Adaptable Capability-Based Planning

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Abstract: Future manufacturing systems are required to be adaptable and to quickly react on changes in markets and demands. There is a shift towards mass customization. Therefore, future manufacturing systems must be able to support individualized products that are tailored to customer needs. The switch between different products should involve little manual intervention. In this paper, the issues that need to be resolved to achieve adaptability in production planning are highlighted and ideas for solutions are presented. A detailed approach for the question of automatically generating action sequences is presented here. It is based on a capability model of the resources and their material flow. We also suggest decoupling product descriptions from factories and planning adaptably based on pre-defined product descriptions and factory setups. Action sequences can then be generated out of these models and later translated into executable action sequences. The action sequence can be automatically downloaded and executed on a resource. The presented approach is evaluated on an educational production system with industrial components. Issues and future research directions are illustrated as well.

Keywords: Flexible manufacturing systems, Information technology, Planning

1. INTRODUCTION AND MOTIVATION

There is a trend towards personalized products (Koren, 2010) following the shift towards mass customization that is slowly replacing mass production (Iacocca Institute, 1991; Hu et al., 2008). This is driven by customer demands that vary over time. Suppliers are forced to be more flexible in their processes to be economically viable in saturated markets (Westkämper and Decker, 2006). Support of heterogeneous products with low volume is a key characteristic for manufacturing systems to compete in highly competitive markets. Future production is characterized by being product-driven. Therefore, switching between different products should be possible with little manual intervention. Moreover, they are characterized by being adaptable, intelligent, and versatile (Zor et al., 2010).

The research ideas presented here aim at enabling quick product-based adaptations of manufacturing systems. The goal is to reduce planning and scheduling effort by automatically generating action sequences that consider product requirements as well as factory setups. A factory setup includes all available resources and their connections.

Flexibility can be increased through decoupling product descriptions from manufacturing systems. Production processes are no longer described based on available resources. Instead, a generic description with all required parameters is defined once and later used with different factory setups. Afterwards, the generic description is automatically transferred to a factory-specific description.

Additionally, a capability-based approach is used for production planning and scheduling. Generic product descriptions and production resources are described in terms of required capabilities and provided capabilities respectively. Moreover, the topology of the factory is described to model possible material flows within the manufacturing system. These descriptions are combined to automatically generate action sequences that consider the material flow without manually reconfiguring the software. These action sequences are translated into executable action sequences that can be downloaded to the resources and executed. Resources have to provide predefined interfaces that give access to available control code implementations to execute actions (Zoitl et al., 2013).

The remainder of this paper is structured as follows: Section 2 gives a brief introduction of the research questions. The state-of-the-art is sketched in Section 3.The required models to enable the approach are explained in Section 4. Section 5 illustrates the suggested approach for production planning. Section 6 describes the future directions of the research. Finally, Section 7 concludes the paper.

2. RESEARCH QUESTIONS

While current approaches have not been a problem in the past, they can no longer be used for future requirements. These approaches where economically viable in a mass production environment that required high throughput at a low cost. However, with the shift towards mass customization, every order has to be considered individually and production strategies for each of them have to be developed separately (Wiendahl, 2002). A fast reaction to dynamic changes is necessary (Schuh et al., 2008). Such flexibility can be achieved by moving decision-making processes from

Enterprise Resource Planning (ERP) down to Manufacturing Execution Systems (MES) (Bratukhin and Sauter, 2010) and making MES more flexible. The production planning and control part is especially important in that case for being economic in industrial countries (Scholz-Reiter and Hamann, 2008; Hamann, 2008).

The goal of this research is to find approaches to make IT and production planning systems in the manufacturing industry more flexible. The focus is on production planning since there is a gap in that field and it is important for the economic viability of the solution. Instead of having fixed production plans for production, this research investigates how to dynamically react on changes and have an individual strategy for each product and its variant. As a result, down times of manufacturing systems should be reduced which helps companies - especially small and medium sized enterprises - stay profitable.

