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Procedia CIRP 130 (2024) 718–723

www.elsevier.com/locate/procedia

57th CIRP Conference on Manufacturing Systems 2024 (CMS 2024)

Charting the Course: Standardization of Quality Assurance in Digital Twin Applications Across Product Lifecycle

Jelena Milisavljevic-Syed*, Mohammed Khan[a], Hanbing Xia[a], Jiahong Li[a], Konstantinos Salonitis[a]

[a] *Sustainable Manufacturing Systems Centre, School of Aerospace, Transport and Manufacturing, Cranfield University, MK43 0AL, United Kingdom*

* Corresponding author. Tel.: +44(0) 1234 758533; E-mail address: j.milisavljevicsyed@cranfield.ac.uk

Abstract

Digital twins hold immense promise in accelerating scientific discovery and revolutionizing industries. The use cases for digital twins are diverse and proliferating, with applications across multiple areas of science, technology, and society, and their potential is wide-reaching. Despite the growing use of quality assurance approaches, standards, and frameworks in digital twins, the promise of digital twin benefits remains more aspirational than reality. Consequently, the confidence level in the prediction of these models is questionable. There is a lack of guidance on establishing standardization and interoperability as a foundation for integration of platforms, systems, and stakeholders within the digital twin ecosystem. To address this gap, we propose guidance for standardized quality assurance of digital twins in simulating product lifecycles, aiming to enhance regulatory decision-making. This proposed guidance is a step towards development of framework for standardized quality assurance of digital twins.

Keywords: digital twin; standardized quality assurance; product lifecycle

1. Introduction

Digital twins, representing virtual counterparts of physical assets, processes, or systems, have emerged as a transformative force in modern industries, offering unparalleled opportunities for efficiency enhancement and innovation. However, their widespread adoption faces significant challenges, including technological complexities and regulatory hurdles. To fully harness their potential, standardized quality assurance approaches are crucial. This paper provides a concise overview of digital twin technologies, exploring their evolution, applications, challenges, standards, and anticipated advancements. Through this synthesis, the authors aim to establish the groundwork for a standardized quality assurance framework for digital twins across the product lifecycle.

2. Literature Review

2.1. Evolution of Digital Twins

The concept of digital twins originated from the early advancements in simulation and modelling techniques. Originally designed to replicate physical systems in a digital setting, the development of digital twins has progressed from basic simulations to advanced, real-time copies that are interconnected with their physical counterparts. Originally, it was employed for the purpose of overseeing the operation of manufacturing machinery and substantial resources [1], but it has subsequently been incorporated into the planning, manufacturing, and maintenance phases [2]. The origins of digital twinning may be traced back to the 1960s, when simulation technologies were used in the Apollo space programme to create replicas of spacecraft for training and testing. It was not until the year 2002 that Dr. Michael Grieves, from the University of Michigan, officially coined the phrase

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10.1016/j.procir.2024.10.154

"digital twin" to describe the notion within the framework of Product Lifecycle Management (PLM) [3]. Grieves' vision established the fundamental concept of digital twins as they are currently comprehended—a dynamic, digital duplicate of tangible assets, procedures, or systems that functions as a connection between the physical and virtual realms as illustrated in Figure 1.

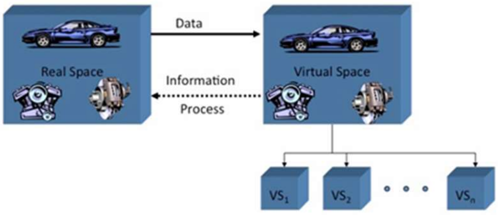

Figure 1-Conceptual Ideal for PLM (Grieves, 2016)

2.2. Key Milestones and technological advancements

The evolution of digital twins, from conceptual frameworks to essential components of Industry 4.0, has been marked by important milestones and technological developments that have greatly enhanced their capabilities and range of applications. The Internet of Things (IoT) has revolutionized communication by enabling seamless interaction between physical assets and their digital counterparts using sensors and networking technologies [4]. The interface facilitated immediate monitoring and data gathering, which is essential for the operational efficiency of digital replicas. Another notable breakthrough was the integration of sophisticated analytics and artificial intelligence (AI), enabling digital twins to not only copy real things but also forecast future conditions and enhance performance by leveraging data-driven insights [5]. Cloud computing is essential in enabling the processing and storage of large volumes of data created by digital twins, as well as aiding complex simulations and analysis, thanks to its scalable infrastructure [6]. Moreover, the introduction of augmented reality (AR) and virtual reality (VR) technology has enhanced the interactive and immersive features of digital twins, enabling users to actively interact with and visualize the digital copies in novel manners. Together, these technological advancements have propelled digital twins into a wide array of applications, ranging from manufacturing and healthcare to urban planning.

