INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

LEAN DIGITAL VALIDATION METHODS WITHIN THE DESIGN PROCESS OF AUTOMATED ASSEMBLY SYSTEMS IN AUTOMOTIVE INDUSTRY

J. Kiefer

Keywords: lean digital validation methods, design process, automated assembly systems, automotive industry

1. Introduction

Due to the hard-fought competition for global market shares, car manufacturers (OEMs) are currently engaged in an innovation race characterized by the following core demands:

- Soaring number of product variants with many customer- and market-oriented product derivates
- Increasing time pressure due to decreasing innovation and model cycles
- Increasing product complexity due to increasing quality demands of the customers (e.g. powerful and reliable driver assistance systems, online services, green technologies)

These market-driven challenges inevitably affect all phases of the overall product lifecycle, especially the project phases both of production engineering and production ramp-up. On the one hand, the considered processes become increasingly more complex and, in consequence, more error-prone. On the other hand, to gain important market shares, the time for production engineering and ramp-ups has to be cut to the bone. Last but not least, these challenges also lead to extensive changes of the production systems themselves: The production facilities become more and more flexible (as base for producing several product types into one production line), their lifecycles are getting longer and longer and the number of worldwide production ramp-ups will be continually rising – especially after integration processes during running production.

The field of automated assembly systems, e.g. the car marriage, is particularly affected by these production-related challenges. In this context, there are different approaches, strategies and goals in order to remain competitive on the hard-fought market such as:

- Reduction of engineering, ramp-up and equipment costs
- Highest engineering quality as base both for shorter and more robust production ramp-ups and highest production quality
- Managing of product, process and resource complexity
- Seamless digital CAx process chain in the field of production engineering
- Seamless and more transparent integration of internal and external partners and suppliers

At Daimler, the development and operational use of lean digital validation methods takes a significant role to fulfill the listed goals above. This paper focuses on the use of these new developed lean digital validation methods within the design process of automated assembly systems. As depicted in Figure 1, the following digital methods are presented: Virtual engineering, virtual commissioning and physics-based analysis. Apart from the characteristics and interactions of these digital validation methods, this paper particularly illustrates their practical applications as well as their corresponding benefits. To do this in the most vivid way, the individual applications are demonstrated taking the design process of a real existing automated screwing station.

