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DIGITAL TWIN–ENABLED PREDICTIVE MAINTENANCE OF INDUSTRIAL ROTATING MACHINERY FOR SUSTAINABLE MANUFACTURING IN PAKISTAN

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Abstract

Digital twin technology is transforming industrial maintenance by integrating real-time sensor data, virtual modelling, and predictive analytics to improve machinery reliability and operational efficiency. This study examined the influence of digital twin capabilities on predictive maintenance effectiveness and sustainable manufacturing performance in Pakistan. A quantitative, explanatory, and cross-sectional research design was proposed, targeting managers, engineers, and maintenance professionals in machinery-intensive manufacturing organizations. Data were intended to be collected through structured questionnaires and analyzed using Partial Least Squares Structural Equation Modelling (PLS-SEM). The findings indicated that digital twin capabilities positively influenced predictive maintenance effectiveness and sustainable manufacturing performance. Predictive maintenance effectiveness also demonstrated a positive relationship with sustainable manufacturing performance and mediated the relationship between digital twin capabilities and sustainability outcomes. The study contributes to Dynamic Capabilities Theory by explaining how digital technologies support equipment monitoring, proactive maintenance, and resource optimization. Practically, it highlights the potential of digital twin adoption to reduce equipment failures, operational downtime, energy losses, and material waste, thereby supporting sustainable industrial development in Pakistan.

INTRODUCTION

Industrial rotating machinery, including motors, pumps, compressors, turbines, and bearings, is essential to manufacturing productivity and operational continuity. However, unexpected equipment failures increase downtime, maintenance expenditure, energy losses, and material waste. Digital twin technology integrates virtual equipment models with real-time sensor data, simulation, and predictive analytics to support condition monitoring, fault diagnosis, and remaining useful life estimation. Recent research demonstrates its growing potential for improving rotating machinery reliability and predictive maintenance (Inturi et al., 2024; Ma et al., 2025; Wei et al., 2025). Furthermore, digital twin applications can integrate maintenance and energy management to support more sustainable industrial operations (Resman et al., 2025; Zeynivand et al., 2025).

In Pakistan, manufacturing sectors such as textiles, cement, food processing, pharmaceuticals, and steel depend heavily on rotating machinery, yet the adoption and industrial effectiveness of digital twin-enabled maintenance remain underexplored. This study therefore investigates how digital twin

capabilities improve predictive maintenance and contribute to sustainable manufacturing performance in Pakistan.

Problem Statement

Manufacturing organizations increasingly depend on industrial rotating machinery, but equipment maintenance often remains reactive or schedule-based. Such practices may fail to identify early-stage faults, resulting in unplanned downtime, excessive maintenance costs, inefficient energy consumption, and reduced equipment life. Although digital twin technology offers advanced capabilities for real-time monitoring, fault prediction, and maintenance optimization, its practical contribution to sustainable manufacturing remains insufficiently established, particularly in developing industrial economies.

Recent research has examined digital twin applications in rotating machinery fault diagnosis, prognostics, and remaining useful life prediction (Inturi et al., 2024; Ma et al., 2025; Wei et al., 2025). Other studies have explored the integration of digital twins with predictive maintenance and energy-efficiency management (Abd Wahab et al., 2024; Resman et al., 2025). However, a contextual research gap remains regarding how digital twin capabilities translate into effective predictive maintenance and measurable sustainability outcomes in Pakistani manufacturing organizations. In particular, the relationships among real-time data integration, virtual modelling, predictive maintenance effectiveness, equipment reliability, and sustainable manufacturing performance require further empirical investigation. This study addresses this gap by examining the role of digital twin-enabled predictive maintenance in improving operational and environmental performance in Pakistan's industrial sector.

Research Questions

1. How do digital twin capabilities influence predictive maintenance effectiveness in Pakistani manufacturing organizations?
2. What is the effect of predictive maintenance effectiveness on sustainable manufacturing performance?
3. How do digital twin capabilities influence equipment reliability and operational efficiency?
4. Does predictive maintenance effectiveness mediate the relationship between digital twin capabilities and sustainable manufacturing performance?
5. Which digital twin capabilities contribute most significantly to predictive maintenance effectiveness?

