Challenges in the engineering of adaptable and flexible industrial factories

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Abstract: To encounter the challenges of faster changing markets and growing individualization of customer requests as well as to efficiently deal with internal disturbances like machine failures, an enhanced adaptability and flexibility of industrial factories is required. In this paper, challenges in the engineering of adaptable and flexible factories are highlighted, which remain unsolved from an industrial point of view. For this purpose, some general challenges are derived from the Industry 4.0 application scenarios “seamless and dynamic engineering of production systems” and “adaptable factory”. Selected general challenges are detailed based on typical engineering tasks ranging from the design of a new production system and the engineering of its self-orchestration capabilities to safety and product quality aspects. Solutions for these challenges will be essential for the future of adaptable and flexible factories.

Keywords: Engineering challenges, adaptable and flexible factory, Industry 4.0, application scenarios, simulation, self-orchestration, safety, process FMEA

1 Introduction

Major trends in the manufacturing sector are the growing individualization of products and volatility of product mixes. This results in an increased amount of disturbances of the production system and, thus, requires easy changeability of these production systems. In general, disturbances can be divided in internal and external disturbances [SS90]. Internal disturbances of the production system are, for example, machine failure or maintenance while external disturbances represent changes of the existing products, the introduction of new products that have to be manufactured – due to new customers or a changing market structure – or changes in the order parameters (lot size, lead times, etc.). While external disturbances require an adaption of the production system to new requirements and internal disturbances reduce the availability of the factory, both disturbances result in increasing cost of manufacturing. Due to a growing amount of external and internal disturbances, factories have to be designed to be easily changeable, which means that factories should be flexible and adaptable.

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According to [VDI17] adaptability and flexibility are defined as follows:

“Adaptability refers to the ability to change involving structural changes to the system” [VDI17]. For instance, if a new product is introduced, the production system’s hardware and software structure might have to be changed in order to meet the new requirements. While the process of changing the structure of hardware and/or software is called reconfiguration, the ability of the production system to be economically changed to these new requirements in its hardware and software structure is called adaptability.

“Flexibility refers to the ability to change without structural changes” [VDI17]. An example is the possibility to produce new products without changing the production system in its structure. This can be achieved by re-parameterization of existing software functions. Hence, the hardware and software structure is not changed.

In this paper, selected technical challenges in the engineering of adaptable and flexible factories are described. The remainder of this contribution is as follows: In section 2, general challenges are described based on the Industry 4.0 application scenarios [Pl16], whereas in section 3, selected challenges are detailed based on typical engineering tasks. Concluding, section 4 provides a summary including an outlook on future work.

2 Challenges derived from exemplary Industry 4.0 application scenarios

Based on typical industrial value chains, the platform Industry 4.0 identified so-called application scenarios which describe challenges that users are going to face through digitizing of manufacturing and business operations [Pl16, Pl17]. Main focus of the application scenarios are the business value network and connected challenges.

With respect to the value network, the following main value-added processes were identified for manufacturing [Pl16, Pl17]: product lifecycle management, production system lifecycle management, supply chain management, and service with respect to the product and the production system. Fig. 1 gives an overview of the application scenarios related to these value-added processes.

It is obvious, that the application scenarios related to production systems, as shown in Fig. 1, are particularly of interest for deriving challenges on the production system. Therefore, the application scenarios “seamless and dynamic engineering of production systems” and “adaptable factory” are used as a basis for deriving concrete challenges in the following.

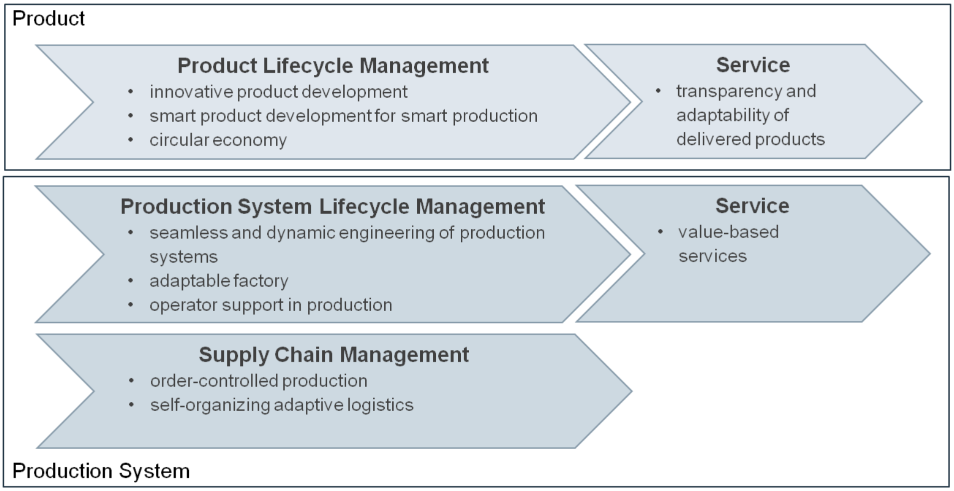

Fig. 1: Product and production system-related Industry 4.0 application scenarios with respect to value-added processes as described in [Pl16]

