NordDesign 2016
August 10 – 12, 2016
Trondheim, Norway

INTEGRATED DEVELOPMENT PROCESS OF PRODUCTS AND PRODUCTION SYSTEMS

Pascal Stoffels, Michael Vielhaber

Institute of Engineering Design, Saarland University
stoffels@lkt.uni-saarland.de, vielhaber@lkt.uni-saarland.de

Abstract

Most approaches that aim at developing sustainable products consider individual phases of the product lifecycle, like for example production, utilization, etc. Depending on the product type, the largest share of the total environmental and social effects shifts to different phases. However, increasing the sustainability of products means an integrated consideration of environmental and social impacts of all lifecycle phases.
Product, material and corresponding production system determine the sustainability and must be taken into an integrated consideration due to the strong correlation between those three domains.
As the influence on the later properties is highest in early development phases, an integrated deployment of solutions for product, material and production system offers a great potential.
For this reason, the research focuses on the integrated development of products and their corresponding production system including material aspects in order to realize more sustainable products. An integrated development process for products and production systems is introduced and supported by suitable methods.

Keywords: Integrated Product and Production System Development, Concurrent Engineering, Set-Based Concurrent Engineering, Sustainability

1 Motivation

The consideration of the environmental and social impacts of individual phases and domains in product development is not sufficient in order to realise real sustainable products. An overall consideration of all lifecycle phases, including material and production system aspects is necessary to meet this challenge.
The sustainability of products depends on the product design, the used materials, as the extraction of raw materials causes high environmental impacts and is responsible for precarious employment conditions and political conflicts and the corresponding production system.

The manufacturing processes of the product create the product characteristics. Moreover, the material selection correlates with the processes as well with the product. A deeper integration of the development processes of products and their corresponding production systems, taking material aspects into account offers therefor a huge potential for generating solutions that fit well with specific constraints like, for example, the sustainability.
Nowadays, products and production systems are more or less developed independently. They follow similar, but separated process steps with common milestones, where requirements are checked and mutual validations of properties are executed. The solutions for both systems are generated separately and not in an integrated approach. Materials are selected using databases that provide data about the properties and often suggest suitable manufacturing processes. Product requirements are taken as input, however the product solutions are only iteratively adjusted and not in combination with material solutions.
For this reason, the author's research focuses on the integrated development of products and their corresponding production systems, taking material aspects into account in order to realize more sustainable products.
The main research question is *how environmental impacts are reduced by an integrated development of product and production system*. The scientific question how an integrated process looks like supporting the usage of new integrated methods besides existing methods is covered.
A development process that connects the domain-specific development processes is presented. Integrated evaluation steps are introduced in order to enhance the usage of methods for the selection of optimal solutions according to several different criteria. A multidimensional evaluation that considers technical value, economic issues besides ecological criteria is necessary in order to avoid bad influences on other constraints. The selected solution represents a global maximum for the fulfilment of all relevant constraints. While this approach may increase the workload in early phases, it is reduced in advanced phases.
For this research the ecological criteria are of special interest, particularly the total energy consumption. Other constraints have to be integrated into the considerations for a comprehensive evaluation tending to create competitive products.
The paper is structured as follows. The state-of-the-art chapter describes the underlying theoretical considerations and gives an overview about the research in the field of simultaneous and integrated engineering. Afterwards, the integrated development process and evaluation method is presented. Finally, the paper will be concluded.

2 State-of-the-art

The state-of-the-art in the relevant topics for this research, integrated product and production engineering and simultaneous/concurrent engineering is presented in this chapter.
Simultaneous Engineering is an integrating approach that takes the collaboration and parallel execution of product and production development activities into account. This approach is aiming at a reduction of development time and costs and the increasing of quality. The effort may increase at the beginning but can be reduced in advanced development phases (Ehrlenspiel 2009).
Bras & Mistree stated that the efficiency and effectiveness in concurrent engineering have to be improved by providing suitable tools to the designers. They developed graphical models for early phases of the design process that are analysed and improved. Furthermore, they identified decisions as a key factor of the development, why the used decision-based design tools. (Bras & Mistree 1991)

