Chapter 2

Uniqueness and the Multiple Fractal Character of Product Engineering Processes

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2.1 Introduction

Every leaf of a tree has a different shape. One cannot understand form and function of a leaf without considering it as part of a whole tree with connections to the soil, the climate in which it grows and the animals living with it. One cannot succeed in describing a whole system from the point of view of one single part of it.

(Sandmeyer, 2009)

This metaphor, taken from an article about the Christian church, is also valid for the complex system of product engineering. Every product engineering process is unique and individual. This is the first out of five hypotheses about product engineering processes (Albers, 2010). In this paper we investigate where the differences between product engineering processes originate from. We examine the integrated product engineering model (iPeM) and its subsystems - the triple systems: *system of objectives*, *system of objects* and *operation system* (see Section 2.3) - and point out reasons for distinctions between individual processes. Not only processes themselves are individual but also their sub-processes with their networked hierarchies of activities, hierarchic levels of systems of objectives *etc.*

In Section 2.2 we review the iPeM as a model of engineering processes, its different abstraction levels and the related state of the art. The sections thereafter analyse the operation system, the system of objectives and the system of objects. It is shown that each of the systems is fractal and can be modelled self-similarly on different hierarchical levels in the iPeM. Examining the interconnections of the subsystems on different levels, we elaborate how different boundary conditions and restrictions in the system of objectives lead to individual subsystems and cause individual and unique engineering processes. The individual subsystems of the different fractal levels are interconnected in various ways and across hierarchic levels. Iterations or unexpected changes of objectives which require redesign have an especially strong impact on the engineering process and cause complexity which needs to be handled by contemplable approaches.

In Section 2.4 we present two examples for a wiki-based implementation of the approach. Both applications are meant to support product engineering processes by modelling and keeping track of hierarchic activities and different iterations of real projects. Concluding the paper, Section 2.5 discusses further work for a successful implementation of the iPeM.

2.2 Integrated Product Engineering Model

The integrated product engineering model (iPeM) was introduced as a modelling approach to depict product engineering processes, based on five hypotheses about product engineering (Albers, 2010). This paper threads the first, second and third hypotheses: *uniqueness of engineering processes*, the *triple system of product engineering* and the central activity *validation*.

2.2.1 Literature Review

An extensive derivation of the iPeM and the related state of the art can be found in Albers and Meboldt (2007) and Albers (2010). With the iPeM, engineering processes are described as a superordinate system consisting of an operation system that continuously generates objectives and transforms these into a system of objects.

This perception traces back to Hubka and Eder (1988) and Daenzer and Huber (2002). The systems engineering approach has been transferred to product engineering (Ropohl, 1979; Ehrlenspiel, 2003; Sim and Duffy, 2003).

There is no single approach commonly accepted as concurrently capturing all sorts of possible design situations while being specific enough to provide support on an operative work level today (Clarkson and Eckert, 2005). See the work of Browning and Ramaseh (2007), Wynn (2007), Meboldt (2008) or Albers *et al.* (2008) for a more detailed literature review on product engineering processes and process models.

2.2.2 Meta Model of Product Engineering

Figure 2.1 shows the meta model of the iPeM with its subsystems. The operation system is shown in the centre of the figure and contains the activities of product engineering (*macro* activities) and the (*micro*) activities of problem solving.

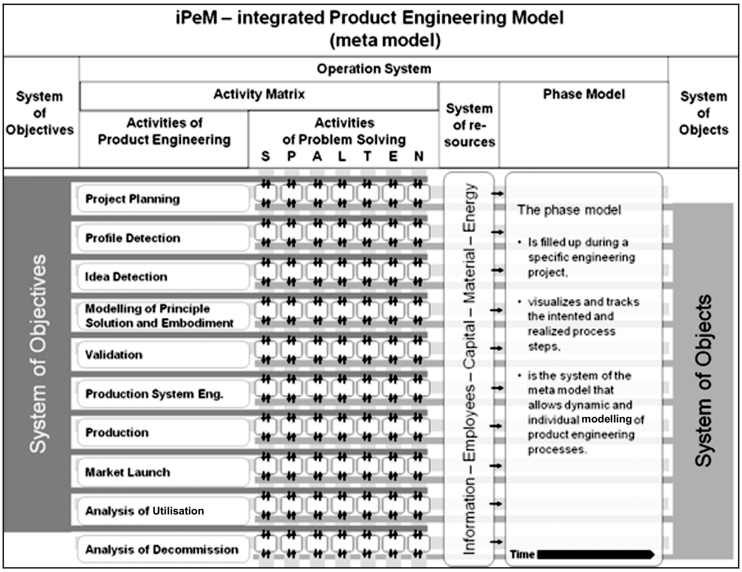

Figure 2.1. Meta model of product engineering (Albers, 2010)

Together they form the activity matrix where operational product engineering takes place. Using sets of generic activities as a basis for modelling processes allows a consistent and coherent description and facilitates a common understanding of a process in a group (Sim and Duffy, 2003). The picture shows the interface to the system of objectives on the left and the system of objects on the right.

