Process Deviations in Cyber-Physical Production Systems

Nadia Galaske, Daniel Strang, and Reiner Anderl

***Abstract* — Global markets lead to the development of new production techniques, to guarantee competitiveness especially in high-wage countries. In this context, the German federal government supports the research and development of production systems based on cyber-physical systems (Industrie 4.0). In cyber-physical production systems all participants of the production process possess individual information about themselves and are equipped with actors, sensors, and a communication interface. Machines, workers, resources and components can interact and autonomously develop and execute process relevant decisions.**

Cyber-physical production systems are characterized as highly flexible systems that enable adaptive production processes. The processes for each individual component of the same product can vary in the order of the process steps and the performing manufacturing stations. For each product, a standard process and alternative processes are defined. If a deviation in the standard process occurs during the production of an individual component, the standard process is not feasible anymore. Through the interaction of process participants, the system can autonomously define an appropriate reaction and execute it by using actors of the participants and the intralogistics. Regardless of the deviation, the production of the individual component can proceed in cyber-physical production systems.

In this paper, process deviations and appropriate reactions of cyber-physical production systems are analyzed, described in models, and simulated, to illustrate the benefits of cyber-physical production systems and to develop a process deviation management system for actual, physical production systems based on cyber-physical systems.

***Index Terms* — cyber-physical production systems, Industrie 4.0, process deviation management, process simulation, process model**

I. Introduction

THE opportunity of globalization for manufacturing industries in low-wage countries is a challenge for production facilities in high-wage countries. For the preservation of jobs, these countries research and develop new production facilities with highly efficient and automated production systems. New approaches aiming in a different direction of research are being developed. The German Federal Government is supporting the research of production systems using cyber-physical systems as part of the initiative “Industrie 4.0” [1]. These cyber-physical production systems are characterized by highly flexible production processes that enable the production of a high variety of products in small batches using the same production system without high costs. Products, components, resources and machines possess individual information about themselves and are part of a provided network of things and data (Internet of Things and Internet of Data). Using this network and communication interfaces, all participants can communicate with each other and develop the production process autonomously through an information exchange.

During these autonomous processes, deviations can occur. These can be induced by missing components, blocked manufacturing stations, missing workforces, or incorrect information of products, manufacturing stations, resources, and workers. These deviations have to be detected, analyzed, and processed to define a reaction behavior.

Due to the novelty of the production system, possible deviations must be identified before applying the production system for mass production. Based on an analysis of the system and possible deviation scenarios, a deviation management system to support decision making process in cyber-physical production systems can be developed.

This paper serves as the foundation in the process deviation management. For that purpose, an Ishikawa diagram with possible causes for process deviations is derived and a model for the reaction behavior of the cyber-physical system is defined for each type of deviation. Based on these models, material flow simulations are developed to illustrate the behavior of cyber-physical production system and the reaction on deviations. These simulations are used for the definition of the best possible reaction and to detect weak points and challenges of the theoretical models of the reactions on deviations.

II. State of the Art

A. Cyber-Physical Systems and Industrie 4.0

Increasing competition due to the globalization leads to challenges for the economies of countries and discrete manufacturing companies. Cyber-physical systems offer an innovative solution to address the challenges in the production. These cyber-physical production systems are the

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foundation of the "Industrie 4.0" initiative of German Federal Government [1].

Cyber-physical systems (CPS) are based on the two principles: "cyberizing the physical" and "physicalizing the cyber" [2]. These systems can be defined by following characteristics [3–5]:

- CPS consist of sensors, actors, embedded systems, mechanical structures, and human-machine interfaces.
- CPS collect information using sensors, analyze these using worldwide services, and use actors to interact with the physical world.
- CPS are equipped with communication devices to connect with each other and with other entities in a global network.

The integration of cyber-physical systems in the production environment leads to a cyber-physical production systems (CPPS) as part of "Industrie 4.0" [1]. These cyber-physical production systems are characterized by highly flexible production processes, which are able to adapt according to the current market circumstances, and enable the production of a high variety of products in small batches. This approach brings many opportunities, as it enables the individualization of customer requirements, increases the resource productivity and efficiency, and optimizes the decision making process due to complete availability of information in real time [6].

