



REVIEW PAPER

Technology Integration Strategies in Smart Manufacturing: From Traditional Manufacturing to Intelligent Manufacturing Systems

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Abstract

Smart manufacturing has become a game-changing approach that leverages digital technologies to create intelligent, interconnected production systems. This literature review explores the history of manufacturing and its evolution from traditional production systems to Industry 4.0 and smart manufacturing, emphasizing technological advancements in modern industrial practices. This paper discusses the evolution of manufacturing from traditional to digital and intelligent manufacturing environments, leveraging Cyber-Physical Systems (CPS), the IIoT, cloud computing, artificial intelligence, big data analytics, and Digital Twin technology. In addition, the smart manufacturing architecture is presented, explaining how physical manufacturing assets, communication networks, enterprise information systems, and intelligent analytics platforms are integrated to create a smart manufacturing environment. Challenges associated with implementing smart manufacturing, such as interoperability, cybersecurity, standardization, scalability, and legacy systems integration, are also explored. In general, this review shows that smart manufacturing provides the technological basis for sustainable, resilient, customer-oriented manufacturing.

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1. Introduction

Smart manufacturing has been identified as one of the most important pillars of contemporary industrialization by integrating state-of-the-art digital technologies into manufacturing processes to create intelligent, interconnected, and data-driven systems. The fusion of technologies such as the IIoT (Industrial Internet of Things), CPS (Cyber-Physical Systems), cloud computing, big data, artificial intelligence, digital twins, and advanced sensor technologies enables manufacturing processes to generate and analyze real-time data, make automated decisions, and optimize operations [1, 2]. The rapid development of digital technologies has accelerated the shift from traditional manufacturing processes to intelligent production systems. Digital Twin is one of the most impactful enablers among technologies for creating a synchronized virtual image of physical manufacturing assets

throughout the entire operation lifecycle. Constant interaction between the physical and virtual worlds enables real-time monitoring, predictive analytics, simulation, fault diagnosis, and optimisation of production processes, making manufacturing more reliable, cost-effective, and efficient. Combining Digital Twin with data-driven manufacturing supports continuous improvement and lifecycle management of manufacturing systems. The application of smart manufacturing requires seamless interoperability and communication among manufacturing assets, enterprise information systems, and supply chains. The integration of digital technologies with manufacturing processes enables intelligent production planning, predictive maintenance, automated quality inspection, machine condition monitoring, process control, and resource optimization throughout the manufacturing process. As a result, companies can increase production efficiency, reduce operational downtime, lower

manufacturing costs, enable mass customization, and improve product quality [3]. The use of smart manufacturing technology is widespread and spans many industries, including automotive, aerospace, electronics, semiconductors, pharmaceuticals, chemicals, food, and advanced manufacturing. They use smart manufacturing technology to enhance manufacturing efficiency, sustainability, and environmental impact through digital integration and decision-making. In addition, smart manufacturing plays a pivotal role in green manufacturing by enabling enhanced energy efficiency, reduced material waste, efficient resource use, and environmentally sustainable production [4]. Despite these advances, several research challenges prevent the large-scale industrial application of smart manufacturing systems. Current research mostly addresses individual enabling technologies or specific industrial applications; however, more systematic research that considers smart manufacturing, digital transformation, sustainability, and green manufacturing as a single system remains underrepresented.

Furthermore, interoperability among heterogeneous manufacturing systems, standardization of communication protocols, secure data exchange, integration with legacy manufacturing systems, scalability, and implementation complexity are other challenges preventing the industrial use of smart manufacturing systems. Overcoming these obstacles requires multidisciplinary research in digital and sustainable manufacturing to create reliable, intelligent, and interoperable manufacturing systems [5, 6]. The smart manufacturing processes are illustrated in Figure 1.

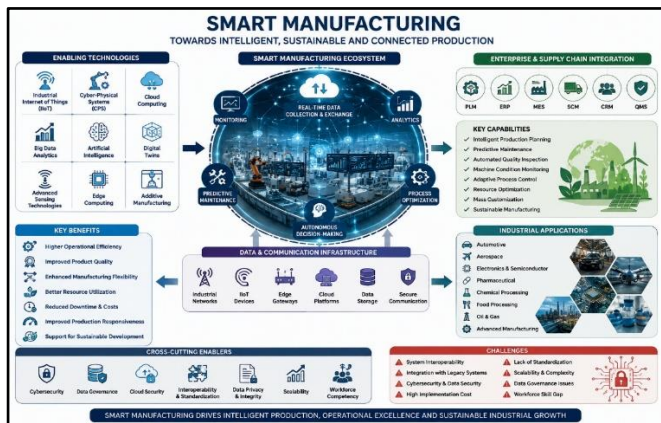


Figure 1: Smart manufacturing process [5,6].

