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Procedia CIRP 62 (2017) 577 – 582

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10th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '16

Simulation of production processes involving cyber-physical systems

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Abstract

It has become common practice to apply simulation during product development and production planning. The increasing demand for individualized goods requires the ability to produce in small lot sizes and therefore more flexible resources, which leads to the use of cyber-physical systems (CPS) in manufacturing. This papers aims to look at the changing requirements, pitfalls and possible solutions when applying simulation to CPS. The research is based on a case study of a large car manufacturing company that has already implemented CPS in one production line. The paper will also provide an overview of simulation types and discuss their fitness.

Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: Simulation, Flexible manufacturing system (FMS), Process, Cyber-physical system (CPS)

1. Introduction

One of the main challenges within the industrial sector is to produce with high resource efficiency. [1] In order to operate at full capacity, and thereby minimizing buffer stock as well as defective parts, it has become common practice to apply simulation methods and models during process planning.[2]

At the same time, industrial companies face the challenge that their customers demand more and more individualized products.[1] In addition, the market changes rapidly and existing parts and products have to be adapted often. To cope with these two conflicting issues, flexible and adaptable concepts are necessary within the field of production. Such concepts are based on decentralization and include e.g. lean management, modularization, or the fractal factory.[3, 4] Companies increase their degree of decentralization as this allows for faster decision-making since there are fewer organizational units involved in a decision.[5] Currently, cyber-physical systems (CPS) and the so-called smart factory are under development as the latest addition to the field. As "self-conscious" resources they are part of a decentralized production environment and able to make independent decisions.

The impact of CPS on production processes and simulation thereof within production planning will be outlined in the following paper, which is structured as follow: First, the research question and the derived methodology are introduced; in the next step, the state of the art in simulation is described. The concept of CPS and the smart factory are defined in the following chapter. The paper closes with the requirements and recommendations with regards to simulation.

2. Research Question and Methodology

This paper aims to answer the following research question: Which impact do CPS have on production processes as well as production planning and how do simulation models and tools have to be adapted to cope with the necessary changes?

The paper follows the research process of design-oriented information systems research, with is in line with the design science approach.[6, 7] The process consists of Analysis, Design, Evaluation and Diffusion (cf. Figure 1).

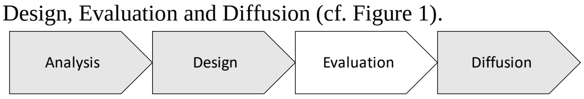

Fig. 1. Research Process

2212-8271
Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering
doi:10.1016/j.procir.2016.06.074

During the analysis phase, the state of the art within simulation as well as cyber-physical systems is depicted. This is based on a literature review on the two topics. In addition to the literature review, a case study [8] of a pilot manufacturing line of internal combustion engines that uses CPS as well as an interview with an expert who produces CPS were conducted.

The case study consists of multiple interviews with the people responsible for the production line (two from production management, one person from IT) and a visit of the factory. The interviews had a duration of at least one hour and took place at two different points of time: the first ones in 2012, the last one in 2015. During the interviews, notes were taken and the visit was documented afterwards

The guided interview with the manufacturer of CPS took place in 2016 and has a duration of two hours and was recorded and transcribed. The interviewee has a background in computer science and has worked at the company for about three years.

During the design phase, first requirements were derived from literature, the case study and the interview. As a second and last step, recommendations on how to adapt simulation tools are given. Evaluation of the results is pending. This paper is part of the diffusion of the results.

3. Simulation

Simulation always deals with complex problems that cannot be solved using simple (mathematical) models because the problems are dynamic and there are elements of uncertainty.

There are different types of simulation. They can be divided by the kind of problem that is supposed to be supported by the usage of simulation. There are managerial, most often strategic problems, with can be assisted with management-oriented simulation methods like Monte-Carlo-simulation or scenario analysis.[9] These methods can be enhanced by visualization or incorporation of historical data.[10] An example might be supply chain planning [11], including warehouse positioning or selection of suppliers.

