Chapter 23

Knowledge-Based Technologies for Future Factory Engineering and Control

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Abstract. Knowledge-based Automation has been a major trend in factory engineering and control research over the last years. In this paper, the main challenges addressed by knowledge-based production systems are identified and the state of the art in supporting factory engineering and control with knowledge-based technologies is investigated. The paper concludes with a discussion of white spots in the research landscape. While there is comprehensive research on applying knowledge-based technology to individual problems such as disruption detection or reactive production planning, the interaction and dependencies between those solutions is less well investigated – although a combined solution is inevitable for addressing real world challenges.

Keywords: Future production systems, knowledge-based systems, production control, disruption detection, diagnostics, rescheduling, flexible field control software.

1 Introduction

During operation, production systems have to cope with a highly dynamic environment. For example, machine breakdowns and disruptions in logistics processes often provoke changes in the production program. Furthermore, changes of business conditions require adaptations of the production processes or updates of the technical equipment. Today, such adaptations involve much manual work and are thus very costly in terms of time and personnel. In order to reduce these costs, factories of the future should be able to automatically adapt their production processes in order to react on environment changes.

The vision of flexible production systems that have the knowledge to support such automatic decisions has been promoted in several research agendas and roadmaps [1–4]. It reflects the fact that information about the system and its environment will be the glue between life-cycle phases of a production system as well as between various involved subsystems [5]. If this information is formally represented and explicitly considered during operation, many manual tasks can be automated and a higher robustness can be achieved.

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In this paper, we review the state of the art in realizing *knowledge-based production systems*. In particular, we investigate to what extend current research leverages knowledge-based technologies for addressing two major challenges of today's production systems, namely handle production disruptions and changing business conditions. We introduce and discuss these two challenges in Section 2. Subsequently in Section 3 we introduce the main building blocks and research topics in the area of knowledge-based production systems. The building blocks disruption detection, adaptive control and factory engineering are discussed in Section 4, Section 5 and Section 6, respectively. In Section 7, the paper is concluded with an identification of white spots in the research landscape.

2 Challenges for Future Production Systems

Analyzing a variety of roadmaps from Europe and the US concerning research and developments towards *future factory automation* [1– 4] conclude the importance of information & communication technology (ICT) for future production systems. Each of them identifies knowledge and know-how as major opportunity of high-waged countries. Based on the author's practical experiences and summarizing the roadmap tenors, future production systems have to cope with two main challenges that concern functional aspects of future production systems. In the following, we will briefly introduce these challenges and derive fundamental ICT functionality essential toward achieving the underlying vision.

2.1 Challenge 1: Handle Changing Business Conditions

In order to ensure competitive business performance in highly dynamic environments, companies have to be capable of quickly adapting operative and strategic directions (see [6] for a detailed discussion on change drivers). Hence, the launch of novel products will take place much more frequently resulting in an increasing divergence of product and plant life-cycle durations. Furthermore, an evolution from the era of mass production towards an era of *market niches* [7] and *mass customization* [8] can be observed. Industrial enterprises face these trends with frequent adaptations of both the production process and the technical system. To this end, they are forced to ensure the adaptability of their production systems. Changeability [9, 10] with respect to easily adaptable production processes and a system's structure which is modifiable in a plug and produce manner are thus major requirements future factories will have to address.

Furthermore, the ongoing paradigm shift "maximum gain from minimum capital to maximum added value from a minimum of resources" [11] increases the demand for intelligent, resource efficient factory operation. Beside improvements concerning construction and materials, ICT can play a crucial role for resource-efficient operation of future production systems and their integration in future intelligent electricity systems (Smart Grids) [12], e.g. to rapidly adapting the operation strategy to changing resource prices or for counteracting load peaks in the transmission system.

Consequently, an adaptation of a system's operation in accordance to given business guidelines as, e.g., "be resource efficient" or "maximize throughput" will be required.

