

# Computer vision-enabled Digital Twins: an exploratory literature review and research opportunities

**Gabriel Rodrigues Santos (Escola Politécnica da Universidade de São Paulo)**

**Syed Nasir Shah (Escola Politécnica da Universidade de São Paulo)**

**Haroon Jan Khan (Escola Politécnica da Universidade de São Paulo)**

**Maurício Barbosa de Camargo Salles (Escola Politécnica da Universidade de São Paulo)**

**Eduardo de Senzi Zancul (Escola Politécnica da Universidade de São Paulo)**



*Digital Twins (DTs) have emerged as a transformative technology in the context of Industry 4.0, offering a dynamic bridge between the physical and digital realms. Conversely, applications of Computer Vision (CV) have been increasingly adopted in industrial and manufacturing processes. CV technologies may enhance DT systems by enabling automated quality control, efficient object detection, and dynamic process validation. However, despite their potential, the integrated, real-world implementation of those technologies remains limited due to challenges in architecture, integration, and scalability. This work provides a literature review on computer vision-enabled Digital Twins, providing an overview of the topic's research landscape. A sample of 202 documents was analyzed using bibliometric and content analysis techniques. The yearly evolution in publications, as well as the most prominent sources and papers were identified, alongside trending research and development topics. By uniting CV and DT technologies, modern manufacturing environments can achieve higher precision, adaptability, and efficiency. This overview can foster the potentials of the integrated research of DTs and CV, paving the way for developments towards the practical implementation of those technologies.*

*Palavras-chave: Digital Twins, Computer Vision, Industry 4.0, Systematic Literature Review.*

## 1. Introduction

Digital Twins (DTs) have been proposed as a prominent technology to enable greater manufacturing control, quality and functionality in the context of industry 4.0. As manufacturing shifts towards cyber-physical systems (KAGERMANN; WHALSTER; HELBIG, 2013), an increasing usage of advanced information technologies is eminent to enable smart manufacturing (FRANK; DALENOGARE; AYALA, 2019). One key technology being highly explored by industry 4.0 academics and practitioners is the application of Digital Twins (DTs). Digital Twins (DTs) can be conceptualized as digital representations of physical entities, which are highly integrated with their physical counterparts. Exploring the potential of Digital Twins has been recently reviewed by Barricelli, Casiraghi and Fogli (2019), and Tao et al. (2022). It is worth noting that their applications exceed industrial or manufacturing contexts, with active research also in other areas, such as human healthcare. In manufacturing, this technology enables more efficient production management and decision-making, but it is not yet widely deployed in practice.

Concurrently, with increasing digitalization of production processes, Computer Vision (CV) is being increasingly adopted in organizations. Historically, manual inspection has been the standard for quality control in manufacturing, despite being labor-intensive and prone to human error. Digitalized and automated systems utilizing real-time object detection can significantly improve the accuracy and efficiency of these processes, and as such, significant attention has been devoted to developing solutions (both in terms of hardware and software) to enable computer vision-based solutions for product inspection, as well as for other applications across industries, and also within teaching contexts (ZANCUL et al., 2020).

Despite their potential, the integrated treatment of digital twins and computer vision has been comparatively seldom studied by researchers, and is still in its infancy in practical applications. In this scenario, this paper provides an academically-focused systematic literature review on the intersection of Digital Twins and Computer Vision applications. This exploratory research lays out the foundations of the topics, and provides an overview of the current research landscape, as well as future research avenues.

The remainder of this paper is organized as follows: Section 2 reviews the extant literature on DT technologies, computer vision focusing on industrial applications, and also computer vision-enabled digital twins. Section 3 describes the methodology for the research, including sampling and analysis procedures for the review. Section 4 presents the results and a critical discussion, highlighting trends and key research topics. Finally, Section 5 presents the conclusions.

## 2. Background

This section provides a brief overview of the background topics for this research, namely the definition of Digital Twins and Computer Vision (with a focus on industrial applications). For a more in-depth look at the current research on those topics, the reader is referred to the results section, which also highlights promising research avenues stemming from the literature review.

