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Digital Twin in manufacturing: A categorical literature review and classification

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Abstract: The Digital Twin (DT) is commonly known as a key enabler for the digital transformation, however, in literature is no common understanding concerning this term. It is used slightly different over the disparate disciplines. The aim of this paper is to provide a categorical literature review of the DT in manufacturing and to classify existing publication according to their level of integration of the DT. Therefore, it is distinct between Digital Model (DM), Digital Shadow (DS) and Digital Twin. The results are showing, that literature concerning the highest development stage, the DT, is scarce, whilst there is more literature about DM and DS.

Keywords: Digital Model, Digital Shadow, Digital Twin, Production, Manufacturing, Literature Review

1. INTRODUCTION

In today's highly competitive markets, where mass customization of products and a rising importance of software components are presenting new challenges: digitalization in manufacturing is seen as an opportunity to achieve higher levels of productivity. (Uhlemann et al. 2017b) The digital technologies, also known as Industry 4.0 technologies, allow easy integration of interconnected intelligent components inside the shopfloor. (Negri et al. 2017) These technologies allow a remotely sense, real-time monitoring and control of devices and cyber physical production elements across network infrastructures and therefore provide a more direct integration and synchronization from the physical to the virtual world. (Negri et al. 2017; Lee et al. 2015)

The use of digitalization technologies enabled virtual product and process planning. The resulting large amounts of data are processed, analysed and evaluated by simulation and optimization tools in order to be able to make them available for planning in real time.(Boschert, Rosen 2016)

One of these simulation based planning and optimization concepts with great potential in many industrial fields is the Digital Twin. (Tao et al. 2017) It is the virtual and computerized counterpart of a physical system. A Digital Twin can be used to simulate it for various purposes, exploiting a real time synchronization of the sensed data originating from the field-level and is able to decide between a set of actions with the focus to orchestrate und execute the whole production system in an optimal way. (Negri et al. 2017; Uhlemann et al. 2017b; Rosen et al. 2015) These results in a higher efficiency, accuracy and gains economic benefits in the production. (Negri et al. 2017)

Based on a comprehensive and systematic literature research, this paper discusses the concept of the Digital Twin in the context of production science. The aim is to provide a holistic overview of the key enabling technologies, areas of application in which a Digital Twin is implemented, and the general level of integration of the individual case-studies and concepts currently used in scientific work. Above all, the technologies used and the level of integration and current maturity of Digital Twins are a major focus of the investigation. This paper serves as the basis for further work in the field of the Digital Twin in manufacturing.

The remainder of the paper is structured as follows: Within section 2 the Digital Twin and its different levels of integration are defined. In section 3, the methodology of the literature classification is presented The outcome of the literature categorization is discussed within section 4 and finally, the paper is concluded within section 5.

2. DEFINITION & METHODOLOGY

The aim of this paper is to provide a literature review with a categorization of the different contributions related to the Digital Twin. They are categorized in terms of their levels of integration, their focused area and the technologies used. Therefore, this section discusses the academic and theoretical definition of the Digital Twin concept and its different levels of integration, followed by an overview of the fields of observation in context to manufacturing and the key digital technologies.

2.1 Digital Twin

Whilst physical twins have been around for some time, the first definition of a concept nowadays known as the Digital Twin was made in 2002 by Michael Grieves in the context of an industry presentation concerning product lifecycle management (PLM). The Digital Twin in its original form is described as a digital informational construct about a physical system, created as an entity on its own and linked with the physical system in question. The digital representation should optimally include all information concerning the system asset

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that could be potentially obtained from its thorough inspection in the real world. (Grieves, Vickers 2017)

A more detailed and in the research field widely recognized definition is given by Glaessgen, Stargel (2012): the *"digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin."* (Tao et al. 2017)

The Digital Twin in its origin describes mirroring a product, while the state of the art allows processes (manufacturing, power generation etc.) to be as well subjects of virtual space reproduction ("twinning") in order to gain the very same benefits. By the time, it was decided to name the concept the DT, first recognition has already appeared in the aerospace world in form of NASA Technology Roadmaps. (Shafto et al. 2010; Negri et al. 2017) A central aspect of the DT is the ability to provide different information in a consistent format. Digital Twins are more than just pure data, they include algorithms, which describe their real counterpart and decide about action in the production system based on this processed data. (Kuhn 2017; Boschert, Rosen 2016; Rosen et al. 2015)

