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Petri net controlled virtual commissioning – A virtual design-loop approach

Benjamin Illmer[a]*, Martin Karkowski[b], Michael Vielhaber[a]

[a]*Institute of Engineering Design, Saarland University, Campus, Geb. E2 9, 1.OG, 66123 Saarbrücken, Germany*
[b]*ZeMA – Centre of Mechatronics and Automation, Eschberger Weg 46, Gewerbepark, Geb. 9, 66121 Saarbrücken, Germany*

* Corresponding author. Tel.: +49-681-302-71614; fax: +49-681-857-870. *E-mail address:* illmer@lkt.uni-saarland.de

Abstract

With the increasing system complexity, in the course of the introduction of modern technologies in today's production systems, the system-related modeling effort in the virtual production planning phase also increases not only in terms of time but also extensively and leads to extended design requirements. Virtual Commissioning (VC) as a digital planning tool for validating highly automated systems in industry or cyber-physical systems (CPS) in research, is an already established method and has to be continually developed to meet these increasing design requirements. In addition, the modelling scope of the control-related behavior models is increasing and inevitably becomes confusing, especially beyond the process designer area, which makes it difficult for process owners to understand the control-specific behavior of the systems. Therefore, this paper deals with methods for the virtual development and validation of control structures of complex system relationships, evaluates them according to the respective area of application and puts them into the context of this work in order to demonstrate the need for a method to be able to provide a clear and interpretable representation of control-related behavior models. Subsequently, a graphically based modeling approach based on a petri-network for the control of virtual production models is presented, applied to an industry-related virtual demonstrator and evaluated for process-related robustness.

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Keywords: Petri net; virtual commissioning; Cyber-physical production systems

1. Introduction

The production planning area is currently at a stage where modern technologies, such as cyber-physical systems (CPS) and cyber-physical production systems (CPPS) whose basic structures are considered as researched, lead to an increasingly complex situation of the production process [1-2]. Advances in the field of virtual planning software and tools support users to develop modern technologies with comprehensive functional validation capabilities in a cost-effectively way [3]. For many years virtual commissioning (VC) as an established development step in production technology has proven its possibility to fully validate highly automated systems on the control side and the opportunity to shorten cost-intensive implementation processes such as systems physical commissioning [4-8]. Nevertheless, the development of control software and the programming languages used with it on the process designer level often leads to ambiguous interpretability on the process owner level, whereby the exchange of information can be guaranteed on the visualized CAD model level, but not on the control level between company divisions.

1.1. Motivation

In the context of increasing production system complexity due to extended system functions and a highly dynamic product variance, there is still a need for consistent definitions, methods, case-independent and interpretable process models on all levels of the company, so that established development processes such as VC can also be used for future technologies [9]. Furthermore,

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existing characteristics in the scientific literature that are associated with CPS must be identified, as they represent the next generation of complex systems.

1.2. Goal and structure

According to the motivation, the goals of this paper are:

- Identification and definition of production characteristics associated with CPS and CPPS in a comparable manner
- Comparison of definitions for the evaluation of a selected characteristic and classification within a hierarchy
- Identification of approaches for the design of CPS in virtual planning tools, such as VC
- Proposal of a method for a comprehensible virtual control framework and validation using an industry-related underbody assembly process
- Evaluation of the method in context of the selected cps descriptive production characteristic

To achieve these objectives, Chapter 2 presents CPS descriptive production characteristics and proposes a definition as well as a classification for identified characteristics in research before a selection of a characteristic is carried out to set the basis for the evaluation of the introduced framework in the following chapters. Subsequently, chapter 3 discusses methods for the validation of complex system control concepts and also concepts of methods developing CPPS in virtual planning and simulation-based environments. Finally, a graphically modeled method based on a petri-net is introduced in chapter 4, validated in chapter 5 and evaluated in the context of the selected CPS descriptive production characteristic. Finally, a conclusion and an outlook were given in chapter 6.

2. Cyber-physical system descriptive characteristics

In this chapter definitions are provided that are continually used for this work and suggest a common understanding of terminologies in the context of a production system. In [10, 11] characteristics of CPS and CPPS are explained on the basis of extensive literature research, which will be further specified below, distinguishing between functional and geometric effects, see Table 1. In addition, impacts of a characteristic adjustment on a physical system and system modules is also discussed.

