Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 36 (2015) 72 – 77

www.elsevier.com/locate/procedia

CIRP 25th Design Conference Innovative Product Creation

Utilization of State Drivers to Support Design for Manufacturing

Thorsten Wuest[a,]*, Ang Liu[b], Wei Wei[c], Stephen C.-Y. Lu[b], Klaus-Dieter Thoben[a,d]

[a]BIBA – Bremer Institut für Produktion und Logistik GmbH, Hochschulring 20, 28359 Bremen, Germany.
[b]University of Southern California,University Park Campus, DRB-260, Los Angeles, CA 90089, USA.
[c]Beihang University, Beijing, 100191, China.
[d]Universität Bremen, Bibliothekstrasse 1, 28359 Bremen, Germany.

* Corresponding author. Tel.: +49-421-218-50171; fax: +49-421-218-50007. *E-mail address:* wue@biba.uni-bremen.de

Abstract

Together with the fast paced technological advances, the complexity and dynamic in manufacturing is steadily increasing. At the same time, the (functional) requirements derived from the customers are becoming more challenging to fulfill. In order to cope with this challenge, designers have to focus more on design for manufacturing besides taking the requirements derived from the customers into account. This is not only important from an economic perspective, e.g., to reduce avoidable expenses during manufacturing but often also directly related to the fulfillment of customer requirements from a quality perspective, e.g., structural behavior of highly stressed products.
In manufacturing, the product state concept describes the subsequent development of a product along the process chain by its accumulated state. It can be used to increase the understanding of the manufacturing processes from a system's point of view and can be applied e.g., to support quality management. Within the concept it is possible to identify so-called 'state drivers', by means of Support Vector Machine based feature ranking on an accumulating product and process state vector. These state drivers take explicit and implicit intra- and inter-relations between states into account and provide an insight which parameters are most relevant for the final quality outcome and where the critical points along the process chain are.
In this paper, the relation between design for manufacturing and the product state concept will be discussed with a special focus on the state drivers. The question, if and how state drivers can be utilized to support the design phase and designers will be examined in detail, whilst the overall question of the appropriate detail of manufacturing feedback to design is also examined.

Peer-review under responsibility of the scientific committee of the CIRP 25th Design Conference Innovative Product Creation

Keywords: Manufacturing; Design; State Drivers; Feature Selection; Design-for-Manufacturing; DfX; DfM.

1. Introduction

Over the last decade, significant developments transpired concerning manufacturing technology including supporting activities like control, monitoring and analysis. Wide availability of cheap and capable sensors in combination with data storage, communication and corresponding ICT infrastructures lead to a steadily increasing amount of data [1]. This availability of manufacturing data, often in real time, is a big chance to improve different dimension like quality. However, large amounts of data may increase the complexity and present significant challenges to companies [2].

At the same time, the (functional) requirements derived from the customers are becoming more challenging to fulfill. This is first of all a challenge for product development and design. However, when the design is becoming more complex this often leads to more challenging requirements towards manufacturing processes and operations. In the end, design is in most cases a compromise of conflicting goals [3].

Overall, it can be stated, that the fast paced technological advances together with increasing customer requirements has an impact on complexity and dynamic of today's manufacturing process chains.

One established approach to support manufacturing is to take manufacturing requirements and/or constraints into consideration during the design phase. This so-called Design for Manufacturing (DfM) (also known as Design for Manufacturability and Design for Manufacture) brought forth

Peer-review under responsibility of the scientific committee of the CIRP 25th Design Conference Innovative Product Creation
doi:10.1016/j.procir.2015.01.081

considerable benefits incl. reduction of manufacturing cost, improvement of quality and reduced time to market [4]. Since the first steps taken by DfM, the method developed along with new technologies, business models and emerging challenges [5].

In this paper, the current level of detail of information and knowledge feedback from manufacturing to design is investigated. Based on that, the possibility and potential benefits of a more product (family) specific, higher level of detail and rather individual feedback is discussed.

To achieve this goal, the possible combination of the DfM methodology with the product state concept is investigated. This combination corresponds loosely with the recommendation of Kuo et al. [4] who suggest the use of Artificial Intelligence and Intelligent Systems in the DfM. The product state concept is an approach to describe the development of a product along the manufacturing programme by its state. It can be used to identify so-called state drivers of a process sequence utilizing a growing data vector along the process chain and supervised machine learning analysis. These state drivers represent relevant parameters of manufacturing that have an impact on the final product quality [6].

