INTERNATIONAL DESIGN CONFERENCE - DESIGN 2008
Dubrovnik - Croatia, May 19 - 22, 2008.

MECHATRONIC-ORIENTED DESIGN OF AUTOMATED MANUFACTURING SYSTEMS IN THE AUTOMOTIVE BODY SHOP

J. Kiefer, T. Baer and H. Bley

Keywords: design methodology, digital factory, mechatronic

1. Introduction

After years of rising profits, companies in the automotive industry are currently confronted with stagnant or even diminishing markets. Due to the resulting competition for key market shares, car manufacturers are engaged in an innovation race characterized by core demands: A soaring number of product variants with many product derivates as well as decreasing innovation and model cycles.
These market-driven challenges particularly affect the processes within the production-related project phases both of production design and ramp-up. On the one hand, these processes become increasingly more complex and, in consequence, more error-prone. On the other hand, in order to gain important market shares, the time for production design and ramp-up processes has to be cut to the bone. In this context, e.g. Reithofer pointed out in an interview: “If we can reach the maximum production capacity in three instead of nine months, it means cash for the company” [Reithofer 2002]. This cost-driven demand for faster ramp-up processes is underpinned by the constantly rising number of ramp-ups due to enhanced innovations and increasing market launches of new products and product variants.
The rising complexity as well as the market-driven demands towards faster design and ramp-up processes contribute substantially to the fact that today approximately “two thirds of product ramp-ups in Europe miss the economical or the technical goals” [Berger 2003]. Thereby, as published in [Denkena 2006], a majority of the ramp-up-referred problems can be attributed to faults, lacks and de-lays of the production design process. In this context, the biggest error sources are both cross-domain misunderstandings due to an insufficient documentation and change management and technical faults that are mostly caused in the field of electrical and/or control engineering. These numerous faults that have to be solved under high time pressure during the production ramp-up inevitably lead to suboptimal soft- and hardware solutions of the respective production facilities.
To master the described conflict situation of designing and commissioning more complex production facilities in shorter design and ramp-up periods, some local approaches have already been developed. However, all the different existing solutions are limited largely to partial aspects of the whole production creation process. In this context, for example, the so-called digital factory is such a solution that is increasingly entering into the operational practice – especially in the automotive area [VDI 2007]. Yet, at present, both the methodical and software-technical solutions of the digital factory have still some substantial deficiencies: On the one hand, there is no seamless, digital design solution. On the other hand, the existing partial solutions can only be used to develop important cost, time, and quality potentials related to the pure mechanic-oriented design process of automated manufacturing systems. Yet, the mechanics represent only a proportionally decreasing part of the functionality of production facilities. In contrast, both the electrical and the control-technical portions of mechatronic manufactu-

ring systems that represent the main cause for delayed production ramp-ups will be increased continuously in the future.
However, in the context of the digital factory, the electrical as well as the control-technical aspects and especially the interface between the mechanical and the electrical/control design are only considered rudimentarily. Currently, both methodical and software-technical solutions targeting a seamless, cross-domain design process chain as a foundation for fast and robust ramp-ups are still missing.
Usually, design methodologies consider the development of consumer products (e.g. car modules). In the digital factory products, processes (e.g. welding processes) and resources (e.g. manufacturing systems) are distinguished. This paper focuses on the design process of production resources.

2. Methodical and software-technical requirements

Based on the deficits described in the chapter above, there is a number of demands that is to be made towards the future production-related design process. Thereby, the superordinate goal is in the realization of accelerated production design and ramp-up processes with the result of higher soft- and hardware maturities of the respective production facilities not only at SOP (start of production) but also during the running production (especially after product-related integration processes). To meet these addressed challenges, new design methodologies within the production creation process are required. Base of this design methodology is the meeting of the methodical requirements specified in Table 1 whose characteristics were determined by practice-oriented investigations. Furthermore, the software-technical implementation of the new design methodology also implies the existence of applicable IT systems that have to be adapted to the listed methodical requirements. Subdivided into user- and company-related requirements, the practice-oriented demands on these IT systems and/or the needed IT infrastructure can also be taken from Table 1.