2.1 Application scenario "seamless and dynamic engineering of production systems"

This application scenario assumes that factories need to change in future rather often and, thus, all partners involved in engineering, operation, and service should work on an integrating model of the production system to avoid inconsistencies and errors. Such an integrating model should be kept up to date and support also the evaluation of the impact of past and future decisions. In addition, it should be enriched with lifecycle information, constraints, context information, and possible variants [Pl16, Pl17].

Technical challenges derived from this application scenario are especially [Pl16, Pl17]:

- setup of an integrating model across organizational boundaries throughout the lifecycle, considering data integrity, intellectual property, data analysis, and usage,
- methods for model analysis which enable, for example,
  - evaluation of the impact of decisions,
  - analysis of prerequisites for modules which have to be integrated (e.g. risks),
  - planning the future capabilities of the factory and its evolution,
  - assessment of a new configuration in terms of functionality, reliability, availability, and safety,
- adequate tool support.

2.2 Application scenario "adaptable factory"

The application scenario "adaptable factory" addresses the adaption of capacities and capabilities of a production system to changing customer as well as market demands and focuses on physical changes in the factory. In particular, the adaption of the production system should be automated as far as possible. In order to create a plug&produce environment, this application scenario suggests a modular design for manufacturing as well as self-adaptable and highly-interoperable modules based on standardized interfaces [Pl16, Pl17].

Technical challenges derived from this application scenario are in particular [Pl16, Pl17]:

- design and creation of self-adaptable and highly-interoperable modules, which implies platform-based modules with interoperable interfaces,
- system architecture for the production system which enables a plug&produce environment for such modules – starting from physical connection up to integrated operation and manufacturing execution systems:
  - self-description of module capabilities and propagation of control-related changes to facilitate integration and rearrangements in production systems, including also e.g. safety aspects,
  - integration concepts for modules for central services such as visualization, archiving, alarms, or manufacturing execution systems, e.g., self-description of modules for visualization,
  - access to all information at field level for manufacturing execution and visualization,
- reconfiguration of a versatile production line without programming or engineering effort, e.g. also by using self-orchestration mechanisms,
- runtime location of software components should be changeable to e.g. enhance reliability and availability.

3 Engineering challenges concerning adaptable and flexible factories

Based on the Industry 4.0 application scenarios described in section 2, four general engineering tasks of high interest for adaptable and flexible factories are used to derive specific challenges for the engineering of such factories.

During the lifecycle of an adaptable and flexible factory from design or concept phase up to its retirement [ISO10], a lot of engineering tasks have to be performed which are very specific for such factories and are still challenging. These engineering tasks can be related to one of the Industry 4.0 application scenarios which address some basic challenges in the engineering of adaptable and flexible factories.

These tasks include, e.g., the design of a new production system, the self-orchestration and the functional safety of a production system during operation, and the accordance to the required quality of the production process as well as the resulting product. These tasks are described in more detail in the following.

3.1 Designing a new production system

To design a new adaptable and flexible factory, it is necessary to find an optimal system configuration for given production scenarios. The possible configurations consisting of production modules, the entire production system, schedule, and product mix can be simulated in advance in order to find the best possible system configuration. The production system has to ensure manufacturability and avoid possible failures such as bottlenecks, missing capabilities, or suboptimal layout.

The production system has to be designed under consideration of given requirements. The important parts of the design of the production system are the design of the production process and the detailed design of the technical system. The production system may consist of several production modules – which can be manual, hybrid, or even fully automated production modules. Each of the production modules consists of several submodules. A production module has the ability to handle varying tasks, has to be designed to correspond to the requirements, and can act independently of other modules.

Production simulation can be used to design and optimize an adaptable and flexible factory. The layout, a production sequence, and even the infrastructure of the production hall have to be taken into account. The modular production system has to be simulated with consideration of a flexible layout. The production sequence aspect can be covered by modeling flexible cells and modular production systems with respect to reusability of installations. The infrastructure of the production hall has to be optimized with respect to the qualities of the new production systems such as different power consumption and for the needs of a changed information and communication behavior.

To create the simulation of such a factory, a lot of challenges have to be managed. Not all possible variants of the product can be defined in a Computer-Aided Design (CAD) environment during the engineering of a new production system. The production simulation can be used to ensure the needed flexibility by modeling the relevant product variants. It has to be done with respect to the module configuration and cycle times and even the necessary change of the layout of a production system has to be considered. To simulate the high flexibility of the production system, models of the collaborative production modules are needed.