Table 1. Cyber-physical system descriptive production characteristics

Characteristic	Proposed definition based on researched references	Impact on physical system by adjusting the characteristic
Flexibility	Flexibility is the ability of a system to fulfill functionalities within the system properties defined in the system requirements planning [12, 13]. Characteristic of a flexible production is the fulfillment of the production process despite disturbances such as capacitive fluctuations caused by e.g. Quantity changes [14].	A change in the geometric arrangement of production resources e.g. System modules are not required to meet production flexibility.
Reconfigurability	Reconfigurability is the ability of a system to allow geometrical interchangeability of system modules to extend system functionality. The requisite requirements in requirements management must be observed [15, 16].	A change in the geometric arrangement of system modules is required to complete the system reconfiguration.
Scalability	Scalability is the ability of a system to resize the production system by increasing or decreasing the number of system modules, for example, with different application rate requirements. [16, 17].	A change of the geometric arrangement of system modules is basically necessary for the achievement of scalability.
Interoperability	Interoperability is the ability of a system to build a consistent manufacturer-independent understanding of communication with other systems, despite different communication protocols. [18, 19].	A change of geometric arrangement of modules is not fundamentally necessary for the fulfillment of interoperability.
De-centrality	Decentralization is the ability of a system to interact with other systems and elements or influence each other distributed in production. The communication between product, human and technical resources as well as their decentralized data collection characterize decentralized production [20,21].	A change or adaptation of the geometric arrangement of system modules is not required to fulfill decentralization.
Robustness	Robustness is the ability of a system to react independently to unavoidable fluctuations and disturbances in production process and to be able to pursue solution strategies in the event of a disruption within a given field of action in order to independently analyze solutions from critical system states [22, 23].	A change or adaptation of the geometric arrangement of system modules is not fundamentally required for the purpose of robustness.
Versality	Versality is the ability of a system to respond to unknown environmental influences, so called turbulences, such as product or technology changing aspects, by reorganization of system modules [16, 24, 25].	A change in the geometric arrangement of system modules is not fundamentally required to fulfill the changeability.

2.1. Robustness as a CPS and CPPS descriptive production characteristic

In this chapter, robustness as a CPS or CPPS descriptive production characteristic is selected from chapter 2 because it is the most relevant characteristic to evaluate the validation of the petri-net based virtual commissioning process, presented in the following chapters. In research several definitions for the evaluation of production systems related robustness exist and will be investigated next. In industry, the robustness of a production system is often associated with system availability. In research literature robustness of technical systems is often assessed in relation with a probability of a system failure, which can express an opposite behavior to availability, see Fig. 1. Common to many references is the definition that system related robustness is insensitive to disturbance factors. According to [26] definitions differ in the respective system-related framework, such as system's behavior, fixed limits or cyber-attacks. In scientific literature, there is no clear definition of robustness in the context of CPS that differs from the definition factors given here, which is why a structural proposal regarding robustness of CPS and CPPS is presented next.

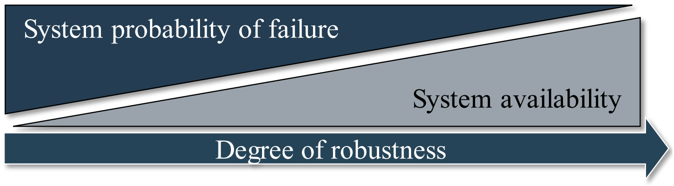

Fig. 1. Robustness depending on system failures and availability.

2.2. Structural proposal for classification of robustness levels

To assess the robustness, four levels are considered for classifying the robustness maturity level, see Fig. 2. In the first level, robustness of a production system refers to a low probability of failure in highly automated production with varying production speeds. This is especially the case with clock changes to intercept production variations. The second level also considers a change in the product variants. A low probability of default is achieved by a flexible designed production. In the third level, artificial intelligence approaches are used to implement the possibility that the system independently finds process-specific solutions from possible error states. The approach is not completely autonomy, since the range of error states must be exclusively influenced or predictable. The fourth level involves a completely autonomous self-configuration of the production system, which extends the workable problem space of the production system through approaches of self-configuration and thus also unforeseen problem states can be processed.

