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Procedia CIRP 50 (2016) 442 – 447

www.elsevier.com/locate/procedia

26th CIRP Design Conference

Disruption Management for Resilient Processes in Cyber-Physical Production Systems

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Abstract

The increasing complexity and dynamics of cyber-physical production systems (CPPS) lead to a high vulnerability to disturbances during production processes. In the event of process disruptions, decisions must be made in short time in order to minimize the impact on production systems. In this paper, a simulation-based decision support for the disruption management process in a resilient cyber-physical production system is presented. Scenarios for disruption events and response strategies are modeled and simulated. The simulation results for each disruption event scenario are evaluated and the best possible strategy is recommended to the decision-maker including the expected impact on production processes.

Keywords: Cyber-physical production systems; Industrie 4.0; Disruption management; Decision support; Process simulation

1. Introduction

In the recent years, discrete manufacturing companies in high-wage countries are facing increasing challenges due to globalization, shorter product life cycles, and rapidly advancing technologies. Furthermore, the growing customer demands for individualized products and the high cost pressure also act as additional requirements. In order to overcome these challenges and maintain their competitiveness, manufacturing companies in high-wage countries are taking a new approach for developing new production systems with the focus on efficiency, individuality, and flexibility.

The research and development of such production systems based on cyber-physical systems is the subject of current research of the initiative Industrie 4.0 supported by the German Federal Government [1]. These highly flexible cyber-physical production systems enable the production of a high variety of products in small batches and similar costs to those of mass production. Due to its adaptivity, a cyber-physical production system is able to respond accordingly to the changes in market situation or turbulences in the production environment.

The increasing complexity and dynamics of processes in cyber-physical production systems, however, leads to a high vulnerability to disturbances during production processes. Moreover, due to the increasing application of digital technologies and connected systems in cyber-physical production systems, a failure in one subsystem can cause a disruption in another subsystem or, in the worst case, a complete standstill of the whole production process. In case of process disruptions or significant deviations from normal state, decisions must be made in short time in order to minimize the impact of failures and disturbances on production processes and guarantee a stable production result and delivery reliability. For this purpose, the reaction behavior of cyber-physical production systems in the event of process disruption has to be analyzed and included in the planning and design of cyber-physical production systems. Additionally, the integration of response strategies and decision logics in the production control is required.

In this paper, a simulation-based decision support system for supporting the disruption management process in cyber-physical production systems is presented. This paper introduces an approach for analyzing process disruptions and their impacts, and proposes the appropriate response strategies

doi:10.1016/j.procir.2016.04.144

that can be taken. The aim of the approach is to increase the resilience of processes in cyber-physical production systems by modeling the decision process and the communication between the decision support system and the simulation, as well as evaluating the response strategy of the system in the event of process disruptions in order to improve the reaction time and to minimize the impact of process disruptions on the entire production system.

2. State of the Art

2.1. Cyber-physical Production Systems

The foundation for modern manufacturing systems are cyber-physical systems. Cyber-physical systems are based on the two principles "*cyberizing the physical*" and "*physicalizing the cyber*" [2]. This means that every physical object has to be represented in the virtual world, and vice versa. Cyber-physical systems are embedded systems, which record data using sensors, analyze them using connected services, influence physical processes using actors, and interact with other systems using communication interfaces [3].

In the production domain, cyber-physical systems can be equipped in all production resources, such as manufacturing stations, automation devices, storage systems, and production facilities. In this way, they are able to autonomously exchange information, trigger actions, and monitor each other [4]. Therefore, cyber-physical systems are the key for the integration of different equipment on all levels of production [5]. The application of cyber-physical systems in the production environment leads to a cyber-physical production system (CPPS), in which every individual manufacturing object is the carrier of its individual manufacturing information [6]. Using this information and the equipped communication interfaces, these manufacturing objects can interact with each other and steer the production process by negotiating the optimum course of production and making autonomous decisions. The communication between each object in a cyber-physical production system can be executed either as an end-to-end communication or by using a central server [7]. The environment where smart products and smart production systems collaborate using internet technologies and context awareness, thus providing a manufacturing solution with an adaptive production process, is also referred to as a Smart Factory [8].

2.2. Failures, Disturbances, and Disruptions

During the course of production, failures and disturbances can take place and disrupt the production process or cause delay in the job execution. Failures and disturbances act as destabilizing factors in the production causing poor performance of the production system [9]. Due to the increasing demand for a short time to market, just-in-time manufacturing, and the trend to reduce inventory, a disturbance that occurs in one element of the system can have a considerable impact as the time to react before the disturbance effect is perceived is becoming shorter [10].