Table 1. Methodical and software-technical requirements

Methodical requirements	Software-technical requirements
• Promotion of SE (simultaneous engineering) (early integration of electrical/control design in the overall design process) • Improvement of cross-domain collaboration (especially between mechanical and electrical/ control design) • Uniform and seamless documentation and change management • Consideration of cross-domain standardization • Automated generation of cross-domain documentation and software • Validation and optimization of software before real commissioning • Consideration of the overall production lifecycle • Consideration of existing IT systems	*Requirements from user side:* • Simple and intuitive operability (usability), stability, performance • Automatism for assistance (e.g. for automated software generation) • Seamless data flow within the used IT infrastructure • Transparent information structuring *Requirements from company side:* • Integration in existing system landscapes (open system interfaces) • Adaptability to future developments, modularity • Profitability (positive benefit-cost relation)

Yet, the sustainable success of new design strategies does not only depend on the meeting of methodical and software-technical requirements. In additions to that, company-specific organizational basic conditions (e.g. responsibility areas, qualification profiles) have to be regarded while developing new design methodologies. These aspects bear an essential part in introducing newly developed design methodologies in the operational practice. For this reason, another requirement is in the development of an adequate strategy that supports a cost-effective introduction of the respective design solution.

Considering the identified requirements, at Daimler Research & Development a new, mechatronic-oriented design methodology was developed. Currently, this new design strategy is at the transition from the research stage to the operational practice. So, comparing with the technology lifecycle model published in [Gausemeier 2001], the newly developed design methodology can also be regarded as a so-called key methodology that will be an important competitive advantage in the future.

In the following chapters, the main aspects of the mechatronic-oriented design methodology as well as its software-technical implementation and/or the proposed IT infrastructure are presented. Thereby, the most important characteristics of the new production-related design approach are illustrated using the development process of automated manufacturing cells in the automotive body shop.

3. Mechatronic-oriented design methodology

When comparing the use of today's design strategies and existing approaches to improve the cell-specific development process, the mechatronic-oriented design methodology is based on some fundamental innovations. These innovations refer particularly to the use of standardized mechatronic resource components that bundle all relevant mechanical, electrical and control-technical resource data and that are made available to the related departments in the form of a mechatronic resource library. As depicted in Figure 1, using these newly configured resource objects, the cross-domain and meshed development of a mechatronic resource model takes place. Related to the overall lifecycle of automated manufacturing systems, this resource model has a diverse role: During the cell-specific design process it serves as a seamless, interdisciplinary documentation platform, which additionaly forms the basis for the automated generation both of standardized working documents and cell-specific control programs. Due to its control-technical contents, the mechatronic resource model also has the function of a validation and optimization platform of the developed control software and the used factory information systems. This new validation process of "virtual commissioning" does not only form the basis for a sustainable improvement of the production-related design process. Moreover, it represents particularly the basis for the accomplishment of accelerated and more robust ramp-ups resulting in higher degrees of maturity and lower overall project costs. In the following sections, the most important aspects and interrelations of the mechatronic-oriented design process are presented in more detail.

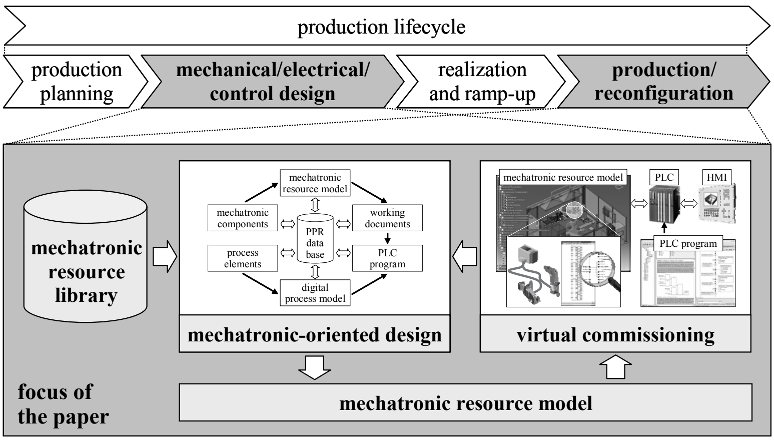

Figure 1. Focus and aspects of the mechatronic-oriented design methodology

3.1 Contents and preparation of mechatronic resource components

As depicted in Figure 2, there is state-of-the-art that resource components (e.g. clamps, robots) used in current design processes are described by technical, organizational, economical and mechanical data. In this way, for example it is possible to check and optimize the mechanical interrelation of the different cell components by DMU analyses and/or robot movements can be simulated using 3D-oriented feasibility analyses. Beside this "geometry-oriented" working method, electrical and control engineers have a quite differentiated view on the same resource components. As written in [Gausemeier 2000], their way of thinking is characterized by a "function orientation". Within these domains, resources are described for example by their electrical, pneumatic or hydraulic connections, their signal information or in form of control-referred PLC function blocks (PLC: programmable logic controller).