The other kind of problem is technical, most often operational problems. These problems arise from engineering and the decisions in this area can be backed by technical simulation. As such, they are part of the digital factory.[12] This paper distinguishes between two types of technical simulation: the simulation of complete production processes [2, 13] and the machine-oriented simulation, which focuses on individual manufacturing cells.[14]

The first type of technical simulation has the goal to support the planning of a specific production process or the improvement of an existing process with regards to its key performance indicators, such as cycle times or OEE. (cf. Fig. 2)

In the past, these used to be single, linear processes, which could be optimized by production planning to reduce waste within this process. As we will describe later on, this will change with the introduction of CPS.

This kind of process simulation can be useful during planning of new production lines, new facilities, their initial implementation and adjustment during operations.[2, 15]

The second type deals with individual production resources, in this case, a machine or a manufacturing cell. The purpose is to explore and define the limits of the machine (e.g. constructed space) and to ensure a stable process quality.[14] The machine-oriented simulation can also be applied during development, implementation and operations, only the scope is different.

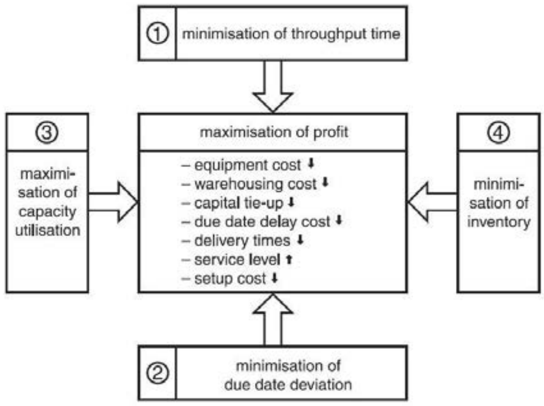

Fig. 2. Goals of process simulation [2]

Considering robots as resources, the focus is on collision detection, especially when interacting with a human.[16, 17] This kind of simulation relies on kinematics and graphics. It is applied during ramp up, but also during product development and operation (e.g. NC simulation).[14]

Another criterion to distinguish different kinds of simulation is the determinism. Simulation like the last-named collision detection or the simulation of individual machines work on the basis of the finite element method and will produce the same result within each simulation run. [18] Non-deterministic simulation however, will lead to divergent results on multiple simulation runs. This will be the case when CPS are introduced to the production environment as the production process will no longer be completely predictable.

4. Cyber-physical Systems

4.1. Definition

CPS are „integrations of computation with physical processes“ [19]. This means that computing gets information on the physical world around it and can react to it. The information is collected using sensors, then processed internally by the CPS and leads to actions that are realized by actors and correspond to the current state of the environment.

CPS can be applied in different fields, in this case the paper focuses on manufacturing. Since CPS have to work in real world and the real world is complex and not predictable, robustness is a basic property of CPS that they are able to react to unforeseen challenges. However, this robustness is hard to achieve.[20]

CPS are based on the internet of things, which means that a CPS has a virtual identity and can be addressed within a network. This enables communication and coordination between the distributed CPS.[21]

CPS use and also provide services that can be enquired by other systems [22, 23], e.g. a smart product that arrives at a CPS and asks for processing. Transferred into the production environment, this means that the PLC of a resource offers modular and encapsulates functionalities, which can be applied to different products.

CPS are considered to be key enablers of the smart factory and industrie 4.0.[22, 24] The vision of a smart factory is that the factory monitors the state of all things it encompasses and is able to automatically react to events by controlling the things.[24] Industrie 4.0 is the forth industrial revolution based on CPS with the intention to leverage the potentials of CPS in production environments.[22, 26]

4.2. Case Study

The case study is about a manufacturer of car engines. It is a large vendor and they produce about 1 million diesel and petrol engines per year. The need for flexible production environments is due to frequent changes of the engines. In average, the engines face structural changes each week, e.g. because a part is replaced or a flaw corrected. At the production site, there are multiple lines of production. In 2012, there was one pilot line that had CPS in place. In 2015, there were three lines equipped with CPS because the flexible lines were as profitable as the other lines. The degree of automation of the line is 95 %. The goal of the line is to reach a high degree of capacity utilization.