In terms of manufacturing, (Garetti et al. 2012) has the following definition for a Digital Twin: "*The DT consists of a virtual representation of a production system that is able to run on different simulation disciplines that is characterized by the synchronization between the virtual and real system, thanks to sensed data and connected smart devices, mathematical models and real time data elaboration. The topical role within Industry 4.0 manufacturing systems is to exploit these features to forecast and optimize the behaviour of the production system at each life cycle phase in real time."* (Negri et al. 2017)

Due to the multiple existing solutions and concepts of a DT across industries a diverse and incomplete understanding of this concept exist.(Tao et al. 2017; Lee et al. 2013a; Rosen et al. 2015) To get a more common understanding of the Digital Twin, the level of integration are discussed in the following section.

2.2 Level of integration

Based on the given definitions of a Digital Twin in any context, one might identify a common understanding of Digital Twins, as digital counterparts of physical objects. Within these definitions, the terms Digital Model, Digital Shadow and Digital Twin are often used synonymously. However, the given definitions differ in the level of data integration between the physical and digital counterpart. Some digital representations are modelled manually and are not connected with any physical object in existence, while others are fully integrated with real-time data exchange. Therefore, the authors would like to propose a classification of Digital Twins into three subcategories, according to their level of data integration.

Digital Model

A Digital Model is a digital representation of an existing or planned physical object that does not use any form of automated data exchange between the physical object and the digital object. The digital representation might include a more or less comprehensive description of the physical object. These models might include, but are not limited to simulation models of planned factories, mathematical models of new products, or any other models of a physical object, which do not use any form of automatic data integration. Digital data of existing physical systems might still be in use for the development of such models, but all data exchange is done in a manual way. A change in state of the physical object has no direct effect on the digital object and vice versa.

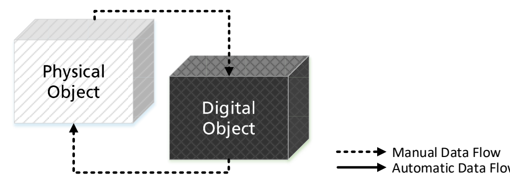

Fig. 1. Data Flow in a Digital Model

Digital Shadow

Based on the definition of a Digital Model, if there further exists an automated one-way data flow between the state of an existing physical object and a digital object, one might refer to such a combination as Digital Shadow. A change in state of the physical object leads to a change of state in the digital object, but not vice versa.

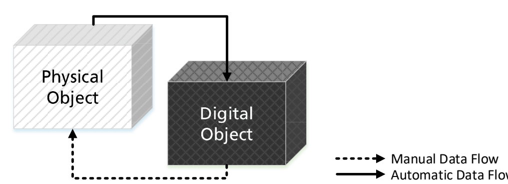

Fig. 2. Data Flow in a Digital Shadow

Digital Twin

If further, the data flows between an existing physical object and a digital object are fully integrated in both directions, one might refer to it as Digital Twin. In such a combination, the digital object might also act as controlling instance of the physical object. There might also be other objects, physical or digital, which induce changes of state in the digital object. A change in state of the physical object directly leads to a change in state of the digital object and vice versa.

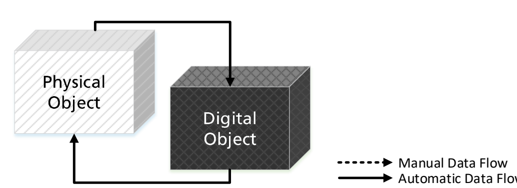

Fig. 3. Data Flow in a Digital Twin

2.3 Focused areas in manufacturing

A manufacturing Digital Twin offers an opportunity to simulate and optimize the production system, including its logistical aspects and enables a detailed visualization of the manufacturing process from single components up to the whole assembly. The Digital Twin encourage following main disciplines of production systems with the common target to increase competitiveness, productivity and efficiency:

- Production planning and control (Rosen et al. 2015)
  - Orders planning based on statistical assumptions
  - Improved decision support by means of detailed diagnosis
  - Automatic planning and execution from orders by the production units
- Maintenance (D'Addona et al. 2017; Susto et al. 2015)
  - Identify the impact of state changes on upstream and downstream processes of a production system
  - identification and evaluation of anticipatory maintenance measures
  - evaluation of machine conditions based on descriptive methods and machine learning algorithms
  - integrate, manage and analyse machinery or process data during different stages of machine life cycle to handle data/information more efficiently and further achieve better transparency of a machine's health condition (Lee et al. 2013b)
- Layout planning (Uhlemann et al. 2017a)
  - continuous production system evaluation and planning
  - Automatic and application independent data acquisition and variation

2.4 Key enabling technologies

Due to the different nature and varying integration levels of Digital Twin concepts, the set of technologies needed for the implementation differs greatly. Often referred technologies include, but are not limited to simulation methods (e.g. Discrete Event Simulation, Continuous Simulation, etc.), communication protocols (e.g. OPC-UA, MQTT, etc.) and other technologies commonly described as Industry 4.0 core technologies (Internet of Things, Cloud Computing, Big Data, etc.). Therefore, the key enabling technologies, referred to in the literature examined, shall be identified.

2.5 Categorization methodology

According to the aforementioned assumptions, it becomes clear that the Digital Twin is a frequently used term, which is applied diversely along the different disciplines. Although some literature reviews of the Digital Twin already exist, most of them analyse literature based on specific views as for example Negri et al. (2017) who are doing a thorough literature review of the Digital Twin's role within Industry 4.0. The aim of this paper is to provide a categorical literature overview among different areas of application of the DT in manufacturing. Particularly, the authors used the search engines Google Scholar and Scopus to gather publications (conference papers as well as journal papers) within the topic Digital Twin. Therefore, the following keywords and phrases were used during the research phase: Digital Twin, Digital Twin in manufacturing, Digital Twin in maintenance, Digital Twin in PPC, Digital Twin in production planning, Digital Twin in layout planning. Even though there are publications, which date before 2014, mainly papers with a publication date latter than 2014 were analysed.

The papers found, were analysed by their content and categorized according to their different perspectives, as shown in Fig.4. Firstly, the publications were analysed concerning their type – if they were case-studies, concept-papers, reviews or definitions. When a publication could be classified within more than one category of type, the dominant one was chosen. Furthermore, the focused area as well as the technologies mentioned, were derived from the papers' contents. The term Digital Twin literally occurred in most of the papers, however, the term was used in slightly different ways. So the papers were classified by their inherent level of integration concerning the described Digital-Twin. Therefore, the categorization, mentioned in section 2 was used. The classified literature is shown in Tab. 1.

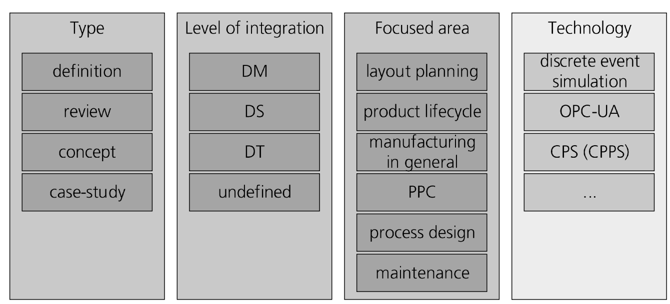

Fig. 4. Categorization Method

3. DISCUSSION

The majority (55 percent) of the reviewed literature is categorized with the type "concept". It is important to note, that some of them contained brief case-studies, but their main parts consist of concept development and description. However, the big share of concepts show that the research concerning the Digital Twin is at its infancy and many researchers are currently starting to derive appropriate concepts as a first step towards applying the Digital Twin in practice. However, 26 percent of the analysed publications are categorized as case-studies, where the focus of the papers is mainly describing the case-studies themselves as well as discussing their results.