The Concurrent Function Deployment (CFD) method developed by Prasad (Prasad 1996, Prasad 1998) is a promising tool that increases the efficiency and effectiveness of the development. Basing on the well-known Quality Function Deployment (QFD) by Akao (Akao 1990), this method provides parallel deployments. A concurrent deployment of different artefact values (Quality, Costs) is performed for each value characteristics (materials, parts). The deployment is repeated for different tiers (product, process and production planning), where a parallel execution is possible. However, the impacts of design decisions in product planning on the process or production system and vice versa are not examined. (Prasad 1996, Prasad 1998)

Sobek et al. present the Set-Based Concurrent Engineering method, developed by Toyota that enables a delayed decision making by working with potential solutions sets that increases the flexibility and is less sensitive to decision errors (Sobek et al. 1999). The set is narrowed step by step during the development process and converges in a final solution. The results are better solutions in contrast to the conventional point-based developing approach and efficiency gains based on less iteration cycles. (Sobek et al. 1999)

This approach does not directly consider how the solutions from both domains product and production system influence each other in detail, but provides an integrated development of both solutions spaces. Defining feasible regions in the solution space is done by checklist (Sobek et al. 1999). A method for an integrated evaluation of the feasibility of solutions would offer additional potential.

Aiming at a higher efficiency of set-based engineering, Raudberget developed a computer tool that supports the engineer working with set-based solutions. An adapted morphological chart is introduced that contains solution sets and integrates also non-functional qualities, like production requirements. Solutions are eliminated and become more concrete with progress. However, the product solutions are only filtered to possible combinations and not evaluated against production solutions. (Raudberget 2011)

As the selected material has a huge influence on the sustainability and correlates with product and production systems solutions, an integration of material aspects is desirable. Ashby et al. proposed a method that combines the material and process selection (Ashby et al. 2004). Design requirements are transformed into material and process specifications and the potential solution space is narrowed using screening and ranking methods. All domains are considered and the selection process is performed iteratively until the solution meets the requirements. (Ashby et al. 2004)

Ashby et al. integrate product aspects into the material and process selection and use screening methods to reduce the solution space (Ashby et al. 2004). However, a set of different product solutions is not considered at the same time, due to the iterative character of the process.

A deeper integration of both processes requires an analysis of the correlations between the product and production development processes. An integrated decision making enables more efficient solutions on both sides.

Eversheim et al. therefor introduced different types of matrices that describe the relations between activities, methods, technical system and the required/created information for both domains as a base for the integration (Eversheim et al. 1997). The activities are put into relation with the generated or required information, from which an optimal sequence can be derived (activity-information-matrix). Another matrix assigns information to the hierarchical structure of the product, including modules and assemblies (technical system-information-matrix). The third matrix correlates methods with the required and created information (method-information-matrix). The last one presents the interdependencies between information of the product design and the process planning (information-interdependencies-matrix). These correlation matrices constitute the essentials for generating new methods, by providing relevant aspects for a deeper integration of the development of products and their corresponding production system. Basing on these results Eversheim et al. introduced planning methods for detecting co-ordination points and methods that identify integrating methods. (Eversheim et al. 1997)

The authors elaborated a matrix that considers correlations between different phases of the product and the production system development, in a past research (Stoffels et al. 2015a). It turned out, that especially in early phases there is a strong mutual interference between both domains. The principle design phase of the product has a huge impact on the technology definition and process design of the production system. Furthermore, the detailed design on the product development side influences the technology definition, process design and process specification on the production development side to a high degree. This situation is valid for new products combined with new production systems. The direction is flipped, when an existing production system is used as an input for the development of a product.

Besides the analysis of relevant aspects that should be focused when improving the integration of both processes, a theoretical formalization of the interdependencies is necessary. A representation form for both systems has to be introduced in order to find out which elements of a product model correlate how and with which elements of the production system.

Weber developed the CPM/PDD approach to model products and product development processes (Weber 2005). The characteristics Cx of a product that are determined by the developer constitute the properties Px of the product. The relation between both is represented by a matrix Rx. External constraints ECx influence this relation matrix (Weber 2005). The characteristics can be summarized to different solutions for the product functions. Deubel et al. applied this approach on production systems, because the structure is similar (Deubel et al. 2006).

