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RESEARCH ARTICLE

Advancing Manufacturing Excellence in the Industry 4.0 Era: A Comprehensive Review and Strategic Integrated Framework

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ABSTRACT

Industry 4.0 is revolutionizing manufacturing by integrating advanced technologies like IoT, AI, and robotics to enable higher levels of automation, real-time insights, and operational agility. This transformation offers substantial opportunities but also poses challenges in achieving manufacturing excellence through enhanced quality, efficiency, responsiveness, and sustainability.

This paper reviews the key technological enablers, strategic priorities, and organizational changes driving smart, resilient, and sustainable manufacturing in the Industry 4.0 era. It proposes an integrated methodology that combines digital technologies—including IoT, AI, digital twins, and collaborative robotics—with a human-centered approach. The methodology organizes Industry 4.0 strategies into five domains: Quality & Innovation, Asset & Operations, Supply Chain & Logistics, Safety & Sustainability, and People & Customer Engagement, demonstrating how these areas improve efficiency, asset management, supply chain transparency, safety, and workforce capabilities to enhance agility and competitiveness. Central to this is the use of cyber-physical systems for real-time data exchange, transforming factories into adaptive smart ecosystems.

Challenges such as legacy system integration, cybersecurity risks, skill gaps, and resistance to change are addressed through phased adoption, robust security, continuous workforce development, pilot projects, and strong leadership. The framework integrates Lean, Six Sigma, and Agile methods with real-time analytics, an enhanced DMAIC cycle, and adaptive KPIs to drive continuous improvement and operational excellence. By aligning technology, processes, people, and sustainability, it supports building agile, resilient, and sustainable production systems that secure long-term competitive advantage.

This conceptual framework presents a practical roadmap for Industry 4.0 transformation and will be further refined and validated through future case studies and pilot projects to facilitate wider adoption and ongoing improvement.

Keywords: Industry 4.0; smart technologies; intelligent automation; modern manufacturing; continuous improvement

1. Introduction

The manufacturing sector is undergoing a profound transformation, propelled by accelerating technological advancements and evolving societal demands. Each industrial revolution has successively reshaped production systems by building upon previous innovations to enhance efficiency, flexibility, and

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connectivity. As depicted in **Figure 1**, this progression spans from mechanized production in Industry 1.0 to electrified mass production in Industry 2.0, and then to the introduction of digital automation and computing in Industry 3.0. Industry 4.0 marks a fundamental paradigm shift, integrating cyber-physical systems, the Internet of Things (IoT), artificial intelligence (AI), and advanced data analytics to enable smart, autonomous, and interconnected manufacturing systems. Concurrently, Industry 5.0 is emerging with a focus on human-machine synergy, ethical AI, and sustainable, human-centric innovation. Looking ahead, Industry 6.0 envisions a transformative industrial future characterized by conscious, regenerative, and resilient ecosystems[1,2].

The First Industrial Revolution introduced steam and water-powered mechanization, initiating the mechanized factory. The Second Industrial Revolution saw breakthroughs in electricity, steel, and transportation, enabling the development of mass production systems. The Third Industrial Revolution—Industry 3.0—ushered in the digital age, marked by the integration of computers, electronics, and early automation technologies that enhanced precision and efficiency.

Industry 4.0, introduced under Germany's high-tech strategy in 2011, builds on this foundation through technologies such as cyber-physical systems (CPS), the Industrial Internet of Things (IIoT), artificial intelligence (AI), cloud computing, and big data analytics. These innovations transform traditional factories into smart, interconnected ecosystems capable of autonomous operation and real-time decision-making. Technologies such as digital twins, autonomous robots, and blockchain enhance operational transparency, system reliability, and predictive capabilities, reinforcing competitiveness in an increasingly volatile global landscape.

As Industry 4.0 becomes more widespread, Industry 5.0 is evolving as a complementary paradigm that emphasizes the value of human-centered innovation. Emerging around 2019, Industry 5.0 seeks to harmonize the power of intelligent technologies with human creativity, ethical considerations, and sustainable practices. Through collaborative robotics (cobots), augmented and virtual reality (AR/VR), edge computing, and wearable devices, it enhances flexibility, personalization, and employee well-being. However, these benefits also raise new challenges in cybersecurity, data governance, and workforce reskilling.

Figure 2 highlights the key technologies underpinning Industry 4.0, as detailed in recent studies. These include the Internet of Things (IoT) for seamless connectivity among devices; smart sensors enabling real-time data collection and monitoring; and advanced robotics that deliver precision and flexibility. Artificial intelligence (AI) supports intelligent automation through data-driven learning, while cyber-physical systems (CPS) integrate digital models with physical assets to enable real-time control. Augmented and virtual reality (AR/VR) enhance design, training, and maintenance with immersive experiences. Cloud computing provides scalable data storage and processing power, complemented by machine learning (ML) for predictive analytics and autonomous improvements. Digital twin technology creates virtual replicas of physical systems for better forecasting and optimization, and additive manufacturing (3D printing) supports rapid prototyping and customized production. Big data analytics turns vast data into actionable insights, secured by robust cybersecurity measures. Blockchain technology ensures secure, transparent, and decentralized data transactions, while location detection technologies such as GPS and RFID improve tracking and operational visibility. Collectively, these technologies form the backbone of Industry 4.0's smart, interconnected, and adaptive manufacturing environments[3-8].

Within this technological context, this study develops a comprehensive Industry 4.0 methodology that integrates cutting-edge digital technologies with a human-centric approach to drive agile, resilient, and sustainable manufacturing excellence. It covers key domains including quality, operations, supply chain, safety, and workforce development, while addressing critical challenges such as legacy system integration, cybersecurity threats, and skill shortages. By leveraging real-time data analytics, advanced process improvement techniques, and adaptive KPIs within an integrated framework, the methodology enables continuous optimization and empowers organizations to maintain a competitive edge in the rapidly evolving Industry 4.0 manufacturing landscape.

This paper is structured as follows: Section 2 provides an overview of the evolution and foundational technologies of Industry 4.0. Section 3 examines the key challenges and organizational barriers to its effective implementation. Section 4 presents the proposed integrated framework, highlighting its application across essential manufacturing domains. Section 5 concludes the paper with key insights and outlines recommendations for future research and strategic development.

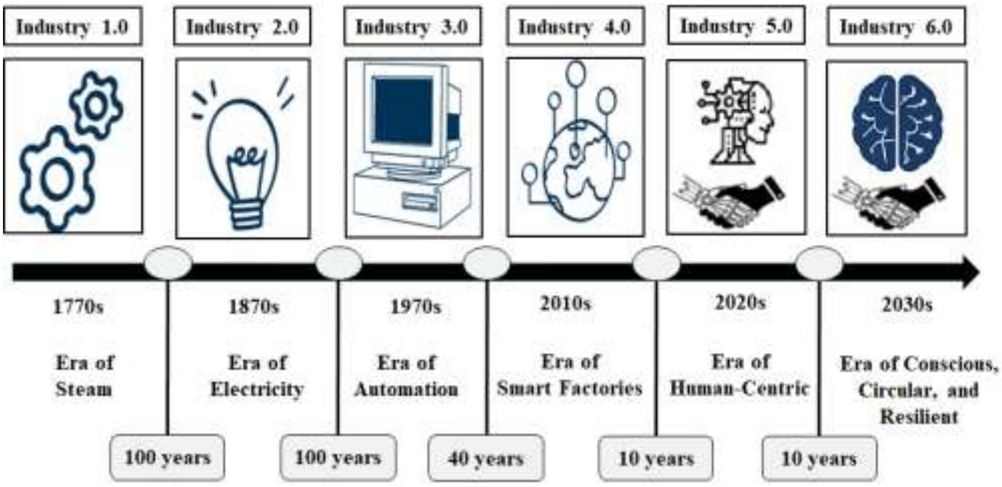

Figure 1. The evolution from industry 1.0 to industry 6.0

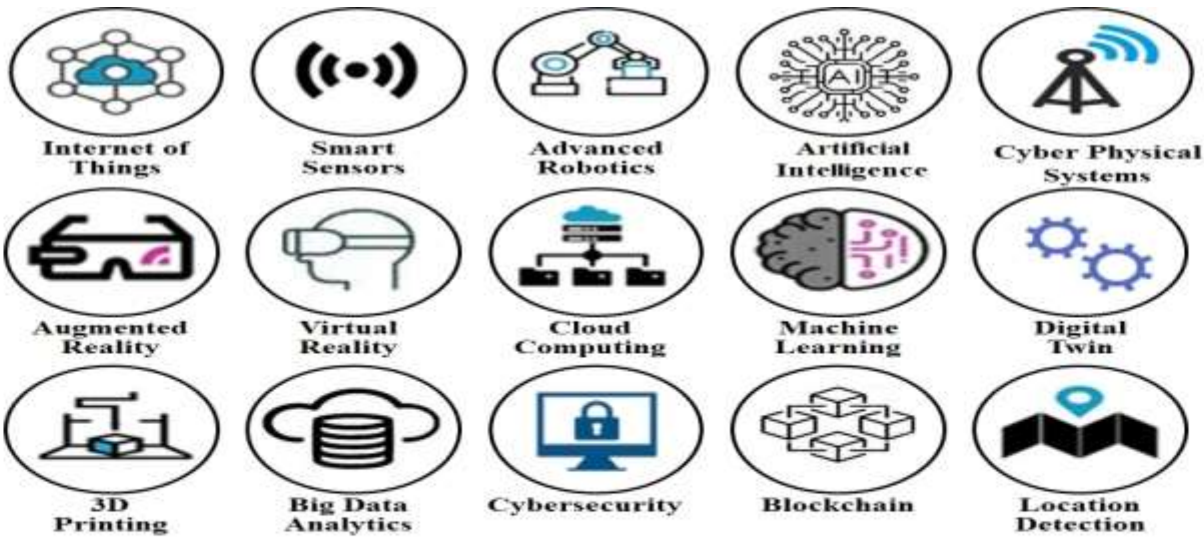

Figure 2. Main technologies of industry 4.0

2. Literature review of industry 4.0 features and technologies

Industry 4.0 (I4.0), first introduced in Germany in 2011, signifies a transformative shift in manufacturing through the integration of cyber-physical systems (CPS), the Industrial Internet of Things (IIoT), artificial intelligence (AI), machine learning (ML), robotics, big data analytics, cloud computing, and digital twins[9,10]. This convergence fosters intelligent, interconnected production environments that enable real-time communication and autonomous decision-making among machines, systems, and humans. By decentralizing control, Industry 4.0 enhances manufacturing agility, flexibility, and responsiveness, facilitating rapid adaptation to evolving market demands and driving operational excellence[11-13].

Core Technologies and Benefits: Central to Industry 4.0 are advanced robotics, additive manufacturing, augmented reality, and big data analytics, which collectively improve resource efficiency, reduce downtime, and enable mass customization[14]. Predictive maintenance, empowered by machine learning and digital twins—virtual replicas of physical assets—enables continuous condition monitoring, early anomaly detection, and risk-informed maintenance strategies, optimizing asset performance while minimizing operational costs[15]. Furthermore, smart machines, self-aware products, and augmented operators enhance production agility, supporting flexible, customized mass production without compromising efficiency[16].

