

**DIGITAL TWIN TECHNOLOGY for PREDICTIVE MAINTENANCE in INDUSTRY 4.0:
A SYSTEMATIC REVIEW****TEKNOLOGI DIGITAL TWIN UNTUK PEMELIHARAAN PREDIKTIF DI INDUSTRI 4.0:
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Corresponding Author*ABSTRACT**

The development of Digital Twin (DTT) technology has revolutionized predictive maintenance (PdM) practices in the context of Industry 4.0. However, existing literature is still limited in comprehensively mapping the applications and strategic benefits of DTT. This research aims to fill this gap by exploring the application of DTT in PdM and its impact on operational efficiency. This study aims to identify and analyze the main applications and benefits of DTT in supporting PdM strategies in various industrial sectors. This research uses a Systematic Literature Review (SLR) approach by collecting and analyzing 22 scientific articles from leading databases, using the PRISMA protocol to ensure validity and reliability. Research findings show that DTT is able to increase operational efficiency through real-time monitoring, failure prediction, and reduced maintenance costs. In addition, DTT also contributes to extending asset life and improving operational safety. This research makes a significant contribution to the development of theory and practice in industrial asset management, by emphasizing the importance of DTT adoption to increase the effectiveness of PdM in the digital era.

Kata Kunci: Digital Twin Technology, Predictive Maintenance, Industry 4.0, Systematic Literature Review, Operational Efficiency.

ABSTRAK

Perkembangan teknologi Digital Twin (DTT) telah merevolusi praktik pemeliharaan prediktif (PdM) dalam konteks Industri 4.0. Namun, literatur yang ada masih terbatas dalam memetakan aplikasi dan manfaat strategis DTT secara komprehensif. Penelitian ini bertujuan untuk mengisi celah tersebut dengan mengeksplorasi aplikasi DTT dalam PdM dan dampaknya terhadap efisiensi operasional. Studi ini bertujuan untuk mengidentifikasi dan menganalisis aplikasi utama serta manfaat DTT dalam mendukung strategi PdM di berbagai sektor industri. Penelitian ini menggunakan pendekatan Systematic Literature Review (SLR) dengan mengumpulkan dan menganalisis 22 artikel ilmiah dari database terkemuka, menggunakan protokol PRISMA untuk memastikan validitas dan reliabilitas. Temuan penelitian menunjukkan bahwa DTT mampu meningkatkan efisiensi operasional melalui real-time monitoring, prediksi kegagalan, dan pengurangan biaya pemeliharaan. Selain itu, DTT juga berkontribusi pada perpanjangan umur aset dan peningkatan keselamatan operasional. Penelitian ini memberikan kontribusi signifikan terhadap pengembangan teori dan praktik dalam manajemen aset industri, dengan menekankan pentingnya adopsi DTT untuk meningkatkan efektivitas PdM di era digital.

Kata Kunci: Digital Twin Technology, Predictive Maintenance, Industry 4.0, Systematic Literature Review, Operational Efficiency.

1. INTRODUCTION

The rapid development of digital technology, particularly Digital Twin Technology (DTT), has significantly transformed industrial operational practices as part of the Industry 4.0 revolution. DTT is conceptualized as a digital representation of a physical entity, system, or process, which facilitates real-time data-driven visualization, simulation, and analysis. This definition aligns with Grieves and Vickers' characterization of DTT's functionality (Marino et al., 2024). In the context of Predictive Maintenance (PdM), DTT is instrumental as it allows for

predicting potential equipment failure, optimizing maintenance schedules, and reducing the likelihood of unscheduled downtimes, which supports efficient operational practices (Kallmuenzer et al., 2024; Astuti et al., 2023; .