Basing on the description of both systems, the interdependencies can be formalized. In order to manufacture the characteristics of the product, defined properties of the production system are necessary. These properties are constituted by the characteristics of the production system that only can be influenced by the developer - similar to the structure of the product description. For this reason, it is important to know how the characteristics and corresponding properties of a production system (for example range of removal tool) interact with the characteristics of the product (length of keyway). A correlation matrix was added to address this issue. (Stoffels et al. 2015b)

Michaelis proposes an integrated platform model that focuses on the conceptual design phase for reusing and redesigning design solutions, components, production systems and the processes. The model is basing on Function-Means trees. Functional requirements are fulfilled with design solutions. The design solutions of the production system create the design solutions of the product. The respective components constitute these solutions. Both objects are linked to the corresponding operations of the manufacturing process. This approach focuses on the modelling of an integrated model and is not covering an integrated view on the development processes of both domains. (Michaelis 2015)

Gausemeier (Gausemeier 2010) and Brökelmann (Brökelmann 2012) structure the product development process into a three cycle model that includes product planning, product development and production system development activities. These cycles interact with each other. Especially, the interaction between the product and production system development are interesting. The result of the conceptual design phase of the product is the input for working out principle solutions for the production system. Both processes are performed in parallel. (Gausemeier 2010)

In summary, there are many existing approaches in concurrent engineering that support the integrated development. Working with set-based solutions allows more robust solutions that enable a delayed decision making. However, methods that support engineers to exploit the correlations and provide an integrated evaluation of solutions from product, material and production system are missing.

The evaluation of potential solutions requires simulation methods to calculate the resulting properties. As the focus of the research is on sustainable aspects, environmental simulation methods are displayed briefly. Lifecycle assessment (LCA) (ISO 2009) or process assessment according to Swat (Swat 2014) provide an evaluation of solutions and are essential for this research. The LCA analyses the environmental impacts of all inputs and outputs of all processes that concern a product. Different solutions for products as well as production systems are assessed according to environmental aspects (ISO 2009). Additionally, a process assessment of manufacturing processes is required in order to evaluate different potential processes, according to their environmental impacts (Swat 2014). This method supports the selection of suitable technologies that constitutes solutions for the production system functions.

3 Integrated Development Process

The literature review in chapter 2 reveals a lack of an integrated evaluation method of product, material and production system solutions. An adapted integrated development process that enables the application of this method is therefore necessary. For this reason, the authors proposed an development process that is aiming at an integrated elaboration of product and production system solutions, as shown in figure 1 (Stoffels 2016).

Based on planning activities in both domains, the specification, like requirements for the product and the corresponding production systems are determined that represents the first milestones. Afterwards, in the conceptual design phase, different product solutions with a selection of matching production system solutions are worked out. Conceptual simulations are executed, if necessary. These solutions are provided to an additional integrated phase that performs a total evaluation. The Integrated Morphological Chart (IMC) according to (Stoffels et al. 2015a) supports the assessment of possible solution combinations considering multidimensional criteria. The result is returned to the domain-specific development, where changes are applied until the concept is finished (M1 and MP1, see figure 1). If the specifications are not complete, an iteration is performed. In the following phase the components that are constituted out of characteristics are being created - on the product and production side. These characteristics have to be checked and evaluated to select the best combination. The Design for energy-efficient manufacturing method supports these activities. The evaluation process regards multicriterial constraints. Subsequently, the combination is returned to the domain specific phase and after all specifications are fulfilled, milestone 3 is reached. In a final step, the product and the production system are integrated in their domains and all properties by means of simulation tools checked. Additionally, both systems are evaluated from an integrated view.

The integrated development process requires efficient assessment tools in order to determine all environmental impacts. The Lifecycle Assessment (LCA) is a well-suited approach to calculate all interactions with the environment of all lifecycle phases (ISO 2006) and is input for the evaluation of all product and production system solutions. Standard manufacturing processes are taken for the production phase that may differ from company internal ones.