Adoption Landscape and Challenges: Developed countries spearhead Industry 4.0 adoption through strategic initiatives such as Germany's Industry 4.0 plan and China's Made-in-China 2025, while emerging economies are progressively embracing these technologies[1,17]. The global Industry 4.0 market is projected to grow substantially—from $66.7 billion in 2016 to $227 billion by 2025[18]. Nevertheless, significant challenges persist, including cybersecurity risks, substantial upfront investments, complex IT-OT integration, and pressing workforce reskilling needs, which hinder widespread implementation[19].

Integration and Smart Factories: Industry 4.0 facilitates both horizontal integration across supply chains and vertical integration within enterprises, seamlessly connecting suppliers, production systems, and customers. Big data analytics plays a pivotal role by transforming massive datasets into actionable insights, thereby enabling optimized decision-making and enhanced operational efficiency[20,21]. These capabilities underpin the rise of smart factories, which proficiently manage complex, dynamic production processes with superior flexibility, productivity, and sustainability[11,22].

Sustainability and Human-Centric Evolution: Beyond economic gains, Industry 4.0 contributes to environmental and social sustainability by improving resource planning, reducing waste, elevating workforce skills, and enhancing workplace safety[23]. Recent studies highlight sustainability risks associated with Industry 4.0 adoption and propose frameworks to mitigate these challenges[24]. Building on this foundation, Industry 5.0 advances a human-centric, sustainable manufacturing paradigm that integrates circular economy principles with advanced human-machine collaboration, supported by edge computing, blockchain, collaborative robots (cobots), and emerging 6G technologies[2,25].

In summary, Industry 4.0 is revolutionizing manufacturing by enabling adaptive, interconnected, and data-driven production systems that enhance operational efficiency, sustainability, and global competitiveness. Table 1 presents a summary of key Industry 4.0 technologies and their impacts, underscoring their vital role in shaping smart, resilient manufacturing ecosystems[2,7,8,26-28].

Table 1. Key industry 4.0 technologies and their impact

#	Technology	Category	Description	Objective	Applications
1	Internet of Things (IoT)	Connectivity	Connects devices for seamless data exchange.	Enhance real-time integration and visibility.	Asset tracking, condition monitoring
2	Smart Sensors	Monitoring	Real-time data capture and transmission.	Enable proactive monitoring and faster decisions.	Equipment health, process control
3	Advanced	Automation	Performs precise and	Increase productivity and	Assembly, material

#	Technology	Category	Description	Objective	Applications
	Robotics		flexible automated tasks.	accuracy.	handling
4	Cyber-Physical Systems (CPS)	Integration	Links physical assets with digital controls.	Enable real-time feedback and automation.	Process control, system coordination
5	Augmented Reality (AR)	Visualization	Overlays digital info for training and support.	Improve training and reduce errors.	Maintenance, operations assistance
6	Virtual Reality (VR)	Simulation	Immersive environments for training and design.	Enhance prototyping and remote learning.	Design validation, safety training
7	Cloud Computing	Data Storage	Scalable remote computing and storage.	Support collaboration and scalability.	Data hosting, application delivery
8	Machine Learning (ML)	Analytics	Data-driven algorithms that learn and adapt.	Enable predictive insights and optimization.	Predictive maintenance, anomaly detection
9	Digital Twin	Modeling	Real-time digital replicas of physical assets/systems.	Optimize performance and predict issues.	Asset monitoring, maintenance planning
10	Additive Manufacturing	Production	Layered 3D printing for rapid prototyping/ customization.	Accelerate innovation and reduce waste.	Custom parts, rapid prototyping
11	Big Data Analytics	Data Analysis	Analyzes large datasets to extract actionable insights.	Drive strategic and operational improvements.	Market trends, process optimization
12	Cybersecurity	Security	Protects systems and data from cyber threats.	Ensure data integrity and system resilience.	Network defense, compliance
13	Blockchain	Data Security	Decentralized, tamper-proof ledger technology.	Increase transparency and trust.	Supply chain tracking, transaction verification
14	Location Detection	Tracking	Real-time positioning via GPS, RFID, and similar tech.	Improve logistics and asset management.	Fleet tracking, warehouse operations
15	Workflow Automation Software	Automation	Automates repetitive tasks and workflows.	Increase efficiency and reduce errors.	Task automation, approvals
16	Collaborative Platforms	Communication	Enables real-time teamwork and knowledge sharing.	Enhance collaboration and productivity.	Project management, remote work
17	Process Mapping Software	Optimization	Visualizes workflows to identify inefficiencies.	Streamline operations and reduce waste.	Lean initiatives, workflow improvements
18	Automated Inventory Systems	Inventory Management	Automates stock tracking and replenishment.	Improve accuracy and responsiveness.	Warehouse and supply chain management
19	Digital Kanban Boards	Workflow Management	Digital visualization of tasks and workflows.	Improve visibility and workflow efficiency.	Task tracking, bottleneck elimination

#	Technology	Category	Description	Objective	Applications
20	Sensor-Based Error Detection	Quality Control	Detects defects and anomalies via sensors.	Prevent defects and minimize downtime.	Quality assurance, fault detection
21	AI-Powered Monitoring	Predictive Operations	AI-driven real-time monitoring and analytics.	Enable predictive maintenance and efficiency.	System monitoring, fault prediction
22	Simulation and Modeling Tools	Risk Analysis	Simulates processes for optimization and risk assessment.	Improve planning and reduce uncertainties.	Capacity planning, risk management
23	Predictive Maintenance Tools	Maintenance	Forecasts failures before occurrence.	Minimize downtime and extend equipment life.	Maintenance scheduling
24	Production Planning Tools	Scheduling	Optimizes schedules and resource allocation.	Maximize throughput and efficiency.	Scheduling, capacity utilization
25	Real-Time Alert Systems	Incident Response	Provides instant alerts for operational issues.	Enable rapid issue resolution.	Incident management, downtime prevention
26	Automated Inspection Systems	Quality Assurance	Automates defect detection and inspections.	Ensure consistent quality and cost reduction.	Quality control, compliance verification
27	Smart Manufacturing Cells	Flexible Automation	Modular, automated units for agile production.	Increase flexibility and efficiency.	Small batch production, reconfiguration
28	Smart Conveyor Systems	Material Handling	Sensor-enabled conveyors optimizing material flow.	Reduce bottlenecks and improve logistics.	Material transport, throughput optimization
29	IoT-Enabled Tool Tracking	Asset Management	Tracks tools and assets via IoT connectivity.	Reduce losses and improve utilization.	Tool management, asset tracking
30	Decision Support Systems	Intelligent Decisions	AI-based systems aiding strategic and operational decisions.	Optimize resource allocation and planning.	Planning, operational decision-making
31	ERP Systems	Integration	Integrates core business processes into one platform.	Streamline operations and data flow.	Finance, supply chain, human resources
32	Cloud-Based Maintenance Platforms	Maintenance Management	Cloud-based asset and maintenance management solutions.	Improve uptime and maintenance efficiency.	Remote monitoring, asset management

Table 1. (*Continued*)

2.1. Overview of industry 4.0 in total quality management

Industry 4.0 technologies—such as Artificial Intelligence (AI), Internet of Things (IoT), Machine Learning (ML), Big Data Analytics, Digital Twins, Blockchain, and Cyber-Physical Systems (CPS)—have fundamentally transformed Total Quality Management (TQM), ushering in the era of TQM 4.0. This evolution moves quality management beyond traditional reactive and manual methods toward intelligent, autonomous systems capable of real-time decision-making, early defect detection, process optimization, and continuous improvement. Consequently, TQM 4.0 substantially enhances efficiency, accuracy, and agility, delivering superior quality outcomes in today's smart manufacturing and service sectors[8,26]. More than a technological enhancement, TQM 4.0 represents a paradigm shift. Leveraging Industry 4.0 capabilities enables organizations to transition from reactive quality control to proactive, data-driven systems that anticipate potential issues and dynamically adjust operations. This fosters resilience, agility, and sustainability, particularly in complex, technology-intensive environments[29,30]. Moreover, integrating human expertise with advanced technologies enhances transparency, accelerates innovation, and strengthens continuous improvement initiatives.

Foundations and Critical Success Factors of TQM 4.0: Recent research highlights the multifaceted nature of Quality 4.0. Dias et al. (2022)[31] emphasize that successful adoption involves not only technological innovation but also strategic, managerial, and human factors. Maganga and Taifa (2022)[32] identify essential enablers including technological infrastructure, data literacy, skilled workforce, leadership, and collaboration. Sureshchandar (2023)[33] proposes a comprehensive framework comprising twelve foundational dimensions, affirming that traditional quality principles remain vital during the digital transition. Thekkoote (2022)[34] outlines ten critical success factors—ranging from data analytics and connectivity to organizational culture and leadership—that provide a roadmap for effective digital transformation in quality management. Zonnenshain and Kenett (2020)[35] position Quality 4.0 as a revitalizing framework, combining data-driven management, evidence-based engineering, and innovation. TQM 4.0 integrates both soft and hard dimensions. Soft dimensions—such as leadership commitment, human resource management, customer focus, and employee development—foster a culture of quality, agility, and innovation by empowering individuals and promoting collaboration (Ali & Johl, 2023)[36]. The hard dimensions encompass the technological backbone, including IoT-enabled process management and quality data analytics powered by big data and advanced algorithms (Ali et al., 2022)[37]. The effective harmonization of these dimensions is critical to achieving operational excellence within the Industry 4.0 framework.

Technologies, Competencies, Challenges, and Future Directions: Key technologies driving TQM 4.0 include predictive maintenance and digital twins. Predictive maintenance utilizes real-time sensor data to forecast equipment failures and minimize downtime, while digital twins simulate and optimize processes virtually before physical execution (Albers et al., 2016)[38]. These technologies enable early defect detection, enhance process quality, and improve operational efficiency. A hallmark of TQM 4.0 is the integration of real-time customer feedback, which allows organizations to rapidly adapt products to evolving customer needs, increase customization, and boost satisfaction. Automated quality control systems identify and rectify defects early, accelerating product iterations and enabling more agile, personalized manufacturing (Sader et al., 2019)[39]. Implementing TQM 4.0 requires a balance of technical expertise and interpersonal skills. Babatunde (2021)[40] highlights the importance of both hard and soft competencies, particularly among early-career engineers. Small and Medium-sized Enterprises (SMEs) often face resource and expertise limitations but can overcome these barriers by aligning leadership, employee engagement, and data-driven process management, ultimately enhancing quality performance and customer satisfaction (Santos et al., 2021)[41]. Cultivating a digital transformation–oriented culture is fundamental to success. While theoretical foundations for TQM 4.0 are robust, empirical studies remain limited, with most research focused on conceptual models or isolated case studies. Future investigations should examine how the interplay between soft and hard dimensions influences Industry 4.0 readiness, adoption, and sustained organizational performance (Ali et al., 2022)[37]. Looking forward, Fundin et al. (2025)[42] propose the "Quality 2030" agenda, highlighting five priority research themes: systems perspectives, stability amid change, smart self-organizing models, integration of sustainable development, and leveraging a higher purpose in quality management. Crucially, they stress maintaining the core values of quality management as the discipline advances.

In summary, TQM 4.0 represents a transformative integration of established quality principles with Industry 4.0 technologies. It enables organizations to evolve toward proactive, data-driven quality systems that improve operational efficiency, product quality, and customer satisfaction. Despite challenges, especially among SMEs, TQM 4.0 offers substantial potential to accelerate digital transformation and enhance organizational performance. Ongoing research into its practical implementation and the dynamic balance of its soft and hard dimensions will be essential to unlocking its full value.