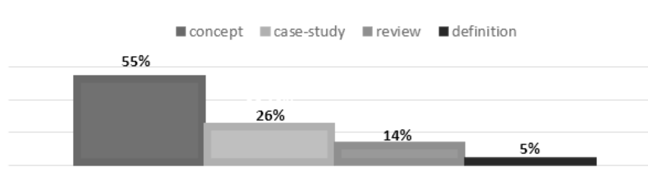

Fig. 5. Publication-types: distribution of publication types

Table. 1. Categorical literature review

Reference	Type	Level of integration	Focused area	Technology
Boschert, Rosen (2016)	review	DT	product lifecycle	simulation
Bottani et al. (2017)	case-study	DT	PPC	simulation
Brenner, Hummel (2017)	definition	DT	PPC	sensors
Cai et al. (2017)	concept	DM	maintenance	simulation
Frazzon et al. (2016)	concept	DM	PPC	discrete event simulation
Friedemann Mattern (2010)	review	undefined	manufacturing in general	RFID
Friedrich et al. (2014)	concept	DS	maintenance	-
GE Power Digital Solutions (2016)	study	DM	product lifecycle	discrete event simulation, sensors
Gyulai et al. (2016)	concept	DM	layout planning	Plant Simulation, TCP/IP, optimization
Jain et al. (2001)	concept	DS	layout planning	simulation
Kaylani, Atieh (2016)	case-study	DM	PPC	discrete event simulation
Kuhlenkötter et al. (2017)	concept	DM	product lifecycle	-
Kuhn (2017)	review	DT	maintenance	simulation
Kumar et al. (2015)	case-study	DM	PPC	optimization
Lee et al. (2013b)	concept	DS	maintenance	PHM, CPS
Lee et al. (2013c)	concept	DS	maintenance	PHM, TCM, sensors
Lindström et al. (2017)	case-study	DS	maintenance	PHM, sensors
Mell, Grance (2011)	case-study	DS	PPC	visualization
Müller et al. (2017)	review	DT	manufacturing in general	-
Pawlaszczyk (2006)	review	DT	manufacturing in general	optimization
Prager, David (2016)	case-study	DM	product lifecycle	simulation, SAP
Reeves (2017)	definition	DT	manufacturing in general	simulation
Rosen et al. (2015)	case-study	DM	layout planning	simulation, MBSE
Salleh et al. (2017)	case-study	DM	process design	CPS, sensors
Schleich et al. (2017)	case-study	undefined	process design	eRobotics, virtual testbed, CPS, MBSE
Schluse, Rossmann (2016)	case-study	undefined	PPC	simulation, XML, CPS. Middleware
Siemens PLM Software (2017)	concept	DS	PPC	simulation, OPC-UA
Simons et al. (2017)	concept	DS	PPC	OPC-UA, Simulation;Physics, Simulation, SmartGlass, SAP, MES
Singh et al. (2017)	concept	DS	PPC	MTConnect;MQTT;Database;NOSQL;Middleware
Söderberg et al. (2017)	concept	DS	PPC	simulation
Stark et al. (2017)	review	DS	product lifecycle	simulation
Tao et al. (2017)	concept	DM	PPC	Semantic Web
Terkaj, Urgo (2015)	concept	undefined	PPC	simulation, CPS
Terkaj et al. (2015)	concept	DM	process design	simulation, Semantic Web, UML
Theuer, Lass (2016)	concept	undefined	PPC	simulation, CPS, System Theory
Uhlemann et al. (2017a)	concept	DT	PPC	Machine Vision, Simulation, optimization
Uhlemann et al. (2017b)	concept	undefined	PPC	Value Stream Mapping, Material Flow Simulation, Learning Factory
Um et al. (2017a)	concept	undefined	PPC	PLC, SOA, OPC-UA, RFID, Middleware, Platform, MQTT, ERP, MES, Visualization
Um et al. (2017b)	concept	undefined	PPC	AutomationML, XML, CPS, PLC, OPC-UA, MQTT, MTConnect
Vachálek et al. (2017)	case-study	DS	PPC	Plant Simulation, OPC-UA
Weyer et al. (2016)	concept	DS	PPC	simulation, CPS, SOA
Yang et al. (2016)	concept	DS	PPC	simulation, optimization
Zhang et al. (2017)	concept	DS	layout planning	simulation

DM = Digital Model, DS = Digital Shadow, DT = Digital Twin;