The effect of failures and disturbances can range from unsatisfied user demands, to insufficient resources, damaged infrastructures, and - in the most extreme cases - danger or harm to humans, machines or the environment [11]. In the production environment, disturbances can be categorized in planned and unplanned downtime, speed losses, and quality problems [9]. Due to the increasing use of communication technologies in a cyber-physical production system and the importance of information transparency, disturbances can also be caused by missing required manufacturing information or a failure of the communication interfaces [12].

In this paper, failures are defined as the nonfunctional state of a system element while disturbances are perceived as the deviation of the normal state of the process. Consequently, the terms failures and disturbances are summarized into the term disruptions, as both failures and disturbances cause the process to be disrupted. Following the definition in [13], a process disruption is defined in this paper as an unexpected temporary event caused by failures or disturbances during the execution of a manufacturing operation, where the deviation between the current and planned state is significantly large that the plan has to be modified substantially.

As process disruptions are unwanted and unplanned events that appear unexpectedly, their time of occurrence and duration can often not be predicted [10]. The lifecycle of process disruptions can be extended from the lifecycle of disturbance handling and is divided in four phases (Fig. 1). The detection phase signifies the time between the occurrence of the disrupting event from a normal operating state and the time the effect of the disrupting event is perceived. In the analysis phase, the cause of the disruptions is diagnosed and analyzed. The development phase describes the decision-making process that is necessary to develop the countermeasure to solve the problem induced by the disrupting event. In the last phase, the solution defined in the previous phase is implemented and the system should return to its normal operating state [14]. The phase before the effect of the disrupting event is perceived can also be referred as the latent phase and the later phases as the manifest phase, which lasts until the disappearance of the disruption [10].

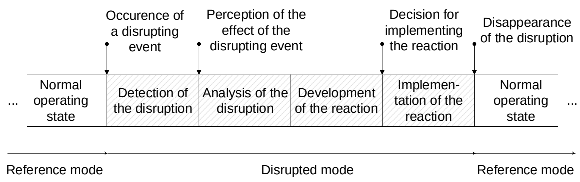

Fig. 1. Lifecycle of process disruption, modified after [14]

2.3. Decision Support System for Managing Process Disruptions

As process disruptions have a negative influence on the performance of a manufacturing system, reducing the effect of the disruption is the key to increased productivity and a better efficiency [9]. Therefore, the main focus of the disruption management is to reduce the overall time of the system in disturbed mode. This can be achieved by ensuring a fast and suitable development of recovery behaviors [14], thus shortening the required response time.

For an efficient disruption management, a constant monitoring of the status of the system is necessary [13]. The production planning and control provides a way to support the disruption management process. The production control is responsible for order generation and release, job sequencing, resource allocation, and capacity control. It aims for a stable production process regardless of dynamic environmental changes or market turbulences [15].

As cyber-physical production systems place great emphasis on information transparency, it is possible to respond faster and more efficiently to disruption in the production. Using sensors integrated in both products and production systems, the production control can obtain an overview of the current production status and gather information from the shop floor about the priority of pending manufacturing operations. These information can be used as feedback to achieve an adaptive process planning [16].

In order to develop solutions as responses for the disruption event during the production, several approaches can be adopted. This can be done for example by rescheduling jobs, reallocation of resources, or by changing the manufacturing operation sequence. For the purpose of determining the best response strategy, a decision support is needed, where different scenarios can be run through and various alternative solutions can be weighed up before the decision for the optimal solution is made.

One of the methods to achieve this is through a simulation-aided decision support. Simulation proves to be a suitable tool to analyze disturbances and demonstrate the impact of a disrupting event [9]. Using simulation, the system behavior for each disruption scenario in the production can be observed without interrupting the running process [17]. The effort and time needed for manually producing feasible solutions can also be significantly reduced [18], as different scenarios and alternate solutions can be simulated. Moreover, the impact of each response strategy on the production environment can be evaluated before the strategy is implemented in the physical production system.

3. Disruption Management for Resilient Cyber-Physical Production Systems

For a cyber-physical production system, the disruption management is of great importance to ensure the resilience of both the cyber-physical production system and process. In a cyber-physical production system, the frequency of the occurrence of a disrupting event can be higher than in a conventional production system. On the one hand, the planning and management of an adaptive and flexible production process with intelligent products and production systems is a complex process which requires a continuous monitoring and full IT-support. On the other hand, the increasing application of information and communication technologies leads to an increasing vulnerability of the cyber-physical production system. Furthermore, due to the connectivity of the system, a disruption in one element of the system can have a large impact on the whole system.