2.2. Overview of industry 4.0 in lean six sigma

Lean Six Sigma 4.0 (LSS 4.0) extends traditional Lean Six Sigma by embedding advanced Industry 4.0 technologies—including Artificial Intelligence (AI), Internet of Things (IoT), Big Data analytics, Digital Twins, and Cyber-Physical Systems—into its core framework. These technologies enable real-time monitoring, predictive analytics, and autonomous optimization, fundamentally shifting decision-making from reactive responses to prescriptive, data-driven actions. This transformation drives significant improvements in operational efficiency, product quality, and resource utilization. However, organizations face challenges such as substantial initial investments, workforce adaptation hurdles, cybersecurity threats, and data interoperability issues that must be managed effectively (Gomaa, 2025b)[8]. Early studies (Sanders et al., 2016[43]; Buer et al., 2018[44]) demonstrated that Industry 4.0 technologies enhance Lean practices by accelerating automation and enabling smarter decision-making, underscoring the importance of structured implementation strategies to align digital innovations with Lean principles. Sector-specific investigations further reveal that while digitalization increases system complexity, it simultaneously boosts Lean outcomes and contributes to sustainability goals. For example, Brazilian manufacturing shows improved operational and environmental performance through digitalization (Tortorella et al., 2019[45]; Varela et al., 2019[46]), whereas healthcare applications of Lean 4.0 highlight gains in efficiency alongside challenges in system integration and data security (Ilangakoon et al., 2022[47]; Akanmu et al., 2022[48]).

Digital Integration and Enablers for Successful Transformation: The convergence of AI, Big Data, and IoT substantially enhances Lean Six Sigma's decision-making capabilities and process optimization potential (Cifone et al., 2021[49]; Kumar et al., 2021[50]). Automation reinforces foundational Lean principles such as Just-in-Time (JIT) and Jidoka, though evidence suggests that technology alone cannot guarantee waste elimination (Rosin et al., 2020[51]; Ciano et al., 2021[52]). Advanced analytics further refine the DMAIC methodology by improving defect prediction, root cause identification, and process control (Moreira et al., 2024[53]; Pongboonchai-Empl et al., 2024[54]). Critical to successful LSS 4.0 adoption are strong leadership commitment, workforce engagement, and a well-established Lean culture (Bittencourt et al., 2021[55]; Santos et al., 2021[41]). Despite resource constraints and expertise gaps, particularly in Small and Medium-sized Enterprises (SMEs), these organizations can overcome barriers by aligning leadership vision, fostering employee participation, and embedding data-driven process management (Walas Mateo et al., 2023[56]). Moreover, the evolution of Total Productive Maintenance (TPM) into TPM 4.0 has proven instrumental in maintaining equipment reliability and minimizing downtime, thereby supporting Lean-driven digital transformation efforts (Komkowski et al., 2023[57]; Torre et al., 2023[58]).

Challenges, Future Directions, and Emerging Frameworks: Despite the clear advantages of Lean Six Sigma 4.0, tensions exist between IoT-enabled automation and Lean's traditional human-centered problem-solving approach (Johansson et al., 2024[59]; Galeazzo et al., 2024[60]). Excessive reliance on digitalization risks diluting the emphasis on human expertise, collaboration, and continuous learning that underpin Lean philosophy (Frank et al., 2024[61]). Additionally, ongoing issues around standardization, interoperability, and integration frameworks pose significant challenges to the seamless deployment of Industry 4.0 technologies within Lean environments (Hines et al., 2023[62]; Kassem et al., 2024[63]). Future research should prioritize refining these integration frameworks, addressing the multifaceted challenges of digital transformation, and rigorously assessing LSS 4.0's impact on sustainability, supply chain resilience, and workforce evolution. Notably, Gomaa (2025)[7,8,26-28] introduces advanced frameworks that harmonize Lean Six Sigma with AI, Digital Twins, and predictive analytics across Lean 4.0, Maintenance 4.0, and Supply Chain 4.0 domains. These approaches facilitate real-time process optimization, enhance asset integrity, and bolster operational resilience within modern manufacturing ecosystems. In conclusion, fully unlocking the potential of Lean Six Sigma 4.0 requires interdisciplinary collaboration, strategic foresight, and a balanced approach that integrates cutting-edge automation with Lean's enduring human-centric principles. This synergy is essential to driving sustainable, intelligent manufacturing and operational excellence across industries.

In conclusion, Lean Six Sigma 4.0 marks a transformative advancement by seamlessly integrating Industry 4.0 technologies with established Lean Six Sigma practices. This fusion drives smarter, data-enabled operations that enhance quality, productivity, and sustainability across diverse sectors. Achieving these benefits requires a careful balance between cutting-edge automation and the indispensable role of human expertise, supported by an agile and innovation-driven organizational culture. Addressing key challenges—including implementation costs, workforce preparedness, cybersecurity, and system interoperability—is particularly vital for SMEs. Ongoing interdisciplinary research and the development of robust, scalable frameworks will be critical to unlocking the full potential of Lean Six Sigma 4.0, fostering resilient and sustainable operational excellence in the era of digital transformation.

2.3. Overview of industry 4.0 in supply chain management

Industry 4.0 (I4.0) is fundamentally reshaping Supply Chain Management (SCM) by integrating advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), blockchain, cloud computing, and cyber-physical systems (CPS). These innovations markedly enhance supply chain efficiency, resilience, sustainability, and decision-making. Central to SCM 4.0 are IoT and CPS, which facilitate smart supply chains through real-time process optimization, autonomous data exchange, and enhanced visibility. Research by Tjahjono et al. (2017)[64] and Pasi et al. (2020) [65] underscores how IoT frameworks improve predictive analytics and demand forecasting. Wang et al. (2023)[66] demonstrate that coupling IoT with blockchain supports sustainability by reducing inefficiencies and carbon footprints. Complementing these core technologies, Big Data and cloud computing form the critical backbone for procurement, production, logistics, and distribution (Frazzon et al., 2019[67]). Despite these advances, challenges such as decentralized decision-making and interoperability persist (Hofmann et al., 2019[68]), though AI, IoT, and cloud platforms continue to enhance agility and resilience amid volatile market conditions (Mhaskey, 2024[69]).

Frameworks, Sustainability Integration, and Lean Foundations in SCM 4.0: To operationalize SCM 4.0, multiple frameworks and models have been proposed. Fatorachian and Kazemi (2021)[70] present an integrated digitalization framework optimizing procurement, production, and inventory management, while Govindan et al. (2022)[71] develop a comprehensive performance measurement model spanning procurement to warehousing. Patel (2023)[72] emphasizes proactive learning and predictive analytics as vital for risk mitigation. AI-driven frameworks enhance demand planning, scheduling, and logistics coordination (Helo & Hao, 2022[73]). Addressing barriers such as cybersecurity, data standardization, and workforce readiness, Zhang et al. (2023)[74] introduce hierarchical models facilitating digital SCM transformation. Sustainability is increasingly embedded within SCM 4.0. Chauhan et al. (2022)[75] identify critical gaps in environmental, social, and governance (ESG) performance assessment in emerging economies, while Samper et al. (2022)[76] categorize sustainability drivers and challenges across economic, environmental, and social dimensions. Liu et al. (2023)[77] propose the CAB2IN framework, which integrates circular economy principles with Industry 4.0 technologies to optimize resource utilization and minimize waste, notably in healthcare. Lean principles and intellectual capital form foundational pillars for successful SCM 4.0 adoption. Rossini et al. (2023)[78] argue that Lean supply chain management streamlines operations and reduces waste, positioning Lean as a strategic enabler of Industry 4.0— which, in turn, enhances Lean practices through automation and real-time decision-making. Mubarik and Khan (2024)[79] emphasize the essential role of intellectual capital—including human, structural, and relational assets—in sustaining competitive advantage within digital supply chains.

Challenges, Future Research, and Strategic Priorities: Despite significant benefits, SCM 4.0 faces challenges such as technological complexity, high implementation costs, cybersecurity vulnerabilities, resistance to organizational change, interoperability hurdles, and talent shortages (Samper et al., 2022[76]; Shadravan & Parsaei, 2023 [80]). The effectiveness of digital SCM platforms in unlocking Industry 4.0 advantages heavily relies on the maturity of supply chain capabilities (Saif-Ur-Rehman et al., 2024 [81]). Moreover, strategic IT investments enhance supply chain resilience by fostering collaboration, risk anticipation, and increased visibility (Huang et al., 2023[82]). Future research should emphasize interdisciplinary approaches that integrate digital supply chain planning, sustainability, and performance measurement (Shadravan & Parsaei, 2023[80]). There is a pressing need to develop sustainability-driven digital transformation frameworks incorporating green SCM practices, ESG automation, and circular economy principles (Chauhan et al., 2022[75]). Empirical studies focused on developing economies are crucial to address infrastructure and regulatory challenges. Additionally, hybrid SCM models blending Lean, Agile, and Industry 4.0 principles merit further exploration (Rossini et al., 2023[78]). Strategically leveraging intellectual capital to boost competitiveness (Mubarik & Khan, 2024[79]), alongside advancing AI-driven predictive analytics, automation, and autonomous decision-making, remains a critical priority (Wang et al., 2023[66]). Sustainability has emerged as a strategic imperative as organizations increasingly seek to align financial success with environmental stewardship and social responsibility. Consequently, smart supply chain innovations are indispensable in achieving these objectives. Tables III and IV provide detailed analyses of digital SCM transformations, AI optimization models, and strategic frameworks guiding this evolving domain.

In conclusion, Industry 4.0 is revolutionizing Supply Chain Management by integrating cutting-edge technologies that enhance efficiency, resilience, and sustainability. While IoT, AI, blockchain, and cloud computing form the backbone of smart, data-driven supply chains, successful implementation depends on addressing challenges such as interoperability, cybersecurity, and workforce readiness. The fusion of Lean principles and intellectual capital further strengthens digital supply chains, driving competitive advantage. Future research must focus on developing interdisciplinary, sustainability-oriented frameworks and hybrid models that combine Lean, Agile, and Industry 4.0 approaches—particularly in developing economies. As businesses increasingly prioritize environmental and social responsibility alongside financial performance, smart supply chain innovations will remain essential to achieving these strategic goals.

2.4. Overview of industry 4.0 in maintenance management

Industry 4.0 technologies are transforming maintenance management by shifting traditional reactive approaches toward data-driven, predictive, and strategic models. Predictive Maintenance (PdM) now harnesses IoT sensors, AI, and Big Data analytics for real-time condition monitoring, failure prediction, and optimized maintenance scheduling (Cachada et al., 2018[83]; Lee et al., 2019[84]). Complementary technologies such as digital twins, cloud computing, Cyber-Physical Systems (CPS), and Manufacturing Execution Systems (MES) enhance integration, simulation, and operational control. Augmented Reality (AR) supports real-time decision-making in maintenance tasks, while Additive Manufacturing (AM) enables rapid, customized parts production (Ceruti et al., 2018[85]). Machine learning and data mining further improve fault detection accuracy and reduce system downtime (Zhang et al., 2019[86]). However, regulatory and standardization barriers still impede broader PdM adoption.

Sustainability and Strategic Role: PdM contributes significantly to sustainability by lowering energy consumption, reducing waste, and extending asset life cycles (Franciosi et al., 2018 [87]; Jasiulewicz-Kaczmarek & Gola, 2019[88]). This repositions maintenance as a strategic enabler of operational excellence and environmental responsibility. Successful implementation requires top management support, strategic alignment, and phased integration plans (Bousdeki et al., 2019[89]; Tortorella et al., 2021[90]). Barriers such as limited resources, digital infrastructure gaps, and skill shortages—particularly in SMEs—can be mitigated through support from Business Support Organizations (BSOs) that provide funding, training, and advisory services[10,91].