The main question is if knowledge of those manufacturing state drivers may benefits designers in the spirit of DfM. And therefore may help handling the previously mentioned increasing complexity in today's manufacturing in return.

The scope of this paper and the introduced ideas are focused on the design and development of next generations of products and/or similar products and not 'new' product development. This is a prerequisite for rerouting such particular input from manufacturing experiences back to the design phase.

The paper is structured as follows. Following the introduction, the two basic concepts, DfM and the product state concept is presented. In the next section, the two concepts are combined. Based on that, section four critically assesses the idea, discussing the requirements, benefits and limitations of an application. Section five concludes the paper and gives an outlook on open questions and further research.

2. Background

In this section, the theoretical foundation for the subsequent concept development is illustrated in form of a description of DfM and the product state concept.

2.1. Design for Manufacturability

As mentioned in the introduction, DfM is an established design method, which has been applied since the 1970s and evolved continuously [5]. DfM is part of the larger Design for Excellence (DfX) methodology, along with design for assembly, recyclability, lifecycle, quality, etc. [4]. The idea behind DfX and all related methods is to include knowledge about manufacturing requirements and characteristics to basically allow lowering manufacturing cost and/or time while not compromising on or even improving product and process quality [3; 7]. As there are different target dimensions, e.g. quality, ease of assembly, etc., the different DfX methods may be inter-related to one another. This has to be taken into account before implementation as optimization of one may have a negative effect on the other. In this case, the focus is solely on DfM without taking potential inter-relations with other DfX methods into consideration.

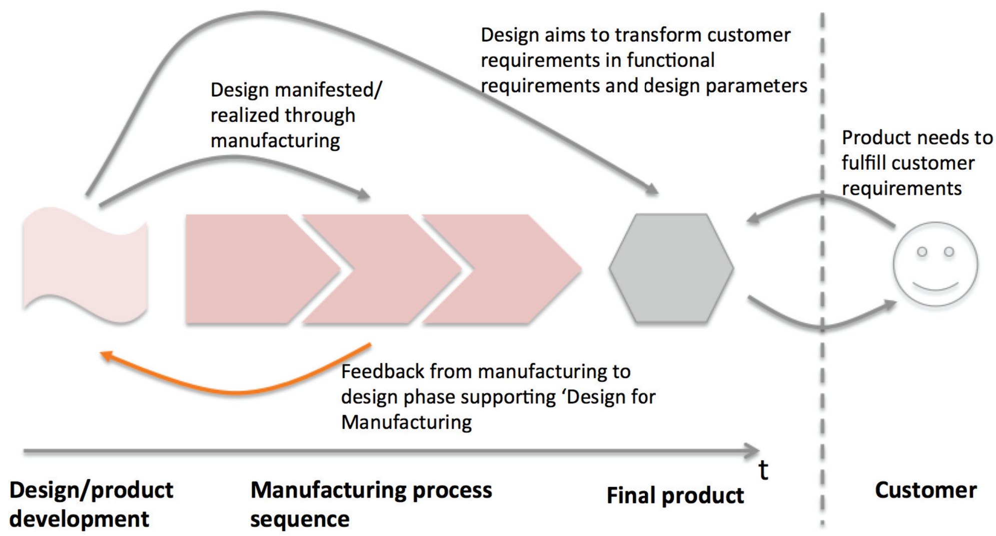

Fig. 1. Feedback from Manufacturing to Design to improve processes

A major part, between 70% and 80%, of the accumulated production cost of a product is defined during the design phase [8]. Therefore, processes later in the chain, like manufacturing, realize a large part of the cost defined during design. To take this potential lever into account is rather important and one of the major reasons for the DfM approach. A subsequent change of the product design based on problems discovered during manufacturing is multiple times more costly compared to the emerging cost if these problems are anticipated (and ideally solved) at an earlier stage, e.g., through feedback loops from manufacturing (see Fig. 1) [9].

Today, there are several guidelines and studies available for a variety of manufacturing technologies, e.g., machining, injection molding and die-casting [4; 10]. DfM guidelines are described by O'Driscoll et al. as "statements […] of good design practice that have been empirically derived from past experience" [3].

These guidelines are often included in existing Computer Aided Manufacturing (CAM) and/or Computer Aided Design (CAD) systems [4]. An example for a manufacturing feature library linked with commercial CAD/CAM software is CREO elements/pro [11]. This integration allows to hide design features which are, e.g., not feasible for a certain production volume [11] or allow the designer to obtain feedback on the (financial) impact of a certain material choice in real-time [4].

