Cyber-Physical Systems as Enablers in Manufacturing Communication and Worker Support

Heimo Gursch
David Cemernek
hgursch@know-center.at
dcemernek@know-center.at
Know-Center GmbH
Knowledge Discovery
Graz, Austria

Andreas Wuttei
andreas.wuttei@novunex.com
Novunex GmbH
Klagenfurt, Austria

Roman Kern
rkern@know-center.at
Know-Center GmbH
Knowledge Discovery
Graz, Austria

ABSTRACT

The increasing potential of Information and Communications Technology (ICT) drives higher degrees of digitisation in the manufacturing industry. Such catchphrases as "Industry 4.0" and "smart manufacturing" reflect this tendency. The implementation of these paradigms is not merely an end to itself, but a new way of collaboration across existing department and process boundaries. Converting the process input, internal and output data into digital twins offers the possibility to test and validate the parameter changes via simulations, whose results can be used to update guidelines for shop-floor workers. The result is a Cyber-Physical System (CPS) that brings together the physical shop-floor, the digital data created in the manufacturing process, the simulations, and the human workers. The CPS offers new ways of collaboration on a shared data basis: the workers can annotate manufacturing problems directly in the data, obtain updated process guidelines, and use knowledge from other experts to address issues. Although the CPS cannot replace manufacturing management since it is formalised through various approaches, e. g., Six-Sigma or Advanced Process Control (APC), it is a new tool for validating decisions in simulation before they are implemented, allowing to continuously improve the guidelines.

CCS CONCEPTS

• **Information systems → Enterprise information systems**; • **Applied computing → Enterprise applications**; • **Computer systems organization** → *Embedded and cyber-physical systems*; • **Human-centered computing** → *Collaborative and social computing systems and tools.*

KEYWORDS

Industry 4.0, Cyber-Physical Systems, Smart Manufacturing, Worker Support

1 INTRODUCTION

Manufacturing businesses are increasingly competing in the "war for talents." Talent management, development and re-skilling of workers are non-technical aspects of "Industry 4.0" [14]. Industry 4.0 applies various technologies, tasks, and concepts to realise the more generic and international "smart manufacturing" paradigm [3]. Smart manufacturing concerns improvements in such manufacturing factors as productivity, quality, delivery, and flexibility by means of Information and Communications Technology (ICT) solutions in the manufacturing industry. The key representatives of ICT in the manufacturing industry are the Internet of Things (IoT), cloud computing, and Cyber-Physical Systems (CPSs) [5]. A CPS is a system of interconnected ICT components, representing physical objects within the cyber space to facilitate the fusion of the cyber with the physical world [6].

Most of the related work in the fields of CPSs, smart manufacturing, and Industry 4.0 is dominated by technological aspects. It is often pointed out that these technological concepts promote the transformation towards efficient and sustainable manufacturing, which in turn is good for the society. However, sociological and communication-related aspects are underrepresented in the literature. Even human-centred publications (e. g., Romero et al. [10]), focus on human interaction with new tools, concepts, and infrastructure rather than on aspects related to communication between workers. The technological changes are expected to greatly affect the daily routines of workers, especially in terms of communication and collaboration between the individual roles. Common tasks currently performed by shop-floor workers might vanish, evolve, or change to include more collaboration with

---

MuC'19 Workshops, Hamburg, Deutschland

https://doi.org/10.18420/muc2019-ws-300-03

other workers outside the immediate manufacturing process, e. g., with colleagues in the product development or testing. The direct inter-departmental collaboration allows to react quicker to problems in the manufacturing process by incorporating feedback and knowledge otherwise not considered. By using ICT strong feedback loops can be created between departments in a manufacturing company that are currently only weakly coupled.

This work researches the impact, challenges, and potentials of ICT in the form of CPS in the manufacturing industry. The next section provides an overview of related literature. Section 3 elaborates on the requirements, challenges, and opportunities associated with applying CPS to connect workers and processes in manufacturing. Finally, Section 4 summarises the main ideas of this work and offers an outlook on future research.