The newly configured mechatronic resource components unite all the relevant domain-specific resource data. In this way, they can also be used along the complete design process. An overview about the different resource data that are integrated in favor of a seamless digital design process in such mechatronic resource components can be taken from Figure 2. Thereby, it is to be noted that the mechatronic components do not have to consist inevitably of all illustrated data of Figure 2. In fact, for each individual component class – as for example for clamps, valves and robots – a class-specific configuration takes place which consists of subsets of the illustrated resource data. Moreover, to realize a design and validation process as efficient and realistic as possible, both company-specific standards (e.g. certain name conventions and interfaces) and possible resource-specific interactions (e.g. clamps-valves dependencies) are to be considered directly with developing the mechatronic component classes.

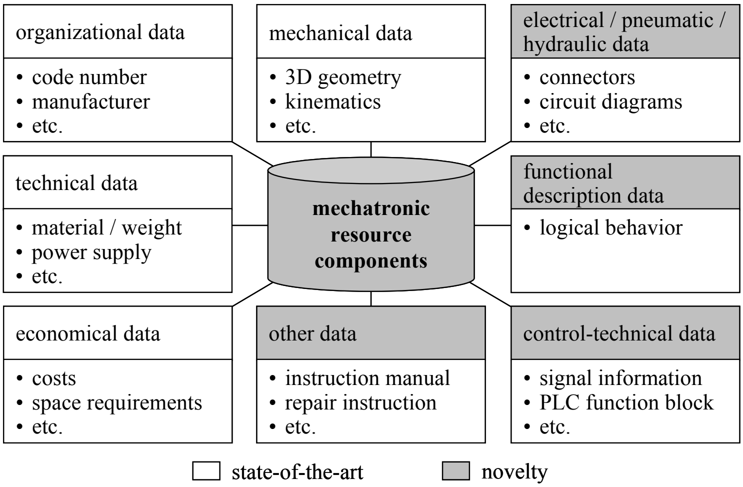

Figure 2. Contents of a mechatronic resource component

In order to allow a company-wide access to the standardized resource objects, all these mechatronic units are made available to the related departments in the form of a centrally organized mechatronic resource library. As depicted in Figure 3, typical body-in-white resources that are stored in such a library are for example mechatronic robots, clamps, valves, sensors, safety gates and inverters. After taking the needed project-neutral resource objects from the library, the responsible department (e.g. the Tooling Design) only has to tailor them to their special installation situations in the respective manufacturing cell.

3.2 Development of a mechatronic resource model

Based on the newly configured mechatronic resource components, the overall mechatronic cell model is developed. In contrast to today's resource models, this 3D-oriented data model does not just solely represent the mechanical or the electrical or the control-technical portion of a real manufacturing system. Instead, the mechatronic resource model forms a holistic, integrated view of the three domains mechanics, electrics, and control engineering. With such a cross-domain data model, the different departments involved in the design process are able to work simultaneously and networked, using up-to-date, complete, and consistent data sets with the result of a higher design transparency.

However, the advantages of using such a mechatronic resource model represent only one side. On the other side, the unification of the different resource data also leads to a larger data volume as well as to a rising total complexity. For this reason, with the development of the mechatronic resource model, clear, uniform and obligatory resource-related data structures are to be kept. The identified practice-oriented demands on such a cell-specific resource structure are:

- Support of the mindsets of the different production engineering departments
- Development of simple, function-oriented and archivable data structures
- Grouping of all single parts and assemblies that accomplish a common movement (more efficient simulation studies with higher performance)
- Realization of task-specific views on the overall resource model (controlled complexity)

Considering these requirements, a resource-related data structure was developed whose result is represented in Figure 3. Therefore, in accordance with the structure of real manufacturing cells, the mechatronic resource model consists of different levels. The mechanical single parts form the lowest structuring level. In favor of an efficient accomplishment of simulation studies, all parts that implement a common movement are combined into so-called subgroups. In a further level, function groups bundle all subgroups as well as the pre-configured, standardized resource components taken from the mechatronic resource library, which fulfill a defined task as a functional construction unit. An example for a typical function group is a clamping group that normally consist both of a mechatronic clamp and of several mechanical subgroups. Using these modular developed function groups so-called main groups (e.g. complete fixtures, robot units) are developed. In a next structuring level, these main groups are finally brought together to the cell-specific mechatronic resource model.