The problem statement above leads to the following research questions that have to be answered:

- How to model workflows in manufacturing? This question is important because it will look into ways to decouple product-specific data from factory-specific data. By doing this, changes in the factory will not affect the description of product-specific information. Thus, production strategies can be developed for each product individually based on this description.
- How to model resources and factories? It is necessary to include information about resource capabilities, possible material flows through the factory, and logistics information to automatically react on changes in an adaptable manufacturing system.
- How to generate valid action sequences? This question aims at finding approaches to facilitate automatic planning of production while reacting on changes in the factory. This is important to improve flexibility.
- How to optimize generated schedules in a multi-product manufacturing system? In order to stay profitable, this question needs to be answered to show that the approach can be used in industrial setups.
- How to handle changes and errors during production? Since production is not always foreseeable and changes and errors can happen at any time, it is necessary to look at error handling and dynamic change management. The idea is to make the approach work even with errors during production.

This paper gives a brief overview of modeling workflows and generating action sequences for adaptable manufacturing systems that can later on be directly executed by production resources. Ideas for solving the other problems are presented in the end. How to define suitable capabilities that can be used within the workflows and resource models is out of scope of this research.

3. STATE OF THE ART

There has been plenty of work in the field of changeable and reconfigurable manufacturing systems due to its increasing importance for future manufacturing. Some approaches to achieve adaptability are explained here.

Wiendahl et al. (2007) give a definition of changeability and the characteristics required in such a system. However, they focus only on the aspects concerning the design of factories. In contrast, the goal of this research is to address the issues related to vertical integration from shop floor to management level.

The approach described by Naumann et al. (2007) introduces the concept of capability descriptions to automatically integrate new devices. Unlike the approach here, they only use the approach for robot cells and do not extend it to include the rest of the manufacturing system. Besides, they focus more on reducing the programming effort, whereas this work aims at reducing configuration time and increasing the adaptability of production systems. In addition, the suggested approach uses models to encode capabilities, which can then be used to automatically configure the different manufacturing stations.

Capability-based approaches are becoming more popular, since they offer more flexibility. However, available approaches mostly have a different focus. Ollinger et al. (2011), for example, use a service-oriented description to ease integration of components. The advantage in this case is the ability to reuse control programs. Järvenpää and Torvinen (2013) also follow a capability-based approach, but use it to evaluate the impact of changes in adaptable manufacturing systems. The capability-based approach serves as an assessment function for the effort needed to adapt to a change.

Zäh et al. (2008) propose a similar approach to ours. They also propose to describe production processes and resources in terms of capabilities. However, they do not model the material flow and the topology of the factory. Production plans are optimized locally on a resource level. Additionally, they suggest using RFID technology to store production plans and plan and schedule according to the information on the RFID transponders. However, RFID is not always suitable for real-world setups due to interference problems, read/write speed, and limited storage capacity Vrba et al. (2008).

There has been much work in the past years to increase software quality and re-usability of control software, e.g., (Sünder et al., 2006; Eckert et al., 2012; Sorouri et al., 2012; Zoitl and Prähofer, 2012). The approaches mainly try to develop design patterns and improve the development of control software to achieve this. However, they focus on control software of a resource only and not on generating the equivalent action sequences. Additionally, they target rigid control software and focus on how to manage variability for different resources. In our case, we also consider that different products and their variants might be produced on the same resource. The resource must be able to support different action sequences and be able to work in different factory setups containing different resources. The goal is to allow the execution of different operations on the same resource depending on the desired product. Nevertheless, such modular concepts for control software are necessary to enable such an approach. They act as a starting point for our approach.

There has been much work in the field of recipes in manufacturing as well. They are similar to action sequences but more static and defined manually for each resource. Examples are standards like ISA 88 developed by the International Standardization Association for the process industry (Brandl, 2006). Similar concepts for the discrete manufacturing exist, e.g., PackML guideline (Arens et al., 2006). General requirements of recipes are defined in NE033 (NAMUR, 2003) by the NAMUR association.

In the field of agent-based planning and scheduling there has been plenty of work to develop suitable platforms and planning strategies (Bussmann and Schild, 2001; Gabel and Riedmiller, 2008; Leitão, 2009; Lepuschitz et al., 2013). Holonic manufacturing tackles similar problems. They are used for coordination and sequencing of resources (McFarlane and Bussmann, 2003; Lohse et al., 2005). Such approaches focus on negotiating schedules and allocating resources for operations. The agents execute available code depending on the negotiated schedule.