2. Evolution of Manufacturing

The history of manufacturing is characterized by constant changes in production processes driven by technological innovations and industrialization, as well as growing demands for productivity, efficiency, and sustainability. The first industrial revolution, known as Industry 1.0, was associated with the introduction of mechanized manufacturing powered by steam and water, which replaced manual processes and considerably increased manufacturing capacity. In turn, Industry 2.0 fostered further industrialization through electrification, assembly-line production, and mass manufacturing, which enabled larger production volumes,

product standardization, and more efficient processes [7]. The third industrial revolution was associated with the advent of automation in manufacturing processes, using electronics, PLCs, CNC systems, and industrial robots. The adoption of computer-based automation contributed to more accurate manufacturing, greater process repeatability, greater production flexibility, and better quality control, with less human participation in manufacturing processes [8]. The Fourth Industrial Revolution (Industry 4.0) has brought about a paradigm shift, moving from traditional automation to intelligent, connected manufacturing systems. This paradigm shift is made possible by the convergence of CPS, the IIoT, cloud computing, artificial intelligence, big data analytics, Digital Twins, and advanced communication technologies, which facilitate real-time data acquisition, autonomous decision-making, predictive maintenance, process optimization, and connectivity within manufacturing systems. The digital technologies have formed the basis of smart manufacturing through intelligent production planning, adaptive manufacturing, resource optimization, and data-driven operations. Industry 5.0 is a new trend that builds on the digital transformation achieved through Industry 4.0 and expands the scope of manufacturing by emphasizing human-machine collaboration, sustainability, resilience, and customer-oriented manufacturing. Instead of replacing humans with intelligent technologies, Industry 5.0 aims to combine human decision-making with intelligent technologies to create flexible, personalized, and environmentally friendly manufacturing systems. This paradigm shift facilitates sustainable industrial development through resource efficiency, lower environmental impact, circular manufacturing processes, and organizational resilience [9, 10]. Figure 2 presents the overall layout of the traditional manufacturing system, which consists of distinct production stages in sequence, such as raw material handling, machining operations, assembly, quality control, and final product delivery.

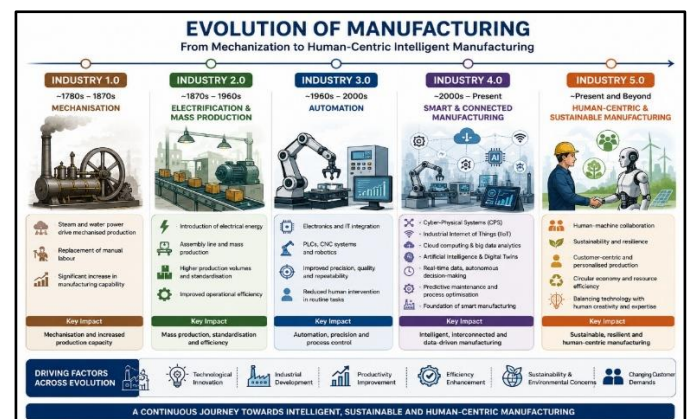


Figure 2: Evolution of manufacturing [9,10].

3. Traditional Manufacturing

Traditional manufacturing is a typical method of industrial manufacturing, in which the process is carried out mainly using individual machines and follows fixed production lines

according to prearranged schedules. Conventional manufacturing uses sequential processes with limited communication between units along the production line, resulting in isolated operations and limited information flow within the production environment. Despite the success of conventional manufacturing in enabling large-scale production of standardized products for many years, its reliance on fixed process configurations makes it inflexible and unable to accommodate rapid product customization and changing market demands [11]. Maintenance activities in conventional manufacturing systems are mostly carried out through reactive or preventive approaches, in which maintenance is performed after equipment failure or at predetermined intervals. Although the preventive method helps reduce equipment failures to some extent, both maintenance methods lead to excessive maintenance activities and production disruptions due to the lack of continuous monitoring of equipment condition [12]. Another significant constraint of the traditional manufacturing system is its lack of real-time data acquisition and intelligent process integration. Machines operate independently, without continuous communication with other machines, enterprise systems, or production management systems. Process monitoring, production control, and quality inspections are carried out by manual workers, whose competence determines the performance of manufacturing operations. Production data is usually stored in isolated databases or paper-based archives, making information flow in the manufacturing system fragmented, slow, and lacking any process visibility. The poor connectivity among processes in conventional manufacturing systems makes it hard to optimize manufacturing and utilize resources efficiently. Many manufacturers face constraints arising from issues such as inconsistent product quality, inefficient energy use, excessive material wastage, low responsiveness, and inefficiency.