Industry Adoption and Human Factors: Empirical evidence from sectors such as aviation and automotive confirms PdM's ability to enhance efficiency and reduce maintenance costs (Silvestri et al., 2020[92]; Taş, 2024 [93]). Yet, human factors remain essential. The success of intelligent maintenance systems depends on workforce readiness, digital literacy, and ongoing upskilling (Hlihel et al., 2022[94]). Human-centric strategies are vital, especially for remote, autonomous, or AI-supported maintenance environments.

Toward Maintenance 4.0: The transition to Maintenance 4.0 reflects a deeper integration of digital technologies—particularly AI, IoT, and digital twins—into proactive maintenance strategies. This evolution enhances asset reliability, availability, maintainability, and safety (RAMS) through real-time monitoring and intelligent analytics (Giacotto et al., 2021[95]). As Gomaa (2025)[27] notes, Maintenance 4.0 facilitates advanced Asset Integrity Management (AIM), aligning maintenance with organizational sustainability, performance, and resilience objectives.

RCM 4.0: An AI-Driven Framework: RCM 4.0, proposed by Gomaa (2025)[28], integrates Reliability-Centered Maintenance (RCM) with Lean Six Sigma's DMAIC methodology, supported by IIoT, digital twins, and Big Data analytics. This AI-driven framework enables real-time fault detection, risk-based maintenance, and continuous performance optimization. By transitioning from reactive to predictive paradigms, RCM 4.0 reduces downtime and operational costs. Emerging technologies such as 5G, autonomous robotics, edge AI, and blockchain are expected to further enhance the agility and intelligence of future maintenance systems.

In conclusion, Industry 4.0 has redefined maintenance as a strategic, technology-enabled discipline that drives operational excellence, sustainability, and asset longevity. PdM, Maintenance 4.0, and RCM 4.0 offer transformative frameworks to optimize performance and mitigate risk through intelligent, data-driven practices. However, to fully realize these benefits, organizations must invest in infrastructure, digital capabilities, and workforce development—ensuring that technology adoption is matched by cultural and organizational readiness.

2.5. Overview of industry 4.0 in safety management

Industry 4.0 has redefined Health, Safety, and Environmental (HSE) management by shifting from reactive, compliance-driven approaches to proactive, predictive, and fully integrated safety systems. Enabled by real-time data from IoT-connected machinery, wearable sensors, and environmental monitoring devices, HSE 4.0 leverages AI-powered platforms for dynamic risk assessment, anomaly detection, and rapid response. This paradigm enhances situational awareness, resource optimization, and adaptive safety protocols, thereby improving operational resilience and worker protection. Foundational technologies—such as Artificial Intelligence (AI), Big Data analytics, the Internet of Things (IoT), and Cyber-Physical Systems (CPS)—support continuous monitoring and advanced hazard prediction. Immersive tools like Virtual Reality (VR), Augmented Reality (AR), and collaborative robots (cobots) are also transforming safety training and reducing human exposure to high-risk environments[96-99].

Sector-Specific Applications and Human Factors: The adoption of HSE 4.0 varies across industries, driven by sector-specific risks and operational complexity. High-hazard industries such as liquefied natural gas (LNG) require sophisticated safety architectures, while sectors like construction—particularly in emerging economies—grapple with institutional and governance limitations that slow digital integration. Common barriers include skill shortages, financial constraints, resistance to change, and concerns over job displacement, all of which highlight the need for targeted workforce development and robust change management strategies. Despite advances in digital technologies, human factors remain essential. Lean management methodologies reduce errors and streamline safety processes, while behavioral and cognitive sciences enrich risk assessment by addressing psychological and social influences. Additionally, rising concerns around occupational health—such as mental fatigue, cognitive overload, and psychosocial risks—demand a more holistic safety framework that integrates physical, mental, and emotional well-being[100-102].

Governance, Challenges, and Future Directions: Effective governance and leadership commitment are critical to realizing the full potential of HSE 4.0. Executive involvement shapes safety culture, drives continuous improvement, and ensures organizational alignment. Cross-sector collaboration among industry, academia, and regulatory bodies mitigates fragmented implementation and strengthens occupational health infrastructure. Emerging frameworks, such as Workplace Safety and Health (WSH) 4.0, emphasize anticipatory governance, adaptive risk management, multi-stakeholder cooperation, and continuous professional development to build resilient, future-ready safety systems. As the transition to Industry 5.0 accelerates, safety management is expected to become even more human-centric, emphasizing well-being, inclusivity, and sustainability. This next paradigm integrates ergonomic design, personalized safety protocols, and intelligent human-machine interfaces to support increasingly automated and interconnected environments. The convergence of Big Data, edge AI, and real-time IoT analytics enables automated and continuous safety monitoring, fostering proactive risk mitigation in dynamic work settings[103-105].

In conclusion, HSE 4.0 represents a fundamental shift toward intelligent, real-time, and human-centered safety management. By integrating advanced technologies with behavioral insights and strategic governance, organizations can move beyond compliance toward proactive, adaptive safety systems that enhance resilience, sustainability, and workforce well-being. As Industry 5.0 emerges, the evolution of HSE will increasingly prioritize collaboration between humans and machines—ensuring safety systems that are not only technologically advanced but also socially and ethically responsive.

3. Research gap analysis in industry 4.0 for manufacturing excellence

While Industry 4.0 has driven significant advancements in automation, connectivity, and data-driven manufacturing, the emerging paradigm of Industry 5.0 emphasizes human-centricity, ethical innovation, and sustainable development. However, the transition toward a harmonized Industry 4.0–5.0 landscape remains fragmented. Key research gaps persist across strategic alignment, human-machine collaboration, technological infrastructure, and sustainability integration. Table 2 synthesizes the most pressing challenges and outlines future research directions necessary to realize manufacturing excellence through a balanced, integrative, and inclusive approach to digital transformation.

Integration & Strategic Alignment: A prominent gap in current research lies in the fragmented treatment of Industry 4.0 and Industry 5.0. Industry 4.0 focuses heavily on automation, digital integration, and data-driven processes, while Industry 5.0 emphasizes human-centric collaboration, ethical AI, and sustainability principles. This siloed approach impedes the understanding and realization of their synergistic potential, which is crucial for achieving comprehensive manufacturing excellence. Furthermore, many digital transformation initiatives fail due to misalignment between the rapid technological adoption and the organization's broader strategy, leadership vision, culture, and workforce preparedness. This misalignment results in underutilized technologies, workforce resistance, and suboptimal outcomes. Future research should prioritize the development of integrative frameworks that holistically combine Industry 4.0’s technological capabilities with Industry 5.0’s focus on human values and sustainability. These frameworks must be empirically validated through rigorous cross-disciplinary case studies and longitudinal analyses to ensure their practical applicability and effectiveness. Moreover, strategic alignment models that weave technology adoption tightly with organizational leadership, culture, and workforce development are critical for ensuring sustainable and impactful digital transformation.

Human Factors & Workforce Development: Another significant research gap pertains to the ethical, safe, and effective collaboration between humans and machines in manufacturing environments. Existing literature often neglects psychological, ergonomic, and motivational aspects such as workforce anxiety related to job displacement, safety in shared human-robot workspaces, and employee engagement. Additionally, workforce skills development is lagging behind the rapid pace of technological innovation, creating a critical mismatch between the demands of Industry 4.0/5.0 environments and employee capabilities. AI governance frameworks tailored to manufacturing contexts, addressing transparency, accountability, and fairness, remain in their infancy. Addressing these gaps requires a multidisciplinary research agenda that explores human-machine interface design, organizational policies, and ergonomics to optimize worker wellbeing and productivity. Developing AI-enabled personalized learning systems and continuous reskilling programs aligned with evolving manufacturing technologies will be essential to prepare the workforce for future challenges. Furthermore, establishing robust, manufacturing-specific ethical AI governance frameworks will ensure responsible deployment of AI technologies, fostering trust and acceptance among employees. Pilot projects and real-world case studies should accompany these developments to evaluate their impacts comprehensively.

Technology & Data Management: The rapid integration of Industry 4.0 and 5.0 technologies introduces new complexities in cybersecurity, data privacy, platform interoperability, and analytics capabilities. Current cybersecurity measures often fall short of addressing the unique vulnerabilities within interconnected manufacturing environments. Data privacy concerns, compounded by regulatory requirements, further complicate digital transformation efforts. Fragmented digital platforms and lack of standardized data models inhibit seamless interoperability and scalability. Moreover, real-time adaptive analytics that blend artificial intelligence with human decision-making remain underdeveloped, limiting manufacturing agility. Digital twin technology, while promising, typically lacks comprehensive multi-tier supply chain integration, reducing its potential for enhancing operational visibility and resilience. Future research must focus on designing advanced cybersecurity frameworks and privacy-preserving technologies specifically tailored to manufacturing ecosystems. Promoting open standards, interoperable middleware, and unified data models will facilitate seamless integration across diverse platforms and supply chain tiers. Research should also prioritize scalable, real-time analytics solutions that augment human expertise with AI-driven insights, enabling adaptive and informed decision-making. The development of sophisticated multi-tier digital twin architectures capturing the full complexity of supply chains will be vital to improve visibility, risk management, and resilience in manufacturing operations.

Sustainability & Societal Impact: Sustainability and resilience often remain secondary concerns in Industry 4.0 and 5.0 implementations, treated as add-ons rather than embedded core objectives. This oversight misses critical opportunities to leverage digital technologies for proactive environmental stewardship and robust operational performance. Additionally, there is a limited understanding of the broader socio-economic impacts of Industry 4.0/5.0 transformations, including workforce displacement, labor market disruptions, inequality, and societal well-being. To bridge these gaps, research should embed environmental, social, and governance (ESG) metrics and sustainability goals directly into manufacturing operations, digital twin models, and decision-support systems. This integration must be accompanied by rigorous evaluation of its effects on environmental footprint reduction and operational resilience. Interdisciplinary research is needed to comprehensively assess economic, social, and labor market implications, especially focusing on displacement risks and equity concerns. Developing inclusive and socially responsible transformation frameworks will be essential to ensure that Industry 4.0 and 5.0 innovations deliver equitable benefits and contribute positively to society at large.

In conclusion, the integration of Industry 4.0's advanced technologies with Industry 5.0's human-centered and sustainable principles offers a significant opportunity to elevate manufacturing excellence. To fully realize this potential, it is essential to address critical research gaps by developing comprehensive frameworks that align technological innovation with strategic leadership, organizational culture, and workforce readiness. Emphasizing ethical human-machine collaboration, strong AI governance, and overcoming challenges related to cybersecurity, data interoperability, and real-time analytics is crucial for secure and agile operations. Embedding sustainability and social responsibility at the heart of digital transformation ensures that manufacturers achieve not only economic growth but also environmental stewardship and social equity. Ongoing interdisciplinary and empirical research will be key to developing actionable strategies that enable manufacturers to drive resilient, responsible, and people-centered transformations, fostering sustainable competitiveness and shared value globally.