Looking at the levels of integration, the majority of the publications are classified as Digital Shadows (35 percent) and Digital Models (28 percent). Although the majority of papers used the term Digital Twin, only 18 percent of them are really describing a Digital Twin with a bidirectional data-transfer. A combined analysis of type and level of integration gives more insight (cf. Tab. 1). The table shows, ignoring the undefined ones (where no exact classification of the level of integration was possible), that the relative number of case-studies decreases with an increase in the level of integration from DM to DT. There is only one case-study concerning a Digital Twin, which was implemented within a laboratory environment. (Bottani et al. 2017)

Table. 2. Level of integration and type matrix

	concept	case-study	review	definition
undefined	11,90%	4,76%	2,38%	0,00%
DM	14,29%	11,90%	0,00%	0,00%
DS	26,19%	7,14%	2,38%	0,00%
DT	2,38%	2,38%	9,52%	4,76%

There are some reviews, which are classified as Digital Twin, as a bidirectional data-exchange is assumed. Table 1 also shows that there are already many concept-papers within the class DM and DS, but not many DT concepts, which is also underlined by Salleh et al. who state that there is a lack of a conceptual basis. (Salleh et al. 2017)

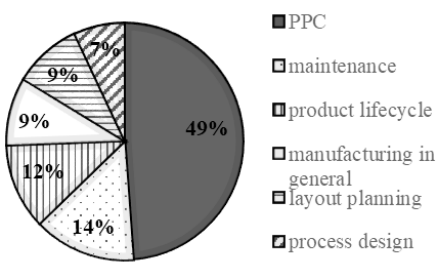

Fig. 6. Focused areas

When it comes to the focused area within the analysed publications, the majority of them focused production planning and control (PPC) as defined in section 2. The second most focused area is maintenance, in particular condition based maintenance (cf. section 2). Product lifecycle management (PLM) was an original idea of the digitalization within product engineering, however mostly the categories DM and DS are belonging to this kind of focused area, because mainly data escort of a product during its whole lifecycle is examined. In the construction phase CAx methods such as CAD, finite element models, etc. are used, which allow a fast engineering process. There is also the possibility of virtually test the behaviour of the product under development and iterate certain parameters in order to optimize its performance and produceability. During the operation phase the Digital Models can be used for maintenance purposes and increasing the speed of finding particular parts of the product, or virtually visualize certain conditions of the product during its operations. The latter one is describing a Digital Shadow, hence, also Digital Twins are possible within PLM. Analogously, layout planning as well as process design are focused areas within the Digital Twin research. Mainly Digital Models are used for engineering purposes, but when it comes to reconfigurable layouts Digital Twins are getting necessary (cf. section 2). Some of the publications do not focus on a particular area within manufacturing, hence they are dealing with the Digital Twin in a broader sense and are therefore classified as "manufacturing in general".

In a nutshell, current literature mainly consists of concept papers within the class of the Digital Shadow and focus on PPC. Some case-studies are already slowly emerging and the Digital Twin in manufacturing is gaining more and more attention. The authors of the analysed papers mainly see need for research in particular areas. While some researchers, especially coming from the class Digital Shadow, see a further research need in developing the optimization and simulation methods, others see the data connectivity as main problem.(Yang et al. 2016; Um et al. 2017b; Vachálek et al. 2017; Schleich et al. 2017; Frazzon et al. 2016; Kuhn 2017; Stark et al. 2017; Singh et al. 2017; Kuhlenkötter et al. 2017; Cai et al. 2017) However, there is consensus that further research concerning the conceptual basis of the Digital Twin is needed. (Zhang et al. 2017; Salleh et al. 2017) There is a tremendous benefit of the Digital Twin for applications in industry, but there is still a lack of case-studies which apply the concepts in practice. (Weyer et al. 2016; Um et al. 2017b; Uhlemann et al. 2017a; Lindström et al. 2017; Kuhn 2017)

4. OUTLOOK & CONCLUSIONS

As also seen by other researchers, there is no common definition of the Digital Twin as the term is used synonymously with Digital Model and Digital Shadow. A main cause is the variety of focused areas within different disciplines. In order to encourage further contribution in this field of study, the establishment of a common definition is necessary. Additionally reference models, which fulfil the domain specific requirements of the focused areas, must be developed. However, a first step towards a common definition is proposed within this paper. Due to a categorical literature review about the Digital Twin, based on the differentiation between particular levels of integration.