2.3. Applications Across Product Lifecycle

2.3.1. Design and Prototyping

Digital twins have significantly impacted various sectors, illustrated through examples like General Electric's use in manufacturing for real-time monitoring and efficiency of jet engines and wind turbines, leading to cost savings and reliability [7]. NASA applies digital twins in aerospace for the Orion spacecraft, enhancing safety and operational efficiency[8]. By employing this method, NASA has been able to replicate and assess the functioning of spacecraft in different situations. In urban planning, Singapore's Virtual Singapore project uses digital twins for city modelling, improving urban welfare by simulating environmental conditions [7]. This concept aims to utilise this technology to improve the welfare of its inhabitants by simulating flash floods, identifying areas with cellular network coverage, and even identifying sheltered walking routes to offer protection from sudden rain. Healthcare sees the potential for personalized medicine through digital twins, predicting individual responses to treatments. Finally, digital twin technologies have been utilized for the military supply chain (MSC) [9] and in particular in 2010, the United States military introduced digital twin technology for F35 aircraft [10], aiming to decrease maintenance and operational costs. Following this, in 2011, the United States Air Force Research Laboratory adopted digital twin technology for monitoring aircraft health, yielding notable outcomes [11]. These case studies demonstrate the wide-ranging usefulness of digital twins across several industries across the product lifecycle as demonstrated in Figure 2.

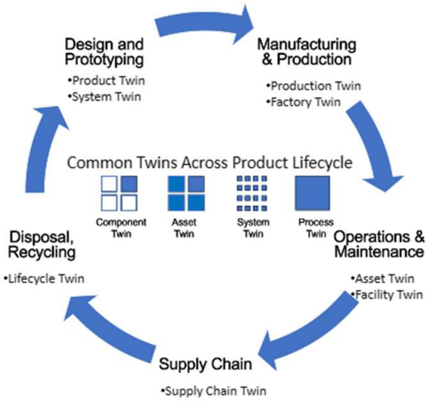

Figure 2-Digital Twins Across Product Lifecycle

2.3.2. Manufacturing and Production

The subsequent stage in the product lifecycle is the production phase. The utilization of digital twins during the production stage of the product lifecycle is varied and has significant effects. [12] highlights the significance of utilizing real-time data and simulation in the development and implementation of shop-floor digital twins. [13] emphasizes the significance of digital twins in promoting sustainable production and maintenance. Their emphasis lies on the capture of data, conversion of knowledge, and improvement of processes. [1] also advocates for further investigation into the utilization of digital twins in both services and product service systems, while also examining the prospects for novel value stream patterns.

2.3.3. Operation and Maintenance

The approach to maintenance has undergone a continuous evolution in recent years, primarily propelled by the increasing availability of technologies that empower companies to forecast the behavior of systems or their components with greater effectiveness [14]. Digital twin technologies emerge as a formidable tool applicable for such system behavior prediction and maintenance action optimization [15]. Through the application of digital twin, it becomes possible to integrate virtual assets with their real-world counterparts. This integration helps enhance asset performance and extend their lifecycle through continuous analysis of data provided by sensors directly connected to the asset's digital twins [16].

Digital twins find application primarily in predictive maintenance (PdM) and prescriptive maintenance strategies (PHM). PdM employs predictive tools to consistently monitor the states of devices or components, thereby proactively identifying potential faults [17]. PHM can be seen as an advancement or complement to PdM; in addition to predicting device/component states, PHM also prescribes action plans [18]. Furthermore, digital twins are used to optimise time-based preventative maintenance to minimize maintenance time and unnecessary activities [15, 19]. In the future, digital twins will also be applied to assist operators in conducting specific maintenance tasks.