The adaptation of a realized production process (excluding physical changes in the structure of the system), i.e. an adjustment of the way a system is operating - referred as operation strategy henceforth - requires adaptable control systems. In case of required hardware adaptations, e.g. adding further machines, future production systems have to be aware of it and adjust their operation strategy accordingly by utilizing additional machinery at least (semi-)automatically, i.e. supervised/supported by operators respectively system integrators. Changing the way, a system operating in order to perform in accordance to given strategic guidelines can also be seen as adaptation of the operation strategy. The variation of lot sizes can be regarded in the same way, e.g., by adjusting the operation speed. Concluding, future production control systems have to be able to adapt their operation strategy dynamically, i.e. they have to be able to switch between different operation modes or act in accordance to given guidelines.

2.2 Challenge 2: Handle Production Disruptions

Over the last years, two major trends can be observed in automotive and other industries. On the one hand, an ongoing trend towards outsourcing and globalization in industrial production result in increasingly distributed production processes. The complexity of these logistics networks rely on the number of involved companies geographically spread around the world. On the other hand, the effort towards lean production result in drastically reduced stock levels and a operation in a just-in-time or even just-in-sequence manner. As a consequence, production depends on the material supply which in turn is faced to increased error-proneness. These uncertainties about timely arrival of vendor goods at the production site have significant impact on the most important performance indicators like throughput or delivery reliability.

Failures in technical systems occur frequently and can not be completely avoided. They also cause undesirable consequences regarding important performance indicators. Undetected failures in the production process can, e.g., result in a great amount of degraded material which leads to product quality problems. The breakdown of components often leads to unplanned downtimes and results in cost-intensive loss of production. The increased complexity of modern production systems handicaps monitoring as well as maintenance and results in an accumulation of unforeseen situations. The frequent appearance of supply and production glitches highlight the need for future supply and production systems that are able to cope with the large variety of influences they are subjected to.

In order to realize robust production systems capable to handle the variety of disruptions affecting them, two basic functionalities can be identified. Firstly, a robust production system has to be aware of the current situation. Accordingly, an automatic disruption detection mechanism which is able to recognize situations deviating from expected ones is inevitable. Secondly, when a critical situation is detected and the system's actual operation plan cannot be pursued, an adequate action aligning operation plan and current situation is required. Such a compensation mechanism, which can either adjust the situation or the local operation plan, has to be identified and executed.

3 Knowledge-Based Production Systems

In this section, we briefly introduce knowledge-based systems and derive their beneficial aspects for addressing the previously described challenges. Classical programming requires to hard-code knowledge explicitly and symbolically within the structure of the software code. In contrast, a *knowledge-based system* is a "software system capable of supporting the explicit representation of knowledge in some specific competence domains and of exploiting it through appropriate reasoning mechanisms in order to provide high-level problem solving performance" [13]. Accordingly, knowledge about the domain of discourse, required functionality and additional constraints are represented explicitly in a formal model. Furthermore, highly optimized automated reasoning mechanisms enable a generic problem solving based on the provided formal model independent of a specific domain or functionality.

This strict separation between declarative domain knowledge and associated reasoning algorithm provides some favourable features for addressing challenges of future production systems. As already identified in Section 2, future production systems need to be adaptable to changing business conditions. This feature is required to determine an adequate operation strategy for given guidelines. It can be realized with a specific reasoning task taking into account knowledge about a system's capabilities. In case of system changes, only the explicit knowledge model has to be adjusted whereas the reasoning algorithm remains the same. Consequently, management and maintenance of a system's capabilities model is improved compared to today’s situation where its encoding in the program code requires extensive reprogramming.

In order to address challenge 2, knowledge about a system's capabilities is also available for disturbance compensation. As discussed e.g. in [14], knowledge-based technologies offer also benefits for detecting disturbances since these tasks rely on a great amount of knowledge. Furthermore, the exchange or enhancement of reasoning mechanisms in order to detect a variety of disturbances is facilitated by knowledge-based technologies.