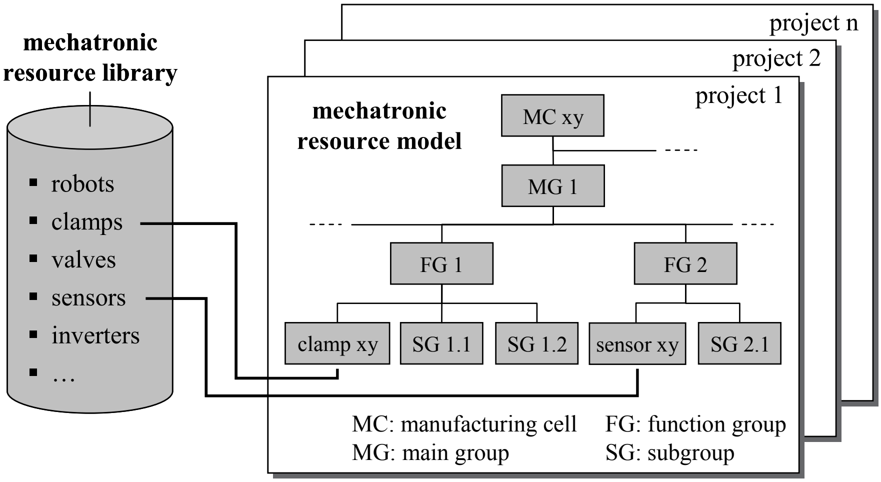

Figure 3. Data structure of a cell-specific mechatronic resource model

Finally, the mechatronic cell model with its underlying resource components does not only have the function of an interdisciplinary communication and documentation platform in the cell-specific design process. Focussing the overall lifecycle of a manufacturing system, this data model also forms the basis for the automated generation of standardized working documents (e.g. signal lists) and the accomplishment of a virtual commissioning. Thus, the validation method of virtual commissioning can not only be used profitably before first ramp-up processes. Particularly, it can also be accomplished profitably before re-ramp-up processes due to product-, process- or resource-related integration processes during the running production. More detailed information regarding the concept, the process integration and the profitability of a virtual commissioning are given in [Kiefer 2007].

4. Software-technical implementation

The software-technical implementation of the mechatronic-oriented design methodology presented in the chapter above requires an appropriate IT infrastructure. In this section, such an architecture is introduced which describes the interrelation of the needed information systems. As written in [Schaeppi 2005], in this context two kinds of information systems are to be differentiated: authoring systems and data management systems. An overview about the needed IT systems, their individual interrelations as well as data flow between these systems is given in Figure 4.

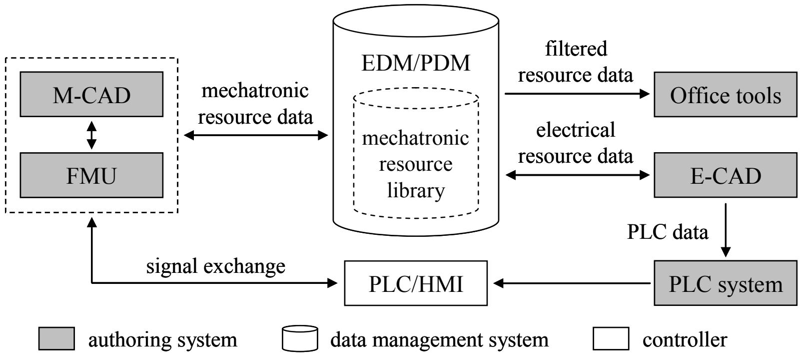

Figure 4. Supporting IT infrastructure

Base of the newly developed design methodology are mechatronic resource units which are developed using appropriate M-CAD (mechanical CAD), E-CAD (electrical CAD) and FMU (functional Digital Mock-Up) systems. According to [Krause 2007], FMU is "the logical extension of the geometry-oriented DMU with the digital representation and investigation of product functions. By the close integration of the simulation models and the appropriate tools, both the representation and the simulation of behavior and usage properties of the digital product are made possible". Basically, FMU tools are primarily used in the design and validation process of consumer products, but they can also be adapted to the functional validation processes of mechatronic manufacturing systems in the digital factory. To ensure a maximum efficiency with the development of the mechatronic resource components and the mechatronic resource model, the used IT systems have to meet some essential requirements. These refer particularly to the existence of open system interfaces (e.g. as base for company-specific system configurations and/or to realize a seamless, cross-domain digital design chain) and to the aspects of usability, stability and system performances. Although there is much progress in the last few years, at present, the biggest needs for actions are still:

- the seamless integration of M-CAD, E-CAD and FMU systems
- the possibilities of EDM/PDM systems in handling mechatronic resource data
- the seamless interaction between CAx applications (e.g. FMU) and data management systems

Using the mechatronic resource model, the validation of the cell-specific software programs (e.g. PLC programs) and/or the interaction between the mechanical, electrical and control-technical components takes place. To accomplish such a virtual commissioning, in a first step, the mechatronic resource model must be imported from the EDM/PDM system into the used FMU tool. Next, in order to ensure a signal exchange between the digital resource model on the one hand and the real control systems on the other hand, the digital model must be connected with the respective control equipment via respective system interfaces (e.g. OPC: OLE for process control). At present, there are at least three comercial production-oriented FMU systems which enable the accomplishment of a virtual commissioning: DELMIA Automation V5 (DELMIA), Process Simulate Commissioning (UGS) and WinMOD (Mewes & Partner). Due to their different origins, these innovative IT systems have individual strenghts and weaknesses whose descriptions and evaluations are presented in [Kiefer 2007].

5. Practice-relevant introduction aspects

In general, new design methodologies can be introduced into the operational practice using different introduction strategies. Due to the modular structure of the newly developed design methodology, a gradual introduction of the new design solution in the form of a so-called "germ cell strategy" is recommended. This means that the mechatronic-oriented design methodology should not be applied to all automated manufacturing systems and/or all manufacturing areas in an automotive factory at once.

Instead of this, an appropriate “germ cell” in the form of one selected manufacturing system is to be specified on that basis the newly developed design and validation methodology is to be applied to. In the sense of a continuous improvement process, the won experience of this pilot study has to be included in the further detailing of the methodology before it is gradually used for designing all automated production facilities.

A basic condition for the operational use of a new solution is its profitability. Basically, this key factor can be determined by the comparison of the solution-associated benefits and the additional costs. Thereby, in the sense of a “lifecycle performance”, not only the yield which can be realized at short-term but especially the overall production lifecycle must be considered. As illustrated in Figure 5, the profitability of the mechatronic-oriented design methodology is related considerably to the extents, the degree of standardization and the continuous maintenance of the mechatronic resource library and its included components. The more standardized and reusable mechatronic components the resource library contains, the less additional expenses for designing the mechatronic resource model have to be spent and/or the higher is the profitability of the new design methodology. In this context, it is advisable to adapt and extent the mechatronic resource library in a continuous way. For example, practical experiences and knowledge as well as used special components of preceded projects are to be collected systematically and should be integrated in the existing resource library. Based on these documented project experiences both the additional modeling expenses for subsequent projects can be reduced continuously and the design quality can be improved sustainably.

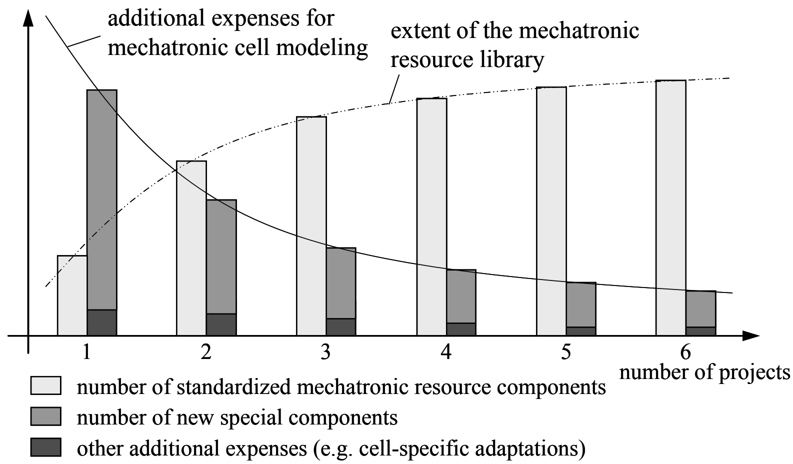

Figure 5. Reducing additional expenses for mechatronic cell modeling

A further important success factor in the context of developing and introducing a new methodology is the early consideration of its users and/or the consideration of the entire “socio-technical” system. To this, Eason explains that new methodologies or technical systems “(…) have to engage with the complex world of tasks, procedures and culture within the organization; they have to be part of a working socio-technical system“ [Eason 2001]. Thus, the introduction of the mechatronic-oriented design methodology has also to be accompanied by flanking measures in the field of work psychology. More detailed information regarding this topic can be taken from [Schulze 2005].