2.3.4. Disposal/Recycling

The final phase of product lifecycle management is the recovery process for products. To effectively manage the increasing waste streams, recycling is considered as a crucial measure [20]. The goal of recycling industry is to improve the recovery of valuable components and materials from end-of-life products, thereby extending the lifespan of material resources and protecting the environment [21]. Although the integration of digital twins within the recycling industry is still in its initial stages, certain digital twin-based systems are employed to facilitate product recovery, thereby enhancing remanufacturing operations. More specifically, recyclers can initiate the recycling process informed by the digital status updates provided by users as products reach their end-of-life and end-of-use stages. For instance, a digital twin-based cyber-physical system (CPS) is developed specifically for recycling waste electrical and electronic equipment (WEEE) [22], enabling recyclers to determine the recycling mode and material recycling based on the recorded cloud data within the digital twin-based system.

3. Challenges and Opportunities

3.1. Phases of Product of Lifecycle

3.1.1. Design and Prototyping

Developing and applying digital twins over the lifespan of a product involves complex issues that encompass technological, organisational, and operational aspects. To properly tackle these challenges, an interdisciplinary strategy is necessary. One of the main challenges is effectively handling the large amounts of data required to precisely replicate physical systems in real-time [23]. This entails sophisticated procedures of gathering, analysing, storing, and verifying the quality and timeliness of the data. Incorporating digital twins into current outdated systems poses a notable challenge, necessitating considerable exertion and financial resources to ensure compatibility and smooth operation. Moreover, the lack of interoperability worsens problems related to the ability of distinct digital twin platforms and their physical equivalents to work together and exchange data [24]. This hinders the ability to scale up and apply these technologies across different industries. The importance of privacy and cybersecurity is of utmost significance, considering the dependence on sensitive and exclusive information. This requires the implementation of strong security measures to protect against unauthorised access and cyber risks [4].

3.1.2. Operation and Maintenance

During product usage, managing and integrating vast amounts of real-time data from multiple products into a digital twin is challenging [13]. The ability to rapidly interpret data, predict maintenance needs and execute maintenance strategies within a digital twin can become challenging to design and implement. This is alongside ensuring data security, and timeliness for the digital twin to mirror the physical products real-time state. The second challenge concerns the accuracy/ transparency of the digital twin, particularly as the physical product experiences wear and tear. Maintaining the digital twin's accuracy to reflect the physical product's rate of degradation is essential [12]. [25] emphasizes the importance of geometric accuracy and the need for a clear definition of this in the context of digital twins, particularly for structural health monitoring. Monitoring and tracking the condition of multiple products in use across entire facilities necessitates substantial resources for each product, leading to scalability issues. Ensuring the scalability of digital twin frameworks for various products requires a flexible and effective data architecture. [26] emphasises the challenges of expanding customised digital twin solutions, especially within the framework of operational value chains.

3.1.3. Recycling/Disposal

The current challenges of implementing digital twins in the recycling sector include two main aspects. Firstly, digital twin-based recycling systems face issues related to information security and privacy. This challenge could lead to the leakage of sensitive corporate and customer data [27]. Therefore, finding feasible solutions to safeguard data-sharing processes across enterprises within the reverse supply chain and ensuring customer information privacy is necessary. Secondly, the potential demand and willingness of enterprises in the recycling industry to adopt digital twins-based system remain ambiguous to researchers and potential developers [28]. It is crucial to understand the demand for information sharing to foster the rational application of digital twins-based systems for end-of-life products. In conclusion, current research related to digital twins-based recycling system is not systematic and leans towards being overly theoretical. Thus, there is a pressing need for more practical applications to address these challenges beyond just theoretical constructs.