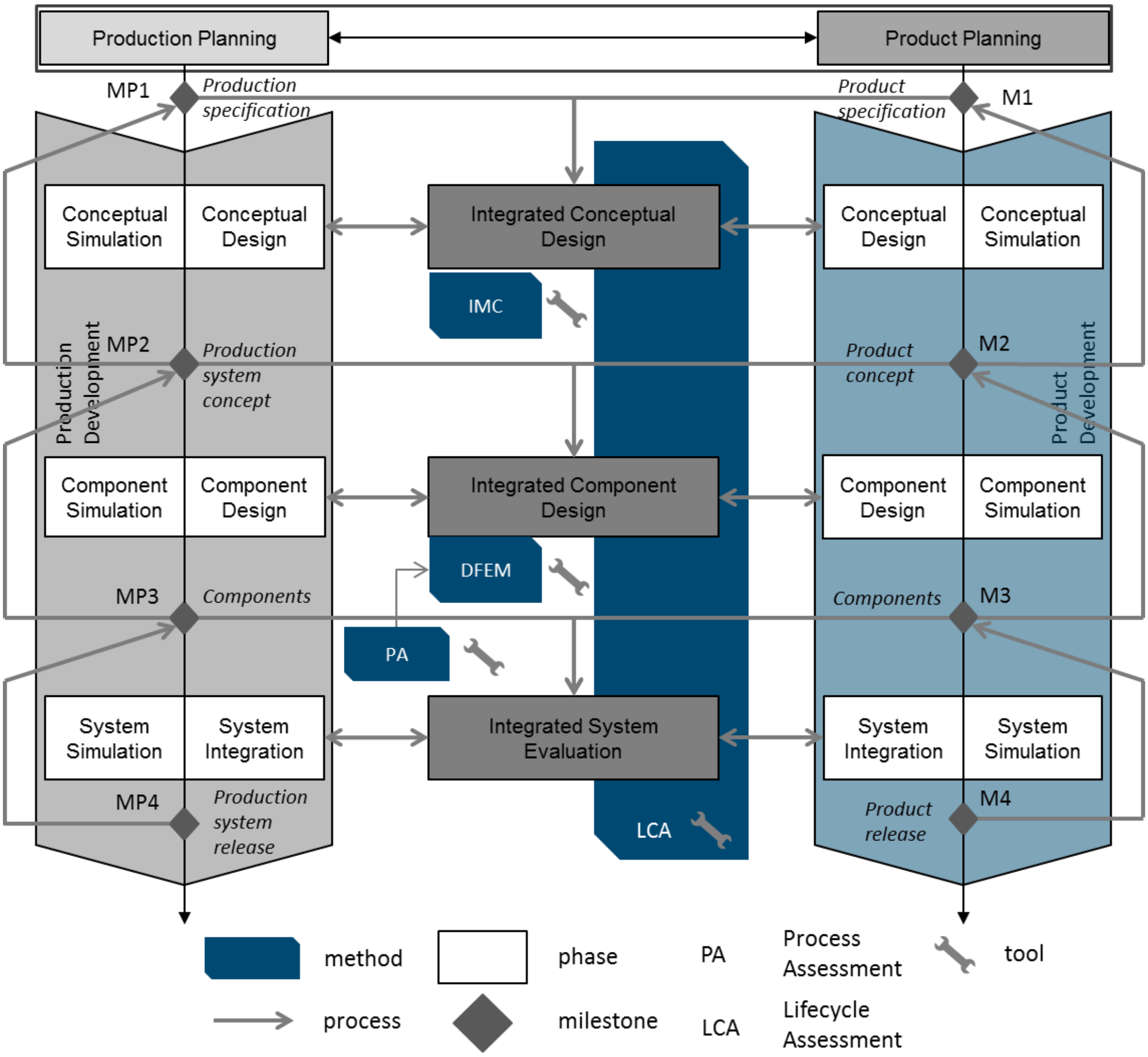

Figure 1 Overall view on the integrated development process, basing on [Stoffels 2016]

Swat et al. therefor proposes a method in order to describe such processes and provides a database in order to support a technology selection, even depending on the shape of the part (Swat 2014).

4 Integrated Morphological Chart

There is a strong need for methods that support the engineer developing solutions for product, material and production system in an integrated approach as they mutually influence each other.

