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Digital Factory Twin: A Practioner-Driven Approach for Integrated Planning of the Enterprise Architecture

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Abstract

The Digital Factory Twin (DFT) is becoming more important in today's manufacturing world, but many companies are struggling to plan for its successful implementation. This paper suggests using an Enterprise Architecture (EA) Management approach to make this process easier and more effective. We start by mapping out current hurdles, challenges and problems in the implementation of the DFT with a Meta-Review on existing studies based on the research method of a Structured Literature Review. Based on that we derive problem fields. Based on this problem fields we propose an integrated planning approach, that helps with these and is focused on helping practitioners in a real-world environment getting the DFT into productive use. Our approach consists of the following phases: (1) Determine initial situation & target picture for the DFT incl. deriving a short list of suitable DFT use cases; (2) Company specific DFT design; (3) Plan EA changes.

Keywords: digital twin; digital factory twin; factory planning; factory operations; product development; enterprise architecture; enterprise architecture management

1. Introduction

Digital Twins (DTs) have become key in the world of product development, offering a powerful way to work with products and their digital representation. They have been used successfully in many areas, proving how useful they can be (e.g. connecting the Digital Master in product development with the DT of product instances and optimize the product based on the DT) [1, 2]. However, when it comes to using DTs in the context of manufacturing, things are different. Digital concepts like the Digital Factory are used successfully for many years and are scalable across the whole factory. In comparison DTs in manufacturing are mostly used for specific use cases and areas in the factory, like a single machine or a production line [3]. These use cases often lack the scalability to the hierarchical level of the entire factory and can usually only add value at the machine level [4].

There's not much information available on successful full-factory DT implementations in the existing literature. This is a sign that DTs haven't fully made their way into the factory setting yet. In fact, only about 8% of companies have put DT use cases in the factory and in general to work successfully [5].

This paper addresses the lack of widespread use of digital factory twins (DFTs) in industrial environments. We aim to look at why it's been difficult to adopt them and suggest an integrated planning approach on how to ensure IT-driven feasibility and business value in the context of production management and factory planning.

In section 2 we look on related work for planning approaches of DTs for the domain of manufacturing and other suitable domains like product development. We then explain our research design (see section 3) and derive problem fields in DT implementation (see section 4). Based on this we suggest an integrated planning approach based on ideas of Enterprise Architecture Management (EAM) to handle the complexity of

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a DFT (see section 5). Finally, we conclude with a discussion of our results including its value and limitations (see section 6).

2. State of research and related work

A DT is a digital representation of a real product or a product service system which sufficiently meet the requirements of a set of use cases [6]. The concept of a DT was first mentioned in 2002 by Grieves in the context of product lifecycle management, which describes an exchange of information between the physical system and the virtual system [7]. NASA describes the DT as the simulation of a flying system, which consists of a physical system, sensors and the received usage data and maintenance history. Over the years, various bodies such as the Digital Twin Consortium and the Industrial Digital Twin Association (IDTA) have published a large number of DT definitions. For a uniform understanding, the following paper is based on the relationships of a DT with the physical system described in Cieply et al [3]: a DT connects the real system with a virtual copy of the system with automated data flow consisting of structural data (reflecting the structure of an object or system), alphanumeric data (describing properties and states of an object or system) and graphical data (visually represent the virtual image of the object or system).

The aim of process models is to present the planning procedure of a complex system in a meaningful and logical sequence. In this way, process models abstract a planning process and structure it into sections. They can also contain information about the people involved, prerequisites and the result to be achieved [9, 10]. Systems engineering process models such as the V-model according to VDI 2206 offer a process for mastering the increasing complexity of intelligent technical systems [11]. The “V model” structures many activities such as the identification of requirements or system verification and validation along the life cycle of a system. Software engineering also offers process models for structuring individual activities, from software requirements to software development and software maintenance [12]. For the successful development and implementation of DTs, the approaches of both disciplines must be considered.

