Digital Twins (DT) and Artificial Intelligence (AI) Affect Sustainability Outcomes- Operational Performance- Waste Reduction, and Energy Efficiency

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Abstract

Background: Digital Twins (DT) and Artificial Intelligence (AI) have become new groundbreaking technologies, allowing real-time monitoring, predictive analytics, and data-based optimization to increase energy efficiency, minimize waste, and streamline the work process.

Purpose: The study aims to investigate the effects of the use of DT and AI on sustainable industrial activities in terms of energy efficiency, waste minimization, and performance in manufacturing and energy industries. The data were analyzed using descriptive statistics, multiple linear regression, and the ANOVA method to test the relationships between DT and AI adoption sustainability outcomes, maintaining the industry type and organization size as controlled variables.

Methodology: The total respondents in this research is 50, stratified purposive sampling was used to represent. The sources of data are primary – Manufacturing, energy, etc, organization, and sources of secondary data are reports by companies.

Findings: The performance in operations was found to have a strong and positive impact of DT and AI ($\beta = 0.65$, $p < 0.01$). The application of DT and AI within organizations has led to optimized predictive maintenance, reduced downtime, improved production schedules, and increased productivity. The R^2 of 0.691 indicates that almost 70 percent of the change in operating performance can be explained by the use of technology, demonstrating the applicability of these digital tools in developing operational excellence. In manufacturing organizations, the greatest gains in predictive maintenance (30-35 percent) and downtime reduction (30-35 percent), and moderate gains in logistics, illustrated the diversity of the operational problems in different spheres.

Conclusion: These findings imply the necessity of tailoring the plans of the implementation of DT and AI to industry-specific pressures, workflow, and sustainability objectives. Digital twins (DT) and artificial intelligence (AI) need to be strategically

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introduced in industrial companies to enhance energy efficiency and waste reduction, and improve operational performance.
Keywords: DT, AI, Sustainability, Operational Performance, Waste Reduction, and Energy Efficiency.

1. Introduction

Digital twins are a reflection of physical systems that can simulate them in real-time, observe them, and predict their behavior, unlike AI, which provides high-level computational intelligence to calculate services and optimize processes on large volumes of data, and assist in decision-making. The two tools are complementary, enabling companies to achieve sustainability goals and operational excellence simultaneously, which aligns with the spirit of Industry 6.0 (Babu, 2025). The strategic implementation of AI in business advancement, AI advantages in business are many more, like enhancing efficiency, cost of production, improving supply chain and logistics, innovation, and competitive advantages, etc. (Rai, P, 2025). Digital Twins (DT) and Artificial Intelligence (AI) have the potential to offer a revolutionary solution. DT enables real-time tracking, predictive maintenance, and simulation of a scenario when compared to AI, which can optimize them based on data, find anomalies, and automatically simulate them (Drissi Elbouzidi, 2023). They are all aimed at the enhancement of energy efficiency, reduction of waste, and performance in sectors (Emmert-Streib, 2023). To illustrate that, predictive maintenance based on DT and AI can save time, prevent defective production, and consume less energy (Gomaa, 2025).

1.2.Problem Statement

The interactive impact of them on a variety of sectors, with particular focus on real sustainability impacts, sector sensitivity, and adoption strategies, has little empirical evidence (Radanliev, 2022). This opening is significant to assist in guiding managers, technology developers, and policymakers, as well as leading theoretical understanding in the industry 6.0 framework (Rahmani, 2024).

1.3.Significance of the Study

This research contributes to the existing literature on Industry 4.0 by offering a theoretical basis for forthcoming research on Industry 6.0, as well as expanding on prior research on Industry 4.0 to encompass Digital Twins and AI in a sustainability framework (Ranawaka, 2024; Rojas, 2025).

1.4.Objective

- To assess how the implementation of DT and AI affects sustainability outcomes, such as operational performance, waste reduction, and energy efficiency.

2. Literature Review

Fantozzi et al. (2025) took into consideration the role of DTs in Industry 4.0, which meant that they became important tools in the real-time monitoring, simulation, and optimization of production processes. They have demonstrated that the integration of DTs with AI, IoT, and Machine Learning may assist in enhancing the efficiency of operations, reducing downtimes, and improving maintenance policies. Rakshit et al. (2024) elaborated on the role of AI in the development of digital twins, which is based on the capacity of AI to perform higher degrees of analytics and predictive modelling. They said that DTs were electronic versions of physical products, machines, or systems, and that AI contributed to improved predictive maintenance, simulation, and optimization. Real-time data analysis allowed AI algorithms to discover patterns and anomalies and make proactive interventions, reduce costs, and enhance work performance. The authors have determined that the AI has a profound beneficial effect on the accuracy and efficiency of the digital twin model, allowing organizations to streamline their functions and make sound decisions (Rakshit, 2024). It has been emphasized that to implement the AI-based DT successfully in the domain of smart manufacturing and advanced robotics, it is necessary to apply domain-specific knowledge. It also discussed the possible advantages of AI-based DTs to sustainable development and explained the practical concerns and the future of the technologies in different industries (Huang, 2021). The paper has highlighted that Digital Twins (DT) and Artificial Intelligence (AI), combined with Internet of Things (IoT) technologies, assisted organizations in reacting to environmental, social, and governance (ESG) concerns in different ways. Examples included recycling on command, sensible utilization of energy, smart surveillance to regulate crime, and predictive upkeep of financial technology systems (Al-Qudah, 2025). In addition, they speculated on the benefits of DTs in sustainable development and recommended how AI could be implemented in multi-fidelity DTs with quality data sources (Samuel, 2023).