### 2.1 Digital Twins

The idea of the Digital Twin first emerged in the 1960s when NASA proposed the creation of physical models of their space systems on Earth during the Apollo missions (FERGUSON, 2019). These models enabled engineers to replicate different conditions, test system responses, and assess performance. In the early 2000s, Michael Grieves built upon this idea by formally introducing digital twins in the manufacturing industry, promoting virtual models of factories to monitor operations, foresee failures, and improve efficiency (GRIEVES, VICKERS, 2017). Fundamentally, a digital twin creates a real-time, precise connection between a physical entity and its digital equivalent, facilitating seamless integration and analysis (JIANG; GUO; WANG, 2021). The collected data is then utilized to create a digital replica, enabling teams to gain insights and analyze the performance of the corresponding physical object or system (ZIDEK et al., 2020). Given these benefits, many organizations leverage cloud-based digital twin services to simulate and manage their infrastructure assets. Maintaining a digital replica in the cloud empowers businesses to monitor changes, adjust, and enhance performance (BARYKIN et al., 2020).

A detailed exploration of the digital twin concept highlights the importance of its features from both narrow specific applications and a broader perspective encompassing a wide range of functionalities (ZHENG; YANG; CHENG, 2019). To tackle this complexity, different conceptual and reference frameworks have been created to mirror physical systems' behavior, performance, and interactions. These frameworks utilize real-time data, ensure compatibility, and accommodate specific system needs, allowing digital twins to simulate, monitor, and enhance manufacturing, healthcare, and urban planning processes. Grieves and Vickers (2017) further developed the digital twin concept by distinguishing between two types: the Digital Twin Prototype (DTP), which is utilized in the design stage to simulate and assess products, and the Digital Twin Instance (DTI), which stands for the operational physical entity. These advancements underscore the impact of digital twins in connecting the physical and digital worlds, fostering innovation and operational excellence across various sectors. Further

exploration of the digital twin concept led to the development of various conceptual frameworks in recent years (TAO et al., 2019b, 2022).

## 2.2. Computer Vision

The integration of computer vision with real-time object detection marks a new era in quality control, promising enhanced accuracy, speed, and automation. This technology employs advanced algorithms and state-of-the-art hardware, enabling real-time object detection. This involves identifying and locating objects of interest within a live video feed (AHMED; DESAI, 2024). These objects can range from defective components on a production line to integral parts of complex assemblies. By integrating cameras and sensors throughout a production facility, computer vision systems continuously analyze and interpret visual data (GILL et al., 2024). This capability can enable for the immediate detection of quality discrepancies, enabling rapid responses to any arising issues. The ability of these systems to provide real-time alerts and facilitate immediate corrective actions offers a significant competitive advantage, reducing waste and enhancing operational efficiency.

## 3. Methodology

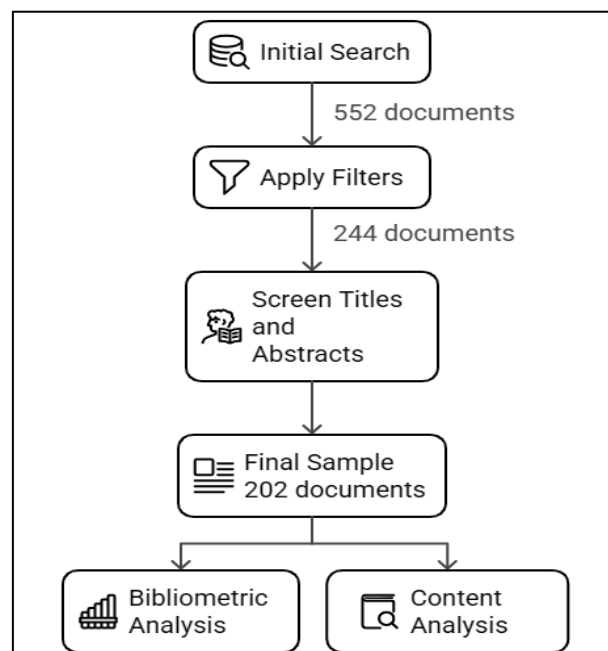
This research was based on the systematic literature review (KITCHENHAM, 2004, 2007), especially to describe the current state of research in the field of computer vision-enabled digital twins. The following search string was applied to the academic database Scopus, including papers published up to May 2025:

*( "digital twin\*" ) AND ( "Computer vision" OR "machine vision" )*

The string was designed to capture results in the intersection of the two key topics of this research, while also including their plural form. The resulting total number of publications was 552. These publications were then filtered according to the following criteria: publications in English, published in academic peer-reviewed journals as articles or reviews. Despite acknowledging the importance of conference papers in the development of novel engineering topics, the search was restricted to journals to provide a more comprehensive and rigorous grounding to the review, focusing on overarching topics and trends, and not on specific developments typically reported in conference papers. After applying the filters, the result was a database containing 244 documents.

