

# Smart Manufacturing Systems for Industry 5.0 Transformation

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## Abstract

The emergence of Industry 5.0 represents a significant transformation in manufacturing systems by emphasizing human-machine collaboration, sustainability, personalization, and resilient production environments. Smart manufacturing systems have become essential for enabling this transformation through the integration of advanced technologies such as artificial intelligence, industrial Internet of Things, robotics, automation, digital twins, and advanced analytics.

This conceptual research article examines the role of smart manufacturing systems in supporting Industry 5.0 transformation and explores their contribution toward improving operational efficiency, flexibility, innovation capability, and sustainable production. The study adopts a conceptual research methodology based on the analysis of existing scholarly literature, smart manufacturing frameworks, Industry 5.0 concepts, and digital transformation models. The findings indicate that smart manufacturing systems provide significant opportunities for intelligent decision-making, adaptive production, resource optimization, and human-centred industrial development.

However, challenges related to technological complexity, workforce readiness, cybersecurity, investment requirements, and system integration remain important barriers. The study concludes that successful Industry 5.0 transformation requires a balanced integration of advanced technologies with human expertise, sustainable practices, and strategic manufacturing management approaches.

**Keywords:** Smart Manufacturing; Industry 5.0; Industrial Automation; Artificial Intelligence; Human-Machine Collaboration; Digital Transformation; Sustainable Manufacturing.

## 1. Introduction

The manufacturing sector is experiencing a significant transformation due to the rapid development of digital technologies and intelligent production systems. Earlier industrial revolutions focused primarily on mechanization, automation, and connectivity, whereas Industry 5.0 introduces a more human-centred approach that combines technological advancement with human creativity and expertise. Smart manufacturing systems have become a critical foundation for this transformation by enabling organizations to develop flexible, intelligent, and sustainable production environments.

Smart manufacturing integrates advanced technologies such as artificial intelligence, industrial Internet of Things, robotics, cloud computing, digital twins, and data analytics to improve manufacturing processes. These technologies allow organizations to monitor operations in real time, optimize production decisions, reduce resource waste, and enhance product quality. Unlike traditional automated

systems, smart manufacturing emphasizes adaptive capabilities and collaboration between humans and intelligent machines.

Industry 5.0 focuses on creating manufacturing ecosystems where technology supports human capabilities rather than replacing human involvement. This approach encourages personalized production, sustainable operations, and resilient manufacturing systems capable of responding to changing market requirements. Organizations adopting smart manufacturing technologies can achieve greater flexibility, improved efficiency, and enhanced innovation potential.

However, implementing smart manufacturing systems for Industry 5.0 transformation involves several challenges, including high investment requirements, technological complexity, cybersecurity concerns, workforce skill gaps, and difficulties in integrating advanced systems with existing manufacturing infrastructure. Addressing these challenges requires strategic planning, workforce development, responsible technology adoption, and effective management practices. This study examines smart manufacturing systems for Industry 5.0 transformation by analysing their conceptual foundations, strategic contributions, implementation challenges, limitations, and future development opportunities.

## **2. Review of Literature**

### **2.1 Evolution from Industry 4.0 to Industry 5.0 Manufacturing Systems**

The evolution of industrial systems has progressed from automation-focused Industry 4.0 approaches toward the human-centred and sustainable objectives of Industry 5.0. Industry 4.0 introduced digital connectivity, intelligent automation, and data-driven manufacturing, while Industry 5.0 extends these capabilities by emphasizing collaboration between humans and machines.

Research indicates that Industry 5.0 aims to create manufacturing environments where technological efficiency is combined with human creativity, customization, and sustainability. This transition reflects the growing need for production systems that are not only efficient but also adaptable and socially responsible.

### **2.2 Smart Manufacturing Technologies and Industrial Intelligence**

Smart manufacturing systems rely on interconnected technologies that enable intelligent production management. Artificial intelligence, robotics, industrial IoT, and digital twin technologies provide organizations with capabilities for predictive maintenance, real-time monitoring, and automated decision-making.

