method (QFD) which systematically integrates the customer requirements in the product development process [19]-[21]. To do so a House of Quality is introduced in the QFD. KROELL generates from this House of Quality a so called House of Technology (HOT). The HOT illustrates the correlation between the product functions, derived from the customer requirements, and the potential product technologies to fulfill the functions. Furthermore the method explains how different product technologies can be logical combined to find the most suitable fulfillment of the product requirements. Those linked technology chains are then assessed using criteria like costs, quality, flexibility, maturity level.

Another interesting method to identify a most suitable solution in a product-production-system is the Axiomatic Design by SUH which analyzes the transformation of customer needs into functional requirements, design parameters and also process variables [22]. The allocation of the requirements to the corresponding solutions is calculated using matrices which makes a systematic and detailed description of the needed domain variables necessary.

### *B. Portfolio Analysis*

For a systematic evaluation of assessment results portfolio analyses are mostly used. In the literature several methods exist [17]. Important examples are the PFEIFFER and the McKinsey portfolios.

The PFEIFFER portfolio consists of two dimensions: technology attractiveness and resource strength [17], [23]. Basic idea of the method is that the innovator can always achieve higher revenue as the imitator. Therefore an early investment in relevant technologies is import to gain a pioneer position. The dimension technology attractiveness is calculated by the technology potential and the technology demand. The resource strength comprises the financial strength and the know-how strength.

In the McKinsey portfolio analysis the market priority and the technology priority are contrasted [17], [24]. This way the qualitative rate of the company´s R&D usage can be identified. The market priority is calculated by the relative market position and the market attractiveness. Likewise the technology priority comprises the relative technology position and the technology attractiveness.

## IV. AdaM Procedure for an Integrative Technology Assessment

As above described most assessment methods are very complex due to the need of the detailed information about the characteristics of the product design and the manufacturing technologies. Because of the development of a new product design and the usage of new innovative manufacturing technologies it is very difficult to specify the specific technology limits and restrictions [11]. We therefore developed in AdaM a combined assessment method with the goal of a practical and simple approach. An overview of the approach for the integrative technology assessment can be found in Fig. 2.