For the manufacturing context, cyber-physical systems can be applied in production resources, such as manufacturing stations, automation devices, single machines, and tools, as well as on individual components or products, resulting in smart products. These smart products are mechatronic products equipped with cyber-physical systems that possess information about their manufacturing operations and are able to communicate with each other using modern internet technologies [7]. The collaboration of smart products and smart production systems using internet technologies and context-awareness leads to a smart factory. A smart factory provides a manufacturing solution with adaptive production processes for solving decision problems and managing increasing complexity in rapidly changing conditions [8].

However, some challenges associated with the implementation of cyber-physical production systems, such as the need of unified standards and reference architectures, the safety and security of the production and communication systems, and the increasing complexity of production processes, e.g. due to Big Data [6], still need to be addressed.

B. Modeling and Simulation of Cyber-Physical Production Systems

For a better understanding of the behavior of a cyber-physical production system and its elements, it has to be represented using models. A model is defined as a simplified reproduction of a system, including its characteristics and processes [9]. Through the simplification in terms of abstraction in modeling techniques, the complexity of the observed problems in the modeled system can be reduced, thus making it easier to find a solution.

An approach to illustrate the relations of the participants in a cyber-physical assembly process and their influence on each other is the UML class diagram [10]. This is possible with the provided UML standards of the Object Management Group [11], which are the foundation of the modelling techniques described in the literature, e.g. Weilkiens [12] or Miles and Hamilton [13]. Fig. 1 shows the packages and the classes of the class diagram in a simplified way.

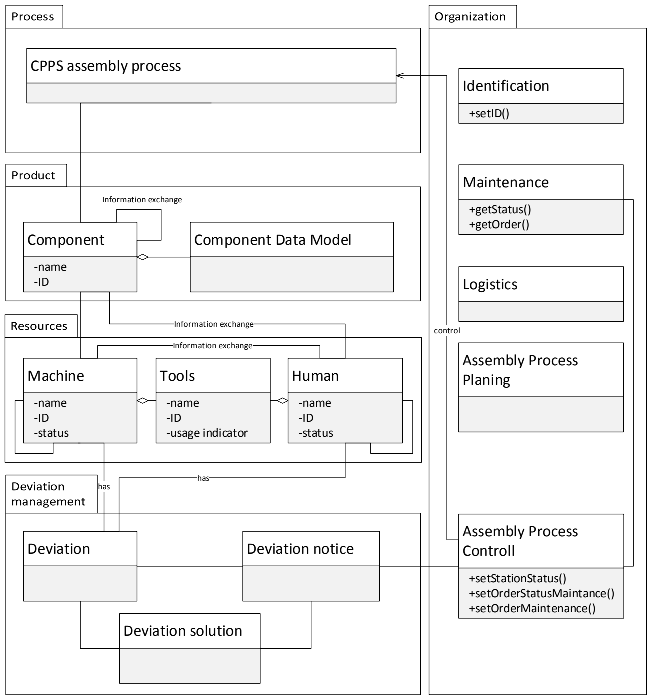

Fig. 1. Meta model of the cyber-physical assembly process [10]

The class diagram is structured into five packages: process, products, resources, deviation management, and organization. This architecture is chosen to combine participants and other elements into groups that have similar tasks in the system.

The key package for this paper is the deviation management. It classifies the occurred deviation, identifies a suitable solution and reaction, and creates a deviation notice for the process control. With a confirmation from the process control, a reaction of the system can be executed and considered in the production process.

Classes in the package of the product are the component and a component data model. The component data model is an individual, digital representation of each component. Therefore, it is possible to represent all product data and the actual data of the manufactured components [4]. With this information, components can influence their own production process and act as a key enabler for smart production planning and process control [14]. The component data model offers a possibility to deposit data of each process event. Thus, information about process deviations can be stored as part of the data model.

A simulation is used to represent a system with its elements and its dynamic processes. It provides the possibility to examine the behavior of a system which does not yet exist and transfer the result into the system development [9]. Simulation methods can be classified according to the time interval, in which state change occurs.

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In the field of manufacturing, discrete-event simulations (DES) offer suitable methods for simulating production processes and sequences, as well as material flow [15].

III. Modeling

The increasing complexity and dynamics of cyber-physical production systems cause a high susceptibility to deviations resulting from failures and disturbances in the production processes. In order to be able to manage process deviations in a cyber-physical production system and determine the suitable reaction, the modeling and simulation of process deviations are required.

