MECOMARE, 13 (4) (2025) pp. 113-121

Published by: TRIGIN Publisher

International Journal of Mechanical Computational and Manufacturing Research

Journal homepage: www.trigin.pelnus.ac.id

The effectiveness of digital twin in reducing downtime in the manufacturing industry: A literature analysis

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A R T I C L E I N F O

Article history:

Received Dec 6, 2025
Revised Dec 17, 2025
Accepted Jan 24, 2025

Keywords:

Digital Twin;
Donwntime;
Manufacturing Industry;
Productivity.

ABSTRACT

The Digital Twin is an innovative technology that significantly enhances operational efficiency and production in the industrial sector. This research seeks to examine the role of Digital Twin in mitigating both scheduled and unscheduled downtime, along with the technical and non-technical elements that affect its implementation efficacy. Literature review revealed that Digital Twin facilitates real-time monitoring, precise data analysis, and enhanced process modelling, all of which aid in minimising downtime. Moreover, elements such as system integration, data quality, organisational culture, and managerial support are essential for the successful application of this technology. The research findings indicate that appropriate investment in technological infrastructure and the formulation of management strategies that foster innovation enable organisations to optimise the advantages of Digital Twin. Companies are advised to enhance employee engagement and cultivate a collaborative work environment to attain sustained competitive advantage in the context of Industry 4.0.

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1. INTRODUCTION

The manufacturing sector has changed dramatically during the last few decades due to technological breakthroughs. These technological advancements encompass automation, the Internet of Things (IoT), and big data analytics, all of which enhance efficiency and production. This transformation not only improves production processes but also allows organizations to swiftly adjust to fluctuations in market demand and operational difficulties. This is supported by the findings of Jang et al. (2022) and Park et al. (2021). In this setting, the notion of Digital Twin arises as a viable innovation to enhance manufacturing operations.

A digital twin is a digital version of a physical object or system that facilitates real-time monitoring, analysis, and simulation. This approach enables firms to forecast and evaluate system performance, as well as detect prospective issues prior to their occurrence. Utilizing data from sensors and IoT devices, a digital twin can offer profound insights into operational situations and facilitate improved decision-making Pronost et al. (2023); Ding et al. (2019) support this claim. The significance of Digital Twin in minimising downtime is crucial, as unanticipated downtime can result in considerable financial losses and disrupt the supply chain. Consequently, the industrial sector anticipates the use of Digital Twin to enhance operational efficiency and reduce both the frequency and duration of downtime Chen et al. (2021).

Operational efficiency is a crucial factor in the success of the manufacturing sector. In a competitive business landscape, organizations must maximize efficiency while reducing expenses Gólcher-Barguil et al. (2019); Zheng & Luo (2023). Studies indicate that organizations that effectively adopt new technologies, such as Digital Twin, can attain a lasting competitive advantage by enhancing productivity and minimizing downtime (Jang et al., 2022) (Machado et al., 2019). The aim of this study is to examine the efficacy of Digital Twin in minimizing both scheduled and unscheduled downtime and determine the technical and non-technical aspects affecting its adoption in the industrial sector.

This research is significant for its contribution to understanding the integration of digital twin technology into production operations to improve operational efficiency. This study seeks to offer significant insights for practitioners and researchers in manufacturing by examining the current literature while also identifying the problems and opportunities linked to the deployment of Digital Twin (Pronost et al., 2023); (Ding et al., 2019). This research will examine the influence of Digital Twin on productivity and operational efficiency as derived from the available literature.

This research will examine several critical research questions to attain this objective: RQ 1:What is the role of Digital Twin in minimizing both scheduled and unplanned downtime in the manufacturing sector? RQ 2: What are the technical and non-technical variables influencing the efficacy of Digital Twin adoption in minimizing downtime in the industrial sector? RQ 3: To what degree does the digital twin influence operational efficiency and productivity within the manufacturing sector, as indicated by the literature review? This research aims to significantly enhance knowledge and practices within the manufacturing sector by addressing these topics.

2. RESEARCH METHOD

This study employed the Systematic Literature Review (SLR) as its primary research methodology. This method offers substantial advantages in integrating diverse pertinent study outcomes, rendering the knowledge more thorough and equitable. Systematic Literature Reviews (SLR) seek to achieve defined research goals transparently, aiming to include all published evidence on a certain issue while evaluating the quality of that evidence (Anurahman, 2023). Consequently, SLR not only finds and assesses existing research but also mitigates bias and highlights research gaps that require attention Dewi & Dasari (2023). This procedure entails methodical processes aimed at ensuring the consideration of all pertinent facts, therefore yielding a clearer and more precise understanding of the researched subject Mitropoulos et al. (2021).