Nevertheless, traditional manufacturing laid the foundation for modern manufacturing systems by implementing standard manufacturing processes, assembly-line manufacturing, quality control, and systematic production planning. This provided a technological basis for future industrial revolutions to develop on. Nevertheless, growing competition in the market, sustainability needs, shortened lifecycle of products, and increased demand for flexible intelligent production forced the development of new manufacturing systems – smart manufacturing. Smart manufacturing is based on the implementation of digital technologies and data processing, which enables the overcoming of most of the basic limitations of traditional manufacturing systems [11-13]. Unlike intelligent manufacturing systems, the conventional manufacturing processes rely heavily on human supervision, standalone machines, manual information management systems, and maintenance techniques that are either preventive or reactive. While such manufacturing systems are well-suited for large-scale production of standardized products, their lack of adaptability, inefficient information flow, high downtime rates, and poor utilization of manufacturing assets reveal the need for digitalization to evolve into intelligent manufacturing systems [14]. Figure 3 highlights the conceptual framework of a conventional manufacturing system, showing the manufacturing process flow sequentially from the handling of

raw materials to the delivery of finished goods. The figure focuses on individual machines, manual intervention, fragmented information systems, and maintenance, which are the major drawbacks driving the use of advanced manufacturing technologies.



Figure 3: Traditional manufacturing system and its key characteristics [14].

4. Digital Manufacturing

The concept of digital manufacturing has evolved into a revolutionary manufacturing philosophy that uses digital technology across all stages of the product lifecycle to build intelligent, connected, data-driven manufacturing processes. In contrast to traditional manufacturing, digital manufacturing enables the seamless exchange of information among product design, production planning, manufacturing execution, and enterprise management systems. The integrated use of these systems enables real-time communication, improves production visibility, and enables effective decision-making at all stages of the manufacturing process. The digital manufacturing system includes components such as PLM, ERP, MES, SCADA, IIoT sensors, and cloud-based databases, creating a single digital infrastructure for manufacturing processes. The continuous collection, processing, and analysis of production data allow manufacturers to synchronize manufacturing processes with enterprise-wide planning and supply chain management. Such integration increases the transparency, traceability, and controllability of the manufacturing process and enables prompt responses to changes in production needs. The implementation of digital manufacturing processes is supported by enabling technologies such as cloud computing, big data, artificial intelligence, Digital Twin, sensing technologies, and cybersecurity [15]. Together, these technologies enable real-time data acquisition, virtual process simulation, predictive analysis, intelligent quality control, and adaptive process optimization. The ability to analyze large volumes of manufacturing data will enable organizations to detect deviations from optimal process performance, optimize production parameters, enhance equipment efficiency, and minimize production inefficiencies. In turn, the introduction of digital manufacturing results in enhanced manufacturing flexibility, improved product quality, greater reliability, and

higher production efficiency, while also contributing to sustainable manufacturing through increased energy efficiency and resource utilization. Beyond implementing digital technologies, digital manufacturing enables industrial digital transformation by providing digital connectivity between physical manufacturing systems and intelligent computational systems. Digital connectivity enables autonomous communication among machines, production systems, and enterprise-level systems, leading to more efficient decision-making, reduced production time, lower costs, and greater manufacturing flexibility.

Furthermore, the digitalization of the manufacturing process provides a technological foundation for intelligent automation, predictive maintenance, and data-driven manufacturing management, thereby paving the way for Smart Manufacturing and Industry 4.0. The digital backbone that integrates PLM, ERP, MES, SCADA, sensing systems via IIoT, and cloud-based information systems enables the continuous flow of information across manufacturing and enterprise systems. At the same time, enabling technologies like cloud computing, artificial intelligence, big data analytics, Digital Twin, and cybersecurity enable smart decision-making, process simulation, production optimization, and safe data management. This digital ecosystem provides the necessary technological foundation for developing interconnected, intelligent, and autonomous Smart Manufacturing systems that can meet the needs of the future industry [16, 17].