The full database was exported, and then the titles and abstracts were screened for suitability to the topic. Papers that were not focused on the development of computer vision or digital twin solutions or advancements, especially coupled together, typically in manufacturing, industry 4.0, medical, construction or engineering environments, were excluded from the data. The final sample was a total of 202 papers, which were then analyzed using bibliometric (IKPAAHINDI, 1985) and content analysis techniques, similarly to previous works (e.g. SANTOS et al., 2023). Figure 1 illustrates the methodology for this work.

Figure 1 – Methodology illustration for the literature review



Source: Elaborated by the authors.

## 4. Results and discussion

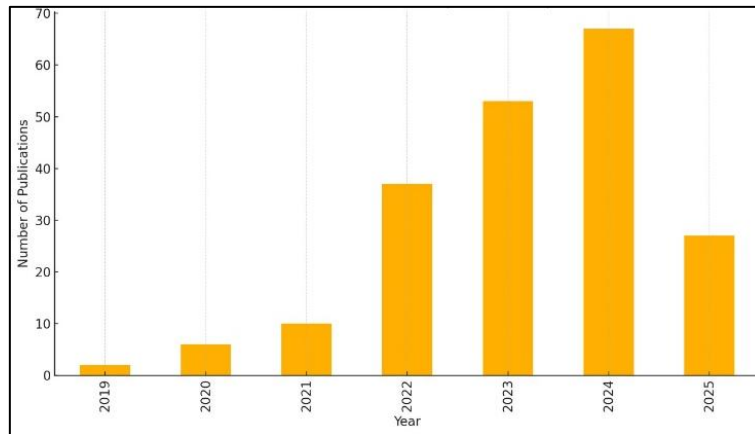
This section presents the results of the review, highlighting key insights and topics. Results of the bibliometric analysis include the yearly evolution of publications and an overview based on citations and references; while the content analysis was used to identify key categories and future research topics.

### 4.1. Evolution of publications

Figure 2 illustrates a pronounced upward trend in publications related to Computer-Vision-enabled Digital Twins from 2019 to 2024. Prior to 2021, the field experienced only modest activity; however, a significant increase commenced in 2022, with a peak in 2024. This growth signifies a rising interest in research and the development of enabling technologies (e.g. Internet of Things (IoT), real time simulation), alongside a growing academic interest in the field. The

decline observed in 2025 can be linked to the incomplete indexing of the full year at the time of review. Overall, this trend underscores the rapid growth and maturation of Computer-Vision-enabled Digital Twins as a dynamic and expanding area of research.