2 RELATED WORK

CPS and Smart Manufacturing

Lee [5] and Lidong and Guanghui [6] presented a 5-level migration plan to transform physical objects into their cyber representation by starting with raw data, refining it step-by-step, and ultimately turning it into valuable and actionable information. The five levels are depicted in Figure 1. The first "Smart Connection Level" collects raw data. At the second "Data-to-Information Conversion Level" relevant information is extracted from the raw data. Level three generates cyber representations of the physical entities, e. g., the digital representations of machines or sensors, allowing to compare entities based on their cyber representations. Applying the cyber representations of all entities, Level four, the so-called "Cognition Level," generates knowledge of the overall system and correlates the effects of the components within the system. Using the system view, Level four provides knowledge for experts, acting as an enabler for decision-support systems. The fifth and final level transfers actions from the cyber space back to the physical space, e. g., by adjusting process parameters in case of emerging process errors.

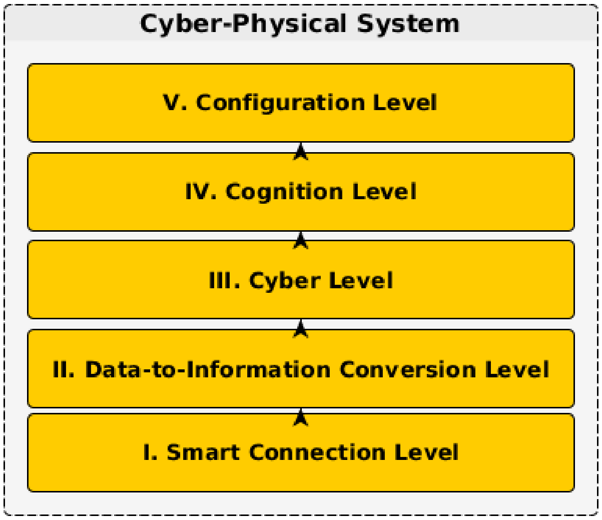

Figure 1: The five levels of Cyber-Physical Systems (CPSs).

A full CPS with all five levels in operation creates a constantly updated digital twin of a manufacturing plant capable of simulating the overall manufacturing process. The simulation allows to evaluate manifold parameter settings and process adaptions in the cyber representation without changing a single physical object. Thus, each potential adaption in the physical world can be extensively evaluated in the cyber representation first, saving valuable resources and time. Furthermore, by monitoring the divergence between the physical and the cyber representations, the digital twin can be used to indicate the maintenance needs of the physical representation [1]. Romero et al. [10] touch on the concept of digital twins and their inherent potential for virtual parameter testing and validation. This means that digital twins can facilitate a major paradigm shift towards an extended information context for shop-floor workers in their operational work. For example, instead of monitoring processes and machines, the workers might perform virtual experiments since simulations give them an opportunity to judge the impact of observed changes and trends in the manufacturing process.

The key assets for unlocking the potential of CPSs, the digital twins, and the simulations are the data associated with them. Lee [5] provides a summary of various data sources required by smart manufacturing and CPSs:

- Machine Data
- Processing Parameters
- Maintenance Records
- Supplier Data
- Order Data
- Scheduling
- Quality Data

Especially data that is directly linked to manufacturing processes, e. g., the machine data created during the process or regulated processing parameters, is indispensable to monitoring and controlling the manufacturing processes.

Manufacturing Management

Approaches to manufacturing management have already been formalised decades ago. Well-known representatives like Six-Sigma or Multivariate Statistical Process Control, cover various monitoring and control techniques [4]. The underlying concept subsuming this broad field of techniques and technologies is referred to as Advanced Process Control (APC) and has been a well-established field for decades [8]. APC techniques primarily refer to the operational and technical aspects of manufacturing processes, focusing on the integration of technical feedback into the respective improvement actions. Together with other aspects (e. g., shop-floor management), the identification and handling of improvement actions is investigated in the research field of lean manufacturing. Lean manufacturing is based on a plethora of lean practices termed "basic principles." The Kaizen continuous improvement approach or the No Muda continuous reduction of waste approach are two common examples [12].

Combining Lean Manufacturing and Industry 4.0

To date, few contributions have been made on the subject of combining lean manufacturing and smart manufacturing. Sanders et al. [11] present a framework of barriers and challenges related to the implementation of lean manufacturing and discuss how this implementation can be supported by Industry 4.0 technologies. Furthermore, the authors stated that further research on the importance of continuous improvement over the dimensions of lean manufacturing is required. Mrugalska and Wyrwicka [9] present a short case study where the authors linked lean manufacturing with Industry 4.0 based on various technologies and tools, such as smart products, smart machines, and augmented operators. Tortorella and Fettermann [13] examined the relationship between lean manufacturing and the implementation of Industry 4.0 by conducting surveys in Brazilian companies. The work supports the claim that lean manufacturing can be combined with Industry 4.0 technologies in a beneficial manner. Buer et al. [2] identified four main research streams concerning the linkage between lean manufacturing and Industry 4.0. Firstly, Industry 4.0 supports lean manufacturing; secondly, lean manufacturing supports Industry 4.0; thirdly, performance implications of Industry 4.0 and lean manufacturing integration; and, fourthly, the effects of environmental factors on Industry 4.0 and lean manufacturing integration.