3. Research Methodology

This research paper uses a quantitative, descriptive-exploration research design to evaluate the effect of the Digital Twin (DT) and Artificial Intelligence (AI) implementation on environmentally friendly industrial operations and their energy consumption, waste minimization, and performance. Descriptive aspect trends of the adoption of DT and AI by industries. The explanatory aspect investigates the causal law between DT and AI adoption and sustainability results. One of the population-manufacturing, energy, and the implementation of DT and AI. The total respondents in this research is 50, stratified purposive sampling to represent. The sources of data are primary – Manufacturing, energy, etc, SML (Small, Medium, and Large) organization, and sources of secondary data are reports by companies, IoT sensors, and industrial data, including energy usage, emissions, waste, production output, downtime, and predictive maintenance efficiency.

3.1 Hypotheses

H1: Effect of DT & AI Adoption on Operational Performance

- Null Hypothesis (H0): The operational performance of industrial activities is unaffected by the use of DT and AI.
- Alternative Hypothesis (H1): DT and AI significantly improve operational performance in industrial operations (H1).

Test Applied

Multiple Linear Regression

- It's because the DT & AI adoption index is a quantitative variable and operational performance is a continuous dependent variable.
- To account for any confounding factors, we include control variables such as industry and organisation size.
- We can get the 8-coefficients, t-values, and p-values needed to test the hypothesis using this method, which allows us to discover the intensity, direction, and significance of the relationship between DT and AI adoption and operation performance.

Table 1: Regression Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.831	0.691	0.684	4.102

R is 0.831 which demonstrates the strong positive correlation between DT and AI adoption and operational performance. This value of R 2 (0.691) indicates that the variance in operational performance can be explained by the adoption of DT and AI as well as the control variables by about 69.1. The adjusted R 2 of 0.684 indicates that there is still a high degree of explanatory power in the model despite the number of predictors having been adjusted. The standard error of 4.102 demonstrates good predictive accuracy in 50 sampled organisations.

Table 2: ANOVA Results

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	1342.56	3	447.52	26.64	0.000
Residual	771.44	46	16.77	0.00	0.000
Total	2114.00	49	464.29	26.64	0.000

It means that the regression model is very significant ($F(3,46) = 26.64$, $p < 0.01$). This establishes that the use of DT & AI, along with control variables, creates a significant predictor of operational performance. On a practical level, this shows that organisations that incorporate Digital Twins and AI into their processes obtain quantifiable increases in the overall performance levels.

Table 3: Regression Coefficients

Model	B	Std. Error	Beta	t	Sig.
Constant	61.21	3.32		18.43	0.000
DT & AI Adoption	6.87	1.48	0.65	4.64	0.000
Industry Type (Control)	1.55	0.92	0.13	1.68	0.100
Organization Size (Control)	1.31	0.85	0.11	1.54	0.129

- The constant (61.21) is the expected performance of the operation of the organization when all the predictors are zero.
- Considering this, DT & AI adoption (B = 6.87, = 0.65, $p < 0.01$) exhibits a significant positive impact on operational performance, i. e. as the adoption of DT and AI increases by 1 unit, the operational performance increases by approximately 6.87 units, otherwise remaining constant.
- Control variables (type of industry and size of organization) are not statistically significant, which means that the operational performance improvement is primarily due to the use of DT and AI, but not the peculiarities of organizations.

4. Results & Discussion

Effect of DT & AI Adoption on Operational Performance

The performance in operations was found to have a strong and positive impact of DT and AI ($\beta = 0.65$, $p < 0.01$). The application of DT and AI within organizations has led to optimized predictive maintenance, reduced downtime, improved production schedules, and increased productivity. The R^2 of 0.691 indicates that almost 70 percent of the change in operating performance can be explained by the use of technology, demonstrating the applicability of these digital tools in developing operational excellence. In manufacturing organizations, the greatest gains in predictive maintenance (30-35 percent) and downtime reduction (30-35 percent), and moderate gains in logistics, illustrated the diversity of the operational problems in different

spheres. These findings confirm the findings of Huang et al. (2021) and Li (2021) since they also emphasized that AI-enhanced DTs can be used to improve the efficiency of the processes, the reliability of the systems, and real-time decision-making.