Alexakos et al. (2012) propose the use of a multi-agent system to achieve adaptive manufacturing. They suggest using an ontology to control production processes. This approach requires that agent software has to be implemented for each control program, which has to be done for each manufacturing system separately. We suggest using models to describe capabilities. These models are independent from the actual setup and can be reused.

In contrast to the presented approaches, the approach proposed in this work aims at automatically generating a production schedule that considers the material flow without having to manually model the problem whenever a change occurs. It does not locally optimize at resource level but rather has a global view on the production process. It can later be combined with genetic and evolutionary approaches to further optimize production.

4. SYSTEM MODELING

To achieve adaptability in planning systems, a generic description of the required production steps as well as the available production resources is necessary. A production step denotes the description of a process with all its parameters that occur at one point in time during production. It contains information about the process like its name and its parameters. Production steps are combined together in workflows to represent a complete description of the production. The workflow includes the involved production steps as well as the order in which these steps have to be executed to result in the right product. Production resources in this context refer to hardware entities that can execute production steps and are called resources throughout this paper. Different production resources are combined to form factories. The workflow model and the factory model can then be combined to generate a factory-specific action sequence that can be executed on the resources. In order to make this approach work, a common vocabulary has to be available and used for modeling.

4.1 Workflow Modeling

The goal here is to decouple production workflows from the actual manufacturing system in order to be more flexible. Currently, production processes are rarely described explicitly, but are rather fixed for a factory setup. They are highly integrated with the control software. Therefore, resources have to be reprogrammed and reconfigured whenever new workflows are introduced or the factory setup changes. The control software cannot be reused as it is done in service-oriented solutions.

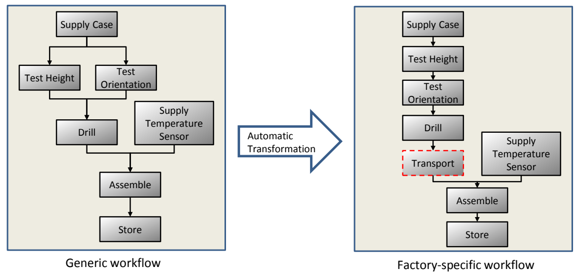

Fig. 1. Transformation of a generic workflow into a factory-specific one.

The proposed approach to tackle this problem is to modularize production processes into atomic production steps that encapsulate certain processes. The steps should abstract from specific implementations and technical information related to the factory setup. Each step contains the required capability as well as production-specific data. Examples for such data are raw materials and products, geometry, process-related data like temperature, and error tolerance and quality requirements. Defining the capabilities that can be used in such workflows depends on the used processes and the domain-specific terms and is out of scope of this research. However, for the evaluation example capabilities are defined to show the feasibility of the approach. The workflow is then composed of such atomic production steps with all the data and the dependencies between them as depicted in Fig. 2. During planning, this generic workflow can be transformed automatically into a factory-specific workflow as illustrated in Fig. 1.

4.2 Modeling Resources

A resource model consists of all its capabilities as well as its internal material flow. A resource is composed of several modules that offer a specific capability. For the defined capabilities, constraints and parameters can be added to enable using the same capability but for different materials for example. Examples for constraints are geometry of materials, timing parameters for capabilities, or material type. The internal material flow represents the connections between the different modules. Each resource also offers an interface to its implementation of the capabilities. This is used to feed the resource with the right parameters depending on the desired product. A detailed example can be found in previous work (Keddis et al., 2013).

4.3 Modeling Factories

After modeling the resource capabilities and internal material flow, instances of the resource models can be combined to model a whole factory. Additionally, external material flow information has to be added to the model to ensure that only feasible action sequences are generated. This is achieved by describing input and output points of each resource in addition to its capabilities. Resources can also have connection points that are used as input as well as output points. The connection points are bidirectional. The material flow is then modeled as connections between connection points of resources. The graph in the lower left box in Fig. 2 depicts a factory model with external material flow information represented by the arrows in the graph. The factory model can be automatically generated at run-time (Keddis et al., 2013). For this, each resource informs the planning system about its availability, capabilities and neighbors. The factory model is then composed out of the gathered information.