The literature suggests that a systematic integration of feedback from various internal and external sources into the manufacturing process is a promising concept based on the combination of well-established lean manufacturing approaches with CPS solutions from smart manufacturing. This systematic, fast, and continuous integration of feedback leverages benefits from both lean and smart manufacturing, as described in the following section.

3 CPS AS ENABLER FOR COLLABORATION

Initial Situation

While a number of Industry 4.0 and CPS applications are already in use [7], the potential of a CPS to connect actors working on completely different aspects of the same product is often underestimated. In other words, a CPS offers each actor a customised view of all task-relevant information, even in the information originates from sources outside of the manufacturing process. In modern manufacturing this is a key success factor, given the multitude of workers, machines, materials, suppliers, and customers involved, each interacting at different levels of abstraction and with different time horizons in the overall process.

In an ICT-driven manufacturing environment, the data collected about the product is the common link between all actors in the process. The data can be distinguished based on its origin in the manufacturing process, as depicted in Figure 2.

- *Process Input:* Covers input data required to setup the process, including raw material information, product requirements, orders, scheduling, and maintenance records. This data typically has a medium- to long-term time horizon, compared to the process internal data. Process input data often originates from external partners and matches the CPS Levels 2 to 4.
- *Process Internal:* Holds all data that is created within the process itself, e. g., processing parameters and machine log data. Internal data is typically short-term, has high update rates, and is located at Level 1 and 2 of CPSs. This data is often collected from systems originally designed for monitoring and controlling of the manufacturing machinery.
- *Process Output:* Set of data characterising the manufactured products in terms of product quality, scrap rate, costs, etc. This data is usually updated on a much slower base than the internal data, corresponding to a mid- to long-term time horizon. The data is often already pre-processed and aggregated matching the Levels 3 to 5 of the CPS definition. It commonly provides the basis for the quality assessment and control of the manufactured products. This data is one of the most important sources of improving the manufacturing process.

While data from all three categories is needed in the manufacturing process, each category has different origins, update rates and validity periods. Especially new requirements and feedback on deviations in the product quality are good indications for the need of changes in the CPS. This might lead to additional sensors, adaption to sensors or sampling rates, change in the data pre-processing methods that previously removed some aspects from the raw data now identified to be important, and adjustment to the existing or creation of new models and simulation programs of the manufacturing process.

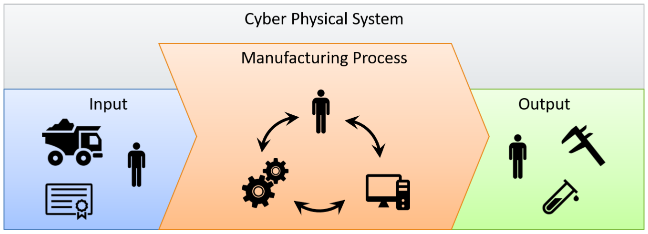

Figure 2: Human workers, machines, and controlling computers are involved in the manufacturing process. All three create data and use external data. The external data is either entering the process, i. e., describing the raw materials and requirements, or outgoing data, i. e., describing the manufactured product. The CPS connects all actors and their data.

CPS as Connecting Element

CPSs create a link between actors, machines, and materials by establishing a common data basis throughout the entire manufacturing process and all its sub- and supporting processes. Since a high data quality is necessary to leverage the potential of CPS, traditional processes and work instructions need to be adapted to ensure it. All workers and suppliers involved need to be aware that the data collection efforts are not merely an end in itself but the enabler for the simulations and data analytics applied over domain, company, or process boundaries. A fast exchange of high-quality data across the previously-existing boundaries paves the way for new, more elaborate applications in data analytics and simulation. Such applications are particularly interesting when they combine data on the requirements of currently produced goods and incoming material with the knowledge obtained from already manufactured and tested products. Under this scenario, it is possible to derive process parameter adaptations for the optimal product quality and suggest them to the worker. This means that involved workers will not follow strict and potentially outdated, guidelines but rather receive relevant and up-to-date instructions optimised for the current situation and requirements.