Each engine is equipped with an auto-ID and is able to identify itself. There is a central Manufacturing Execution System (MES) which is responsible for the data exchange. It contains the data on the product and has information on which work steps of production have already been completed and which ones are missing. To clarify, the MES controls only the information flow, not the flow of production. It also enforces rules, such as sequences that need to be followed and one overall rule that is applied in case of degrees of freedom. In this case, the rule is First-In, First-Out.

The CPS are manufacturing cells, which are arranged like a job shop production; even though is series production with a lot of variances. The CPS register at the central MES and deliver constant updates on their state. The engine enters the production line and can be transported to all CPS by means of a very flexible and sophisticated logistic system. When one work step is finished, the CPS request data from the central MES on the next possible steps as well as the state of the other resources. It is decided locally and ad-hoc, during the vacation of one CPS, which CPS will be chosen for the next step of production (cf. Fig. 3). These decisions are repeated after each step until the product is completed.

The CPS have to be maintained and updated with the latest NC-programs at some point in time, which reduces their availability.

The company uses simulation extensively, particularly for capacity planning and for the start-up of new products.

5. Properties of production processes involving CPS

The main reason for the integration of CPS in a production process is the quest for flexibility. This flexibility is needed because the products and parts are more or less individual parts that either subject to ongoing changes or they are engineered to a specific order by a customer. The parts are therefore not alike.

Each product has different technical properties or is built of only partly overlapping parts.

Following this logic, there can be no single production process that can serve all needs of the various products. Instead, a multitude of production processes is needed to be able to handle the variation. As the next changes are impossible to predict and the definition and testing of production processes is very time-consuming, the production processes are no longer pre-defined, but are created ad hoc. Haußmann et al. proposed to replace work plans with feature technology from CAD systems to deal with the increasing variation.[27] This means that features are extracted from CAD models and are handed over to the production environment as requirements that have to be realized during production until the part is complete. [28] Such features include, e.g. a hole with a certain diameter, its position and an expected surface quality.

Fig. 3. Negotiation of next step

As soon as the part arrives at a machine, they have to negotiate the next step of production (cf. Fig. 3). Either the machine itself or a central instance (e.g. a manufacturing execution system) have to be aware of the capabilities, the CPS possesses and the requirements of the part. Based on this information and the current state of the other CPS, it can be decided whether the CPS is able to deliver the required step. Some CPS might be under maintenance or may need mounting.

It has to be considered that a requirement, like a hole in a part can be created by various methods, tools and resources (e.g. laser, drilling, milling). This makes it even harder to predict the next step. Each resource has different cycle times and rates.

If there is more than one possible next step, an overall rule is implemented to decide on the next step. This rule could be to prioritize a certain customer or product or to prefer short production time over quality. These rules have to be created beforehand and are applied to control the autonomous production system and the cyber-physical systems.[29]

Whenever new production resources are added, they are included in the process using plug and produce. As a prerequisite, the capabilities of the CPS have to be defined. The capabilities can be described with Automation ML.[30, 31]

As the production processes are no longer known in advance, the relevance of historical data on delivered processes in the past increases. From this data, valuable information can be derived that may help in future processes (e.g. identification of causes of failures, required maintenance).[32] In the long run, CPS will be asked to optimize themselves by such information that is acquired during production and analyzed afterwards or in real-time.

The generation of individualized and optimized NC code for each work step and each part is problematic due to the variation. Instead, CPS must possess functionalities that are able to perform the required task at an acceptable pace and with high accuracy. This is again a tradeoff between individualization and the efficient use of resources.

6. The role of production and process planning

As stated in the introduction, the goal of CPS is to enable companies to produce different products and variants without losing resource efficiency. This is also the scope of production and process planning, which means that both constructs interfere with each other.

The main task of production planning has been to define which step of production will be completed by which resource. This concerns scheduling and capacity planning. This is now changing as CPS organize themselves. Production planning will focus more on long term planning instead of individual production orders or products. [28] As an example, it has to be examined whether a certain product mix can be produced with the resources that are available or if additional resources are necessary.