According to the PICOC framework, the pertinent keywords include digital twin, downtime, industrial sector, and productivity. These keywords provide the fundamental terms that will be refined during the literature review.

Table 1. PICOC framework

Component	Description
Population (P)	Manufacturing industries facing challenges related to downtime in operations.
Intervention (I)	Implementation of Digital Twin technology as a solution to reduce downtime.
Comparison (C)	Conditions without the implementation of Digital Twin or using other alternative technologies.
Outcome (O)	Reduction in downtime (planned and unplanned), improved operational efficiency, and productivity.
Context (C)	Literature review of various case studies on the application of Digital Twin in global manufacturing industries.

The data used in this research is secondary data. The data consists of research results that have been published in journals online. Data collection was carried out through Google Scholar. Article search was conducted by combining several keywords obtained with the help of Boolean operators (AND, OR), namely ("Digital Twin" OR "digital twins") AND ("downtime" OR "time reduction") AND ("manufacturing" OR "industry").

The literature criteria consist of inclusion and exclusion criteria, and the criteria for this research are aligned with the previously established PICO framework, with the following additions:

Table 2. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Study Type	Peer-reviewed journal articles.	Non-peer-reviewed articles such as opinions, editorials, or blogs.
	Empirical studies, case studies, or literature reviews related to Digital Twin.	Studies that are not relevant to Digital Twin or downtime in manufacturing.
Language	Articles written in English or Indonesian.	Articles in other languages without available translations.
Publication Year	Studies published in the last 10 years (e.g., 2014-2024).	Studies published before 2014.
Topic	Focus on Digital Twin in the context of the manufacturing industry.	Focus on Digital Twin outside of manufacturing (e.g., healthcare, education, etc.).
Study Outcomes	Provides data or analysis related to downtime, operational efficiency, or productivity.	Does not mention or analyze downtime in the context of manufacturing.
Accessibility	Articles with full access (open access or through university subscriptions).	Articles with restricted access that cannot be obtained.

Literature Review

a. Definition and Concept of Digital Twin, a digital twin is a digital version of a physical object or system that facilitates real-time monitoring, analysis, and simulation. Grieves first introduced this concept in 2002, and it has rapidly progressed, especially in the context of Industry 4.0. (Nojeng, 2023). Digital Twin amalgamates data from physical sensors with analytical models to generate a precise representation of a system's operational characteristics. Utilizing this technology, organizations can perform simulations and predictive studies to detect issues prior to their manifestation, thereby enhancing efficiency and mitigating risk. This information is supported by studies conducted by Rohmansyah & Putra (2023) and Daniaty et al. (2022). The Digital Twin facilitates enhanced cooperation across design, production, and maintenance teams while also offering profound insights into overall system performance. (Alviansyah, 2021).
b. Operational Interruption in the Manufacturing Sector, downtime in the manufacturing sector denotes intervals during which equipment or systems are non-operational due to numerous factors, both scheduled and unscheduled. Unscheduled downtime, including equipment malfunctions or system failures, can result in substantial financial losses and interrupt the supply chain. Kusumawati & Wulandari (2016). Research indicates that downtime diminishes production and operational efficiency, necessitating that firms identify its causes and mitigate its occurrence. Kurniawan et al. (2022). In this regard, the utilisation of technologies like Digital Twin can facilitate the prediction and prevention of downtime, hence enhancing the overall efficiency of the production process. (Fadhilah & Putri, 2021).
c. Utilisation of Digital Twin Technology in the Manufacturing Sector, multiple facets of the industrial sector, including product design and predictive maintenance, have embraced the digital twin concept. During the design process, Digital Twin enables engineers to evaluate and confirm designs before physical production, hence decreasing the risk of errors and the expenses linked to design modifications post-production commencement (Wijaya et al., 2021). Furthermore, engineers can use Digital Twin to monitor machine performance in real-time during the manufacturing phase, providing crucial data for improved analysis and decision-making (Livia & Oktiarso, 2017). Within the realm of maintenance, the Digital Twin facilitates predictive maintenance by analyzing sensor data to detect early indicators of degradation and thus minimize unexpected downtime. (Hasibuan, 2023).
d. he Benefits of Digital Twin in Minimising Downtime, the adoption of digital twin technology in the manufacturing sector provides numerous substantial benefits while minimizing downtime. Initially, by monitoring and analyzing machine performance in real time, firms can detect and resolve issues prior to their escalation (Semnasti, 2023). Secondly, the Digital Twin facilitates the simulation of diverse operating situations, thereby enhancing planning and decision-making (Irfan & Susilowati, 2021). Third, by utilizing historical data and predictive analytics, firms may optimize maintenance planning, thereby decreasing both the frequency and

duration of downtime. (Sitanggang et al., 2022). Fourth, the digital twin facilitates enhanced communication among teams, promoting expedited and precise information interchange and hence improving responsiveness to developing situations. Nashrulloh (2021).