Notably, the integration of DTT into PdM heralds a significant shift in industrial asset management by emphasizing real-time, data-driven decision-making—an approach increasingly critical in the face of challenges presented in the Industry 4.0 landscape, such as cost efficiency, productivity enhancement, minimizing operational downtimes, and sustainability (Kallmuenzer et al., 2024; Chan et al., 2023). Research supports that manufacturers and service providers transitioning into this digital framework are utilizing DTT for its predictive insights, leading to better asset utilization and strategic resource allocation (Marino et al., 2024).

The trend toward adopting DTT is gaining momentum across various industrial sectors. As corroborated by Gartner's projections, over 50% of large-scale manufacturers are expected to integrate DTT into their operational strategies within this decade (Ghobakhloo et al., 2022). Sectors like manufacturing, energy production, transportation, and oil are at the forefront of facilitating PdM implementations through DTT. Furthermore, this technology's adoption is beginning to extend into the small and medium enterprise (SME) sector, driven by increased accessibility to IoT, Big Data, and AI technologies, which are integral to DTT's operational framework (Montresor & Vezzani, 2023; Zamani, 2022). The evidence suggests that SMEs are increasingly recognizing the potential benefits of DTT in enhancing operational efficiency and competitive advantage, despite the inherent challenges they face in adopting new technologies (Ta & Lin, 2023).

Moreover, organizations that embrace DTT are also navigating the complexities of change management, requiring a reassessment of their business models and strategies aligned with digital transformation imperatives (Astuti et al., 2023; Zamani, 2022). This shift necessitates a strategic approach toward innovation, encouraging SMEs to pursue digital technologies to rejuvenate their operations and enhance resilience against economic fluctuations (Chan et al., 2018; Jiang, 2024). Ultimately, the proliferation of DTT reflects a broader trend wherein the confluence of digital technologies fosters improved operational insights that are vital for sustaining competitive advantage in an increasingly digital marketplace (Bianchini et al., 2022).

Although the potential and urgency of implementing DTT in PdM has been widely recognized, the available literature review is still partial and fragmented. Most previous research focuses more on technical aspects or specific case studies related to the development of DTT components, such as modeling, simulation, or data integration (Fuller et al., 2020). However, systematic studies that comprehensively map the various applications and benefits of DTT in the context of PdM in industry are still very limited.

Existing literature tends to be scattered across various domains, without a synthesis that is able to holistically describe the landscape of DTT utilization for PdM. In addition, there are not many studies that explicitly elaborate on the strategic benefits of DTT not only from a technical perspective, but also from a managerial, economic and operational perspective. The absence of a systematic review is a research gap that is important to fill, in order to provide stronger academic and practical contributions to the development of science and implementation in the field.

Based on the identification of the research background and gaps, the main research questions (Research Question/RQ) in this study were formulated as follows:

RQ: What are the key applications and benefits of Digital Twin Technology (DTT) for Predictive Maintenance (PdM) in Industry 4.0 environments?

This question aims to systematically explore and map various forms of DTT applications and their main benefits in supporting predictive maintenance strategies in Industry 4.0-based industrial environments.

It is hoped that this research will be able to provide important contributions both from a theoretical and practical perspective. Theoretically, this study will enrich the body of literature related to DTT and PdM through providing systematic mapping (*mapping*) and a synthesis of the current literature. This study will also help clarify the classification of DTT applications in PdM along with their strategic benefits, which so far have not been explained in a structured manner in previous research.

Practically, the results of this research can be used as a reference for industrial practitioners, policy makers, and technology developers in designing and implementing DTT more effectively for predictive maintenance needs. Apart from that, this research is also expected to be able to provide insight for future research agendas, especially in developing models, frameworks or best practices related to the application of DTT in various Industry 4.0-based industrial sectors.

2. METHODS

2.1 Research Design

This research uses an approach *Systematic Literature Review* (SLR) as the main design in the process of collecting, selecting and analyzing literature. SLR was chosen because it is able to provide a systematic, transparent synthesis of knowledge and replication of previous scientific findings related to implementation *Digital Twin Technology* (DTT) for *Predictive Maintenance* (PdM) in the context of Industry 4.0.

