MULTI-SCALE PRODUCTION SYSTEM MODELLING
Motivation – Concepts – Method

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Abstract: This paper presents the first research steps and required foundations for the development of a method for a structured and multi-scale modelling of production systems. Thereby the importance to support the modelling process is stated and the motivation for the development of such a method is pointed out. State-of-the-art concepts in system theory as well as suitable modelling methods and their applicability on the production system modelling are analysed. The approach and the process of modelling a multi-scale production system are firstly introduced. The paper concludes with the selection of suitable enabling technologies and a roadmap of future activities.

1 INTRODUCTION

Manufacturers have to face shorter product life cycles, increasing number of variants and efficient integration of new technologies. These challenges induce an increasing number of adaptations of existing production systems and associated processes. Therefore production systems are characterized by evolved structures with high complexity and diversity, caused by permanent adaptation and integration of new technologies. However, reliable models of production systems are essential to understand the complex structure and are the basis for efficient processing of further planning and continuous adaptation as well as optimization (Jovane et al., 2009).

Production systems are complex socio-technical and multi-scale systems consisting of performance units. A multi-scale model of a production system can be developed to support a permanent "look ahead" with e.g. simulation to optimize and adapt existing production systems. Additionally it enables the development of suitable workflows or best practices. The increasing frequency of adaptation projects, the growing variety and complexity of production system structures and the suitable characterization of interdependences lead to an exponential increasing effort when developing, adapting and maintaining corresponding models (Brinkkemper, 1999).

This paper introduces our first research steps for developing a method for multi-scale production system modeling. As a first step in this research topic the technical aspects of a production system, consisting of machines, resources, equipment and production processes are considered. The organizational and social aspects are at the moment leaned in secondary plan.

Some terms used in this paper have to be clarified in advance. Today, a production system is approached as a complex socio-technical system, consisting of subsystems called performance units (Westkämper and Zahn, 2009). A performance unit is understood as e.g. a production cell, or a single workstation.

Thereby a performance unit can consist of several sub-performance units. Every sub-performance unit has different manufacturing objects, e.g., information, resources, material, tools or products. These objects and their related sub performance unit as well as performance units are related by such called interdependencies. These are represented by e.g. material, informational, energetic or functional properties.

After emphasizing the potential and the requirements for such a method, an overview over the state of the art in the fields of system theory as well as suitable modeling methods regarding their applicability on the production system modeling is given. Afterwards the approach is introduced. The

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paper concludes with a roadmap for future research activities to support a multi-scale modeling of the current state of a production system.

2 PRODUCTION SYSTEM MODELLING – MOTIVATION

A model is an important instrument to manage the complex structure of a production system and to enable its active configuration and optimisation, regarding its continuous planning and adaptation (Mertins et al., 1994). It comprises the needed performance units, objects and interdependencies in a transparent and application-oriented way and supports a consistent understanding of the current state of the production system (Vernadat, 2002). A model enables an efficient communication of all involved planning actors about relevant information and supports the explanation of the functionality of processes. It allows a fast reaction to a turbulent market through a permanent foresight and enables a continuous adaptation and balancing of the production system (Westkämper and Zahn, 2009). Furthermore a model is the basis for the description and analysis of different planning solutions (Vanja et al., 2009).

However, before and while modelling a production system certain issues emerge. Firstly the purpose of the model has to be clarified. Is the model used as a model to understand the complexity of a system or as a basis for further planning and adaptation processes. Regarding the last point a possible employment for simulations has to be considered in the modelling process. Secondly, an important step is to define system boundaries. These boundaries vary for every application of the model, depending on the performance units, objects and production processes taken into account (Mertins et al., 1994). Thirdly, a suitable application-oriented characterisation of the interdependencies between the objects and the implementation of necessary data and information, as well as knowledge is needed (Vanja et al., 2009). Fourthly, the modelling of complex structures has to be supported by suitable modelling methods (Scheer, 1994). Today a huge number of modelling methods exist and each has its own advantages and disadvantages as well as limitations. The selection of a suitable method to generate a specific application-oriented model is a difficult task, and is mostly done using common sense and intuition (Schen et al., 2004). Fifthly, the comprehensibility of a model and its level of detail have to be suitable for its specific application. An extensive model with all performance units, objects and interdependencies is not expedient, because of the huge modelling effort (Mertins et al., 1994). A model with a reduced level of detail may not be able to provide a suitable accuracy (Feig et al., 2004).