How such measures like DfM feature libraries can be implemented and how they are adopted by the organization depends to a large part on the product design process in use. A purely sequential approach puts a limit on attempts to reduce overall product cost [3]. DfM offers the opportunity to extend the sequential approach by connecting (inter-)related processes and boost information and knowledge exchange along the value chain.

Even though DfM offers a lot of benefits, there are also challenges to overcome. Utilizing DfM may include the potential for friction within the organization since the application requires designers and engineers to work together in interdisciplinary teams [4]. Whether this presents a challenge or not, depends strongly on the organization and how the interdisciplinary interaction is established. Anderson et al. identified different organization success factors of DfM. Among others these are:

- cross-functional product development teams
- existing links between design and production departments
- forum for communication, etc..

Anderson et al. also derived process related success factors:

- usage early in the design process
- use of checklist, etc. [7].

In this paper DfM is understood as a rather loose framework and more of a philosophy to consider knowledge, information or data from manufacturing as input for design decisions. The goal of DfM is understood in this context to realize manufacturing process and product improvements, e.g., in terms of quality following the perspective of Gonçalves-Coelho et al. [12].

After this brief introduction to DfM, in the following the product state concept as a means of analyzing a manufacturing process sequence with the goal of identifying relevant parameters, so called state drivers is introduced.

2.2. Product State Concept

The product state concept derives from a holistic perspective on the manufacturing process sequence as a system. The product state concept is a method to comprehensively describe a product by its state along a complete manufacturing programme. A core mechanism of this concept is to describe a product's state along its manufacturing process chain by a set of relevant state characteristics, the so-called state drivers [13]. In Fig. 2 a simple manufacturing programme is depicted and illustrates the different states of the product along the manufacturing process chain.

A major aspect within the identification of those state drivers was found to be process intra- and inter-relations. Inter-relations describing relations between processes, e.g., machining and heat treatment, intra-relations referring to relations within a process itself [14]. As of today, a comprehensive mapping of the necessary process intra- and inter-relations is not applicable in most manufacturing systems due to several factors. Among those factors are:

- lack of sufficient knowledge and transparency for most manufacturing process sequences with regard to process intra- and inter-relations
- time and effort needed to map the process intra- and inter-relations

challenge of low adaptability to changes of product, process and environment [6].

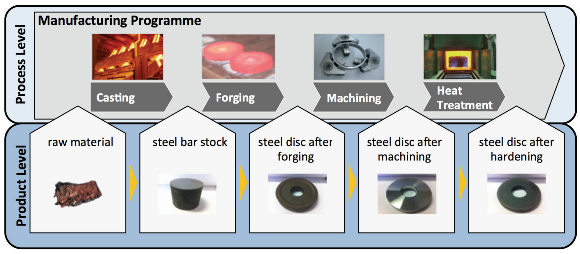

Fig. 2. Progressing product state along a manufacturing programme

To overcome these challenges, modern machine learning techniques show promising results. In order to include these important but only implicitly known process intra- and inter-relations, in as an extension of the product state concept, supervised machine learning is applied. Utilizing a Support Vector Machine (SVM) based feature ranking [15] on proceeding product and process state information allows identifying relevant state drivers for the manufacturing process sequence of a product.

The ranking can be applied at certain points of the developing state along the process sequence. Developing describes the enrichment by accumulated product and process data with every manufacturing process or operation. In other words, depending on the development of the growing state vector. This has the advantage that the importance of the state drivers can be observed at different times during the manufacturing program.

Once identified, the knowledge about the state drivers of the manufacturing process sequence allow for a specific optimization, monitoring and control.

However, this information could also be beneficial for other parts of the process from ideation to delivery to the final customer. The question whether knowledge of these state drivers may be beneficial for designers in the spirit of DfM is the focus of this work. In a more general sense, as state drivers represent in depth manufacturing knowledge, another question to be discussed is, whether more detailed manufacturing information and knowledge is applicable in DfM.

In the following section, the combination of the two concepts is elaborated, with a focus on the current ways of feeding manufacturing information and knowledge to the designers and a subsequent presentation of state drivers as a source of specific manufacturing information and knowledge.