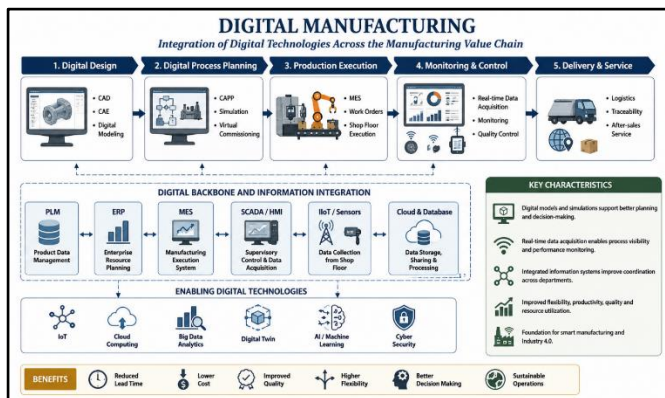


Figure 4: Conceptual framework of digital manufacturing [17].

The concept of digital manufacturing represents the perfect integration of digital design, intelligent production systems, enterprise management, and information technology, enabling real-time communication, process optimization, and decision-making. It creates the technological background for Smart Manufacturing by improving production efficiency, flexibility, quality, and sustainability through continuous digital connectivity and intelligent data analysis (Figure 4).

5. Industry 4.0

Industry 4.0 is the fourth industrial revolution, denoting the transformation from digitally enabled manufacturing systems to intelligent and autonomous systems. Industry 4.0 combines information and communication technology with manufacturing operations to create smart factories that capture

real-time data, make intelligent decisions, and optimize processes automatically. In contrast to automation technology, Industry 4.0 allows continuous interaction between physical manufacturing elements and digital technologies through CPS, IIoT, cloud computing, artificial intelligence, big data, and Digital Twin technologies. The integration of the above-mentioned technologies provides a foundation for creating highly adaptive and responsive manufacturing systems [18]. An interconnected manufacturing ecosystem in which all machines, production equipment, sensors, enterprise systems, and supply chain networks communicate with one another through digital communication platforms is one of the key features of the fourth industrial revolution. Production data collected with the help of IIoT sensors is then shared via cloud-based platforms and processed using advanced analytical tools, AI algorithms, and Digital Twin models for intelligent monitoring, prediction analysis, and adaptive manufacturing control. Thus, manufacturing operations could be optimized through data-driven decisions to schedule production, increase equipment utilization, minimize process variability, and improve reliability. Moreover, enterprise information systems, such as PLM, ERP, MES, SCM, CRM, and QMS, are integrated within the Industry 4.0 manufacturing environment to provide coordination throughout the entire manufacturing value chain. Integration of these business and manufacturing platforms enables improved production planning, better inventory management, product traceability and quality assurance, and resource allocation, as well as synchronized communication among production plants, suppliers, and customers. As a result, manufacturing organizations can improve their transparency and adaptability to ever-changing market conditions. With the growing interconnection of manufacturing systems, cybersecurity becomes one of the key components of Industry 4.0.

It is very necessary for the integrity, confidentiality, and accessibility of manufacturing data that secure communication protocols and data protection techniques be in place. Cybersecurity will not only protect manufacturing systems from cyberattacks but also increase reliability and trust in intelligent manufacturing systems, thereby enabling seamless operations and the digital transformation of industrial manufacturing processes. The advent of Industry 4.0 has brought significant change to manufacturing, enabling intelligent manufacturing planning, predictive maintenance, autonomous process control, real-time quality monitoring, and production optimization. This results in improved manufacturing productivity, efficiency, equipment availability, product quality, and resource utilization, while minimizing production downtime, operating costs, and environmental impact. Moreover, Industry 4.0 bridges the gap between digital manufacturing and Smart Manufacturing. Figure 5 presents the architecture of the Industry 4.0 approach, wherein CPPS, sensing technologies via the IIoT, cloud computing, and enterprise information systems are used to develop an intelligent manufacturing environment. Information on manufacturing processes generated by connected machines and sensors is analyzed with big data analytics, AI, and Digital Twins to enable real-time monitoring, prediction, and autonomous decision-making. At

the same time, enterprise systems such as PLM, ERP, MES, SCM, CRM, and QMS ensure efficient coordination throughout the manufacturing value chain, and cybersecurity guarantees secure and reliable communication between connected manufacturing resources. The adoption of all the aforementioned digital technologies ultimately leads to increased manufacturing efficiency, flexibility, predictive maintenance, quality, and sustainability, forming the technological foundation of modern smart manufacturing systems [19-21].

