Digital Twins for Production Logistics

Subjects: Engineering, Industrial | Engineering, Manufacturing | Operations Research & Management Science
Contributor: Manuel Woschank

Digital Twins (DTs) are one of the main opportunities to strengthen the overall competitiveness of manufacturing enterprises. Various technologies and technological concepts are discussed in production logistics, which can be classified as Cyber-Physical Systems (CPS), Internet of Things (IoT), interfaces, decentralized applications, real-time localization systems, automatic identification, virtual environments including Digital Twins (DTs), and applications of data science such as machine learning, data mining, and big data analytics.

Digital Twin | modeling | virtual model | simulation | production logistics

1. Introduction

In today's hyper-dynamic environment, the Industry 4.0 paradigm is reaching far beyond the basic concepts of automation by revolutionizing manufacturing enterprises especially in the areas of smart production and smart logistics. Moreover, Industry 4.0 is characterized by the vertical and horizontal integration of production and logistics systems as well as the merging between the physical and virtual worlds [1]. Industry 4.0 approaches can, therefore, be divided into digitalization, digital interconnectivity, and self-controlling systems [2]. Various technologies and technological concepts are discussed in production logistics, which can be classified as Cyber-Physical Systems (CPS), Internet of Things (IoT), interfaces, decentralized applications, real-time localization systems, automatic identification, virtual environments including Digital Twins (DTs), and applications of data science such as machine learning, data mining, and big data analytics [3]. Companies are challenged with increasing dynamics, structural complexity, increased uncertainties and risks, and multiple feedback cycles. This leads to difficulties in the optimal design and control of production logistics systems [4][5]. However, DT technology offers several approaches to overcome these problems [6][7]. Originally, the concept of a Digital Twin was presented at the University of Michigan by Grieves in 2003. It was first introduced as a concept for product lifecycle management (PLM). At this stage, it was not explicitly called a Digital Twin, but the paper described the idea and important components of such a system [8]. NASA has taken up this concept and described a Digital Twin in the technology roadmap for their flight system, to make comprehensive diagnostics and prognostics, enabling continuous safe operations over the life cycle of the system [9]. Furthermore, Glaessgen and Stargel described a Digital Twin for the next generations of NASA and U.S. Air Force vehicles, giving more detail [10]. Nevertheless, different fields of research adapt the original concept of a Digital Twin to their specific domain. Therefore, several publications discuss the application of DTs in production planning and control, maintenance, process design, layout design, product design, production process optimization, as well as prognostics and health management (PHM) [11][12][13]. This may also be the reason why there is no common definition of a DT [14]. One approach to finding a standardized and common definition of DTs has been elaborated by the International Organization for

Standardization (ISO). According to this proposal, the basic idea of a Digital Twin is to create a digital representation of an observable system or element [15]. More specifically, other authors suppose it to mirror a product, process, or service in virtual space [16]. Convergence between the physical and the virtual space is mandatory [17] to create a closed-loop interaction between these components [18]. A bidirectional communication enhances this convergence [17], as real-time data integration plays a key role for Digital Twins [19]. The concept of Cyber-Physical Systems (CPS) can be described similarly. Tao et al. compared the differences and correlations of the two concepts. DTs are often discussed in the engineering area and are more focused on virtual models (VMs) that enable one-to-one communication between physical and virtual parts. CPS on the other hand is more frequently discussed in the scientific area. To enable fusion and one-to-many communication between the spaces, CPS emphasizes 3C capabilities (computation, communication, and control) [20]. The DT technology can also be seen as a key enabler for realizing a Cyber-Physical Production System (CPPS) [21][22][23]. Among many other application areas, there is great potential for use in production logistics processes [3].