Table 2. Key research gaps and future directions in industry 4.0 for manufacturing excellence

#	Research Area	Key Research Gaps	Future Research Directions
1	Integration & Strategic Alignment	Disconnected implementation of Industry 4.0 technologies and Industry 5.0 values; weak alignment with strategy, leadership, culture, and workforce capabilities.	Develop unified frameworks integrating digital technologies with human-centric and sustainable principles. Validate through strategic alignment models and cross-industry case studies.
2	Human Factors & Workforce Development	Inadequate focus on ethical, psychological, and ergonomic dimensions of human-machine collaboration; skills lag; limited AI ethics in industrial contexts.	Design socio-technical systems promoting well-being and safe interaction. Develop AI-enabled learning platforms and establish context-specific ethical AI governance models.
3	Technology & Data Management	Insufficient cybersecurity and interoperability; fragmented systems; limited deployment of real-time analytics and full-scale digital twins.	Build secure, interoperable digital infrastructures with unified data models. Advance real-time, AI-driven analytics and end-to-end digital twin ecosystems across supply chains.
4	Sustainability & Societal Impact	Sustainability and equity often treated as secondary concerns; limited assessment of socio-economic impacts such as displacement and inequality.	Embed ESG indicators into digital and operational systems. Conduct interdisciplinary studies on societal implications and develop inclusive, equitable transformation frameworks.

4. Research methodology for manufacturing excellence in industry 4.0

Achieving manufacturing excellence in the Industry 4.0 era demands the integration of advanced digital technologies with a human-centered approach to create production systems that are agile, resilient, and sustainable. This methodology covers key Industry 4.0 principles, enabling technologies, challenges and solutions, integrated frameworks, enhanced process improvement methods, and dynamic performance metrics essential for successful digital transformation.

1) Industry 4.0 Methodology Classification: Industry 4.0 approaches are grouped into five domains: Quality & Innovation, Asset & Operations, Supply Chain & Logistics, Safety & Sustainability, and People & Customer Engagement. Technologies such as IoT, AI, big data, and automation optimize manufacturing processes, improve asset management, increase supply chain visibility, enhance safety and sustainability, and foster a digitally skilled workforce—driving agility and competitiveness.

2) Core Principles of Industry 4.0: Industry 4.0 relies on cyber-physical systems enabling real-time data exchange and rapid adaptation to market changes. It emphasizes automation, connectivity, and data-driven decision-making, transforming factories into smart, interconnected ecosystems and establishing the foundation for future human-centric manufacturing.

3) Enabling Technologies of Industry 4.0: Key technologies include IoT sensors for real-time data capture; AI and machine learning for analytics and automation; digital twins for simulation and optimization; and collaborative robotics for precise, safe human-machine collaboration. AR/VR supports immersive training and remote assistance, enabling flexible, customized operations.

4) Challenges and Solutions in Industry 4.0 Adoption: Challenges include legacy system integration, cybersecurity threats, skill shortages, financial barriers, and resistance to change. Solutions involve phased technology adoption, robust cybersecurity, ongoing workforce development, pilot projects demonstrating value, and leadership committed to innovation and cultural transformation.

5) Integrated Industry 4.0 Framework: A robust framework aligns technology, processes, people, and sustainability goals. IoT, AI, and digital twins form the technological core, while Lean, Six Sigma, and Agile methodologies, enhanced by real-time analytics, drive continuous improvement and adaptability. Leadership, digital skills, and AI-powered dashboards with adaptive KPIs ensure sustained operational excellence.

6) Enhanced DMAIC for Industry 4.0: The DMAIC cycle (Define, Measure, Analyze, Improve, Control) is augmented by Industry 4.0 technologies: digital collaboration speeds up Define; IoT provides real-time measurement; AI deepens analysis; digital twins and AR/VR enable risk-free improvements; continuous monitoring sustains control. This embeds data-driven continuous improvement at the heart of smart manufacturing.

Strategic Objectives and KPIs in Industry 4.0: Focus areas include operational efficiency, product quality, asset reliability, workforce empowerment, and environmental sustainability. KPIs such as Overall Equipment Effectiveness (OEE), cycle time, First Pass Yield (FPY), Mean Time Between Failures (MTBF), training and safety metrics, energy use, and waste reduction are monitored in real time. Flexible KPI systems enable alignment with evolving Industry 4.0 technologies and market demands, securing lasting competitive advantage.

In summary, manufacturing excellence in Industry 4.0 hinges on integrating advanced digital innovations with a strong human focus. Leveraging IoT, AI, digital twins, and collaborative robotics within an Industry 4.0 framework enables organizations to overcome transformation challenges, build agile and sustainable systems, and drive continuous optimization, maintaining operational excellence and competitive advantage in today's dynamic manufacturing landscape.

4.1. Industry 4.0 methodology classification in manufacturing

This framework classifies Industry 4.0 methodologies into five essential domains: Quality & Innovation, Asset & Operations, Supply Chain & Logistics, Safety & Sustainability, and People & Customer Engagement. By leveraging IoT, artificial intelligence, big data analytics, and automation, these methodologies enhance process efficiency, asset performance, supply chain transparency, workplace safety, sustainability, and workforce capability. Tables 3 and 4 provide a detailed overview, illustrating how Industry 4.0 drives agility, efficiency, and competitiveness in today's evolving manufacturing landscape.

1) Quality & Innovation: Enabling superior product quality and continuous improvement, this domain integrates real-time IoT data, AI, and analytics. Technologies such as Total Quality Management 4.0 (TQM 4.0) and Quality Management System 4.0 (QMS 4.0) reduce defects and enable predictive quality control. Lean Six Sigma 4.0, Lean Manufacturing 4.0, and Kaizen 4.0 combine traditional process improvement with digital automation and analytics to eliminate waste and reduce variation. Root Cause Analysis 4.0 (RCA 4.0) uses advanced analytics for proactive failure diagnosis, while Innovation Management 4.0 accelerates development through collaborative digital tools and predictive models, enhancing agility.

2) Asset & Operations: This domain optimizes asset reliability and operational efficiency via smart maintenance and management. Maintenance 4.0, Total Productive Maintenance 4.0 (TPM 4.0), and Reliability-Centered Maintenance 4.0 (RCM 4.0) employ IoT sensors and AI to predict maintenance needs, reduce downtime, and extend asset life. Failure Mode and Effects Analysis 4.0 (FMEA 4.0) dynamically assesses risks using real-time data. Asset Integrity Management 4.0 (AIM 4.0) applies digital twins and risk-based inspections to ensure safety and compliance. Enterprise Asset Management 4.0 (EAM 4.0) centralizes asset data for informed decision-making, while Manufacturing 4.0 and Operations Management 4.0 enable connected, automated production for enhanced responsiveness.

3) Supply Chain & Logistics: Digital technologies enhance supply chain visibility, agility, and efficiency in this domain. Supply Chain Management 4.0 (SCM 4.0) integrates blockchain, IoT, and AI to provide end-to-end transparency, improve traceability, and foster collaboration, boosting resilience. Logistics 4.0 uses automation, robotics, and AI optimization to streamline warehousing, transportation, and delivery, reducing costs and improving speed and accuracy.

4) Safety & Sustainability: Industry 4.0 innovations promote safer workplaces and sustainable operations. Health, Safety, and Environment 4.0 (HSE 4.0) uses IoT sensors, wearables, and AI to monitor hazards and prevent accidents in real time. Environmental Management 4.0 continuously tracks emissions, waste, and resource use to meet compliance and sustainability goals. Energy Management 4.0 optimizes consumption via smart meters, AI forecasting, and renewable integration, lowering costs and environmental impact.

People & Customer Engagement: Focused on workforce empowerment and enhanced customer experience, this domain employs e-learning, AR/VR, and AI analytics to upskill employees, boost productivity, and improve safety. Customer Relationship Management 4.0 (CRM 4.0) leverages AI-driven insights and omnichannel platforms to personalize engagement, anticipate needs, and build loyalty. Together, these methodologies cultivate agile teams and deepen customer connections in fast-paced markets.

In conclusion, Industry 4.0 methodologies are transforming manufacturing by embedding advanced digital technologies across all functions. This integration boosts quality, innovation, asset management, supply chain agility, safety, sustainability, and workforce development. Leveraging IoT, AI, big data, and automation, manufacturers enhance efficiency, anticipate risks, and better serve customers. Beyond technology, Industry 4.0 represents a strategic shift that enables resilient, competitive, and sustainable operations primed for long-term success in a complex global economy.

Table 3. Industry 4.0 applications in the manufacturing domain

#	Domain	Focus	Key Technologies & Methods	Benefits
1	Quality & Innovation	Improve product quality and drive continuous improvement	IoT, AI, Big Data, TQM 4.0, QMS 4.0, Lean Six Sigma 4.0, Kaizen 4.0, RCA 4.0, Innovation Management 4.0	Real-time quality control, defect reduction, predictive insights, faster innovation cycles
2	Asset & Operations	Enhance asset reliability and operational efficiency	IoT sensors, AI predictive analytics, Maintenance 4.0, TPM 4.0, RCM 4.0, FMEA 4.0, Digital Twins, AIM 4.0, EAM 4.0	Reduced downtime, extended asset life, risk-based maintenance, data-driven decisions
3	Supply Chain & Logistics	Boost transparency, agility, and efficiency	Blockchain, IoT, AI, SCM 4.0, Logistics 4.0, Automation, Robotics	End-to-end visibility, improved traceability, resilience, cost reduction, faster delivery
4	Safety & Sustainability	Promote safety and sustainable operations	IoT sensors, wearables, AI analytics, HSE 4.0, Environmental Management 4.0, Energy Management 4.0	Real-time hazard monitoring, accident prevention, emissions and waste reduction, optimized energy use
5	People & Customer Engagement	Empower workforce and enhance customer experience	E-learning, AR/VR, AI analytics, Workforce 4.0, CRM 4.0, Omnichannel platforms	Upskilled workforce, increased productivity and safety, personalized customer engagement, stronger loyalty

Table 4. Industry 4.0 methodology classification in the manufacturing domain

Group	Domain	#	Key Methodology	Description	Objective
1. Quality & Innovation	Smart Quality	1	Total Quality Management 4.0 (TQM 4.0)	Advances traditional TQM by integrating IoT, AI, and Big Data analytics for proactive, real-time quality assurance.	Consistently deliver superior, defect-free products through predictive quality control.
		2	Quality Management System 4.0 (QMS 4.0)	Digital-first quality systems leveraging cloud computing, automated audits, and predictive analytics for compliance and efficiency.	Streamline quality workflows, ensure regulatory compliance, and enable swift data-driven corrective actions.
		3	Lean Six Sigma 4.0 (LSS 4.0)	Merges Lean Six Sigma principles with AI, machine learning, and automation to rapidly identify defects and optimize processes.	Minimize waste and process variability by accelerating data-informed continuous improvements.