Existing studies highlight that smart manufacturing improves operational performance by reducing downtime, optimizing resources, and increasing production flexibility. However, successful implementation requires appropriate technological infrastructure and skilled human resources.

### **2.3 Human-Centred Manufacturing and Sustainable Industrial Transformation**

Industry 5.0 introduces a human-centred perspective where workers and intelligent systems collaborate to achieve improved manufacturing outcomes. This approach emphasizes employee involvement, creativity, personalization, and sustainable production practices.

Literature suggests that future manufacturing systems must balance technological innovation with environmental responsibility and human capabilities. Smart manufacturing provides the technological foundation required to achieve this balance through intelligent and adaptive production models.

### 3. Objectives of the Study

#### 3.1 Understanding the Role of Smart Manufacturing Systems in Industry 5.0 Transformation

The primary objective of this study is to examine the role of smart manufacturing systems in supporting Industry 5.0 transformation. The research focuses on understanding how intelligent manufacturing technologies such as artificial intelligence, industrial Internet of Things, robotics, digital twins, and advanced analytics contribute to the development of modern production environments. Industry 5.0 represents a shift from technology-centred automation toward human-centred manufacturing, where intelligent systems enhance human capabilities and improve industrial performance. This objective aims to analyse how smart manufacturing systems enable organizations to achieve greater flexibility, efficiency, and sustainability.

Furthermore, this objective seeks to explore the relationship between smart manufacturing capabilities and industrial transformation outcomes. The study examines how intelligent production systems support real-time monitoring, predictive decision-making, resource optimization, and customized manufacturing processes. It also evaluates the importance of integrating advanced technologies with workforce skills, strategic planning, and sustainable manufacturing practices.

**Through this analysis, the research aims to establish smart manufacturing as a key enabler of Industry 5.0 development:**

- Smart manufacturing systems improve production intelligence by enabling real-time analysis and adaptive decision-making.
- Industry 5.0 transformation requires integration of intelligent technologies with human expertise and sustainable practices.

#### 3.2 Evaluating the Contribution of Advanced Technologies to Intelligent Manufacturing Performance

The second objective of this study is to evaluate the contribution of advanced technologies toward improving smart manufacturing performance. The research examines the role of artificial intelligence, robotics, industrial IoT, digital twins, cloud computing, and automation systems in enhancing manufacturing operations. These technologies are analysed to understand their influence on production efficiency, predictive maintenance, quality improvement, operational flexibility, and innovation capability. The objective focuses on identifying how organizations utilize digital technologies to create intelligent manufacturing ecosystems.

In addition, this objective aims to investigate the importance of combining technological innovation with organizational capabilities. The study explores how manufacturing enterprises develop effective strategies by integrating digital infrastructure, workforce development, and process optimization. It emphasizes that successful Industry 5.0 transformation depends not only on technology adoption but also on effective management practices and human-machine collaboration.

**Through this evaluation, the research aims to identify approaches for achieving sustainable and intelligent manufacturing performance:**

- Artificial intelligence and advanced analytics strengthen manufacturing decision-making and operational optimization.
- Human-machine collaboration improves flexibility and supports personalized production requirements.

### **3.3 Identifying Challenges and Future Directions of Industry 5.0 Manufacturing Development**

The third objective of this study is to identify major challenges associated with implementing smart manufacturing systems for Industry 5.0 transformation. The research examines issues including technological complexity, cybersecurity risks, high implementation costs, workforce skill limitations, system integration difficulties, and organizational resistance. These challenges can influence the effectiveness of intelligent manufacturing initiatives and require strategic approaches for successful adoption.

Additionally, this objective seeks to explore future directions for developing advanced Industry 5.0 manufacturing ecosystems. The study investigates the potential role of autonomous systems, sustainable production technologies, intelligent analytics, and collaborative robotics in shaping future industrial development.

**It highlights the importance of continuous learning, responsible technology governance, and adaptive manufacturing strategies for achieving long-term transformation:**

- Future smart manufacturing systems require secure, flexible, and sustainable technological frameworks.
- Workforce development and continuous innovation are essential for successful Industry 5.0 adoption.

