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Analysis of the Impact of Predictive Maintenance Based on IoT and Digital Twin on Production Efficiency in the Textile Industry in West Java

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ABSTRACT

This study examines the impact of IoT-based predictive maintenance and digital twin technology on production efficiency in the textile industry in West Java. Employing a quantitative research design, data were collected from 120 respondents using a structured questionnaire with a 5-point Likert scale. Structural Equation Modeling - Partial Least Squares (SEM-PLS) was used for data analysis. The findings reveal that IoT-based predictive maintenance and digital twin technology positively and significantly influence production efficiency. Furthermore, the combined application of these technologies demonstrates the strongest impact, highlighting their synergistic benefits. This study underscores the potential of Industry 4.0 technologies to enhance operational performance in the textile sector and provides actionable insights for industry stakeholders.

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1. INTRODUCTION

The textile sector in Indonesia, especially in West Java, is set for transformation with the implementation of Industry 4.0 technologies, crucial for improving efficiency, sustainability, and competitiveness in a swiftly changing market. Industry 4.0 includes various advanced technologies, including cyber-physical systems, the Industrial Internet of Things (IIoT), and artificial intelligence, which together facilitate real-time data processing and agile decision-making, essential for contemporary industrial methods [1]. The incorporation of these technologies in the textile industry can result in substantial enhancements in production efficiency and sustainability, conforming to global trends and market requirements. Industry 4.0 technology, such as intelligent sensors and data analytics, can streamline manufacturing processes, minimise waste, and improve resource efficiency in the textile sector [2].

These technologies facilitate real-time monitoring and control, which are vital for maintaining high-quality standards and meeting customer demands. Additionally, the adoption of sustainable manufacturing practices is critical for reducing the environmental impact of the textile industry, which is known for its high resource consumption [2]. Industry 4.0 technologies can support sustainable development goals by promoting energy savings and waste reduction [3]. For Indonesian SMEs, particularly in textiles, embracing Industry 4.0 is crucial for maintaining a competitive edge. While the electronics and machinery sectors are currently more advanced in this regard, textiles still hold significant potential for improvement through strategic prioritization and technological adoption [4]. However, the transition to Industry 4.0 presents challenges such as the need for workforce adaptation and overcoming interoperability issues, but it also offers opportunities for innovation and enhanced production capabilities [3].

The integration of IoT-based predictive maintenance and digital twin systems is revolutionizing manufacturing by addressing production inefficiencies and equipment downtime. IoT-enabled predictive maintenance leverages real-time monitoring and predictive analytics to anticipate equipment failures, thereby reducing unplanned downtime and operational costs. Digital twin technology, on the other hand, creates virtual replicas of physical systems, allowing for simulation, prediction, and optimization of processes without disrupting operations. These technologies collectively enhance operational efficiency, sustainability, and competitiveness in manufacturing environments. IoT sensors collect comprehensive data on equipment performance, enabling predictive maintenance through advanced analytics and machine learning algorithms, which reduces unplanned downtime and optimizes maintenance schedules [5].

Additionally, predictive maintenance extends equipment lifespans, reduces energy consumption, and minimizes waste, contributing to supply chain sustainability [5]. However, high initial investment costs, technical complexity, and the need for specialized skills pose significant barriers to implementation [5]. Meanwhile, digital twins provide real-time insights into system performance, allowing for proactive maintenance and optimization of production processes, particularly in managing machine vibrations that can lead to reduced product quality and increased wear and tear [6], [7]. When integrated with Industry 4.0 technologies such as IoT, AI, and machine learning, digital twins enhance operational efficiency and competitiveness by enabling continuous improvement and data-driven decision-making [7]. However, challenges like data integration complexity, substantial computational demands, and financial ramifications must be resolved to guarantee effective implementation [6].

Despite the potential of these technologies, their implementation in Indonesia's textile industry remains limited and understudied. Existing research on IoT and digital twin systems largely focuses on their application in advanced manufacturing industries, with limited emphasis on textile production in developing regions. This creates a gap in understanding how these technologies influence production efficiency within the unique operational, cultural, and economic context of West Java's textile industry. This study aims to analyze the impact of IoT-based predictive maintenance and digital twin technology on production efficiency in the textile industry in West Java.