In addition to the generally existing approaches of the disciplines, domain specific approaches for the introduction and implementation of DTs are available in the existing literature. Tao et al. present a method in product development that can be integrated into the phases of the design process. The procedure for creating a DT considers units in physical space, models in virtual space and data that links the two worlds. The aim of the process model is a DT that facilitates design activities [13]. Monye describes a framework based on previously identified requirements through an analysis of DT definitions, implemented DT solutions, DT use cases and DT trends in the context of production. For the implementation of DT, a distinction is made between offline development and online development [14]. Segovia and Garcia-Alfaro present a methodological approach that includes the creation of a DT and the synchronization with the physical system. The different phases of creation are addressed, from the selection of requirements, the integration of digital models and the exchange of data in real time via DT [15]. Rasor et al. describes the need for a collaborative approach for the development of DTs in the production value chain. The paper presents a specification technique that combines Model-Based Systems Engineering and Product Lifecycle Management approaches for the development and specification of DTs [16]. In Schweigert-Recksiek et al., a guideline for the data- and simulation-supported design and introduction of DTs in product development is presented. The guideline comprises five steps, from project initiation and target definition to actual implementation. At the beginning, a situation analysis is carried out based on use cases, which identify and reflect the expectations and challenges. The use cases are then evaluated in terms of opportunities and risks and the benefits are assessed. The results are used to derive requirements for a DT and the final implementation [17]. Follath et. al. describe a process model for the creation of DTs for production and logistics. In the first step, the current situation is also determined in the form of a use case, which is then categorized in terms of hierarchy levels and life cycle phase. In further steps, the use case-specific data and other digital models are described, the quality of these is evaluated and the necessary DT interfaces and tools are identified. Once the DT has been modeled, it is evaluated and used for the initial application. A complete validation of this approach is not addressed [18].

The planning systems shown for the use of DTs are based exclusively on identified use cases in the different life cycle phases of a system. A generally valid system for considering the higher-level architecture perspective is not considered in the literature and is not the focus of the existing approaches.

3. Research Design

According to Hiebl, the paper combined two basic search approaches to identify relevant research topics to select suitable literature to develop a process model for DFT implementation [19]. To select relevant literature, a meta-literature analysis by Sinkovics [20] et al. combined with a classical database-driven approach and a journal-driven approach were conducted. The literature analysis was conducted in autumn 2023 and completed on 5 November 2023. Both approaches are briefly described below:

- Database-driven approach: The database-driven approach starts with the identification of keywords in a scoping study and then uses these keywords to search electronic databases. Some databases only consider the title, abstract and keywords provided by the author, while others also consider the full text of the articles.
- Meta-literature analysis by Sinkovics et al.: Sinkovics et al. examined various literature analyses and extracted results from the papers on this basis [20].
- Journal-driven approach: In the journal-based approach, a list of journals is created before the actual search. In contrast to the database-driven approach, the journals and not the databases form the basis for the search. This approach should ensure that no relevant literature for known implementation challenges is missing.

Following the literature analysis, 236 SCOPUS-listed articles and 129 relevant FT50 journal articles were identified.

This resulted in a total of 365 reviews and studies that were analysed.

The further procedure is strongly orientated towards the procedure of a systematic literature analysis [21-25].

The titles and abstracts of the papers were analyzed. 277 papers were eliminated because they for example focussed on a digital product twin or weren't focused on implementation challenges. This resulted in a total of 47 papers that were read. Furthermore, the snowballing method was used to identify secondary literature and include it in the literature analysis. Snowballing is described in detail by Jalali and Wohlin [23] and by Keele [24]. This resulted in a total of 5 papers that could be used for the research goal of finding existing implementation challenges.

The theoretical knowledge was then enriched with empirical knowledge. To this end, expert workshops were held with companies that manufacture complex products respectively intelligent technical systems. Our hypothesis is that especially these manufacturing environments could benefit from a DFT. Solution approach for the DFT were developed during the workshops.