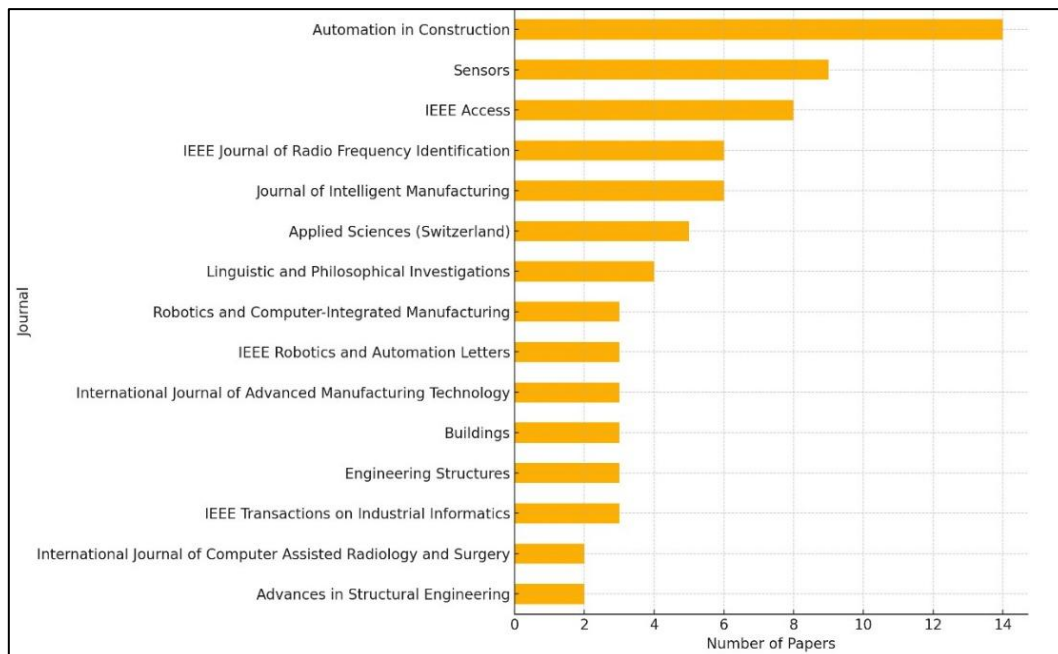
Figure 2 – Yearly evolution of publications (2019-2025)



Source: Elaborated by the authors.

Figure 3 presents the top 15 journals ranked by the number of publications related to Computer-Vision-enabled Digital Twins (CV-DTs) and is discussed afterwards.

Figure 3 – Illustration of Top 15 Journals by number of published papers (2019-2025)



Source: Elaborated by the authors.

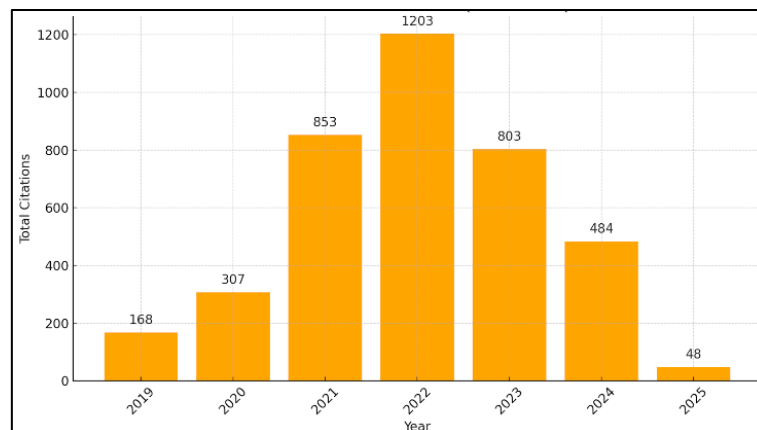
The journal Automation in Construction leads the list, highlighting the significant adoption of CV-DT techniques within the built environment. Journals like Sensors and IEEE Access also rank prominently, reflecting a shift towards publishing in multidisciplinary and open-access

formats. However, the dominance of high-volume, generalist journals raises an important question: Is the growth in this field driven by genuine innovation, or is it merely the result of increased publication output? Many prolific journals show limited correlation with citation impact, suggesting a potential disconnect between publication venues and their scholarly significance. While the rising number of publications signals growing interest, it may also indicate fragmentation or a dilution of research quality. This trend warrants careful consideration in a field like CV-DTs, which still establishes its identity; a high volume of papers does not necessarily guarantee progress in theoretical development or methodological sophistication.

#### 4.2. Most cited documents and topics

The bar chart in Figure 4 illustrates the number of citations from 2019 to 2025, showcasing trends in scholarly interest.

Figure 4 – Accumulated total citations per year.



Source: Elaborated by the authors.

Beginning with 168 citations in 2019, the count increased to 307 in 2020 and surged to 853 in 2021, signaling a growing enthusiasm for the research. The peak occurred in 2022, reaching 1,203 citations and significantly impacting the academic community. However, there was a marked decline in 2023, with citations dropping to 803, and this downward trend continued with only 484 citations in 2024, indicating a diminishing relevance. By 2025, citations plummeted dramatically to just 48, reflecting a considerable reduction in recognition of previous work.

