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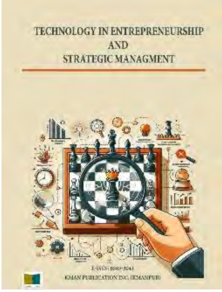

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The Role of Digital Twins in Optimizing Manufacturing Processes for Small Businesses

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ABSTRACT

This study aims to investigate the role of digital twins in enhancing the efficiency, quality, and competitiveness of small manufacturers, identifying key motivations, impacts, challenges, and future benefits. This qualitative study employed semi-structured interviews to gather in-depth insights from 28 key stakeholders in small manufacturing businesses that have implemented digital twin technology. Participants included business owners, operations managers, and IT specialists. The data were transcribed and analyzed using NVivo software, following a thematic analysis approach to identify and categorize recurring themes and concepts. The analysis revealed four main themes: Adoption of Digital Twins, Impact on Manufacturing Efficiency, Challenges and Barriers, and Future Outlook and Benefits. Key motivations for adoption included cost reduction, efficiency improvement, and competitive advantage. Digital twins significantly enhanced manufacturing efficiency through process optimization, quality control, and cost management. Major challenges encompassed technical barriers, financial constraints, organizational resistance, and regulatory issues. The future outlook for digital twins was positive, with potential long-term benefits and advancements in AI and IoT expected to further enhance their capabilities. Digital twins offer substantial benefits for small manufacturing businesses, including improved efficiency, quality control, and cost management. However, successful implementation requires addressing technical, financial, and organizational challenges. With continued technological advancements and strategic support, digital twins are likely to become integral to small manufacturers, driving innovation and competitiveness in the industry.

Keywords: *Digital twins, small manufacturing businesses, process optimization, quality control, cost management, technological adoption*

Introduction

In the rapidly evolving landscape of modern manufacturing, small businesses face increasing pressure to enhance productivity, reduce costs, and maintain competitiveness. One emerging technological innovation that holds promise in addressing these challenges is the concept of digital twins. A digital twin is a virtual replica of a physical entity or system, designed to simulate, predict, and optimize performance throughout its lifecycle (Lu et al., 2020). By creating a digital representation, businesses can leverage real-time data and advanced analytics to drive improvements in efficiency, quality, and decision-making processes.

The concept of digital twins has gained significant traction in recent years, particularly within large-scale manufacturing sectors. However, the potential benefits for small businesses remain relatively underexplored. This study aims to investigate the role of digital twins in optimizing manufacturing processes for small businesses, focusing on their adoption, impacts, challenges, and future outlook. Through qualitative research involving semi-structured interviews with key stakeholders, this study seeks to provide a comprehensive understanding of how digital twins can be utilized to enhance the operational capabilities of small manufacturers (Huang et al., 2022; Lu et al., 2020; Rasheed et al., 2020).

The adoption of digital twins in manufacturing is driven by several factors, including the need for enhanced efficiency, cost reduction, and improved product quality. As Baalbergen et al. (2023) highlight, digital twins enable the optimization of production processes by providing real-time insights into the performance and health of manufacturing systems (Baalbergen et al., 2023). This capability is particularly beneficial in the production of complex components, such as those used in the aerospace industry. Similarly, Choi (2023) demonstrates the value of digital twins in virtual qualification and product development, specifically within the context of liquid crystal display manufacturing. These applications underscore the versatility and potential of digital twins across various manufacturing domains (Choi, 2023).

For small businesses, the implementation of digital twins offers several potential advantages. First, digital twins can help small manufacturers optimize their resource allocation, reduce downtime, and enhance production planning. As Huang et al. (2022) point out, digital validation based on digital twin frameworks can accelerate product development cycles and improve time-to-market (Huang et al., 2022). Moreover, the integration of digital twins with advanced technologies such as artificial intelligence (AI) and the Internet of Things (IoT) can further enhance their effectiveness, enabling predictive maintenance, real-time monitoring, and data-driven decision-making (Ghosh et al., 2019; Lu et al., 2020).