## **4. Research Methodology**

### **4.1 Research Design and Conceptual Framework**

This study adopts a conceptual research design to examine smart manufacturing systems and their contribution toward Industry 5.0 transformation. The conceptual approach is appropriate because the research focuses on analysing existing smart manufacturing theories, Industry 5.0 frameworks, industrial digitalization models, and technology-enabled production approaches rather than conducting direct experimental research. The study integrates perspectives from manufacturing management, industrial automation, artificial intelligence, and sustainable production to understand how intelligent systems support next-generation manufacturing environments.

The conceptual framework of the study is structured around the relationship between smart manufacturing technologies, human-machine collaboration, operational performance, sustainability, and industrial transformation. It considers smart manufacturing as a strategic capability that enables organizations to improve production intelligence, optimize resources, enhance flexibility, and develop resilient manufacturing ecosystems. The framework evaluates how digital technologies contribute to Industry 5.0 objectives through intelligent and human-centred production approaches.

### **4.2 Data Sources and Literature Analysis Approach**

The study utilizes secondary data sources collected from peer-reviewed research articles, academic publications, smart manufacturing studies, Industry 5.0 literature, industrial technology frameworks, and

digital transformation research. The literature-based methodology enables systematic examination of existing knowledge related to intelligent manufacturing systems, industrial automation, collaborative robotics, artificial intelligence applications, and sustainable production practices.

The literature analysis process involved identifying major research themes related to smart manufacturing technologies, human-machine collaboration, production optimization, digital infrastructure, and sustainability. The collected information was categorized according to technological drivers, operational benefits, implementation challenges, and future opportunities. This thematic analysis approach supported the identification of relationships between smart manufacturing adoption and Industry 5.0 transformation outcomes.

#### **4.3 Analytical Framework and Evaluation Parameters**

The analytical framework evaluates smart manufacturing systems through multiple dimensions, including technological intelligence, production efficiency, human-machine collaboration, sustainability performance, and organizational adaptability. These parameters were selected because they represent important indicators for assessing the effectiveness of Industry 5.0 manufacturing transformation. The framework provides a structured approach for understanding how organizations develop intelligent and flexible production systems.

The evaluation process considers both technological and human factors influencing manufacturing transformation. Technological factors include artificial intelligence, industrial IoT, robotics, digital twins, and automation platforms, while human factors include workforce skills, collaboration capability, innovation culture, and management readiness. This multidimensional evaluation approach enables a comprehensive assessment of smart manufacturing maturity.

#### **4.4 Research Procedure and Interpretation Method**

The research procedure followed a structured process involving identification of Industry 5.0 concepts, analysis of smart manufacturing technologies, evaluation of transformation strategies, and interpretation of future industrial development opportunities. Qualitative thematic analysis was applied to examine patterns within the collected literature and identify significant relationships between intelligent manufacturing systems and industrial performance.

The interpretation process involved comparative analysis of different smart manufacturing approaches and their contribution to Industry 5.0 transformation. The findings were synthesized to identify effective implementation strategies, technological advantages, and potential limitations. Ethical considerations related to responsible automation, workforce impact, cybersecurity protection, and sustainable industrial practices were also considered throughout the research process.

**Table 1: Research Methodology Framework**

| Research Component    | Description                                                                                                                   |
|-----------------------|-------------------------------------------------------------------------------------------------------------------------------|
| Research Design       | Conceptual research design based on smart manufacturing and Industry 5.0 frameworks                                           |
| Data Sources          | Peer-reviewed studies, industrial technology literature, manufacturing innovation research, and digital transformation models |
| Research Approach     | Qualitative thematic analysis and conceptual synthesis                                                                        |
| Evaluation Parameters | Technological intelligence, production efficiency, human-machine collaboration, sustainability, and adaptability              |
| Interpretation Method | Comparative analysis of smart manufacturing systems and Industry 5.0 transformation approaches                                |

**Table Interpretation:** The methodology framework demonstrates that the study follows a structured conceptual approach by combining manufacturing technology perspectives with Industry 5.0 transformation analysis. The selected research components support systematic evaluation of how smart manufacturing systems contribute to intelligent, sustainable, and human-centred industrial development.

