



AI-5G Convergence in Smart Manufacturing: A Conceptual Framework for Next-Generation Manufacturing

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ARTICLE INFO

Keywords:

Artificial Intelligence (AI);
5G Communication
Networks, Smart
Manufacturing, Industry 4.0
/5.0, Digital Twins, Cyber-
Physical Systems, Human-
Machine Collaboration.

Received: Feb, 21, 2026

Accepted: May, 20, 2026

Published: Jun, 25, 2026

ABSTRACT

Artificial Intelligence (AI) and fifth-generation (5G) communication technologies are transforming today's manufacturing systems. In this conceptual study, the authors explore the potential impact of combining the two enabling technologies to create highly connected, intelligent and adaptive smart factories. It underscores the complementary nature of AI-powered analytics in supporting decision-making, predictive maintenance, and process optimization, as well as the 5G's ability to deliver low latency and ultra-reliable connectivity essential for real-time control and human-machine collaboration. The study also highlights digital twins, edge computing and cyber-physical systems as key technologies that enable this convergence. These features allow for continuous monitoring, autonomous adaptation, and data exchange across various domains in complex industrial environments. Also discussed as key barriers to large-scale adoption are issues of infrastructure readiness, data security and interoperability. In conclusion, AI-5G convergence as a key enabler for future factories to be more intelligent and efficient, sustainable, resilient, and human-centric. The study concludes with future research directions such as transition to 6G networks, human-AI co-creation and ethics influencing the development of Industry 5.0.

1. INTRODUCTION

The digital transformation of smart manufacturing is a wide-spread process which aims to eliminate manual processes, improve the efficiency of operations and system flexibility. Fifth-generation (5G) communication networks are one of the technologies that are instrumental in the development of the manufacturing ecosystem which is called Industry 4.0 or Industry 4.5 (Lasi et al., 2014; Xu et al., 2021).

Highly flexible and modular production systems are expected to be implemented in future factories which require reliable, low-latency and scalable communication and computation solutions to support real-time production processes (Bockelmann et al., 2018). The move towards this

vision was already underway, but the COVID-19 pandemic has further ramped up the shift to such systems by underscoring the need for resilience, adaptability, and quick response to disruptions in global manufacturing systems (Ivanov & Dolgui, 2020; Kamble et al., 2023).

The Fourth Industrial Revolution (4IR) has ushered in a manufacturing paradigm shift that has focused on the integration of digital technologies, automation and real-time data analytics into production processes (Schwab, 2017; Lu, 2017). In this context, smart factories are becoming a key concept to facilitate smart manufacturing, which can increase manufacturing productivity, manufacturing efficiency, and manufacturing cost

reduction, by implementing intelligent production equipment and information systems, and by making production decisions based on the information generated by these systems. In this context, the concept of smart factory has become a key aspect to facilitate smart manufacturing, in which the use of intelligent production equipment and information systems, and the use of the information generated by these systems to make production decisions, can increase production productivity, enhance production efficiency, and reduce production costs.

In recent years, advanced digital technologies are steadily entering the production scene to upgrade production systems and build digital factories, as a new generation of industrial environments built from interconnected machines, sensors, software platforms and analytics (Tao et al., 2018).

The digital factory systems enable the manufacture of highly customised products, while simultaneously minimising the amount of resources used, production time and the level of labour required (Lee et al., 2015). Therefore, smart manufacturing has emerged as a key strategy for companies to stay competitive in the rapidly changing and technologically advanced global market (Kamble et al., 2018). Therefore, it is crucial to have an understanding of the technological elements and the architectural layout of smart factories. In this context, 5G communication technology has become a major enabler of intelligent manufacturing systems, offering the necessary connectivity to facilitate real-time data exchange, automation, and integration of systems within the complex industrial environment (Moura et al., 2021).

Geographical boundaries are less relevant in today's smart manufacturing environments. The 5G ultra-reliable low-latency communication (URLLC) feature allows for near-instantaneous communication and command execution, no matter the distance between equipment, from a nearby control room to a facility thousands of kilometers away (Popovski et al., 2018). This real-time connectivity eliminates latency-related restrictions that were previously found in remote operations.

In this way, manufacturing systems can become more synchronized, decrease the need for on-site human intervention, and enhance occupational safety, especially in hazardous industrial

environments where human intervention is likely to involve significant danger (Chen et al., 2020).

The digital factory can be summarized as a set of organizational models and technological solutions for digitalizing flexible manufacturing processes and facilitating seamless information flow between the interlinked parts of an industrial enterprise (Tao et al., 2018; Wang et al., 2020). A digital factory can be deployed by a single organisation to replicate, optimise and coordinate various operational functions, thereby improving agility, efficiency and adaptability in the fast-changing industrial landscape.