The literature review shows, that the development of the DT is still at its infancy as literature mainly consists of concept papers without concrete case-studies. However, some applied case-studies already exist – especially at the lower levels of integration (DM and DS). As shown, a main focus of recent research concerning the DT in manufacturing is dealing with production planning and control as it is a main data-sink within a production system that ties everything together. Hence, it has a mid-level time-horizon, simulation is often used in order to exploit the models at their best. However, the DT can also be used in domains with higher time-frequencies as e.g. process control and condition based maintenance, without using time intense simulation, but using other data driven approaches. There is a further research need for case-studies industrial environments in order to evaluate the possible benefit of the DT.

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REFERENCES

Boschert, Stefan; Rosen, Roland (2016). Digital Twin—The Simulation Aspect. In Peter Hehenberger, David Bradley (Eds.): Mechatronic Futures. Cham: Springer International Publishing, pp. 59–74.

Bottani, E.; Cammardella, A.; Murino, T.; Vespoli, S. (2017). From the Cyber-Physical System to the Digital Twin: the process development for behaviour modelling of a Cyber Guided Vehicle in M2M logic.

Brenner, Beate; Hummel, Vera (2017). Digital Twin as Enabler for an Innovative Digital Shopfloor Management System in the ESB Logistics Learning Factory at Reutlingen - University. In Procedia Manufacturing, 9, pp. 198–205.

Cai, Yi; Starly, Binil; Cohen, Paul; Lee, Yuan-Shin (2017). Sensor Data and Information Fusion to Construct Digital-twins Virtual Machine Tools for Cyber-physical Manufacturing. In Procedia Manufacturing, 10, pp. 1031–1042.

D'Addona, Doriana M.; Ullah, A. M. M. Sharif; Matarazzo, D. (2017). Tool-wear prediction and pattern-recognition using artificial neural network and DNA-based computing. In J Intell Manuf, 28 (6), pp. 1285–1301.

Frazzon, Enzo Morosini; Albrecht, André; Hurtado, Paula Andrea (2016). Simulation-based optimization for the integrated scheduling of production and logistic systems. In IFAC-PapersOnLine, 49 (12), pp. 1050–1055.

Friedemann Mattern, Christian Floerkemeier (2010). From the Internet of Computers to the Internet of Things.

Friedrich, Christian; Lechler, Armin; Verl, Alexander (2014). Autonomous Systems for Maintenance Tasks – Requirements and Design of a Control Architecture. In Procedia Technology, 15, pp. 595–604.

Garetti, Marco; Rosa, Paolo; Terzi, Sergio (2012). Life Cycle Simulation for the design of Product–Service Systems. In Computers in Industry, 63 (4), pp. 361–369.

GE Power Digital Solutions (2016). GE Digital Twin.

Glaessgen, E. H.; Stargel, D. S. (2012). The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. In 53rd Struct. Dyn. Mater. Conf. Special Session: Digital Twin, Honolulu, HI, US.

Grieves, Michael; Vickers (2017). Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems.

Gyulai, Dávid; Pfeiffer, András; Kádár, Botond; Monostori, László (2016). Simulation-based Production Planning and Execution Control for Reconfigurable Assembly Cells. In Procedia CIRP, 57, pp. 445–450.

Jain, Sanjay; Fong Choong, Ngai; Maung Aye, Khin; Luo, Ming (2001). Virtual factory. An integrated approach to manufacturing systems modeling. In Int Jrnl of Op & Prod Mnagemnt, 21 (5/6), pp. 594–608.

Kaylani, Hazem; Atieh, Anas M. (2016). Simulation Approach to Enhance Production Scheduling Procedures at a Pharmaceutical Company with Large Product Mix. In Procedia CIRP, 41, pp. 411–416.