## 5. Analysis

### 5.1 Evaluation of Smart Manufacturing Technologies in Industry 5.0 Transformation

The analysis indicates that smart manufacturing systems have become essential components of Industry 5.0 transformation by enabling intelligent, flexible, and sustainable production environments. Modern manufacturing organizations increasingly utilize advanced technologies such as artificial intelligence, industrial Internet of Things, robotics, digital twins, and advanced analytics to improve operational performance. These technologies allow enterprises to monitor production processes, identify inefficiencies, optimize resources, and make data-driven decisions.

The findings demonstrate that smart manufacturing technologies provide significant benefits by improving production accuracy, reducing operational disruptions, and supporting customized manufacturing. However, the effectiveness of these technologies depends on their integration with organizational strategies, workforce capabilities, and sustainable production objectives.

**Industry 5.0 requires a balanced approach where intelligent systems enhance human capabilities rather than completely replacing human involvement:**

- Artificial intelligence enables predictive decision-making and improves manufacturing process optimization.
- Digital twins support real-time simulation and performance improvement of industrial operations.
- Collaborative robotics enhances human-machine interaction and flexible production capabilities.

### 5.2 Strategic Contribution of Smart Manufacturing to Industrial Performance

Smart manufacturing systems contribute significantly to industrial performance by improving efficiency, flexibility, and innovation capacity. The analysis reveals that intelligent production systems enable organizations to achieve better resource utilization, faster response to market changes, and improved product quality. Real-time data collection and analytical capabilities allow manufacturers to identify potential issues before they affect production outcomes.

Furthermore, Industry 5.0 transformation emphasizes sustainable and human-centred manufacturing practices. Smart manufacturing technologies support this objective by reducing waste, improving energy efficiency, and enabling personalized production approaches.

**Organizations that effectively integrate smart manufacturing capabilities can achieve stronger competitiveness while maintaining sustainability and workforce involvement:**

- Intelligent manufacturing systems improve operational resilience by enabling adaptive production planning.
- Sustainable smart manufacturing practices support environmental responsibility and long-term industrial growth.

### 5.3 Comparative Assessment of Smart Manufacturing System Components

The comparative assessment examines major components of smart manufacturing systems, including artificial intelligence, industrial Internet of Things, robotics, digital twins, and advanced analytics. These components represent important technological foundations supporting Industry 5.0 transformation. The analysis highlights that each technology contributes differently to intelligent manufacturing depending on organizational requirements and production complexity.

The findings suggest that artificial intelligence and industrial IoT provide strong strategic value because they enable intelligent monitoring, automation, and data-driven decision-making. Robotics improves production flexibility and human-machine collaboration, while digital twins support simulation-based optimization. Advanced analytics strengthens predictive capabilities and operational improvement. Therefore, successful Industry 5.0 transformation requires integration of multiple technologies rather than dependence on a single technological solution.

**Table 2: Comparative Analysis of Smart Manufacturing System Components**

| Smart Manufacturing Component | Primary Function                          | Manufacturing Benefit           | Transformation Contribution |
|-------------------------------|-------------------------------------------|---------------------------------|-----------------------------|
| Artificial Intelligence       | Intelligent analysis and decision support | Improved process optimization   | Very High                   |
| Industrial IoT                | Real-time connectivity and monitoring     | Enhanced operational visibility | Very High                   |
| Collaborative Robotics        | Human-machine cooperation                 | Flexible production capability  | High                        |
| Digital Twins                 | Virtual modelling and                     | Improved planning and           | High                        |

| Smart Manufacturing Component | Primary Function        | Manufacturing Benefit              | Transformation Contribution |
|-------------------------------|-------------------------|------------------------------------|-----------------------------|
|                               | simulation              | performance                        |                             |
| Advanced Analytics            | Data-driven forecasting | Predictive operational improvement | High                        |

**Table Interpretation:** The table demonstrates that artificial intelligence and industrial IoT provide the highest transformation contribution because they directly improve intelligence, connectivity, and decision-making within manufacturing systems. Collaborative robotics, digital twins, and advanced analytics further strengthen Industry 5.0 capabilities by supporting flexibility, simulation, and predictive improvement.