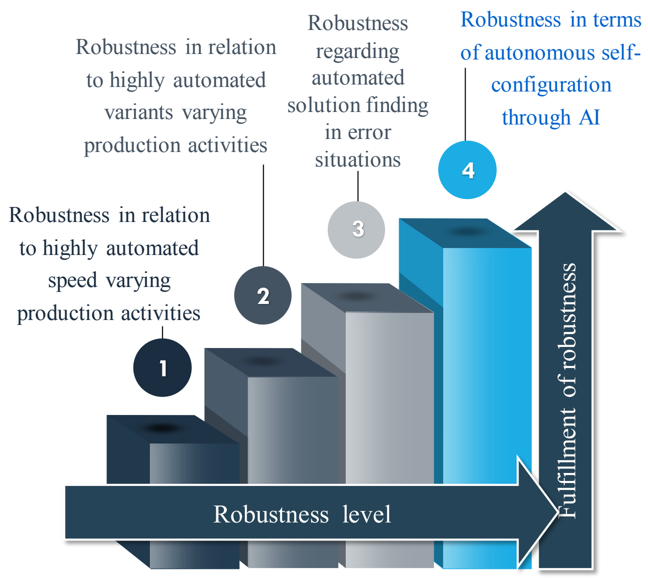

Fig. 2. Robustness levels regarding production related CPS characteristics.

3. Virtual validation methods of cps-based productions

Increasing workloads in production planning due to the introduction of CPS and CPPS require new methods for simulation-based development and validation of planned and existing systems with complex control structures. Therefore, this chapter presents a state of industry and research in terms of virtual validation of production systems with CPS aspects.

3.1. State of science

In the area of research, there are already a large number of proposals, methods and models for the development of cyber-physical systems in various areas of engineering. In [27], industrial cyber-physical systems (iCPS) were examined, which conveyed the entire environment of the production facility, including economic aspects. The field of human-centered cyber-physical production (HCPS), in which humans should effectively be involved in the modern industrial environment, is discussed in [28]. The use of cyber-physical systems in logistics making material flow more efficient and in production technology to successfully integrate or combine modern technologies is presented in [29-31].

3.2. State of industry

In [11], industrial research results and their methods in the field of virtual validation of cyber-physical systems have already been presented. In this work they should be used further and supplemented by other research activities. Toyota is concerned with robustness in cyber-physical systems and categorizes the notion of robustness in terms of technical error rate, real-time system integration, and robust system parameters [22]. Volkswagen continues to work on the virtual validation of cyber-physical systems by connecting different simulation tools via a connecter to an overall framework, thus enabling cross-sector simulation [32].

3.3. Evaluation of presented methods

The presented methods are now interpreted in Table 2, whereby criteria such as CPPS validation, the use of VC and the integration possibilities of the developed method are used.

Table 2. Evaluating aspects of CPS, VC and methods in presented literature.

Reference	CP(P)S validation	Using VC	Method provided
[22]	+	-	-
[27]	+	-	+
[28]	+	-	+
[29]	-	+	-
[30]	++	+	-
[31]	+	-	+
[32]	++	+	-

3.4. Need for action

The analysis of the references shows that a lot is already being done in the area of CPPS development and validation, also in connection with VC. However, there is still a need for a method which offers extensive control programs for complex systems, e.g. CPS, structured in a clear manner and thus entails a more efficient validation of virtual production models. Furthermore, methods or approaches often lead to additional, very time-consuming development work.

4. Petri-net controlled virtual commissioning method

4.1. Petri-net control using automated planning and acting

Automated Planning and Acting (APaA), established by [33], is used to automatically find solutions in a given problem space, whereby a problem space describes an entire state or parts of it as system states maps. The prerequisite for this is the process plans to be determined which, in the problem space, can reach a target state starting from an initial state. In order to design these process plans, the impacts of actions that may only be executed under defined conditions is to be considered before a sequence of actions for changing the system state will be determined. In this way, the actual planning process can be transformed into a solution-oriented searching process. While a complete plan is first determined during offline planning, online systems already act after the determination of sub-plans, which permanently adjusts the process plan leading to a flexibly event responsiveness [33].