Also the development of a single and overall production system reference model is not suitable to represent the conditions and to consider all the needs of different manufacturers, due to its generic structure (Vernadat, 2002). However owing to the high variety and complexity of production systems a range of smaller generic reference models of production systems are not efficient. These smaller reference models have to be adapted for every individual application, which generates huge effort (Mirbel and Jolita, 2005).

Modelling of productions systems, as presented, is a complex task which requires a huge amount of experience, effort and implicit as well as explicit knowledge. Based on this fact, the development of a model is usually performed interdisciplinary between a factory and process planner and a modelling expert. The planner has the necessary knowledge of the production system and its corresponding technical processes and the modelling expert possesses the required knowledge of the modelling methods and languages. To develop a model, the planner has to describe the functionalities of production system objects and the interdependencies in an understandable language for the modelling expert. Different ways of thinking and different terminologies often make this a complex, difficult and time consuming task (Scheer, 1994).

This paper proposes a method that enables an efficient development of a structured and application-oriented model of the current state of a production system. With such a method the selection of a suitable modelling method is based on theoretical and empirical foundations, which allows an efficient application-oriented modelling of the considered part of the production system (Shen et al., 2004). Additionally, this method is able to decrease the effort and complexity of developing a specific production system model by structuring the modelling process in an application-oriented way. Through embedding knowledge of the modelling process the planner is able to develop an application-oriented model of a complex structure like a production system. Furthermore the modelling of interdependencies between performance units or objects and their appropriate characterisation is supported, so that they require less experience and effort.

3 PRODUCTION SYSTEM MODELLING – TODAY

Today's production system modelling relies on different concepts, approaches and methods. These provide the foundations to represent the performance units, objects and interdependencies of a production system in a suitable and multi-perspective way. The first section addresses the state-of-the-art concepts in system theory and their applicability on the production system. The second section addresses and examines modern modelling methods in order to evaluate their employment for MePro. The third section explains the foundations for developing a modelling method as a basis for MePro.

3.1 System Theory as a Basis for Production System Modelling

Since the beginning of the sixties the system theory is an interdisciplinary science and is employed and further developed in different research fields like biology, physics or economics (Bertalanffy, 1964). The overall goal is the representation of general systems on an abstract level through the use of consistent terms and tools, to be able to predict the future behaviour and performance of a system (Westkämper and Zahn, 2009). Thereby a system or a production system is described as an open, dynamic, productive and socio-technical organisation (Hermann, 2010). A model developed from the system theory perspective comprises an arrangement of elements, which are defined through specific attributes, connections and different activities within a determined system boundary.

Today production systems are modelled through the employment of generic system theory, due to the fact that they are defined as complex socio-technical and multi-scale systems (Westkämper and Zahn, 2009). Thereby a production system can be approached using different concepts. (Ropohl, 2009) (Figure 2).

- Functional concepts are also known as black box systems. In these concepts a system is described through the attributes input, output and condition of an object (Schenk et al., 2010).
- Structural concepts represent objects and their interdependencies within a system. Thereby the behaviour and characteristic of the system is more than the sum of its parts (Ropohl, 2009).
- Hierarchical concepts represent a system with their related sub- and supersystems. Several subsystems represent a system. A supersystem in turn can consist of several individual systems (Westkämper and Zahn, 2009).

There are several approaches to represent a production system through the employment of one, two or all mentioned concepts (Schenk et al., 2004).

To visualise process chains the functional concept is employed. Thereby the sequence of processes is shown and potential for improvement, e.g. parallelisation of processes, can be revealed. This concept is used in the product development process (PEP). The structural concept is employed to model the arrangement of the production system layout. Thereby machines, resources and information systems and their interdependencies are taken into account. Hernandez developed a generic system theory model, considering all three concepts, of an organisation to assess the flexibility and adaptability of a factory (Hernández, 2003). Schenk, Wirth and Müller developed a model, based on system theory, to represent and structure existing flows (e.g. material, information, energy, cash flow) in a factory (Schenk et al., 2010). One of the most advanced approaches to represent a production system through the use of system theory is the "Structure Model of Factory Scales" (Jovane et al., 2009).