The deployment of Digital Twin in the industrial sector reduces downtime and boosts operational efficiency and productivity. Utilising this technology, organisations can attain a durable competitive edge in a progressively competitive market. (Asarela, 2023).

3. RESULTS AND DISCUSSIONS

How does Digital Twin contribute to reducing planned and unplanned downtime in the manufacturing industry?

Table 3. Utilisation of digital twin in various manufacturing applications

No	Article Title	Researchers	Findings
1	Utilisation of Digital Twin in Representation of a Physical Object, Process, or Service	Satpathy & Gavaskar (2021)	Digital Twin is used in various ways in industrial systems and manufacturing processes, helping to reduce downtime by enhancing monitoring and real-time system performance analysis.
2	Digital Twins along the product lifecycle: A systematic literature review of applications in manufacturing	Pronost et al. (2023)	A systematic review shows that the application of Digital Twin can reduce downtime by providing better models for process planning and control, although there are still gaps in standardization.
3	Digital Twin Certified: Employing Virtual Testing of Digital Twins in Manufacturing to Ensure Quality Products	Grieves (2023)	The Digital Twin Certified (DTC) methodology is proposed to ensure product quality, which can reduce unplanned downtime through more efficient virtual testing.
4	Digital twin-driven rapid individualised designing of automated flow-shop manufacturing system	Liu et al. (2018)	Case studies show that applying Digital Twin in manufacturing system design can speed up the production process and reduce downtime by improving responsiveness to demand changes.
5	Digital Twin Service towards Smart Manufacturing	Qi et al. (2018)	Digital Twin serves as a service supporting smart manufacturing, contributing to reducing downtime by facilitating faster and more accurate decision-making based on real-time data.
6	Review of digital twin applications in manufacturing	Cimino et al. (2019).	A review of Digital Twin applications in manufacturing shows that this technology can reduce downtime through predictive maintenance and better performance analysis, improving overall operational efficiency.

Satpathy & Gavaskar (2021) demonstrate that the implementation of Digital Twin technology in industrial systems and manufacturing processes facilitates real-time performance monitoring and analysis. This is crucial since it aids in identifying issues prior to their escalation, thereby minimising unanticipated downtime. 2021. Digital Twin leverages data from sensors and IoT devices to enhance the understanding of operating situations, facilitating expedited and precise decision-making.

Pronost et al. (2023) performed a comprehensive review demonstrating that Digital Twin technology can mitigate downtime by offering enhanced models for planning and process control. Despite existing gaps in standardisation, the implementation of Digital Twin across different stages of the product lifecycle can improve efficiency and mitigate the risk of unforeseen downtime. (Pronost et al., 2023). This indicates that despite being in the developmental phase, the prospective advantages of this technology are considerable.

Grieves (2023) presented the Digital Twin Certified (DTC) system designed to guarantee product quality via virtual testing. Through DTC, organisations can model and evaluate items prior to actual production, hence minimising unanticipated downtime caused by product failures in the field. (Grieves, 2023). This method enhances product quality while simultaneously decreasing expenses related to repairs and replacements.

Liu et al. (2018) illustrate that employing Digital Twin technology in the design of automated flow systems can expedite production and minimise downtime in manufacturing system design. Utilising Digital Twin models enables organisations to swiftly adapt to fluctuations in demand and implement requisite modifications in the production process. (Liu et al., 2018). This demonstrates that the Digital Twin serves not only as a monitoring instrument but also as a proficient planning tool.

Qi et al. (2018) emphasise that Digital Twin operates as a service facilitating smart manufacturing. Utilising real-time data, Digital Twin facilitates expedited and precise decision-making, aiding in the minimisation of both scheduled and unscheduled downtime. (Qi et al., 2018). The incorporation of Digital Twin technology in production processes can improve operational responsiveness and flexibility.