2. LITERATURE REVIEW

2.1 Internet of Things (IoT)-Based Predictive Maintenance

Predictive maintenance, leveraging IoT, is a transformative approach in manufacturing, including the textile industry, aimed at reducing downtime, lowering costs, and enhancing equipment effectiveness. By utilizing IoT sensors, cloud computing, and data analytics, predictive maintenance enables real-time monitoring and analysis of equipment performance, predicting failures before they occur. This proactive strategy aligns with Industry 4.0

principles, promoting smarter manufacturing environments. However, challenges such as high implementation costs, lack of skilled personnel, and data security concerns remain barriers to adoption, especially in developing regions. Predictive maintenance can save maintenance expenses by as much as 40% and diminish equipment downtime by 50%, concurrently enhancing equipment reliability by 30–50% [8].

Additionally, AI-driven predictive maintenance enhances operational efficiency by optimizing resource utilization and maintenance scheduling [9]. Extending equipment lifespans and reducing energy consumption further contribute to environmental sustainability [5]. However, the implementation of predictive maintenance systems requires significant initial investment [5], and the need for specialized skills and technical complexity poses challenges [5]. Ensuring data security and model interpretability also remains a critical issue [9]. IoT sensors gather real-time data, which AI systems evaluate to forecast equipment malfunctions [8], supporting Industry 4.0 by enhancing connectivity and interoperability [9]. Moreover, advanced analytics techniques like machine learning and anomaly detection are employed to identify potential issues [10].

2.2 *Digital Twin Technology*

Digital twin technology improves manufacturing by generating virtual replicas of physical systems for real-time simulation and analysis. In the textile industry, it enables scenario testing, process optimization, and inefficiency detection without disrupting operations. This supports predictive analytics, improves decision-making, and boosts resource utilization, leading to greater agility, reduced waste, and better product quality. However, challenges such as high complexity, investment costs, and integration with legacy systems persist, particularly in regions like West Java. Digital twins aid predictive maintenance by simulating system behaviors, preventing quality issues and downtime [6].

In smart manufacturing, they process IoT sensor data with sub-second latency, essential for real-time decision-making [11]. Their incorporation of Industry 4.0 technologies, including IoT, AI, and machine learning, improves operational efficiency via real-time monitoring and optimisation [7]. Additionally, human-robot collaboration via digital twins and deep learning improves production quality and reduces downtime [12]. Principal obstacles encompass data integration intricacies, substantial computational requirements, and financial ramifications [6], along with difficulties in integrating digital twins with enterprise systems like ERP and MES, requiring scalable architectures [11].

2.3 *Production Efficiency in the Textile Industry*

Production efficiency in the textile industry is crucial for maintaining competitiveness, particularly in markets like Indonesia, and is achieved through optimizing machine utilization, reducing energy consumption, and minimizing downtime. Technological advancements such as IoT and digital twins enhance efficiency by providing real-time visibility and enabling rapid adjustments to production processes, while data analytics and predictive techniques further support operational improvements and sustainability. Comprehensive energy audits, like those in the Borujerd Textile Factory, highlight significant energy losses in steam and hot oil boilers, underscoring the need for efficiency improvements in heating processes [13]. Big Data and AI/ML optimize production by analyzing historical data to identify inefficiencies and predict trends, enabling manufacturers to make informed decisions on machine utilization and process adjustments [14].

Additionally, data analytics, combined with Lean Manufacturing and Six Sigma methodologies, streamlines production, reduces waste, and improves product quality, making supply chain optimization vital for sustainability [15]. IoT technologies further contribute by facilitating automation, quality control, and resource management, reducing energy and water consumption, and minimizing waste. In garment manufacturing, predictive analytics techniques like ensemble models improve decision-making and operational efficiency by managing labor, work-in-progress, and other critical production factors [16].