The connection established via a CPS spanning across the product's lifecycle stages creates a common understanding of manufacturing parameters and requirements. Specialised views of the data are required, showing relevant sections for specific tasks, otherwise the sheer available volume of data would obfuscate the information the workers need in order to make informed decisions in reaction to chaining conditions. Another valuable tool is the ability to make annotations in the data, directly marking records corresponding to problematic products or situations. The annotations can trigger all kinds of actions, e. g., requesting an inspection and re-work, reporting problems, or even raising design-related issues. This leads to new collaborative aspects of CPS, with workers interacting with each other and working on the product issues using a direct link to the data representing those. In this regard, the CPS offers the ideal supplement to process management approaches. Issue tracking and improvement actions are directly linked with the data describing the issues, simulations identifying the solutions, and the updated process parameters for addressing the issues.

Product Quality Example

A good example in this regard is product quality. For instance, if the manufacturing process requires arc welding, the quality of weld seam depends on many parameters, including the alloy of the base metal, the weld metal, and the welding rod. Other process parameters, such as rod feed and electric current, have to be controlled to react to the material changes in order to achieve the required weld seam quality. These adaptations are commonly carried out by shop-floor workers based on the process guidelines derived from the simulation models and the product tests. Feedback on the achieved welding quality may be obtained from a fatigue test run in a test laboratory or from customers using the finished product days or weeks after the manufacturing is completed.

The CPS connects all this information, including raw material data from the supplier, welding parameters, product requirements, and test results of the finished product. With this data, specialised simulations of the welding process can be carried out in parallel with or even ahead of the actual welding. The results of these simulations provide the welders with updated limits for the rod feed and electric current settings based on the current raw materials and product requirements. It is no longer necessary to follow static limits specified during the development. Rather it is possible to adapt to the actual situation on the shop-floor and quickly react to a new set of customer requirements. Obviously, this requires coordination with the manufacturing management, e. g., documenting the changes and following the validation processes. The welders on the shop-floor can access information about past problems, are made aware of when special care is needed for challenging products, and can give feedback to the design engineer and recommend possible improvements. Each of these exchanges are linked to data representing specific products or lots. Thus, feedback loop from the shop-floor can be shared with the development, testing, and any other departments.

4 CONCLUSION AND OUTLOOK

ICT offers new possibilities in manufacturing, which are formalised in Industry 4.0 and smart manufacturing paradigms. In deep integration with the process management, a CPS offers new possibilities to workers from different departments to collaborate in solving issues and reacting to changed requirements based on an exchange of process input, internal, and output data. Hence, organisational boundaries can be digitally overcome offering new targeted communication channels, which are vital in terms of quickly adapting to changing conditions and requirements, creating digitalis twins and simulations for validation purposes, sharing data to follow up on problems, and directly incorporating feedback from any stakeholder into the central manufacturing process. The CPS is the connecting element since it provides the right information, at the right time, and at the right level of detail to all workers. Hence, the CPS can be viewed as an addition to the existing manufacturing management methods, creating new collaboration ways across processes and departments, offering an opportunity to validate parameter changes in simulation, and guiding workers using situation-depended and continuously updated process parameters.

In the future, more research into how CPS changes the way workers from different department collaborate should be performed. While the technical and the process foundations are already investigated in the literature, little research on the impact on the daily routines of shop-floor workers is currently available. Moreover, a closer investigation of the CPS application and its ability to provide updated and digitally validated guidelines is needed.

ACKNOWLEDGMENTS

This work has been supported by the Austrian Federal Ministry for Transport, Innovation and Technology (BMVIT) programme "ICT of the Future", managed by the Austrian Research Promotion Agency (FFG), under grant № 861264 and № 867530.

The Know-Center is funded within the Austrian COMET Program—Competence Centers for Excellent Technologies—under the auspices of the Austrian Federal Ministry of Transport, Innovation and Technology, the Austrian Federal Ministry of Economy, Family and Youth and by the State of Styria. COMET is managed by the Austrian Research Promotion Agency FFG.