To be able to consider organisational aspects of engineering processes as well, the system of resources and the phase model, where processes can be planned and tracked completes the operation system (for further explanation see Albers, 2010).

2.2.3 Abstraction Levels of the iPeM

Reasons for the fractal character on different levels of abstraction can be found in systems theory and the fundamentals of modelling. Models can be differentiated by their level of abstraction of formal structure as well as by their level of individuality (Rupprecht, 2002). Ropohl deduces the hierarchic dimension of the triple system based on the model theory by Stachowiak (Ropohl, 1979).

Concerning the formal structure, the *meta model* of the iPeM provides the basis to derive more specific *reference models*. These describe patterns of successful processes. They constitute the basis for formulating *implementation models* for specific projects. *Application models* monitor the actual course of a process for deriving information about improvement potentials for further reference models (Albers and Muschik, 2010a). The different abstraction levels of content-based individuality for an application of the iPeM in research are described as the *general* view, *domain-specific* level and *product-specific* level. For the application in industry, the second content-based level can be substituted by the *company-specific* level. Models for the different abstraction levels can be derived through two main procedures: *induction* or *deduction* (Albers and Muschik, 2010a) - see figure below.

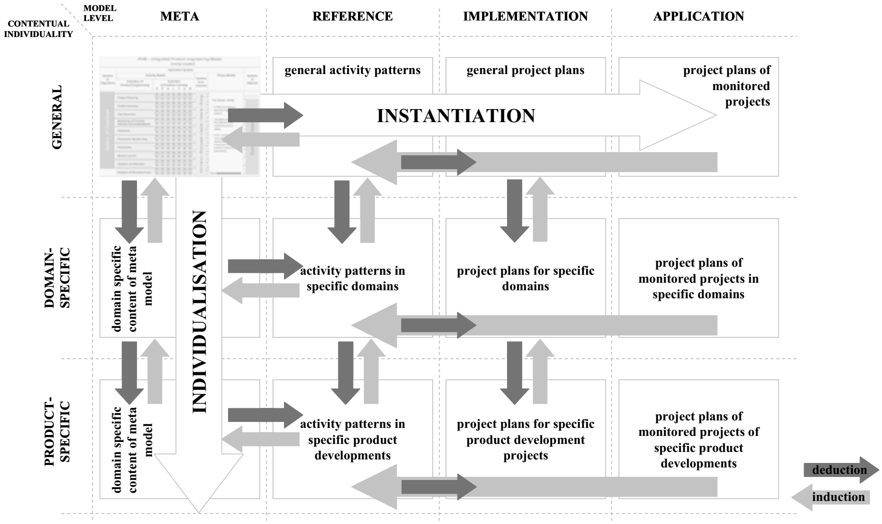

Figure 2.2. Abstraction levels of the iPeM (research application) (Albers and Muschik, 2010a)

2.3 System of Product Engineering

The following picture illustrates the interdependencies between the system of objectives, the operation system and the system of objects.

Initial objectives are derived from early information (*e.g.* about the market situation or competitor's activities) by the *operation system*. On this basis new objectives are generated continuously by forming and successively enhancing the *system of objectives*. The necessary activities are contained in the activity matrix to which elements of the system of resources are assigned. Through the activities of engineering processes, objects are produced, *e.g.* drawings, information documents, and plans *etc.,* which build up the *system of objects*. This influences the operation system in turn, leads to new objectives or can - in the case of a negative validation result - cause iterations in the engineering process.