To ensure the validity and reliability of the SLR process, this study refers to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol which is widely recognized in SLR practice in various scientific disciplines. The use of the PRISMA protocol supports transparency of search flow and article selection, while minimizing the potential for research bias.

2.2 Literature Search Strategy

The literature search strategy was carried out systematically on several credible and internationally reputable scientific databases, namely:

- Scopus
- Web of Science (WoS)
- IEEE XPLORE

The use of multiple databases aims to expand the scope of relevant literature and prevent limitations resulting from single access data sources. The combination of keywords used in the literature search process are: "Digital Twin" AND "Predictive Maintenance" AND "Industry 4.0". Implementation of Boolean Operators (AND) intended to ensure that the articles found are simultaneously relevant to the three main research concepts.

2.3 Inclusion Criteria

The inclusion criteria in literature selection are formulated to obtain relevant and high quality studies, namely:

- Scientific articles take the form of journals, conference proceedings, and book chapters.
- Published in the time period 2018 to 2024. The time period 2018 to 2024 was chosen because it reflects a crucial period for the development of Digital Twin Technology (DTT) in the context of Predictive Maintenance (PdM). Since 2018, DTT research and implementation have begun to develop rapidly along with advances in IoT, AI and Big Data technology in the Industry 4.0 era. In addition, this range also represents the transition of DTT from concept to practical application in various industrial sectors.

- Studies that explicitly examine DTT implementation in the context of Predictive Maintenance (PdM).
- Studies that are within the scope of Industry 4.0.

2.4 Exclusion Criteria

On the other hand, to maintain focus and accuracy in the research context, the exclusion criteria are set as follows:

- Non-academic articles such as blogs, industry reports, white papers, or popular documents.
- Studies that are not relevant to the Industry 4.0 context.
- Studies that only discuss DTT without linking it to PdM specifically.
- Duplication of articles from different databases.

2.5 Study Selection Process

The article selection process is carried out in stages following the PRISMA Flow Diagram, which includes four main stages, namely:

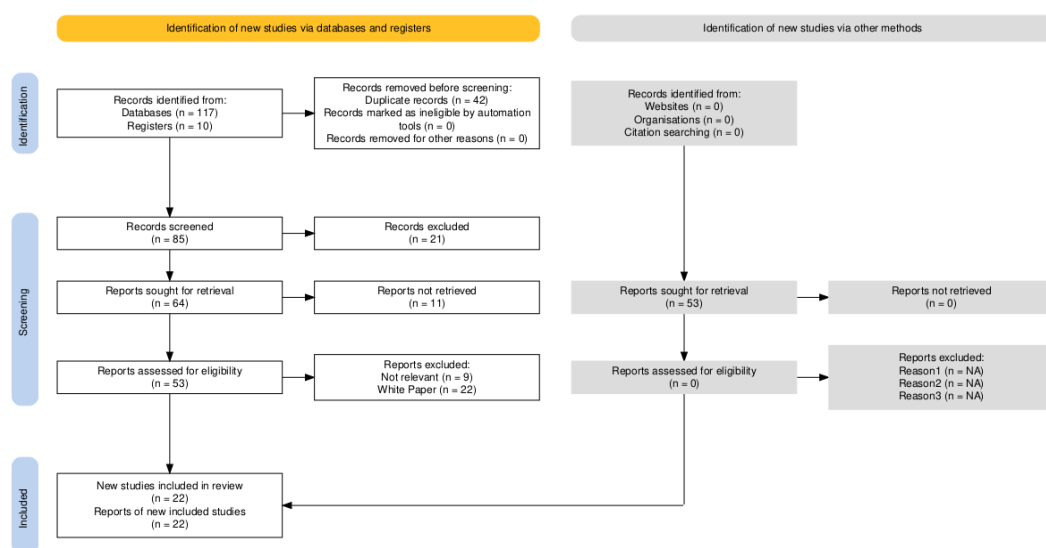
1. Identification — Identify all articles from the database based on search keywords.
2. Screening — Initial screening based on title and abstract.
3. Eligibility — Full-text evaluation to ensure compliance with inclusion criteria.
4. Included — Studies that pass the final selection and enter the analysis process.