3.2. Quality Assurance Challenges in Digital Twins

Digital twin development and utilisation present numerous quality assurance challenges that must be approached differently based on the specific circumstances. Without standardised quality assurance procedures, validating data across many businesses is challenging [29]. An important research obstacle in digital twins is creating techniques for evaluating data quality to guarantee the robustness of digital twins against misleading anomalies, while properly depicting significant rare occurrences [23]. The primary problem is anomaly detection, particularly in identifying outlier data caused by sensor breakdowns and ensuring that the digital twin disregards it. [30] discusses the concept of digital twin for geometry assurance, states that data quality is very important, and devises a mathematical equation to measure deviation and measurement error to consider any sensor outliers. This contributes to another difficulty in creating two-way feedback systems between the physical and virtual realms [23]. Technical difficulties, such the absence of standardised data and models, are especially worrisome [31]. Non-technical challenges, such as a shortage of expertise and professionals, make implementation more complex [32].

3.3. Existing Quality Assurance Approaches

There are a range of standards for specific industries on Quality Assurance for digital twins as seen below:

Manufacturing: ISO 9001 is a widely recognized standard within the manufacturing industry, which is among the first sectors to adopt digital twin technologies. In manufacturing, the standardization of digital twins aims to guarantee interoperability [33]. Efforts have been made to establish a unified framework for digital twins in this sector, including initiatives like the Platform Industry 4.0 and the Industrial Internet Consortium, which seek to facilitate this integration [34].

Aerospace and Defense: Digital twins can be utilized for predictive maintenance of the aircraft. The most common standard used is AS9100 within the aerospace sector which incorporates requirements for quality assurance systems along with the use of digital twins for design, testing and maintaining aircraft components. However, the Aerospace & Defence PLM Action Group is specifically focusing on developing digital twin standards within the aerospace sector, with an emphasis on ensuring the reliability of safety-critical systems [6].

Automotive: IATF 16949 is an automobile Quality Management System (QMS) standard that enhances ISO 9001 by including specific standards for the automobile industry. The approach emphasises ongoing enhancement, fault avoidance, and minimising variance and waste in the supply chain. IATF 16949 guarantees systematic management and control of the procedures for developing, validating, and using digital twins.

Healthcare: Digital twins in healthcare are utilized to simulate patient conditions, enhancing personalized care strategies [33]. ISO 13485 represents a standard focused on a Quality Management System (QMS) specifically designed for the development and manufacture of medical devices [35]. Additionally, there have been initiatives to establish standards for healthcare information exchange, notably through Health Level Seven International (HL7) [36].

Power Systems: Within the power systems sector, standards for digital twins are currently lacking. However, the International Organization for Standardization (ISO) has established ISO 23247 for digital twins' application in production. This standard facilitates the development of observable manufacturing digital twins by mandating regular updates on data related to employees, equipment, materials, manufacturing processes, facilities, and the environment. It's important to note that this framework does not specify data formats or communication protocols [37].

Supply Chain: Industry-specific quality standards are crucial for effective quality assurance in global supply chains [38], and the application of digital twin concepts in supply chains can offer benefits such as operational control, replicability, and efficiency [39]. The potential of digital twins to optimize operations and supply chain management functions is a growing area of research [40].

4. Frameworks and Standards

Various frameworks and standards have been created for digital twin technologies. [41] and [42] emphasise the significance of standardisation in digital twin structures, particularly focusing on the ISO 23247 standard for digital twins in the industrial sector, however this standard is not completely followed in practice. [43] presents conceptual models for digital twins in the context of cyber-physical systems and Industry 4.0 shipbuilding, respectively. [44] develops a framework that aims to guarantee the seamless flow and tracking of information by integrating behavioral simulation and physical control components. This framework encompasses guidelines for organisational architecture, security measures, user access, databases, and software requirements. [45] highlights the need of technical standards to facilitate the compatibility of digital twins and examines ongoing efforts in standardisation. In [46], the authors define the shared characteristics of a digital twin and establish a connection between these characteristics. Additionally, the authors introduce a new framework called the Feature-based Categorization and Development Guidance Framework (FPTF) to classify and provide guidance for the creation of digital twins based on these characteristics. The framework seeks to streamline preexisting concepts and phenomena, rather than introducing novel intricacies.

4.1. Requirements for a standardised quality assurance framework

The main challenges for designing and maintaining the digital twin solutions across the product lifecycle are establishing standardized procedures across businesses, a two-way feedback system between cyber and physical worlds, shortage of experts and professionals, managing-analysing-storing large volume of data, developing trust in concept and among stakeholders. To ensure digital twin models used across product lifecycle are of high fidelity for high-consequence decision-making the following requirements need to be fulfilled in order as depicted in Figure 3.