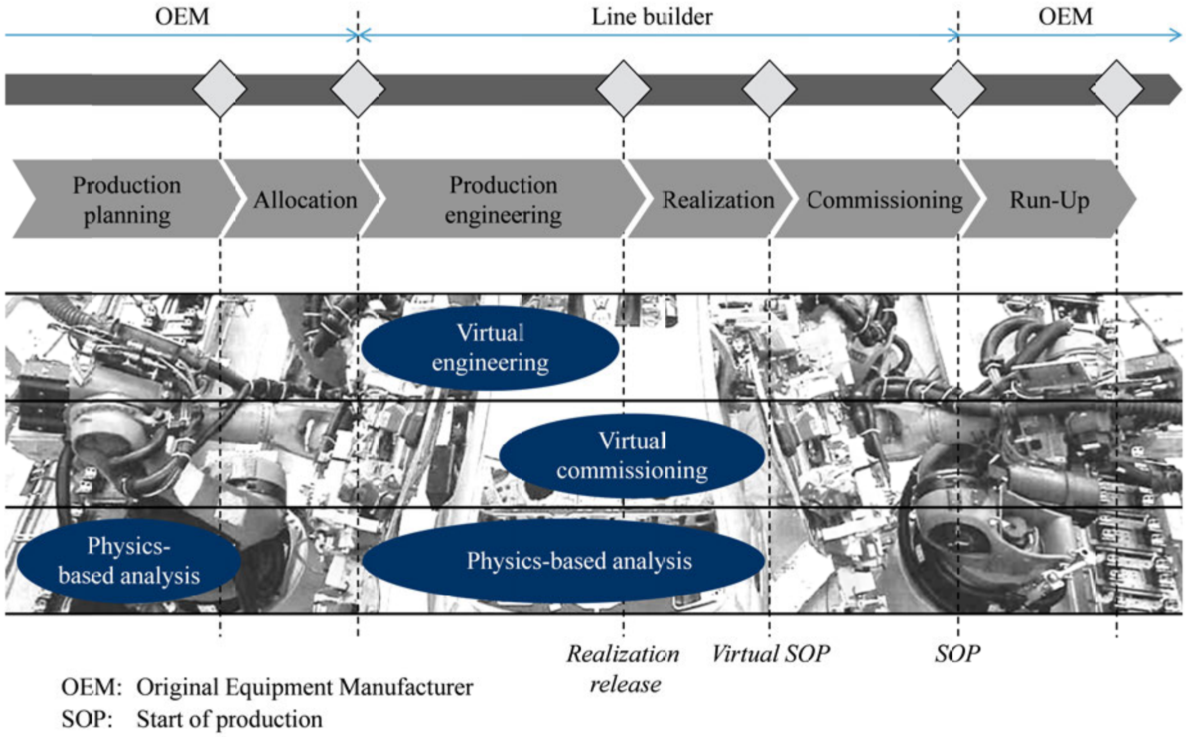

Figure 1. Lean digital validation methods within the production creation process

2. Lean digital validation methods in production engineering

In automotive industry, there is a wide range of validation methods that are used along the whole product creation process. In the context of this paper, validation methods are defined as methods to check and evaluate specific product-, process- or production-related quality characteritics. These quality characteristics refer both to qualitative characteristics as for example “no contacts” or “no collisions” and to quantitative characteristics such as “cycle time” or “hardware costs”. The goals of using validation methods are the guarantee of compliance with the quality demands on the one hand and the illustration of potentials for product-, process- or production-related optimization approaches on the other hand. In order to reach these goals in the most efficient and effective way, validation methods should always be used as early as possible in product creation processes according to the maxim of preventive quality management “avoiding errors instead of detecting and fixing errors in real production”. In general, validation methods can be divided into two main groups:

- Validation methods using real (hardware) prototypes
- Validation methods using digital (computer-based) models

As published in Bär [2013], digital validation methods have a continuous rising significance in automotive industry – especially within the project phase of production engineering. Due to economic and strategic issues, there is an ongoing trend towards less validations using hardware prototypes and towards more and more validations using digital simulation models. An overview regarding digital validation methods used in product and production engineering phases as well as corresponding IT tools and quality characteristics are portrayed in Table 1. While product-related digital validation methods (e.g. computer-based tolerance analysis) are well established and used in daily business, the situation in the field of production engineering, especially in the field of automated assembly systems, is differrent: Although the powerful benefits of using digital validation methods are well known in the head of the production planners and designers, they are still not comprehensively used in operational practice. Up-to-date, in the context of planning and designing automated assembly systems, the use of digital validation methods is still a topic that is only used by a very few simulation experts. Reasons for this phenomenon are for example the big complexity of current IT tools, the mostly big efforts in order to prepare the validation studies or the poor integration of digital validation methods in existing IT environments and organizational structures. Moreover, the line builders and further engineering suppliers who usually realize the design of the assembly systems by order of the OEM don't mostly possess the necessary IT tools due to their high costs or they don't have the required experience and competence in using the production-related digital validation methods in an economic way.

Table 1. Used digital validation methods in product and production engineering

No.	Digital validation methods	IT Tools	Quality characteristics
1	Packaging analysis	DMU/ VR applications	Installation space
2	Tolerance analysis	Tolerance simulation	Deviations, gap dimensions
3	Stress/ crash analysis	FEM simulation	Material stresses, deformations
4	Flexible parts analysis	FEM applications	Geometrical parameters
5	Material flow analysis	Material flow simulation	Cycle times, buffersizes
6	Ergonomics analysis	Ergonomics simulation	Assembly times, stresses
7	Robots analysis	Robots simulation	Motion paths/ times, locations
8	Virtual commissioning	FMU applications	PLC program characteristics

To improve the company and user acceptance in using digital methods decisively, at Daimler, lean digital validation methods within the design process of automated assembly systems are developed. In general, the core goal of lean is to provide perfect value for customers through a most efficient value creation process that is characterized by zero waste [Womack 2003]. Referring to this definition of Womack, lean digital validation methods can be characterized by:

- Value-focused methods and functionalities by concentrating on the "right" issues
- Highest efficiency (minimal efforts and maximal benefits) by using standards and automatisms
- Easy handling and reducing of complexity by user-oriented methods and tool design
- Seamless integration in existing IT environments by focusing on standardized data interfaces
- Easy integration in existing organizational structures

In the following, the lean digital validation methods of virtual engineering, virtual commissioning and physics-based analysis are illustrated both from scientific and industrial point of view.

2.1 Virtual engineering

At Daimler, in the context of automated assembly systems the method of virtual engineering is used to visualize and validate plant-specific process sequences, times (e.g. cycle times, machine times), movements, accessibilities, reachabilities and geometrical collisions considering any product variants based on intelligent simulation models of the respective production system. To prepare and accomplish these validation analyses in the most efficient way, one central method of lean management is mainly used: Standardization [Töpfer 2009]. Thus, the data inputs, the development processes of the required simulation models as well as the accomplishment of the digital validation studies are based on standardized data objects and standardized procedures such as:

- Standardized description and provision of all relevant product data (e.g. product variants)
- Standardized description and provision of process data (e.g. process types)
- Standardized procedure to develop plant-specific process sequences
- Standardized description and provision of resource (plant) data (e.g. resource structures)
- Standardized procedure to develop 3D CAD plant models
- Standardized procedure to link product, process and resource data
- Standardized accomplishment and documentation of the digital validation studies

As depicted in Figure 2, the core of virtual engineering are the 3D CAD models both of product(s) and resources (plant components) including kinematic data as well as the description of process sequences in a digital, evaluable way. The plant-specific process sequences are composed of pre-configured standardized assembly operations (e.g. loading, positioning or screwing operations) that are characterized by individual process attributes (e.g. names, times, degree of added value). To allow a company-wide access to these digital data objects, they are made available to the production planners and designers in the form of a centrally organized process library. In this way, a consistent planning and documentation procedure for all internal as well as external project members with a maximum degree of transpareny is guaranteed [Manns 2013].

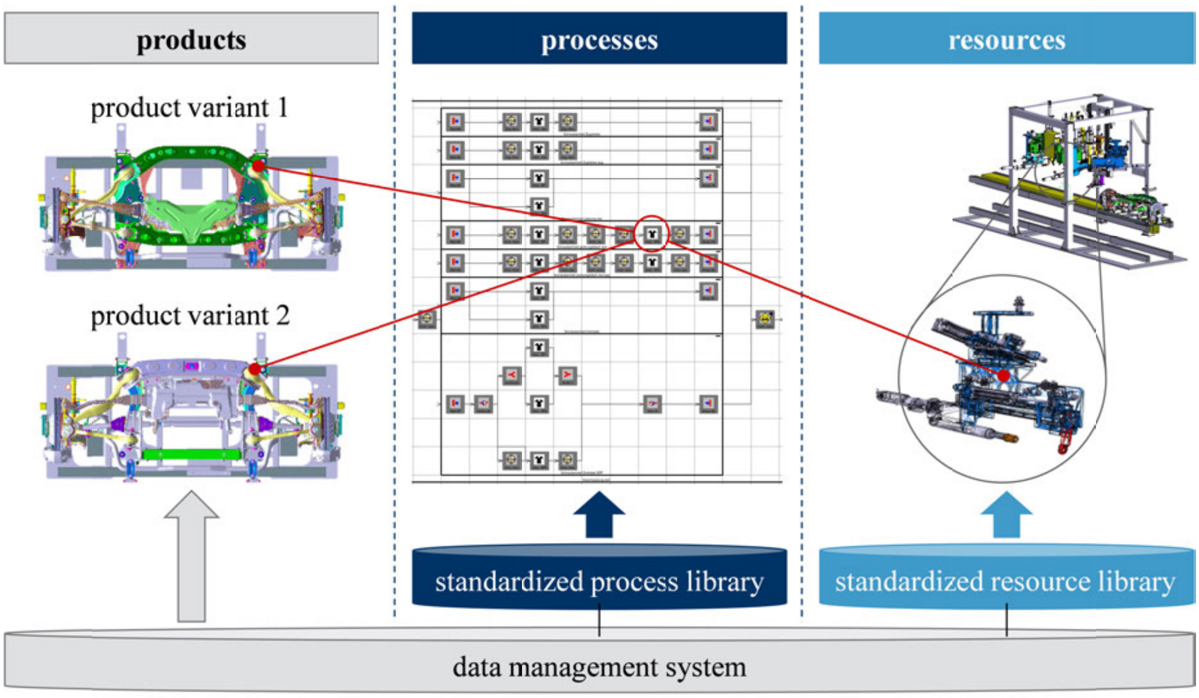

Figure 2. Linked product, process and resource data in the context of virtual engineering

In a next step, after developing the 3D CAD plant model and the plant-specific process model, the appropriate product, process and resource data are linked together. That means for example, that there is link between a screwing operation (process), the screw (product) and the screwdriver (resource) that is used to tighten the screw in the context of the screwing operation (see Figure 2). More detailed information regarding the structure and the development process of the 3D CAD plant model are presented in Strahilov [2012]. Based on the linked product, process and resource data, several digital validation investigations are accomplished such as accessibility, cycle time or dynamic collision analyses. In this way, according to the principles of preventive quality management, errors can be detected and avoided at a very early stage and product-, process- or plant-specific optimizations can be done without having the real production facilities.