• ***Automation Reinvented through 5G Connectivity:***

While automation has long been a part of industrial production, 5G technology is changing automation to be a more intelligent, interconnected and adaptive system (Moura et al., 2021; Mahan, 2023). By using the URLLC features of 5G, real-time machine-to-machine (M2M) communication is provided with minimal delay, which means machines, robots and control systems can be operated in precise synchronization.

This feature greatly improves production process efficiency, reduces downtime and manual intervention (Chen et al., 2020). For instance, assembly lines can self-regulate production rates according to the real-time performance, and robotic systems can synchronize the motion with millisecond precision in material handling and assembly processes. These capabilities work together to improve the efficiency, flexibility and safety of manufacturing processes (Mahan, 2023).

• ***Improving AI-supported Manufacturing:***

Real-time data communication is crucial for the implementation of Artificial Intelligence (AI) in smart manufacturing environments, where data needs to be shared across various systems and components in real time. High bandwidth and reliable connection of 5G supports the continuous data flow of AI-powered quality inspection, predictive maintenance, and process optimization systems (Lu, 2017; Wang et al., 2020). The data's availability in real-time allows AI algorithms to make data-driven decisions without human intervention, helping manufacturing systems identify anomalies, predict equipment failures, and optimize production parameters dynamically. The

combination of AI and 5G technology, therefore, provides the tools for intelligent, self-regulating manufacturing ecosystems that can evolve over time, continuously learning and adapting (Tao et al., 2018; Moura et al., 2021).

Part One: The Concept Of Smart Manufacturing:

Smart Manufacturing (SM) is a paradigm shift in manufacturing production systems and uses advanced digital technologies, cyber-physical systems and intelligent connectivity to provide increased flexibility, efficiency and adaptability. The core of SM is the idea of smart factories, which are the organizational manifestation of intelligent and data-driven manufacturing. Smart factories combine machines, robots, human operators and digital systems into unified cyber-physical systems (Lee et al., 2015; Al-Ali, 2023).

1.1. Key Enabling Technologies

Smart manufacturing depends on the combination of different technologies that all have their own unique contribution to the operational intelligence. According to Al-Ali (2023), there are eleven digital technologies that are crucial for Industry 4.0:

Mobile devices and IoT platforms

- Location detection technologies
- Advanced human-machine interfaces
- Data encryption and security measures

3D printing and additive manufacturing

- Smart remote sensors
- Big data analytics and advanced algorithms

Multiple customer engagement and needs analysis
Use augmented reality (AR) and wearable technologies

- Cloud computing

The integration of physical and cyber systems in production processes is known as cyber-physical production systems (CPPS).

These technologies, when combined, help to create modular, flexible and cost effective manufacturing systems, but the challenges with implementing these technologies into a single system include interoperability and complexity management.

1.2. 5G as a Core Enabler:

Fifth-generation (5G) communication technology is a major step in smart manufacturing. With 5G, real-time control, synchronization of robotics and seamless human-robot collaboration is possible through ultra-reliable low-latency communication

(URLLC), enhanced mobile broadband (eMBB), and massive machine-type communication (mMTC). (Popovski et al., 2018; Moura et al., 2021)

1.2.1. 5G-SMART Project and Industrial Trials:

The 5G-SMART project is a Horizon 2020 project investigating applications of 5G in the industrial domain. Through trials in real factories, it proves the technical viability, economic benefits, and operational effects of 5G deployment in factories (5G-SMART Consortium, 2021). Key applications include industrial automation, robotic connectivity, digital twin integration, and AI-driven predictive maintenance.

1.2.2 Key 5G Applications:

Robotic Connectivity: With 5G, autonomous and collaborative robots can communicate via wireless, high bandwidth, and low latency, facilitating real-time interactions and remote supervision (Chen et al., 2020; Latif et al., 2021).

Edge or cloud-based AI processing enables the visual data from cameras and sensors to be processed, analyzed and sent via 5G networks, enabling accurate remote assembly and quality checking (Liu et al., 2022).

The processed data is then sent back over the 5G network to the robotic system and human operator for bi-directional communication and immediate feedback. Low latency feedback loop is essential for applications requiring precise coordination, such as remote assembly, quality inspection, and robotic teleoperation (Moura et al., 2021; Latif et al., 2021).

Factory Floor Visualization: 5G takes the wired SCADA system to the next level by providing real-time, interactive visualization and monitoring of production processes from anywhere (EU Horizon, 2022). Traditional supervisory control and data acquisition (SCADA) and industrial monitoring solutions were constrained by wired infrastructure, bandwidth limitations and latency problems which prevented real-time visualization and remote decision-making (Kang et al., 2016; Popovski et al., 2018).

Wireless Acoustic Monitoring: By utilizing 5G-enabled acoustic sensors, real-time monitoring of machining conditions, tool wear, and process quality can be achieved, with the data fed into AI algorithms for adaptive process control (Latif et al., 2021; Popovski et al., 2018).