4.2. Related Work – Modular Control System MCS

In [34, 35] an adaptable and modular control system was developed in which the assembly task was described by means of a petri-net-based approach. For a solution-neutral description, assembly operations are described by skills. Subsequently, the assembly operations are assigned to functional and property-appropriate resources from a resource kit. This will detail the petri-net through resource-specific behaviors, properties, and customizations to ensure the compatibility of various assets. For a complete description of the system, the modeling of information flows for the representation of the system behavior and the creation of a model about the mechanical and electrical structure of the system are carried out. The system behavior and the model are finally transferred to the modular control system. To perform the defined assembly task the system essentially consists of five elements. A dynamic logic interpreter implements the described process logic, ensuring the implementation of the information flow through the volatile memory system. An extensible broker delegates the activities determined by the logic to the corresponding modules via communication layers. These in turn provide the modules as services. Thus, a simpler replacement of the resources can be ensured.

4.3. Petri-net based virtual commissioning design method

The petri network-based virtual commissioning method consists of two design loops, see Fig. 3.

In the first design loop, the behavioral model of the production system has to be clearly specified in the logical editor in a graphically manner. This can be done within the petri-net to be designed by defining different technical contexts, restrictions and requirements of individual subcomponents using petri-net design principles. To be able to influence the virtual resources and apply the strategies of the APaA, a connection between the function calls and the designed events and actions must be modeled. Conditions for executing an action can be modeled by corresponding edges in the petri-net. Subsequently, the behavioral modelling process can be exported as a standardized control program. During runtime, the standardized control program determines the possible state space of the modeled production system and, based on the current system state, is able to determine a solution plan for achieving the destination. If deviations from the determined plan occur, the plan is adjusted online. Thus, if defined in modeling the behavioral model, recovery strategies can be automatically determined by the system. To be able to optimize and validate the specified system behavior in the simulation environment, a coupling is performed by the simulated PLC. Therefore, the outputs of the simulated PLC are triggered by the control system, i.e. the processes within the simulation system. This will lead to a change of sensor values within the simulation environment. These are provided to the standardized control software via the inputs of the PLC.

In the second design loop, the optimized behavior is tested and validated for release on the designated (virtual) hardware. For this purpose, the defined behavior model is used as a basis for the automatic generation of PLC code for productive use. This code and thus the system behavior is then deployed on the (virtual) hardware using the provided development tools (in our case TIA Portal). The simulation environment is then used to test, validate and release the system behavior.

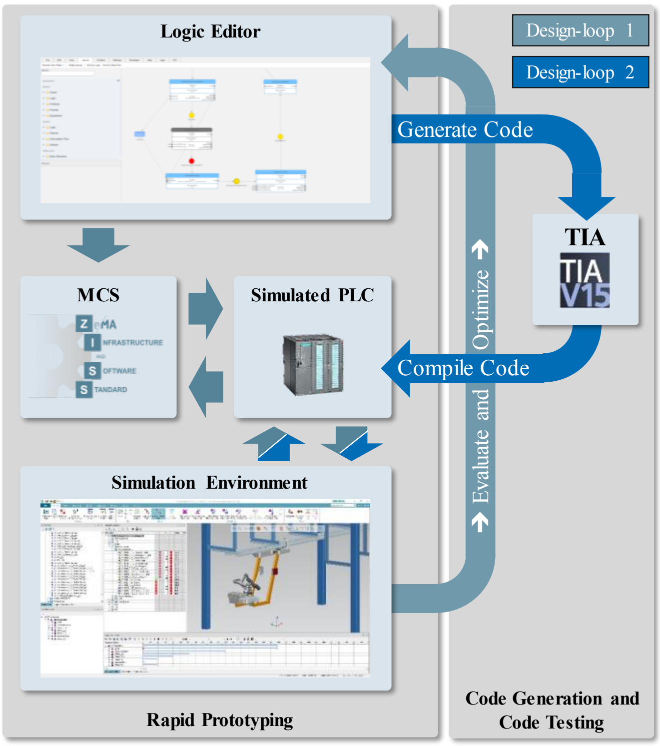

Fig. 3. Petri net based virtual validation and commissioning framework.

5. Robustness of a petri net based virtual commissioning

In this chapter, the findings from chapter 2 are used to assess the robustness of the petri-net based virtual commissioning approach. For this, the use case is described, possible error situations are identified and finally the robustness of the approach is evaluated.

5.1. Related Work – Demonstrator

To validate the presented method, based on the previous work in [14, 36], an application from the automated underbody assembly of vehicle elements is used. To simplify the evaluation, only the processes of the swivel unit with mounted screwing robot UR10 and a synchronizing mandrel are considered as a digitally constructed twin, see Fig. 4.