This made it possible to develop an overall procedure for an implementation and planning approach for the DFT. A detailed overview of the procedure for preparing the literature research can be seen in Figure 1.

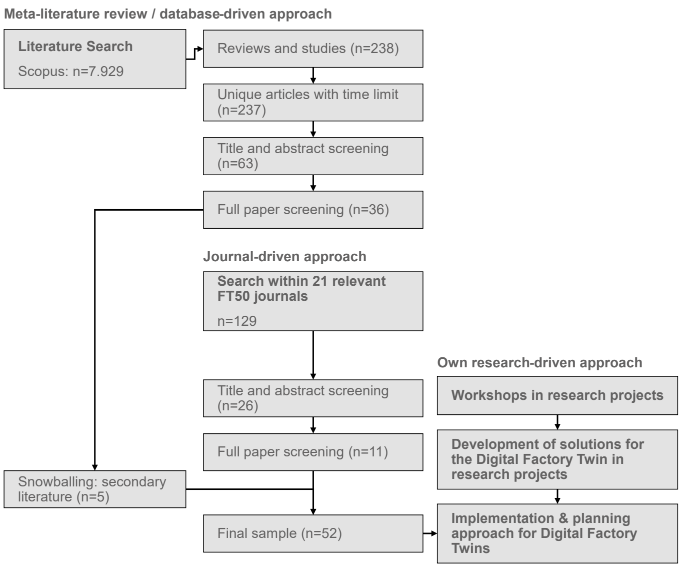

Fig. 1. Search strategy and research process.

4. Derivation of problem fields

The deployment of DFTs encompasses a diversity of challenges that can be categorized into three core areas: human, technological, and organizational (HTO) aspects according to Rollenhagen [25] In total we could identify 87 different implementation challenges.

An effective analysis of these challenges necessitates a deeper exploration of the organization and technology area. Therefore, the EA framework as defined by The Open Group Architecture Framework (TOGAF) was used. TOGAF organizes the EA into five levels: strategy, business architecture, application & data architecture, and technical infrastructure [26]. Using these categories, we analyzed the common challenges identified in the literature that we reviewed (see Fig. 2).

At the strategy level, specific challenges include the formulation of a clear value proposition for a DT implementation. Companies struggle to articulate the tangible benefits and justify the investment in technology that is often perceived as novel and unproven [27-29]. Additionally, the protection of intellectual property remains a critical concern, especially given the collaborative and interconnected nature of DTs, which can expose sensitive data and proprietary processes to potential vulnerabilities [30, 31].

Moving to the business architecture level, problems revolve around displaying relevant information in an appropriate format at the correct time. The overload of data and the complexity of DTs can lead to information being presented in a way that is not actionable for decision-makers [32]. Furthermore, there is the challenge of integrating DTs into existing business processes, which often requires substantial adaptation and re-engineering to ensure seamless operation [33-36].

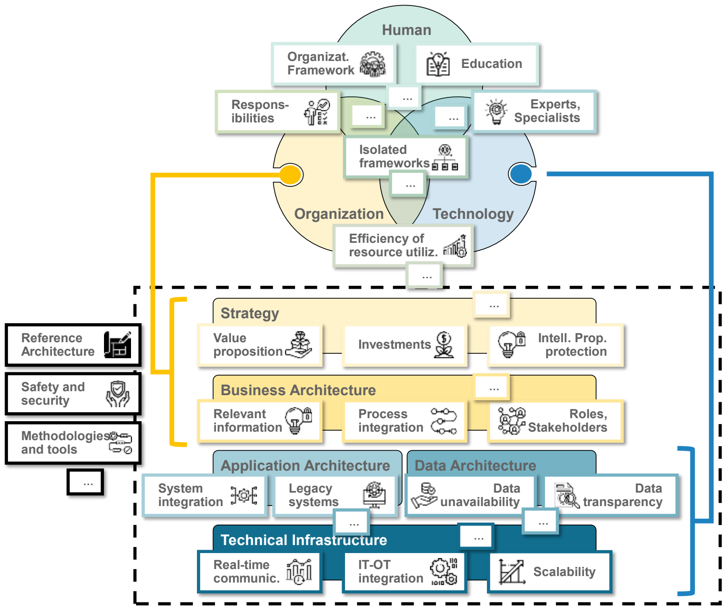

Fig. 2. Exemplary presentation of the challenges found along the HTO categories extended by the EA levels according to TOGAF.