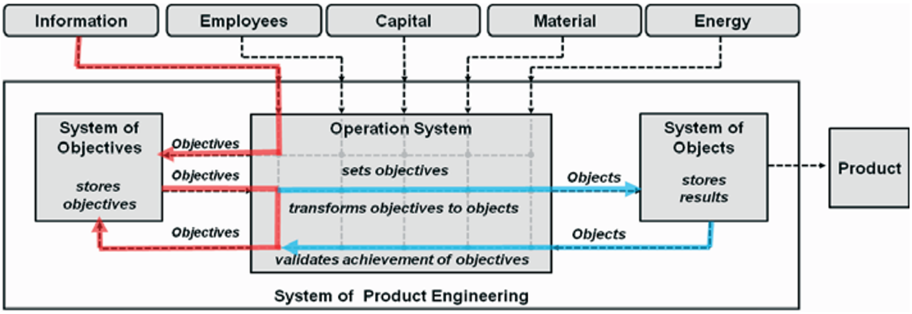

Figure 2.3. System of product engineering (see also Albers, 2010)

2.3.1 Operation System

The operation system incorporates all necessary means for the transformation of the system of objectives into the system of objects (Ropohl, 1979). Apart from the necessary resources such as labour, funding, equipment and supplies *etc.* the iPeM models the operation system by means of the activity matrix (see Section 2.2.2).

The activities can be explicated as systems that transform an input into an output according to the functional concept of a system (Albers and Muschik, 2010a). This output is again input to other activities leading to various interrelationships within the activity matrix. The input and output flows - so-called *deliverables* - lead to a hierarchic meshwork of different aggregation levels and differing granularity (Browning *et al.*, 2006).

2.3.1.1 Fractal Dimensions of Operation Systems

The activity matrix with its manifold interrelationships is of a fractal character. The iPeM's understanding of activities in the context of modelling product engineering processes is based on Hubka and Eder's hypothesis that designing is a rational cognitive activity, which is decomposable into smaller steps, *i.e.* into different levels of abstraction to match the relevant design problem. They propose a hierarchy of design activities, from design stages and according operations to basic operations, conducting a problem-solving cycle down to the lowest level of elementary activities and operations (Hubka and Eder, 1996). Every activity on one level comprises the activities on the following lower level and is itself part of all of its superior activities (Albers and Muschik, 2010a).

It is vital to understand that the set of activities in the meta model of the iPeM is dynamic, *i.e.* it develops according to the knowledge of product engineering processes. Therefore, it is never completed. An information transfer about occurring activities, their attributes and relations must be ensured to keep the model complying with changing constraints in continuously developing product engineering processes.

As the set of activities is adaptable to different abstraction levels, the iPeM can support modelling all kinds of design situations in order to handle the complexity of product engineering processes (see Section 2.1). It is possible to assign knowledge directly to the design situation in which it was generated *e.g.* for reuse in other developments (Albers and Muschik, 2010a) - see examples in Section 2.4. Another fractal aspect of the operation system is reasoned by the problem-solving process SPALTEN, which is a German acronym for the activities of problem solving such as *situation analysis*, *problem containment* and so on (Albers and Meboldt, 2005).

The problem solving procedure can be repeated self-similarly at any level of abstraction. Each micro activity of engineering processes can be considered as a whole SPALTEN cycle itself and so on. This repeating sub-process is independent from the particular level of abstraction. Even though it can be performed case-relatedly (which means that not every SPALTEN-step necessarily needs to be taken) the overall procedure is similar for every engineering activity in operational practice.

2.3.2 System of Objectives

A system of objectives contains all objectives, the boundary conditions and relations between them relevant to the development of a product. Equivalently to the operation system it is built of multiple subsystems. These cluster the elements of the system of objectives in so-called objective sections with respect to their content-based affiliation (*e.g.* objectives concerning technical, financial or social aspects) (Albers and Muschik, 2010b). Elements are information about boundary conditions relevant to an objective and objectives themselves (*e.g.* "weight has to be decreased by 20 kg"), expressed through tendency (*"to be decreased"*), parameter (*"weight"*) and value (*"20 kg"*).

Systems of objectives develop dynamically. During an engineering process information is allocated to respective objective sections and elaborated until a profound basis for the definition of an objective exists. A decision, *i.e.* setting an objective, is always a subjective procedure conducted by an agent. Consequently, at any point in time a system of objectives contains objectives in different development states (Albers and Muschik, 2010b).

2.3.2.1 Influence on the Uniqueness of Product Engineering Processes

The execution of a certain activity in the engineering process never proceeds equivalently in different projects. One reason for this is the evolved state of the assigned system of objectives that is regulating the sub-activities necessary for the transformation of objectives into objects. It can be differentiated from its previous states by different sub-activities that are necessary for the transformation, by the elements added, deleted or changed (*e.g.* tendency of objective or value).