This model can be used to check the logical model of the material flow. However, the physical compatibility of the different production resources has to be guaranteed as well. This is out of scope of this research.

5. FLEXIBLE PLANNING

In adaptable manufacturing systems several products can be produced using the same resources. If it is possible, the factory setup is reused for the different products and only the action sequences are updated accordingly. In some cases a change in the factory setup might be necessary. Changes include adding or removing resources, or changing the position of a resource within the factory. It is also possible to use different modules of a resource for different products. In order to automatically generate action sequences for the different products, two aspects have to be considered during the generation process: the product description and the factory setup. These can then be combined to automatically generate executable action sequences. Fig. 2 illustrates this approach.

5.1 Capability-based Planning

The production workflow as well as the factory setup can be used as a starting point for automatic generation of action sequences. The workflow models and the capability-based descriptions of resources in the factory can be combined to determine a mapping from operations to resources. A simple matching algorithm can be used to determine such a mapping. The initial mapping can be refined to only consider possible material flows and hence only generate action sequences that match the current factory setup. In this section, the algorithm that was developed based on the approach depicted in Figure 2 is introduced. It automatically generates action sequences based on the capability models of the production resources. It starts with a definition of the production plan for a specific product illustrated in the upper left corner. Based on the required capabilities and the factory setup (both shown in the lower left corner), a resource mapping can be calculated. This can be extended to only include solutions with valid material flow. The best action sequence is then used to control the production. Which action sequence is the best, depends on the defined optimality criteria that were chosen by the users. This was not part of the evaluation, but is intended in future research.

The proposed solution is to use a complete search with branch-and-bound and backtracking to generate action sequences. The first step of the scheduling procedure results in a mapping of required capabilities to available resources. For each capability in the workflow model, a list of possible resources that provide the capability is generated. By iterating over all available resources in the factory and using a simple matching algorithm, such a list can be provided for each step in the workflow. The resource mapping is the starting point for the material flow calculation in the following step. Since the factory can have different topologies, the resource mapping is not sufficient. The topology refers to how resources are connected in the factory, meaning which resource is next to which. Therefore, it is also necessary to check whether the material can flow between the chosen resources. This is achieved by generating action sequences based on the resource mapping and the factory topology information. In order to maintain precedence relations between operations the action sequence is generated backwards, i.e., the last step of the workflow is inserted in the action sequence first but at the end of the sequence. The operations that are scheduled afterwards are inserted at the beginning of the action sequence. Thus, the starting point is the sink of the workflow. This ensures that no operation is scheduled before its predecessors are finished.

The last step of this approach is the automated control of the production. After a valid action sequence is generated for each ordered product, the production can be started automatically. For this, operations in the action sequence are translated into resource recipes that can be executed on the resource. Each resource maintains a list of operations that are scheduled on it. The lists are a result of splitting the generated action sequence according to resources. When the system is ready, the central control system sends a “start production” signal to all resources. The resources start with the first operation in their list. Whenever a resource finishes an operation, it informs the supervisory control system which starts the next operation if there are operations left in the list. The production is finished when all operations are done.

5.2 Evaluation

A simplified industrial manufacturing system for educational purposes is used to evaluate the approach. It consists of different combinable resources from the Festo Modular Production System. One possible setup is shown in Fig. 2 in the lower right box [1] . A detailed description of the setup can be found in our previous work (Keddis et al., 2014). The evaluation showed that switching between different setups and calculating action sequences for different products on each setup was possible without manual intervention.

6. FUTURE RESEARCH DIRECTION

As mentioned earlier, the goal of this research is to make planning systems for manufacturing more adaptable. The presented results are a good starting point to achieve this. Nevertheless, there are still some open issues that need to be addressed to make this approach feasible for industry.