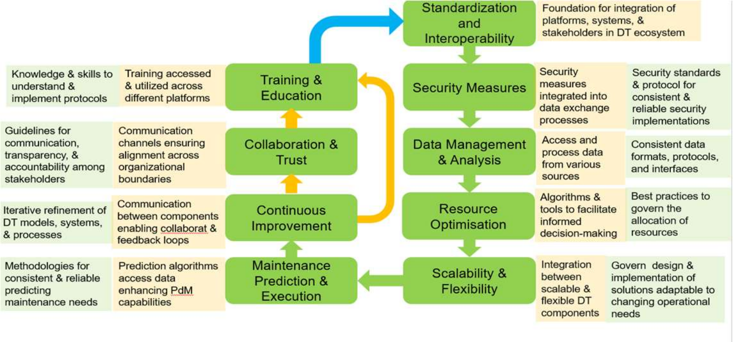

Figure 3. Requirements for standardised quality assurance framework

Standardization and Interoperability. Develop standardized procedures that can be universally adopted across businesses. Ensure interoperability between digital twin platforms and physical systems to facilitate seamless data exchange [47].

Data Management and Analysis. Implement robust data gathering, analysis, storage, and verification mechanisms to ensure the quality and timeliness of data used in digital twin models [48].

Security Measures. Incorporate strong security measures, including encryption and AI-supported cybersecurity protocols, to address privacy and cybersecurity concerns associated with handling sensitive data in digital twin environments [49].

Resource Optimization. Develop ROI models to justify investments in digital twin technologies, considering the trade-offs between accuracy requirements and computational resources, as well as economic constraints [50].

Training and Education. Address the disparity in skills by providing specific training programs for professionals working with digital twin technologies. This includes interdisciplinary training to bridge the gap between domain expertise and technical knowledge required [51].

Scalability and Flexibility. Ensure that digital twin solutions are scalable to monitor multiple products and can adapt to changing operational needs. This involves designing flexible data architectures and maintenance strategies that can accommodate future growth and technological advancements [52].

Maintenance Prediction and Execution. Develop algorithms and predictive analytics capabilities to rapidly interpret data, predict maintenance needs, and execute maintenance strategies in real-time. This includes integrating digital twin solutions throughout the operations value chain to improve accuracy and transparency in maintenance processes [53].

Continuous Improvement. Establish a two-way feedback system between the physical and virtual worlds to continuously improve digital twin models based on real-world performance data. This involves leveraging cloud-based manufacturing solutions and incorporating feedback loops into digital twin platforms [54].

Collaboration and Trust. Foster trust and collaboration among stakeholders by demonstrating the reliability and effectiveness of digital twin technologies through rigorous testing, validation, and transparent communication of results [55].

5. Future Directions

Emerging technologies are playing a vital role in the implementation of digital twins, enhancing various levels of digital twins with the advancements in artificial intelligence, internet of things, big data, and more. The integration of these technologies into digital twins represents a transformative shift in how industries can monitor, diagnostic, predict, and enhance product performance of across their entire lifecycle, moving beyond a focus on any single stage of a product's life. More specifically, the progression in sensor technology and IoT, including barcodes, QR codes, and RFID, allows for the collection and sharing of vast amounts of real-time data from the physical to the digital worlds [56]. AI algorithms offer sophisticated data analysis techniques to process these data and information, enabling a deep understanding of product lifecycle stages, rapid defect detection, personalized solutions, enhanced decision support, and superior integration and interoperability [57].

The integration of technologies such as AR, VR, and mixed reality (MR) with digital twins could be set to revolutionize immersive visualization and simulation, offering more engaging and intuitive virtual replicas of physical assets and enabling complex system and process simulations [58]. In addition, the evolution of digital twins is expected to incorporate more advanced AI techniques that learn and adapt with their corresponding assets, paving the way for recommendations on sustainable product design, manufacturing, operations, maintenance, and recycling, while minimizing environmental footprints. As digital twins technology grows in popularity and maturity, establishing industry standards and security protocols becomes imperative. Although efforts towards standardization of emerging technologies are underway by the joint advisory group of ISO and IEC [59], specific standards and security frameworks for the technical aspects of digital twins remain undeveloped.