The application architecture level faces the challenge of dealing with legacy Information Technology (IT) systems and their integration with newer, more advanced systems. These legacy systems, which are often deeply embedded within the organization's operations, often lack the flexibility to interface effectively with advanced DT technologies, leading to integration issues and data silos [37-39].

On the data architecture level, the primary issue is the lack of availability of the right data at the right time. The data needed to create a comprehensive and accurate DT may be incomplete, outdated, or locked within other systems [40, 41]. Data transparency is also a significant concern, as stakeholders require visibility into data sources, quality, and reliability to trust and effectively utilize the DT [42].

Finally, at the technology infrastructure level, the integration of IT with Operational Technology (OT) poses a significant hurdle. The distinct nature of IT and OT systems, where IT is data-oriented and OT is process-oriented, requires thoughtful integration to achieve efficient and reliable operations [43-45]. Real-time communication is another critical requirement at this level, where the DT must reflect live operational conditions accurately and without delay to be truly effective.

In summary, the successful implementation of a DFT is dependent on overcoming multifaceted problems across various dimensions of a factory. The problems, challenges and hurdles identified can be abstracted into the following five problem fields:

1. *Identification of suitable starting points for DFT implementation to support strategic goals of a factory (addressed by phase 1)*
2. *Integration into existing business architecture (business processes, roles, stakeholders, etc., addressed by phase 1 & 2)*
3. *Consideration of a company's existing application & data architecture in terms of reusing already implemented systems (addressed by phase 2 & 3)*
4. *Integration of legacy systems via suitable interfaces in the application architecture (addressed by phase 2 & 3)*
5. *Providing and linking the right data objects with sufficient quality (latency, validity, data quality, etc., addressed by phase 2)*
6. *Ensure consistency from technical solutions of the DFT to strategic business goals of the manufacturing domain through capability-based planning (addressed by phase 1 & 2)*

Addressing these issues requires a holistic and concerted effort that aligns with the strategic goals, operational processes, and technology infrastructure of a factory.

5. Development of an integrated planning approach based on EAM

Considering the identified problem fields, we propose an integrated planning approach focused effectively operationalize the DFT within real-world manufacturing settings. This EAM-based approach is divided into three sequential phases, each of which is designed to be based on the previous one. In the following text we explain each phase and the provided tools and aids to carry out the phase. (see Fig. 3).

Phase 1: Determine initial situation & target picture for the DFT incl. deriving a short list of suitable DFT use cases

Description: The first phase involves an initial assessment of the current state using a capability map, which details the existing competencies of the factory in scope. This serves as a first step to understand the baseline from which the DFT initiative will progress. Concurrently, practitioners must develop a target picture, in which outlines the envisioned future state of the relevant capabilities in the factory. This target picture is developed on business capability basis and defines what a DFT needs to be capable of to support the manufacturing strategy and derived business goals.

The transformation of the capabilities can be planned over time in several incremental improvements towards the target state or in one single transformation step.

With an understanding of the initial situation and a clear target picture, the next phase is to identify a short-list of suitable use cases with the help of a use case catalogue. The short-listing process should involve stakeholders from across the organization to ensure that the chosen use cases resonate with the needs and expectations of various departments like maintenance, logistics, etc.