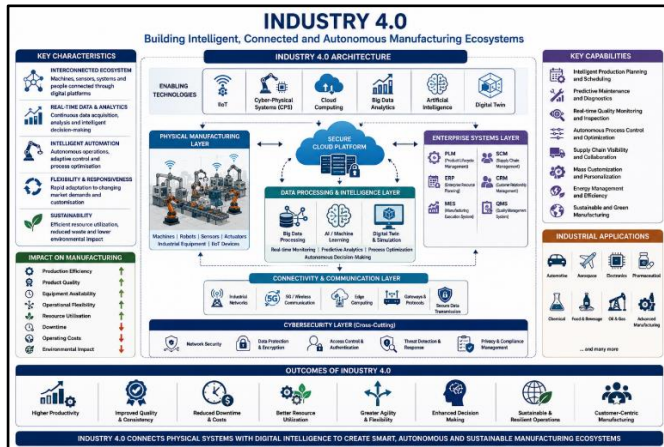


Figure 5: Industry 4.0 architecture and enabling technologies [19, 20].

6. Smart Manufacturing Architecture

The architecture of smart manufacturing provides a comprehensive digital environment that integrates physical manufacturing assets, an intelligent communication network, enterprise information systems, and sophisticated analysis tools into a connected, autonomous, and data-driven manufacturing ecosystem. In contrast to traditional manufacturing systems, the architecture of smart manufacturing facilitates real-time information sharing among machines, products, production systems, and enterprise applications, supporting real-time monitoring and intelligent decision-making in the manufacturing process [22].

The basis of architecture lies in the physical manufacturing layer. This layer consists of machine tools, manufacturing machinery, industrial robots, sensors, actuators, and IIoT devices, all of which are used to extract real-time data on manufacturing operations. Physical resources monitor the machine's condition, process parameters, production status, and machinery health by providing a large volume of manufacturing data that forms the basis of intelligent manufacturing activities. The introduction of IIoT devices allows seamless interaction between physical devices and digital systems, leading to increased visibility and condition-based monitoring throughout the manufacturing lifecycle [23]. The communication and data management layer provides connectivity between manufacturing resources through industrial communication networks, cloud computing facilities, and distributed databases. The continuous transmission and storage of manufacturing data enable

efficient information exchange among various production facilities and interoperability among heterogeneous manufacturing systems. Cloud computing technology also provides scalability, remote access to computing resources, and collaborative data management, enhancing flexibility and organizational responsiveness in manufacturing operations. The intelligence layer is the central component of the smart manufacturing architecture, using advanced technologies such as artificial intelligence, big data analytics, and digital twins to convert manufacturing data into knowledge. The use of advanced technologies such as real-time process monitoring, predictive maintenance, diagnostic analysis, virtual simulation, and production optimization enables continuous analysis of process data to identify irregularities. This way, it becomes possible to improve equipment reliability, minimize downtime, optimize production conditions, and produce high-quality products [24,25].

At the enterprise level, PLM, ERP, MES, SCM, CRM, and QMS help integrate manufacturing processes and business functions to create comprehensive coordination across the manufacturing value chain. The integration of those enterprise systems helps improve manufacturing planning, inventory management, quality control, tracking, and responsiveness to customer needs while increasing organizational efficiency and the effectiveness of resource utilization. Digital integration helps manufacturers align their operational processes with business objectives and adapt quickly to changes in product demand. Cross-functional enablers such as cybersecurity, data management, cloud security, and interoperability enable the secure and reliable exchange of manufacturing information across all layers of the architecture. In today's environment, where manufacturing systems are becoming more interconnected, these enablers are critically important for protecting industrial data, system integrity, and secure communication among manufacturing resources and enterprise systems. In addition, interoperability helps integrate legacy manufacturing infrastructure with modern digital systems, thereby accelerating industrial digital transformation [26,27]. In summary, smart manufacturing architecture enables the creation of an integrated digital ecosystem that brings together manufacturing resources, enterprise systems, and intelligent technologies on a cohesive platform. The interplay between these different levels of architecture enables decision-making, maintenance, process control, optimization, and continuous improvement in the manufacturing process, while also promoting sustainable manufacturing through efficient material and energy use. This means that smart manufacturing architecture powers Industry 4.0 through intelligent, sustainable, and resilient manufacturing systems [28]. Figure 6 shows the layered architecture of Smart Manufacturing, demonstrating the incorporation of physical manufacturing capabilities with a communication system, intelligent analytics, enterprise management systems, and application services. In real time, data captured by machines and IIoT-enabled devices is communicated via industrial communication networks, while it is processed using cloud computing, artificial intelligence, big data analytics, and digital twin technology. Enterprise systems, including PLM, ERP, MES, SCM, CRM, and QMS, manage manufacturing