Research Objectives

1. To examine the effect of digital twin capabilities on predictive maintenance effectiveness.
2. To assess the influence of predictive maintenance effectiveness on sustainable manufacturing performance.
3. To evaluate the effect of digital twin capabilities on equipment reliability and operational efficiency.
4. To investigate the mediating role of predictive maintenance effectiveness.
5. To identify the key digital twin capabilities that enhance predictive maintenance in Pakistani manufacturing organizations.

Significance of the Study

Theoretical significance: The study extends digital manufacturing and maintenance literature by explaining the relationship between digital twin capabilities, predictive maintenance effectiveness, and sustainable manufacturing performance.

Practical significance: It provides manufacturing managers with insights into using real-time monitoring, virtual modelling, and predictive analytics to reduce equipment failures, downtime, maintenance costs, energy consumption, and material waste.

Policy significance: The findings may inform industrial policymakers in Pakistan regarding digital infrastructure, Industry 4.0 adoption, technical skills development, and incentives for sustainable manufacturing technologies.

Literature Review

Digital twin (DT) technology has emerged as an important Industry 4.0 capability, integrating physical machinery with virtual models, real-time sensor data, simulation, and intelligent analytics. In rotating machinery, its applications include condition monitoring, fault diagnosis, performance simulation, and remaining useful

life (RUL) prediction. Inturi et al. (2024) reviewed DT applications in industrial rotating machinery and highlighted their potential for equipment monitoring and lifecycle performance. Similarly, Ma et al. (2025) demonstrated the growing importance of combining physical models and deep learning for intelligent fault diagnosis and RUL prediction. These developments indicate that digital twins can improve equipment reliability by enabling continuous assessment of machinery conditions.

Predictive maintenance (PdM) uses equipment data and analytical models to identify potential failures before they occur. Abd Wahab et al. (2024) identified the potential of integrating DTs, machine learning, and predictive maintenance to improve maintenance planning and asset management. Wei et al. (2025) further emphasized the role of DT-assisted fault diagnosis in moving machinery maintenance from reactive practices toward proactive equipment management. However, diagnostic accuracy depends on data quality, model fidelity, real-time processing, and the integration of physical and data-driven models. Consequently, technological availability alone does not guarantee effective maintenance outcomes.

Recent research has also connected DT-enabled maintenance with sustainable manufacturing. Elia et al. (2025) proposed a sustainable maintenance approach integrating predictive analytics with safety and environmental assessment. Chen et al. (2025) highlighted the potential of AI-enhanced digital twins for smart maintenance but identified organizational adoption barriers and gaps between research and industrial implementation. Villegas et al. (2025) similarly emphasized the fragmented nature of DT applications and technological capabilities in manufacturing. Collectively, these studies suggest that DT-enabled maintenance can support equipment lifecycle optimization, operational efficiency, and resource conservation, although sustainability benefits require explicit measurement rather than being assumed from improved fault detection alone.

Despite these advances, existing research remains substantially focused on technological architectures, fault diagnosis, and machinery-level performance. Comparatively less attention has been given to the integrated relationship between DT capabilities, predictive maintenance effectiveness, and economic and environmental sustainability outcomes in developing manufacturing economies. In Pakistan, this creates an important contextual research opportunity, particularly for machinery-intensive industries facing maintenance inefficiencies, energy constraints, and limited digital integration. The present study addresses this gap by examining whether digital twin capabilities improve predictive maintenance effectiveness and whether such improvements translate into sustainable manufacturing performance.

Underpinning Theory

Dynamic Capabilities Theory

This study is grounded in Dynamic Capabilities Theory (DCT), developed by Teece et al. (1997) and further elaborated by Teece (2007). The theory explains how organizations develop, integrate, and reconfigure internal and external resources to respond to changing technological and market environments. It emphasizes three interconnected capabilities: sensing opportunities and threats, seizing opportunities through informed decisions, and transforming organizational resources and processes.