6. Conclusions

Digital twins represent a groundbreaking advancement with immense potential to revolutionize industries across various sectors. Through our exploration of the abstract, literature review, challenges, standards and frameworks, and future directions, it is evident that while digital twins offer unprecedented opportunities for efficiency enhancement and innovation, their widespread adoption faces significant hurdles. These challenges range from technological complexities to organizational barriers and regulatory concerns. However, by establishing standardized quality assurance approaches and leveraging emerging technologies, such as AI, IoT, and AR/VR, we can overcome these obstacles and unlock the full potential of digital twins. Moving forward, collaboration among industry stakeholders, regulatory bodies, and research communities will be essential to drive the development and adoption of standardized frameworks for digital twins across the product lifecycle. With continued efforts and advancements in this field, digital twins are poised to play a pivotal role in shaping the future of industries worldwide.

References

[1] Zhang H, Ma L, Sun J, Lin H, Thürer M. Digital Twin in Services and Industrial Product Service Systems:: Review and Analysis. Procedia CIRP. 2019;83:57-60.

[2] Zhuang C, Miao T, Liu J, Xiong H. The connotation of digital twin, and the construction and application method of shop-floor digital twin. Robot Comput-Integr Manuf. 2021;68:102075.

[3] Grieves M. Origins of the Digital Twin Concept2016.

[4] Fuller A, Fan Z, Day C, Barlow C. Digital Twin: Enabling Technologies, Challenges and Open Research. IEEE Access. 2020;PP:1-.

[5] Bariah L, Debbah M. The Interplay of AI and Digital Twin: Bridging the Gap between Data-Driven and Model-Driven Approaches. IEEE Wireless Communications. 2024:1-7.

[6] Xu L, Xu E, Li L. Industry 4.0: State of the art and future trends. International Journal of Production Research. 2018;56:1-22.

[7] Fukawa N, Rindfleisch A. Enhancing innovation via the digital twin. 2023;40(4):391-406.

[8] Pierce JH, J ; Hill, T. Orion SysML Model, Digital Twin, and Lessons Learned for Artemis I. 33rd Annual INCOSE International Symposium; Honolulu, HI2023.

[9] Sani S, Schaefer D, Milisavljevic-Syed J. Utilising Digital Twins for Increasing Military Supply Chain Visibility. 2022.

[10] Yao J-F, Yang Y, Wang X-C, Zhang X-P. Systematic review of digital twin technology and applications. Visual Computing for Industry,