Cimino et al. (2019) performed a review of Digital Twin applications in manufacturing, revealing that this technology can diminish downtime via predictive maintenance and enhanced performance analysis. By utilising past data and analytics, firms may optimise maintenance planning, therefore minimising both the frequency and duration of downtime. (Cimino et al., 2019). The installation of Digital Twin enhances operational efficiency and positively influences overall production.

Numerous studies indicate that Digital Twin technology possesses significant promise for minimising both scheduled and unscheduled downtime in the industrial sector. Utilising this technology enables organisations to augment operational efficiency, decrease expenses, and elevate product quality, hence fostering long-term success in a progressively competitive corporate landscape.

What are the technical and non-technical variables influencing the efficacy of Digital Twin adoption in minimising downtime within the industrial sector?

Table 4. Factors affecting digital twin implementation and adoption in industry

No	Article Title	Researchers	Findings
1	Digital Transformation Revolution with Digital Twin Technology	Erol et al. (2020)	This study shows that the success of Digital Twin implementation is highly influenced by the readiness of existing technology and infrastructure, as well as the organization's ability to adapt to technological changes.
2	The Application of Industry 4.0 Technological Constituents for Sustainable Manufacturing	Ng et al. (2022)	Technical factors such as system integration and interoperability between hardware and software are crucial for the effectiveness of Digital Twin implementation. Additionally, management support is a key non-technical factor.
3	Digital twin-driven product design, manufacturing and service with big data	Tao et al. (2017)	This study emphasizes the importance of high-quality data and accurate analytics in supporting the effectiveness of Digital Twin. The availability of accurate data is a technical factor influencing implementation outcomes.
4	Potensi Penerapan Teknologi Digital Twin pada Industri Pertanian dan Pangan di Indonesia	Baladraf (2024)	Non-technical factors such as organizational culture and employee involvement in the implementation process significantly impact the effectiveness of Digital Twin. The involvement of all stakeholders is necessary for the success of this technology.
5	Pengaruh Implementasi Internet of Things Terhadap Pengambilan Keputusan Bisnis	Judijanto (2024)	This study shows that the adoption of IoT technology impacts the effectiveness of decision-making, which is also relevant for Digital Twin implementation. The organization's readiness to adopt new technologies is a crucial factor.

The adoption of digital twin technology in the manufacturing sector holds significant promise for minimizing scheduled and unscheduled downtime. Numerous technical and non-

technical aspects significantly affect the efficacy of deploying this technology. The preceding table encapsulates various articles elucidating these variables, which will be elaborated upon thereafter.

a. Technological Elements, a critical technical factor is the preparedness of technology and infrastructure within the organisation. Erol et al. (2020) assert that the efficacy of a digital twin deployment is significantly contingent upon the organization's capacity to adapt to technological advancements and the requisite infrastructure. 2020. In this context, system integration and compatibility between hardware and software are critical elements. Ng et al. (2022) illustrate that inadequate integration might impede the efficacy of Digital Twin in minimizing downtime, as disconnected data may result in analytical and decision-making errors. Ng et al. (2022).

The quality of the data used in the Digital Twin system significantly influences its efficacy. Tao et al. (2017) assert that high-quality data and accurate analytics are essential for enhancing the efficacy of Digital Twin. (Tao et al., 2017). The availability of precise data allows organizations to conduct predictive maintenance and detect problems prior to their escalation, thereby minimizing unanticipated downtime.

b. Non-Technical Considerations, organisational culture and staff engagement in the Digital Twin implementation process are essential on the non-technical front. Baladraf (2024) demonstrates that the engagement of all stakeholders is essential for the success of this technology. An organizational culture that fosters innovation and collaboration might facilitate the adoption of Digital Twin, whereas opposition to change can impede effective implementation.

Management support constitutes a vital non-technical element. Ng et al. (2022) emphasize that the absence of robust managerial support can hinder the implementation of Digital Twins, particularly with resource allocation and employee training. Proactive management in facilitating technological advances can foster an environment suitable for the deployment of digital twins.

Numerous technical and non-technical variables affect the effectiveness of employing digital twin technology to mitigate downtime in the industrial sector. Key factors that firms must consider when using this technology include: technology readiness, data quality, organizational culture, and managerial support. By comprehending and regulating these elements, organizations can maximize the advantages of digital twins and attain enhanced operational efficiency.

What is the extent of the impact of Digital Twin technology on operational efficiency and productivity within the industrial sector, as evidenced by literature reviews?