6.1 Optimization of Schedules

To have an economically viable solution for the industry, it is not sufficient to just generate an action sequence for a single product. The generated action sequences have to

[1] The experimental setup and the results can be seen in the following video: http://www.youtube.com/watch?v=Tkcv-mbhYqk.

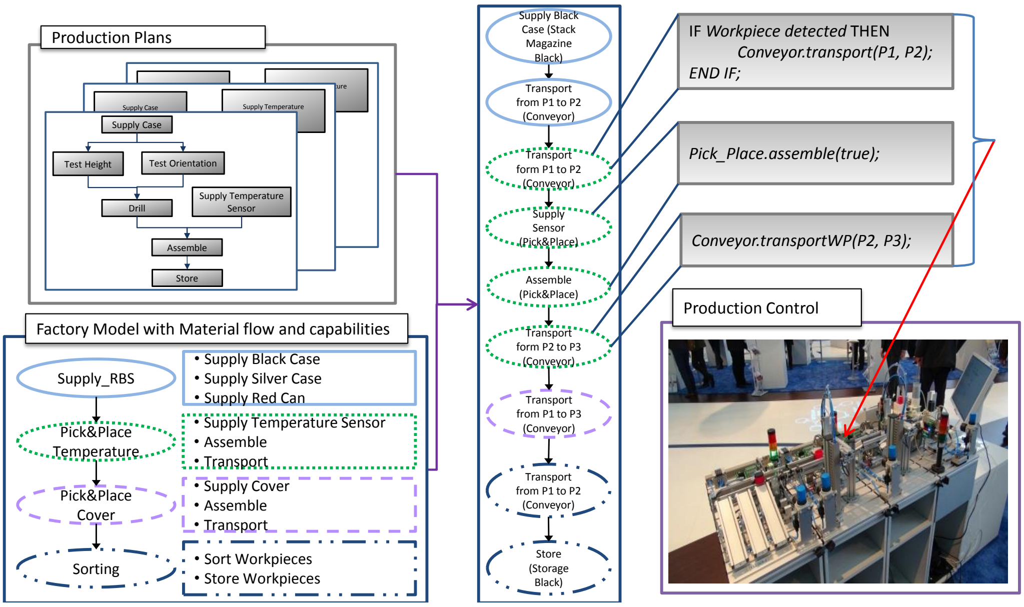

Fig. 2. The workflow for generating action sequences. A valid action sequence is generated from the product and factory descriptions. This is later translated into an executable action sequence.

be scheduled in an efficient manner. The schedule should include different products and optimize the production based on the defined criteria. Examples could be throughput, energy-efficiency, or costs. The main question is which efficiency criteria are important and what the trade-off between optimality and flexibility is.

For this, future research will look into developing and implementing algorithms that can automatically transform the generated action sequences into problem instances for scheduling with timed automata or genetic algorithms. The choice will depend on the evaluation of scheduling techniques. Timed automata show a good potential for scheduling in manufacturing (Panek et al., 2008). Genetic algorithms got a lot of attention in the past, since they can handle multiple criteria and a large solution space. Therefore, this alternative should be evaluated as well.

6.2 Error and Change Management during Production

Another important question in this context is the dynamic adaptation to changes and the automatic handling of errors during production. Currently, the modeled workflows only cover the error-free case and reactions on errors and changes require manual steps. This is timely and costly. Of course some errors cannot be handled automatically and need manual intervention. The first idea is to reroute workpieces through the factory when production resources are not available anymore. Another scenario involves rerouting workpieces to a defined waste resource if process errors occur that affect the quality of the product. In this case, a substitute action sequence is scheduled afterwards to deliver the order. The third aspect of error handling involves a specific definition of error handling in the production workflow. Whenever an error occurs, the defined procedure is triggered according to the workflow and the necessary steps are scheduled on the resources.

Hence, the proposed solution involves modeling the error-handling in the production workflows as well. Alternatively, the waste position needs to be modeled in the factory setup and the route is then calculated at runtime. In the second step the state of the resource needs to be monitored to detect changes and errors. Whenever errors occur, the corresponding path in the workflow can be used to react or the route to the waste position can be calculated. The calculation of new routes or routes to waste resources is done using the same mechanisms of planning defined in this paper and in earlier research. Afterwards, substitute orders can be generated in case the error results in a faulty product. In all other cases, an automatic rescheduling should be triggered.