Group	Domain	#	Key Methodology	Description	Objective
		4	Lean Manufacturing 4.0 (Lean 4.0)	Enhances Lean manufacturing with IoT, automation, and digital tools to improve process flow and eliminate waste.	Boost manufacturing agility and efficiency through real-time visibility and rapid response.
		5	Kaizen 4.0	Combines AI-driven feedback and collaborative platforms to support continuous, incremental innovations.	Cultivate a culture of sustained improvement and innovation across teams.
		6	Root Cause Analysis 4.0 (RCA 4.0)	Utilizes AI and data mining to uncover fundamental failure causes, enabling proactive and precise problem resolution.	Reduce downtime by preventing issue recurrence with accurate root cause identification.
	Smart Innovation	7	Innovation Management 4.0	Deploys digital innovation ecosystems and predictive analytics to accelerate ideation, development, and market introduction.	Strengthen innovation capabilities and shorten product development cycles.
2. Asset & Operations	Smart Maintenance	8	Maintenance 4.0	Employs IoT sensors and predictive analytics to monitor asset health in real time and anticipate failures.	Optimize maintenance, reduce breakdowns, and prolong asset life, minimizing operational disruptions.
		9	Total Productive Maintenance 4.0 (TPM 4.0)	Integrates augmented reality, IoT, and mobile technologies to empower operators in autonomous maintenance and fault detection.	Maximize equipment uptime by fostering proactive maintenance and operator involvement.
		10	Reliability-Centered Maintenance 4.0 (RCM 4.0)	Applies AI-enhanced risk assessment to prioritize maintenance based on asset criticality and potential impact.	Enhance reliability and safety by focusing maintenance efforts on critical failure modes.
		11	Failure Mode and Effects Analysis 4.0 (FMEA 4.0)	Leverages AI and real-time data streams to dynamically predict and mitigate potential failures.	Proactively prevent disruptions by addressing failure risks early and effectively.
	Smart Asset Management	12	Asset Integrity Management 4.0 (AIM 4.0)	Combines digital twins, real-time monitoring, and risk-based inspections to maintain asset safety and compliance.	Ensure sustained asset performance, safety, and regulatory adherence across the lifecycle.
		13	Enterprise Asset Management 4.0 (EAM 4.0)	Cloud-integrated platforms unifying asset data, maintenance schedules, and analytics for strategic decision-making.	Optimize asset utilization, reduce costs, and support proactive long-term management.
	Smart	14	Manufacturing 4.0	Establishes fully connected	Achieve flexible, efficient,

Group	Domain	#	Key Methodology	Description	Objective
	Operations			production ecosystems integrating robotics, AI, IoT, and automation for real-time optimization.	and high-quality manufacturing through digital integration.
		15	Operations Management 4.0	Employs AI-powered platforms for real-time planning, scheduling, and resource allocation to streamline operations.	Increase operational agility, minimize bottlenecks, and maximize throughput.
3. Supply Chain & Logistics	Smart Supply Chain	16	Supply Chain Management 4.0 (SCM 4.0)	Enables end-to-end digital integration using IoT, blockchain, AI, and analytics for enhanced visibility and collaboration.	Build resilient, adaptive supply chains optimizing inventory and logistics flows.
	Smart Logistics	17	Logistics 4.0	Applies AI and automation in warehousing, transport, and last-mile delivery to boost speed, accuracy, and cost-efficiency.	Optimize logistics operations to reduce costs, improve delivery times, and elevate customer satisfaction.
4. Safety & Sustainability	Smart Safety	18	Health, Safety, and Environment 4.0 (HSE 4.0)	Integrates IoT devices, wearable tech, and AI analytics for proactive hazard detection and safety compliance.	Foster safer workplaces by preventing incidents and ensuring regulatory adherence.
	Smart Environment	19	Environmental Management 4.0	Utilizes IoT and AI analytics for real-time monitoring and reduction of environmental impacts.	Drive sustainable manufacturing by minimizing waste, emissions, and resource use.
	Smart Energy Management	20	Energy Management 4.0	Employs smart meters, AI optimization, and renewable integration to enhance energy efficiency and sustainability.	Reduce energy consumption and carbon footprint while ensuring reliable energy supply.
5. People & Customer Engagement	Smart Workforce	21	Workforce 4.0	Combines digital training, AR/VR, AI-driven analytics, and collaboration tools to empower and upskill employees.	Improve workforce productivity, safety, and engagement through continuous, personalized learning.
	Smart Customer Engagement	22	Customer Relationship Management 4.0 (CRM 4.0)	AI-enabled omnichannel platforms delivering personalized, predictive customer interactions and service.	Increase customer loyalty and satisfaction via proactive, data-driven engagement.

Table 4. (*Continued*)

4.2. Core principles of manufacturing excellence in industry 4.0

Manufacturing excellence in Industry 4.0 is driven by the integration of advanced digital technologies with a human-centered approach. This convergence transforms traditional manufacturing into intelligent, connected, and adaptive systems grounded in core principles that foster innovation, resilience, and sustainability. Table 5 summarizes these key principles.

1) Digital Integration & Technology Enablement: Excellence starts with unifying cyber-physical systems, IoT, cloud platforms, and IT infrastructure into a smart, interconnected ecosystem. Real-time data flows seamlessly across the entire value chain—from raw materials to customer delivery. Digital twins enable virtual simulation and optimization without halting production, as seen in automotive assembly enhancements. Integrated supply chain platforms boost visibility and support proactive, cost-effective decisions. Strong cybersecurity and data governance ensure data protection and trust.

2) Operational Excellence & Agility: Operational agility is achieved through AI-powered analytics and machine learning that enable real-time process optimization and predictive maintenance, reducing downtime and costs. Flexible automation allows quick product customization and volume shifts, exemplified by apparel manufacturers adapting to trends. Autonomous controls and self-healing capabilities strengthen system resilience, maintaining continuity amid disruptions.

3) Human & Ethical Focus: Industry 5.0 centers on collaboration between humans and intelligent machines. Cobots augment human creativity and precision, while continuous upskilling prepares the workforce for evolving technologies, boosting innovation and engagement. Ethical principles—responsible AI use, data privacy, inclusivity, and transparency—build trust and align operations with social responsibility.

Innovation & Customer Orientation: Customer-driven innovation is vital for competitiveness, integrating real-time customer insights into product development. Automotive firms personalize features based on connected vehicle data, enhancing loyalty. An open innovation culture encourages ideas from customers, employees, and partners, driving continuous improvement. Agile development and digital collaboration accelerate responsiveness to market demands.

In conclusion, together, these principles—digital integration, operational agility, human-centric collaboration, and customer-focused innovation—define manufacturing excellence in Industry 4.0 and 5.0. They enable organizations to create intelligent, adaptive, resilient, and ethical manufacturing ecosystems poised for success in today's fast-evolving global landscape.

Table 5. Core principles of manufacturing excellence in industry 4.0

#	Core Area	Key Focus	Description & Examples
1	Digital Integration	Seamless connectivity & data flow	Integration of CPS, IoT, cloud, and IT for continuous real-time data exchange; digital twins for simulation and optimization; improved supply chain visibility; robust cybersecurity.
2	Operational Excellence	Data-driven optimization & agility	AI/ML-powered predictive maintenance and process enhancement; flexible automation enabling rapid customization; resilient autonomous systems.
3	Human & Ethical Focus	Collaborative interaction & ethics	Cobots augmenting human skills; ongoing workforce upskilling; ethical AI use emphasizing privacy, inclusivity, and transparency.
4	Innovation & Customer Focus	Agile, customer-centric innovation	Real-time customer insights fueling innovation; open collaboration culture; agile prototyping and iterative development.

4.3. Enabling technologies for manufacturing excellence in industry 4.0

Manufacturing excellence in Industry 4.0 is driven by advanced technologies that enable intelligent, adaptive, and human-centric production systems. IoT sensors provide continuous monitoring and predictive maintenance to reduce downtime. AI optimizes processes and automates decisions, while digital twins offer real-time virtual simulations without disrupting operations. Robotics, including collaborative robots (cobots), enhances precision and safety through human-machine collaboration. Augmented and virtual reality improve training, design, and remote support. Industry 5.0 further emphasizes personalization and enriched human experiences. Collectively, these technologies create resilient, flexible, and efficient manufacturing ecosystems. Table 6 summarizes eight key technology groups powering this transformation.

1) Connectivity & Data Infrastructure: Integrates IoT, edge computing, cloud platforms, big data analytics, and 5G to enable secure, real-time data flow across operations. This foundation ensures transparency, agility, and synchronization from raw materials to finished goods.
2) Artificial Intelligence & Analytics: Converts sensor data into actionable insights via AI and machine learning. Predictive analytics forecast failures to minimize downtime; prescriptive analytics optimize operations. Edge AI enables rapid autonomous decisions on the production floor.
3) Digital Modeling & Simulation: Uses digital twins and cyber-physical systems to create dynamic virtual models for continuous simulation and autonomous control without halting production. Emerging quantum computing offers potential breakthroughs in solving complex industrial challenges.
4) Automation & Robotics: Includes industrial robots, cobots, and swarm robotics. Cobots work safely alongside humans, enhancing flexibility and creativity, while swarm robotics provide scalable, decentralized automation. These technologies increase productivity and support Industry 5.0’s human-centric focus.
5) Human-Machine Interaction (HMI): Employs AR, VR, mixed reality, natural language processing, conversational AI, and wearables to enhance training, communication, and safety. These immersive, intuitive interfaces foster a skilled and motivated workforce.
6) Manufacturing Technologies: Combines additive manufacturing, smart sensors, and advanced materials to enable flexible, customized, and sustainable production. Sustainable practices reduce waste and support circular economy goals.
7) Security & Governance: Utilizes blockchain, cybersecurity, and data governance to protect manufacturing systems. These ensure transparency, data privacy, regulatory compliance, and resilience against cyber threats.

Supply Chain & Resource Management: Leverages AI, IoT, and blockchain for supply chain visibility, demand forecasting, and automated procurement. Energy management systems optimize resource use, reducing costs and environmental impact.

In conclusion, these technologies collectively underpin manufacturing excellence in Industry 4.0 and 5.0, enabling adaptive, efficient, and sustainable production. Emphasizing human-centric collaboration and robust security ensures ethical innovation and long-term competitiveness in a rapidly evolving market.

Table 6. Key technology groups powering smart manufacturing in industry 4.0

#	Category	Technologies	Description & Role
1	Connectivity & Data Infrastructure	IoT Sensors, Edge Computing, 5G, Cloud, Big Data	Enable seamless, real-time data acquisition, transmission, storage, and scalable processing across manufacturing systems.
2	Artificial Intelligence & Analytics	AI, Machine Learning, Predictive & Prescriptive Analytics, Edge AI	Convert data into actionable insights for predictive maintenance, process optimization, and autonomous control.
3	Digital Modeling & Simulation	Digital Twins, Cyber-Physical Systems, Quantum Computing (emerging)	Provide virtual replicas and cyber-physical integration for simulation, optimization, and innovation.
4	Automation & Robotics	Robotics, Collaborative Robots (Cobots), Swarm Robotics, Human-Centric Automation	Enhance production precision, speed, flexibility, and enable safe human-machine collaboration.
5	Human-Machine Interaction (HMI)	AR, VR, Mixed Reality, NLP, Conversational AI, Wearables	Facilitate immersive training, intuitive interfaces, enhanced decision-making, and improved safety.
6	Manufacturing Technologies	Additive Manufacturing, Advanced Sensors, Smart Materials, Sustainable Technologies	Enable flexible, customized, and sustainable manufacturing aligned with circular economy principles.
7	Security & Governance	Blockchain, Cybersecurity, Data Governance	Ensure data integrity, privacy, transparency, and regulatory compliance in interconnected operations.
8	Supply Chain & Resource Management	Smart Supply Chain Technologies, Energy Management Systems	Improve supply chain visibility, traceability, efficiency, and optimize sustainable resource utilization.

4.4. Strategic challenges and solutions for manufacturing excellence in industry 4.0

Adopting Industry 4.0 faces key challenges: integrating legacy systems requires phased, expert approaches; increased connectivity raises cybersecurity risks needing strong defenses and training; the digital skills gap demands ongoing workforce development and innovation culture; financial constraints and unclear ROI slow adoption, making pilot projects vital; and resistance to change calls for committed leadership and inclusive management. Proactive management of these issues is essential. Table 7 summarizes five strategic challenges in Industry 4.0 and 5.0 manufacturing.