In order to prevent these, the processes and elements of a cyber-physical production system have to be designed for resilience. Resilience describes the system's behavior when a disrupting event occurs during runtime [11]. Resilience of a production system can be measured through the ability of the production system to withstand disruption [10] and to recover from a disrupted state to the normal operating state by the system itself [11]. In this context, the concept of resilience incorporates both the principles of robustness and agility. Robustness describes the ability of the system to cope with minor disruptions without adaptations while agility describes the ability of the system to regain its original state by adapting to changes caused by severe disruptions [10, 19]. As resilience is strongly influenced by a good disruption management strategy, the development of a simulation-based disruption management concept is the focus of this paper.

3.1. Requirements for Designing a Resilient Cyber-Physical Production System

Based on the definitions of resilience and in respective of the principles for designing and managing resilient manufacturing systems in [11], we derive following requirements for developing a resilient cyber-physical production system:

- *Robustness and adaptability:* A resilient cyber-physical production system has to be able to withstand external influences or be adaptive to disruptions.
- *Self-regulation and self-recovery:* A resilient cyber-physical production system must be able to regulate its production process and recover from a disruption event to the ideal state by itself.
- *Short response time:* Fast development and implementation of suitable response is required in order to encounter process disruptions and minimize the time in disturbed mode.
- *Intelligent component:* Every component in a resilient cyber-physical production system has to possess a component data model [6] containing information about its manufacturing and assembly operations.
- *Autonomous decision:* Every component is able to exchange information with the manufacturing station to negotiate and autonomously make decisions.
- *Redundancy:* Redundancy is incorporated in the architecture of a resilient cyber-physical production, either by including several manufacturing stations that are able to process similar manufacturing operations or by including flexible operation sequence in the process that can be alternated according to current needs.
- *Dynamic disruption database:* A resilient cyber-physical production system possesses a knowledge database of disruption scenarios and possible countermeasures.
- *Escalation scenario:* An escalation scenario simulation that takes into account several disruption events is required to enrich the decision support system.

3.2. Methodology for the Disruption Management

A first approach for defining, analyzing, modeling, and simulating of process disruptions in a cyber-physical production system was presented in [12]. For the purpose of developing a disruption management concept in cyber-physical production systems, the following methodology is presented in this paper.

In the first step, possible disruption event categories (DEC) and the corresponding disruption events (DE) in the production process are identified. The disruption categories represent the objects where the disruption occurs. For example, a disruption event category and its associated disruption event in parenthesis can be: products (faulty component), human resources (absent worker), or production equipment (machine breakdown) [20, 21]. For a cyber-physical production system, the disruption event categories can be expanded in information (outdated component data model) and communication (failed to send query). Additionally, for each use case it can be defined whether the disruption event has an effect on the time factor (delay in the process), quality factor (rejected product), or cost factor (replacement of resources).

In order to analyze the plausibility and interdependencies of different disruption events, a consistency matrix is used (Fig. 2). In the consistency matrix, the consistency values of the disruption events are entered and summarized. The consistency value is used to evaluate the probability of two different disruption events affecting each other. The consistency value can range between 1 (total inconsistent) to 5 (strongly consistent). Based on the analysis using the consistency matrix, similar disruption events can be clustered and disruption scenarios for these disruption events can be derived using scenario development techniques [22].

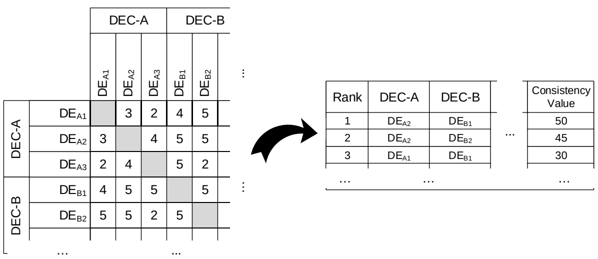

Fig. 2. Consistency matrix for analyzing disruption scenarios

For each disruption scenario, possible actions as response strategy for the disruption event are defined and stored in a disruption database. This allows the decision support system (DSS) to find solutions for similar disruption use cases. In order to determine the best response strategy, the impact of each action on the production system is simulated using a simulation tool and the simulation result is evaluated and compared with each other using selected key performance indicators (KPI). In regard to resilience, the KPIs can be for example production loss, throughput settling time, or total underproduction time [23], but also order fulfillment rate, overall equipment efficiency (OEE), or value added rate. Based on the result, the decision support system for the disruption management can recommend the best response strategy to the decision maker including the forecasted impact on the production.