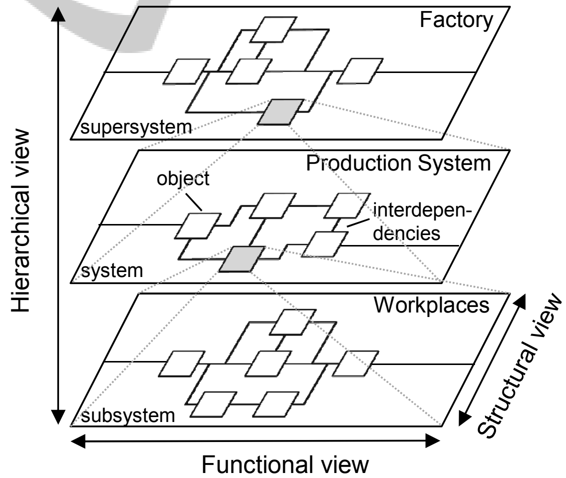

Figure 2: System theory concepts of production system structure (adapted from Hermann, 2010).

Thereby the mentioned concepts are employed and unified to one generic structure model of a production system. These approaches provide the foundation for the representation of a complex system like a production system, regarding its performance units, objects and interdependencies, which will be analysed to be used and/or adapted for MePro.

3.2 Modelling Methods

To model complex systems, like production systems, with their objects and interdependencies state-of-the-art modelling methods have to be employed. They consist of modelling notations, -languages and instructions to describe a system and to support the structuring, representation and visualisation of a specific part of a system. But even for a specific part of a system, a great number of models and different points of view have to be considered for an application-oriented representation.

However, each modelling method has its specific advantages, disadvantages and limitations regarding the representation of a system (Shen et al., 2004). To cluster the modelling methods, they are classified according to their modelling paradigms. The main modelling methods are described in the following section.

- Object-oriented modelling methods (OOMM) enable an integrated modelling of information and functions of objects. These objects are defined through attributes and linked with relations. The object oriented modelling is employed in the research field of production modelling in several research works (Schady, 2007). The modelling of non-physical objects however is insufficient (Schady, 2007).
- Process-oriented modelling methods (POMM) enable the representation of defined sequences of transformation processes regarding an object like material or information. Within the production system modelling production- and logistics processes, like material flows or value streams are modelled. The description of objects behind the processes with POMM is insufficient (Scheer, 1994).
- Ontology-based modelling methods (OBMM) enable a detailed description of interdependencies between objects of a production system model. These modelling methods create a higher effort while modelling, but offer great possibilities regarding maintenance of knowledge bases and expressiveness of knowledge representation (Hitzler et al., 2008).
- Graphic-oriented modelling methods (GOMM) enable the representation of objects in a 2D or 3D model. These models are used to visualize e.g. the layout of a production system and the material flow in a production system (Schady, 2007).

These modelling methods can provide a valuable contribution to the approach introduced here. In this context it has to be clarified which modelling method or combination of modelling methods enables an application-oriented and efficient modelling of a production system.

4 DEVELOPMENT OF MODELLING METHODS

To support an efficient, structured and application-oriented production system modelling, a suitable method has to be developed. In this case a method is an approach to perform a model development, based on a particular way of thinking and consists of constructs and rules and also knowledge that allow a structured and systematic modelling of a specific part or perception of a production system (Brinkkemper, 1999). On the one hand a modelling method limits the flexibility of modelling through the use of constructs and rules, on the other hand it allows making models more comparable and reusable. Within the development of a method for production system modelling, different aspects have to be considered (Lankhorst, 2009; Wenzel et al., 2005):

- Modelling (syntactic aspect), identifies the concepts and modelling methods for modelling a particular system. It deals with data integration and data maintenance as well as exchange formats.
- Working (semantic aspect), defines tasks and subtasks and provides guidelines and workflows for the modelling process. It includes the meaning of used signs, elements and symbols and their structuring concepts. This aspect ensures the correct meaning of the modelled information.
- Communicating (pragmatic aspect), defines the representation (e.g. spatial, format, application) of a model and puts the meaning of the used elements in the correct context.
- Using (pragmatic aspect), defines for what situation, perception or application a model is suitable.

As a basis for such a method and to consider these aspects a metamodel has to be employed (Mirbel, 2005). A metamodel can be seen as a conceptual model of a development method. Considering this metamodelling takes place at one level of abstraction higher than standard modelling (Brinkkemper, 1999). A metamodel comprises suitable concepts for modelling and related modelling methods for a particular system e.g. a particular part or perception of a production system. It defines the used exchange formats, communication protocols and architectural concepts. Through this, the mentioned aspect of modelling (syntactic aspect) is represented in the method to develop. Additionally, a metamodel considers the process of modelling and provides paradigms and guidelines in form of method knowledge and rules to generate a model, with respect to the objects and interdependencies in a system (Lankhorst, 2009). It comprises conventions, tasks and concepts to include semantic aspects. Owing to this, the aspect of working (semantic aspect) is considered in MePro. Every modelling method provides a range of elements and fulfils different purposes regarding modelling a system (Vernadat, 2002). A metamodel can suggest suitable modelling methods for a specific modelling application, through the employment of comparison and systematisation methods that characterise modelling methods according different attributes (Söderström et al., 2002). So, the mentioned aspects of communication and using (pragmatic aspect) are considered.