To create a simulation of a plug&produce environment, the modeling of self-adaptable modules based on standardized interfaces is essential. The communication between the modules has to be implemented in the simulation. As a result, this will lead to a valid production simulation with time evaluation and necessary module and layout reconfigurations. The simulation results have to be analyzed under consideration of given Key Performance Indicators (KPIs).

In case of the valid simulation of the production system, the output is the system configuration and validated control concept. The simulated production system has to meet all relevant production constraints such as lead times and quality. The simulation provides an optimal system configuration and ensures that all required production capabilities are able to produce the product according to its production bill of material as well as bill of process. The KPIs for a factory's output are ensured by the simulative optimization of the adaptable and flexible factory.

Designing a new production system for adaptable and flexible factories is related to the application scenario "seamless and dynamic engineering of production systems" which implies an integrating production system model across organizational boundaries throughout the lifecycle of the production system which is also used for assessing future configurations. Such an integrating model should be set up already in the design phase and, thus, can be used for any necessary simulations.

3.2 Engineering of production systems with self-orchestration capabilities

An adaptable and flexible factory needs to cope with various disturbances during operation. These include both internal as well as external disturbances, see section 1. In order to tackle these challenges in the future and to respond to the increasing trend towards individualization of products, one possible solution can be the self-orchestration of a production system at runtime. Depending on the type of disturbance, the system needs to perform either structural changes (e.g. reconfiguration) or non-structural changes (e.g. parameterization). Self-orchestration mechanisms may be required, for example, if there is a change in the product requirements or production parameters.

If the production system is able to successfully self-orchestrate itself, it can also deal with unexpected changes, e.g. by reconfiguration and re-parameterization or an autonomous re-scheduling and execution of production workflows. The boundaries in which the system can orchestrate changes are determined beforehand by the engineering during the design phase. In case that the system fails to self-orchestrate at runtime, a report with reasons for the failure (e.g. missing capabilities) could be issued and tasks could be proposed which are needed to be done manually by a technician.

There are several challenges that need to be addressed with respect to self-orchestration mechanisms: First of all, the production system needs to be equipped with various skills. These include self-management capabilities like self-awareness of its own manufacturing/process capabilities and its status, awareness of its context as well as the ability to communicate and interact with other systems in order to negotiate and collaborate.

In that regard, it is also necessary to investigate the optimal degree of autonomy of the systems. It needs to be examined whether there is still a central instance required for an overall optimization of production or whether several rather loosely-coupled collaborating systems can manage the interplay of different production orders without any central coordination. Furthermore, there is the challenge of predicting a system's behavior after each change and enabling adequate testing or even virtual commissioning in order to ensure the proper functioning of the production system. Apart from functional testing, also safety and product quality aspects need to be considered (see also 3.3 and 3.4).

Those challenges are aggravated by the fact that the fundamental engineering decisions for an adaptable and flexible factory are made during design time without full knowledge of the factory's context at runtime. Therefore deliberate planning at design time as well as the application of an integrated engineering approach covering all lifecycle phases are necessary to ensure a suitable and economically viable degree of flexibility and adaptability of production systems during operation.

The self-orchestration of production systems during operation is associated to the application scenario "adaptable factory". Self-adaptability of modules, propagation of control-related changes to facilitate integration and rearrangements in production systems as well as reconfiguration of production lines are mentioned in this application scenario and form a basis for the self-orchestration of the whole production system.

3.3 Safety of production systems

In order to ensure functional safety in the context of industrial factories, machine manufacturers and operators in Europe are required by law to ensure the protection of persons and the environment. The basic requirements for system safety, machine manufacturers or system operators must comply with, are defined in the safety standards ISO 13849 [ISO06] or EN 62061 [IEC05] (see Machinery Directive 2006/42/EC of the European Commission [EC06]).

Safety standards provide guidelines to keep the residual risk in machine construction and operation within tolerable limits. Therefore, a comprehensive risk assessment and, if required, risk reduction is performed (e.g. by introducing specific risk reduction measures). The risk assessment provides safety requirements which apply to the machinery. The machinery must then be designed and constructed taking into account the results of the risk assessment. The corresponding safety documentation describes the assessment principles and the resulting measures in order to minimize hazards. This documentation also lays the foundation for safe operation of a machine and it proves the compliance with the machinery directive.

In the context of an adaptable and flexible factory, the risk analysis must be conducted after each production system reconfiguration, for each new product, and for each path of product steps so that the safety of the system group or machinery is proven. This is a prerequisite for operating the factory. Therefore, the list of possible risks w.r.t. hazards for humans must be updated automatically during the operation of an adaptable and flexible factory in order to have the current list of risks. The list of risks serves as a basis to assess the new configuration of a factory in terms of safety every time the production process is changed, a new product is produced, or the factory configuration is changed. The update must be performed fully automatically in order to enable flexible production scenarios, see section 2, and to avoid long maintenance intervals between the changes of factory configuration.