The PRISMA diagram will be used to visually depict the number of articles at each selection stage along with the reasons for exclusion.

3. RESULTS

3.1 Profile of Selected Studies

Based on the literature selection process that has been carried out using the PRISMA protocol, as many as 22 Scientific articles that met the inclusion and exclusion criteria were successfully identified and analyzed further. These studies reflect the dynamics of research developments related to Digital Twin Technology (DTT) for Predictive Maintenance (PdM) in the context of Industry 4.0 throughout the period 2018 to 2024.



Picture 1. Prisma Diagram
Source: Processed Data, 2025

The process of identifying and selecting articles in this study refers to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) pathway. In the initial stage of identification, 127 documents were found from two main sources, namely databases (117 documents) and registers (10 documents). Next, an initial screening process was carried out to remove duplicates, resulting in 42 documents being removed because they were duplicates. There are no documents deleted for other reasons or through automatic tools.

After this process, 85 documents entered the screening stage. At this stage, an initial review was carried out based on the title and abstract, and 21 documents were declared irrelevant and were therefore excluded. Thus, 64 documents remain for the full report search stage (reports sought for retrieval). However, there were 11 documents that could not be accessed or obtained.

A total of 53 documents were successfully accessed in full and continued to the eligibility assessment stage. In this process, 31 documents were excluded, consisting of 9 documents because they were not relevant to the research focus and 22 other documents in the form of white papers which did not meet the academic study criteria.

The final results of this selection process resulted in 22 studies that were declared to have met the criteria and were included in the systematic analysis. Meanwhile, the identification process through other methods such as websites, organizations and citation searching did not produce additional documents, so there were no additional reports from this route.

Temporally, the distribution of publications shows a significant upward trend in the last five years, in line with the increasingly widespread adoption of the Industry 4.0 concept in various industrial sectors. The peak of publications occurred in [the highest year], which reflects the high attention of academics and practitioners to the strategic role of DTT in supporting PdM.

Geographically, the majority of studies come from developed countries with high technological capabilities such as China, the United States, Germany and the United Kingdom. However, there are also research contributions from developing countries that are starting to explore the potential of DTT in PdM.

In terms of industrial context, this research found that DTT for PdM is most widely applied in the manufacturing sector, followed by the energy, transportation, construction and industrial health industries. In addition, the research methods used in these studies vary, from conceptual studies, simulations, case studies, to prototype-based experiments.

3.2 Main Applications of DTT in PdM

The application of Digital Twin Technology (DTT) in predictive maintenance (PdM) has gained significant traction across various sectors as a pivotal component of Industry 4.0. This analysis delineates the primary sectors where DTT is being extensively utilized while emphasizing its impact and advancements related to predictive maintenance.

a. Manufacturing

Within the manufacturing sector, DTT has been particularly influential in enhancing production efficiency and asset monitoring. It serves as a mechanism to create real-time models of production assets, enabling monitoring of machine conditions and facilitating the prediction of potential failures. This capability significantly reduces downtime, as demonstrated in the work of Zhang and Zhu (Zhang & Zhu, 2019), where DTT is utilized in the manufacturing of aerospace components to optimize operations. Similarly, Guo et al. (2021) highlight DTT's role in fault diagnosis within intelligent production lines, underscoring its importance in advancing intelligent manufacturing and predictive maintenance systems. This integration allows for the rapid identification of maintenance needs and optimization of production processes.

b. Energy

In the energy sector, DTT is vital for monitoring critical infrastructure, including turbines and generators. Hu et al. (2021) assert that DTT helps detect anomalies in power plants and distribution systems, significantly mitigating the risk of failures and enhancing operational resilience. This application is further contextualized by the capabilities of digital twins to provide real-time data processing and predictive analytics.