Digital Twin Integration: 5G can be used to connect

virtual robots or production lines with physical robots in real-time, which enhances predictive maintenance, simulation, and process optimization (Lee et al., 2015; Tao et al., 2018).

5G based digital twins can predict component wear in manufacturing systems, estimate failure likelihood, and autonomously determine the maintenance plan, minimizing downtime and maximizing equipment life (EU Horizon, 2022; 5G-SMART Consortium, 2021). This is a change from conventional preventive maintenance to data-driven, predictive and adaptive maintenance strategies (Moura et al., 2021).

Cloud Based Mobile Robotics: AI-powered robots using 5G connectivity can offload significant computing power to the cloud or edge nodes, allowing them to navigate autonomously, perform SLAM, and coordinate multiple robots (Kang et al., 2016; Liu et al., 2022).

Robots have access to huge amounts of computational and data resources, which enable AI capabilities such as visual recognition, simultaneous localization and mapping (SLAM), and dynamic path optimization (Popovski et al., 2018; Liu et al., 2022). The connectivity also enables multiple robots to coordinate and collaborate autonomously to complete tasks in a more efficient way, making the system more adaptable and flexible in dynamic industrial environments (Kang et al., 2016; EU Horizon, 2022).

Cross-Domain and Inter-Company Collaboration: 5G enables low-latency and secure data transfer between companies and across domains, enabling collaborative networks, remote maintenance and supply chain integration (5G-SMART Consortium, 2021).

In addition, 5G enables the integration of different sectors across the domains, for example, in the manufacturing and logistics sectors, energy and healthcare, etc., thus creating the vision of an industrial ecosystem where data and intelligence move across the different sectors. Edge and cloud computing are important components of this model, as they provide the following capabilities: hosting shared services, distributed data analytics, and local and global AI-driven decision making (Lee et al., 2015; Tao et al., 2018).

AI-enabled 8-AGV Real-Time Trajectory Adaptation: Automated Guided Vehicles (AGVs)

with AI capabilities adapt their routes in real-time, ensuring efficient, collision-free and synchronized intralogistics (Latif et al., 2021).

Continuous data streams of various types, such as onboard sensors, cameras, and LiDAR systems are fed into AI-based control algorithms, which then adjust paths and optimize routes to avoid obstacles. The use of 5G-based connectivity allows AGVs to communicate instantly with the edge servers and the central control systems, facilitating coordinated decision making and multi-vehicle synchronization (Moura et al., 2021). Continuous data streams from onboard sensors, cameras, and LiDAR systems feed into AI-driven control algorithms, which then analyze and interpret the data to identify obstacles, determine paths, and optimize routing.

In this case, by using the 5G connectivity, AGVs can communicate instantly with the edge servers and central control systems, which allows for synchronized decision making and multi-vehicle synchronization (Moura et al., 2021).

9- AI-Driven Quality Management: This requires machine learning and deep learning models to analyse sensor and visual data to detect defects, predict failures and optimize processes with the help of edge and cloud computing over 5G (Tao et al., 2018; EU Horizon, 2022).

This ecosystem is essential to the 5G URLLC, which enables near real-time data transfer between production machinery, edge-AI systems and human operators (Popovski et al., 2018). With edge computing, the quality analytics can be performed locally near the production line, thus limiting the need for bandwidth and minimizing latency while securing the data. Together these developments set the groundwork for predictive, autonomous and intelligent quality assurance processes in smart manufacturing (EU Horizon – 2022).

1.3. Distinguishing Smart Manufacturing and Smart Factories:

Smart manufacturing and smart factories exist in different levels of abstraction, but are closely related to each other.

Smart Manufacturing is the production process that is enabled by digital technology, including the integration of machines, systems, people and processes via IIoT, big data analytics and cloud computing (Kang et al., 2016; Tao et al., 2018).

Smart Factories are physical implementations of SM, which are the integrated cyber-physical systems that are capable of self-monitoring, optimizing and adapting production processes in real-time (Lee et al., 2015; Al-Ali, 2023).

Both concepts are part of Industry 4.0, with the smart factories being flexible and self-organizing factories that are coordinated by a central platform to ensure optimal performance, product quality, and adaptability (Moura et al., 2021).

1.4. Automation and AI in Smart Factories

The combination of 5G and AI has revolutionized the capabilities of automation. Machine-to-machine communication enables robots and assembly lines to synchronize with millisecond precision, whereas AI-driven algorithms can forecast equipment failures, identify anomalies, and optimize processes. Machine-to-machine communication facilitates precise synchronization of robots and assembly lines, while AI algorithms can predict equipment failures, detect anomalies, and optimize processes. Edge computing enables local decision-making, which means that the system can function without interruption even if there are fluctuations in the network. AI and 5G are the foundation of autonomous, adaptive and self-optimizing manufacturing ecosystems.