2.2 Virtual commissioning

According to Kiefer [2009a], virtual commissioning describes a methodology in order to validate and optimize real control programs (e.g. PLC, HMI, RC), production-related IT systems (e.g. production control systems) and the whole system behavior (cross-functional interactions inside a production system) using digital product and resource as well as real control data. As illustrated in Figure 1, the execution of virtual commissioning is accomplished parallel to the realization phase (purchase and manufacturing of the required components) before real commissioning. In this way, many powerful benefits can be gained such as:

- More efficient software programming and debugging
- Higher soft- and hardware quality at start of production (SOP)

- Accelerated, more efficient and more robust production ramp-ups – especially in the context of integration processes during running production
- Less costs in production ramp-ups due to less real crashs and less real testing parts
- Higher availability of the manufacturing systems during running production

To take advantage of all these benefits in a most profitable way, a digital data model is needed that represents not only the mechanical but also the electrical and functional portions of the real production facilities in a sufficiently exact way. Due to its contained information, this integrated data model is called mechatronic plant model. As portrayed in Figure 3, this mechatronic plant model is fundamentally composed of two corresponding parts: the 3D geometry model on the one hand and the control-oriented behavior model on the other hand. According to the lean principles, the development of the mechatronic plant model has to be done as efficient as possible using standards and automatisms in order to create a widely accepted digital validation solution for operational use. At Daimler, such a lean engineering workflow for generating the mechatronic plant model as efficient as possible was developed, which main characteristics are illustrated in the following sections.

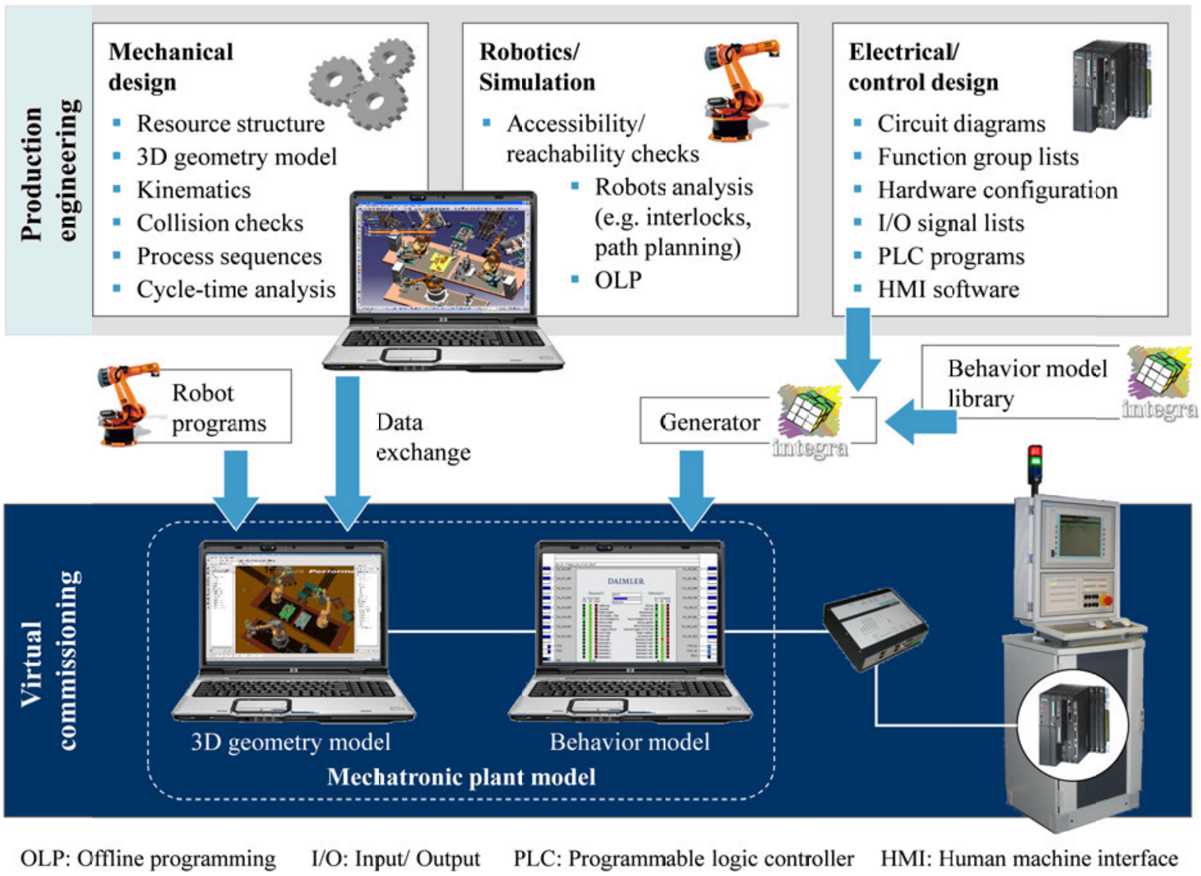

Figure 3. Virtual commissioning – Data supply and workflow

The 3D geometry model with its components is the result of the virtual engineering phase. In the context of virtual commissioning it is mainly used for visualization purposes, collision and cycle time investigations, robot programs analysis as well as communication platform and as base for decision making. Dependent on the respective company strategy, this digital data model has to be converted from the IT tool of the mechanical engineering (e.g. CATIA V5, Siemens NX) to the 3D IT tool that is used in the context of virtual commissioning (e.g. Invision, RF::Suite).