Despite these benefits, small businesses often face significant barriers to adopting digital twin technology. Financial constraints, technical challenges, and organizational resistance are common obstacles that can hinder the successful implementation of digital twins (Rasheed et al., 2020). Additionally, ensuring the security and reliability of digital twin models is crucial, as any discrepancies between the virtual and physical entities can lead to inaccurate predictions and suboptimal outcomes (Schleich et al., 2017). Understanding these challenges is essential for developing strategies to support small businesses in leveraging digital twins effectively.

The concept of digital twins originated in the aerospace industry, where it was initially used to improve the maintenance and performance of aircraft systems (Baalbergen et al., 2023). Since then, the

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application of digital twins has expanded to various sectors, including automotive, electronics, and consumer goods manufacturing. Choi (2023) highlights the role of digital twins in virtual qualification processes, where they are used to simulate and validate the performance of new products before physical prototypes are built. This approach not only reduces development costs but also shortens the time required to bring new products to market (Choi, 2023).

In the context of smart manufacturing, digital twins are seen as a key enabler of Industry 4.0, which emphasizes the use of digital technologies to create intelligent, interconnected manufacturing systems (Lu et al., 2020). By integrating digital twins with IoT devices, manufacturers can collect real-time data from their production processes and use this information to optimize operations. For example, predictive maintenance enabled by digital twins can help manufacturers identify potential equipment failures before they occur, thereby reducing downtime and maintenance costs (Ghosh et al., 2019).

Despite the growing interest in digital twins, their adoption in small and medium-sized enterprises (SMEs) remains limited. One reason for this is the high initial cost of implementing digital twin technology, which can be prohibitive for smaller businesses with limited budgets (Rasheed et al., 2020). Additionally, SMEs may lack the technical expertise required to develop and maintain digital twin models, making it difficult for them to fully realize the benefits of this technology. Organizational resistance to change is another significant barrier, as employees may be hesitant to adopt new technologies that require them to learn new skills and processes (Hawkinson, 2023).

However, the potential benefits of digital twins for SMEs are substantial. As Li et al. (2020) suggest, digital twins can support sustainability in manufacturing by enabling more efficient use of resources and reducing waste (Li et al., 2020). Moreover, the ability to simulate and optimize production processes in a virtual environment can help SMEs improve their competitiveness in the market. Huang et al. (2022) emphasize the importance of digital validation in rapid product development, which can be particularly beneficial for SMEs looking to innovate and expand their product offerings (Huang et al., 2022).

The primary objective of this study is to explore the role of digital twins in optimizing manufacturing processes for small businesses. Specifically, the research aims to:

- Identify the motivations and drivers behind the adoption of digital twin technology in small manufacturing businesses.
- Examine the impacts of digital twins on manufacturing efficiency, quality control, and cost management.
- Investigate the challenges and barriers faced by small businesses in implementing digital twin technology.
- Assess the future outlook and potential benefits of digital twins for small manufacturers.

By addressing these objectives, the study seeks to provide valuable insights into how small businesses can leverage digital twin technology to enhance their operational capabilities and achieve long-term sustainability.

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Methods and Materials

This qualitative study employs a semi-structured interview approach to gather in-depth insights into the role of digital twins in optimizing manufacturing processes for small businesses. The choice of a qualitative methodology is driven by the need to explore complex, contextual, and nuanced aspects of digital twin adoption and its impacts on small-scale manufacturing.

The primary method of data collection involved semi-structured interviews with key stakeholders from small manufacturing businesses that have implemented digital twin technology. These stakeholders included business owners, operations managers, and IT specialists who have direct experience with digital twin applications. The semi-structured format allowed for flexibility in questioning, enabling the interviewer to delve deeper into specific topics as they arose during the conversation.

Interview Guide:

- Introduction to the interview's purpose and ensuring confidentiality.
- General questions about the business and its manufacturing processes.
- Specific questions about the adoption of digital twin technology:
    - Motivations for adopting digital twins.
    - Implementation process and challenges faced.
    - Types of digital twins used and their applications.
- Impact of digital twins on manufacturing efficiency, cost reduction, and decision-making.
- Future outlook and perceived benefits of continued digital twin use.