A. *Definition of Process Deviations*

A standard or default situation describes a sequence of events that is the result of previously planned actions. This sequence of events is subjected to certain principles and is connected in a causal relationship. In a standard situation, the production process runs as planned and no intervention is needed.

During the production, process deviations can occur, which lead to a non-executable process. Such events are called nonstandard situations. In this case, the production process is not feasible and problems arise in the execution of manufacturing operations. In order to prevent the escalation of the problem, the production system has to react accordingly.

Process deviations can be caused by failures or disturbances in production processes. Disturbances are defined as temporary events that appear unexpectedly and cause an interruption or delay in the task execution. When disturbances take place, the process drifts from its optimum course [16, 17]. Failures also leads to inconsistency between the planned and the actual production process, in which process deviation can be observed. Failures on production system elements can be caused for example by missing workforce, quality problems, or mechanical breakdowns [18].

B. *Process Deviations in Cyber-Physical Production Systems*

Due to the intelligence carried in the component data model, a manufacturing component in cyber-physical production systems possesses information about its manufacturing and assembly operation. In case of a process deviation, the manufacturing component must be able to react accordingly and to make the decision between possible alternative processes based on the stored and available information.

Before process deviations in cyber-physical production systems can be modeled, it has to be defined, what kind of deviation can occur in a production system in the first place. Meyer et al. [19] provides an overview of approaches for determining and categorizing failures and disturbances causing process deviation in production processes. In this paper, an Ishikawa diagram is used to identify potential factors causing a process deviation. The source of deviation is divided in five categories (referring to [20]):

- Material (Component),
- Machine (Manufacturing stations),
- Method (CPPS),
- Man Power (Worker), and
- Milieu (Environment).

In this paper, a theoretical concept of cyber-physical production systems is analyzed. Therefore, the Ishikawa diagram is used to find the cause of a problem in a system which does not yet exists, so it can be analyzed and modeled.

The Ishikawa diagram illustrated in Fig. 2 contains possible causes of process deviations in cyber-physical production systems. Since the modeling and simulation for many of the causes are similar, only major causes will be considered in detailed scenarios. These are:

1. The required manufacturing station is not available
2. The required worker is not available
3. The required component is not available

In the next chapter, the process deviation caused by unavailability of the manufacturing station is selected for the modeling and simulation due to its representativeness.