The development of the control-oriented behavior model is based on pre-configured standardized behavior components, which describe the logical- and time-related behavior of the production equipment compared to the respective control devices. In order to allow a company-wide access to these standardized component-related behavior models, these digital data models are made available to its users in the form of a centrally organized behavior model library. On the basis of so-called function group lists (output from the electrical design) that describe what kind and how many function groups are used in the production system, the component-specific behavior models are combined stepwise to the overall plant-specific behavior model in an automatic way. Due to the existing standard in the field of electrical/ control engineering called “integra”, at Daimler, this described procedure is used both in the fields of body shop and automated assembly systems in exactly the same manner.

In a last step, the 3D geometry model and the control-oriented behavior model are connected to each other. Basis of this connection are pre-configured standardized interfaces (in-/ outputs) of the two data models. Due to predefined name conventions in both data models, this process step can be realized in a completely automatic way.

More detailed information regarding the structure, the characteristics and the design process of the mechatronic plant model can be found in Kiefer [2009a,b].

2.3 Physics-based analysis

According to a continuous improvement process (CIP), the existing digital validation methods that are currently used within production engineering are permanently optimized regarding the presented lean aspects. In this way, due to first experiences in apply the validation methods of virtual engineering and virtual commissioning in operational practice, two improvement goals were identified:

- More efficient development process of the 3D CAD model in the context of virtual engineering (e.g. reduction of error-prone programming efforts by define kinematic chains and reactions due to contacts of the mechanical parts and devices)
- Realization of a more realistic product- and plant-specific behavior (e.g. more realistic behavior of mechanical contact reactions and of flexible parts such as cables or tubes)

In order to develop these lean-oriented potentials, the method of physics-based analysis takes a promising role. Using this new innovative method, the maturity level of automated assembly systems within production engineering can be further increased (Figure 4), and, at the same time the modeling efforts to develop the 3D CAD models can be significantly reduced.

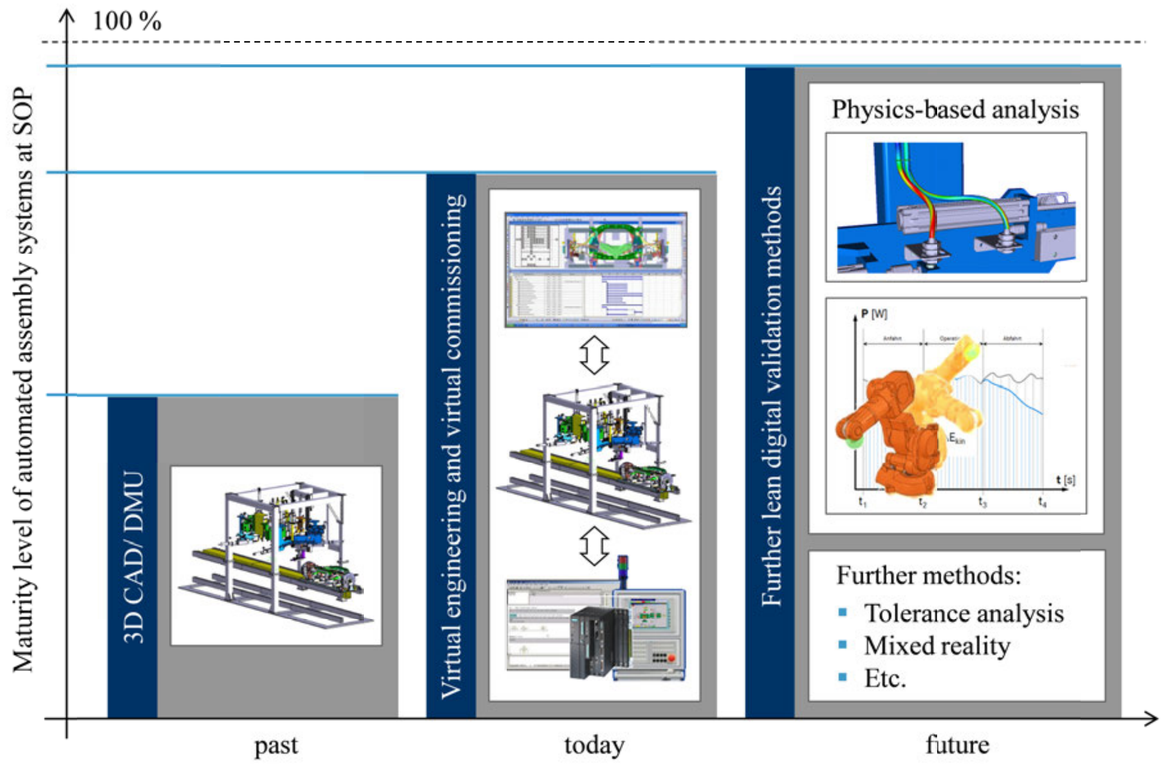

Figure 4. Physics-based analysis as new future-oriented digital validation method