A cause for this development of systems of objectives is the *change of boundary conditions* to objectives. These can be induced exogenously, *e.g.* through changes in society's trends. A rising consciousness of the environment might be relevant for a new product generation or changes of competitors' strategies might be important during a product's development. Changes can also be evoked endogenously, *e.g.* by changes in a company's financial situation. Another reason is the *subjectivity* of each *decision* necessary for the setting of an objective.

Different agents might derive different conclusions from boundary conditions for the definition of an objective. Also the *gain of insights* from further development projects *i.e.* from validating objects with according objectives during an engineering process causes changes in the systems of objectives.

Additionally changes to elements cause relations between them to develop. For example, the combination of two technologies in one product that has not been possible in a previous product engineering process might be technically feasible in the generation of a new product. Overall consistency of the elements might also be affected.

Decision situations for the definition of objectives, prioritisation of objectives in the engineering process as well as their value and consistency depend on the development of boundary conditions, performing agents and state of insight into a product. Therefore each system of objectives is unique.

2.3.2.2 Fractal Dimensions of Systems of Objectives

This uniqueness of systems of objectives aggravates its modelling and management for product engineering. The iPeM approach tries to overcome this difficulty in describing the fractal dimensions of the system of objectives on different abstraction levels. One product's system of objectives can be seen as a subsystem to the system of objectives of a company, which itself is subsystem to the system of objectives of society. The product's system of objectives can be subdivided into systems of objectives for its components and its parts *etc.* This is the content-based individualisation of the meta model for a system of objectives (see Figure 2.1).

Each of these models can be concretised with regard to the content of its elements (instantiation). Whereas the system of objectives on the meta level contains the main building blocks for objective sections and elements, a reference model specifies the relevant objective sections, *i.e.* elements, tendencies and relations for process patterns known from experience. Specific values for objectives are described on the implementation level.

These models on the different abstraction levels are derived deductively or inductively from project insights. Each model of the system of objectives triggers activities of the operation system which transforms the objectives into the system of objects by applying the problem solving steps in the product engineering activities - no matter on which abstraction level.

2.3.3 System of Objects

The result of product development processes are products. Nevertheless much more output is generated during the transformation of a company's system of objectives. There are three main output classes:

- (physical) objects that constitute the system of objects;
- information which is stored in the system of objectives;
- expert knowledge and know-how in the operation system.

2.3.3.1 Fractal Dimensions of Systems of Objects

As stated in Section 2.3.1, each activity can be considered as a system that transforms a system of objectives into a system of objects. Since the system of objectives can be modelled hierarchically in different levels of abstraction, also the resulting system of objects is a hierarchy with different abstraction levels and consists of individual objects that are correlating with each other through various relations. Especially design changes and iterations during engineering processes lead to individual cross-references between the system's elements and cause distinct systems of objects. Objects that are usually generated by activities later in the life cycle such as in the activity *production system engineering* need to be generated and essayed in early engineering stages such as *modelling of principle solution and embodiment*: the minimal radii of milling tools determine minimal radii of inner contours and have to be known before the actual life cycle phase is reached. Therefore, it can be necessary to jump from one macro activity of product engineering to another when additional information is needed and requires the analysis of certain objects *e.g.* in order to find out the minimal radius for a curve as exemplified above.

Another cause for iterations and design changes in particular are negative results of validation activities. On the one hand we find the macro activity *validation* in the iPeM. It represents engineering activities such as digital or physical prototyping, testing or final inspection. The object *product* is validated which means that it is verified according to the requirements that have been documented in the system of objectives and stored as information objects during the early engineering activities (Oerding, 2009). Objects are validated with respect to other objects.

On the other hand, objects are validated in reference to themselves or better: in reference to the information that is gained during their development's micro activities. During SPALTEN, activities such as *analysis of consequences* are performed. This step can be considered as a whole SPALTEN-process at a deeper level of abstraction starting with *situation analysis etc.* The object(s) created at this level influence the validation of superordinate objects.

2.4 Application in Wiki-based Implementations

The immense growth of (cross-linked) information that is produced during today's product engineering processes and the vast amount of knowledge in the hierarchic levels of abstraction that has to be handled by operation systems challenges product development. Useful tools are needed that help to manage this knowledge and to organise engineering processes. The iPeM as generic engineering process model can be considered as a universal structure for documenting and accessing this knowledge. In this section we present two approaches designed as first implementations of the iPeM in order to explore its applicability to real world processes. The exemplary implementations illustrate the advantages for structuring processes and point out weak points when applying the approach which are to be addressed by future research.