3. State Driver Information to Support Design for Manufacturability

In this section, the combination of the two concepts with the goal to utilizing the specific knowledge of relevant manufacturing state drivers during the design phase is illustrated. To do so, first, currently employed information and knowledge streams from manufacturing to design are analyzed and elaborated as a basis for further investigation. The granularity and level of detail of these feedback streams provides a first indication if the compatibility of manufacturing state drivers and DfM may be promising. In a final step, manufacturing state drivers are envisioned and described in an applicable fashion in their role as a source of information for DfM.

3.1. Manufacturing Feedback to Design Phase

Before looking into the possibility to use very specific and detailed knowledge and information from the manufacturing phase in DfM, in this subsection, it is important to elaborate on the current practices.

A very popular and successful way to utilize feedback from manufacturing to design is through the previously mentioned DfM guidelines. Those can be provided by, e.g., libraries for CAD/CAM systems, other computer-based programmes, ontology supported systematic feedback [18] or as generic, paper-based guidelines to help the designers during decision-making [11]. These means of communicating feedback can be summarized as ‘indirect’.

Another way, manufacturing knowledge is utilized is through inter-disciplinary teams. In this case, the feedback is less guided. This can lead to a productive and close collaboration but also to friction within the team [4]. Other factors may play a role in this case too, like size of the company, location of manufacturing operations and design office, background of designers’, etc.. From a communication perspective, these measures characterize as ‘direct’.

Some researchers indicated that the use of artificial intelligence promises benefits for DfM practices [4] often in combination with established practices like the aforementioned guidelines [16]. However, there has been no generally adopted breakthrough to this point.

In summary, as of today, there are different approaches on feedback from manufacturing to design in a DfM sense. The level of detail, the degree of standardization and how the feedback it is incorporated in design and manufacturing processes depends on various factors like company size, organization, proximity of facilities for design and manufacturing, etc., just to name a few. In the next subsection, the level of detail of the knowledge and information is analyzed.

3.2. Level of Detail of Manufacturing Feedback to Design

As mentioned previously, a lot of DfM guidelines are derived empirically from past experience [10]. This indicates, that the level of detail, allowing for such a generalization is rather low. The input in such a case is more likely to consist of rather generic principals. This corresponds with the observation that DfM studies focus on certain manufacturing technologies, like machining [4], in order to derive ‘universal’ DfM guidelines.

Edwards [10] mentions that guidelines “range from high level and generic to low level and domain specific practice”. However, even this low level, domain specific information is still not on an individual product left alone parameter level which is the case when utilizing state drivers.

Influence on the level of detail is the means of communicating the manufacturing knowledge and information to designers. In cases process engineers work closely together in inter-disciplinary teams, the level of detail may range from high (more generic) to very low (more individual).

Giachetti [17] discusses an information model of DfM. The different information models for design and manufacturing increase the level of detail for manufacturing information and knowledge feedback along the product realization process from generic down to the individual product/process related information. This approach brings together the different goals and perspectives of DfM in a structured way and theoretically integrates the different level of details from an ICT perspective. Based on this, the rather detailed and individual source of information for DfM in form of manufacturing state drivers seems applicable. In the next subsection, this is presented in greater detail.

3.3. State Drivers as a Source of Information for DfM

Manufacturing state drivers are relevant parameter with a strong influence on a certain target value, e.g., product quality. Being derived through a comprehensive analysis of the specific manufacturing sequence, they allow for targeted monitoring and optimization efforts as a means of improvement. As the underlying product state concept takes not only explicit knowledge and information into account but also implicit process and product intra- and inter-relations. The identified state drivers serve also as an indication where further, in-depth analysis of the process may be beneficial.

With the objective of utilizing this knowledge and information in the design phase following the DfM philosophy, the benefit of using state drivers is not directly evident. The main limitations are discussed in the following section.

State drivers indicate critical points of manufacturing for a certain target measure. If this information is provided to the responsible designers in a way, that they can adjust the product design accordingly, critical situations during manufacturing may be avoided.

Thinking this further, in a next effort to further the optimization, the manufacturing data of the manufacturing process of the adapted product can be analyzed again. Adapted in this case means the product resulting from the new design inspired by the manufacturing feedback. The result may be a different set of state drivers as the critical points may have shifted due to the adjustments. In the end this could lead to a continuous improvement effort. This is depicted in the following Fig. 3.