The method of physics-based analysis is a new approach within the field of production engineering to prepare and analyse simulation studies by using physical effects (e.g. forces, gravitation, friction) in a most efficient and realistic way. Due to the integration of physical laws, the real behavior of products or plant components (e.g. cylinders, turntables) can be simulated without having additional efforts: Expensive modeling and programming efforts are replaced by easy settings of physical parameters.
As published in Lacour [2011], the information-technical core for accomplishing physics-based simulation studies are physics engines. A physics engine is a computer software that provides the simulation of certain physical systems, such as rigid body dynamics (including collision detection), soft body dynamics or fluid dynamics. In general, there are two classes of physics engines: real-time and high-precision physics engines. High-precision physics engines require high processing power to calculate very precise physical effects and are usually used by scientists and computer animated movies. In contrast to this technology, real-time physics engines – as used in video games and other forms of interactive computing – use simplified calculations and decreased accuracy to compute in real-time.
In research studies, application and profit potentials of physics-based methods and tools in the context of assembly-specific production engineering were evaluated [Drescher 2013]. Due to the promising results of these activities, at Daimler, new physics-based validation methods to further increase the maturity level of automated assembly systems within production engineering are currently developed:

- Validation of complex kinematics, movements or mechanical contacts
- Validation of system times (e.g. times of pneumatic systems, cycle times)
- Validation of the behavior of flexible parts (e.g. cables, tubes)
- Computation and visualization of energy cosumptions (e.g. energy consumptions of robots)
- Visualization and analyse of fluid flows (e.g. filling processes)

Apart from the efficient analyse and evaluation of realistic product-, process- or resource-specific behavior patterns at a very early project stage, all these physics-based validation studies also provides the basis for optimization approaches in the sense of a continuous improvement process.

3. Operational applications and gained benefits

While Daimler has been permanently used the validation method of virtual commissioning in the operational practice in the field of body shop since 2010 [Kiefer 2010], the first operational application of the lean digital validation methods of virtual engineering and virtual commissioning in the field of automated assembly systems was in 2012 [Kiefer 2012].

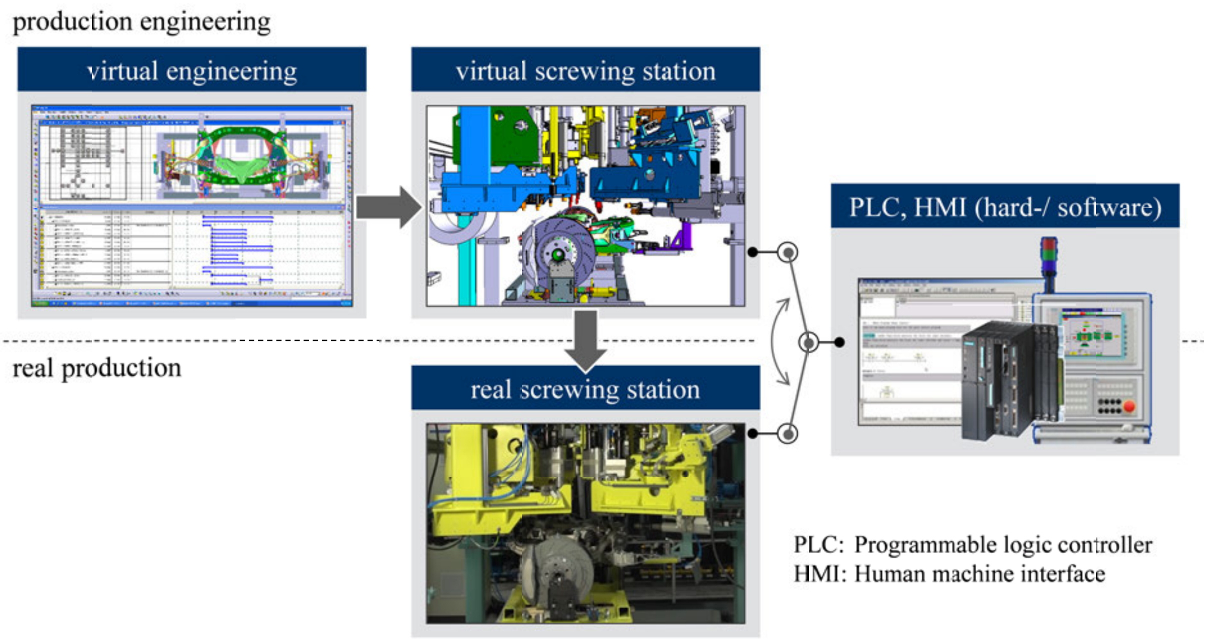

Figure 5. Operational application of virtual engineering and virtual commissioning