Tools and aids: The **capability map** used in this phase structures the most important capabilities in a factory along the business processes of factory planning and production

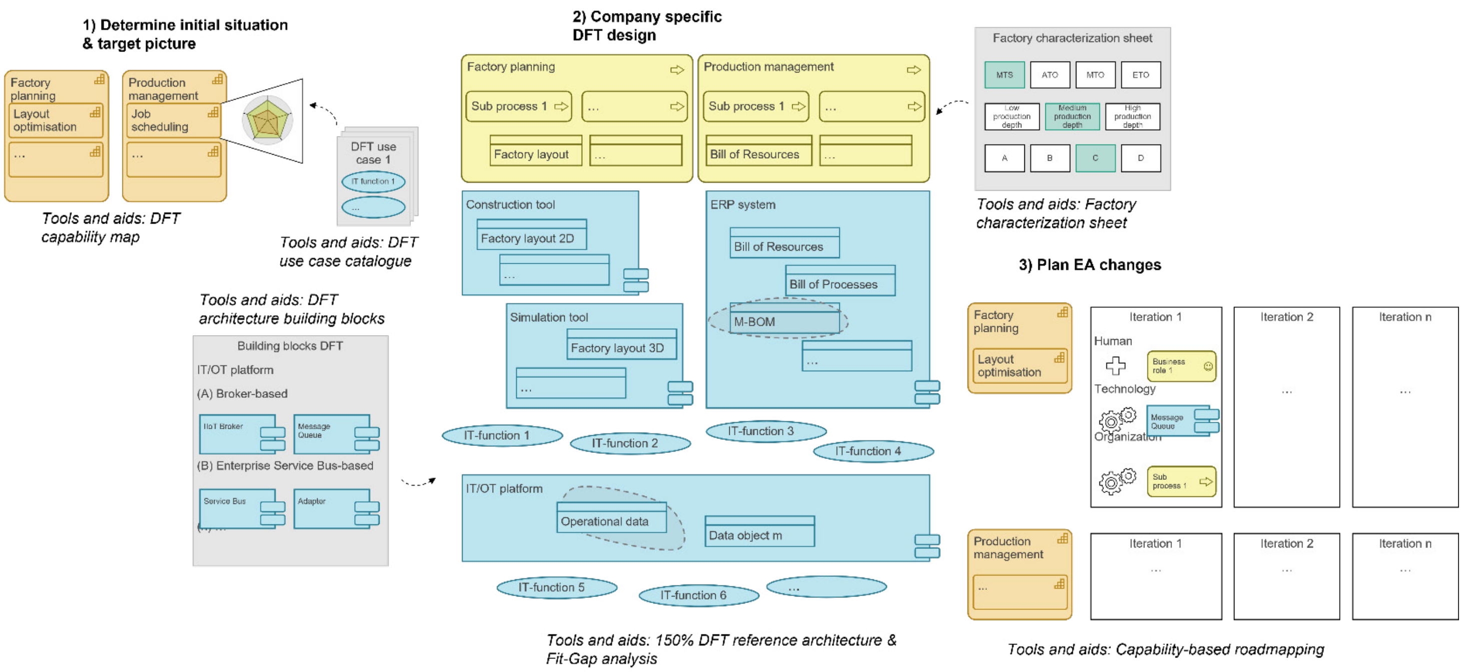

Fig. 3. Proposed integrated planning approach.

management. Different maturity levels are defined for each capability, along which the current status and the target picture are developed. Part of the maturity levels of the capability map are the concrete DFT use cases and in which maturity level they can add value to the overarching factory-capabilities.

The **use case catalogue** provides structured solution knowledge for DFT use cases. Each use case is assigned to the corresponding capabilities from the capability map used before. The cutout EA for implementing the particular use case is shown on each factsheet from the catalogue.

Phase 2: Company specific DFT design

Description: Following the identification of use cases, the second phase is the planning of their implementation within the company-specific EA. This is achieved with the aid of a '150% DFT reference architecture'. The reference architecture acts as a complete template for all possible features of a DFT from which the company can derive a customized architecture that caters to the identified use cases while considering the unique characteristics and constraints of the company.