1.5- Enhancing AI-Driven Processes:

Continuous and real-time data exchange are crucial for the integration of Artificial Intelligence (AI) in Smart Factories. 5G's high bandwidth and minimal latency ensure that AI systems for quality inspection, predictive analytics, and process optimization receive uninterrupted, high-speed data streams (Chen et al., 2020; Latif et al., 2021). This real-time connectivity allows algorithms to autonomously and data-informedly make decisions, facilitating manufacturing systems to identify anomalies, anticipate equipment failure, and dynamically optimize production parameters. AI and 5G are the core of intelligent, autonomous manufacturing ecosystems that learn and evolve over time (5G-SMART Consortium, 2021).

1.6. This course covers learning, decision making, and digital twins.

Smart factories continuously learn from the operational data and digital twins to gain insight for predictive and prescriptive decision making

(Tao et al., 2018; Lee et al., 2015). The digital twin can enable simulation, optimization and scenario analysis, allowing factories to respond quickly to disruption, demand variability and external challenges like the COVID-19 pandemic (EU Horizon, 2022).

1.7. Operational Excellence & Industry 4.0 Practices: Smart factories are based on Industry 4.0 best practice, which means they adopt the following rules:

Overall Equipment Efficiency (OEE)

- Continuous improvement
- Quality cost reduction
- Inventory minimization
- Rapid time-to-market
- Operational cost reduction
- Energy efficiency

Applications cover value chains and digital ecosystems, fostering lifecycle management, interoperability, and the development of value added services (De Carolis et al., 2011; Moura et al., 2021; Tao et al., 2018). The architecture of a typical smart factory is shown in Figure (1).

Incorporating multiple functions and disciplines, however, adds to system complexity and can constrain the advantages of making the switch to digital production. As shown in figure (1), the simple architecture of smart factory is built.

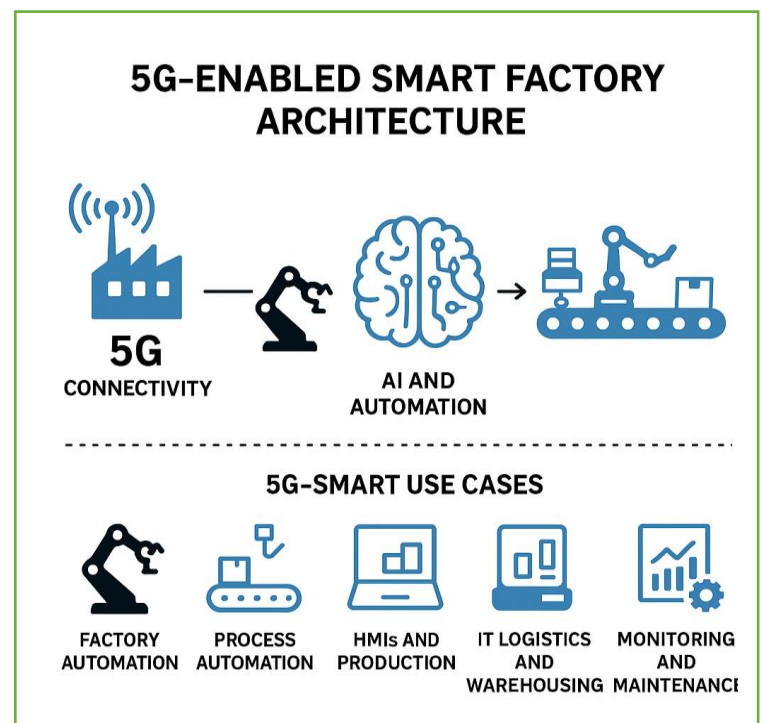


Figure (1), the simple architecture of smart factory is built.

1.8. Digital Factories as Cyber-Physical Ecosystems

Digital factories are cyber-physical systems that combine IIoT, big data analytics, robotics and enterprise software to support flexible, efficient and data-driven manufacturing (Lee et al., 2015; Tao et al., 2018). They are used throughout the product life cycle, ranging from the design and engineering through to production execution and optimization, in line with Industry 4.0 and Industry 5.0 principles (Moura et al., 2021; EU Horizon, 2022).

2. LITERATURE REVIEW

Part Two- KEY COMPONENTS OF SMART FACTORIES:

The smart factory represents the essence of Smart Manufacturing (SM), and the ultimate vision of

Industry 4.0. It is distinguished by its adaptability, self-optimization and dynamic response to varying production situations (Kang et al., 2016; Lee et al., 2015). Smart factories combine physical and digital spaces, leveraging cutting-edge technologies to optimize processes, reduce waste, improve productivity and allow for more flexible and data-driven production methods (Tao et al., 2018; Moura et al., 2021).

With the interoperability of digital technologies in smart manufacturing systems, the range of their functions has been significantly broadened, which has allowed cost reduction, time savings, simplified configuration, improved decision-making, quick market response, operational flexibility, and remote monitoring (Phuyal et al., 2020). Figure (2) shows the key components of a smart manufacturing system, such as flexible manufacturing, computing and virtual simulation, connectivity and data processing.