Both challenges previously discussed addresses operational aspects but lead to a further requirement not discussed until now. In order to achieve a desired level of adaptability and intelligence, the production system's complexity will arise and consequently its engineering will be more time- and cost-intensive, as well as error-prone. Furthermore, the application of knowledge-based technology for factory operation results in an increasing demand on explicit knowledge required in order to identify disturbances, reason about their criticality and initiate adequate compensation. In contrast, competitive business performance comprises a reduction of the time-to-market enabling a firm to reap higher net revenues [15]. Consequently, improving recent development techniques is required for future production systems.

In order to provide an almost complete virtual model of a production system, the effort spent on digital factories [16, 17] focusing on the integration of various computer-aided design tools is the first step towards engineering future production systems. The application of knowledge for systematically reusing product and process engineering knowledge, called *knowledge-based engineering* [18], will improve the engineering by reducing effort and the provision of adequate, explicit formal knowledge models for operating knowledge-based systems addressing future production system challenges.

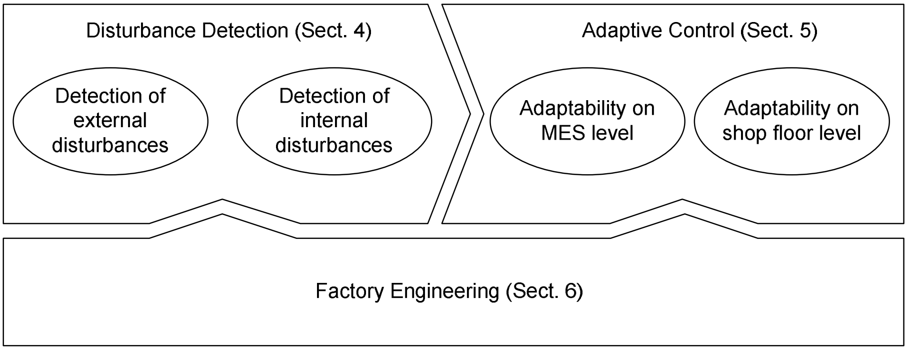

Fig. 1. Overview of addressed topics in the remainder of this contribution

For this reason, the vision of a *knowledge-based production system* (KbPS) in order to prepare production systems for the challenges of the future is discussed in the remainder of this paper. A KbPS is considered as a production system whose various control layers from shop floor to business level are enhanced with knowledge-based technologies, as well as comprises a knowledge-based engineering. Major building blocks constituting a KbPS are depicted in Fig. 1. In the remainder of this paper, research conducting these relevant aspects will be surveyed and work of the others in order to enable KbPS will be presented.

4 Disruption Detection

4.1 Detection of External Disturbances

Global and lean supply chains are subject to sudden disruptions of different severity that affect performance [19]. Disruptions can be addressed by preventive and reactive measures [20]. Usually *risk management* concepts [21] are applied as preventive measures in the procurement processes in order to reduce the risk of severe events during operation. However, theoretical results [22] as well as many real-world examples [23] indicate that no prevent measures are able to completely eliminate disruptions during operation. Therefore, reactive measures are required to reduce the negative impact of supply chain problems.

The concept of *supply chain event management* (SCEM) aims at observing objects along the supply chain, at detecting important events, and at reacting on identified events to avoid severe disruptions [20]. In order to detect external disruptions before their effect will manifest on site, upstream and downstream logistic processes have to be made transparent to the manufacturer. Improving the transparency of supply chains requires seamless tracking of objects along the processes. Auto-ID technology [24] such as Radio-Frequency Identification (RFID) is a main enabler for effective tracking solutions. However, today RFID-based monitoring solutions are predominantly deployed only within companies or in retail scenarios (e.g. [25]). In fact, [26] found in an academic literature review the top three categories of RFID-based solutions to be retailing, library services and food with a combined share of 42.7 %. Logistics and SCM applications were only the topic in 10.7 % of cases. Thus, reports of inter-organizational RFID-enabled supply chains in manufacturing (e.g. automotive industry) are still rare.