Biomedicine, and Art. 2023;6(1):10.
[11] Glaessgen E, Stargel D. The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference. Structures, Structural Dynamics, and Materials and Co-located Conferences: American Institute of Aeronautics and Astronautics; 2012.
[12] Schützer K, Bertazzi JdA, Sallati C, Anderl R, Zancul E. Contribution to the development of a Digital Twin based on product lifecycle to support the manufacturing process. Procedia CIRP. 2019;84:82-7.
[13] Rojek I, Mikołajewski D, Dostatni E. Digital Twins in Product Lifecycle for Sustainability in Manufacturing and Maintenance. Applied Sciences. 2020;11:31.
[14] Abbate R, Caterino M, Fera M, Caputo F. Maintenance Digital Twin using vibration data. Procedia Computer Science. 2022;200:546-55.
[15] Rabah S, Assila A, Khouri E, Maier F, Ababsa F, bourny V, et al. Towards improving the future of manufacturing through digital twin and augmented reality technologies. Procedia Manufacturing. 2018;17:460-7.
[16] Qi Q, Tao F. Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. IEEE Access. 2018;6:3585-93.
[17] Li J, Schaefer D, Milisavljevic-Syed J. A Decision-Based Framework for Predictive Maintenance Technique Selection in Industry 4.0. Procedia CIRP. 2022;107:77-82.
[18] Consilvio A, Sanetti P, Anguìta D, Crovetto C, Dambra C, Oneto L, et al., editors. Prescriptive Maintenance of Railway Infrastructure: From Data Analytics to Decision Support. 2019 6th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS); 2019 5-7 June 2019.
[19] Luo W, Hu T, Zhu W, Tao F, editors. Digital twin modeling method for CNC machine tool. 2018 IEEE 15th International Conference on Networking, Sensing and Control (ICNSC); 2018 27-29 March 2018.
[20] Sun X, Yu H, Solvang W. A Digital Reverse Logistics Twin for Improving Sustainability in Industry 5.0. 2023. p. 273-86.
[21] Xia H, Han J, Milisavljevic-Syed J. Forecasting the Number of End-of-Life Vehicles: State of the Art Report. Proceedings of the Design Society. 2022;2:1169-78.
[22] Wang X, Wang L. Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0. International Journal of Production Research. 2019;57:3892-902.
[23] Engineering NAo, National Academies of Sciences E, Medicine. Opportunities and Challenges for Digital Twins in Engineering: Proceedings of a Workshop—in Brief. Casola L, editor. Washington, DC: The National Academies Press; 2023. 13 p.
[24] Schmidt C, Volz F, Stojanovic L, Sutschet G. Increasing Interoperability between Digital Twin Standards and Specifications: Transformation of DTDL to AAS. 2023;23(18):7742.
[25] Kunzer BE, Berges ME, Dubrawski AJA. The Digital Twin Landscape at the Crossroads of Predictive Maintenance, Machine Learning and Physics Based Modeling. 2022;abs/2206.10462.
[26] Werner R, Takacs R, Geier D, Becker T, Weissenberg N, Haße H, et al. The Challenge of Implementing Digital Twins in Operating Value Chains. 1772020.
[27] Prabhu V, Oyekan J, Eng S, Woei LE, Tiwari A. Towards data-driven cyber attack damage and vulnerability estimation for manufacturing enterprises2018.
[28] Chen Z, Huang L. Digital twins for information-sharing in remanufacturing supply chain: A review. Energy. 2020;220:119712.
[29] VanDerHorn E, Mahadevan S. Digital Twin: Generalization, characterization and implementation. Decis Support Syst. 2021;145:113524.
[30] Wärmefjord K, Söderberg R, Lindkvist L, Lindau B, Carlson J. Inspection Data to Support a Digital Twin for Geometry Assurance2017. V002T02A101 p.
[31] Trauer J, Mutschler M, Mörtl M, Zimmermann M. Challenges in Implementing Digital Twins – a Survey2022.
[32] Trauer J, Schweigert-Recksiek S, Schenk T, Baudisch T, Mörtl M, Zimmermann M. A Digital Twin Trust Framework for Industrial Application. Proceedings of the Design Society. 2022;2:293-302.
[33] Khan TH, Noh C, Han S. Correspondence measure: a review for the digital twin standardization. The International Journal of Advanced Manufacturing Technology. 2023;128(5):1907-27.
[34] Yli-Ojanperä M, Sierla S, Papakonstantinou N, Vyatkin V. Adapting an Agile Manufacturing Concept to the Reference Architecture Model Industry 4.0: a survey and case study. Journal of Industrial Information Integration. 2018;15.
[35] Kheir O, Smedts S, Jacoby A, Verwulgen S. Efficient Quality Management in MedTech Start-Ups (Based on ISO 13485). Medical devices (Auckland, NZ). 2021;14:313-9.