## 6. Challenges

### 6.1 Technological Complexity and System Integration Challenges

One of the major challenges associated with implementing smart manufacturing systems for Industry 5.0 transformation is the complexity of integrating advanced technologies with existing manufacturing infrastructure. Modern smart manufacturing environments require the coordination of artificial intelligence, industrial Internet of Things, robotics, digital twins, automation platforms, and data management systems. Many organizations operate with legacy production systems that may not be fully compatible with advanced digital technologies, creating difficulties in achieving seamless integration and efficient information flow.

Furthermore, the implementation of smart manufacturing requires significant technological investment, specialized expertise, and continuous system maintenance. Organizations must develop reliable digital infrastructure, ensure interoperability between different technologies, and establish effective data management practices.

**Without proper planning and technical capabilities, manufacturing enterprises may face operational disruptions and fail to achieve the expected benefits of Industry 5.0 transformation:**

- Effective technology integration requires compatibility between existing industrial systems and emerging digital solutions.
- Strategic investment planning is essential for reducing implementation risks and improving transformation outcomes.

### 6.2 Workforce Skills, Human Adaptation, and Organizational Change Challenges

Another significant challenge in Industry 5.0 transformation is preparing the workforce for technology-enabled manufacturing environments. Smart manufacturing systems require employees to develop new skills related to digital technologies, data analysis, automation management, and human-machine collaboration. However, many organizations face difficulties in upgrading workforce capabilities due to skill gaps, limited training opportunities, and resistance to technological changes.

In addition, organizational culture plays an important role in successful smart manufacturing adoption. Employees may experience uncertainty regarding automation and changing job

responsibilities, which can influence acceptance of new technologies. Industry 5.0 emphasizes human-centred manufacturing, making workforce engagement and continuous learning essential.

**Organizations must develop training programs, encourage collaboration, and create supportive environments where technology enhances human performance:**

- Continuous workforce development is necessary to achieve effective human-machine collaboration.
- Employee involvement improves acceptance and sustainability of smart manufacturing transformation.

### **6.3 Cybersecurity, Data Protection, and Sustainable Implementation Challenges**

The increasing connectivity of smart manufacturing systems creates significant cybersecurity and data protection challenges. Industrial IoT devices, cloud-based platforms, and interconnected production networks increase exposure to cyber threats and unauthorized access. Security breaches can disrupt manufacturing operations, compromise sensitive production data, and negatively affect organizational performance. Therefore, cybersecurity has become a critical requirement for reliable Industry 5.0 implementation.

Furthermore, sustainable implementation of smart manufacturing requires organizations to balance technological advancement with environmental and social responsibilities. Excessive dependence on technology, resource consumption associated with digital infrastructure, and inadequate sustainability planning may reduce the long-term benefits of transformation.

**Organizations must adopt secure, energy-efficient, and responsible manufacturing strategies to ensure that Industry 5.0 development supports both industrial growth and sustainable objectives:**

- Strong cybersecurity frameworks are essential for protecting intelligent manufacturing ecosystems.
- Sustainable technology adoption ensures long-term value creation from smart manufacturing investments.

## **7. Discussion**

### **7.1 Smart Manufacturing as a Foundation for Industry 5.0 Transformation**

The findings of this study demonstrate that smart manufacturing systems represent a fundamental foundation for achieving Industry 5.0 transformation. Unlike previous industrial approaches that primarily focused on automation and productivity improvement, Industry 5.0 emphasizes collaboration between intelligent technologies and human expertise. Smart manufacturing provides the technological infrastructure required to develop flexible, adaptive, and sustainable production environments through real-time data processing, intelligent decision-making, and connected industrial systems.

The discussion further highlights that successful Industry 5.0 transformation requires a balanced integration of advanced technologies with human-centred manufacturing principles. Technologies such as artificial intelligence, industrial Internet of Things, robotics, and digital twins create significant opportunities for improving manufacturing performance, but their effectiveness depends on workforce capabilities, organizational readiness, and strategic implementation.