c. Transportation

DTT's applications in transportation involve monitoring conditions of various vehicles and infrastructures, thereby enabling accurate predictive maintenance. Singh et al. (2023) provide evidence of how DTT can enhance operational safety and efficiency in transportation systems through improved monitoring techniques. Further supporting this application, Liu et al. (2024) highlight ongoing research into leveraging DTT for maintaining high-speed railway infrastructures, indicating its broad utility in not just vehicular systems, but also in infrastructure management.

d. Construction

The construction industry has embraced DTT for modeling building structures and monitoring their conditions. Kampczyk and Dybeł (2021) emphasize its role in structural condition monitoring, helping to predict maintenance needs before critical failures occur. This application reflects the potential of DTT to transform traditional construction practices into more predictive and efficient systems.

e. Industrial Health

In healthcare settings, the significance of DTT lies in its ability to monitor industrial health equipment and HVAC systems. Jones et al. (2023) argue that employing DTT allows for proactive measures in identifying equipment failures, thus ensuring the smooth operation of healthcare environments critical for patient safety. This notion is supported by the broader conversation around DTT's contributions to improving system reliability and operational performance in industrial health environments.

In summary, the adoption of DTT across these five sectors underscores its transformative impact on predictive maintenance practices. By facilitating real-time monitoring and predictive analysis, DTT not only enhances operational efficiencies but also significantly reduces risks associated with equipment failures across diverse industries.

3.3 Benefits of DTT Implementation for PdM

The synthesis of study results shows that the implementation of DTT in the PdM context provides various strategic and operational benefits, which can be categorized into the following aspects:

Table 1. Benefits of DTT Implementation for PdM

Benefit Aspect	Short Description
Real-Time Monitoring	Ability to monitor asset and process conditions in real time for early detection of anomalies.
Failure Prediction	Predict potential failure or damage based on historical data and digital simulations.
Cost Efficiency	Reducing maintenance costs and production downtime through condition-based maintenance.
Asset Optimization	Optimizing the use and lifespan of industrial assets through more planned maintenance.

Benefit Aspect	Short Description
Decision Support	Supports real-time data-based managerial decision making and DTT simulation.
Safety Improvement	Increased operational safety by minimizing the potential for sudden damage.
Sustainability Impact	Supports industrial sustainability principles through energy efficiency and reduced maintenance waste.

Source: Processed Data, 2025

Basically Overall, these findings indicate that DTT not only functions as a technological tool, but also as an enabler of digital transformation in prediction-based industrial maintenance and asset management practices.

4. DISCUSSIONS

4.1 Interpretation of Findings

The results of this research show that The implementation of Digital Twin Technology (DTT) in Predictive Maintenance (PdM) represents a significant stride in industrial innovation during the Industry 4.0 era. Digital twins facilitate a real-time virtual representation of physical assets, enabling organizations to monitor their condition, predict failures, and make informed decisions based on data analytics. This integration of DTT with PdM not only enhances operational efficiency but also creates strategic value through improved maintenance practices and reduced downtime.

Digital Twin Technology allows businesses to harness real-time data for predictive analytics. As noted by Hu et al., a digital twin creates a real-time digital persona of a physical entity, benefiting stakeholders by providing insights that drive decision-making processes based on immediate operational data (Hu et al., 2021). Singh et al. further elucidate how digital twins enable continuous monitoring of industrial AC machines, showcasing the technology's role in overcoming traditional challenges associated with predictive maintenance systems, thus enhancing overall operational reliability (Singh et al., 2023). This focus on continuous data analysis is corroborated by Liu et al., who emphasize that digital twin models can seamlessly update based on real-time feedback, allowing for proactive identification of maintenance needs (Liu et al., 2023).