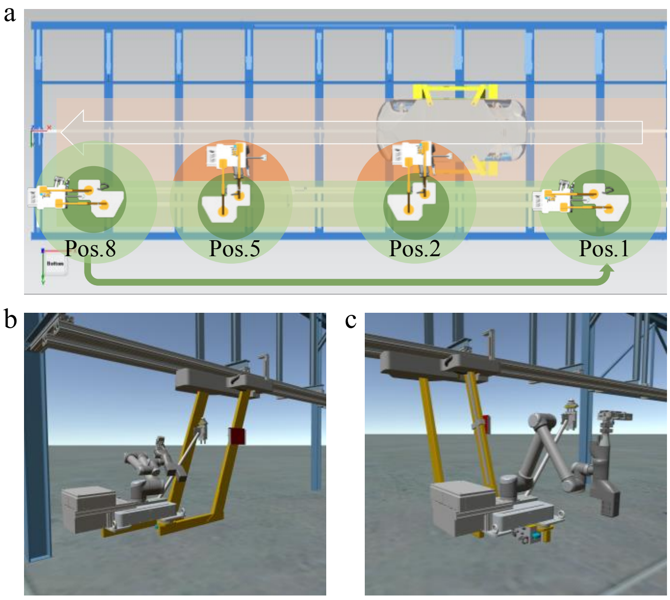

Fig. 4. (a) Bottom view of vehicle mounting - swivel module extended; (b) VR-view - retracted swivel module with screwing robot in home position; (c) VR-view - extended swivel module with screwing robot in working position.

5.2. Validation of petri-net based VC design method

The petri-net-based virtual commissioning method was validated using the virtual underfloor assembly demonstrator. The validation takes place following the process mentioned within the first design loop. The poses of the swivel module are described in Table 3 and partially presented in Fig. 4a.

Table 3. Swivel module (SM) pose declaration in ideal conditions.

Pos.	SM pose	SM conveyor axis	Mandrel pose
1	At outline	Standing still	Entrenched
2	At Inline	Moves forwards, synchronizes	Entrenched
3	At Inline	Moves, synchronized	Extended
4	At Inline	Moves, synchronized	Extended
5	At Inline	Brakes, desynchronize	Entrenched
6	At Inline	Standing still	Entrenched
7	At outline	Standing still	Entrenched
8	At outline	Moves backwards	Entrenched

The functional sequence without errors and the behavior of the system through the situation interpretation of the APaA approach in the event of errors are described in Table 4. The evaluation of the results shows that the method is able to find solution strategies within the given parameters of the designed petri network. Finally, it also shows that the changes made to the process plan are highly dependent on the input parameters, as the solution made in each case leads to a solution, but must be studied more closely in terms of cycle time and process reliability in order to propose ideal solutions.

Table 4. Validation of the simulation behavior of the petri-net controlled virtual commissioning using APaA.

Pos. of Table 3	Considered error states	Situation handling by APaA	Handling evaluation
1	During the process from pos. 1 to pos. 2 human enters the work area	SM waits until human leaves, then attempts to catch up the vehicle	adequate
2	The synchronization between SM and overhead conveyor cannot be established	Keep trying to synchronize until point of no return is reached, then moves to start pose	adequate
3	The synchronization between SM and overhead conveyor is lost during the process	Mandrel is first retracted, afterwards it is tried to synchronize again and mandrel is extended	adequate
4	The mandrel for synchronization does not extend	Further attempts of mandrel extension until end of line	adequate
5	The SM conveyor axis does not break successfully	Simulation aborting, because of mechanical error case, which is avoided by physical emergency stop devices	Out of scope
6	During the process from pos. 6 to pos. 7 human enters the work area	SM waits until human leaves and then swings out	adequate
7	No error case considered	-	-

5.3. Interpretation of the degree of robustness

In order to be able to evaluate the approach of the framework for robustness, it is recommended to unambiguously identify the functionality so that a sustainable classification can be ensured. Because the framework is able to search for solutions within a defined problem area independently and semi-automatically. This enables the petri net to be able to interpret an error situation from the defined process contexts. The predefined states allow the framework to act independently within a specific area. For this purpose, the area responsible for independent action in the petri net is included in the process planning, which is why only predictable and influenceable situations can be implemented. However, the approach also offers the user the possibility of being able to perform an automated check of the action fields. So far, it has been the case that error situations in the simulation need to be time-consuming modeled and subsequently functionally secured. This additional time is not required when using the framework. From the listed points it follows that this framework can be attributed to the level three of Fig. 2.