2. Current Insights

Although different definitions of DT can be found in the analyzed literature, commonly used definitions can be identified. A comparison between these shows that the levels of detail, as well as the focus area, differ, but the basic concept remains the same. In comparison with Grieves, Tao et al. added two dimensions and described the dimensions in more detail. This is also the most often used definition within the analyzed literature. Therefore, the level of implementation of the found case studies is also evaluated on this basis. It turns out that only four papers present a fully implemented DT for the core activities of logistics [24][25][26][27]. Two of these papers show implementation in laboratory environments, leaving two industrial applications. In general, most case studies can be assigned to laboratory production lines, followed by applications in the automotive, electronic, and metalworking industries. Besides the different levels of implementation, different approaches for the creation of a VM can also be observed. For production logistics processes, DES is most often used, as it is also the state-of-the-art for simulating production logistics systems. Some authors present predefined building blocks and standardized processes to speed up the creation of DES models. However, most available DES software solutions still lack real-time capabilities [28], which are an essential part of DT technology. For the identified PHM processes, physical simulations are used. Some hybrid simulation approaches can also be found to integrate control mechanisms of decentralized applications. To successfully integrate a DT, a connection to enterprise information systems, as well as to sensors and actuators must be established. Different information systems can be found in various configurations in companies. The connection between and consistency of data in these systems can also vary widely. Another difference in the analyzed DTs is their main objective. Consequently, different requirements must be met, and individual consideration must be given to the information systems to which a bidirectional connection must be established. It is also conceivable that DT technologies will become an inherent part of enterprise information systems or manufacturing execution systems. In the study of Kritzinger et al., a DT was described as consisting of a digital shadow, a digital model, and a bidirectional link between these two elements. Based on this description, the level of integration of the analyzed literature was evaluated. A focus area and the core technologies of these papers are also described [11]. Stark and Damerau analyzed 19 different definitions of DT. Based on this, they defined a DT with three components: a digital master, a digital shadow, and a linking mechanism. In addition, the scope and type of a DT are divided into eight dimensions, with each dimension having three to four levels. The dimensions include integration breadth, connectivity mode, update frequency, CPS intelligence, simulation capabilities, digital model richness, human interaction, and product life cycle [14]. Tao et al. analyzed 50 papers, eight patents, and six best practices of leading companies. The literature was assigned to the application areas of design, production, PHM, and others, showing that PHM is the most popular application area for DT. The importance of DT modeling is highlighted, as well as the fact that no consensus can be found in how to build a DT model. The authors conclude that cyber-physical fusion is one of the major challenges of DT and a lack of universal frameworks is identified [12]. Researching a different application area, the literature review of Agilianos et al. is focused on DT for warehouse processes, stating that the development of DT in this area is still at the initial stage and that DES models must be enhanced with real-time functionalities [28]. This work complements the previous reviews on DTs by adding non-investigated aspects focusing on production logistic processes. First, the most used definitions of DTs in this application area are analyzed and discussed, highlighting similarities and differences between these definitions. As a result, the main components and important functionalities of a DT have been pointed out. In addition to mentioned concepts and reviews, 20 case studies are analyzed in more detail in a second step and evaluated based on the five dimensions of Tao et al. Due to the integral role of the VM in a DT, the approaches and technologies used to create a VM are analyzed and discussed. Together with the analysis of the pursued optimization goals, this provides a starting point for new developments based on already existing approaches and an overview of the potential benefits in this area. The literature analyzed reveals some research gaps and future research directions. It has been shown that there are different approaches for the implementation of a DT for production logistics. Therefore, different requirements must be met as well. These requirements for a DT implementation have not been systematically surveyed and addressed so far. All the literature analyzed deals with discrete production systems, without addressing logistics challenges in the process industry. Despite the description of various information sources, no data models could be found that would allow the DT to be independently connected via APIs. As described, much of the analyzed literature deals with the creation of VMs. Thus, the real-time capabilities and the connection with the physical entity as well as the service system are often neglected. This should be considered in more detail in future research. Overall, only a few fully implemented DTs in industrial environments for production logistics processes could be found. To comprehensively determine the potential benefits in real-world applications in this area, further fully implemented DTs in industrial environments need to be investigated. Although the use of DTs within the design phase is discussed, virtual commissioning with DT technologies is not addressed at all. This is supported by a review by Lechler et al., focusing on virtual commissioning and showing no hits for application in logistics processes [29]. Due to the close relationship between DT and CPS concepts, in future literature reviews, this term should be included to extend the search.