**Therefore, smart manufacturing should be viewed as an enabler of human creativity and industrial innovation rather than only an automation mechanism:**

- Industry 5.0 requires collaboration between intelligent machines and skilled human workers.

- Smart manufacturing systems provide the digital foundation for adaptive and sustainable industrial development.

## 7.2 Human-Machine Collaboration and Sustainable Manufacturing Development

The analysis indicates that human-machine collaboration is one of the most important characteristics of Industry 5.0 manufacturing systems. Collaborative robotics, intelligent automation, and advanced analytics enable workers and machines to perform complementary roles within production environments. This approach improves operational flexibility while maintaining human decision-making, creativity, and problem-solving capabilities.

The discussion emphasizes that sustainable manufacturing development requires organizations to integrate technological innovation with environmental responsibility. Smart manufacturing systems can support sustainability by reducing resource waste, improving energy efficiency, and optimizing production processes.

**However, achieving these outcomes requires effective management strategies, responsible technology adoption, and continuous improvement practices:**

- Human-machine collaboration improves productivity while preserving the value of human expertise.
- Sustainable smart manufacturing supports efficient resource utilization and responsible industrial growth.

## 7.3 Future Development of Intelligent Manufacturing Ecosystems

Future manufacturing ecosystems are expected to become increasingly intelligent, connected, and sustainable through the continued development of Industry 5.0 technologies. Advanced artificial intelligence, autonomous systems, digital twins, and intelligent analytics will further enhance manufacturing capabilities by enabling predictive decision-making, adaptive production, and personalized manufacturing solutions. These developments will allow organizations to respond more effectively to market changes and customer requirements.

Furthermore, future Industry 5.0 transformation will depend on addressing challenges related to cybersecurity, workforce development, technological accessibility, and ethical technology management. Organizations must develop comprehensive strategies that combine digital innovation with human-centred approaches. The discussion suggests that successful manufacturing enterprises will be those capable of creating intelligent ecosystems where technology, people, and sustainability.

**objectives work together to achieve long-term industrial competitiveness:**

- Future manufacturing systems will require continuous innovation and adaptive management approaches.
- Responsible technology governance will be essential for sustainable Industry 5.0 development.

## 8. Limitations of the Study

This study has certain limitations that should be considered while interpreting the findings related to smart manufacturing systems and Industry 5.0 transformation. The research adopts a conceptual approach based on existing literature, theoretical frameworks, and previously developed industrial transformation models rather than primary empirical investigation. Therefore, the study does not include direct observations, experimental validation, or organization-specific implementation data from

manufacturing industries. The conceptual nature of the research may limit the ability to evaluate practical outcomes across different industrial sectors.

Another limitation is related to the rapidly evolving nature of smart manufacturing technologies. Technologies such as artificial intelligence, industrial Internet of Things, autonomous robotics, and digital twins continue to develop at a fast pace, which may influence future manufacturing practices and transformation strategies. Existing frameworks and approaches analysed in this study may require continuous modification to remain relevant with emerging technological advancements and changing industrial requirements.

The study also acknowledges limitations related to variations in industrial infrastructure, organizational capabilities, and workforce readiness across different regions and manufacturing sectors. The adoption of Industry 5.0 technologies depends on factors such as investment capacity, technological maturity, regulatory environments, and employee skill development. Therefore, the findings may not represent identical transformation outcomes for all manufacturing organizations.

Future research can address these limitations by conducting empirical studies, industry-based case analyses, comparative investigations across different manufacturing sectors, and evaluation of real-world Industry 5.0 implementation outcomes. Such studies can provide deeper insights into technology adoption challenges, performance improvements, and practical strategies for successful smart manufacturing transformation.

## 9. Conclusion

Smart manufacturing systems have become a critical foundation for Industry 5.0 transformation by enabling intelligent, flexible, sustainable, and human-centred production environments. This study highlights that advanced technologies such as artificial intelligence, industrial Internet of Things, robotics, digital twins, and advanced analytics provide significant opportunities for improving manufacturing efficiency, decision-making capability, and operational adaptability. These technologies support organizations in developing connected and intelligent production systems capable of responding to changing market requirements.