The integrated morphological chart enables an integrated evaluation of potential solution sets that facilitate the decision making.

Figure 2 depicts an overview, how the method is elaborated. Starting from the requirements, the functions of the product are derived. Similar to the conventional morphological chart, potential solutions are developed that have to fulfil these functions. Subsequently, production system functions as well as material functions that are required to realize the product solutions are deployed. Databases or catalogues support the engineer and facilitate the deployment. Predefined functions are

As with the product functions, potential solutions are developed that fulfil the functions of the material and the production system. The derivation of solutions is also assisted by catalogues.

Conflicts and contradictions between different functions or different solutions are identified by certain rules and fixed.
The potential solutions for product, material and production system are transferred to the integrated morphological chart (a cube. due to the three-dimensional structure) and constitute a solution space. All solution combinations are subsequently assessed. A rough evaluation basing on expert knowledge is performed in early stages of the development. As the development project progresses, the evaluation becomes more detailed and existing simulation methods like Lifecycle Assessment are used to calculate for example the environmental impacts of potential solution combinations.
Besides sustainability aspects, the method provides the possibility to evaluate the solutions sets according to many other constraints. Economic goals like costs and minimum technical value are for example key factors for competitive products and may not be violated.

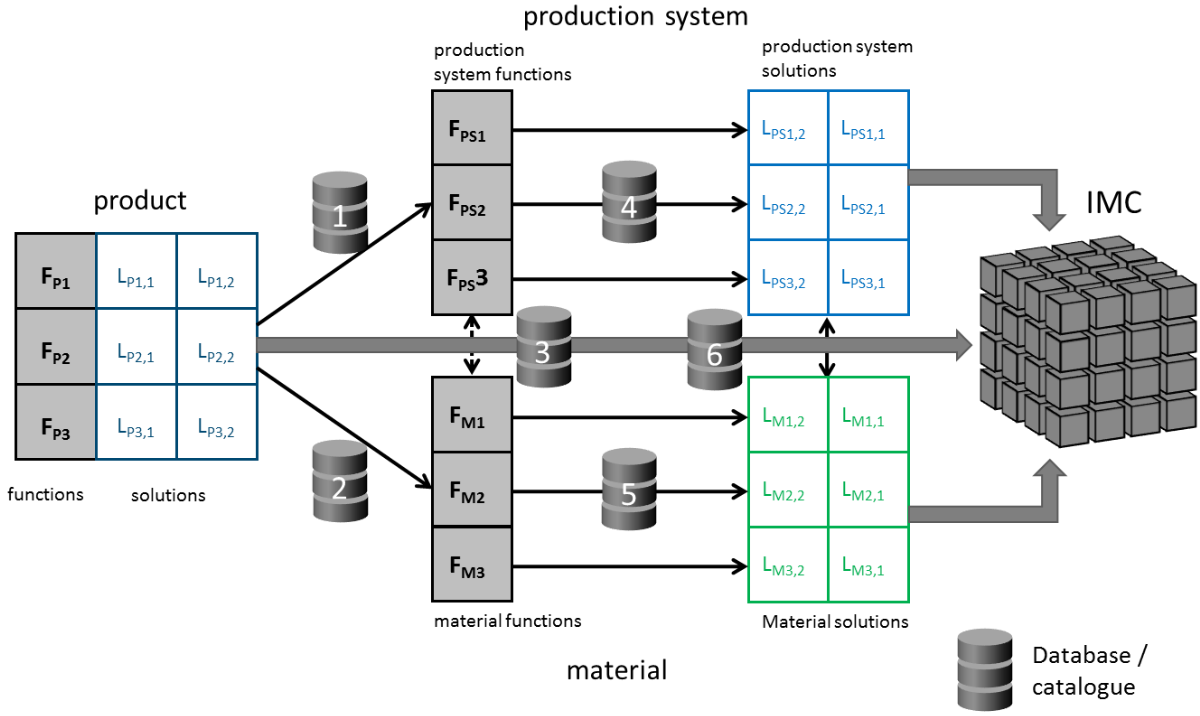

Figure 2 Elaboration of an integrated morphological chart

In real development projects, the complexity of the cube is significantly increasing. A software toll is required in order to enable a productive and efficient use of the method.
An example for the evaluation by the integrated morphological chart is presented in figure 3. It is an extract of a 1-stage transmission for electric vehicles. The cross-section of the material dimension for Al-Alloys is depicted here. Different product and production solutions are evaluated according to the energy efficiency considering the aforementioned material. The execution of the evaluation for all constraints and all materials (not shown here, due to the limited space) is, of course, prerequisite for finding an overall solution.