To address the RFID challenges of manufacturers a novel standardized architecture for real-time information exchange of object tracking data is currently under development within the German research project named RFID-Based Automotive Network[1]. As tracking & tracing of objects has to be realized across several companies to enable supply chain monitoring, the system architecture is based on the *EPC information services* (EPCIS), a publicly available industry standard [27]. It specifies an XML-based syntax to represent events and master data. The semantics of the vocabulary terms is defined informally using natural language.

In order to exchange and process EPC-based tracking & tracing data and reason about them in order to recognize situations of interest (e.g. disruptions), a formal representation of the data is required. A formal language for specifying relations between terms is provided by *ontologies* [28], which are typically a subset of first order logics. Based on this formal grounding, an EPCIS Event Ontology has been defined and its relationship to ontologies about physical locations and processes based on the terminology given IEC 61512 and IEC 62264 standards has been proposed in [29]. The EPCIS Event Ontology reduces the number of rules required for situation recognition, eases their specification at design time, and supports the validation of their logical consistency.

For detecting critical disruptions in the supply chain, the system leverages logic-based complex event processing where typically each situation is defined by specifying the interdependency between events using *event patterns* [30]. These event patterns can be seen as templates which match certain combinations of events describing a situation of interest. *Complex Event Processing* enables reasoning about event hierarchies as well as additional temporal language constructs and has been applied to processing RFID data streams in supply chains [31, 32]. A detailed description about its application to realize a reactive manufacturing execution system based on the Siemens MES system SIMATIC IT can be found in [29].

4.2 Detection of Internal Disturbances

To achieve higher robustness of the production processes, failure detection of production facilities is inevitable. Diagnostic tasks have been a vivid research topic over decades and various approaches, specialized and generalized ones, exist [33]. Knowledge-based approaches for industrial diagnostics are characterized by a strict separation between *diagnostic knowledge* and the *reasoning algorithm* realizing the

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[1] `www.autoran.de/en/`

diagnostic functionality. This facilitates the application to various different diagnostic problems and eases the adaptation of diagnostic systems, e.g., in case of changes of the technical system or new insights into relevant diagnostic correlations (see [14] for a detailed discussion). Manifold theoretical groundings have been proposed to define diagnostic knowledge (see [34] for a comprehensive overview). In the following, a brief discussion of recent work investigating knowledge-based diagnostics is presented.

Supervisory control theory [35] is often applied in order to identify unexpected behaviour of technical systems. Ferrarini et al. [36] for example proposes such an approach for failure detection of machine centres which is executable on a programmable logical controller. A component-oriented diagnostic approach for bottling plants based on a mathematical material flow model is presented in [37]. Lo et al. rely in [38] on bond graphs to define the diagnostic knowledge, whereas in [39] a genetic algorithm is used to construct optimal fuzzy rules for monitoring. Description Logics [40] which is the formal grounding of *semantic web ontologies* are proposed in [41] for monitoring and diagnosis of industrial systems. Since diagnostic tasks are often faced with uncertain behaviour of production facilities, Geramifard et al. [42] rely on Hidden Markov Models (HMM) for diagnostic reasoning. A comparative discussion of a diagnostic approach based on HMM and Description Logics reasoning is presented in [43].

Motivated by an ongoing effort to increase the dependability of large-scale industrial systems like manufacturing or power plants, the need for an efficient diagnostic framework applicable for various different technical systems arise. Driven by the declarative nature of Description Logics to formulate maintainable diagnostic knowledge, *logic-based abductive inference* [44] has been identified as a valuable complement to deductive reasoning for handling incompleteness of information [45]. Whereas standard abduction has to explain all observations regardless of relevance, the relaxation of the abductive problem formulation leads to an increased robustness for information interpretation [46]. A generic knowledge-based diagnostic framework based on a novel, efficient logic-based abduction algorithm has been developed [47].