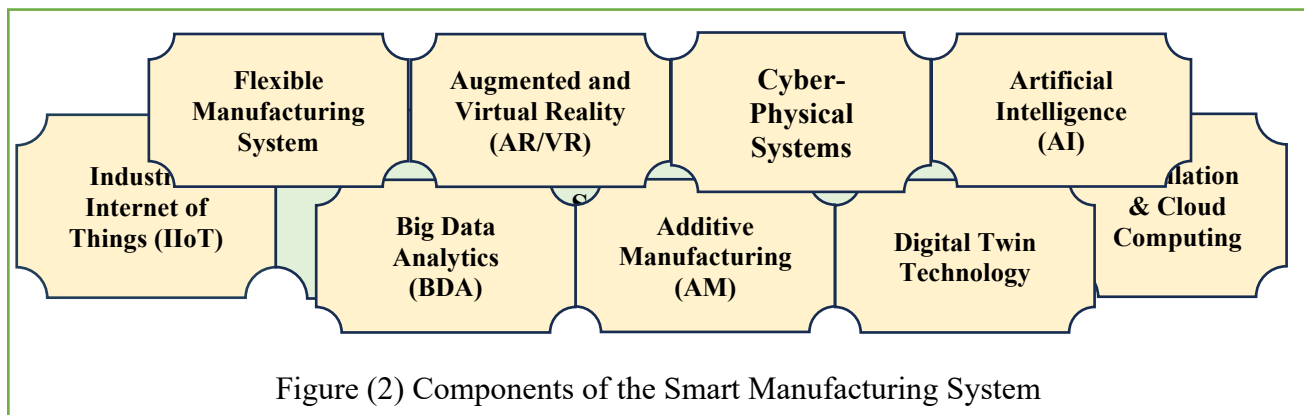


Figure (2) Components of the Smart Manufacturing System

2.1. Flexible Manufacturing Systems (FMS):

The Flexible Manufacturing Systems (FMS) are able to adapt to the changing demands of production in terms of priority, integrated functions, and scheduling change due to the changes in the market and product reconfiguration. FMS help to maintain cost efficiency, quick response and flexibility in operations. They can deal with different batch sizes, even small-scale production and can enable production equipment to be quickly reconfigured for different product types. There are two types of flexibility:

Production line flexibility – allowing production cells to produce new product types.

Machine-level flexibility – allowing station flexibility in scheduling.

The system's adaptive capabilities are enhanced by digital programming, automated tool replacement,

and integrated monitoring systems. Some of the important features are modularity, scalability, diagnostic features, and adaptive control (Kang et al., 2016; Tao et al., 2018).

2.2. Blockchain and Artificial Intelligence (AI)

AR and VR technologies can connect the digital and physical realms and provide visualization, simulation, and interactive training. The AR technology uses wearables or mobile platforms to fuse synthetic parts with the real world to facilitate design validation, training and operational planning in a safe virtual environment. VR can be used for immersive simulation of production processes to optimize workflow and skill development of the workforce (Phuyal et al., 2020; Moura et al., 2021).

2.3. Cyber-Physical Systems (CPS)

Cyber-Physical Systems combine physical and computational elements to allow for seamless data exchange and coordination throughout the manufacturing process. By connecting to industrial engineers through cloud computing platforms, CPS enables them to monitor and control production remotely, making predictive maintenance, autonomous decision making and improving operational efficiency easier. Cloud-based SCADA systems represent CPS, which combines sensors, actuators, machinery, software and communication networks (Lee et al., 2015; Tao et al., 2018).

4. Artificial Intelligence (AI) and Cloud Computing: AI empowers smart factories to analyze data, make autonomous decisions, and adapt to dynamic production conditions. By integrating AI algorithms, human-robot collaboration is optimized, along with quality control and predictive maintenance and operational efficiency (Chen et al., 2020; Latif et al., 2021).

With the infrastructure of cloud computing, AI can power operations from simulation and testing to optimization and real-time coordination between production units. Cloud platforms enable smooth data sharing, big data analysis and collaborative innovation, in order to move from reactionary to predictive and prescriptive management approaches (Moura et al., 2021). AI and cloud computing are the basis of smart factories and Industry 4.0, which is known as a cyber-physical ecosystem.

2.4. Simulations and Virtual Testing

Manufacturers can use simulation platforms to simulate production processes, machines, and the entire factory operations. When combined with digital twins, simulation can be used in real time to optimize production, to determine bottlenecks, and to test production schedules without any physical impact, which minimizes cost, time, and operational risk. Cloud computing provides centralized access to data, coordination of distributed operations, and deployment of AI applications across various sites (Phuyal et al., 2020).