6. Conclusion and Outlook

6.1. Conclusion

In this paper, based on literature research, CPS characteristics were identified in the form of production properties. In addition, a characteristic was scientifically nurtured, on the one hand to present definitions from different areas and on the other hand to develop the basis for a classification of the property. This paper also presented a method, divided into two design loops, whereby the first design loop leads to efficient modeling and validation through an automated planning and acting approach for efficient error analysis. In addition, the graphical development interface offers the possibility of integrating company levels into the planning beyond process designer levels. In addition, a proposal for the classification of the robustness degree of production systems was made, which allows the robustness to be broken down according to various requirements.

6.2. Outlook

As a next step, the design loops will be methodically integrated into an overall development process of CPPS, whereby design parameters are identified that are to be classified into the individual planning steps for information enrichment, further development and more efficient design of the development of CPPS.

References

[1] Berger C, Zipfel A, Braunreuther S, Reinhart G. Approach for an even-driven production control for cyber-physical production systems. In: Proceedings of the 12th CIRP ICME Conference, vol. 79, 2019, p. 349-354.
[2] Monostori L, Kádár B, Bauernhansl T, Kondoh S. Cyber-physical systems in manufacturing. In: CIRP Annals vol. 65, 2016. pp. 621-641.
[3] Price A. Automotive Circle – Virtual Manufacturing Engineering at Jaguar Land Rover. Presentation of Automotive Circle Advanced Manufacturing Engineering. 2016.
[4] Geckler D, Rehnelt C. Die Digitale Fabrik als Wissensdrehscheibe zwischen OEM und Zulieferer. In: *projektManagement,* vol.1, 2014.pp. 26.
[5] ABB Press realease. ABB reduces project costs through virtual commisioning for drives by 25 percent. Released: 2017 at: http://www.abb.com/cawp/seitp202/0f58dfe7b53b6829c12581d90064cf06.aspx
[6] Preiml H, Pieloth R. Effektives Engineering durch die virtuelle Inbetriebnahme. In: Tagungsband: Digitales Engineering und virtuelle Techniken zum Planen, Testen und Betreiben technischer Systeme. Vol.13, 2010. pp. 29-36.
[7] Kiefer J. Lean Digital Validation Methods Within The Design Process Of Automated Assembly Systems In Automotive Industry. In: Proceedings of the 13th International Design Conference, 2014. pp. 1957-1966.
[8] Langosch M. Virtual Commissioning @ BMW GROUP. Presentations of the 11th Assembly meeting. 2018.
[9] Geisberger E, Broy M. Living in a networked World – Integrated research agenda Cyber-Physical Systems (agendaCPS). Acatech Study, 2015.
[10] Illmer B, Vielhaber M. Synchronizing Digital Process Twins between virtual products and resources – A virtual Design method. In: Proceedings of the 29th CIRP Desing Conference, vol. 84, 2019. pp. 532-537.
[11] Illmer B, Kaspar J, Vielhaber M. Cyber-Physical Effects on the virtual Commissioning Architecture. In: Procedings of the 21th International Conference on Engineering Design, vol. 5, 2017. P. 169-178.
[12] De Toni A, Tonchia S. Manufacturing flexibility: a literature review. In: International Journal of Production Research. 1998, 36:6, pp. 1587-1617.
[13] Marks P, Hoang XL, Weyrich M, Fay A. A systematic approach for supporting the adaption process of discrete manufacturing machines. In: Research in Engineering Design, vol. 29, 2018, pp. 621-641.
[14] Scholer M. Wandlungsfähige und angepasste Automation in der Automobilmontage mittels durchgängigem modularem Engineering. 2018.
[15] Ullrich A, Lass S, Hein T. Reconfigurable Production Systems – An Appraisal of Applied Production Breakdown Solution Strategies. In: Proceedings of the 5th International CARV Conference, 2013. pp. 105-110.