Beside the definition of diagnostic knowledge and the diagnostic algorithm itself, a knowledge-based diagnostic system requires operational data in order to determine the current situation of the system. In order to realize the vision of a generic diagnostic framework, an automatic transformation between operational data from field level (sensor data, machine information, etc.) and the applied Description Logics formalism is required. In order to utilize the expressiveness of ontological models, a middleware for semantically querying various sorts of available information has been developed [48]. Based on flexible proxy architecture various accessing technologies can be integrated. In addition to a semantic discovery mechanism, an automatic semantic lifting mechanism from a syntactic to a semantic level has been realized. In order to retrieve field level data, the integration of semantic technologies with OPC UA has been investigated [49].

In some cases, the effects of malfunctions on the good to be manufactured are relevant for diagnosis, too. In order to observe these effects, the concept of intelligent products (see [50] for an introduction) has been integrated with the semantic information architecture [51]. Thus, an embedded system mounted on a product or product carrier can provide product related information to the diagnostic system [52]. Since wireless communication technology required for communicating with intelligent products is not pervasive in industrial environments and the bandwidth for communication is limited (e.g. in case of RFID), *embedded logic-based reasoning* has been developed to perform diagnostic tasks directly by the intelligent product itself [53], [54]. Furthermore, sophisticated novel applications like *product lifecycle management* [55] or *product-driven manufacturing* can be realized [56].

5 Adaptation of Operation Strategies

5.1 Adaptation of MES Level Operation Strategies

Operations management of manufacturing systems is realized by a *Manufacturing Execution System* (MES) in accordance to the IEC 62264 [57] standard. Production jobs to be executed in a manufacturing system at a respective time interval are typically given by the *Enterprise Resource Planning System*. The execution of a respective production job is one of the important missions of a MES. The adaptation of the schedule of jobs or the way executing a single job is the flexibility utilizable by a MES in order to address previously introduced challenges.

The adaptation of a production system's operation to changing business conditions, e.g. in order to switch from resource-efficient operation to throughput maximization, mostly requires a complete re factoring of the schedule. Accordingly, scheduling techniques for optimizing production processes with respect to varying objectives, based on automated planning [58], scheduling [59], and operations research techniques [60] are applicable. Distributed agent-based optimization approaches are available as described e.g. in [61]. Structural adaptations of manufacturing system are addressed, e.g., by the research on Evolvable Assembly Systems [62]. Based on a product recipe, self-organizing agents realize the production process by a dynamic allocation of tasks [63].

In contrast, reactions to detected disturbances comprise short-term adaptability. In case of a detected disturbance, e.g. deviated material supply or machine breakdowns, an adjustment of the job schedule might be directly necessary in order to determine a new schedule since the previous one is not valid any more, e.g. planned material or a required machine is not available any more, or the schedule is at least not optimal in the altered situation.

In literature, lots of research has been conducted on complex approaches for rescheduling of manufacturing processes. Chrwan-Jyh [64] clustered the approaches into two groups according to the type of uncertainty discussed in challenge 2 – *environmental uncertainty* and *system uncertainty*. An overview of various approaches for scheduling under uncertainty can be found, e.g., in [65]. An orthogonal classification is the way the algorithm handles uncertainty. It is done either dynamically (mostly event-driven) or predictive. The latter mode addresses uncertainty using preventive measures (e.g. by planning with slack). This approach, however, reduces performance and limits its effectiveness. Critical effects can hardly be handled without direct reactions. These dynamic scheduling approaches (see [66] for surveys), especially reactive approaches, can be seen as an extension of the predictive approach with the addition of an online schedule recovery repair strategy. A comparative study of various rescheduling policies is given in [67]. Unfortunately, most of the researches conducted on scheduling do not rely on assumptions realizable in practice [68]. Since the complexity of the (re-)scheduling problem is in general computationally very hard [69], application of agents for distributed production planning [70, 71] and scheduling [72, 73] have also been intensively investigated. Beside its opportunities, distributed production control also entails various drawbacks discussed, e.g., in [74, 75].