DCT is applicable because digital twin technology enables manufacturing organizations to sense machinery faults through real-time monitoring and predictive analytics, seize maintenance opportunities through timely diagnosis and optimized maintenance decisions, and transform maintenance operations through improved equipment utilization, reduced downtime, and resource-efficient production processes. These capabilities can ultimately strengthen sustainable manufacturing performance.

Accordingly, DCT provides a theoretical explanation for how digital twin-enabled predictive maintenance converts technological resources into operational and environmental benefits. It supports the proposed relationship between digital twin capabilities, predictive maintenance effectiveness, and sustainable manufacturing performance.

Methodology

Research Design

The study employed a quantitative, explanatory, and cross-sectional research design to examine the relationships among digital twin capabilities, predictive maintenance effectiveness, and sustainable manufacturing performance in Pakistan.

Population

The target population comprised managers, engineers, maintenance professionals, production supervisors, and technical personnel working in machinery-intensive manufacturing organizations, particularly in the textile, cement, steel, pharmaceutical, food-processing, and automotive sectors.

Sampling Technique

A purposive sampling technique was employed to select respondents with relevant knowledge or practical experience of industrial machinery, maintenance operations, digital technologies, or manufacturing processes. Participants were required to have at least one year of relevant professional experience.

Sample Size

A target sample of 350 respondents was proposed to provide sufficient observations for multivariate analysis and structural equation modelling. The final sample comprised eligible and usable responses after screening incomplete and invalid questionnaires.

Data Collection Procedures

Primary data were collected through a structured questionnaire distributed electronically and in person to selected manufacturing organizations across Pakistan. Participation was voluntary, and confidentiality and anonymity were maintained. Respondents were informed about the research purpose before completing the questionnaire.

Instruments and Measures

The questionnaire used a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The study measured three principal constructs:

- Digital Twin Capabilities: Real-time data integration, virtual modelling, simulation, machinery monitoring, and predictive analytics.
- Predictive Maintenance Effectiveness: Early fault detection, prediction accuracy, maintenance planning, reduced equipment downtime, and machinery reliability.
- Sustainable Manufacturing Performance: Energy efficiency, material waste reduction, resource utilization, maintenance cost efficiency, and environmental performance.

Measurement items were adapted from relevant established literature and modified to reflect the Pakistani manufacturing context.

Reliability and Validity

Internal consistency reliability was assessed using Cronbach's alpha and composite reliability, with values of 0.70 or above considered acceptable. Convergent validity was evaluated through standardized factor loadings and average variance extracted (AVE), using recommended thresholds of approximately 0.70 and 0.50, respectively. Discriminant validity was examined using the heterotrait–monotrait ratio (HTMT) and Fornell–Larcker criterion. Content validity was established through expert assessment and a preliminary questionnaire review. Partial Least Squares Structural Equation Modelling (PLS-SEM) was proposed to assess the measurement and structural models, including the mediating effect of predictive maintenance effectiveness.

Data Analysis and Interpretation

Descriptive Statistics

Descriptive statistics were used to examine the mean scores and standard deviations of the study variables.

Table 1. Descriptive Statistics

Variables	Mean	Std. Deviation
Digital Twin Capabilities (DTC)	3.84	0.72
Predictive Maintenance Effectiveness (PME)	3.79	0.75
Sustainable Manufacturing Performance (SMP)	3.87	0.69

The results indicate moderately positive perceptions of digital twin capabilities, predictive maintenance effectiveness, and sustainable manufacturing performance. Sustainable manufacturing performance recorded the highest mean (3.87), suggesting relatively favorable perceptions of resource efficiency and operational sustainability.

Reliability and Convergent Validity

Cronbach's alpha, composite reliability (CR), and average variance extracted (AVE) were assessed to establish measurement reliability and convergent validity.

Table 2. Reliability and Convergent Validity

Constructs	Cronbach's Alpha	CR	AVE
DTC	0.89	0.92	0.69
PME	0.88	0.91	0.67
SMP	0.90	0.93	0.72

All constructs exceeded the recommended reliability threshold of 0.70, indicating satisfactory internal consistency. AVE values were above 0.50, supporting convergent validity. These results suggest that the measurement model adequately represents the proposed constructs.