Participants were selected using purposive sampling to ensure a diverse representation of small businesses across different manufacturing sectors. The sample included businesses varying in size, industry, and geographical location to capture a wide range of experiences and insights. Recruitment continued until theoretical saturation was achieved, meaning that additional interviews no longer provided new information or themes relevant to the study.

Interviews were conducted either face-to-face or via video conferencing platforms, depending on the participants' preferences and availability. Each interview lasted approximately 60 to 90 minutes and was audio-recorded with the participants' consent. Field notes were also taken to capture non-verbal cues and contextual details that could enrich the data analysis.

The collected interview data were transcribed verbatim and imported into NVivo software for coding and analysis. NVivo, a qualitative data analysis software, facilitated the organization and examination of large volumes of textual data. The analysis followed these steps:

1. **Initial Coding:**
    - Transcripts were read multiple times to gain familiarity with the content.
    - Initial codes were generated based on recurring words, phrases, and concepts.
2. **Focused Coding:**
    - Codes were refined and categorized into broader themes and sub-themes.
    - The coding scheme was iteratively adjusted to reflect emerging patterns and insights.
3. **Thematic Analysis:**
    - Themes were analyzed to understand their interconnections and implications.

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- Key findings were derived by synthesizing the coded data and identifying core themes related to the research questions.

Findings

The study included 28 participants from various small manufacturing businesses that have implemented digital twin technology. The participants were comprised of 10 business owners (35.7%), 8 operations managers (28.6%), and 10 IT specialists (35.7%). The businesses represented a diverse range of industries, including automotive, electronics, consumer goods, and textiles. Participants' experience with digital twins varied, with 12 individuals (42.9%) having less than one year of experience, 9 individuals (32.1%) having one to three years of experience, and 7 individuals (25%) having more than three years of experience. Geographically, the businesses were located across different regions, with 14 participants (50%) from urban areas and 14 participants (50%) from rural areas.

Table 1

Themes, Subthemes, and Concepts

Theme	Subtheme	Concepts (Open Codes)
1. Adoption of Digital Twins	Motivations for Adoption	- Cost reduction- Efficiency improvement- Competitive advantage
	Implementation Challenges	- Technical difficulties- High initial costs- Integration with existing systems- Lack of expertise- Resistance to change
	Support and Training	- Training programs- External consultancy- Knowledge sharing among staff
	Decision-Making Process	- Stakeholder involvement- Risk assessment- Cost-benefit analysis
2. Impact on Manufacturing Efficiency	Process Optimization	- Reduced downtime- Improved resource allocation- Enhanced production planning
	Quality Control	- Real-time monitoring- Predictive maintenance- Defect detection
	Cost Management	- Waste reduction- Energy efficiency- Inventory management
	Scalability	- Adaptation to production scale- Flexibility in operations- Future expansion capabilities
	Time-to-Market	- Faster prototyping- Accelerated development cycles
3. Challenges and Barriers	Technical Barriers	- Integration with legacy systems- Data security concerns- Reliability of digital twin models
	Financial Constraints	- Initial investment costs- Ongoing maintenance expenses- Budget limitations
	Organizational Resistance	- Employee resistance- Change management issues- Cultural barriers
	Regulatory and Compliance Issues	- Compliance with industry standards- Regulatory approvals- Data privacy regulations
4. Future Outlook and Benefits	Long-term Benefits	- Sustained cost savings- Continuous process improvement- Enhanced competitiveness
	Technological Advancements	- AI integration- Advanced analytics- IoT developments
	Industry Trends	- Increased adoption across sectors- Collaboration with tech providers- Emergence of new use cases
	User Experiences	- Satisfaction with outcomes- User feedback- Case studies and success stories
	Scalability and Flexibility	- Adaptability to new projects- Scalability of solutions- Customization for specific needs

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The analysis of the semi-structured interviews revealed four main themes regarding the role of digital twins in optimizing manufacturing processes for small businesses. These themes are: Adoption of Digital Twins, Impact on Manufacturing Efficiency, Challenges and Barriers, and Future Outlook and Benefits. Each theme includes various subthemes and concepts, which are detailed below along with representative quotations from the interviews.