Tools and aids: The **150% Reference Architecture** is structured along the considered levels according to TOGAF (see section 4). The instantiation of the reference architecture to the company context depends, for example, on the organization of production (e.g. Engineering-to-Order vs. Make-to-Order) and other factors. These factors are recorded in a **'Factory characterization sheet'**.

Based on this characterization the company-specific instantiation is realized with the help of so-called **architecture building blocks**, which are selected according to the characterization sheet for the current as-is EA. For planning the target EA with implemented DFT use cases the building blocks also help when several technical concepts are suitable for the same IT functions (e.g. Broker-based approach for required IT/OT platform vs. Enterprise Service Bus-based approach).

The reference architecture is structured as follows: at the strategy level, all possible goals of a factory (e.g. adaptability) are presented. The possible capabilities for their operational achievement are derived from the objectives. These are congruent with the capabilities already used in the capability map in phase 1. Each capability is then assigned the implementation in business processes, business and data objects, IT functions and IT applications on the levels below.

For example, the objective "adaptability" can be achieved through the capability "rapid rescheduling of the factory layout", among others. This in turn is implemented in the factory planning business process and the respective sub-processes. One of the relevant business objects is the "factory layout" that is stored in a specific data format as a data object in the corresponding IT application. The assigned IT function is, for example, "provision of the current factory layout".

Phase 3: Plan EA changes

Description: The third phase is the planning of the migration from current as-is EA to post-DFT implementation EA (EA change to accommodate the implementation of the DFT). In this phase a fit-gap-analysis is conducted to identify gaps between as-is and to-be state.

Based on the gaps a roadmap is created to address these identified gaps. This roadmap is not merely a timeline; it aligns further company-specific project initiatives with the affected capabilities. The roadmapping process ensures that each initiative is not only scheduled but is also in synergy with other projects and the overall strategic direction of the company.

Tools and aids: The **fit-gap analysis method** according to TOGAF is adapted for this phase. The capabilities from phase 1 are analyzed one after the other and the gap or need for change is derived for each capability.

Also, the **migration planning** from TOGAF is adapted. For each capability, the identified gaps from phase are broken down into specific work packages. These are then analyzed for interactions across all capabilities and placed in a chronological order. Other important input for the placement on a roadmap are current and planned projects in the factory context and their interaction with the defined work packages.

Through this structured approach the problem fields identified in section 4 can be addressed.

By mapping the DFT capabilities and use cases to the strategic factory goals and existing factory capabilities, a clear starting point for DFT initiatives can be identified.

The DFT reference architecture ensures specific integration into the existing business, application and data architecture of an existing factory.

The approach of analyzing the necessary IT functions of the DFT use cases to be implemented makes it possible to reuse and connect existing IT landscapes, including legacy systems.

6. Conclusion and outlook

The developed integrated planning approach leveraging EAM principles provides a structured framework to implement a DFT effectively. Currently there is a research gap regarding applying the EAM-approach for a systematic planning of a DFT implementation in manufacturing companies. Its main advantage lies in aligning the DFT with strategic and operational goals, ensuring relevant stakeholder involvement, and utilizing a '150% DFT reference architecture' for a tailored fit within the company's context.

However, the presented approach is not without limitations. The validity and practicality of this approach will be tested in collaboration with industrial partners in suitable research projects. This will validate the approach's real-world applicability and enable its refinement, ensuring that it addresses the requirements of different manufacturing environments. Also, the approach is focused on the architectural analysis and planning necessary for implementing a DFT but is not intended to go into more technical details for concrete software development activities.