Table 1 highlights the top 10 most cited papers in the sample. A discussion of the key contributions and thematic areas is presented afterwards.

Table 1 - Most cited papers in Computer-Vision-enabled Digital Twin

<b>Paper title</b>	<b>Year</b>	<b>Total citations</b>	<b>Total citations/yr</b>
Roles of artificial intelligence in construction engineering and management: A critical review	2021	712	178.0
Intelligent Small Object Detection for Digital Twin Perception in Industrial Logistics	2022	217	72.3
Agrilora: A digital twin framework for smart agriculture	2020	123	24.6
Sustainable and flexible industrial human machine interface (HMI) for Digital Twin	2019	109	18.2
Computer vision-based construction progress monitoring using deep learning and digital twins	2022	101	33.7
Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues	2022	98	32.7
SmartSteelFactory: A digital twin framework for steel industry 4.0	2023	91	45.5
Applications of digital twins in the built environment: A systematic review	2020	90	18.0
A review on digital twin applications in manufacturing	2021	87	21.8
Digital twin and smart product-service systems: A comprehensive review	2021	84	21.0

Source: Elaborated by the authors.

The most frequently cited work, “Roles of Artificial Intelligence in Construction Engineering and Management” by Pan and Zhang (2021), underscores the significant intersection of artificial intelligence, construction, and digital twins. This trend is echoed in several other highly cited publications. Notably, a considerable proportion of the top-cited papers were published post-2020, reflecting the rapid growth in relevance and adoption within this field.

These papers span a variety of sectors, including industrial logistics, agriculture, manufacturing, and the built environment, demonstrating the broad applicability of CV-DT frameworks. Interestingly, while the papers focus on different domains, they thematically converge around concepts of system integration, real-time perception, and deep learning. This convergence suggests that the most impactful studies push conceptual and technical boundaries, offering novel frameworks or applications across various domains. The high citation counts of these studies highlight their foundational role in shaping the discourse surrounding CV-DTs, providing valuable reference points for future research and development.

### **4.3. Towards Computer Vision-Enabled Digital Twins**

The Digital Twin, introduced as a digital replica of physical systems, thrives on its ability to mirror, predict, and optimize real-world operations using real-time data. Computer Vision adds

to this framework by providing robust mechanisms for data acquisition, image processing, and object recognition, laying the groundwork for intelligent, adaptive systems. When combined with CV, DT systems can extract, analyze, and utilize visual data, promoting improved synchronization and control (TAO et al., 2019a, 2019b).

The synergy between DT and CV is achieved through a combination of real-time image processing and digital simulation. Jakhotiya, Rahul and Chiddarwar (2024) demonstrate this in a pick-and-place system, in which CV detects object coordinates using MATLAB and then simulates them in Tecnomatix Process Simulator for validation; this feedback loop ensures accuracy while minimizing human intervention. Similarly, Tao et al. (2018) present a DT framework that incorporates CV to enhance predictive capabilities in manufacturing processes. Using visual data from IoT sensors and machine learning models, the system achieves advanced levels of operational precision and adaptability (TAO et al., 2019b).

Multiple industrial applications have also been highlighted, including manufacturing, predictive maintenance and infrastructure management. CV-enabled DTs have transformed manufacturing operations by automating repetitive tasks and increasing production accuracy. In collaborative robotics, for example, CV systems identify object positions, whereas DT simulations verify task feasibility prior to execution. This methodology decreases setup times and increases efficiency, as demonstrated in industrial use cases such as assembly line operations (JAKHOTIYA; RAHUL; CHIDDARWAR, 2024). Integrating DT and CV allows for early detection of defects and predictive maintenance. CV-driven DT models can be used to simulate equipment wear and predict failure points, reducing downtime and increasing system reliability. DT-CV systems offer significant benefits for infrastructure monitoring. High-resolution CV techniques have also been used to identify structural anomalies, which were then fed into DT platforms to model repair scenarios and predict future maintenance needs.