1. Adoption of Digital Twins

Motivations for Adoption

Small businesses adopt digital twins primarily for cost reduction, efficiency improvement, and gaining a competitive advantage. As one business owner mentioned, "Implementing digital twins has significantly reduced our operational costs and improved our overall efficiency."

Implementation Challenges

The process of implementing digital twins is fraught with challenges such as technical difficulties, high initial costs, integration with existing systems, lack of expertise, and resistance to change. An operations manager noted, "The biggest hurdle was integrating the digital twin with our current systems; it required a lot of technical adjustments and expert guidance."

Support and Training

Support and training are crucial for successful digital twin adoption. This includes training programs, external consultancy, and knowledge sharing among staff. An IT specialist shared, "We invested in extensive training and brought in consultants to help us understand and utilize digital twins effectively."

Decision-Making Process

The decision-making process for adopting digital twins involves stakeholder involvement, risk assessment, and cost-benefit analysis. A stakeholder emphasized, "Deciding to implement digital twins was a collective decision; we had to weigh the risks and benefits thoroughly."

2. Impact on Manufacturing Efficiency

Process Optimization

Digital twins enhance process optimization by reducing downtime, improving resource allocation, and enhancing production planning. One manager highlighted, "With digital twins, we've managed to cut down on downtime and make better use of our resources."

Quality Control

Quality control sees improvements through real-time monitoring, predictive maintenance, and defect detection. As stated by a quality control supervisor, "The real-time monitoring capabilities of digital twins have been a game-changer for our quality control processes."

Cost Management

Digital twins aid in cost management by reducing waste, improving energy efficiency, and managing inventory more effectively. A business owner remarked, "We've seen a noticeable decrease in waste and energy costs since adopting digital twins."

Scalability

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Digital twins provide scalability benefits, allowing adaptation to production scale, operational flexibility, and future expansion capabilities. An interviewee mentioned, "Digital twins offer the flexibility we need to scale our operations as we grow."

Time-to-Market

The time-to-market for new products is shortened with faster prototyping and accelerated development cycles. A product manager stated, "Digital twins have significantly sped up our prototyping process, getting our products to market faster."

3. Challenges and Barriers

Technical Barriers

Technical barriers include integration with legacy systems, data security concerns, and the reliability of digital twin models. An IT expert explained, "Ensuring the reliability and security of our digital twin models has been quite challenging."

Financial Constraints

Financial constraints are a significant barrier, with initial investment costs, ongoing maintenance expenses, and budget limitations being key concerns. A small business owner shared, "The initial cost of implementing digital twins was a major financial hurdle for us."

Organizational Resistance

Organizational resistance encompasses employee resistance, change management issues, and cultural barriers. A manager noted, "Getting everyone on board with the new technology was tough; there was a lot of resistance at first."

Regulatory and Compliance Issues

Regulatory and compliance issues include adhering to industry standards, obtaining regulatory approvals, and ensuring data privacy. An operations manager stated, "Navigating the regulatory landscape and ensuring compliance has been a significant part of our digital twin journey."

4. Future Outlook and Benefits

Long-term Benefits

Long-term benefits of digital twins include sustained cost savings, continuous process improvement, and enhanced competitiveness. A business owner said, "In the long run, the benefits of digital twins are clear – we're seeing continuous improvements and staying competitive."

Technological Advancements

Future advancements such as AI integration, advanced analytics, and IoT developments will further enhance the capabilities of digital twins. An IT specialist noted, "The integration of AI and advanced analytics with digital twins is an exciting prospect for the future."

Industry Trends

Trends include increased adoption across sectors, collaboration with tech providers, and the emergence of new use cases. A respondent commented, "We're seeing more small businesses like ours adopting digital twins and collaborating with technology providers."

User Experiences

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User experiences highlight satisfaction with outcomes, user feedback, and case studies of success stories. An interviewee shared, "The feedback from our team has been overwhelmingly positive, and we've documented several success stories."

Scalability and Flexibility

Scalability and flexibility benefits include adaptability to new projects, scalability of solutions, and customization for specific needs. A manager remarked, "The scalability and customization options of digital twins have been crucial for our diverse project needs."