Kuhlenkötter, Bernd; Wilkens, Uta; Bender, Beate; Abramovici, Michael; Süße, Thomas; Göbel, Jens et al. (2017). New Perspectives for Generating Smart PSS Solutions – Life Cycle, Methodologies and Transformation. In Procedia CIRP, 64, pp. 217–222.

Kuhn, Thomas (2017). Digitaler Zwilling. In Informatik Spektrum, 40 (5), pp. 440–444.

Kumar, Divya; Chen, Ye; Esmaili, Ali (2015). Inclusion of Long-term Production Planning/Scheduling into Real-time Optimization. In IFAC-PapersOnLine, 48 (8), pp. 229–233.

Lee, Jay; Bagheri, Behrad; Kao, Hung-an (2015). A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. In Manufacturing Letters, 3, pp. 18–23.

Lee, Jay; Lapira, Edzel; Bagheri, Behrad; Kao, Hung-an (2013a). Recent advances and trends in predictive manufacturing systems in big data environment. In Manufacturing Letters, 1 (1), pp. 38–41.

Lee, Jay; Lapira, Edzel; Bagheri, Behrad; Kao, Hung-an (2013b). Recent advances and trends in predictive manufacturing systems in big data environment.

Lee, Jay; Lapira, Edzel; Yang, Shanhu; Kao, Ann (2013c). Predictive Manufacturing System - Trends of Next-Generation Production Systems. In IFAC Proceedings Volumes, 46 (7), pp. 150–156.

Lindström, John; Larsson, Hans; Jonsson, Martin; Lejon, Erik (2017). Towards Intelligent and Sustainable Production. Combining and Integrating Online Predictive Maintenance and Continuous Quality Control. In Procedia CIRP, 63, pp. 443–448.

Mell, P. M.; Grance, T. (2011). The NIST definition of cloud computing. Gaithersburg, MD. National Institute of Standards and Technology.

Müller, Rainer; Vette, Matthias; Hörauf, Leenhard; Speicher, Christoph; Burkhard, Dirk (2017). Lean Information and Communication Tool to Connect Shop and Top Floor in Small and Medium-sized Enterprises. In Procedia Manufacturing, 11, pp. 1043–1052.

Negri, Elisa; Fumagalli, Luca; Macchi, Marco (2017). A Review of the Roles of Digital Twin in CPS-based Production Systems. In Procedia Manufacturing, 11, pp. 939–948.

Pawlaszczyk, Dirk (2006). Scalable Agent Based Simulation. Considering Efficient Simulation of Transport Logistics Networks. In S. Wenzel (Ed.): Simulation in der

Produktion und Logistik. 12. ASIM Fachtagung, San Diego, pp. 479–488.

Prager; David (2016). Digital Twin Demystified - IoT Application Enablement - PartnerEdge[4].

Reeves, Chris (2017). Spotlight on the Digital Twin. In ANSYS Advantage, 2017 (1/2017).

Rosen, Roland; Wichert, Georg von; Lo, George; Bettenhausen, Kurt D. (2015). About The Importance of Autonomy and Digital Twins for the Future of Manufacturing. In IFAC-PapersOnLine, 48 (3), pp. 567–572.

Salleh, Noor Azlina Mohd.; Kasolang, Salmiah; Mustakim, Muhamammad Azri; Kuzaiman, Nur Asiah (2017). The Study on Optimization of Streamlined Process Flow Based on Delmia Quest Simulation in an Automotive Production System. In Procedia Computer Science, 105, pp. 191–196.

Schleich, Benjamin; Anwer, Nabil; Mathieu, Luc; Wartzack, Sandro (2017). Shaping the digital twin for design and production engineering. In CIRP Annals, 66 (1), pp. 141–144.

Schluse, Michael; Rossmann, Juergen (Eds.) (2016). From simulation to experimentable digital twins. Simulation-based development and operation of complex technical systems. Systems Engineering (ISSE), 2016 IEEE International Symposium on. IEEE.

Shafto, Mike; Conroy, Mike; Doyle, Rich (2010). NASA Modeling, Simulation, Information Technology & Processing - TA11.

Siemens PLM Software (2017). MindSphere. The cloud-based, open IoT operating system for digital transformation.