7. CONCLUSION

In this paper an approach for planning in adaptable manufacturing systems was presented. The approach takes the requirements of the product into consideration and generates an action sequence that can be executed directly on the given manufacturing system. The product requirements are described through workflows and include all process-related data. For different products and factory setups different action sequences were generated without manual effort and user interaction. The action sequences were automatically downloaded to the resources when needed and the production was triggered and executed without further intervention. The approach can be extended in the future to include error handling and reaction on changes in the production environment. Additionally, action sequences for different products should be scheduled in an optimized manner that allows flexibility.

REFERENCES

Alexakos, C., Georgoudakis, M., Kalogeras, A., and Likothanassis, S. (2012). Adaptive Manufacturing Utilizing Ontology-driven Multi-Agent Systems: Extending Pabadis' Promise Approach. In *IEEE Int. Conf. on Industrial Technology (ICIT)*, 42–47. IEEE.

Arens, D., Hopfgartner, T., Jensen, T., Lamping, M., Pieper, M., and D., S. (2006). *Packaging Machine Language V3.0 Mode & States Definition Document*. OMAC Motion for Packaging Working Group.

Brandl, D. (2006). *Design Patterns for Flexible Manufacturing*. ISA.

Bratukhin, A. and Sauter, T. (2010). Distribution of MES Functionalities for Flexible Automation. In *8th IEEE Int. Workshop on Factory Communication Systems (WFCS), 2010*, 157–160. IEEE.

Bussmann, S. and Schild, K. (2001). An agent-based approach to the control of flexible production systems. In *Proc. of the 8th IEEE Int. Conf. on Emerging Technologies & Factory Automation*, volume 2, 481–488. IEEE.

Eckert, K., Hadlich, T., Frank, T., Fay, A., Diedrich, C., and Vogel-Heuser, B. (2012). Design Patterns for Distributed Automation Systems with Consideration of Non-Functional Requirements. In *IEEE Int. Conf. on Emerging Technologies & Factory Automation (ETFA)*. IEEE.

Gabel, T. and Riedmiller, M. (2008). Adaptive Reactive Job-Shop Scheduling with Reinforcement Learning Agents. *Int. Journal of Information Technology and Intelligent Computing*, 24(4).

Hamann, T. (2008). *Lernfähige intelligente Produktionsregelung*, volume 7. GITO mbH Verlag.

Hu, S., Zhu, X., Wang, H., and Koren, Y. (2008). Product Variety and Manufacturing Complexity in Assembly Systems and Supply Chains. *CIRP Annals-Manufacturing Technology*, 57(1), 45–48.

Iacocca Institute (1991). 21st Century Manufacturing Enterprise Strategy: An Industry-Led View. Technical report, Iacocca Institute, Bethlehem, Pennsylvania.

Järvenpää, E. and Torvinen, S. (2013). Capability-based Approach for Evaluating the Impact of Product Requirement Changes on the Production System. In *Advances in Sustainable and Competitive Manufacturing Systems*, 173–185. Springer.

Keddis, N., Kainz, G., Buckl, C., and Knoll, A. (2013). Towards Adaptable Manufacturing Systems. In *IEEE Int. Conf. on Industrial Technology (ICIT), 2013*, 1410–1415. IEEE.

Keddis, N., Kainz, G., and Zoitl, A. (2014). Capability-based Planning and Scheduling for Adaptable Manufacturing Systems. In *IEEE Int. Conf. on Emerging Technologies & Factory Automation (ETFA)*. IEEE.

Koren, Y. (2010). The Global Manufacturing Revolution. *John Willey & Sons, New Jersey*.

Leitão, P. (2009). Agent-based Distributed Manufacturing Control: A State-of-the-art Survey. *Engineering Applications of Artificial Intelligence*, 22(7), 979–991.

Lepuschitz, W., Groessing, B., Merdan, M., and Schitter, G. (2013). Evaluation of a Multi-Agent Approach for a Real Transportation System. In *IEEE Int. Conf. on Industrial Technology (ICIT), 2013*, 1273–1278. IEEE.