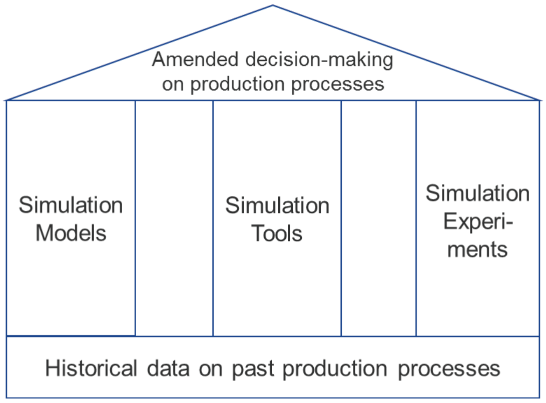

Fig. 4. The house of production simulation

This is challenging for classical production planning and control systems. Therefore, production planners need different tools besides enterprise resource planning or production planning and control systems to support their work. One solution could be business intelligence, another simulation. However, the combination of both is most promising as business intelligence provides insights on problems that occurred in the past, e.g. bottlenecks, based on data from tracking past production processes. This leads to the house of production simulation (cf. Fig. 4). It is based on historical data, which provides areas to focus on during simulation. The three main fields of design within simulation are the model, the experiments and the tools. These are described in the next chapter. If applied appropriately, it will lead to better decision support in production and process planning.

7. Requirements and recommendations for simulation

From the description of production processes that include CPS above, the following requirements and recommendations can be derived:

Requirements regarding the simulation model:

- The simulation model must be able to incorporate not only one, but many different products.
- The simulation model must allow for different lot sizes, down to a lot size of 1, to be realized.
- The simulation model must reflect the flexibility of the process and must be able to work without a predefined work plan.
- The simulation model must allow more than one incoming and outgoing path for each resource. This leads to production networks instead of linear production lines (cf. Fig. 5).
- The simulation model must collect information on the state of all available resources.
- The simulation model must include the capabilities of the resources.
- The simulation model must include the requirements of the product and must be able to implement different sequences of fulfillment.
- The simulation model must be able to implement the local decision making that happens ad-hoc during the production process based on the overall state of all resources, the capabilities of the resources, the requirements of the products, and additional master data like costs or customer.
- The simulation model must be able to apply pre-defined rules that control the production processes.

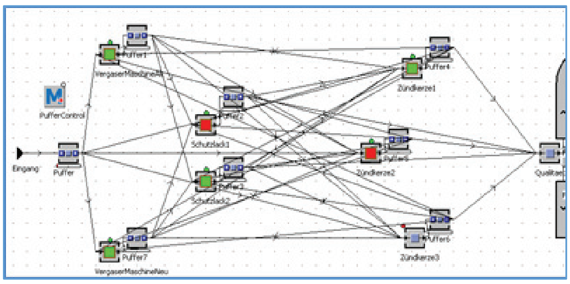

Fig. 5. A production network in Siemens Tecnomatix

Requirements regarding the simulation experiments:

- Multiple simulation runs must be conducted within one simulation experiment to explore the range of possible outcomes.

- The experiments should include varying product mixes as an input factor to explore the maximum of possible outcomes.
- The experiments and the runs with the related input and results should be documented.
- Including failures of resources and set-up times will help to explore capacity bottlenecks.

Requirements regarding the simulation tools:

- Simulation tools should support upcoming standards like Automation ML or BPMN 2.0.
- Simulation tools should be tied closer to CAD-systems that define the products and to MES or Business Intelligence systems that provide information on past instances.
- Simulation tools should provide helpful advice when problems are detected. It should recommend e.g. changes to a given set of rules.

Requirements regarding the machine-oriented simulation:

- Vendors can use machine-oriented simulation to define the capabilities of their CPS.
- Prerequisites of simulation (e.g. digital mock-ups) should be shared with customers so that they can simulate their production with the CPS.
- Extended simulation is recommended to ensure a high process quality and reduced failures. This will increase the robustness of the CPS.
- The results from simulation should be incorporated into the development of PLC.
- Machine-oriented simulation can especially be of value when new or changed products are introduced and it has to be ascertained that the given resources are suitable for their production.