#### **4.4. Future research venues**

Based on the literature review and analysis, it was possible to note a few trends and five research areas, especially concerning the application focus of the research. The first category concerns papers that deal with Digital Twins and Computer Vision in the context of construction and civil engineering, and includes journals such as "Automation in Construction", "Buildings" "Advances in Structural Engineering", listed in Figure 3. This includes works that integrate Building Information Modelling (BIM) and Smart Cities, as well as using Digital Twins to improve building design and construction efficiency. Integrative CV-DT frameworks in this

context have also been proposed, such as the recently published by Zhou et al. (2025). The second group of sources include technical works concerning core advanced technologies, such as sensors and instrumentation, in journals such as “Sensors”, and “IEEE Journal of Radio Frequency Identification”. A third group of papers can be grouped in the categories of healthcare and medical sciences. Wearables, improving health condition monitoring and building human digital twins are some of the topics related to this cluster. A fourth group of papers relate to applications in the agricultural sector, including frameworks for precision farming, with applications such as computer vision-based analysis of crops, and real time monitoring of crop health and conditions. Finally, the fifth cluster concerns the research of DT-CV in manufacturing and industrial applications. These include advanced robotics, industrial automation and industrial internet of things (IIoT), with journals such as “Journal of Intelligent Manufacturing”, “Robotics and Computer-Integrated Manufacturing”, and “IEEE Transactions on Industrial Informatics”. Within this cluster, the usage of computer vision within production and assembly processes, as well as for quality inspection are the most prominent.

Highly related to the latter cluster is the research in Industry 4.0 applications and technologies, towards smart manufacturing, smart supply chain, smart products and smart working (FRANK, DALENOGARE, AYALA, 2019), which could be shaped by a bidirectional communication flow enabled by Digital Twins. Effectively applying computer vision in industrial and manufacturing processes has been discussed for some time, but doing so in conjunction with a digital twin application is relatively new. An exploratory prototype developed in this intersection within the context of a learning factory is also subject to a working paper.

## 5. Conclusion

This study provides a current overview of research in Computer Vision-enabled Digital Twins (CV-DTs), highlighting a rapidly expanding field with significant disruptive potential in production engineering. Since 2019, there has been a notable increase in publications, particularly in the construction, manufacturing, and healthcare sectors, indicating a growing interest in integrating digital twins with real-time visual technologies. However, the data also reveals that a high volume of publications does not necessarily correspond to a high scholarly impact, suggesting that the field is still maturing.

Integrating computer vision and digital twins represents a strategic advancement toward innovative production systems. These systems not only replicate physical reality but also learn from it and adapt in real time. To fully realize this potential in a scalable and sustainable manner, progress is needed in several areas, including platform interoperability, standardized

architectures, and robust industrial applications. The future of production relies on more autonomous, connected, and data-driven digital solutions, with CV-DTs positioned as one of the candidate enabling technologies of this transformation.

## REFERENCES

AHMED, Varalakshmi S. Zahid; DESAI, Karishma. Real-time Object Detection in Computer Vision for Quality Control in Industries. *In: 2024 International Conference on Advances in Computing Research on Science Engineering and Technology (ACROSET). Proceedings...* Indore, India: IEEE, 2024.

BARRICELLI, Barbara Rita; CASIRAGHI, Elena; FOGLI, Daniela. A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications, **IEEE Access**, v. 7, pp. 167653-167671, 2019.

BARYKIN, Sergey Yevgenievich; BOCHKAREV, Andrey Aleksandrovich; KALININA, Olga Vladimirovna; YADYKIN, Vladimir Konstantinovich. Concept for a supply chain digital twin. **International Journal of Mathematical, Engineering and Management Sciences**, v. 5, n. 6, pp. 1498-1515, 2020.

JAKHOTIYA, Yash; RAHUL, M. R.; CHIDDARWAR, Shital S. Integrating digital twin and computer vision system for efficient pick-and-place operation using Tecnomatix Process Simulate. **International Journal on Interactive Design and Manufacturing (IJIDeM)**, v. 18, pp. 7429–7443, 2024.

FERGUSON, Stephen. Apollo 13: The First Digital Twin. **Siemens Blogs**, April 14, 2020. Available at: <https://blogs.sw.siemens.com/simcenter/apollo-13-the-first-digital-twin/>. Accessed in: 20 Oct. 2024.