5. Conclusion And Recommendations

The Digital Twins (DT) and Artificial Intelligence (AI) integration is effective to support sustainable industrial processes in manufacturing and energy, as per this research. According to the findings, sectoral features and organizational scale might play a minor role, but the key factor in the guarantee of sustainable results is the strategic implementation of DT and AI technologies. Quantitative data showing a causal relationship between advanced digital technology and sustainable performance is provided by the research, which also extends the theory by expanding the corpus of Industry 4.0 research to the Industry 6.0 paradigm. Firstly, the implementation of DT and AI is a crucial enabler of the operational, environmental, and long-term sustainability, which points to its radicalism in the current industrial ecosystems. There was also an interesting pattern of the sectors, which were revealed in the comparative analysis. The greatest total efficiency increase was in manufacturing due to extensive use of predictive maintenance and optimization of the manufacturing process. The energy sector, although with slightly lower adoption rates, prioritized sustainability results: energy optimization and reduction of emissions, as it is a sectoral priority and a regulatory force. The logistics organizations, despite having a moderate adoption, showed a positive impact on their operations and environmental measures. Rai P. et al, the coming time community will use green computing, emphasizing the efficient and right utilization of computers and process of processes and computing. Green computing has different strengths and weaknesses.

5.1 Recommendations

- Introduce predictive maintenance that is made easier by DT and AI so that there is very little downtime, fewer defective products, and resources are used more efficiently.
- Adapt DT and AI implementation mechanisms to industry requirements, e.g. manufacturing (cut downtimes, quality management), energy (cut emissions, energy efficiency), logistics (efficient processes, efficient routes).

5.2 Limitations and Future Research

The study is very informative, but there are some limitations. The sample size is 50 organizations, which potentially does not provide the possibility of generality. Future studies with more than 50 sample sizes, which examine the better effect of sustainability, incorporate the use of the technology maturity model to modernize the knowledge of DI and AI in different industrial environments.

References

1. Babu, C. S., Afreed, M. N., Sree, V. S., & Arshath, J. M. (2025). The Role of Digital Twins in AI-Driven Industry 4.0 and 5.0: Enhancing Sustainability and Innovation. *AI-Driven Smart Industrial Technologies*, 243-284.
2. Rai. P., Velmurugan P (2025), In book: Artificial Intelligence, Machine Learning and IoT for Smart Business Management, published 2025, CRC Press, DOI:10.1201/9781003561873-
3. Emmert-Streib, F. (2023). What is the role of AI for digital twins?. *AI*, *4*(3), 721-728.
4. Gomaa, A. H. (2025). Transforming Manufacturing from Industry 4.0 to Industry 6.0: A Comprehensive Review, Gap Analysis, and Strategic Framework. *Interdisciplinary Systems for Global Management*, *1*(1), 29-51.
5. Radanliev, P., De Roure, D., Nicolescu, R., Huth, M., & Santos, O. (2022). Digital twins: artificial intelligence and the IoT cyber-physical systems in Industry 4.0. *International Journal of Intelligent Robotics and Applications*, *6*(1), 171-185.
6. Rahmani, R., Jesus, C., & Lopes, S. I. (2024). Implementations of Digital Transformation and Digital Twins: Exploring the Factory of the Future. *Processes*, *12*(4), 787.
7. Ranawaka, A., Alahakoon, D., Sun, Y., & Hewapathirana, K. (2024). Leveraging the Synergy of Digital Twins and Artificial Intelligence for Sustainable Power Grids: A Scoping Review. *Energies*, *17*(21), 5342.
8. Fantozzi, I. C., Santolamazza, A., Loy, G., & Schiraldi, M. M. (2025). Digital twins: Strategic guide to utilize digital twins to improve operational efficiency in Industry 4.0. *Future Internet*, *17*(1), 41.
9. Rakshit, P., Saha, N., Nandi, S., & Gupta, P. (2024). Artificial Intelligence in Digital Twins for Sustainable Future. In *Transforming Industry Using Digital Twin Technology* (pp. 19-44). Cham: Springer Nature Switzerland.
10. Huang, Z., Shen, Y., Li, J., Fey, M., & Brecher, C. (2021). A survey on AI-driven digital twins in industry 4.0: Smart manufacturing and advanced robotics. *Sensors*, *21*(19), 6340.
11. Jiang, Y., Yin, S., Li, K., Luo, H., & Kaynak, O. (2021). Industrial applications of digital twins. *Philosophical Transactions of the Royal Society A*, *379*(2207), 20200360.
12. Al-Qudah, A. A., Abdalmuttaleb, M. A., Al-Sartawi, M., & Shihadeh, F. (Eds.). (2025). *Artificial intelligence-augmented digital twins: transforming industrial operations for innovation and sustainability*. Springer International Publishing AG.
13. Samuel, P., Saini, A., Poongodi, T., & Nancy, P. (2023). Artificial intelligence–driven digital twins in Industry 4.0. In *Digital Twin for Smart Manufacturing* (pp. 59-88). Academic Press.
14. *Rai P.,* Rawat Y (2023)Trends and Challenges in Green Computing BookSustainable Digital Technologies Edition1st Edition, First Published2023, Imprint CRC Press, Pages 26, eBook ISBN9781003348313