Today, the list of risks of a production plant is set up manually during its design phase. To realize the above application scenarios, the list of risks must be synthesized automatically during the operation of a factory (i.e. when the system configuration is modified or a new product is produced). Besides the risks of each individual production step also the risks to harm a person resulting from specific sequences of production steps must be considered. For instance, if a specific work piece is cut by a machine then sharp edges may result. A worker who performs a subsequent production step may be injured by these sharp edges. So either the sharp edges must be deburred in an additional process step or the worker must be protected (e.g. by wearing specific hand gloves), if possible.

Ensuring the functional safety of production systems is associated both with the application scenarios “seamless and dynamic engineering of production systems” and “adaptable factory”. First, an integrating production system model is needed to assess the functional safety. And second, the modules within the production system should provide self-description of module capabilities also related to safety aspects.

3.4 Ensuring product quality

In order to ensure the quality of the products produced in an adaptable and flexible factory, each new configuration of the production process must be assessed. It must be ensured that the specified requirements w.r.t. quality of the production process and the resulting product are met. This can be done by dynamically creating a so-called Process-FMEA for each product in each system configuration.

Failure Modes and Effects Analysis (FMEA) [IEC91] is a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product/service. FMEA is a bottom-up, inductive analytical method which may be performed at either the functional or piece-part level. The Process-FMEA is a methodical approach used to identify and evaluate the potential failures of manufacturing and assembly processes, where both the quality and the reliability may be affected from process faults. The input for this FMEA is, amongst others, a work process or recipe of the current configuration of an adaptable and flexible factory for a specific work piece. By conducting a Process-FMEA the failure modes of each production step as well as their effects on the process are identified. For each effect of a failure, the severity of this effect is determined. Then, causes and their mechanisms of the failure mode are identified. Thus, the Process-FMEA can be used to select quality assurance measures and to add them to the production process to ensure the target product quality.

Since the factory's configuration as well as its products constantly change in adaptable and flexible factory scenarios, a Process-FMEA must be performed dynamically during the production of each product based on a new configuration. This is necessary to ensure that the requirements w.r.t. quality of the production process and the resulting product are met. Thus, the dynamic Process-FMEA provides feedback if a new configuration meets the quality requirements defined for the production and if the residual risk of producing products that do not meet the given quality requirements is sufficiently low.

For instance, a specific production step (e.g. drilling a hole) can be performed by different machines but with a different failure probability for potential failures (e.g. the hole drilled too deep, etc.). Then, it is better to test the quality of the work piece after a machine with a high failure probability before performing the next production step in order to sort out work pieces with an incorrect drilling depth. However, if the hole was drilled by a machine with a very high precision, it could be sufficient to perform the test at the regular end of line. Such scenarios should be considered after each reconfiguration of the factory in order to ensure a target product quality and produce a certain amount of products for a specific price in a given time.

Dynamically creating a Process-FMEA during the operation of an adaptable and flexible factory requires to identify all possible failure modes and automatically associate the effects of individual failures (e.g. from machinery or production steps) with the possible effects on the specific product. This open challenge must be addressed.

Ensuring the quality of products produced in an adaptable and flexible factory addresses both the application scenarios "adaptable factory" and "seamless and dynamic engineering of production systems". As a basis for a Process-FMEA, the modules within the production system should provide self-description, including also possible failure modes and their effects. Consequently, an integrating production system model is needed to use these self-descriptions of the modules to assess the failure modes of each production step and their effects on the production process described in the second application scenario.

4 Summary

In this paper, challenges for the engineering of adaptable and flexible factories are described which are derived from selected Industry 4.0 application scenarios as well as general engineering tasks during the lifecycle of such factories. It is left to further research activities to derive concrete requirements from these challenges and evolve solutions in order to enable the design and operation of adaptable and flexible factories in future. Since changes within these factories are expected to happen rather often, the support of engineering tasks related to production system and product changes must be efficient and effective in order to enhance the availability of the factory.

Further challenges on adaptable and flexible factories can be derived from the complementary Industry 4.0 application scenarios as well as from other engineering tasks such as the check for manufacturability of given products, production planning, performance and reliability improvements, and self-management capabilities of production systems. Since the lifecycle of factories may be some decades, in addition, migration concepts for existing factories are highly required. Such migration concepts shall provide a transition path from traditional factories to adaptable and flexible factories based on a step-by-step approach. These challenges have to be analyzed as well in order to provide a stable requirements basis for future solutions for adaptable and flexible factories.

5 Acknowledgement

The work leading to this paper was funded by the German Federal Ministry of Education and Research under grant number 01IS16043Q – Collaborative Embedded Systems (CrESt).

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