2.5. Digital Twin Technology:

Digital twins are virtual copies of physical assets, systems or processes that mirror their real-world status, performance and operational behavior in real time (Tao et al., 2018; Lee et al., 2015). They

combine sensors, IoT devices, and simulation models to allow for real-time monitoring, predictive maintenance, scenario planning and decision making. Digital twins are a key element of smart factories of the future, with a significant contribution to their efficiency, reliability, and flexibility.

2.6. Additive Manufacturing (AM)

The 3D printing technology, commonly known as Additive Manufacturing, allows for on-demand production, rapid prototyping and high customization. AM decreases production time, material waste, and costs by manufacturing components on-site. It is widely applicable in the manufacturing of medical devices, civil engineering and complex parts, which greatly improves the flexibility, responsiveness and customer satisfaction of smart factories.

2.7. Big Data Analytics

Big data analytics includes the gathering, assimilation, and analysis of vast amounts of data from manufacturing units, internal departments, and customer interactions. In the context of smart manufacturing, analytics play a vital role in predictive maintenance, real-time decision-making and operational optimization (Tao et al., 2018; Chen et al., 2020). Decision making, customer engagement, production planning and product design, all informed by insights derived from big data.

2.8. Industrial Internet of Things (IIoT)

The IIoT brings together sensors, actuators, control systems and monitoring units through cloud platforms, allowing them to interact seamlessly with each other across all manufacturing elements (Lee et al., 2015; Tao et al., 2018). Predictive maintenance, process optimization, intelligent use of resources and real-time coordination are all enabled by IIoT and are key components of smart factories and digital ecosystems.

2.9. Integration of Components

FMS, AR/VR, CPS, AI, Cloud Computing, Digital Twin, Additive Manufacturing, Big Data, and IIoT are all able to bring highly flexible, efficient, and intelligent manufacturing systems. Smart factories illustrate all the principles of Industry 4.0: digitalization, connectivity and advanced analytics to optimize resources, product quality, competitiveness and react quickly and adapt to market and production changes.

Part Three: STRUCTURE of the SMART FACTORY:

The smart factory can be described in four main areas: Business, Product, Factory, and Operations

Management, which are all provided with smart technologies, also known as the Intelligent Function. The information on these domains and dimensions are summarized in Table 1:

Table (1): The Four Domains of the Smart Factory (Al-Ali, 2023)	
Domain	Dimensions
Business	Markets, levels and layers, demand/supply flow, demand lifecycle
Product	Core product, lifecycle, value flow, knowledge/engineering flow and their lifecycles, and product lifecycle
Factory	Hierarchical levels, system hierarchy, factory lifecycle, and organizational scope
Operations Management	Manufacturing and Manufacturing hierarchy

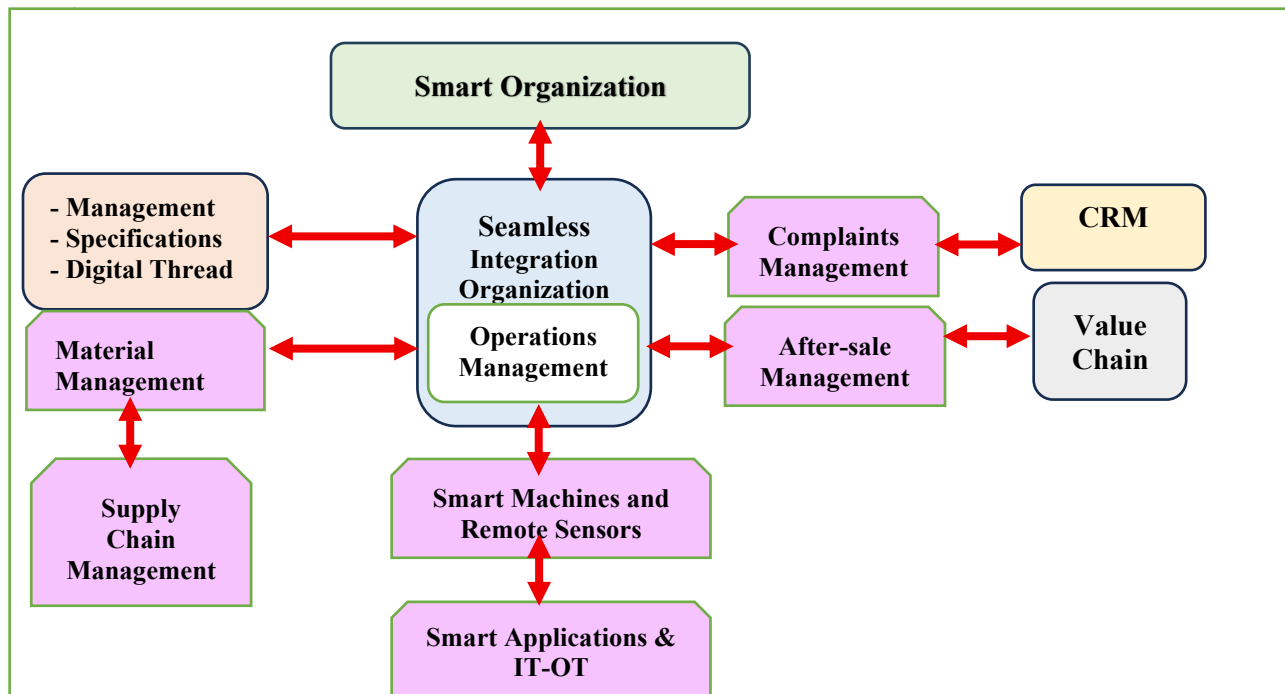
There are four smart manufacturing domains related to smart technologies:

1. Connected Supply Chain (Business) – Improves supply chain visibility, agility and coordination via digital and data-driven supply chains.
2. Digital Thread (Product) – Ensures seamless data continuity and traceability throughout the product lifecycle.
3. Smart Factory (Factory) – Cyber-physical

systems completely connected for real-time optimization and operational efficiency.

Digital Operations Management (Operations) – allows for intelligent coordination, monitoring and control of production processes.

These 4 domains are interconnected, forming the core of a smart and flexible manufacturing system as shown in Figure (3).



These domains have the following key aspects: Real-time data exchange leads to higher visibility,

collaboration, traceability, and resilience throughout the supply chain, from suppliers to

manufacturers to customers.

Digital Thread – Linking product lifecycle continuously with digital integration, to ensure traceability, decision-making and speed of the product cycle.

Smart Factory – Industrial IoT: machines, people, systems connected; real-time data for predictive maintenance and optimization.

Digital Operations Management (DOM) – Decentralization with data-driven operations, improves autonomy, responsiveness and intelligent process control.

Part 4: SMART MANUFACTURING MATURITY:

A digital technological system on its own is not a complete solution to improving an organization's efficiency, maturity or capability. Digital transformation involves co-evolution of both technology and work systems – production, administrative and social processes (De Carolis et al., 2017). Such a dual transformation defines the entangled connection between the technical and social aspects of the organization, which is conceptualized in Sociomaterial Theory as entanglement (Orlikowski, 2007; Leonardi, 2011). Smart manufacturing is a production paradigm that is based on the use of a wide range of smart technologies and the integration of the four core domains of business, product, factory and operations management (Al-Ali, 2023). Hence, organizations transforming to become smart and flexible manufacturing systems should be regarded as a socio-technical system.

The readiness can be best measured using a Smart Factory Maturity Model, which is a tool for evaluating the technological development, integration level and digital transformation path. This type of model allows companies to assess cultural and process change as well as technological change – giving them the ability to demonstrate not just technological adoption, but cultural and process adaptation and therefore sustainable performance increases in both technical and human systems.

Construction of a Smart Factory can be broken down into the following phases:

1. Planning – Data collection, digital twin creation, simulation and analysis.
2. Design – Factory layout optimization, integration of digital systems, iterative simulation.
3. Validation – Feasibility, safety and alignment

with strategic objectives.

Construction – Physical implementation with the support of digital twin and Building Information Modeling (BIM).

5. Full integration of digital and physical systems, real-time monitoring, predictive control, self-optimization.
6. Synthesis & Integration – Progressive & interdependent integration of technology & organizational adaptability.

The shift from traditional to smart manufacturing is not just a technological transition; it's a sociotechnical transformation, where digital systems, intelligent technologies, and human expertise work together to build a responsive, efficient, and resilient production ecosystem (Al-Ali, 2023).

In this context, the maturity assessment model mentioned above is a key element in assessing the readiness, capability and evolution of an organization when undergoing a change process. Regularly reviewing technological integration, the adaptability of the workforce, and process optimization can help organizations ensure the strategic alignment, sustainable scalability, and disruption resilience of their smart factory efforts (Mittal et al., 2018).

Part Five: DIGITAL INFRASTRUCTURE of the SMART FACTORY SYSTEM:

As mentioned in previous sections, the digital factory incorporates a variety of interconnected systems, tools and smart technologies. Industrial components included in the smart factory's digital technological infrastructure are essential for the management, monitoring, and optimization of industrial operations (Berg, 2023; Al-Ali, 2023; Deloitte, 2024).

The key digital infrastructure elements are:

1. Manufacturing Execution System (MES) – Single point of production management, workflow optimization, real-time information and predictive maintenance.
2. Machine-to-Machine (M2M) Communication – Allows devices to communicate seamlessly with one another in the industrial space.
3. Digital Twins – virtual copies of asset, component, system or process for simulation, prediction and optimization.
4. Digital Backbone – Network layer that connects all digital and physical systems for real-time

coordination and analytics.

Recipe Management System (RMS) – Centralized control of operational parameters for standardization, quality and traceability.

6. Automated Material Handling Systems (AMHS) – robotics and conveyors working with MES for efficient material flow.

7. Augmented Reality (AR) – Improves assembly instruction, maintenance, training and workflow visualization.

8. Core Processes – 3D printing (additive manufacturing) and Advanced Manufacturing Intelligence (AMI) for flexible production and data-driven optimization.