Compared to existing simulation solutions (especially Siemens Tecnomatix; comparison executed by Meyer/Schopf, two bachelor students), it can be stated that most of the requirements can be fulfilled if the solutions are used in an appropriate manner. Therefore, the requirements can also be interpreted as recommendations for the users of such simulation tools.

8. Discussion, Limitations and Outlook

The paper analyzed the changes in production processes that are typical for the introduction of CPS based on a case study and an additional interview. These changes have to be reflected in the way, technical simulations are conducted.

The limitations of the study consist in the small number of CPS companies that were considered and the focus on Siemens as one of many simulation tool providers that can be found. The evaluation of the results must be the next step in the research as well as an extension of simulation models with historical data to learn faster from experiences that happened in the past.

As production lines are changing into flexible production networks, it is necessary to adjust the pyramid of automation, which is currently done by the Industrial Internet Consortium and the Plattform Industrie 4.0 which develop new reference architectures.

The importance of simulation will continue to grow in the future as production environments' complexity increases. This will be the case as more and more companies implement CPS and increase their degree of automation and automated coordination. To make simulation easy to use, it should be able to import master data from common standards and graphical user interfaces should be extended to allow for more people to use simulation. A crucial requirement that has been mentioned by many other authors is the lack of integration of simulation tools within the IT landscape. Only if the models that are the foundation of simulation can be acquired easily, simulation can be performed fast, more automated and come up with better results.

References

[1] A. Majumdar and H. Szigeti, ICT FOR MANUFACTURING - The ActionPlanT Vision for Manufacturing 2.0 Online, 2011.
[2] VDI, Simulation of systems in materials handling, logistics and production - Fundamentals. Düsseldorf: Beuth Verlag GmbH, 2014.
[3] H. Wildemann, "Dezentralisierung von Kompetenz und Verantwortung," in Handbuch Unternehmensorganisation, D. S. H.-J. Bullinger, H.-J. Warnecke, E. Westkämper, Ed., ed Berlin: Springer, 2009, pp. 182-197.
[4] H.-J. Warnecke, "The fractal company," in Neue Impulse für eine erfolgreiche Unternehmensführung, H.-J. Bullinger, Ed., ed Berlin: Springer, 1994, pp. 55-79.
[5] M. Koch, Entwicklung eines Informationsversorgungskonzepts als Basis unternehmensspezifischer Business-Intelligence-Lösungen industrieller Unternehmen. Lohmar: Eul, 2014.
[6] A. R. Hevner, S. T. March, J. Park, and S. Ram, "Design Science in Information Systems Research," MIS Quaterly, vol. 28, pp. 75-105, 2004.
[7] H. Osterle, Becker, J., Frank, U., Hess, T., Karagiannis, D., Krcmar, H., Loos, P., Mertens, P., Oberweis, A., Sinz, E. J., "Memorandum on design-oriented information systems research," European Journal of Information Systems, vol. 20, pp. 7-10, 2010.
[8] R. K. Yin, Case study research design and methods, 5.Aufl. ed. Los Angeles: SAGE, 2014.
[9] F. Romeike and J. Spitzner, Von Szenarioanalyse bis Wargaming - Betriebswirtschaftliche Simulationen im Praxiseinsatz Weinheim: Wiley, 2013.
[10] S. Sabbour, Lasi, H., Tessin, P., "Business Intelligence and strategic decision simulation " Proceedings of the International Conference on Computer Science and Applied Mathematics (ICCSAM), pp. 108-115, 2012.
[11] D. V. der Zee and J. V. der Vorst, " A Modeling Framework for Supply Chain Simulation: Opportunities for Improved Decision Making," vol. 36, pp. 65– 95, 2005.
[12] VDI, Digital factory fundamentals. Berlin: Beuth, 2008.
[13] D. D'Addona, R. Teti, 2011, "Queuing Network Modelling Techniques For Response Time Enhancement In Electronics Assembly", International Journal of Computer Aided Engineering and Technology (JICAET), Vol. 3, No. 3/4, pp- 399-413, 2011.
[14] VDI, Simulation of systems in materials handling, logistics and production - Machine-oriented simulation. Düsseldorf: Beuth Verlag GmbH, 2007.
[15] E. E. Aleisa and L. Lin, "For effeictive facilities planning: Layout optimization then simulation, or vice versa?," Proceedings of the 2005 Winter Simulation Conference pp. 1381-1385, 2005.
[16] J. Li, Y. Lu, and Y. Song, "Efficient Motion Simulation and Collision Detection Algorithm Suitable for Serial Industrial Robot," in Advances in Reconfigurable Mechanisms and Robots II. vol. 36, X. Ding, X. Kong, and J. S. Dai, Eds., ed Heidelberg: Springer, 2016, pp. 901-912.
[17] N. Wang, C. Zheng, and X. Zhang, "Efficient Collision Detection for Industrial Robot Simulation System," in Intelligent Robotics and Applications, Proceedings of the 8th International Conference, H. Liu, N. Kubota, X. Zhu, R. Dillmann, and D. Zhou, Eds., ed Heidelberg: Springer, 2015.