1) Technology Integration & Infrastructure: A key challenge in implementing Industry 4.0 and 5.0 is the integration of legacy systems with cutting-edge digital technologies. Many existing systems are incompatible, resulting in isolated data silos that hinder real-time data exchange and process optimization. Scaling these technologies across manufacturing operations also requires significant planning and resources. To address this, manufacturers employ phased modernization strategies—retrofitting equipment with IoT sensors and adopting modular, cloud-based architectures that enable scalable, flexible growth. Strong data governance ensures the integrity and security of data, while the convergence of Operational Technology (OT) and Information Technology (IT) establishes a unified, adaptable infrastructure. This integrated foundation supports continuous optimization through tools such as digital twins and real-time analytics.

2) Cybersecurity & Regulatory Compliance: As connectivity expands within smart manufacturing environments, cybersecurity threats become more pronounced—particularly where IT and OT systems intersect. Traditional security approaches often fall short in protecting industrial control

systems, exposing vulnerabilities to cyberattacks. Simultaneously, manufacturers must comply with evolving regulations covering data privacy, safety, and environmental standards. Effective mitigation involves comprehensive cybersecurity frameworks that cover both IT and OT, utilize AI-driven threat detection and automated response capabilities, and adopt zero trust security models that presume no implicit trust. Regular training enhances workforce awareness, while automated compliance tools streamline adherence to complex and shifting regulatory demands.

3) Workforce & Organizational Change Management: Digital transformation highlights critical gaps in workforce skills and often encounters resistance to change. Many employees lack the expertise to work effectively with advanced digital tools, and organizational cultures may resist rapid innovation. Overcoming these challenges requires targeted upskilling and reskilling initiatives, fostering collaboration across departments to break down silos. Inclusive change management actively involves employees throughout the transformation, reducing resistance and cultivating a culture of innovation. Additionally, designing human-centric systems improves usability, worker satisfaction, and safety. Strong, committed leadership plays a vital role in aligning change initiatives with strategic innovation and sustainability objectives.

4) Financial & Business Model Transformation: High initial investment costs and uncertainty about returns often act as barriers to adopting Industry 4.0 and 5.0 technologies. Concerns about disrupting existing operations also contribute to hesitation. To navigate this, organizations begin with pilot projects to demonstrate tangible benefits and build momentum for wider deployment. Investments are made in phases to balance risks and returns, and external funding sources such as grants or partnerships may help ease financial pressures. Furthermore, adopting innovative business models—such as product-as-a-service—creates new revenue opportunities and aligns financial goals with performance. Expanding key performance indicators (KPIs) to include sustainability and social impact ensures a broader assessment of value beyond traditional financial metrics.

Supply Chain Visibility & Sustainability: Supply chains today are often fragmented and lack transparency, making them vulnerable to disruptions. Meanwhile, manufacturers face increasing pressure to meet environmental, social, and governance (ESG) standards. To address these challenges, technologies like IoT and blockchain enable real-time, end-to-end visibility that enhances traceability and transparency. AI-powered predictive analytics improve resilience by anticipating risks and optimizing logistics. Circular economy practices—including material reuse, remanufacturing, and waste reduction—help minimize environmental impact while reducing costs. Smart resource management systems optimize energy and material consumption, and automated ESG reporting simplifies compliance. Close collaboration with suppliers ensures shared commitment to sustainability, creating supply chains that are both responsible and resilient.

In conclusion, thriving in Industry 4.0 and 5.0 manufacturing requires addressing key strategic challenges through targeted technology upgrades, comprehensive cybersecurity, workforce empowerment, innovative business models, and sustainable supply chain management. By adopting these strategic solutions, manufacturers can enhance resilience, drive effective digital transformation, and maintain a competitive edge in an increasingly dynamic and complex industrial landscape.

Table 7. Key strategic challenges and mitigation strategies in industry 4.0 manufacturing

#	Strategic Area	Key Challenges	Mitigation Strategies
1	Technology Integration	Legacy system incompatibility, data silos, scaling complexity	Phased IoT retrofitting, modular cloud-native architectures, strong data governance, seamless OT-IT integration, real-time digital twins
2	Cybersecurity & Compliance	Rising cyber threats, weak OT security, evolving regulations	Comprehensive IT-OT security frameworks, AI-driven threat detection, zero trust models, continuous training, automated compliance monitoring
3	Workforce & Change Management	Digital skill gaps, resistance to change, cultural misalignment	Targeted upskilling/reskilling, cross-functional collaboration, inclusive change management, committed leadership
4	Financial & Business Models	High upfront costs, uncertain ROI, operational disruption	Pilot projects, phased investments, strategic partnerships, innovative models (e.g., product-as-a-service), expanded KPIs including sustainability
5	Supply Chain & Sustainability	Limited visibility, disruption risks, growing ESG requirements	IoT and blockchain for transparency, AI-driven forecasting, circular economy initiatives, smart energy/resource management, supplier collaboration

4.5. Integrated framework for manufacturing excellence in industry 4.0 and 5.0

Manufacturing excellence in Industry 4.0 and 5.0 requires a unified framework that integrates advanced technologies, efficient processes, skilled people, and sustainability. Core technologies such as IoT, AI, digital twins, and human-centric automation form the foundation. Process excellence combines Lean, Six Sigma, and Agile methods with real-time analytics and predictive insights to drive continuous improvement and rapid adaptation. Strong leadership, an innovation-driven culture, and a digitally proficient workforce are essential for success. Embedding sustainability ensures operations are environmentally responsible and economically viable. Table 8 summarizes this Integrated Framework for Manufacturing Excellence.

1) Leadership & Strategy: Visionary leadership guides digital transformation aligned with Industry 4.0 and 5.0 goals. Agile governance supports fast, data-informed decisions and fosters a culture of learning and resilience. Clear communication, empowerment at all levels, and cross-functional collaboration ensure effective strategy execution.

2) Technological Backbone: A reliable, interoperable technology infrastructure underpins manufacturing excellence. IoT sensors provide real-time data that feed AI and machine learning for predictive maintenance and automation. Digital Twins allow process simulation and optimization, while collaborative robots enhance human-machine interaction. Secure IT/OT integration with strong cybersecurity and data privacy is critical.

3) Process Excellence: Combining Lean Six Sigma with real-time analytics and modular manufacturing systems enables quick adaptation to changing needs. Predictive quality control reduces defects and bottlenecks, while transparent supply chains improve responsiveness. Automated workflows, cross-functional teams, and data literacy support continuous process improvement.

4) Empowered Workforce & Leadership: A motivated, digitally skilled workforce is vital for transformation. Leadership commitment, ongoing upskilling, and AR/VR training build essential capabilities. Inclusive engagement fosters collaboration and innovation. Transparent change

management, partnerships with education providers, and recognition programs ease adoption and retention.

5) Sustainability & Compliance: Sustainability is integrated through real-time monitoring of resources and emissions and circular economy practices. Automated compliance reduces risk, and ethical sourcing enhances brand value. Adherence to global standards, sustainability KPIs, ESG integration, and supplier collaboration strengthen environmental and social responsibility.

6) Performance Measurement & Decision-Making: Dynamic KPIs across quality, efficiency, cost, safety, and sustainability deliver actionable insights via AI-driven dashboards. Democratized data access empowers agile, aligned decisions. Continuous feedback boosts adaptability. Strong data governance, scalable analytics, regular KPI reviews, and workforce training are key enablers.

7) Continuous Improvement & Scaling: A culture of innovation and agility drives ongoing excellence. Scalable digital solutions and AI predictive analytics anticipate challenges and opportunities. Cross-functional collaboration accelerates best practice sharing. Investment in flexible infrastructure, dedicated teams, and benchmarking sustains growth, resilience, and competitive advantage.

In conclusion, this Integrated Framework for Manufacturing Excellence in Industry 4.0 and 5.0 offers a clear, strategic path that combines visionary leadership, advanced technologies, optimized processes, and a skilled workforce. By embedding sustainability, robust performance measurement, and continuous improvement, organizations can build resilient, agile, and future-ready operations. Success depends on aligned strategy execution, secure technology infrastructure, and a culture that embraces innovation and adaptability. Embracing this framework empowers manufacturers to meet today's challenges and lead the evolution toward a smarter, human-centered industrial future.

In conclusion, the Integrated Framework for Manufacturing Excellence in Industry 4.0 and 5.0 delivers a strategic roadmap that seamlessly combines visionary leadership, cutting-edge technologies, optimized processes, and a digitally empowered workforce. By embedding sustainability, real-time performance insights, and a culture of continuous improvement, organizations can build resilient, agile, and future-ready operations. Success hinges on aligned strategy execution, a secure and interoperable technology foundation, and a relentless focus on innovation and adaptability. Adopting this comprehensive framework equips manufacturers to confidently navigate evolving challenges and lead the transition toward a smarter, human-centered industrial future.

Table 8. Integrated framework for manufacturing excellence in industry 4.0

#	Dimension	Key Components	Benefits	Implementation Considerations
1	Leadership & Strategy	- Visionary leadership aligned with Industry 4.0/5.0 goals - Agile governance and rapid decision-making - Culture of continuous learning and adaptability	- Greater agility and innovation - Unified strategy execution - Resilient change management	- Communicate vision clearly - Empower leaders at all levels - Foster collaboration and accountability
2	Technological Backbone	- IoT for real-time data capture- AI/ML -driven predictive analytics and automation	- Real-time visibility and control - Minimized downtime-	- Deploy interoperable IT/OT systems - Enforce robust cybersecurity

#	Dimension	Key Components	Benefits	Implementation Considerations
		- Digital Twins for simulation and optimization - Collaborative robots (cobots) - Edge and cloud computing	Flexible, customized production - Safer human-machine interaction	- Adopt open standards - Maintain strict data privacy
3	Process Excellence	- Lean Six Sigma combined with real-time analytics- Agile, modular manufacturing- Predictive quality control- Transparent, collaborative supply chains	- Continuous process improvement- Quick market responsiveness- Reduced defects and waste- Resilient supply networks	- Automate workflows- Establish cross-functional teams- Cultivate data literacy and learning culture
4	Empowered Workforce & Leadership	- Committed leadership- Ongoing upskilling and reskilling- AR/VR-enabled immersive training- Inclusive employee engagement	- Digitally skilled and motivated workforce- Improved safety and retention- Accelerated innovation- Smooth change adoption	- Implement inclusive change management- Partner with training providers- Leverage digital feedback tools- Recognize innovation and learning
5	Sustainability & Compliance	- Real-time monitoring of energy, materials, and emissions- Circular economy practices- Automated compliance reporting- Ethical sourcing and social responsibility	- Reduced environmental impact and costs- Enhanced brand reputation- Minimized regulatory risks- Strengthened long-term resilience	- Adopt standards like ISO 14001- Define and track sustainability KPIs- Integrate ESG into performance- Engage suppliers in sustainability initiatives
6	Performance Measurement & Decision-Making	- Dynamic KPIs covering quality, cost, safety, and sustainability- AI-powered dashboards- Democratized data access- Continuous feedback loops	- Early issue detection- Agile, data-driven decisions- Increased transparency and accountability- Responsive to market changes	- Enforce strong data governance- Deploy scalable analytics platforms- Regularly update KPIs- Train workforce in data interpretation
7	Continuous Improvement & Scaling	- Culture of innovation and refinement- Scalable digital and process solutions- AI-driven predictive optimization- Cross-functional collaboration	- Sustained excellence and competitive advantage- Rapid scaling of best practices- Greater agility and resilience- Enabled growth and transformation	- Foster continuous learning- Invest in scalable infrastructure- Create enterprise-wide teams- Benchmark and monitor performance consistently

Table 8. (*Continued*)

4.6. Enhanced DMAIC methodology for manufacturing excellence in industry 4.0

The DMAIC (Define, Measure, Analyze, Improve, Control) methodology continues to be essential for process improvement and is now significantly enhanced by Industry 4.0 technologies. These innovations embed intelligent tools throughout each phase, enabling more precise, collaborative, and continuous improvements within smart manufacturing systems. Table 9 presents the Enhanced DMAIC Framework adapted for today's manufacturing landscape.