In these primary implementation cases the meta model was used to build implementation models. After completed projects, the resulting application models shall be used for the development of reference models for future engineering processes.

2.4.1 Implementation in an Industrial Environment

The implementation and validation of the expounded approach took place in cooperation with one of the leading solution providers for the print media industry using a SemanticMediaWiki with Halo-extension.

The implementation is characterised by four elements. Firstly, the documentation is designed referring to the iPeM approach with *separated but cross-linked systems of objectives and objects*. Secondly, these systems' *evolution can be tracked* during the engineering process by a continuous representation of the project's actual state. The third element is a functional-based subdivision of the necessary activities leading to a *hierarchy of levels of abstraction* as outlined in Section 2.3. Finally, *iterations are captured* by documenting the affected activities with the ambition of creating a fictive linear-chronological development process (Albers *et al.*, 2010c).

The application in the industrial context revealed several advantages and possible problems. The clear separation of objectives and objects helped to develop the correct thing in the correct way. The explicit linking structure allowed a comfortable and efficient change of perspectives between the objectives and the progress of the project respectively the latest version of the system of objects. The cross-linking of the hierarchic, functional structure helped to avoid interface problems between the systems and their corresponding sub-/super-systems. By the realisation of the knowledge base and the project documentation (in this case a product development process) within one (wiki-) system, a smooth and easy exchange of information *i.e.* knowledge was provided.

Problems were identified concerning the general acceptance *i.e.* comprehension of the iPeM as a mental model and its contained aspects such as system of objectives and objects and the activity matrix. It is sometimes not clear when and under which circumstances a system needs to get divided into several subsystems. It was questioned how much time should be spent on documenting and transferring the project's information into the knowledge base. An important conclusion was that the organisational culture of a company needs to accept and live for the approach of sharing knowledge (Albers *et al.*, 2010c).

2.4.2 Application in an Undergraduate-student's Project

The second exemplary application takes place in an undergraduate-student's project. In a team of four research assistants and 13 students of mechanical engineering an innovative automobile has to be designed. This engineering process started from scratch by identifying the market demands and will be accomplished with the roll-out of a prototype car.

Considering the aspect of knowledge management the challenge of this project is the huge amount of distributed information to be organised in one common document in order to capture the team's knowledge. Not only current work has to be supported but also future projects at the institute will benefit from the coherent knowledge base being generated during the engineering process.

In this application a semantic wiki system has also been chosen. The core idea of the representation is a twofold access to the knowledge base. In terms of the system of objects, the subprojects' information bases are arranged and represented in the order of their hierarchical level in the project. The documentation of the project's actual state can be described by the users directly in their subproject's workspace using the taxonomy of the iPeM. At the same time, the corresponding systems of objectives are connected via hyperlinks that enable users to switch to the description of their individual objectives as well as to the neighbouring constraints by a single mouse click (See Figure 2.4).

Before the application in the undergraduate-student's project an unstructured wiki system has been used as a platform for the students to share their contents. A survey revealed the need for an implementation of a meta model such as the iPeM that provides a structure in which designers are able to case-relatedly share knowledge and cooperate. The presetting of the formal structure of the iPeM *top down* in cooperation with the extension of the structure *bottom up* was due to project insights that the students found the deductive/inductive modelling approach from Section 2.2.3 to be helpful in operational use. Further results will be investigated in a second survey in the near future. The gained insights shall then be used as requirements for a revised implementation approach of the iPeM to be established in future work.

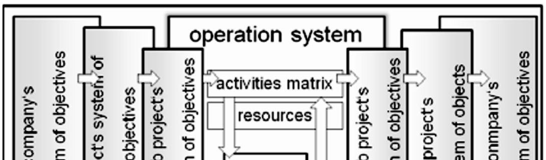

Figure 2.4. Layout of the wiki system in the student's project

2.5 Further Work and Conclusion

Today's product engineering processes are characterised by a huge complexity that amongst others can be explained by the multiple fractal character. One promising approach to handle this complexity is the model approach of the iPeM because it captures the different levels of abstraction of engineering processes. The application of the iPeM in wiki-based implementations has been suggested and exemplified. The two examples showed the general feasibility of the approach but also revealed weak points of current implementation approaches.