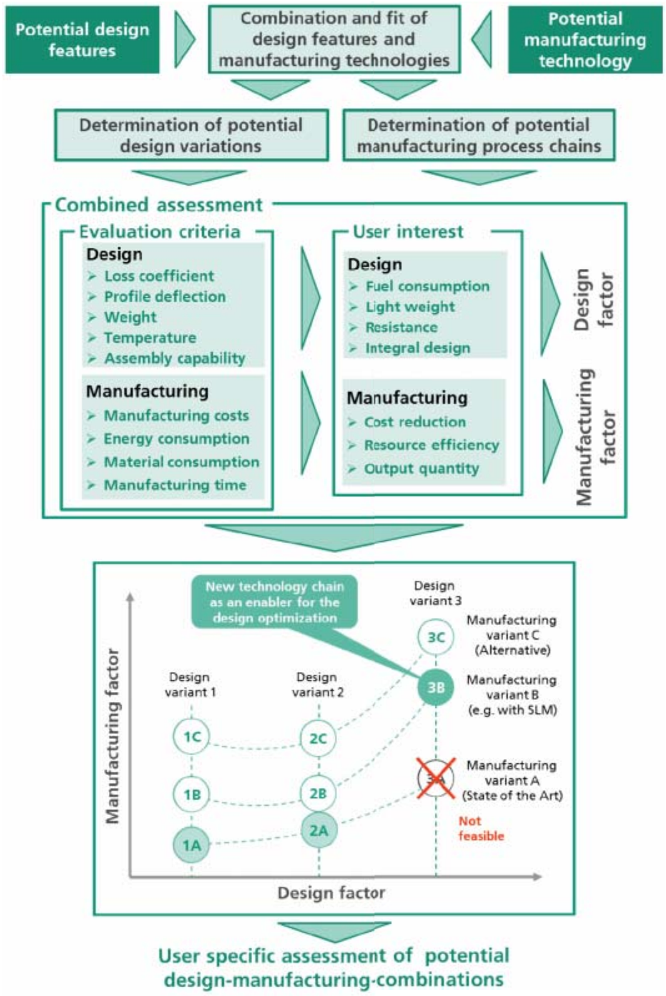


Fig. 2 Procedure of the integrative technology assessment

For a first estimation what product features can be realized by which manufacturing technologies a morphological box can be used. For a detailed examination of the connections a relationship matrix is needed, which contrasts the product features and manufacturing technologies [19]. This relationship matrix can be derived from the House of Technology (HOT) after KROELL [19]. The derived HOT ensures a systematic description of complex dependencies between product features and manufacturing technologies.

Those correlations can then be easily illustrated using recognizable symbols. This way it is possible to identify whether a specific individual product function can be represented by several manufacturing technologies. Conversely, a manufacturing technology can also contribute to the fulfillment of several product functions. Furthermore, it can be checked if all functions have been adequately captured by the manufacturing technologies and on the other hand what manufacturing technologies are even needed for functional performance. To illustrate the mutual influence of manufacturing technologies during a production process an additional correlation matrix can be used. Here interactions between the manufacturing technologies can be captured to support building the process chains. By determining these interactions it is possible to tell whether certain manufacturing technologies either enhance (+), weaken (-) or neutral (o) each other. With this additional correlation matrix a »roof« on top of the product - manufacturing relationship matrix is built, see Fig. 3. As with the manufacturing technologies it is also conceivable to flange the axis of the product functions with an additional correlation matrix to illustrate their mutual influences. This way an overall evaluation of the product design and the manufacturing process would be possible.

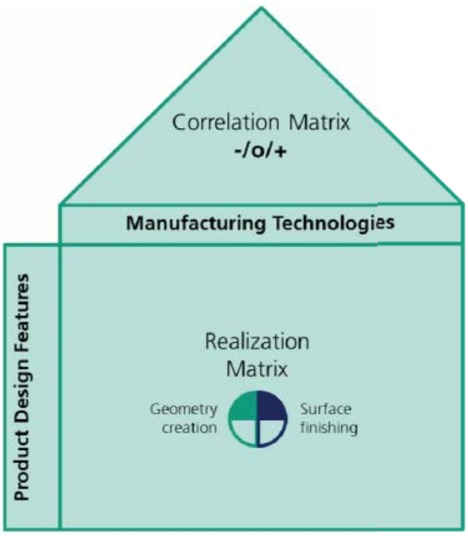


Fig. 3 House of Technology modelled after KROELL [19]

To achieve a combined evaluation of the product-manufacturing system a multi-criterial assessment is needed to consider all relevant dimensions [18], [19]. The combined assessment is achieved in a portfolio by contrasting a design factor and a manufacturing factor, see Fig. 2. Each factor is calculated by a multi-criterial assessment before. The design factor considers the product geometry as well as the material effects. Therefore the total pressure loss, the profile deflection, the product weight, the maximum temperature and the assembly capability are taken into account. The values of the criteria: pressure loss and profile deflection will be calculated by the IST RWTH Aachen. The product weight can be either calculated or measured. The maximum temperature is given by data material sheets. The assembly capability will be a qualitative statement compared to a single vane product.

The manufacturing factor consists of the manufacturing costs, process time as well as the energy and the material consumption during production. The process time, energy and material consumption are measured during production or calculated from previous similar measurements for each step of the manufacturing process. The energy and material consumption also contributes to the manufacturing costs. In addition all auxiliary means like tools, gas etc. and the machine purchase price are considered in the manufacturing costs.

To perform a comparable manufacturing assessment a balance envelope with defined cause variables is needed, see Fig. 4. With the help of ISO 14040 for an overall life cycle assessment a bounded ecological assessment can be derived for the manufacturing research in AdaM [25].