Table 5. Digital twin technology for legacy systems and operational efficiency

No	Article Title	Researchers	Findings
1	Digital Twin for Legacy Systems: Simulation Model Testing and Validation	Khan et al. (2018)	The Digital Twin simulation model increases productivity by providing a platform for testing future modifications and assisting in system operations and services during production system operations.
2	Digital Twin in Manufacturing: A Categorical Literature Review and Classification	Kritzinger et al. (2018)	A literature review shows that the application of Digital Twin can enhance operational efficiency through reduced downtime and increased productivity, focusing on technology integration and accurate data.
3	Digital Twin—Cyber Replica of Physical Things: Architecture, Applications and Future Research Directions	Qian et al. (2022)	Digital Twin functions as a cyber replica of physical objects, enabling better monitoring and control, thus contributing to operational efficiency and productivity in the manufacturing sector.
4	Shaping the Digital Twin for Design and Production Engineering	Schleich et al. (2017)	This study emphasizes the importance of the Digital Twin model concept in design and production engineering, which can enhance operational efficiency by enabling better simulations and analyses during the product lifecycle.
5	Digital Twin: Enabling Technologies, Challenges and Open Research	Fuller et al. (2020)	This study identifies the challenges and enabling technologies for implementing Digital Twin, showing that this

No	Article Title	Researchers	Findings
			technology can improve operational efficiency and productivity through better data analysis.

The digital twin technology has emerged as a transformative force that greatly enhances operational efficiency and productivity within the manufacturing sector. The previously shown table summarizes various research findings that demonstrate how the adoption of digital twin technologies can enhance firms' operational effectiveness.

Khan et al. (2018) discovered that digital twin simulation models can augment productivity in older systems by offering a platform for evaluating prospective improvements. This facilitates the better implementation of systems and services throughout manufacturing operations, thereby minimizing downtime and enhancing efficiency, as stated by Khan et al. (2018). Consequently, the digital twin functions not only as a monitoring instrument but also as a proficient testing apparatus.

Kritzinger et al. (2018) conducted a literature study that demonstrated how the implementation of digital twin technology can enhance operational efficiency by reducing downtime and boosting productivity. This study underscores the significance of incorporating technology and precise data to attain optimal outcomes. By consolidating diverse data sources, organizations can enhance their decision-making speed and quality, thereby improving their operational performance (Kritzinger et al., 2018).

Moreover, Qian et al. (2022) elucidate that the Digital Twin serves as a cybernetic counterpart of physical entities, facilitating enhanced monitoring and control. By monitoring conditions in real-time, organisations can detect and resolve issues prior to their escalation, therefore enhancing operational efficiency and productivity in the manufacturing industry (Qian et al., 2022). This suggests that Digital Twin can function as a significant asset in risk management and predictive maintenance.

Schleich et al. (2017) underscore the significance of the Digital Twin model concept in design and production engineering. This study demonstrates that the implementation of Digital Twin enhances operational efficiency by facilitating superior simulation and analysis across the product lifecycle. Utilising the Digital Twin paradigm enables companies to enhance design and production processes, hence augmenting productivity (Schleich et al., 2017).

Fuller et al. (2020) delineate the obstacles and technology facilitating the adoption of Digital Twin. This research demonstrates that, despite implementation hurdles, this technology can improve operational efficiency and productivity via enhanced data analysis. By using data gathered from many sources, firms may make more informed and strategic decisions, enhancing their overall performance (Fuller et al., 2020).

The reviewed research shows that Digital Twin significantly boosts operational efficiency and productivity in the manufacturing sector. Using this technology enables organizations to optimize production management, minimize downtime, and elevate product quality, fostering long-term success in a progressively competitive marketplace.

4. CONCLUSION

This study highlights how adopting Digital Twin technology can significantly boost efficiency and productivity in the industrial sector. By enabling real-time monitoring, precise data analysis, and improved process modeling, this technology helps reduce both planned and unexpected downtime. Our research underscores the importance of not only technical factors like system integration and data quality but also non-technical aspects such as organizational culture and managerial support in ensuring successful implementation. The findings suggest that organizations should invest in robust technological infrastructure, actively involve employees in the transformation process, and develop management policies that foster innovation and collaboration. However, there are some limitations to this study. It primarily focuses on specific industrial sectors and lacks long-term data to assess the enduring impact of Digital Twin technology. Future research should explore its application in a broader range of industries and conduct long-term studies to better understand its lasting effects. By adopting this comprehensive approach, organizations can achieve a sustainable competitive edge, keeping pace with the advancements of Industry 4.0.

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