A further classification of (re-)scheduling approaches is based on the knowledge taken into account for determining a valid schedule. This results in a division into two groups: machine-oriented and inventory-oriented (re-)scheduling approaches. Detailed machine (re-)scheduling concepts focus on the decision about the task to be executed by a respective machine. In order to address uncertainty of job execution and the dependency between configuration options, a totally reactive rescheduling approach, i.e. an ongoing self-adjusting product-centric schedule, has been proposed in [76]. Furthermore, it has been shown that looking ahead to the remaining production process of a product when determining the task to be executed can increase the system's reliability.

As shown [77], the application of even straight forward rescheduling strategies improves the performance of real industrial settings drastically. Inventory-oriented (re-)scheduling approaches incorporate the material supply and are consequently susceptible to logistic events. As shown in [29], inventory-oriented production order optimization outperforms approaches applied in industrial practice significantly already without an early detection of supply disturbances. First evaluation results not published until now leads to the assumption that an early identification of supply disturbances in combination with inventory-oriented scheduling approaches will further reduce the sensitivity to logistics events and consequently increase the robustness of production processes.

An ongoing investigation of cause-effect relationships between events, their knock-on effects and company-internal performance indicators [78, 79] lead to the conclusion that a classification of interfering effects and optimal schedule adaptations exist. Consequently, an automatic identification of a limited set of adequate operation strategies required for robust production can be achieved for robust production operation whereas complex (re-)scheduling approaches can be utilized for learning and supervision in case of unexpected situations, such as, for example, changing business conditions.

5.2 Adaptation of Field Level Control Strategies

Much research has been conducted on increasing flexibility of field level control software (see [81] for surveys). State of the art technology, esp. IEC 61131 [82], is often identified as major handicap. Therefore, various alternative architectural concepts have been proposed, e.g. *multi-agent systems* [83] or *service-oriented architecture* [84].

To define an agent's responsibility, organizational concepts for *holonic control* [85–87] have been investigated. In manufacturing agent technology is applied to deal with different kinds of system failures (see [88, 89] for overviews). Agent technology in industrial environments is mostly deployed for supervision on top of real-time control technology. The reconfiguration of IEC 61131-based control systems to handle module breakdowns in inner logistics systems is addressed in, e.g., [90]. Since the IEC 61499 [91] standard has been proposed, an increased research on dynamic reconfiguring of PLC software can be observed. In [93] for example, different approaches based on the novel standard IEC 61499 for industrial distributed automation control is applied to reconfigure transportation systems. Agent-based technology has also been applied successfully in process industry (see [83] for a survey) to handle critical situations in a fault-tolerant manner [94]. The dynamic adjustment of process parameters in order to assure quality assurance and prevent system damage of thermo-hydraulic presses based on a real-time capable multi-agent system is presented in [95, 96].

The service-oriented encapsulation of components and their control functionality for production systems have been investigated for many years. Its applicability for integrating heterogeneous devices [97], ease deployment of new components [98] or increase the agility of automation systems composed of them [99] has been explored.

The impact of flexibility on a technical system's robustness has been investigated in [76]. It has been shown that the robustness of a production process can be increased if enough configuration options on the field level are available. Unfortunately, the flexibility of current field level automation systems is rather limited. The reasons are manifold, but two major drivers can be identified: Firstly, automation hardware is limited in flexibility. This issue will be addressed in the subsequent section in detail. Secondly, the dynamic reconfiguration of automation software based on recent standards on automation control, e.g. IEC 62264 [57] and IEC 61131 [82], is rarely investigated. Instead, novel architectural paradigms resulting in high investment costs for practitioners are proposed without addressing the basic question: Will the novel architecture ever become profitable in future?

For this reason, research should also focus on the *dynamic reconfiguration of field level automation software* under consideration of existing, established standards. A novel, knowledge-based approach for reconfiguring IEC 61131-based field level automation software has been developed. First results of this effort are presented in [100]. Currently, various reconfiguration issued are evaluated under real conditions.

6 Knowledge-Based Technologies for Future Factory Engineering

Bringing knowledge-based production systems into practice will result in an increased demand for knowledge during operation. Furthermore, to address adaptability requirements, the complexity of a production system and consequently its engineering process will increase. To overcome engineering complexity, a trend towards reusable modules can be observed [101]. The granularity of modules in order to balance between reusability and adaptation effort is already an object of research and investigation [102].