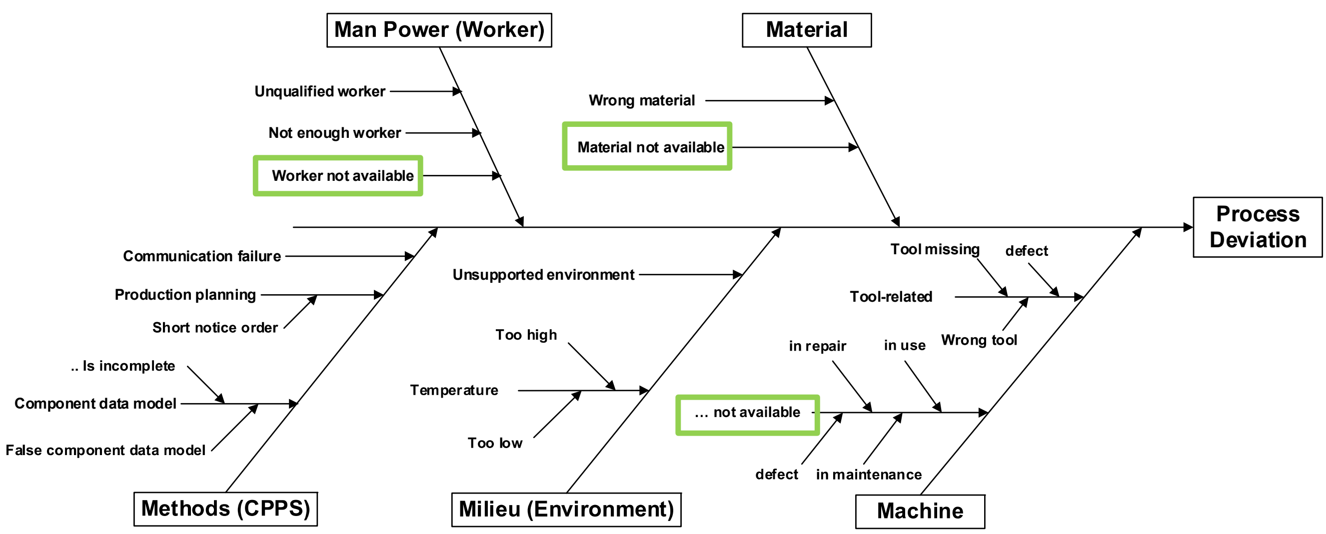

Fig. 2. Ishikawa diagram for determining causes of process deviation in cyber-physical production

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C. Modeling of Process Deviations and Reaction Behavior

The goal of this paper is to develop a logical model for the description of the system and the system's behavior during a process deviation scenario [21]. The model aims to show how a cyber-physical production system behaves in certain situations under certain circumstances. The modeling of the cyber-physical production system consists of the development of a dynamic simulation model, the execution of the simulation, and the analysis of the simulation results. The behavior of a cyber-physical system will be demonstrated using only a section of the production line with a number of manufacturing station, as shown in Fig. 3.

The modeling of the chosen scenario is done using UML activity diagrams. The standard scenario is described as follows: a manufacturing component in a cyber-physical production line arrives at a manufacturing station according to the information stored in its component data model. The station is available and the manufacturing process can begin.

In the deviation scenario, the required manufacturing station is not available. Thus, the production process is interrupted and the system has to determine the suitable reaction for the component as quickly as possible. Fig. 4 visualizes the decision process model for determining the suitable reaction for the process deviation caused by unavailability of the required manufacturing station. Each action is associated with the corresponding system element represented as swim lanes.

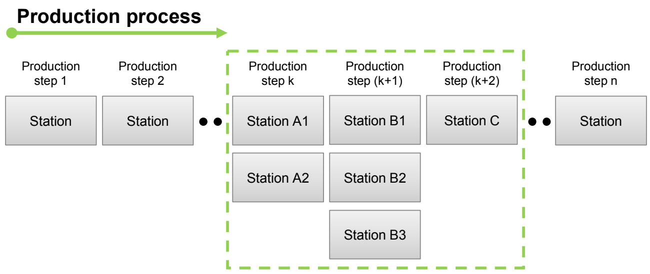

Fig. 3. System boundary of the cyber physical production systems with exemplary number of parallel stations.

In the first step, the component reads the information stored on its component data model. As specified by the component data model, the current process step is determined and the component is transported to the required station according to this process step. Using the cyber-physical system approach, the component is able to communicate with other components, as well as with the manufacturing station. The component sends a request to the station, whether the manufacturing operation can be started. When the component detects that the manufacturing station, on which the current manufacturing operation should take place, is not available, the component tries to identify alternative or parallel stations for the current process step using its component data model. If an alternative station exists, the component is transported to this station and requests for the manufacturing process to be performed.