Simons, Stephan; Abé, Patrick; Neser, Stephan (2017). Learning in the AutFab – The Fully Automated Industrie 4.0 Learning Factory of the University of Applied Sciences Darmstadt. In Procedia Manufacturing, 9, pp. 81–88.

Singh, Shaurabh; Angrish, Atin; Barkley, James; Starly, Binil; Lee, Yuan-Shin; Cohen, Paul (2017). Streaming Machine Generated Data to Enable a Third-Party Ecosystem of Digital Manufacturing Apps. In Procedia Manufacturing, 10, pp. 1020–1030.

Söderberg, Rikard; Wärmefjord, Kristina; Carlson, Johan S.; Lindkvist, Lars (2017). Toward a Digital Twin for real-time geometry assurance in individualized production. In CIRP Annals, 66 (1), pp. 137–140.

Stark, Rainer; Kind, Simon; Neumeyer, Sebastian (2017). Innovations in digital modelling for next generation manufacturing system design. In CIRP Annals - Manufacturing Technology.

Susto, Gian Antonio; Schirru, Andrea; Pampuri, Simone; McLoone, Seán; Beghi, Alessandro (2015). Machine learning for predictive maintenance: A multiple classifier approach. In IEEE Transactions on Industrial Informatics, 11 (3), pp. 812–820.

Tao, Fei; Cheng, Jiangfeng; Qi, Qinglin; Zhang, Meng; Zhang, He; Sui, Fangyuan (2017). Digital twin-driven product design, manufacturing and service with big data. In Int J Adv Manuf Technol, 10 (4), p. 2233.

Terkaj, W.; Urgo, M. (2015). A Virtual Factory Data Model as a Support Tool for the Simulation of Manufacturing Systems. In Procedia CIRP, 28, pp. 137–142.

Terkaj, Walter; Tolio, Tullio; Urgo, Marcello (2015). A virtual factory approach for in situ simulation to support production and maintenance planning. In CIRP Annals, 64 (1), pp. 451–454.

Theuer, Hanna; Lass, Sander (2016). Mastering Complexity with Autonomous Production Processes. In Procedia CIRP, 52, pp. 41–45.

Uhlemann, Thomas H.-J.; Lehmann, Christian; Steinhilper, Rolf (2017a). The Digital Twin. Realizing the Cyber-Physical Production System for Industry 4.0. In Procedia CIRP, 61, pp. 335–340.

Uhlemann, Thomas H.-J.; Schock, Christoph; Lehmann, Christian; Freiberger, Stefan; Steinhilper, Rolf (2017b). The Digital Twin. Demonstrating the Potential of Real Time Data Acquisition in Production Systems. In Procedia Manufacturing, 9, pp. 113–120.

Um, Jumyung; Fischer, Klaus; Spieldenner, Torsten; Kolberg, Dennis (2017a). Development a Modular Factory with Modular Software Components. In Procedia Manufacturing, 11, pp. 922–930.

Um, Jumyung; Weyer, Stephan; Quint, Fabian (2017b). Plug-and-Simulate within Modular Assembly Line enabled by Digital Twins and the use of AutomationML. In IFAC-PapersOnLine, 50 (1), pp. 15904–15909.

Vachálek, J.; Bartalsky, L.; Morhác, M.; Lokšík, M.; Rovný, O.; Šišmišová, D. (2017). The Digital Twin of an Industrial Production Line Within the Industry 4.0 Concept. Available online at http://ieeexplore.ieee.org/servlet/opac?punumber=7970056.

Weyer, Stephan; Meyer, Torben; Ohmer, Moritz; Gorecky, Dominic; Zühlke, Detlef (2016). Future Modeling and Simulation of CPS-based Factories. An Example from the Automotive Industry. In IFAC-PapersOnLine, 49 (31), pp. 97–102.

Yang, Shun; Arndt, Tobias; Lanza, Gisela (2016). A Flexible Simulation Support for Production Planning and Control in Small and Medium Enterprises. In Procedia CIRP, 56, pp. 389–394.

Zhang, Hao; Liu, Qiang; Chen, Xin; Zhang, Ding; Leng, Jiewu (2017). A digital twin-based approach for designing and decoupling of hollow glass production line. In IEEE Access, p. 1.