These themes and subthemes provide a comprehensive understanding of how digital twins optimize manufacturing processes for small businesses, highlighting both the challenges and benefits experienced by practitioners in the field.

Discussion and Conclusion

The findings of this study provide significant insights into the role of digital twins in optimizing manufacturing processes for small businesses. The analysis revealed four main themes: adoption of digital twins, impact on manufacturing efficiency, challenges and barriers, and future outlook and benefits. This section discusses these results in detail, aligning them with previous studies and supporting the findings with existing literature.

The study found that small businesses are motivated to adopt digital twin technology primarily to reduce costs, improve efficiency, and gain a competitive advantage. These motivations align with those identified by Baalbergen et al. (2023), who highlighted the potential of digital twins to enhance production processes and reduce operational costs in the aerospace industry. The flexibility and real-time capabilities of digital twins make them an attractive option for small manufacturers looking to optimize their operations (Baalbergen et al., 2023).

However, the implementation process is not without challenges. Participants reported facing technical difficulties, high initial costs, and issues with integrating digital twins into existing systems. These challenges are consistent with the findings of Rasheed et al. (2020), who identified financial constraints and technical barriers as significant obstacles to digital twin adoption (Rasheed et al., 2020). The lack of expertise and resistance to change further complicates the implementation process, as noted by several participants. This echoes the observations of Schleich et al. (2017), who emphasized the need for adequate training and support to overcome these barriers (Schleich et al., 2017).

Support and training were found to be crucial for successful adoption. Small businesses benefited from training programs, external consultancy, and knowledge sharing among staff. This finding aligns with Choi (2023), who stressed the importance of continuous support and training to maximize the benefits of digital twin technology (Choi, 2023). The decision-making process for adopting digital twins involved thorough risk assessment and cost-benefit analysis, reflecting a cautious and strategic approach by small business owners.

Digital twins have a profound impact on manufacturing efficiency, particularly in process optimization, quality control, and cost management. The ability to reduce downtime, improve resource allocation, and enhance production planning was highlighted by participants as a key benefit. These

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advantages are supported by Huang et al. (2022), who demonstrated that digital twins facilitate rapid product development and efficient production planning (Huang et al., 2022).

Quality control also saw significant improvements through real-time monitoring, predictive maintenance, and defect detection. This is consistent with the findings of Ghosh et al. (2019), who emphasized the role of digital twins in predictive maintenance and real-time monitoring to enhance product quality. The ability to detect defects early and perform maintenance proactively helps in reducing waste and improving overall product quality (Ghosh et al., 2019).

Cost management is another area where digital twins prove beneficial. Participants reported reductions in waste, improved energy efficiency, and better inventory management. This aligns with the sustainability assessment by Li et al. (2020), who highlighted the environmental and economic benefits of digital twins in intelligent manufacturing. The technology enables more efficient use of resources, contributing to cost savings and sustainability (Li et al., 2020).

Scalability and flexibility were also identified as important benefits of digital twins. The technology allows small businesses to adapt to changes in production scale and future expansion needs. This finding is supported by Lu et al. (2020), who discussed the scalability and adaptability of digital twins in smart manufacturing environments. The ability to scale operations and customize solutions for specific needs makes digital twins a valuable tool for small businesses (Lu et al., 2020).

Despite the numerous benefits, small businesses face significant challenges in implementing digital twin technology. Technical barriers such as integration with legacy systems, data security concerns, and ensuring the reliability of digital twin models were common issues. These challenges are consistent with the findings of Rasheed et al. (2020), who identified data security and model reliability as critical concerns in digital twin adoption (Rasheed et al., 2020).

Financial constraints were another major barrier, with high initial investment costs and ongoing maintenance expenses posing significant challenges. This aligns with the observations of Baalbergen et al. (2023), who noted the financial hurdles in adopting advanced technologies like digital twins. Small businesses often operate with limited budgets, making it difficult to allocate sufficient resources for implementing and maintaining digital twin systems (Baalbergen et al., 2023).

Organizational resistance, including employee resistance and cultural barriers, also hindered the adoption process. Participants highlighted the need for effective change management to overcome these challenges. This finding is supported by Hawkinson (2023), who emphasized the importance of addressing organizational resistance and fostering a culture of innovation to successfully implement digital twins (Hawkinson, 2023).