As shown in Figure 4, this first application project was about the design process of the automated front axle screwing station of the current Mercedes S class. Due to the great success of this project, Daimler decided to integrate the methods of virtual engineering and virtual commissioning as obligated binding project milestones within the future design process of all automated assembly systems (see Figure 1). In this way, the requested product, process and plant quality can be guaranteed at a very early project stage. Moreover, attributable to the gained transparency by using the new developed digital validation methods, the product-, process- and plant-specific degree of maturity can be evaluated much better and more efficient during production creation process.
As already mentioned, the key principle of lean is to provide perfect value through a most efficient value creation process. Relating to CAx processes lean means to develop a seamless digital process chain in order to minimize non-value processes (e.g. extensive modelling activities, repeated inputs of same data in different IT tools due to data loss) and to focus on pure value-adding activities. At Daimler, the IT landscape (IT tools, data exchange formats) that is currently used within the engineering process of automated assembly systems is portrayed in Table 2.

Table 2. Used IT tools and data exchange formats within the production engineering process

IT Tools	Application fields	Data exchange formats	
		Import data formats	Export data formats
CATIA V5	CAD/ Tooling design	–	V5 specific data formats
DELMIA V5	Virtual engineering	V5 specific data formats	AutomationML
Invision	Virtual commissioning: 3D geometry model	AutomationML	–
WinMOD	Virtual commissioning: Behavior model	CSV, TXT	–

In order to exchange data from one IT tool to another two types of data exchange formats are currently used: Monolithic data formats (in case of using IT tools from same vendors) and standardized, system-neutral data formats (in case of using IT tools from different vendors). For example, the data exchange between the CAD tool CATIA V5 and the CAP tool DELMIA V5 (3D geometry data, kinematic data, structure data) is accomplished by using vendor-specific data formats such as CATProduct, CATPart or CGR. In case of transfer the 3D CAD plant model (result of virtual engineering) from DELMIA V5 to Invision (3D tool for virtual commissioning) the situation is different: In order to exchange the plant data (3D geometry data, kinematic data, structure data) between these two IT tools that are developed by different IT vendors, the standardized, system-neutral data format AutomationML is used. More information regarding structure and characteristics of the cross-functional data format AutomationML is given in Drath [2010]. Both types of these used system interfaces works very good in operational practice (no data loss, good performance, easy-to-use) so that there is a lean solution in the form of a seamless value-focused CAx process chain.
To integrate the method of physics-based analysis in the existing IT landscape of Daimler in the most efficient way, both IT tools and data exchange formats are currently evaluated. According to the lean principles, the realization of a seamless and high performance data flow based on standards as well as the smooth integration of physics-based analyses in organizational structures are intensively promoted.

4. Summary and outlook for further research activities

In automotive industry, the development and operational use of digital validation methods takes a key role in order to reduce time and costs on the one hand and to improve product, process and production quality on the other hand. However, today, these digital validation methods are not comprehensively and seamlessly used along the whole product creation process in operational practice. These facts particularly relates to the design process of automated assembly systems. The main reasons for this phenomenon are the mostly huge efforts to prepare the required simulation models, the big complexity of the respective IT tools as well as the missing integration of these new methods and tools in existing

IT and organizational environments. Finally, all these aspects lead to a missing user acceptance regarding the operational use of digital validation methods.
At Daimler Research & Development, to improve this current situation, so-called lean digital validation methods within the design process of automated assembly systems are developed. This paper focuses on the illustration of the three lean digital validation methods of virtual engineering, virtual commissioning and physics-based analysis. Apart from the presentation of the main characteristics of these new methods, their applications and interactions are demonstrated taking the design process of a real existing automated screwing station.
In 2012, the lean validation methods of virtual engineering and virtual commissioning were used in a real car project within the design process of an automated assembly system for the first time with great success: The technical feasibility, the lean use and the profitability of these innovative methods could be demonstrated. Due to these positive effects, Daimler decided to integrate these new developed validation methods of virtual engineering and virtual commissioning as new obligated project milestones within the future design process of all automated assembly systems.
Although much progress has been already made in the topic field of lean digital validation methods in recent times, following issues still remain to be addressed in further research activities such as:

- **Virtual commissioning**
  Future challenges in this topic field relate for example to the lifecycle management of the needed behavior models (e.g. activities towards cooperation models between OEM, line builder, engineering provider and component producer; standardized descriptions of behavior models; change management) or to the accomplishment of virtual commissioning (e.g. using of digital models versus hardware components; standardized generation, evaluation and documentation of plant-specific test cases in an automatic way).
- **Physics-based analysis**
  As potrayed in chapter 2.3, further research activities in the field of physics-based analysis are for example the development of lean methods to simulate and validate the realistic behavior of flexible parts (e.g. cables or tubes), to compute and visualize energy cosumptions (e.g. energy consumptions of robots) or to visualize and analyse fluid flows (e.g. filling processes) as base for product-, process-, or resource-specific optimizations. In addition to that, the information-technical as well as the organizational integration of physics-based analysis into existing environments and structures have to be analysed and solutions have to be developed.
- **Further lean digital validation methods**
  Due to the high complexity and interactions of joining and screwing processes within automated assembly systems, both methods of tolerance analysis and mixed reality takes a promising role in future processes (see Figure 4). In this context, lean solutions have to be developed regarding methodical-, information-technical- as well as organizational issues.

Due to the great importance in operational practice, parts of these research activities are currently elaborated within the DFG project “AutoPhyS – Auslegung automatisierter Produktionsanlagen im Automobilbau mit Hilfe der physikbasierten mechatronischen Simulation” (project duration: 03/13 – 02/15) and within the public funding ITEA project “AVANTI – Test methodology for virtual commissioning based on behaviour simulation of production systems” (project duration: 10/13 – 02/15). More detailed information regarding the project AVANTI are available at: http://www.avanti-project.de.

References

Bär, T., Prieur, M., Arteaga, N. A., "Intuitive Montageabsicherung für jedermann?", Proceedings of the 14th International colloquium on Production Engineering – PTK 2013, Berlin, Germany, 2013.
Drath, R., "Datenaustausch in der Anlagenplanung mit AutomationML", Springer-Verlag Berlin Heidelberg, ISBN: 978-3-642-04673-5, 2010.
Drescher, B., Stich, P., Kiefer, J., Strahilov, A., Bär, T., Reinhart, G., "Physikbasierte Simulation im Anlagenentstehungsprozess – Einsatzpotenziale bei der Entwicklung automatisierter Montageanlagen im Automobilbau", Proceedings of the 15th Symposium of Simulation in Production and Logistics – ASIM 2013, Paderborn, Germany, 2013.

Kiefer, J., Borutta, H., "Virtuelle Inbetriebnahme im Rohbau Werk Wörth", Proceedings of the 6th International Congress of Digital Factory@Production, Fulda, Germany, 2010.

Kiefer, J., Ollinger, L., Bergert, M., "Virtuelle Inbetriebnahme – Standardisierte Verhaltensmodellierung mechatronischer Betriebsmittel im automobilen Karosserierohbau", Journal of atp – Automatisierungstechnische Praxis, 7/2009, 2009, pp. 40-46.

Kiefer, J., Prieur, M., Schmidgall, G., Baer, T., "Digital Planning and Validation of Highly Flexible Manufacturing Systems in the Automotive Body Shop", Proceedings of the 42nd CIRP International Seminar on Manufacturing Systems – ICMS 2009, Grenoble, France, 2009.

Kiefer, J., Walla, W., "Potenziale im Sondermaschinenbau: Effizienzsteigerung in der Planung am Beispiel der PKW-Hochzeit", Proceedings of the 8th International Congress of Digital Factory@Production, Regensburg, Germany, 2012.

Lacour, F.-F., "Modellbildung für die physikbasierte Virtuelle Inbetriebnahme materialflussintensiver Produktionsanlagen", Forschungsberichte IWB, Vol. 257, Herbert Utz Verlag Wissenschaft, 2012.

Manns, M., Arteaga, N. A., "A vagueness measure for concurrent engineering of manual assembly lines", Journal of Production Engineering – Research and Development, DOI 10.1007/s11740-013-0494-y, 2013.

Strahilov, A., Mrkonjic, M., Kiefer, J., "Development of 3D CAD Simulation Models for Virtual Commissioning", Proceedings of the 9th International Symposium on Tools and Methods of Competitive Engineering – TMCE 2012, Karlsruhe, Germany, 2012, pp. 1281-1288.

Töpfer, A., "Lean Six Sigma", Springer-Verlag Berlin Heidelberg, ISBN: 978-3-540-85059-5, 2009.

Womack, J. P., Jones, D. T., "Lean Thinking – Banish waste and create wealth in your corporation", FREE PRESS, ISBN: 0-7432-4927-5, 2003.

Prof. Dr.-Ing. Jens Kiefer
University of Applied Sciences, Ulm
Production engineering and production management
Prittwitzstraße 10, 89075 Ulm, Germany
Telephone: +49 (0)731 50-28188
Email: jens.kiefer@hs-ulm.de