Modularity plays also an important role for reconfigurable systems' design [103]. However, the integration of various involved disciplines during a module's development, e.g. mechanical and electrical engineering and software development, remain a challenge [104]. For integrating various trade-specific languages, transformations between the underlying logical models is one way to address this challenge [105, 106]. In order to provide a unified language for modelling various aspects of automation components, intensive research on systems engineering based on the UML and SysML has been conducted [107-109]. Unfortunately, the often semi-formal grounding of these approaches hinders further knowledge-based applications. However, due to complexity reasons the direct definition of a desired formal model results in a time-intensive and error-prone process. Even modelling of production systems using Petri Nets - a formalism that enjoys the reputation of very handy modelling and tooling, as e.g. applied in [110] remains very complex. For this reasons, an approach that enhances model-based engineering with specific formal semantics seems to be favourable. The engineer does not need to create logical models and still automatic processing can be supported. Research towards this solution can be found for automatic model verification [111-113], validation [114, 115], generation of PLC automation projects [116] or even PLC code generation [117].

Regarding intelligent assembly systems, various research that aims at automatically deriving operation sequences for product assembling has been conducted [118, 119]. Based on executable robot operations and an adequate description (extracted from CAD data) a plan of operations is generated by means of artificial planning techniques (see [58] for a comprehensive introduction). In order to ease the engineering of restartable robot cells, support for engineering desired sequences and guiding the planning tool is presented in [120].

Some research towards semantic descriptions of production facilities by means of ontologies have also been conducted (see [121] for a brief survey). In [122], an ontological vocabulary based on the IEC 61499 reference model has been proposed to describe a module's hardware and software features. A further application of ontologies utilizing its formal grounding by means of reasoning functionality for specifying and discovering devices during engineering is proposed in [123]. Supporting interoperability between distributed project teams during engineering utilizing an ontology-based semantic vocabulary is focused in [124].

The coordination of- and information integration between- various trades involved during the engineering process is the main purpose of a *Plant Lifecycle Management System* (PLMS). It provides a common data model which allows developing future production systems according to its functions rather than trade-specific oriented structures. In order to provide an adequate formal model for further automatic processing of various knowledge-based applications, a generic model-based approach to extract desired information from PLMSs has been proposed in [14].

Based on this concept, an extension of the Siemens PLMS product COMOS[2] has been developed featuring an abstract description of possible system failures in an abstract way based on the PLMS data model. Desired diagnostic knowledge with

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[2] `www.automation.siemens.com/mcms/plant-engineering-software`

adequate Description Logics based semantics and enriched with structural information of the system is automatically extracted without further effort. Furthermore, this enables to automatically update any operating diagnostic system.

Model-based engineering for developing field-level automation software (compared to a direct implementation) reduces engineering effort [125]. Existing paradigms aim at developing a finite set of production processes inside a defined technical configuration of a production system. In order to realize flexible, easily adaptable control software, this approach results in high effort to develop the maximum degrees of freedom. For this reason, a UML Profile encapsulating all information about the complete space of action of a field level automation software in a consolidated way has been proposed in [126]. Based on the strict formal, logics-based semantics of the model, an automatic inference of all realizable processes and identification of the optimal sequence of operations to realize a respective production process can be achieved [100]. This knowledge-based approach for developing field level automation software will provide required flexibility to adapt the behaviour of field level control in order to compensate detected disturbances or adapt a system's operation strategy in accordance to changing business conditions. Furthermore, a reduction of lifecycle costs can by achieved by improved changeability of the field level control software utilizing the knowledge now available for guiding the engineer in case of required re-engineering and automatic synthesis of control code.