The pilot applications showed a basic practicability of the iPeM but also that further refinements of the approach are necessary. Changes in processes, organisational culture and parallel education about the use of the model are important to improve its benefit. However, the possibility to describe the gap between product life cycle activities and detailed engineering process steps through abstraction levels of activities has been shown. A revised implementation of the iPeM that satisfies the requirements that have been accumulated in the previous sections can lead to a concept that allows the approach to enter engineering processes in industry on a large scale. A new implementation of the approach that takes the findings of the exemplary applications into account is scheduled.

This paper develops the idea of using activities on different abstraction levels for modelling the transformation of systems of objectives into systems of objects. The main focus lies on the detection of multiple reasons for the fractal character of these levels. As self-similar structures could be verified, knowledge-management approaches that implement the fractal structures of the subsystems of the iPeM appear to be suited to handling the rising complexity of product engineering processes which has been affirmed in two exemplary applications. Further work will lead to an extensive and comprehensive implementation that will be used to validate the approach in sizeable industrial or educational projects with the overall aim to establish the applicability of the iPeM approach in the industry.

2.6 References

Albers A, Meboldt M (2005) SPALTEN problem solving methodology in the product development. In: Proceedings of the 15th International Conference on Engineering Design (ICED'05), Melbourne, Australia

Albers A, Meboldt M (2007) iPeMM. Integrated product development process management model, based on systems engineering and systematic problem solving. In: Proceedings of the 16th International Conference on Engineering Design (ICED'07), Paris, France

Albers A, Meboldt M, Deigendesch T (2008) Handling complexity - a methodological approach comprising process and knowledge management. In: Proceedings of the 7th International Symposium on Tools and Methods of Competitive Engineering (TMCE 2008), Kusadasi, Turkey

Albers A (2010) Five hypotheses and a meta model of engineering design processes. In: Proceedings of the 8th International Symposium on Tools and Methods of Competitive Engineering (TMCE 2010), Ancona, Italy, in press

Albers A, Muschik S (2010a) The role and application of activities in the integrated product engineering model (iPeM). In: Proceedings of the 11th International Design Conference (DESIGN 2010), Dubrovnik, Croatia, in press

Albers A, Muschik S (2010b) Development of systems of objectives in early activities of product development processes. In: Proceedings of the 8th International Symposium on Tools and Methods of Competitive Engineering (TMCE 2010), Ancona, Italy, in press

Albers A, Ebel B, Sauter C (2010c) Combining process model and semantic wiki. In: Proceedings of the 11th International Design Conference (DESIGN 2010), Dubrovnik, Croatia, in press

Browning TR, Fricke E, Negele H (2006) Key concepts in modeling product development processes, Systems Engineering, 9(2): 104-128

Browning TR, Ramaseh RV (2007) A survey of activity network-based process models for managing product development projects. Production and Operations Management, 16(2): 217-240

Clarkson PJ, Eckert C (2005) Design process improvement - a review of current practice. Springer Verlag, London, UK

Daenzer WF, Huber F (2002) Systems Engineering. Verlag Industrielle Organisation, Zürich, Austria

Ehrlenspiel K (2003) Integrierte produktentwicklung: Denkabläufe, methodeneinsatz, zusammenarbeit. Hanser, München, Germany

Hubka V, Eder E (1988) Theory of technical systems. Springer, Berlin, Germany

Hubka V, Eder WE (1996) Design science: Introduction to needs, scope and organization of engineering design knowledge. Springer-Verlag, Berlin, Germany

Meboldt M (2008) Mental and formal modeling, a contribution to the integrated product development model (iPeM). Institute of product development Karlsruhe (IPEK), Karlsruhe, Germany

Oerding J (2009) Ein Beitrag zum modellverständnis in der produktentstehung. Strukturieren von Zielsystemen mit Hilfe von C&CM. Institute of product development Karlsruhe (IPEK), Karlsruhe, Germany

Ropohl G (1979) Eine systemtheorie der technik: zur Grundlegung der Allgemeinen technologie. Hanser, München/Wien, Germany

Rupprecht C (2002) Ein Konzept zur projektspezifischen individualisierung von prozessmodellen. Dissertation, University of Karlsruhe, Karlsruhe, Germany

Sandmeyer P (2009) Christentum - die lehre der liebe. Stern Extra 5: 26-43

Sim SK, Duffy AHB (2003) Towards an ontology of generic engineering design activities. Research in Engineering Design, 14: 200-223

Wynn DC (2007) Model-based approaches to support process improvement in complex product development. PhD thesis, Cambridge Engineering Design Centre, University of Cambridge, Cambridge, UK

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