3. Conclusions

This work shows current developments and approaches to DTs in this area. The current state of research on DTs for production logistics processes is highlighted and discussed. Basic concepts, other reviews as well as implementation approaches are analyzed. An overview of the most common definitions of DTs in this field is given and commonalities and differences in the understanding of DT are presented as a basis for further discussion. Detailed analyses of reviewed case studies show possible application areas as well as objectives addressed by the different DT implementation approaches. The technologies used for the creation of the VM are also considered. Research gaps and possible future research directions in this area are also identified and discussed. In sum, it must be stated that investigations regarding the application of Digital Twins in production logistics are still in an early stage of development and profound industrial applications are still missing. This can be seen as motivation for future research initiatives which aim to combine theory-based explorations of logistics systems with a set of empirical research methods.

References

1. Thoben, K.-D.; Wiesner, S.; Wuest, T. “Industrie 4.0” and Smart Manufacturing—A Review of Research Issues and Application Examples. Int. J. Automot. Technol. 2017, 11, 4–16.
2. Bosch, G.; Bromberg, T.; Haipeter, T.; Schmitz, J. Industrie und Arbeit 4.0: Befunde zu Digitalisierung und Mitbestimmung im Industriesektor auf Grundlage des Projekts „Arbeit 2020“. IAQ Rep. 2017, 2017, 1–24.
3. Woschank, M.; Kaiblinger, A.; Miklautsch, P. Digitalization in Industrial Logistics: Contemporary Evidence and Future Directions. In Proceedings of the International Conference on Industrial Engineering and Operations Management, IEOM Society, Singapore, 7–11 March 2021; pp. 1322–1333.
4. Ivanov, D.; Sethi, S.; Dolgui, A.; Sokolov, B. A survey on control theory applications to operational systems, supply chain management, and Industry 4.0. Annu. Rev. Control 2018, 46, 134–147.
5. Scholz-Reiter, B.; Görges, M.; Philipp, T. Autonomously controlled production systems—Influence of autonomous control level on logistic performance. CIRP Ann. 2009, 58, 395–398.
6. Resman, M.; Protner, J.; Simic, M.; Herakovic, N. A Five-Step Approach to Planning Data-Driven Digital Twins for Discrete Manufacturing Systems. Appl. Sci. 2021, 11, 3639.
7. Haße, H.; Li, B.; Weissenberg, N.; Cirullies, J.; Otto, B. Digital twin for real-time data processing in logistics. In Proceedings of the Hamburg International Conference of Logistics (HICL), Hamburg, Germany, 26–27 September 2019; Epubli GmbH: Berlin/Heidelberg, Germany, 2019.
8. Grieves, M. Digital Twin: Manufacturing Excellence through Virtual Factory Replication. White Pap. 2014, 1, 1–7.
9. Piascik, R.; Vickers, J.; Lowry, D.; Scotti, S.; Stewart, J.; Calomino, A. DRAFT Materials, Structures, Mechanical Systems, and Manufacturing Roadmap: Technology Area 12; National Aeronautics and Space Administration: Washington, DC, USA, 2010; pp. TA12-1–TA12-30.

Available online: https://www.nasa.gov/pdf/501625main_TA12-MSMSM-DRAFT-Nov2010-A.pdf (accessed on 21 June 2021).