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References

[1] Lim, Kendrik Yan Hong, Pai Zheng, and Chun-Hsien Chen. "A state-of-the-art survey of Digital Twin: techniques, engineering product lifecycle management and business innovation perspectives." Journal of Intelligent Manufacturing 31 (2020): 1313-1337.
[2] Stoll, Oliver, et al. "The successful commercialization of a digital twin in an industrial product service system." IFIP International Conference on Advances in Production Management Systems. Cham: Springer International Publishing, 2020.
[3] Cieply, Jonas, et al. "A systematic literature review on the Digital Twin of the factory in the context of the product and factory lifecycle." Procedia CIRP 119 (2023): 834-840.
[4] Cieply, Jonas, et al., „Methoden für die Gestaltung der Unternehmensarchitektur produzierender Unternehmen – EAM als Enabler für die Konzipierung übertragbarer KI-Lösungen“. IM 391(2023), S. 37-42. Online: https://doi.org/10.30844/IM_23-1_37-42
[5] Riedelsheimer, Theresa, et al. "Digital twin readiness assessment." Eine Studie zum Digitalen Zwilling in der fertigenden Industrie (2020).
[6] Industrial Internet Consortium, IIC vocabulary, https://hub. iiconsortium.org/vocabulary, (Accessed on 07/30/2020).
[7] Grieves, M. "PLM Initiatives [Powerpoint Slides]." Product Lifecycle Management Special Meeting. 2002.
[8] Shafto, Mike, et al. "Draft modeling, simulation, information technology & processing roadmap." Technology area 11 (2010): 1-32.
[9] Schmidt, Götz. Einführung in die Organisation: Modelle-Verfahren-Techniken. Springer-Verlag, 2013.
[10] Broy, Manfred, and Marco Kuhrmann. Projektorganisation und Management im Software Engineering. Springer Berlin Heidelberg, 2013.
[11] VID-Richtlinie, "Gesellschaft Produkt-und Prozessgestaltung: VDI 2206. Entwicklungsmethodik für mechatronische Systeme." (2004).
[12] Broy, Manfred, and Marco Kuhrmann. Einführung in die Softwaretechnik. Springer Berlin/Heidelberg, 2021.
[13] Tao, Fei, et al. "Digital twin-driven product design framework." International Journal of Production Research 57.12 (2019): 3935-3953.
[14] Moyne, James, et al. "A requirements driven digital twin framework: Specification and opportunities." IEEE Access 8 (2020): 107781-107801.
[15] Segovia, Mariana, and Joaquin Garcia-Alfaro. "Design, modeling and implementation of digital twins." Sensors 22.14 (2022): 5396.
[16] Rasor, Rik, et al. "Towards collaborative life cycle specification of digital twins in manufacturing value chains." Procedia CIRP 98 (2021): 229-234.
[17] Schweigert-Recksiek, Sebastian, et al. Einführung eines digitalen Zwillings in die technische Produktentwicklung. Lehrstuhl für Produktentwicklung und Leichtbau, 2022.
[18] Follath, Alexander, Florian Bross, and Stefan Galka. "Vorgehensmodell zur Erstellung Digitaler Zwillinge für Produktion und Logistik." Zeitschrift für wirtschaftlichen Fabrikbetrieb 117.10 (2022): 691-696.
[19] Hiebl, Martin RW. "Sample selection in systematic literature reviews of management research." Organizational research methods 26.2 (2023): 229-261.
[20] Ahi, Alan A., et al. "Advanced technologies and international business: A multidisciplinary analysis of the literature." International Business Review 31.4 (2022): 101967.
[21] Lame, Guillaume. "Systematic literature reviews: An introduction." Proceedings of the design society: international conference on engineering design. Vol. 1. No. 1. Cambridge University Press, 2019.
[22] Xiao, Yu, and Maria Watson. "Guidance on conducting a systematic literature review." Journal of planning education and research 39.1 (2019): 93-112.
[23] Jalali, Samireh, and Claes Wohlin. "Systematic literature studies: database searches vs. backward snowballing." Proceedings of the ACM-IEEE international symposium on Empirical software engineering and measurement. 2012.