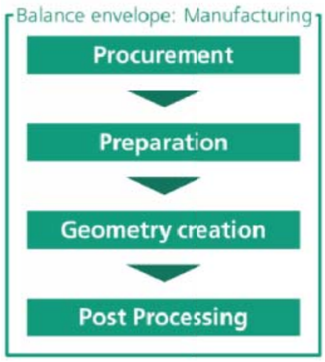


Fig. 4 Balance envelope of the resource efficiency assessment

The ecological assessment of the manufacturing processes will be modelled in the GaBi Software, which is a tool for a systematic and detailed product life cycle assessment [27]. This way additional examination regarding the ecological impact like $CO_2$, $NO_x$ and usage of primary energy is also possible.

By this described multi-criteria assessment economic and ecological aspects can be included in the evaluation. This enables the customer to choose which fits his needs best. To do so the customer can weigh the design and the manufacturing factor. For the design factor the customer can weigh between the following weighting factors: fuel consumption, light weight, resistance and integral design. Likewise for the manufacturing factor the customer can weigh between the weighting factors: cost reduction, resource efficiency and output quantity.

After entering and weighting all values, the design factor and the manufacturing factor are calculated and the combined product-manufacturing-portfolio is created. In this portfolio a higher factor represents a better outcome of the assessed product design and the corresponding manufacturing process and is there for aimed at. This way, the best solution fit is positioned at the top right. For the calculation of the design and the manufacturing factor the Analytic Hierarchy Process (AHP) is used [26]. The AHP allows the automatic calculation of the ranking and the weighting of the assessment criteria. To do so the user makes a pair comparison of the assessment criteria. Furthermore a combination of different scaled numbers as well as the combination of quantified and qualified numbers is possible.

## V. Evaluation and Selection of the Suitable Manufacturing Technologies

The operative combination of the product design and the manufacturing technologies was achieved by doing workshops with the support of the specific technology experts due to the difficulty of a systematic and detailed description of the technology restrictions [11]. As result the House of Technology (HOT) with the evaluation criteria geometry creation and surface finishing can be presented, see Fig. 5.

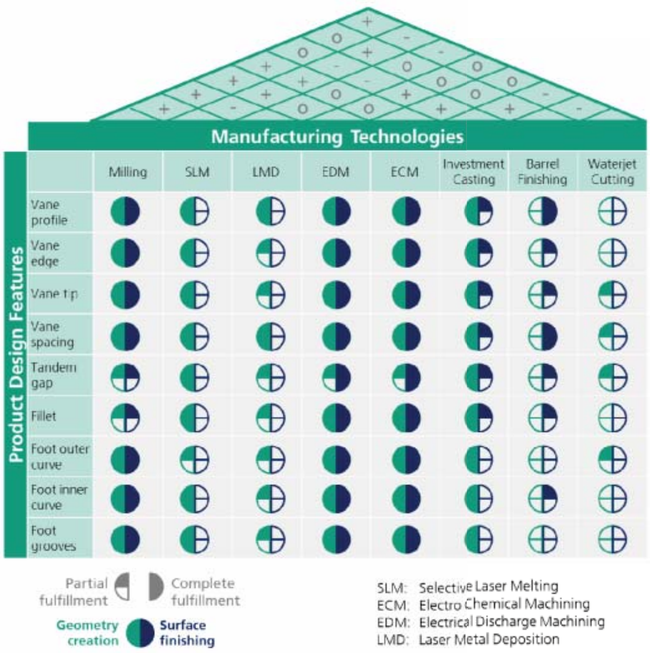


Fig. 5 Resulting House of Technology (HOT) in AdaM

In the roof of the HOT we evaluated the technology correlations with a plus (+) when technologies form a sensible manufacturing chain like laser metal deposition for geometry creation and milling for post processing. Technologies like selective laser melting and investment casting, which substitute each other and are therefore not suitable for combination, we marked with a minus (-).