REFERENCES

[1] Ahmad T. Al-Hammouri. 2012. A Comprehensive Co-Simulation Platform for Cyber-Physical Systems. *Computer Communications* 36, 1 (dec 2012), 8–19. https://doi.org/10.1016/j.comcom.2012.01.003

[2] Sven-Vegard Buer, Jan Ola Strandhagen, and Felix T. S. Chan. 2018. The Link Between Industry 4.0 and Lean Manufacturing: Mapping Current Research and Establishing a Research Agenda. *International Journal of Production Research* 56, 8 (April 2018), 2924–2940. https://doi.org/10.1080/00207543.2018.1442945

[3] Hyoung Seok Kang, Ju Yeon Lee, Sangsu Choi, Hyun Kim, Jun Hee Park, Ji Yeon Son, Bo Hyun Kim, and Sang Do Noh. 2016. Smart Manufacturing: Past Research, Present Findings, and Future Directions. *International Journal of Precision Engineering and Manufacturing-Green Technology* 3, 1 (Jan. 2016), 111–128. https://doi.org/10.1007/s40684-016-0015-5

[4] James V. Kresta, John F. MacGregor, and Thomas E. Marlin. 1991. Multivariate Statistical Monitoring of Process Operating Performance. *The Canadian Journal of Chemical Engineering* 69, 1 (Feb. 1991), 35–47. https://doi.org/10.1002/cjce.5450690105

[5] Jay Lee. 2015. Smart Factory Systems. *Informatik-Spektrum* 38, 3 (June 2015), 230–235. https://doi.org/10.1007/s00287-015-0891-z

[6] Wang Lidong and Wang Guanghui. 2016. Big Data in Cyber-Physical Systems, Digital Manufacturing and Industry 4.0. *International Journal of Engineering and Manufacturing* 6, 4 (July 2016), 1–8. https://doi.org/10.5815/ijem.2016.04.01

[7] Yang Lu. 2017. Industry 4.0: A Survey on Technologies, Applications and Open Research Issues. *Journal of Industrial Information Integration* 6 (2017), 1–10. https://doi.org/10.1016/j.jii.2017.04.005

[8] James Moyne, Jamini Samantaray, and Michael Armacost. 2016. Big Data Capabilities Applied to Semiconductor Manufacturing Advanced Process Control. *IEEE Transactions on Semiconductor Manufacturing* 29, 4 (Nov. 2016), 283–291. https://doi.org/10.1109/TSM.2016.2574130

[9] Beata Mrugalska and Magdalena K. Wyrwicka. 2017. Towards Lean Production in Industry 4.0, In Proceedings of the 7th International Conference on Engineering, Project, and Production Management (EPPM 2016), Katarzyna Halicka and Lukasz Nazarko (Eds.). *Procedia Engineering* 182, 466–473. https://doi.org/10.1016/j.proeng.2017.03.135

[10] David Romero, Johan Stahre, Thorsten Wuest, Ovidiu Noran, Peter Bernus, Asa Fast-Berglund, and Dominic Gorecky. 2016. Towards an Operator 4.0 Typology: A Human-Centric Perspective on the Fourth Industrial Revolution Technologies. In *Proceedings of the 46th International Conference on Computers & Industrial Engineering (CIE 2016)*. Computers & Industrial Engineering, Curran Associates, Inc., New York, USA, 608–618. http://www.proceedings.com/33189.html

[11] Adam Sanders, Chola Elangeswaran, and Jens Wulfsberg. 2016. Industry 4.0 Implies Lean Manufacturing: Research Activities in Industry 4.0 Function as Enablers for Lean Manufacturing. *Journal of Industrial Engineering and Management* 9, 3 (Sept. 2016), 811–833. https://doi.org/10.3926/jiem.1940

[12] Rachna Shah and Peter T. Ward. 2003. Lean Manufacturing: Context, Practice Bundles, and Performance. *Journal of Operations Management* 21, 2 (March 2003), 129–149. https://doi.org/10.1016/S0272-6963(02)00108-0

[13] Guilherme Luz Tortorella and Diego Fettermann. 2018. Implementation of Industry 4.0 and Lean Production in Brazilian Manufacturing Companies. *International Journal of Production Research* 56, 8 (2018), 2975–2987. https://doi.org/10.1080/00207543.2017.1391420

[14] Alp Ustundag and Emre Cevikcan (Eds.). 2018. *Industry 4.0: Managing the Digital Transformation* (first ed.). Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-319-57870-5