Integrated Morpholigcal Chart - 1-stage Transmission (extract)

Criterion: Energy Efficiency

Material Class 1: Al-Alloys

Product: F	S											
transmit torque	gear combination	pulleys + belt	torque converter (pump impeller, turbine wheel, guide wheel)	3	3	3	1	1	1	x	x	x
				2	2	2	1	1	1	x	1	x
				x	x	x	2	x	x	x	x	x
torque input	splined shaft	flange		3	3	x	x	x	x	x	x	x
				2	2	x	1	1	x	x	1	x
				x	x	x	x	x	x	x	x	x
bearing	rolling bearings	hydrodynamic bearings		x	3	x	x	x	x	x	x	x
				x	2	x	x	1	x	x	1	x
				x	x	x	x	2	x	x	x	x
Production System: F			S	casting			Sintering			Injection Moulding		
create shape				casting			Sintering			Injection Moulding		
change shape				grinding			milling			lathing		
adjust material properties				induction hardening			hardening furnace					

4 unfavorable
3 rather unfaborable
2 medium
1 rather favorable
0 favorable

x not possible

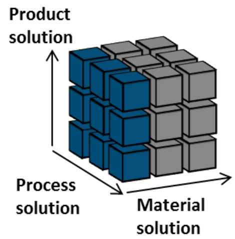

Figure 3 Evaluation of a 1-stage Transmission

5 Conclusion

Most approaches that aim at an improvement of sustainability only focus one particular lifecycle phases or an individual domain. However, only an integrated development that takes product, material and production system solution in early stages into account makes real sustainable products possible. As product solutions - sets of characteristics - strictly correlate with the production system properties and the associated characteristics, the interaction between both systems should be analysed and eventually exploited during their development processes. The material selection correlates with both solutions and should therefore also integrated into these considerations.

In order to meet this challenge, an integrated development process has been introduced. Existing methods from both domains, complemented with new integrating methods can be used in the different phases. Evaluations of product and production system solutions combined with material solutions are enabled and efficient combinations can be selected with this approach. The integrated morphological chart addresses this issues and facilitates consequently the decision making process. Besides sustainable aspects, economic and technical constraints are also considered in order to avoid an isolated optimisation that can potentially have bad effects. Furthermore, the method can be used for a rough evaluation in early phases as well as for a detailed assessment during the component design.

Using an integrating development process enables an exploitation of the correlation of both domains and generates better solutions, to meet the rising challenges of today's products.

As the complexity of the integrated morphological chart is very high in real development projects, a software tool will be developed by the authors in order to increase the efficiency and effectiveness of this method.

References

Akao, Y. (1990). Quality Function Deployment. *Productivity Press. Cambridge, MA.*

Ashby, M. F., Bréchet, Y. J. M., Cebon, D., Salvo, L. (2004). Selection strategies for materials and processes. *Materials & Design, 25 (1),* 51–67.

Prasad, B. (1996). Concurrent Function Deployment - An Emerging Alternative to QFD: Conceptual Framework. In *Mark Fox und Michael Sobolewski (ed.): Advances in concurrent engineering. Collaborative work, organization and management ... ; presented at Third ISPE International Conference on Concurrent Engineering: Research and Applications, Toronto, Ontario, Canada. Lancaster, Pa. [u.a.]: Technomic Publ. Co*, 105–112.

Prasad, B. (1998). Review of QFD and Related Deployment Techniques. *Journal of Manufacturing Systems*, 17 (3), 221–234.

Bras, B., Mistree, F. (1991). Designing Design Processes in Decision-Based Concurrent Engineering. *SAE Transactions, Journal of Materials and Manufacturing, 100,* 451–458.