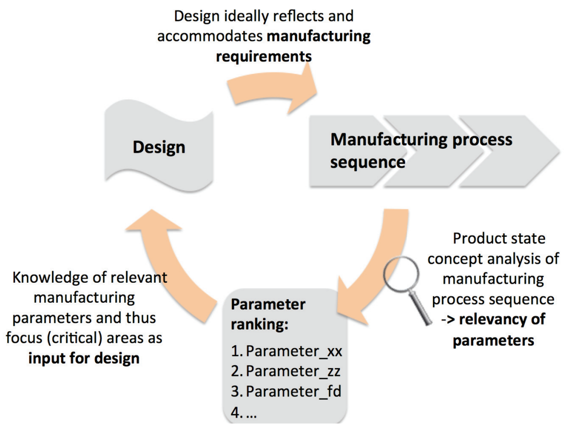

Fig. 3. Illustration of the continuous feedback loop and improvement effort

In this section, the theoretical applicability and potential benefit of a utilization of state drivers in DfM was presented. The following section discusses the requirements of an application, the potential benefits and finally the limitations of the approach.

4. Discussion

In this section the previously introduced combination of the product state concept with the DfM philosophy is critically discussed.

4.1. Requirements of application

There are several requirements that need to be considered in order to apply the proposed concept. Among those are that the organization must have access to, be able to and also willing to share data and information. Ideally, design and manufacturing are in close physical proximity or at least within the same organizational roof. In cases of outsourced manufacturing operations, getting access to the needed, detailed manufacturing data that allows the application of the product state analysis may cause problems. In the same direction the problem of capturing the needed granularity and quality of data along the manufacturing process sequence is still proving to be challenging for many companies [6].

Today, only selected industries have the means to provide data in the level of detail needed. Among those are blade manufacturers (aviation), semiconductor manufacturing and selected manufacturers of highly stressed products like gear wheels. As those are set in highly competitive environments, they have often high thresholds before they release and share data.

On the other hand, the designers need to establish a better understanding of the manufacturing processes to being able to utilize the additional input in a beneficial way. This is necessary because the information and knowledge provided through the state drivers is likely to be more detailed and not as generic and thus not as easy to grasp. As state drivers are derived from data in a product and process specific manufacturing environment, the universal applicability cannot be assumed.

4.2. Benefits of method application

Besides the requirements, there are potential benefits of providing more detailed manufacturing information to the designers. In general, if the manufacturing process and the identified state drivers can be abstracted enough, the derived knowledge may be interpreted and utilized to some degree in new designs and further the success of design for manufacturing.

Introducing the opportunity to narrow the focus of DfM down to a more detailed and specific, product instance centric level can be also regarded as a potential benefit. This might present a chance to move forward from the established, generic DfM approach. It could support the move towards a more case-specific connection between manufacturing and design which is propagated by, e.g., the Product Lifecycle Management (PLM) approach. It could also lead to a better utilization of today's advanced artificial intelligence and machine learning techniques.

Especially with ever-increasing customer requirements bringing both design and manufacturing on the edge of what is possible, a further integration of both departments seems necessary. If design has the chance to improve manufacturing process quality by adapting to specific information, the final product quality may become better and the (expensive) need for in-process adjustment and subsequent failure search may be reduced.

Giving the designers specific input regarding where in the manufacturing process sequence the critical points are, provides also a chance to establish a learning culture within the organization. However, that is probably not applicable for all organizations and organizational settings.

4.3. Limitations of method application

Besides the previously elaborated requirements and potential benefits of the proposed combined concept, there are several limitations to be considered which are illustrated in the following.

The probably most significant limitation is that the applicability of the concept is not directly applicable for 'new' product design and development. Ideally the method is applied in a setting where the to-be-developed product is based on a previous generation and/or has many similar characteristics to an existing product. This is based on the low level of detail which is directly linked to the individual process and product. As mentioned in the benefits, this limitation may also have a positive side in inspiring new developments in DfM.

Another limitation is the required resources to implement a system like that. Especially at the beginning, with little experience in that matter the cost (time and money) may proof rather high compare to the realized benefit. Corresponding with the requirements regarding data capturing and sharing, in this case it might make sense to implement this at first only in companies which already use the product state concept (or comparable analysis tools) for manufacturing optimization already.

5. Conclusion and Outlook

In this paper, the general idea of expanding Design for Manufacturing (DfM) by increasing the level of detail and individual nature of manufacturing data, information and knowledge is discussed. More specifically, the combination of the product state concept as a means of identifying relevant state drivers of a manufacturing programme with the DfM philosophy is presented.

In summary, the results are ambivalent. On the one hand side, the increasing pressure on design and manufacturing from demanding customers and the global competition forces companies to evaluate every opportunity to optimize their processes. Utilizing more detailed, even product-instance specific manufacturing information and knowledge to incorporate within DfM is a valid approach that seems promising and needs to be analyzed more closely.