The analysis of existing metamodels and workflow schemes for modelling a production system provides a basis for the development of the Method for Multi-Scale Production System Modelling (MePro).

5 PRODUCTION SYSTEM MODELLING – MEPRO

The pursued approach aims at the employment of a method to enable a structured and multi-scale modelling of production systems in an application-oriented way. Here, structured means to support the modelling process by workflows or guidelines for an efficient development of a production system model. A workflow, in this context, is a semi-automated realization of a modelling process on the basis of schemes and management systems. It defines which element, information or document is used in which step of the production system modelling. It also supports the description of interdependencies between objects and/or performance units (Wenzel et al., 2005). Through this, necessary inter-dependencies between performance units and its objects to model a specific aspect of a production system can be represented.

To structure the MePro modelling process suitable system theory models of production systems will be analysed, employed and refined. This enables an efficient application-oriented development of a model. Parts of models which can be reused or attributes of objects and interdependencies which can be predefined have to be identified and provided by MePro, to enable an efficient modelling process. Therefore a supporting resource library for objects and interdependencies will be employed. Additionally suitable detailed reference models for application-oriented production system modelling have to be identified and analysed regarding their applicability and integration in MePro.

Multi-scale considers the possibility of different views on a production system for different end users. This means, that a specific model of a production system is represented in the way of e.g. business processes, information flow, material flow (Mertins et al., 1994). Multi-scale also means that the model of a production system is represented with the appropriate level of detail along the different scales and regarding specific aspects of a production system. Therefore multiple modelling methods along the production system structure, which reaches from processes, machines and workplaces to production systems, have to be employed. The selection of a suitable modelling method for a specific application and representation is supported by a selection method. This selection method uses criteria and suggests a suitable modelling method for a modelling application regarding the developer, the end user, the level of detail and the application field. Fields of modelling of a production system, which have to be considered, are e.g. information and material flow modelling (Mertins et al, 1994). To enable a structured and multi-scale modelling process a metamodel, which conduces as a foundation for MePro, is employed. This metamodel supports the development of a modelling process by providing knowledge and rules concerning the aspects mentioned in Section 3.3.

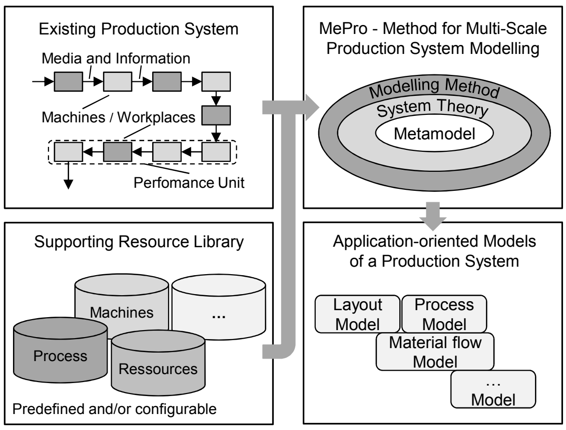

Figure 3: Method for Multi-Scale Production System Modelling (MePro).

With respect to the mentioned facts an efficient and application-oriented modelling of the current state of the production system with a method called Method for Multi-Scale Production System Modelling (MePro) is supported (Figure 3).

6 ROADMAP TO MEPRO

The development of a method for structured and multi-scale modelling of an existing production system is a new and complex research topic where future steps are of huge interest. Thus, the next research steps for building the foundations of MePro are the analysis and evaluation of:

- System theory for production system modelling;
- Application fields for production system modelling and of existing modelling methods;
- Existing production system resource libraries;
- Metamodels for modelling processes;

The research results will be merged in a MePro. Different challenges have to be considered on this way:

- Development of criteria for application-oriented modelling method selection;
- Development of workflows for an application-oriented modelling of a production system;
- Development of a supporting resource library with predefined and/or configurable objects and interdependencies.

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