2.4 Theoretical Framework and Hypotheses Development

This study is theoretically grounded in the Technology-Organization-Environment (TOE) framework, which analyses the impact of technological, organisational, and environmental factors on technology adoption and its results. The TOE framework posits that the adoption of IoT and digital twin technologies is affected by perceived utility, organisational readiness, and external forces [17].

Based on the literature, this study hypothesizes that:

H1: IoT-based predictive maintenance has a positive impact on production efficiency.

H2: Digital twin technology has a positive impact on production efficiency.

H3: The combined implementation of IoT and digital twin technologies enhances production efficiency more significantly than either technology alone.

2.5 Research Gap

Although previous studies have highlighted the benefits of IoT and digital twins in manufacturing, limited research focuses on their application in the textile industry, especially in developing regions like West Java. Most studies are conducted in advanced economies, leaving a gap in understanding how these technologies can address the unique challenges of textile manufacturing in Indonesia.

By addressing this gap, the present study contributes to the existing body of knowledge by exploring the combined impact of IoT-based predictive maintenance and digital twin technology on production efficiency in the West Java textile industry.

3. METHODS

3.1 Research Approach

The quantitative approach was chosen to provide a structured and objective analysis of the relationships between the variables. Using this method, the study seeks to quantify the impact of IoT-based predictive maintenance and digital twin technology on production efficiency through statistical analysis. Structural Equation Modeling - Partial Least Squares (SEM-PLS) was utilized for data analysis, given its suitability for examining complex relationships between latent variables.

3.2 Population and Sample

The population of this study consists of stakeholders in the textile industry in West Java, including production managers, engineers, and technical staff involved in implementing Industry 4.0 technologies. A purposive sampling technique was used to ensure that the respondents had relevant knowledge and experience in IoT-based predictive maintenance and digital twin systems.

A total of 120 respondents were selected as the sample size. This sample size is considered sufficient for SEM-PLS analysis, which requires a minimum of 10 times the number of indicators in the most complex construct.

3.3 Data Collection

Data were collected through a structured questionnaire distributed to respondents via email and in-person interviews. The questionnaire was divided into three sections: demographic information, which included questions about respondents' roles, years of experience, and familiarity with IoT and digital twin technologies; variables measurement, which focused on assessing IoT-based predictive maintenance, digital twin technology, and production efficiency using validated scales; and optional open-ended questions that allowed respondents to provide additional insights or challenges regarding the implementation of these technologies. A 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree) was used to measure responses.

3.4 Variables and Measurements

The study involves the following variables: the independent variables include IoT-based predictive maintenance, measured using indicators such as real-time monitoring, predictive analytics, and maintenance scheduling, and digital twin technology, measured using indicators such as simulation capability, process optimization, and system integration. The dependent variable is production efficiency, which is measured using indicators such as machine utilization, downtime reduction, and output quality.

3.5 Data Analysis Techniques

The gathered data were examined utilising SEM-PLS, a robust statistical method appropriate for exploratory research and small to medium sample sizes. The analytical procedure comprised three essential phases: measurement model evaluation, which examined the reliability and validity of constructs via Composite Reliability (CR) and Average Variance Extracted (AVE), while confirming convergent and discriminant validity; structural model evaluation, which scrutinised the proposed relationships among variables using path coefficients and t-statistics, and assessed the coefficient of determination (R^2) to gauge the model's explanatory capacity; and bootstrapping analysis, which entailed performing bootstrapping with 5,000 subsamples to verify the robustness of the findings.

4. RESULTS AND DISCUSSION

4.1 Descriptive Statistics

The demographic analysis showed that the majority of respondents were production managers (45%), engineers (30%), and technical staff (25%), with an average of 7.5 years of experience in the textile industry. Most respondents reported familiarity with

IoT-based predictive maintenance (78%) and digital twin technology (65%), indicating a knowledgeable sample for assessing the impact of these technologies on production efficiency.

4.2 Measurement Model Evaluation

The constructs' reliability and validity were evaluated by Composite Reliability (CR), Cronbach's Alpha, and Average Variance Extracted (AVE). Reliability was validated as all constructs had CR values over 0.7 and Cronbach's Alpha surpassing 0.6, signifying substantial internal consistency. Convergent validity was established with AVE values beyond the 0.5 criterion, affirming that the indicators sufficiently represented their corresponding constructs. Discriminant validity was confirmed by the Fornell-Larcker criterion, guaranteeing that each construct was separate from the others. The results confirmed the measurement model, strengthening the integrity of the structural model analysis.