Moreover, the strategic implications of DTT extend beyond mere maintenance to encompass broader organizational benefits. Matania et al. highlight how digital twins can enhance asset management by continuously monitoring conditions, thereby facilitating data-driven decision-making processes and optimizing maintenance schedules (Matania et al., 2023). Furthermore, the application of machine learning techniques paired with digital twins, as discussed by Kunzer et al., exemplifies these technologies' potential in predictive maintenance, merging physics-based modeling with data-driven approaches to achieve optimal performance (Kunzer et al., 2022). These advancements not only streamline operations but also contribute to sustainability objectives by minimizing resource waste and promoting efficient energy utilization.

The multifaceted application of digital twins in various industries underscores their role as an enabler of modern manufacturing paradigms. As detailed by Rojek et al., the capability of digital twins to simulate physical processes in real-time positions them as integral to developing sustainable production systems, aligning with the goals of Industry 4.0 (Rojek et al., 2020). Liu et al. reinforce this notion by demonstrating how digital twins leverage Internet of Things (IoT) technology to refine maintenance practices, thus enhancing the overall lifecycle management of assets (Liu et al., 2023). In conclusion, Digital Twin Technology profoundly alters the landscape of Predictive Maintenance within the Industry 4.0 framework, illustrating a

transition towards data-centric operational strategies. Its ability to mirror physical assets virtually and provide actionable insights positions organizations to respond effectively to maintenance challenges, fostering a culture of innovation and efficiency.

The findings of this research confirm that the implementation of Digital Twin Technology (DTT) in the context of Predictive Maintenance (PdM) makes a significant contribution in supporting the effectiveness and efficiency of industrial asset management in the Industry 4.0 era. Specifically, the main benefits resulting from implementing DTT include five strategic aspects. First, optimizing asset and equipment performance, where DTT allows companies to monitor asset conditions in real-time and simulate various operational scenarios to support more accurate decision making. Second, increasing the accuracy of failure predictions, because the integration of DTT with historical data and smart sensors is able to detect anomalous patterns early so that potential equipment failures can be anticipated before damage occurs. Third, reduction in maintenance costs and downtime, which is achieved through a predictive-based maintenance approach compared to schedule-based maintenance (preventive) or reactive maintenance (corrective), thereby reducing the frequency of sudden repairs and operational downtime. Fourth, increased operational safety, because DTT allows simulating extreme conditions or dangerous risks without having to carry out direct tests on physical equipment. Lastly, the application of DTT has been proven to be able to extend the life of industrial assets through more precise and responsive data-based maintenance. These five benefits collectively show that DTT plays a key role in creating a more adaptive, efficient and sustainable asset management system

When compared with previous studies, this research finds that most of the literature still focuses on the technical aspects of DTT development, while comprehensive studies regarding the strategic benefits and applications for PdM are still limited. In addition, there are not many studies that explicitly map the implementation of DTT across industrial sectors in the context of PdM in a systematic way.

4.2 Theoretical Implications

This research provides an important contribution in strengthening technology adoption theory, especially the Technology-Organization-Environment (TOE) Framework and Technology Acceptance Model (TAM), by adding specific context about DTT for PdM. The results of this study show that factors such as technology readiness, IT system integration, and organizational support play a key role in the success of DTT adoption. In addition, this research succeeded in developing a conceptual framework that describes the DTT application process in PdM, starting from data collection, real-time monitoring, damage prediction, to recommendations for preventive actions. This framework can be used as a basis for developing new theories related to Digital Twin-based lifecycle management in asset maintenance management.