[16] Tram Mortensen S, Madsen O. Operational Classification and Method for Reconfiguration & Recommissioning of Changeable Manufacturing Systems in System level. In: Proceedings of the 28th International CARV Conference, 2019. pp. 90-95.
[17] Eilers JJ. Methodik zur Planung skalierbarer und rekonfigurierbarer Montagesysteme. (Reihe: Fertigungsmesstechnik & Qualitätsmanagement, Band 9/2015). 1. Aufl. Aachen: Apprimus-Verl., 2015.
[18] VDI/VDE Gesellschaft Mess- und Automatisierungstechnik. Industrie 4.0 Service Architecture – Basic concepts for interoperability.Report, 2016.
[19] Cousin P, Serrano M, Soldatos J. Internet of Things Research on Semantic Interoperability to address manufacturing challenges. In: Enterprise remaining poseInteroperability, John Wiley & Sons, Inc., Hoboken, 2015.
[20] Gräßler I, Pöhler A. Intelligent Devices in a Decentralized Production System Concept. In: Proceedings of the 11th CIRP ICME Conference, vol. 67, 2018. p. 116-121.
[21] Bochmann L, Bänziger T, Kunz A, Wegener K. Human-robot Collaboration in Decentralized Manufacturing Systems: An Approach for Simulation-based Evaluation of Future Intelligent Production. In: Proceedings of the 10th CIRP ICME Conference, vol. 62, 2017. pp. 624-629.
[22] Fränzle M, Kapinski J, Prabhakar P. Robustness in Cyber-physical Systems. Report from Dagstuhl Seminar, 2016.
[23] Monostori L. Cyber-physical production systems: Roots, Expections and R&D challenges. In: Procedia CIRP, 2014, Vol. 17, p. 9-13
[24] Weber J, Förster D, Kößler J, Paetzold K. Design of Changeable Production Units within the Automotive Sector with Axiomatic Design. In: Proceedings of the 9th CIRP ICAD Conference, vol. 34, 2015. pp.93-97.
[25] Zaeh MF, Moeller N, Vogl W. Symbiosis of Changeable and Virtual Prodcution – The Emperor's New Clothes or Key Factor for Future Success. In: Proceedings of the 1st International CARV Conference, 2005.
[26] Stricker N, Lanza G. An Approach towards improving the Robustness of Production Systems. In: Advanced Materials Research, Vol. 1018, 2014. Pp 461-468
[27] Oks SJ, Fritzsche A, Möslein KM. Engineering industrial cyber-physical systems: An application map based method. In Proceedings of the 51st CIRP CMS Conference, vol. 72, 2018. pp. 456-461.
[28] Hadorn B, Courant M, Hirsbrunner B. Towards Human-Centered Cyber-Physical Systems: A Modeling Approach. Technical Report. 2016.
[29] Hofmann W, Ulrich JH, Lang S, Reggelin T, Tolujew J. Simulation and Virtual Commissioning for a Plug-and-Play Conveying System. In: IFAC Papers Online, vol. 51, 2018. Pp. 649-654.
[30] Glatt M, Aurich J. Physical modeling of material flows in cyber-physical production systems. In: Proceedings of the International CARV Conference, 2019. vol. 28, 2019. pp.10-17.
[31] Francalanza E, Mercieca M, Fenech A. Modular System Design Approach for Cyber Physical production Systems. In: Proceedings of the 51st CIRP CMS Conference, Vol. 72, 2018. pp. 486-491.
[32] Brandstetter V, Wehrstedt JC, Meyer T, Munske S. Virtuelle Inbetriebnahme cyber-physikalischer Produktionssysteme mit gekoppelten Simulationsmodellen. In: VDI Berichte Nr. 2330, 2018.
[33] Ghallab M, Nau D, Traverso P. Automated Planning and Acting. Cambridge University press, 2016.
[34] Müller R, Scholer M, Karkowski M. Increasing the Flexibility of Customized Assembly Systems with a Modular Control System. In: Proceedings of the 5th IoTSMS Conference, 2018.
[35] Müller R, Scholer M, Karkowski M. Generic automation task description for flexible assembly systems. In: Proceedings of the 52nd CIRP CMS Conference, vol. 81, 2019, p. 730-735.
[36] Scholer M, Müller R. Modular configuration and control concept for the implementation of human-robot-cooperation in the automotive assembly line. In: IFAC-PapersOnLine. Vol. 50, Issue 1, ScienceDirect: E-Publishing; 2017. P. 5694-5699.