4. Modeling and Simulation

For the modeling and simulation, the disruption management procedure in regard of the communication between the cyber-physical production system, the production control, the disruption management decision support system, and the simulation tool is modeled using UML sequence diagram (Fig. 3). The main focus in this context is the communication between the Disruption-Management-DSS and the simulation tool.

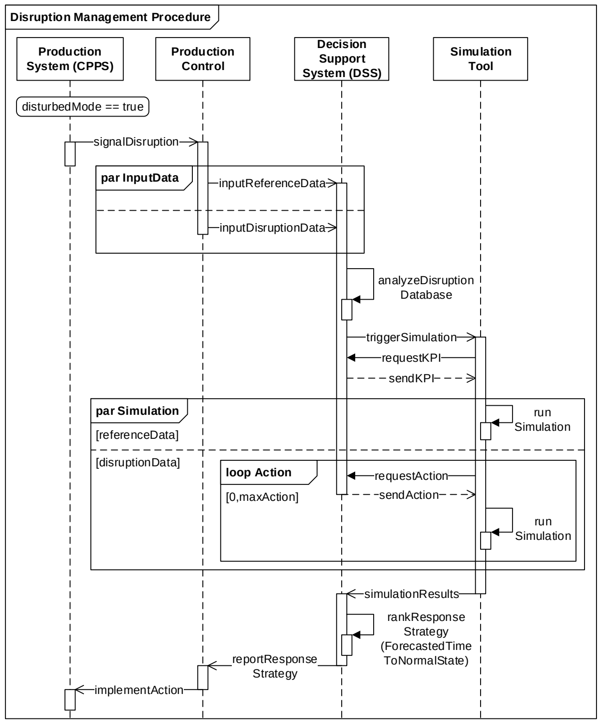

Fig. 3. Procedure for a disruption management in CPPS

During a running production process, the cyber-physical production system is assumed to possess the ability to self-diagnose. If a disruption event occurs, the system can signal the disruption to the production control. The report can be signaled either through a central server or by an individual component or manufacturing station directly. For the disruption management process, the production control has to input the current information of the disrupted state and the information from the production planning system as the reference state to the Disruption-Management-DSS. This information is analyzed using the information from the disruption database and the Disruption-Management-DSS triggers two types of simulations over the network: The simulation with the planning data as the reference state and the simulation with the current data as the disrupted state. Based on the requested KPIs, the simulation tool performs the simulation and sends the results back to the Disruption-Management-DSS. For the disrupted state, the simulation has to be executed for each possible action according to the Disruption-Management-DSS. For the purpose of analyzing the impact of the disruption event and the comparison of different actions as response strategy, the action of doing nothing is included in the simulation as the default response. Based on the results, the Disruption-Management-DSS ranks the response strategy including the forecasted time to normal state (FTNS) and report to the production control. In the production control, the best response strategy is selected and implemented in the physical production process.

The disruption management procedure can be expanded with a monitoring process after the selected response strategy is implemented (Fig. 4). After the system returns to its normal state, the status is reported to the production control and the real time to normal state (RTNS) is determined and compared with the forecasted value of the Disruption-Management-DSS. Consequently, the disruption database has to be updated in order to improve future forecasts of the Disruption-Management-DSS and enhance the quality of the simulation.

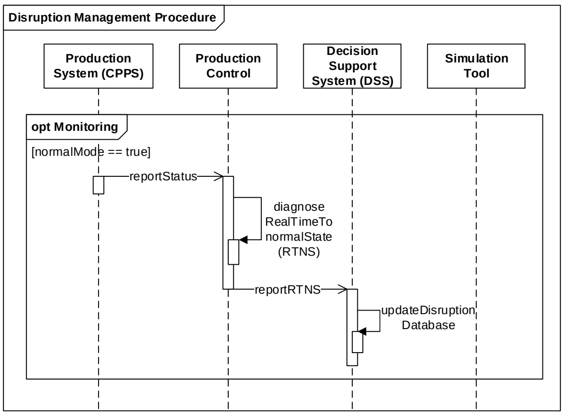

Fig. 4. Production monitoring for updating disruption database

In the following section, the practical use of the concept is presented using an example simulation. The simulated production process is based on the assembly process of a physical product manufactured in a university learning factory environment. The assembly process can be described as follows: a small batch of pneumatic cylinders has to be assembled on a set of independent assembly stations AS_j. To complete the assembly, a set of six different assembly operations O_i has to be performed. Each assembly station is able to perform a specific assembly operation at a time and every assembly operation requires a given processing time T_{ij}. The pneumatic cylinders are designed as intelligent products and each of the components carries information about the required assembly operations and the operation sequence. Each product is able to communicate with the assembly station and enquire whether the assembly station can perform the requested assembly operation and whether the assembly station is currently available.