4.3 Structural Model Evaluation

The structural model was evaluated using path coefficients, t-statistics, and the coefficient of determination (R^2). All hypothesized paths were positive and statistically significant, as shown in Table 1. The R^2 value for production efficiency was 0.68, indicating that 68% of the variance in production efficiency was explained by IoT-based predictive maintenance and digital twin technology.

Table 1. Path Coefficients and Hypothesis Testing

Hypothesis	Path	Coefficient	t-Statistic	p-Value	Result
H1	IoT → PE	0.423	5.311	<0.001	Supported
H2	DT → PE	0.375	4.874	<0.001	Supported
H3	IoT + DT → PE	0.528	6.157	<0.001	Supported

(PE = Production Efficiency, DT = Digital Twin)

The hypothesis testing results confirmed that IoT-based predictive maintenance positively impacted production efficiency ($\beta = 0.423$, $p < 0.001$), while digital twin technology also had a significant positive influence on production efficiency ($\beta = 0.375$, $p < 0.001$). Furthermore, the combined implementation of IoT and digital twin technologies had the strongest impact ($\beta = 0.528$, $p < 0.001$), highlighting the synergistic effect of integrating these technologies in enhancing production efficiency.

Discussion

The findings highlight the transformative potential of IoT-based predictive maintenance and digital twin technology in improving production efficiency in the textile industry. IoT systems provide real-time insights into machinery performance, enabling predictive interventions that minimize downtime and reduce maintenance costs. These results underscore the importance of adopting IoT technologies to enhance operational reliability in high-stress textile production environments. Similarly, digital twin technology plays a crucial role by simulating and analyzing production processes, allowing manufacturers to optimize resource allocation and identify inefficiencies without disrupting operations. The positive impact of digital twins on production efficiency validates the growing interest in this technology within the textile industry.

Furthermore, the integration of IoT and digital twins offers a comprehensive approach to enhancing production efficiency. IoT serves as the data foundation, while digital twins enable actionable insights through simulation and optimization. This combination ensures a proactive and adaptive manufacturing environment, aligning with the principles of Industry 4.0 and providing a strategic advantage for textile manufacturers seeking to improve productivity, sustainability, and competitiveness.

Practical Implications

1. For Managers: The findings highlight the need to invest in IoT and digital twin technologies to remain competitive.
2. For Policymakers: The results advocate for supportive policies and training programs to facilitate technology adoption.
3. For Researchers: The study provides a foundation for exploring these technologies in other manufacturing sectors.

Limitations and Future Research

This study offers significant insights, although it possesses specific limitations:

The sample size was restricted to 120 responders, perhaps impacting the generalizability of the results.

The study focused on the textile industry in West Java, which may not represent other regions or industries.

Future research could explore the long-term impact of these technologies and their integration with other Industry 4.0 innovations, such as artificial intelligence and blockchain.

5. CONCLUSION

This research highlights the significant role of IoT-based predictive maintenance and digital twin technology in enhancing production efficiency within the textile industry in West Java. IoT-based predictive maintenance improves efficiency by reducing downtime and enabling proactive maintenance strategies, while digital twin technology enhances production through process simulation, optimization, and virtual testing. The combined implementation of these technologies yields the highest efficiency gains, demonstrating their complementary and synergistic effects. These findings emphasize the transformative potential of integrating Industry 4.0 technologies in manufacturing, fostering a more adaptive and efficient operational environment. For industry practitioners, adopting IoT and digital twin technologies can lead to substantial improvements in operational performance, while policymakers can facilitate adoption by developing supportive infrastructure and training programs for the textile sector. Additionally, researchers can explore the application of these technologies in other industries and assess their long-term benefits. By leveraging these insights, the textile industry can embrace technological advancements to achieve sustainable growth and competitiveness in a rapidly evolving market.

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