and business processes. At the same time, cybersecurity, data governance, cloud security, and interoperability serve as cross-cutting enablers for safe and effective information exchange within the manufacturing environment [29,30].

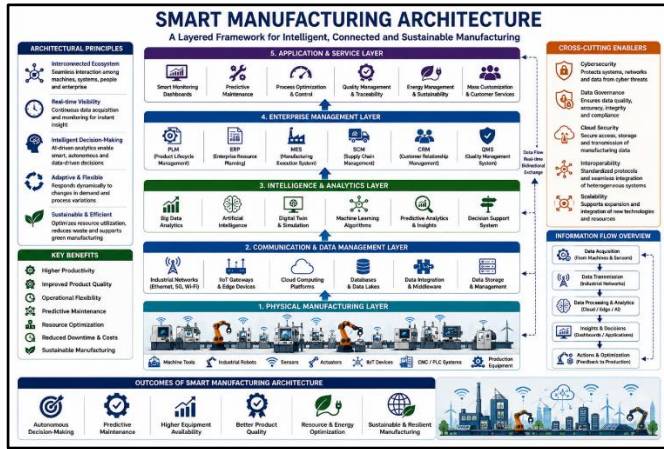


Figure 6: Smart manufacturing architecture [29,30].

7. Conclusions

The smart manufacturing approach is a revolutionary concept that combines modern digital technologies with existing manufacturing systems to create intelligent, interconnected, data-driven manufacturing environments. The progression from the traditional manufacturing approach to digital manufacturing and Industry 4.0 has completely changed manufacturing processes through real-time communication, autonomous decision-making, and intelligent process optimization. The combination of several enabling technologies, such as CPS, IIoT, cloud computing, artificial intelligence, big data, and Digital Twin, has enabled manufacturers to implement predictive maintenance, process adaptation, quality management, and optimal resource use. Based on the literature review, the smart manufacturing architecture creates an integrated digital ecosystem by integrating physical manufacturing assets, communication network infrastructure, enterprise management systems, and intelligent analysis systems. This kind of integration enables a smooth flow of information through the manufacturing value chain, leading to greater operational visibility, lower operating costs, improved equipment reliability, and better decision-making. Additionally, digital technology plays a vital role in sustainable manufacturing by enabling efficient energy use, reducing material waste, and optimizing resource utilization. Notwithstanding tremendous technological advancements, some issues persist and pose obstacles to achieving large-scale, industry-wide adoption of smart manufacturing technologies. Interoperability of the system, integration with existing manufacturing systems, cybersecurity, data management, communications standardization, implementation costs, and employee skill levels are key issues that manufacturers, especially SMEs, face. Solving these problems entails designing standardized digital platforms, secure information-exchange capabilities, and robust integration strategies that can operate in heterogeneous manufacturing settings.

Future manufacturing systems will need to become highly autonomous, resilient, sustainable, and human-centered by integrating intelligent digital technologies and advanced manufacturing techniques. More attention needs to be paid to developing an interoperable smart manufacturing architecture, improving cybersecurity measures, enhancing Digital Twin techniques, advancing explainable artificial intelligence, advancing sustainable manufacturing techniques, and fostering collaboration between intelligent manufacturing systems and humans. Moreover, future research should focus on developing a common framework that integrates concepts from Smart Manufacturing, Green Manufacturing, and Industry 5.0 to enable future-ready manufacturing systems.

Smart manufacturing is not only a technological development but also a strategic shift in modern manufacturing systems. The realization of such smart manufacturing is expected to have positive impacts on industrial competitiveness, digitalization, and economic sustainability through intelligent, environmentally friendly manufacturing operations. Future research and industrial cooperation are necessary for achieving this goal.

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Disclosure of Interests

The author (s) claims no knowledge of financial or personal conflicts that could have influenced the work presented in this study.

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