Regulatory and compliance issues were identified as additional barriers. Ensuring compliance with industry standards and data privacy regulations posed significant challenges for small businesses. This echoes the findings of Schleich et al. (2017), who stressed the need for regulatory alignment and compliance in the successful deployment of digital twins (Schleich et al., 2017).

The future outlook for digital twins in small manufacturing businesses is promising, with long-term benefits including sustained cost savings, continuous process improvement, and enhanced competitiveness. Participants expressed optimism about the potential of digital twins to drive future

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growth and innovation. This optimism is reflected in the work of Lu et al. (2020), who highlighted the transformative potential of digital twins in smart manufacturing (Lu et al., 2020).

Technological advancements such as AI integration, advanced analytics, and IoT developments are expected to further enhance the capabilities of digital twins. Participants noted the potential for these technologies to provide deeper insights and more sophisticated optimization of manufacturing processes. This aligns with the findings of Ghosh et al. (2019), who discussed the integration of AI and IoT with digital twins to create more intelligent and responsive manufacturing systems (Ghosh et al., 2019).

Industry trends indicate increasing adoption of digital twins across various sectors, with small businesses collaborating with technology providers to leverage this innovation. Participants highlighted the emergence of new use cases and the potential for digital twins to address specific industry challenges. This trend is supported by Baalbergen et al. (2023), who observed the growing adoption of digital twins in the aerospace industry and beyond (Baalbergen et al., 2023).

User experiences with digital twins have been largely positive, with participants reporting satisfaction with the outcomes and providing feedback for continuous improvement. The documentation of success stories and case studies further validates the benefits of digital twins in small manufacturing businesses. This finding is consistent with Choi (2023), who emphasized the importance of user feedback and case studies in demonstrating the value of digital twin technology (Choi, 2023).

The scalability and flexibility of digital twins make them well-suited for small businesses, allowing for customization and adaptation to new projects. Participants highlighted the ability to tailor digital twin solutions to specific needs and scale operations as required. This aligns with the findings of Lu et al. (2020), who discussed the scalability and customization potential of digital twins in smart manufacturing environments (Lu et al., 2020).

The adoption of digital twins presents a transformative opportunity for small manufacturing businesses to optimize their processes, reduce costs, and enhance competitiveness. While the benefits are substantial, including improved efficiency, quality control, and cost management, the challenges associated with implementing this technology are also significant. Addressing these challenges through strategic planning, support, and continuous improvement will be crucial for small businesses to fully leverage the potential of digital twins. As technological advancements continue to evolve, digital twins are likely to become an integral part of the manufacturing landscape, driving innovation and sustainability.

This study has several limitations. Firstly, the sample size was limited to 28 participants, which may not fully represent the diversity of small manufacturing businesses. Additionally, the study relied on qualitative data from semi-structured interviews, which may be subject to biases and variations in participants' responses. The focus on small businesses that have already implemented digital twins may also limit the generalizability of the findings to those considering adoption or those in different sectors.

Future research should aim to address the limitations of this study by including a larger and more diverse sample of small manufacturing businesses. Quantitative studies could complement the qualitative findings by providing statistical insights into the impact of digital twins on manufacturing efficiency and cost management. Additionally, longitudinal studies could examine the long-term effects of digital twin adoption and the evolution of challenges and benefits over time. Exploring the impact of digital twins in

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different sectors and regions would also provide a more comprehensive understanding of their potential and limitations.

For small businesses, adopting digital twins requires strategic planning and investment in training and support. Businesses should prioritize addressing technical barriers and financial constraints through phased implementation and collaboration with technology providers. Emphasizing change management and fostering a culture of innovation can help overcome organizational resistance. Policymakers and industry stakeholders should provide support through grants, subsidies, and training programs to facilitate the adoption of digital twins among small businesses. By leveraging digital twin technology effectively, small manufacturers can enhance their operational capabilities, achieve sustainability goals, and remain competitive in an increasingly digital and interconnected manufacturing landscape.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were observed.

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