[18] A. P. Markopoulos, “Finite Element Method in Mashining Processes”, ed. Heidelberg, Springer, 2013.
[19] E. A. Lee, "Cyber Physical Systems: Design Challenges," 11th IEEE Symposium on Object Oriented Real-Time Distributed Computing (ISORC), pp. 363-369, 2008.
[20] L. Sha, S. Gopalakrishnan, X. Liu, and Q. Wang, "Cyber-Physical Systems: A New Frontier," 2008 IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing, pp. 1-9, 2008.
[21] R. R. Rajkumar, I. Lee, L. Sha, and J. Stankovic, "Cyber-Physical Systems: The Next Computing Revolution," Design Automation Conference 2010, pp. 731-736, 2010.
[22] Arbeitskreis Industrie 4.0, Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0. Frankfurt a.M., 2013.
[23] D. Zuehlke, "SmartFactory - Towards a factory-of-things," Annual Reviews in Control, vol. 34, pp. 129–138, 2010.
[24] S. Wang, J. Wan, D. Li, and C. Zhang, "Implementing Smart Factory of Industrie 4.0: An Outlook," International Journal of Distributed Sensor Networks, vol. 2016, pp. 1-10, 2016.
[25] D. C. Lucke, C., Westkämper, E., "Smart factory – a step towards the next generation of manufacturing.," Manufacturing systems and technologies for the new frontier: the 41st CIRP conference on manufacturing systems, pp. 115–118, 2008.
[26] H. Lasi, H.-G. Kemper, P. Fettke, T. Feld, and M. Hoffmann, "Industry 4.0," Business & Information Systems Engineering, pp. 239-242, 2014.
[27] C. Haussmann and H.-G. Kemper, "A feature-based concept for decision support to cope with product variety," Proceedings of CIRP CMS 2015 - 48th CIRP Conference on Manufacturing Systems, vol. 41, pp. 454–459, 2015.
[28] J. Lachenmaier, Lasi, H., Kemper, H.G., "A Concept for Extracting and Sharing Technical Data from Digital Product Models for Subsequent Processing " in 48th Hawaii International Conference on System Sciences (HICSS), Kauai, USA, 2015, pp. 987-997
[29] J. Lachenmaier, Lasi, H., Kemper, H.G., "Entwicklung und Evaluation eines Informationsversorgungskonzepts für die Prozess- und Produktionsplanung im Kontext von Industrie 4.0 " in WI2015, Osnabrück, 2015.
[30] M. W. S. Wrede, J. Steil, O. Beyer, C. Frobieter, V. Franke, "Modulare Fertigungslinien für die individualisierte Produktion (in Print)," Werkstatttechnik Online, 2016.
[31] R. Drath, A. Lüder, J. Peschke, and L. Hundt, "AutomationML – the glue for seamless Automation Engineering," 2008 IEEE International Conference on Emerging Technologies and Factory Automation pp. 616-623, 2008.
[32] H. Baars, C. Felden, P. Gluchowski, A. Hilbert, H.-G. Kemper, and S. Olbrich, "Shaping the Next Incarnation of Business Intelligence," Business & Information Systems Engineering, vol. 6, pp. 11-16, 2014/02/01 2014.