7 Conclusion

In this contribution, efforts towards future factory automation systems are presented and the demand for automatic processable knowledge about the production system itself, the good to be produced as well as the supply chain has been highlighted. In this context, knowledge-based technologies have been identified as enabler for future production systems leading to the concept of knowledge-based production systems. By bringing these knowledge-based production systems into practice, the adaptability of future production systems on different control levels ranging from production order optimization to a reconfiguration of field level automation software will be increased.

A multitude of research has been conducted addressing selected aspects of future production systems which are surveyed throughout this paper. But also various open issues have been identified which are unsettled so far. Especially border regions and dependencies between several research issues of future knowledge-based productions systems can be identified as major research directions as depicted in Fig. 2.

Most of the knowledge required to identify disturbances inside and outside a production system, reason about their criticality, initiate adequate compensation strategies or adjust the operation strategy in accordance to given strategic guidelines is generated during engineering. Accordingly, totally integrated industrial automation, integrating life-cycle phases as well as vertical and horizontal (sub-) systems require inherent knowledge sharing and exchange. Consequently, the importance of knowledge and its impact towards competitive production operation will increase. Whereas disturbances inside a production system are comparatively well studied and sophisticated mechanisms for detecting them are available, disruptions in globalized production and delivery networks are still an open research issue (cp. Fig. 2, region 1). In fact, there is a strong correlation between disruptions, internal as well as external ones, and the way they can be handled efficiently. For this reason, future research on the correlation between disruptions, their effects and ways to mitigating them by adapting a production system's operations is required (cp. Fig. 2, region 3). Since practitioners having the know-how about respective sources of disruptions are often not familiar with modelling of desired formal models, improving the development of formal models for knowledge-based production systems is required. For this reason, established modelling notations used by knowledge carriers have to be explored with respect to their information content utilizable for knowledge-based production systems. This enables also to define interrelationships between these separated models in order to provide an overall virtual model of a plant (in accordance to the digital factory effort). A definition of a strict formal semantics for these often informal or semi-formal models would be profitable in two aspects: On the one hand, dependencies between models can be described in a way that supports automatic reasoning. Thereby, engineering can be guided, e.g., by detecting inconsistencies between different models automatically. On the other hand, formal semantics can be utilized directly as knowledge base during production operation. As depicted by regions 1 and 2 of Fig. 2, these research issues are currently not addressed sufficiently. Formal, processable models describing explicitly what a plant is able to do and consequently describing the whole range of options available for adapting the operation strategy (either due to changing business conditions or disruptions) are not available until now.

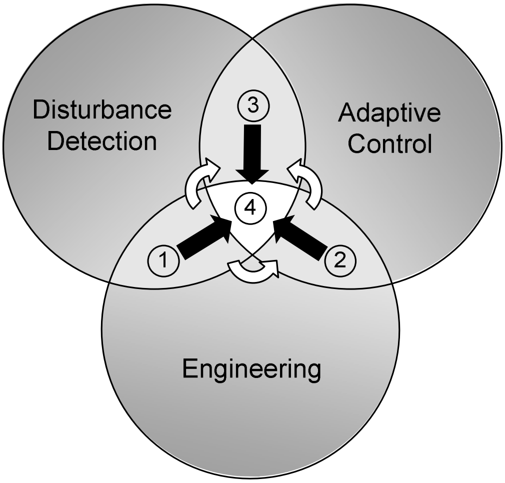

Fig. 2. Research directions for future knowledge-based production systems (grey scale indicates research coverage)

Once knowledge about disruptions affecting a production system or a production network is available, it can be utilized in order to determine a required level of adaptability, and consequently can be applied in order to realize a robust production operation. Consequently, challenge 2 can be addressed by a combination of the research directions one to three described above (indicated by white arrows in Fig. 2). As identified in Section 2, future production systems have also be aware of varying business conditions, e.g. introduction of new products or adaptation of the production process. This can not be considered a priori during systems' engineering. Accordingly, in order to prepare knowledge-based production systems towards challenge 1, single research directions identified previously have to be combined in a coordinated way (indicated by black arrows towards region 4 in Fig. 2). As a consequence, research on robust knowledge-based production systems can be seen as the first step towards addressing future challenges.

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