[24] Keele, Staffs. "Guidelines for performing systematic literature reviews in software engineering." (2007).
[25] Rollenhagen, Carl. "A framework for assessment of organisational characteristics and their influences on safety." Safety Science Monitor 4.1 (2000): 1-16.
[26] Josey, Andrew. The TOGAF® Standard, Version 9.2-A Pocket Guide. Van Haren, 2018.
[27] Melesse, Tsega Y., Valentina Di Pasquale, and Stefano Riemma. "Digital Twin models in industrial operations: State‐of‐the‐art and future research directions." IET Collaborative Intelligent Manufacturing 3.1 (2021): 37-47.
[28] Niederer, Steven A., et al. "Scaling digital twins from the artisanal to the industrial." Nature Computational Science 1.5 (2021): 313-320.
[29] Perno, Matteo, Lars Hvam, and Anders Haug. "Implementation of digital twins in the process industry: A systematic literature review of enablers and barriers." Computers in Industry 134 (2022): 103558.
[30] Mittal, Sameer, et al. "A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs)." Journal of manufacturing systems 49 (2018): 194-214.
[31] VanDerHorn, Eric, and Sankaran Mahadevan. "Digital Twin: Generalization, characterization and implementation." Decision support systems 145 (2021): 113524.
[32] Xiong, Minglan, and Huawei Wang. "Digital twin applications in aviation industry: A review." The International Journal of Advanced Manufacturing Technology 121.9-10 (2022): 5677-5692.
[33] Aziz, Abdullah, Olov Schelén, and Ulf Bodin. "A study on industrial IoT for the mining industry: Synthesized architecture and open research directions." IoT 1.2 (2020): 529-550.
[34] Biller, Bahar, Jinxin Yi, and Stephan Biller. "A Practitioner’s Guide to Digital Twin Development." Tutorials in Operations Research: Advancing the Frontiers of OR/MS: From Methodologies to Applications. INFORMS, 2023. 198-227.
[35] Olsen, Tava Lennon, and Brian Tomlin. "Industry 4.0: Opportunities and challenges for operations management." Manufacturing & Service Operations Management 22.1 (2020): 113-122.
[36] Apte, Pushkar P., and Costas J. Spanos. "The digital twin opportunity." MIT Sloan Management Review 63.1 (2021): 15-17.
[37] Choi, Tsan‐Ming, et al. "Disruptive technologies and operations management in the Industry 4.0 era and beyond." Production and Operations Management 31.1 (2022): 9-31.
[38] Kumar, Subodha, Vijay Mookerjee, and Abhinav Shubham. "Research in operations management and information systems interface." Production and Operations Management 27.11 (2018): 1893-1905.
[39] Jones, David, et al. "Characterising the Digital Twin: A systematic literature review." CIRP journal of manufacturing science and technology 29 (2020): 36-52.
[40] Stark, Andreas, et al. "Hybrid digital manufacturing: Capturing the value of digitalization." Journal of operations management 69.6 (2023): 890-910.
[41] Barricelli, Barbara Rita, Elena Casiraghi, and Daniela Fogli. "A survey on digital twin: Definitions, characteristics, applications, and design implications." IEEE access 7 (2019): 167653-167671.
[42] Semeraro, Concetta, et al. "Digital twin paradigm: A systematic literature review." Computers in Industry 130 (2021): 103469.
[43] Mithas, Sunil, et al. "How will artificial intelligence and Industry 4.0 emerging technologies transform operations management?." Production and Operations Management 31.12 (2022): 4475-4487.
[44] Engländer, Jacques, and Martin Bremer. "IT-Komplexität und ihre Bedeutung für produzierende Unternehmen im Kontext von Industrie 4.0: Marktstudie: IT-Komplexität." UdZForschung 21.1 (2020): 58-60.
[45] Wu, Jiaju, et al. "The development of digital twin technology review." 2020 Chinese Automation Congress (CAC). IEEE, 2020.