10. Glaessgen, E.; Stargel, D. The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. In Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference—Special Session on the Digital Twin, Honolulu, Hawaii, 23–26 April 2012; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2012; p. 1818.
11. Kritzinger, W.; Karner, M.; Traar, G.; Henjes, J.; Sihn, W. Digital Twin in manufacturing: A categorical literature review and classification. IFAC-Pap. 2018, 51, 1016–1022.
12. Tao, F.; Zhang, H.; Liu, A.; Nee, A.Y.C. Digital Twin in Industry: State-of-the-Art. IEEE Trans. Ind. Inform. 2019, 15, 2405–2415.
13. Tao, F.; Cheng, J.; Qi, Q.; Zhang, M.; Zhang, H.; Sui, F. Digital twin-driven product design, manufacturing and service with big data. Int. J. Adv. Manuf. Technol. 2018, 94, 3563–3576.
14. Stark, R.; Damerau, T. Digital Twin. In CIRP Encyclopedia of Production Engineering; Chatti, S., Laperrière, L., Reinhart, G., Tolio, T., Eds.; Springer: Berlin/Heidelberg, Germany, 2019; pp. 1–8. ISBN 978-3-642-35950-7.
15. ISO. Automation Systems and Integration—Digital Twin Framework for Manufacturing: Overview and General Principles; Draft; Vernier: Geneva, Switzerland, 2020; ISO/DIS 23247-1:2020(E).
16. Qi, Q.; Tao, F.; Hu, T.; Anwer, N.; Liu, A.; Wei, Y.; Wang, L.; Nee, A. Enabling technologies and tools for digital twin. J. Manuf. Syst. 2019, 58, 3–21.
17. Tao, F.; Zhang, M. Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing. IEEE Access 2017, 5, 20418–20427.
18. Parrot, A.; Warshaw, L. Industry 4.0 and the digital twin: Manufacturing meets its match. In A Deloitte Series on Industry 4.0, Digital Manufacturing Enterprises, and Digital Supply Networks; Deloitte University Press: New York, NY, USA, 2017; pp. 1–17.
19. Kuehn, W. Digital twins for decision making in complex production and logistic enterprises. Int. J. Des. Nat. Ecodynamics 2018, 13, 260–271.
20. Tao, F.; Qi, Q.; Wang, L.; Nee, A. Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison. Engineering 2019, 5, 653–661.
21. Sommer, M.; Stjepandic, J.; Stobrawa, S.; von Soden, M. Improvement of Factory Planning by Automated Generation of a Digital Twin. In Proceedings of the 27th ISTE International Conference on Transdisciplinary Engineering for Complex Socio-technical Systems, Warsaw, Poland, 2–10 July 2020; IOS Press: Amsterdam, The Netherlands, 2020. ISBN 978-1-64368-110-8.

22. Zheng, Y.; Yang, S.; Cheng, H. An application framework of digital twin and its case study. J. Ambient Intell. Humaniz. Comput. 2019, 10, 1141–1153.
23. Tao, F.; Qi, Q. New IT Driven Service-Oriented Smart Manufacturing: Framework and Characteristics. IEEE Trans. Syst. Man Cybern. Syst. 2017, 49, 81–91.
24. Wang, Y.; Wu, Z. Digital twin-based production scheduling system for heavy truck frame shop. Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci. 2020, 1–12.
25. Wang, W.; Zhang, Y.; Zhong, R.Y. A proactive material handling method for CPS enabled shop-floor. Robot. Comput. -Integr. Manuf. 2020, 61, 101848–101849.
26. Herakovič, N.; Zupan, H.; Pipan, M.; Protner, J.; Šimic, M. Distributed manufacturing systems with digital agents. Stroj. Vestn. J. Mech. Eng. 2019, 65, 650–657.
27. Yao, F.; Keller, A.; Ahmad, M.; Ahmad, B.; Harrison, R.; Colombo, A.W. Optimizing the Scheduling of Autonomous Guided Vehicle in a Manufacturing Process. In Proceedings of the 2018 IEEE 16th International Conference on Industrial Informatics (INDIN), Porto, Portugal, 18–20 July 2018; IEEE Xplore: New York, NY, USA, 2018.
28. Agalianos, K.; Ponis, S.T.; Aretoulaki, E.; Plakas, G.; Efthymiou, O. Discrete Event Simulation and Digital Twins: Review and Challenges for Logistics. Procedia Manuf. 2020, 51, 1636–1641.
29. Lechler, T.; Fischer, E.; Metzner, M.; Mayr, A.; Franke, J. Virtual Commissioning: Scientific review and exploratory use cases in advanced production systems. Procedia CIRP 2019, 81, 1125–1130.