9. Work-in-Process (WIP) Management – Real time material flow tracking to increase efficiency and quality.

10. Data Collection – High frequency sensor and system data allows predictive analytics and evidence-based decision making.

11. Reporting & Analytics – Performance, Maintenance, KPI, Process Improvement Dashboards.

12. Integrated Automation – Unified management of control systems, MES, DCS, AMHS, IT-OT integration.

3. STUDY FINDINGS

Future directions of SMART MANUFACTURING:

A paradigm shift is underway in manufacturing, commonly known as Industry 5.0, which involves an increase in collaboration between human and AI and intelligent autonomy. Unlike Industry 4.0, which was mainly focused on the digital connectivity and cyber-physical systems, Industry 5.0 is more about human-centered, sustainable and resilient production ecosystems (Nahavandi, 2019; Xu et al., 2021).

The future factories will be hyperconnected systems, where 5G/6G communication, edge-cloud computing, and the Industrial Internet of Things (IIoT) will work together for real-time coordination in the distributed manufacturing networks (Lu et al., 2021). In these networks, digital twins will be virtual representations of physical assets that continuously update and feed into predictive maintenance, performance optimization, and system simulation (Tao et al., 2019; Zhang & Xu, 2020).

Artificial intelligence (AI) and machine learning (ML) will enable self-optimizing processes and

smooth data-driven decision-making, fault detection and adaptive quality control. At the same time, collaborative robots (cobots) will be used to supplement human abilities, allowing for flexible assembly and cognitive cooperation in dynamic working environments (Li et al., 2017). The immersive visualization tools, including augmented and virtual reality (AR/VR) interfaces, will facilitate intuitive real-time monitoring and control, backed by high-speed 5G connectivity (Chen et al., 2021).

Circular economy will be a key element in the next generation of manufacturing, with the principles of reuse, reduce and recycle being applied to material reusability and energy efficiency (European Commission, 2021). Carbon footprints will be monitored by factories using integrated sensors, and AI-driven, optimization efforts will be used to reduce environmental effects. In the end, the Factory of the Future will combine automation, intelligence and the creative power of people, creating autonomous, yet human production systems, efficient, sustainable, and technologically advanced, yet ethically sound.

The focus of next-generation manufacturing (Industry 5.0) is on:

Collaborative Human-AI – Flexible and adaptive production with intelligent machines (cobots).

Hyperconnected Ecosystems – 5G/6G networks, Industrial IoT, and cloud-edge computing are all in real-time connecting the assets of the factory.

Digital Twin Integration – For every asset and process there is a virtual asset and process that supports predictive maintenance and simulation of scenarios.

AI and real-time analytics enable data-driven autonomy, self-optimizing, adaptive processes.

Sustainability & Circular Manufacturing – Waste reduction, energy efficiency, tracking carbon footprint, closed-loop systems.

Immersive Visualization & Control – AR/VR interfaces for real-time monitoring, simulation and management.

AI-powered Adaptive Networks that dynamically manage demand, logistics, and production: Cognitive Supply Networks.

Ethical & Human-Centered Design – Reskilling, wellbeing of workers, creative collaboration.

5G Technologies in Smart Factories:

- Helps with ultra-low latency, high-speed data and real-time communication in autonomous,

decentralized manufacturing.

- Supports immersive AR/VR monitoring, edge computing, AI planning and advanced robotics.

6G developments will also support the development of AI-native networks, quantum-secured communication, and complete swarm robotics autonomy.

Last, the focus of future research is on embedding 6G capabilities, including AI-native networks, quantum-secured communication, and ultra-high reliability machine communication (uHRMC), to further develop collaborative robotics and autonomous manufacturing. With the evolution of 5G to 6G, it is likely that we will see the appearance of fully autonomous swarm robotics, tactile internet, and immersive telepresence, marking the dawn of Industry 5.0, in which humans and machines work together in symbiotic collaboration (Dang et al., 2020; Saad et al., 2021).

4. CONCLUSION

Smart factories are a sociotechnical ecosystem that interweaves humans, materials, and technology for optimized, resilient, and sustainable production. Key insights:

Implementation involves systematic planning, design, testing, construction and operation.

Strong digital infrastructure, such as MES, digital twins, digital backbone, plays a vital role in real-time monitoring, predictive analytics and automation.

The concept of Industry 5.0 focuses on human-centric, sustainable and intelligent manufacturing. 5G and future 6G connectivity quickly enable autonomy, collaboration and immersive visualization.

For successful adoption, it requires organizational preparedness, inter-functional collaboration and ongoing innovation, which will allow for an efficient operation, safe workforce and environmental sustainability.

Smart manufacturing is shown through real-world use cases, such as Porsche Production 4.0, to achieve greater flexibility, efficiency and predictive decision making in value chains.

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