[36] Dolin RH, Alschuler L, Beebe C, Biron PV, Boyer SL, Essin D, et al. The HL7 Clinical Document Architecture. Journal of the American Medical Informatics Association : JAMIA. 2001;8(6):552-69.
[37] Yassin MAM, Shrestha A, Rabie S. Digital twin in power system research and development: Principle, scope, and challenges. Energy Reviews. 2023;2(3):100039.
[38] Bandyopadhyay JKJTIJoM. A Model Framework for Developing Industry Specific Quality Standards for Effective Quality Assurance in Global Supply Chains in the New Millennium. 2005;22:294.
[39] Srai J, Settanni E, Tsolakis N, Aulakh P. Supply Chain Digital Twins: Opportunities and Challenges Beyond the Hype2019.
[40] Bhandal R, Meriton R, Kavanagh RE, Brown A. The application of digital twin technology in operations and supply chain management: a bibliometric review. Supply Chain Management: An International Journal. 2022;27(2):182-206.
[41] Ferko E, Bucaioni A, Pelliccione P, Behnam M, editors. Standardisation in Digital Twin Architectures in Manufacturing. 2023 IEEE 20th International Conference on Software Architecture (ICSA); 2023 13-17 March 2023.
[42] Shao G, Helu M. Framework for a digital twin in manufacturing: Scope and requirements. Manufacturing Letters. 2020;24:105-7.
[43] Josifovska K, Yigitbas E, Engels G, editors. Reference Framework for Digital Twins within Cyber-Physical Systems. 2019 IEEE/ACM 5th International Workshop on Software Engineering for Smart Cyber-Physical Systems (SEsCPS); 2019 28-28 May 2019.
[44] Pang TY, Pelaez Restrepo JD, Cheng C-T, Yasin A, Lim H, Miletić MJAS. Developing a Digital Twin and Digital Thread Framework for an 'Industry 4.0' Shipyard. 2020.
[45] Wang K, Wang Y, Li Y, Fan X, Xiao S, Hu L. A review of the technology standards for enabling digital twin [version 1; peer review: awaiting peer review] Digital Twin. Digital Twin. 2022;2.
[46] Autiosalo J, Vepsäläinen J, Viitala R, Tammi K. A Feature-Based Framework for Structuring Industrial Digital Twins. IEEE Access. 2019;PP:1-.
[47] Vincenzo F, Naser A, Maya R, Morris KC, editors. Adapting Digital Twin Frameworks Toward Lean Manufacturing for the Circular Economy2023 2023-11-21 05:11:00: The 2023 ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Boston, MA, US; The 2023 ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Boston, MA, US.
[48] Batini C, Cappiello C, Francalanci C, Maurino A. Methodologies for data quality assessment and improvement. 2009;41(3 %J ACM Comput. Surv.):Article 16.
[49] Brooks CJ, Grow C, Craig PA, Short D. Cybersecurity Essentials: Wiley; 2018.
[50] Tao F, Sui F, Liu A, Qi Q, Zhang M, Song B, et al. Digital twin-driven product design framework. International Journal of Production Research. 2019;57(12):3935-53.
[51] Longo F, Padovano A, De Felice F, Petrillo A, Elbasheer M. From "prepare for the unknown" to "train for what's coming": A digital twin-driven and cognitive training approach for the workforce of the future in smart factories. Journal of Industrial Information Integration. 2023;32:100437.
[52] Jiang Z, Guo Y, Wang Z. Digital Twin to Improve the Virtual-Real Integration of Industrial IoT. Journal of Industrial Information Integration. 2021;22:100196.
[53] Aivaliotis P, Georgoulias K, Chryssolouris G. The use of Digital Twin for predictive maintenance in manufacturing. Int J Comput Integr Manuf. 2019;32.
[54] Wang P, Luo M. A digital twin-based big data virtual and real fusion learning reference framework supported by industrial internet towards smart manufacturing. Journal of Manufacturing Systems. 2021;58:16-32.
[55] Korotkova N, Benders J, Mikalef P, Cameron D. Maneuvering between skepticism and optimism about hyped technologies: Building trust in digital twins. Inf Manage. 2023;60(4):103787.
[56] Hu W, Zhang T, Deng X, Liu Z, Tan J. Digital twin: a state-of-the-art review of its enabling technologies, applications and challenges. Journal of Intelligent Manufacturing and Special Equipment. 2021;2:1-34.
[57] Kaur M, Mishra VP, Maheshwari P. The Convergence of Digital Twin, IoT, and Machine Learning: Transforming Data into Action. 2020. p. 3-17.
[58] Tang YM, Kuo W-T, Lee C. Real-time Mixed Reality (MR) and Artificial Intelligence (AI) Object Recognition Integration for Digital Twin in Industry 4.0. Internet of Things. 2023;23:100753.
[59] Rathore MM, Shah S, Shukla D, Bentafat E, Bakiras S. The Role of AI, Machine Learning, and Big Data in Digital Twinning: A Systematic Literature Review, Challenges, and Opportunities. IEEE Access. 2021;PP:1-.