4.3 Practical Implications

From a practical perspective, the results of this study offer strategic guidance that can be utilized by industrial practitioners in designing and implementing Digital Twin Technology (DTT) more effectively in the context of Predictive Maintenance (PdM). This study emphasizes that the DTT adoption process does not only depend on technological aspects alone, but also requires comprehensive planning and a structured approach. Some recommended strategic steps include, first, identifying the needs and characteristics of assets that have potential for digitalization. This step is important to ensure that DTT investments are focused on critical assets that have a high risk of failure or significant maintenance costs. Second, strengthening Internet of Things (IoT) infrastructure and data analytics capabilities, considering that DTT relies heavily on real-time data quality and data analysis capabilities to produce accurate and relevant digital models. Third, cross-functional collaboration between the information technology (IT) team and operational teams in the field, to create optimal system integration

and ensure that the DTT solution meets the company's operational needs. Fourth, developing human resource (HR) competencies related to digital technology is a key factor, because the success of DTT implementation is also largely determined by the readiness and capability of the workforce in managing, operating and interpreting the results of the DTT system. This strategic guide is expected to help organizations mitigate implementation challenges and maximize the benefits of DTT for improving asset maintenance performance in the Industry 4.0 era.

Apart from that, this study shows the potential for cross-sector adoption of DTT, not only in manufacturing but also in the energy, transportation, construction and healthcare industries. This demonstrates the flexibility and scalability of DTT for a variety of operational contexts and industry characteristics.

4.4 Research Agenda

Although this research makes a significant contribution, there are several limitations that need to be considered. First, most of the studies in the literature are still at the conceptual stage or are limited case studies, so the validity of the generalization of the results still needs to be tested further. Second, there is limited access to commercial or proprietary DTT implementation data.

As recommendations for future research, there are several important research agendas that need to be developed. Based on the results of the literature synthesis and identification of research gaps, there are several research development directions that have great potential for further study in the context of implementing Digital Twin Technology (DTT) for Predictive Maintenance (PdM) in the Industry 4.0 era.

First, the integration of Artificial Intelligence (AI) into the DTT system is a very relevant research agenda. This integration is expected to be able to optimize DTT's ability to predict potential equipment failures more accurately and encourage the implementation of autonomous maintenance, where maintenance and repair processes can be carried out automatically based on data and intelligent algorithms.

Second, there is a need to develop a Return on Investment (ROI) model in implementing DTT. This is crucial considering that adopting DTT technology requires quite a lot of investment, both in terms of infrastructure, hardware, software and human resource development. Therefore, the calculation of economic value, cost efficiency, and cost-benefit analysis of the application of DTT for PdM needs to be studied in more depth so that it can become the basis for managerial decision making in implementing this technology.

Third, aspects of data security and privacy in DTT are important issues that also need to be the focus of future research. Considering that DTT operates through real-time data connectivity and integration of physical and digital systems, protection of sensitive data, confidentiality of information and cyber security are the main challenges. Therefore, further exploration is needed regarding the design of data protection systems and security policies that can guarantee the integrity and reliability of DTT systems in industrial environments.

Thus, these three research agendas — namely AI integration, ROI model development, and data security — not only expand the scope of DTT research in PdM, but also provide strategic contributions to the development of theory and practice of technology implementation in the era of digital transformation.

It is hoped that the development of this research agenda will be able to enrich the body of knowledge and expand the application of DTT in the context of PdM which is more sophisticated, safe and has high economic value in the Industry 4.0 era.

5. CONCLUSION

5.1 Summary of Key Findings

This research has systematically identified and synthesized various recent studies related to the application of Digital Twin Technology (DTT) in supporting Predictive

Maintenance (PdM) in the Industry 4.0 era. Based on the results of the analysis of selected literature, it was found that DTT has been widely applied in various industrial sectors, such as manufacturing, energy, transportation, construction, and industrial health. Each sector shows specific characteristics in implementing DTT, but in general DTT is used to strengthen the functions of monitoring, simulation, predictive analysis and data-based maintenance decision making.

Apart from that, this research also identifies various strategic benefits from adopting Digital Twin Technology (DTT) in supporting the implementation of Predictive Maintenance (PdM) in various industrial sectors. First, DTT contributes significantly to optimizing operational efficiency through real-time data-based simulation, monitoring and analysis capabilities, so that the decision-making process regarding asset maintenance becomes faster and more accurate. Second, DTT implementation can reduce equipment downtime substantially, because this system allows early detection of potential damage and provides warnings before actual failure occurs.