Brökelmann, J., Gausemeier, P., Gausemeier, J., Seliger, G. (2012). A Method for an Integrated Development of Product-Production System Combinations. In *Proceedings of Sustainable manufacturing. Shaping global value creation, G. Seliger (ed.), Berlin, New York: Springer (EcoProduction)*, 71–75.

Deubel, T., Zenner, C., Bley, H., Weber, C. (2006). Adaptation of a new Design Method for the Requirement-Driven Planning of Manufacturing Systems. In *Proceedings of the 16th CIRP International Design Seminar. International Design Seminar Design & Innovation for a Sustainable Society, D. Xue A. Ramirez-Serrano S. Park &. D. Fletcher P. Gu (ed.), University of Calgary, Kananaskis, Alberta, Canada*, 529–534.

Ehrlenspiel, K. (2009). Integrierte Produktentwicklung. Denkabläufe. Methodeneinsatz, Zusammenarbeit. 4. ed. München, Wien: Hanser.

Eversheim, W., Bochtler, W., Gräßler, R., Kälscheid, W. (1997). Simultaneous engineering approach to an integrated design and process planning. *European Journal of Operational Research*, *100*, 327–337.

Gausemeier, J., Brandis, R., Reyes-Perez, M. (2010). A Specification Technique for the integrative conceptual design of mechatronic products and production systems. In *Proceedings of the 11th International Design Conference, D. Marjanović (Ed.), Dubrovnik - Croatia, 2010, Zagreb*, 711–722.

International Organization for Standardization. (2009). DIN EN ISO 14040:2006. Environmental management - Life cycle assessment - Principles and framework. *Berlin Beuth*.

Michaelis, M., T., Johannesson, H., ElMaraghy, H., A. (2015). Function and process modeling for integrated product and manufacturing system platforms. *Journal of Manufacturing Systems, 36*, 203–215.

Raudberget, D. (2011). Enabling Set-Based Concurrent Engineering in Traditional Product Development. In: Steve Culley (Hg.): ICED 11, København. *The 18th International Conference on Engineering Design : 15th-18th August, 2011, Technical University of Denmark (DTU), Copenhagen, Denmark : proceedings : impacting society through engineering processes. [Great Britain]: Design Society*, 45–56.

Stoffels, P., Bähre, D., Frey, G., Vielhaber, M. (2015). Energy Efficiency Engineering- Towards an Integrated Method Framework for Energy-Oriented Product and Production Development. In *2nd International Congress on Energy Efficiency and Energy Related Materials (ENEFM2014, A.Y Oral, Z.B Bahsi Oral und M. Ozer (ed.), Cham, Springer International Publishing (Springer Proceedings in Energy)*, 291–297.

Stoffels, P., Vielhaber, M. (2015). Methodical Support for Concurrent Engineering across Product and Production (System) Development. In *Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. 4: Design Information and Knowledge Management, Milan, Italy*, 155-162.

Stoffels, P., Vielhaber, M. (2016). Decision support for energy efficient production in Product and Production Development. In *13th Global Conference on Sustainable Manufacturing – Decoupling Growth from Resource Use, Ho Chi Minh City, Vietnam, Procedia CIRP, 40,* 530-535.

Sobek, D. K. Ward A. C. and Liker J. K. (1999). Toyota's principles of set-based concurrent engineering. *Sloan management review Winter, 40 (2),* 67–83.

Swat, M., Brünnet, H., Bähre, D. (2014). Selecting manufacturing process chains in the early stage of the product engineering process with focus on energy consumption, Technology and manufacturing process selection. In *The product life cycle perspective, E. Henriques, P. Peças und A. Silva (ed.): London: Springer-Verlag London (Springer series in advanced manufacturing)*, 153–173.

Weber, C. (2005). An Extended Theoretical Approach to Modelling Products and Product Development Processes. In *Proceedings of the 2nd German-Israeli Symposium on Advances in Methods and Systems for Development of Products and Processes, 2nd German-Israeli Symposium on Advances in Methods and Systems for Development of Products and Processes, H. Bley, H. Janssen und M. Shpitalni F.-L. Krause (ed.), Stuttgart: Fraunhofer-IRB-Verlag, Berlin*, 159–179.