6. Summary and outlook for further research activities

Accelerated and more robust ramp-up processes of highly complex automated manufacturing systems based on shorter design cycles are a key demand in the automotive industry. To cope with these market- and/or cost-driven challenges, new solutions for production design and ramp-up processes are required. Thus, a mechatronic-oriented design methodology is introduced, taking the example of the development process of automated manufacturing cells in the automotive body shop. Apart from the presentation of the most important characteristics of the newly developed methodology, its software-technical implementation as well as some practice-relevant introduction aspects are also illustrated.

So far, a majority of the presented aspects of the mechatronic-oriented design methodology have been implemented into an existing IT environment of the digital factory successfully. At present, the seamless implementation is being verified and evaluated critically using real practical scenarios from the automotive body shop. Although much progress has been made in the field of mechatronic-oriented production design, the following questions still remain to be addressed in further research activities:

- Which degree of detail should the mechatronic cell model possess ideally, so that it contains as much as possible cross-domain resource data on the one hand and that it also meets the demands on profitability on the other hand?
- To what extent do the internal task distributions and responsibility areas need to be adapted to the new design methodology and/or what kind of effects will the introduction of this integrative design methodology have regarding the future interaction between the OEMs (original equipment manufacturer) and their suppliers?
- To what extent can this production-oriented design methodology be adapted to the product development process (e.g. to mechatronic components in consumer products) and/or what basic conditions have to be considered to effect this adaptation?

References

Denkena, B., Ammermann, C., Kowalski, P., "Ramp-up time reduction in high volume production", proceedings of the 4th International Conference on Manufacturing Research (ICMR2006), Liverpool, 2006.

Eason, K., "Changing Perspectives on the organizational consequences of information technology", Behaviour & Information Technology, no. 20 (5), 2001, pp. 323-328.

Gausemeier, J., Ebbesmeyer, P., Kallmeyer, F., "Produktinnovation", Carl Hanser Verlag, Munich, 2001.

Gausemeier, J., Lueckel, J., "Entwicklungsumgebungen Mechatronik – Methoden und Werkzeuge zur Entwicklung mechatronischer Systeme", HNI Schriftenreihe, no. 80, university of Paderborn, 2000.

Kiefer, J., "Mechatronikorientierte Planung automatisierter Fertigungszellen im Bereich Karosserierohbau", Schriftenreihe Produktionstechnik, no. 43, Saarland university, 2007.

Krause, F.-L., Franke, H.-J., Gausemeier, J., "Innovationspotenziale in der Produktentwicklung", Carl Hanser Verlag, Munich, 2007, pp. 117-128.

Reithofer, N., "Menschen sind für mich unverzichtbar", VDI nachrichten, no. 23, 2002, p. 11.

Berger Roland, "Zu hohe Kosten bei Fahrzeuganläufen", Automobilwoche, no. 25, 2003, p. 21.

Schulze, H. et al., "Human-centered Design of Engineering Applications – Success Factors from a Case Study in the Automotive Industry", Human Factors and Ergonomics in Manufacturing, no. 4, 2005, pp. 421-444.

Schaeppi, B., Andreasen, M. M., Kirchgeorg, M., Radermacher, F.-J., "Handbuch Produktentwicklung", Carl Hanser Verlag, Munich, 2005, pp. 419-448.

Verein Deutscher Ingenieure (Hrsg.): VDI-Richtlinie 4499, Blatt 1: "Digitale Fabrik – Grundlagen", VDI-Verlag, Duesseldorf, 2007.

Dr. Jens Kiefer
Daimler AG, Group Research & Advanced Engineering
Department: Function and Production Modeling
Wilhelm-Runge-Straße 11, 89013 Ulm, Germany
Tel.: +49 (0)731 - 505 - 2459
Fax.: +49 (0)731- 505 - 4400
Email: jens.kiefer@daimler.com