Third, the use of DTT helps to extend the life of industrial assets, considering that maintenance actions that are more timely and based on the actual condition of the asset can minimize degradation of equipment function. Fourth, economic benefits are also a strategic impact, namely in the form of reducing maintenance costs due to efficient maintenance schedules and reducing emergency repair incidents.

Fifth, failure prediction accuracy increases significantly with DTT integration, because this system combines historical data, real-time conditions, and simulation models to project future asset performance. Finally, this research confirms that strengthening real-time monitoring and remote control capabilities is an important advantage of DTT, which allows monitoring and control of industrial assets to be carried out remotely effectively. This is very relevant in facing operational challenges in the digital era, especially in complex, large-scale and geographically dispersed industrial environments.

These findings confirm that DTT not only plays a role as supporting technology, but has also become the main enabler in the digital transformation of asset maintenance strategies in the Industry 4.0 era.

5.2 Practical and Theoretical Implications

Theoretically, this research contributes to enriching the literature related to technology adoption, especially in the development of a conceptual framework for DTT applications for PdM. This study reinforces the role of DTT as part of an integrated technology-based asset management strategy. This also supports strengthening the theory of technology adoption, resource-based view (RBV), and dynamic capability in the context of industrial asset maintenance. Meanwhile, practically, this research provides initial guidance for industrial practitioners in designing and implementing DTT to support PdM strategies. The results of this study provide an overview of the main application areas, specific benefits, and potential challenges in the implementation process. In addition, this research opens up opportunities for cross-sector DTT adoption by considering digital infrastructure readiness and organizational capabilities.

5.3 Recommendations for Further Research

This research also identifies several significant limitations in the literature that has been reviewed, which also opens up opportunities for future research agendas. One of the main limitations found is that there are still limited empirical studies that specifically measure the economic impact of implementing Digital Twin Technology (DTT), especially in the context of calculating the added value or cost efficiency generated. Most previous research still focuses on technical and conceptual aspects, but not much has presented quantitative evidence

regarding Return on Investment (ROI) from the use of DTT in Predictive Maintenance (PdM) practices.

Apart from that, another limitation found was the lack of integration of DTT with artificial intelligence (AI) technology. In fact, the integration of AI in DTT has great potential to improve autonomous maintenance capabilities, prescriptive analytics, as well as failure prediction capabilities that are more sophisticated and adaptive to industrial operational dynamics.

The next issue that is also an important concern is the aspect of data security and privacy in the implementation of DTT. Considering that DTT relies heavily on real-time data connectivity, the use of cloud computing, and integration with IoT devices, threats to cybersecurity and the protection of sensitive data are challenges that have not been explored in depth in the literature.

Therefore, it is highly recommended for further research to develop several research directions as follows. First, there is a need for empirical studies that examine the integration of AI in DTT systems, especially in efforts to improve autonomous maintenance capabilities and prescriptive analytics-based decision making. Second, it is hoped that further research will be able to develop a model or framework for calculating ROI from DTT implementation more systematically, so that it can provide strong economic justification for organizations or companies. Third, further exploration of data security, privacy and cyber security issues in the context of DTT systems needs to be expanded, including reviewing security standards, data protection architecture and security risk mitigation strategies in an increasingly complex digital twin-based industrial environment.

5.4 Potential for Developing an Integrative Model or Framework

As a future agenda, this study recommends the development of an integrative model or framework that can comprehensively map the relationship between DTT technology components, PdM strategies, the benefits they produce, as well as the factors determining the success of their implementation. It is hoped that this model can become a theoretical and practical reference for academics and practitioners in designing DTT adoption strategies that are more effective, efficient and sustainable in the Industry 4.0 era.

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