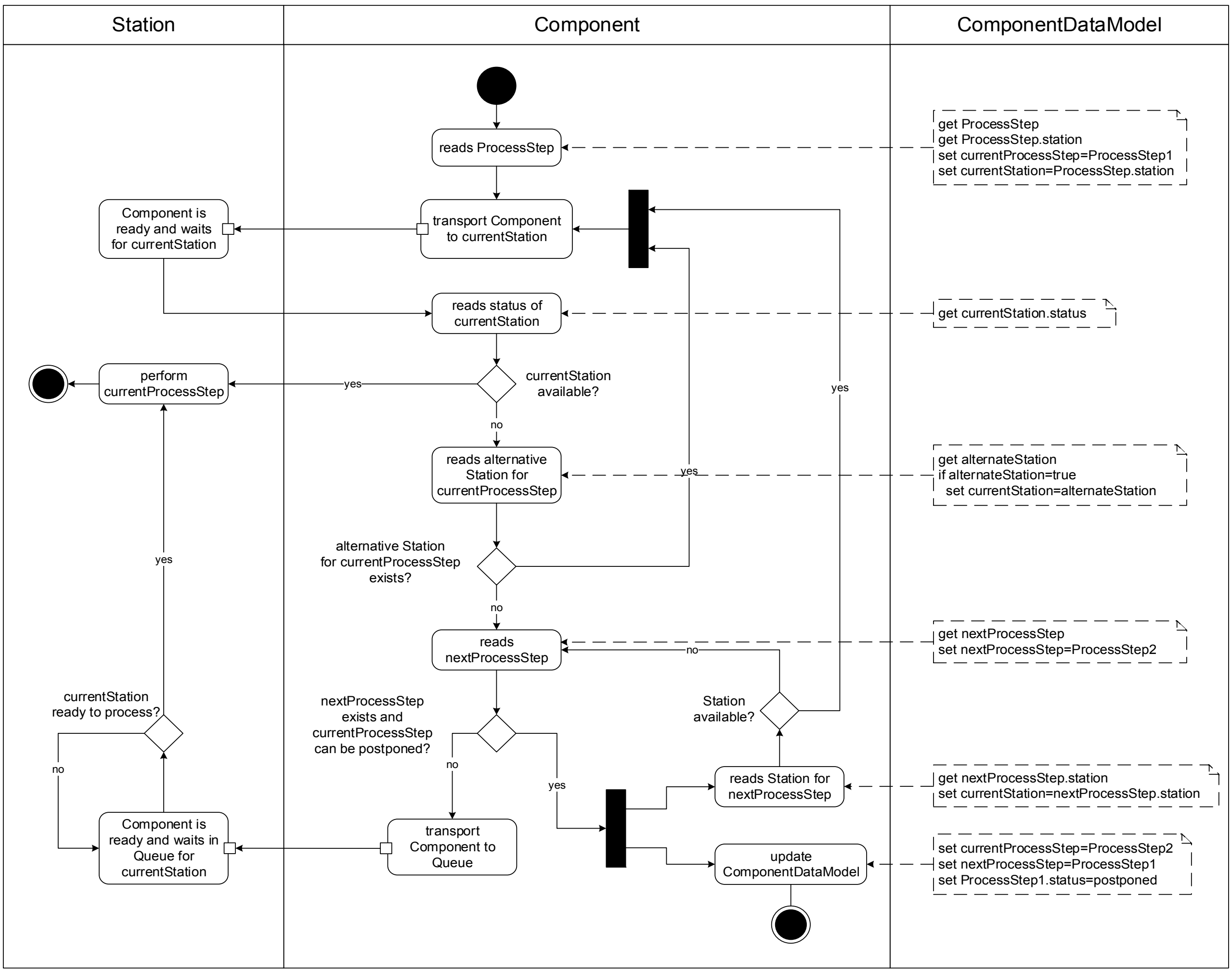

Fig. 4. Process Model

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If no alternative station exists, the component reads the next process step from its component data model and sends an inquiry, whether the process sequence can be altered. If this is the case, the current process step is postponed and the next process step is set as the new current process step. The component data model is overwritten with the updated process sequence. The manufacturing station for the new process step is identified and the manufacturing process can be carried on.

If no parallel station is available or no subsequent process step exists, the component is added to the queue of the current manufacturing station and waits for the current station to be ready to perform the current manufacturing process step.

IV. Simulation

A. Implementation

In this chapter, the modeled process deviation scenario is implemented using a discrete-event simulation software. Fig. 5 shows the design of the simulation, with the manufacturing process steps marked in boxes and the manufacturing stations underlined. In this simulation, the production line consists of three subsequent process steps, in which the first process step consists of two manufacturing stations that can work parallel. In conformity with the chosen scenario in the previous chapter, the process deviation occurs because *Station1A* as default station of the first manufacturing step is not available.

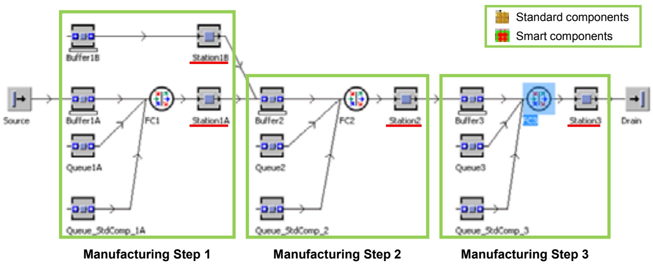

Fig. 5. Simulation design

For the simulation, the behavior of two different types of manufacturing components are observed and analyzed:

1. Standard components
2. Smart components

Standard components represent normal or default objects in traditional manufacturing and assembly processes. They are neither equipped with sensors, actors, nor a communication interface and do not have the intelligence provided by the component data model. The production process of standard components runs according to the planned process sequences. If a deviation happens, the standard components cannot react autonomously and thus must wait until the problem is solved.