Lohse, N., Hirani, H., Ratchev, S., and Turitto, M. (2005). An Ontology for the Definition and Validation of Assembly Processes for Evolvable Assembly Systems. In *The 6th IEEE Int. Symposium on Assembly and Task Planning: From Nano to Macro Assembly and Manufacturing, 2005. (ISATP 2005)*, 242–247.

McFarlane, D.C. and Bussmann, S. (2003). Holonic Manufacturing Control: Rationales, Developments and Open Issues. In *Agent-based Manufacturing*, 303–326. Springer.

NAMUR (2003). *NE 033 Requirements to be met by Systems for Recipe-Based Operations*.

Naumann, M., Wegener, K., and Schraft, R. (2007). Control Architecture for Robot Cells to Enable Plug'n'Produce. In *IEEE Int. Conf. on Robotics and Automation*, 287–292. IEEE.

Ollinger, L., Schlick, J., and Hodek, S. (2011). Leveraging the Agility of Manufacturing Chains by Combining Process-oriented Production Planning and Service-oriented Manufacturing Automation. In *Proc. of the 18th IFAC World Congress*.

Panek, S., Stursberg, O., and Engell, S. (2008). Produktionssteuerung auf der Grundlage von Echtzeitautomaten (Production Scheduling Using Timed Automata). *at-Automatisierungstechnik*, 56(4/2008), 171–180.

Scholz-Reiter, B. and Hamann, T. (2008). The behaviour of learning production control. *CIRP Annals-Manufacturing Technology*, 57(1), 459–462.

Schuh, G., Gottschalk, T., Höhne, T., Welter, T., and Hille, P. (2008). Dezentrale Montagesteuerung im variantenreichen Maschinen- und Anlagenbau. *Werstattstechnik online*.

Sorouri, M., Patil, S., and Vyatkin, V. (2012). Distributed Control Patterns for Intelligent Mechatronic Systems. In *IEEE Conf. on Industrial Informatics (INDIN)*. IEEE.

Sünder, C., Zoitl, A., and Christoph, D. (2006). Functional Structure-based Modelling of Automation Systems. *Int. Journal of Manufacturing Research*, 1(4), 405–420.

Vrba, P., Macurek, F., and Mařík, V. (2008). Using Radio Frequency Identification in Agent-based Control Systems for Industrial Applications. *Engineering Applications of Artificial Intelligence*, 21(3), 331–342.

Westkämper, E. and Decker, M. (2006). *Einführung in die Organisation der Produktion*. Springer.

Wiendahl, H.P., ElMaraghy, H., Nyhuis, P., Zäh, M.F., Wiendahl, H.H., Duffie, N., and Brieke, M. (2007). Changeable Manufacturing – Classification, Design and Operation. *CIRP Annals-Manufacturing Technology*, 56(2), 783–809.

Wiendahl, H.H. (2002). *Situative Konfiguration des Auftragsmanagements im turbulenten Umfeld*. Jost-Jetter.

Zäh, M.F., Beetz, M., Shea, K., Reinhart, G., Stursberg, O., Ostgathe, M., Lau, C., Ertelt, C., Pangercic, D., Rühr, T., et al. (2008). An Integrated Approach to Realize the Cognitive Machine Shop. In *Proc. of the 1st Int. on Cognition for Technical Systems*, 6–8.

Zoitl, A. and Prähofer, H. (2012). Guidelines and Patterns for Building Hierarchical Automation Solutions in the IEC 61499 Modeling Language. *IEEE Trans. on Industrial Informatics*, PP(99), 1. doi: 10.1109/TII.2012.2235449.

Zoitl, A., Kainz, G., and Keddis, N. (2013). Production Plan-Driven Flexible Assembly Automation Architecture. In *Industrial Applications of Holonic and Multi-Agent Systems*, 49–58. Springer.

Zor, S., Görlach, K., and Leymann, F. (2010). Using BPMN for Modeling Manufacturing Processes. In *Proc. of the 43rd CIRP Int. Conf. on Manufacturing Systems*, 515–522.