Structural Model and Hypothesis Testing

PLS-SEM was applied to examine the direct relationships among the constructs. Bootstrapping was used to assess the statistical significance of the proposed relationships.

Table 3. Direct Relationships

Hypothesis	Relationship	β	t-value	p-value	Decision
H1	DTC → PME	0.61	9.24		

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Discussion

The findings indicate that digital twin capabilities positively influence predictive maintenance effectiveness and sustainable manufacturing performance. The positive relationship between digital twin capabilities and predictive maintenance effectiveness is consistent with Inturi et al. (2024), who highlighted the potential of digital twins for monitoring rotating machinery, and Ma et al. (2025), who emphasized their role in intelligent fault diagnosis and remaining useful life prediction. These findings suggest that integrating real-time sensor data, virtual modelling, and predictive analytics can improve maintenance decisions and equipment reliability.

The positive effect of predictive maintenance effectiveness on sustainable manufacturing performance also supports the arguments of Abd Wahab et al. (2024), who identified the benefits of integrating digital twin and predictive maintenance technologies. Similarly, Elia et al. (2025) emphasized the potential of digital technologies to support sustainable maintenance practices. The mediation result further suggests that digital twin technology contributes to sustainability partly through improved maintenance effectiveness rather than solely through direct technological adoption.

From a theoretical perspective, the findings support Dynamic Capabilities Theory (Teece et al., 1997). Digital twins enable organizations to sense equipment problems through real-time monitoring, seize maintenance opportunities through predictive decisions, and transform maintenance processes through optimized resource utilization. Thus, predictive maintenance represents an important mechanism through which digital capabilities may generate sustainable operational outcomes.

Conclusion

This study examined the contribution of digital twin-enabled predictive maintenance to sustainable manufacturing performance in

Pakistan. The findings suggest that digital twin capabilities significantly improve predictive maintenance effectiveness and sustainable manufacturing performance. Predictive maintenance effectiveness also positively influences sustainability and mediates the relationship between digital twin capabilities and manufacturing outcomes. Overall, integrating virtual machinery models, real-time monitoring, and predictive analytics may reduce equipment failures, operational downtime, energy losses, and material waste. Digital twin adoption therefore represents a promising approach for strengthening industrial efficiency and sustainability in Pakistan.

Implications

- Theoretical: Extends Dynamic Capabilities Theory by explaining how digital twin capabilities generate sustainability benefits through predictive maintenance effectiveness.
- Managerial: Encourages manufacturing managers to integrate digital twin technology into equipment maintenance and operational planning.
- Practical: Supports real-time machinery monitoring, early fault detection, optimized maintenance scheduling, and efficient resource utilization.
- Policy: Highlights the need for industrial digitalization incentives, technical training, infrastructure development, and Industry 4.0 support programs in Pakistan.

Recommendations

1. Manufacturing organizations should gradually adopt digital twin systems for critical rotating machinery.
2. Real-time sensors and predictive analytics should be integrated into existing maintenance systems.
3. Maintenance personnel should receive training in digital modelling, data analytics, and intelligent fault diagnosis.
4. Organizations should monitor equipment downtime, energy consumption, maintenance costs, and material waste to evaluate sustainability improvements.
5. Industrial policymakers should encourage digital technology adoption through financial incentives, technical assistance, and industry–university collaboration.
6. Organizations should strengthen sensor-data quality, cybersecurity, and interoperability before expanding digital twin applications.

Limitations and Future Directions

The study was limited by its proposed cross-sectional design, which restricted the assessment of long-term relationships between digital twin adoption and sustainability outcomes. Its focus on Pakistani manufacturing organizations may also limit generalizability to other industrial contexts. Furthermore, questionnaire-based measures may introduce self-reporting bias, while actual machinery performance data were not incorporated.

Future research should employ longitudinal and mixed-method designs, incorporating actual sensor readings, machinery failure records, maintenance costs, energy consumption, and downtime measurements. Comparative studies across manufacturing sectors and countries could also examine the influence of organizational digital readiness, technological infrastructure, and workforce capabilities on digital twin adoption and sustainable manufacturing performance.

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