In the simulation design shown in Fig. 5, standard components can only be manufactured on the default station (*Station1A*). In case of a process deviation, the standard components have to wait in the corresponding queue (*Queue_StdComp_#*) until they can be processed again.

Smart components, on the other hand, are intelligent manufacturing and assembly objects equipped with cyber-physical systems (sensors, actors, and a communication interface) and a component data model. Using the information stored in the component data model, smart components can communicate with each other as well as with the manufacturing stations. The processing sequence for each component can also be varied to a certain extent. Thus, the originally planned process sequence can be adjusted in case of a deviation caused by failures or disturbances in the production process.

In the simulation design shown in Fig. 5, smart components can be manufactured either on *Station1A* or *Station1B*. The process sequence between the first and the second manufacturing step can also be varied. If the process deviation takes place, a smart component can choose to do one of the following three actions:

1. Search for an alternative station from the same manufacturing step (*Station1B*),
2. Search for an available station from the next manufacturing step (*Station2*), and then go back to the first manufacturing step (either *Station1A* or *Station1B*) after it has been processed, or
3. Wait in the *Queue1A* until *Station1A* is available.

B. Simulation Results and Discussion

Using the decision logics stored as algorithms for each of the component in the simulation model, it is possible to run the simulation and verify the behavior of both types of components in the simulation model using Sankey diagrams, as shown in Fig. 6.

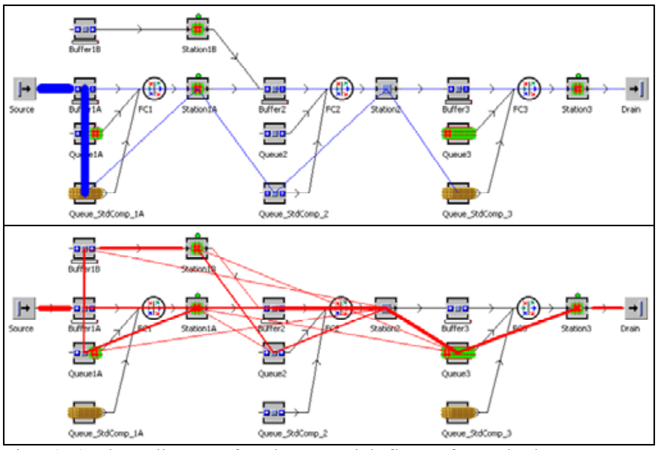

Fig. 6. Sankey diagram for the material flow of standard components (above) and smart components (below)

However, the analysis of the process deviation scenario in this simulation model is isolated from other deviation scenarios. The analysis of interdependencies between different possible deviations is still part of the research.

Another challenge for the future is the size of the observed system. In the simulation model, only a section of the production line is analyzed. This does not mean, however, that the methods and the results cannot be transferred for the modeling and simulation of a real production system.

V. Conclusion and Future Work

In this paper, process deviations in cyber-physical production systems are defined, analyzed, and modeled using UML. Using basic modeling elements of UML, it is

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possible to visualize the decision process for smart components in a cyber-physical production line. The modeled concept is implemented in a simulation model using discrete-event simulation software. With the simulation, the differences in behavior of standard and smart components during a process deviation in a cyber-physical production system can be illustrated and observed.

The concept for modeling and simulation of process deviations in cyber-physical production systems presented in this paper serves as a recommendation for further research of the behavior of cyber-physical production systems. This is the foundation for developing concepts to ensure the robustness for the real application of cyber-physical production systems.

Future works need to address the responsiveness of the management of process deviation and the reaction behavior. For a full contemplation of a cyber-physical deviation management, the communication between the simulation software and the decision response system plays an important role in order to enable a near real-time response. Therefore, research in this particular area is needed.

For a holistic approach in managing process deviations and the escalation training, several scenarios where different process deviations occur in random sequences should be modeled and simulated. In this case, the dependencies and consequences of each cause of process deviations can be considered and the robustness of the cyber-physical production system can be tested.

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