For the demonstration of the concept, two scenarios are derived from the disruption event “assembly station failure”. In this case, the assembly station AS_3 that was assigned to perform the assembly operation O_3 experiences failures and cannot be used for a limited time. The disruption time (DT) denotes the required repair time for the assembly station AS_3. The two scenarios differ in the following specification:

- *Scenario 1:* An inferior substitute assembly station AS_{3-1} that can perform the assembly operation O_3 exists. However, the processing time in this assembly station is three times as long.
- *Scenario 2:* An alternative assembly station AS_{3-2} exists. This assembly station can perform not only the assembly operation O_3 for the pneumatic cylinder but also for another product. Thus, the utilization rate is high.

For the evaluation of the disruption management, different response strategies are simulated. The default response strategy is to stop the assembly process and wait for the assembly station AS_3 to be repaired. The alternative response strategy is to temporarily perform the required assembly operation using the alternative assembly station (AS_{3-1} in Scenario 1 and AS_{3-2} in Scenario 2) until the default assembly station AS_3 is repaired. In order to show the impact of the disruption event, the reference state, which is the planned assembly process in the original state without disruption, is also simulated.

5. Results and Discussion

The simulation is executed using the discrete-event simulation software (DES) Tecnomatix Plant Simulation and a custom Disruption-Management-DSS developed in Java. The communication between both systems is implemented using a socket interface to simulate a client-server network connection.

For the simulation, the following KPIs are selected: throughput per hour (TPH), average throughput time (TT), and the value added rate (VAR). For the comparison purpose, Table 1 shows the simulation results with short disruption time of 5 process cycles and Table 2 shows the simulation results with high disruption time of 30 process cycles.

Table 1. Simulation results with minor disruption.

KPI	Reference state	Response strategy		
		Default	Scenario 1	Scenario 2
TPH [pcs.]	75	72	68	66
∅ TT [mm:ss]	02:35	02:48	03:05	03:17
VAR [%]	62,7	60,4	59,5	57,5

Table 2. Simulation results with severe disruption.

KPI	Reference state	Response strategy		
		Default	Scenario 1	Scenario 2
TPH [pcs.]	75	42	68	41
∅ TT [mm:ss]	02:35	05:10	03:04	05:30
VAR [%]	62,7	38,4	61,7	33,7

The simulation results show that the disruption time has a great influence on the decision for the best response strategy. For a minor disruption with a short disruption time, the recommended strategy in this case is to wait for the designated assembly station to be repaired. On the contrary, for a major disruption with a high disruption time the recommended strategy is to transfer the product to a substitute assembly station, if such a station exists, even if the processing time would take longer. Due to the high utilization rate of the alternative assembly station, the decision to transfer the product to this assembly station should only be made if it is unavoidable.

Other simulation scenarios also show that if the assembly operation sequence can be altered, meaning that the current assembly operation can be postponed first, a better result can be achieved. Furthermore, a predictive maintenance is highly recommended for a cyber-physical production system to prevent unplanned downtime in the first place. Due to the communication using a network socket between the Disruption-Management-DSS and the simulation tool, the simulation run time increases with the number of simulated parts produced as well as the number of simulation runs.

6. Conclusion and Future Work

In this paper, a simulation-based decision support system for supporting the disruption management process in cyber-physical production systems is presented. This paper proposes requirements for designing a resilient cyber-physical production system and introduces an approach for analyzing process disruptions and determining the recommended response strategy using a simulation-based evaluation. The disruption management process is developed with the main focus on the communication between the Disruption-Management-DSS and the DES, which simulates the information exchange and the autonomous decision-making process between intelligent components and manufacturing stations. Using simulations of an example product from the learning factory, the practical use for the developed approach can be presented and the impact of the disruption event can be shown in order to determine the best response strategy.

For future research, an automatic generation of possible actions according to the current disruption event scenario and the information stored in the disruption database is required. This can be realized for example by using a data mining technology to derive actions from similar disruption events. In this way, it is possible to reduce the required number of simulation runs and therefore achieve a short response time.

Acknowledgements

This work was funded in part by the German Federal Ministry of Education and Research (BMBF) under grant number 01|S13015 (project SmartF-IT). The responsibility for this publication lies with the authors.

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