With this rough technology assessment technology chains for further examination could be identified. All in all 24 technology chains with 48 specific process steps were chosen. Those technology chains can be clustered into three technology modules: geometry creation, foil surface finishing and contact surface finishing, see Fig. 6. This way only 11 separate chain steps need to be measured in detail and not the entire process chains. The other possible combinations can then be derived from those examined steps. Of course, in comparison to the examination of all 24 possible technology chains a certain inaccuracy due to the slightly different input for the specific finishing process step has to be accepted. But after first investigations those inaccuracies are not immense and will not affect the comparison the different technology chains.

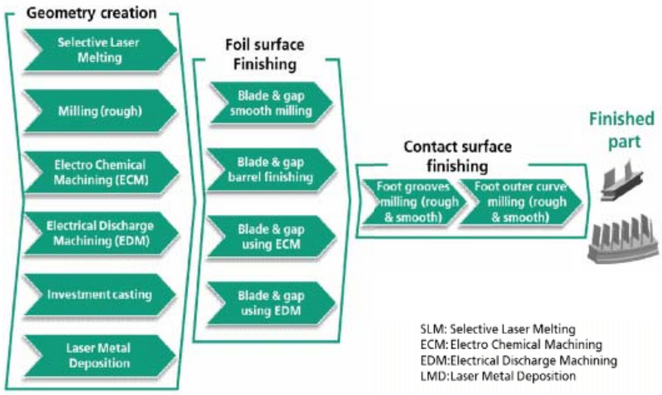


Fig. 6 Examination of potential manufacturing process chains

The examination of such many different manufacturing process chains enables a resource efficiency evaluation of additive manufacturing, slotting and casting technologies, see Fig. 7.

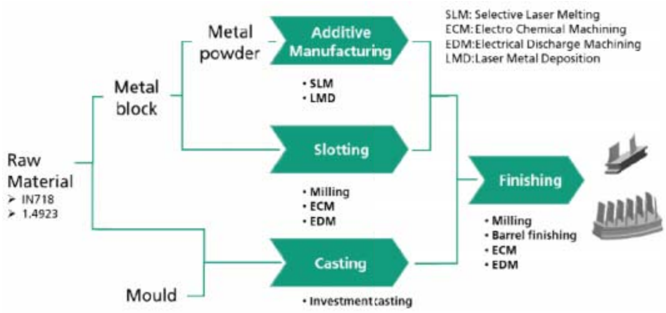


Fig. 7 Evaluation of the resource efficiency of the different manufacturing process chains

This resource efficiency evaluation enables the comparison of different manufacturing paths with different states of initial material. Firstly there is the additive path using metal powder as initial material, secondly there is the slotting path using a metal block as initial material and thirdly there is the casting path using a raw material mix in the crucible. Due to the complex component geometry the full potential of the addressed technologies is needed and no best solution can be identified in advance.

## VI. Conclusion

New manufacturing technologies allow additional degrees of freedom in product designing. Therefore, an additional evaluation dimension is needed, which observes the potential of a manufacturing technology for the resulting product design. We therefore proposed a practical assessment method which combines the product design and the manufacturing process. A relationship matrix was introduced which contrasts the product features and manufacturing technologies. Thereby a description of the complex dependencies between product features and manufacturing technologies is possible. Afterwards a multi-criterial assessment is carried out to achieve a combined evaluation of the product-manufacturing system by contrasting a design factor and manufacturing factor. The design factor considers the product geometry as well as the material property. The manufacturing factor shows the results of an economic and ecological assessment. Each factor can be weighted to meet the user´s interest. Therefore the best user specific combination of the product design and the manufacturing process can be identified. To ensure a practical usability a guide vane cluster is used as demonstrator. Several different manufacturing processes will be examined in detail during the research.

At the current research state the guide vane cluster has been manufactured using SLM by Fraunhofer ILT. The milling for the contact surface finishing has also been implemented by Fraunhofer IPT. First tests using barrel finishing have also been performed. During the research we identified that conventional finishing technologies, like barrel finishing, reach their performance limits in order to realize this complex product design. To achieve the aimed surface quality other post processing technologies like pressure lapping or abrasive blasting will therefore be considered in further research.

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