However, given the currently established DfM methods which compromise to a large extent of generic guidelines and CAD/CAM implementations, a large step towards too detailed information and knowledge may be asking too much from an organization and individuals at this point in time.

Exceptions are selected industries and companies where designers and (process) engineers work closely together and a common understanding is part of the culture. In such circumstances, a working framework like the product state concept seems promising to achieve continuous improvements along the value chain.

In a next step, the plan is to discuss the ideas put forward in this conceptual paper with representatives of selected companies that resemble the previously stated requirements. Together with industry, the concept shall be applied and evaluated by its performance in a case study. Furthermore, the possibility to derive generic guidelines from the identification of state drivers and the implication of the DfM applicability shall be researched.

Acknowledgements

Part of this research has been funded under the EC 7th Framework Programme, in the context of the LinkedDesign project (http://www.linkeddesign.eu). The authors wish to acknowledge the Commission and all the LinkedDesign project partners for a fruitful collaboration. Finally, the authors would like to thank the reviewers for their comments that helped to improve the manuscript.

References

[1] Wang, Y. Combining data mining and Game Theory in manufacturing strategy analysis. Journal of Intelligent Manufacturing 2007:18;505–511.

[2] Jansen-Vullers, M. H., van Dorp, C., Beulens, A. J. M. Managing traceability information in manufacture. Journal of Information 2003;23:395–413.

[3] Driscoll, M. O. Design for manufacture. Journal of Materials Processing Technology 2002:122;318–321.

[4] Kuo, T.-C., Huang, S. H., Zhang, H.-C. Design for manufacture and design for "X": concepts, applications, and perspectives. Computers & Industrial Engineering 2001:41;241–260.

[5] Sandberg, M. Design for manufacturing using knowledge engineering. Lulea University of Technology. Dissertation. 2007.

[6] Wuest, T., Irgens, C., Thoben, K.-D. An approach to monitoring quality in manufacturing using supervised machine learning on product state data. Journal of Intelligent Manufacturing 2014:25;1167–1180.

[7] Andersson, F., Hagqvist, A., Sundin, E., Björkman, M. Design for Manufacturing of Composite Structures for Commercial Aircraft – The Development of a DFM Strategy at SAAB Aerostructures. Procedia CIRP 2014:17;362–367.

[8] Vajna, S. Wissensnutzung in der Produktentwicklung. 12. Symposium "Design for X" 2001;1–7.

[9] Schmitt, R.; Pfeifer, T. Qualitätsmanagement: Strategie, Methoden, Technik. 4th ed. Munich: Hanser; 2010.

[10] Edwards, K. Towards more strategic product design for manufacture and assembly: priorities for concurrent engineering. Materials & Design 2002:23; 651–656.

[11] Hoque, a. S. M., Halder, P. K., Parvez, M. S., Szecsi, T. Integrated manufacturing features and Design-for-manufacture guidelines for reducing product cost under CAD/CAM environment. Computers & Industrial Engineering 2013:66;988–1003.

[12] Gonçalves-Coelho, a. M., & Mourão, A. J. F. Axiomatic design as support for decision-making in a design for manufacturing context: A case study. International Journal of Production Economics 2007:109;81–89.

[13] Wuest, T., Klein, D., Thoben, K. State of steel products in industrial production processes. Procedia Engineering 2011:10;2220–2225.

[14] Wuest, T., Klein, D., Seifert, M., Thoben, K.-D. (2012). Method to describe interdependencies of state characteristics related to distortion. Materialwissenschaft Und Werkstofftechnik 2012:43;186–191.

[15] Guyon, I., Weston, J., Barnhill, S., Vapnik, V. A gene selection method for cancer classification using Support Vector Machines. Machine Learning, 2002:46;389–422.

[16] Devireddy, C. R. Feature-based modelling and neural networks-based CAPP for integrated manufacturing. International Journal of Computer Integrated Manufacturing 1999:12;61–74.

[17] Giachetti, R. E. A standard manufacturing information model to support design for manufacturing in virtual enterprises. Journal of Intelligent Manufacturing 1999:10;49–60.

Molcho, G., Zipori, Y., Schneor, R., Rosen, O., Goldstein, D., Shpitalni, M. Computer aided manufacturability analysis: Closing the knowledge gap between the designer and the manufacturer. CIRP Annals - Manufacturing Technology 2008:57;153–158.