The analysis demonstrates that Industry 5.0 transformation is not solely focused on automation but emphasizes collaboration between humans and intelligent machines. Smart manufacturing systems enable organizations to combine technological capabilities with human creativity, expertise, and strategic decision-making. The integration of digital technologies with workforce development and sustainable manufacturing practices creates opportunities for improving productivity, innovation capacity, and long-term industrial competitiveness.

The study further concludes that successful implementation of smart manufacturing systems requires addressing several challenges, including technological complexity, cybersecurity risks, workforce skill gaps, investment requirements, and organizational adaptation issues. Effective transformation depends on strategic planning, continuous learning, secure digital infrastructure, and responsible technology management. Organizations must ensure that technological advancement supports both operational excellence and human-centred industrial development.

In conclusion, smart manufacturing systems represent a transformative pathway toward achieving Industry 5.0 objectives by connecting advanced technologies, human capabilities, and sustainability principles. Future manufacturing success will depend on the ability of organizations to

create intelligent ecosystems where automation, collaboration, and responsible innovation work together. Enterprises that effectively adopt smart manufacturing strategies will be better positioned to achieve resilience, competitiveness, and sustainable industrial growth.

## References

1. Alcácer, V., & Cruz-Machado, V. (2019). Scanning the Industry 4.0: A literature review on technologies for manufacturing systems. *Engineering Science and Technology, an International Journal*, 22(3), 899–919.
2. Demir, K. A., Döven, G., & Sezen, B. (2019). Industry 5.0 and human-robot co-working. *Procedia Computer Science*, 158, 688–695.
3. Frank, A. G., Dalenogare, L. S., & Ayala, N. F. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics*, 210, 15–26.
4. Kagermann, H., Wahlster, W., & Helbig, J. (2013). *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0*. acatech.
5. Kamble, S. S., Gunasekaran, A., & Sharma, R. (2018). Analysis of the driving and dependence power of Industry 4.0 technologies. *Technological Forecasting and Social Change*, 145, 102–113.
6. Kusiak, A. (2018). Smart manufacturing. *International Journal of Production Research*, 56(1–2), 508–517.
7. Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration*, 6, 1–10.
8. Nahavandi, S. (2019). Industry 5.0—A human-centric solution. *Sustainability*, 11(16), 4371.
9. Oztemel, E., & Gursev, S. (2020). Literature review of Industry 4.0 and related technologies. *Journal of Intelligent Manufacturing*, 31, 127–182.
10. Park, K. T., Son, Y. H., & Noh, S. D. (2020). The architectural framework of a cyber physical factory for Industry 4.0. *Procedia Manufacturing*, 51, 85–92.
11. Porter, M. E., & Heppelmann, J. E. (2014). How smart, connected products are transforming competition. *Harvard Business Review*, 92(11), 64–88.
12. Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., & Harnisch, M. (2015). Industry 4.0: The future of productivity and growth in manufacturing. *Boston Consulting Group Report*.
13. Sader, S., Husti, I., & Daróczy, M. (2022). Industry 4.0 as a key driver toward Industry 5.0 transformation. *Applied Sciences*, 12(14), 1–18.
14. Schwab, K. (2016). *The Fourth Industrial Revolution*. World Economic Forum.
15. Sony, M., & Naik, S. (2020). Key ingredients for evaluating Industry 4.0 readiness. *International Journal of Production Research*, 58(5), 1505–1519.
16. Stock, T., & Seliger, G. (2016). Opportunities of sustainable manufacturing in Industry 4.0. *Procedia CIRP*, 40, 536–541.
17. Tao, F., Zhang, M., Liu, Y., & Nee, A. Y. C. (2019). *Digital twin driven smart manufacturing*. Academic Press.
18. Thames, L., & Schaefer, D. (2017). *Cybersecurity for Industry 4.0: Analysis and Future Directions*. Springer.