FRANK, Alejandro Germán; DALENOGARE, Lucas Santos; AYALA, Néstor Fabián. Industry 4.0 technologies: Implementation patterns in manufacturing companies. **International Journal of Production Economics**, v. 210, April 2019, p. 15–26, 2019.

GILL, Rupali, SRIVASTAVA, Durgesh; HOODA, Susheela, SINGLA, Chaitanya; CHAUDHARY, Rekha. Unleashing Sustainable Efficiency: The Integration of Computer Vision into Industry 4.0. **Engineering Management Journal**, pp. 1–19, 2024.

GRIEVES, Michael; VICKERS, John. Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. *In: KAHLLEN, Franz-Josef; FLUMERFELT, Shannon; ALVES, Anabela (org.) Transdisciplinary perspectives on complex systems: New findings and approaches*, pp. 85-113, 2017.

IKPAAHINDI, Linus. An overview of bibliometrics: Its measurements, laws and their applications. **Libri**, v. 35, 1985.

JIANG, Zongmin; GUO, Yangming; WANG, Zhuqing. Digital twin to improve the virtual-real integration of industrial IoT. **Journal of Industrial Information Integration**, v. 22, 100196, 2021.

KAGERMANN, Henning; WHALSTER, Wolfgang; HELBIG, Johannes. **Recommendations for implementing the strategic initiative INDUSTRIE 4.0 - Final report of the Industrie 4.0 WG**. Frankfurt: acatech, 2013.

KITCHENHAM, Barbara. **Guidelines for performing Systematic Literature Reviews in Software Engineering**. Keele: Keele University, 2007

KITCHENHAM, Barbara. **Procedures for Performing Systematic Reviews**. Keele: Keele University, 2004.

PAN, Yue; ZHANG, Limao. Roles of Artificial Intelligence in Construction Engineering and Management. **Automation in Construction**, v. 122, p. 103517, 2021.

SANTOS, Gabriel Rodrigues; VISELLI, Bruno Pegoretti; ZANCUL, Eduardo de Senzi; SAMPAIO, Claudio Mueller Prado; CARVALHO, Marly Monteiro de. Megaprojetos: Desafios e Oportunidades de Pesquisa In: **ENEGEP 2023 Encontro Nacional de Engenharia de Produção**, 2023, Fortaleza: ABEPRO, 2023

TAO, Fei; ZHANG, He; LIU, Ang; NEE, A. Y. C. Digital Twin in Industry: State-of-the-Art. **IEEE Transactions on Industrial Informatics**, v. 15, n. 4, p. 2405–2415, 2019a.

TAO, Fei; SUI, Fangyuan; LIU, Ang; QI, Qinglin; ZHANG, Meng; SONG, Boyang; GUO, Zirong; LU, Stephen C.-Y.; NEE, A. Y. C. Digital twin-driven product design framework. **International Journal of Production Research**, v. 57, n.12, pp. 3935–3953, 2019b.

TAO, Fei; XIAO, Bin; QI, Qinglin; CHENG, Jiangfeng; JI, Ping. Digital twin modeling. **Journal of Manufacturing Systems**, v. 64, pp. 372-389, 2022.

ZANCUL, Eduardo. MARTINS, Henrique O. LOPES, Fernando P.; DA SILVA NETO, Fernando A. T. V. Machine Vision applications in a Learning Factory. **Procedia Manufacturing**, v. 45, pp. 516-521, 2020.

ZHENG, Yu, YANG, Sen, CHENG, Huanchong. An application framework of digital twin and its case study. **Journal of ambient intelligence and humanized computing**, v. 10, pp. 1141-1153, 2019.

ZHOU, Xiaoping; LI, Xiang; ZHU, Yingying; MA, Chengxi. Towards building digital twin: A computer vision enabled approach jointly using multi-camera and building information model. **Energy and Buildings**, v. 335, p. 115523, 2025.

ŽIDEK, K.; PITEĽ, J.; ADÁMEK, M.; LAZORÍK, P.; & HOŠOVSKÝ, A. Digital twin of experimental smart manufacturing assembly system for industry 4.0 concept. **Sustainability**, v. 12., n. 9, 2020.