1) In the Define phase, cloud-based collaboration platforms enable seamless communication across global, cross-functional teams, ensuring clear alignment of project goals. AI-powered stakeholder

mapping and sentiment analysis help prioritize objectives, reducing risks such as scope creep and delays. Real-time customer insights dynamically capture market and user requirements to focus efforts on high-value improvements.

2) During the Measure phase, IoT sensors and edge devices provide continuous, real-time data collection from the shop floor. Integration with Manufacturing Execution Systems (MES) automates KPI tracking, minimizes manual errors, and establishes a reliable baseline for performance evaluation. Cyber-physical systems link physical assets with their digital twins, enabling synchronized, high-fidelity monitoring of production and quality metrics.

3) In the Analyze phase, advanced AI and machine learning algorithms quickly detect anomalies and identify root causes. Process mining tools reconstruct workflows from digital footprints, revealing detailed process dynamics. Predictive analytics forecast failure modes and optimize maintenance, enabling proactive, data-driven decisions that go beyond reactive problem-solving.

4) The Improve phase uses digital twins—virtual replicas of assets and processes—to test and validate improvements without risk. Immersive AR/VR platforms foster collaborative design and accelerate innovation. Generative AI recommends optimized process parameters and designs, supporting rapid prototyping and agile adaptation to changing operational conditions.

Finally, the Control phase employs AI-driven adaptive systems that autonomously adjust process parameters in real time to sustain optimal performance. Interactive dashboards provide transparent monitoring, alerts, and actionable insights for operators and managers. Self-learning algorithms continuously refine control strategies, embedding continuous improvement within operations.

In summary, the Enhanced DMAIC Framework leverages Industry 4.0 and 5.0 technologies to elevate manufacturing excellence across all stages of process improvement. By integrating cloud collaboration, AI analytics, real-time IoT data, digital twins, and adaptive controls, it delivers precise insights that drive innovation and agility. This holistic digital approach minimizes risks, accelerates optimization, and fosters a culture of continuous advancement—empowering manufacturers to meet complex challenges and seize emerging opportunities for lasting competitiveness and resilience.

Table 9. DMAIC framework for manufacturing excellence in industry 4.0

Phase	Objective	Digital Enablers	Strategic Impact
Define	Set clear, aligned project goals	Cloud collaboration, AI stakeholder mapping, real-time customer insights	Aligns strategy, boosts cross-team coordination, prioritizes value
Measure	Gather accurate, continuous data	IoT sensors, automated KPI tracking, digital twins	Delivers precise, real-time monitoring and reliable baselines
Analyze	Diagnose root causes, predict risks	AI anomaly detection, process mining, predictive analytics	Enables fast diagnosis and proactive, data-driven decisions
Improve	Test and implement solutions	Digital twins, AR/VR simulations, generative AI	Reduces risk/cost, speeds innovation, enhances adaptability
Control	Sustain improvements, monitor closely	AI adaptive controls, interactive dashboards, self-learning algorithms	Maintains gains, increases visibility, fosters continuous improvement

4.7. Strategic objectives and KPIs for manufacturing excellence in industry 4.0

Achieving manufacturing excellence in Industry 4.0 demands focused strategic objectives that enhance operational performance, innovation, and sustainability. As shown in Table 10, these objectives are continuously tracked through Key Performance Indicators (KPIs), ensuring alignment with evolving technologies and market dynamics. Advanced digital tools—such as IoT, AI, digital twins, and immersive training—enable real-time monitoring, analysis, and optimization across all manufacturing facets.

1) Efficiency and Flexibility: Maximizing throughput while enabling rapid adaptation to market changes is paramount. KPIs like Overall Equipment Effectiveness (OEE), cycle times, and setup durations measure efficiency and responsiveness. IoT sensors provide continuous machine data, supporting automated scheduling and robotics to minimize downtime and speed up changeovers. This integration fosters agile manufacturing capable of handling customization without compromising scale or cost-effectiveness.

2) Quality Assurance: Consistent quality minimizes defects, rework, and customer dissatisfaction. First Pass Yield (FPY), defect rates, and customer feedback serve as primary KPIs. AI-driven inspection systems and machine learning analytics detect defects early and identify root causes swiftly. Real-time feedback loops enable prompt corrections, reducing waste and ensuring compliance with quality standards—ultimately strengthening brand reputation and customer loyalty.

3) Asset Reliability and Maintenance: Reliable assets reduce unplanned downtime and maintenance costs, boosting productivity. Key metrics include Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), and total downtime. Predictive maintenance leverages AI and digital twins to forecast failures and optimize maintenance schedules. Continuous condition monitoring enables proactive interventions, extending equipment lifespan and minimizing costly breakdowns.

4) Workforce Development and Safety: A skilled, safe workforce underpins manufacturing excellence. KPIs encompass training hours, effectiveness of human-machine collaboration, safety incidents, and engagement scores. Industry 5.0 technologies—such as AR/VR training, wearable safety devices, and collaborative robots—enhance skill development and workplace safety. These tools foster innovation, improve productivity, and cultivate a resilient, engaged workforce ready to embrace technological advances.

5) Sustainability: Environmental and social responsibility are critical strategic priorities. KPIs track energy consumption, carbon footprint, waste generation, and regulatory compliance. Smart meters, IoT, and AI analytics provide actionable insights to reduce emissions and waste. Automated compliance systems improve transparency and accountability. Embedding sustainability reduces costs, mitigates environmental impact, and strengthens corporate reputation in line with global standards.

Real-Time Monitoring and Agile KPI Management: Continuous, dynamic performance management is essential in a rapidly changing landscape. IoT networks, cloud computing, and AI dashboards offer real-time visibility and predictive insights. Automated alerts and flexible KPI adjustment enable swift, data-driven responses to emerging challenges. This fosters a culture of continuous improvement, ensuring operational resilience and sustained excellence.

In summary, integrating Industry 4.0 and 5.0 technologies into manufacturing frameworks empowers organizations to optimize efficiency, quality, reliability, workforce capability, and sustainability. Leveraging real-time data and advanced analytics enables proactive, agile operations that minimize risks and drive innovation. This comprehensive approach secures a sustainable competitive advantage and positions manufacturers for long-term success in an increasingly dynamic industrial environment.

Table 10. Strategic objectives and KPIs for manufacturing excellence in industry 4.0

#	Strategic Objective	Key Performance Indicators (KPIs)	Digital Enablers & Technologies	Strategic Impact
1	Efficiency & Flexibility	- Overall Equipment Effectiveness (OEE) - Cycle Time - Setup Time	- IoT sensors & MES integration - Automated scheduling - Robotics for rapid changeovers	- Optimizes production flow in real time - Minimizes downtime - Enables rapid response to market demands
2	Quality	- First Pass Yield (FPY) - Defect Rate - Customer Satisfaction	- AI-driven visual inspection - Machine learning root cause analysis - Real-time feedback loops	- Detects and prevents defects early - Reduces scrap and rework - Enhances customer loyalty through superior quality
3	Asset Reliability & Maintenance	- Mean Time Between Failures (MTBF) - Mean Time To Repair (MTTR) - Downtime Reduction	- Predictive maintenance with AI - Digital twins - Condition monitoring sensors	- Minimizes unplanned outages - Cuts repair costs and downtime - Extends asset lifespan and reliability
4	Workforce Development & Safety	- Training Hours - Human-Machine Collaboration Metrics - Safety Incidents - Engagement Scores	- AR/VR training - Wearable safety devices - Collaborative robots (cobots)	- Boosts workforce skills and safety - Reduces incidents and downtime - Fosters a culture of innovation and engagement
5	Sustainability	- Energy Consumption - Carbon Footprint - Waste Reduction - Regulatory Compliance	- Smart energy meters - AI-driven emission tracking - Automated waste management	- Cuts environmental impact - Ensures compliance with regulations - Drives corporate social responsibility initiatives
6	Real-Time Monitoring & Agile KPI Management	- Dynamic KPI adjustment - Predictive analytics - Data-driven decision-making	- Integrated IoT networks - Cloud-based AI dashboards - Automated alerts and anomaly detection	- Enables proactive, agile management - Quickly adapts to technology and market changes - Embeds continuous improvement in operations

5. Conclusion and future work

This study outlines a comprehensive methodology for achieving manufacturing excellence in the industry 4.0 era by integrating advanced digital technologies with a human-centered approach. It categorizes Industry 4.0 methodologies into five key domains—Quality & Innovation, Asset & Operations, Supply Chain & Logistics, Safety & Sustainability, and People & Customer Engagement—demonstrating how technologies like IoT, AI, big data, and automation optimize processes, improve asset management, enhance supply chain transparency, and foster a digitally skilled workforce, thereby driving agility and competitiveness.

At the core of Industry 4.0 are cyber-physical systems enabling real-time data exchange and intelligent connectivity, transforming traditional factories into adaptive, smart ecosystems. Critical enabling technologies include IoT sensors for continuous data capture; AI and machine learning for advanced analytics and automation; digital twins for simulation and optimization; collaborative robotics for safe human-machine interaction; and AR/VR for immersive training and remote assistance.

The study identifies key challenges such as legacy system integration, cybersecurity risks, skill shortages, financial limitations, and organizational resistance. It recommends phased technology adoption, strong cybersecurity measures, ongoing workforce development, pilot projects to demonstrate value, and visionary leadership to ensure successful transformation.

An integrated Industry 4.0 framework aligns technology, processes, people, and sustainability goals. This framework combines Lean, Six Sigma, and Agile methodologies enhanced by real-time data analytics and adaptive KPIs, supported by AI-powered dashboards to facilitate continuous improvement and operational excellence.

Additionally, the traditional DMAIC cycle is enhanced with Industry 4.0 technologies—digital collaboration accelerates problem definition; IoT delivers precise, real-time measurement; AI deepens analysis; digital twins and AR/VR enable risk-free improvements; and continuous monitoring sustains control—embedding data-driven, agile improvement at the core of smart manufacturing.

Strategic objectives emphasize operational efficiency, product quality, asset reliability, workforce empowerment, and environmental sustainability. Key performance indicators—such as Overall Equipment Effectiveness (OEE), cycle time, First Pass Yield (FPY), Mean Time Between Failures (MTBF), training and safety metrics, energy consumption, and waste reduction—are monitored in real time via flexible KPI systems that evolve with advancing Industry 4.0 technologies and market demands.

In summary, this study emphasizes that manufacturing excellence in Industry 4.0 requires a holistic integration of cutting-edge digital innovations with human expertise. By leveraging Industry 4.0 technologies within a unified strategic framework, organizations can overcome transformation challenges, develop agile and sustainable production systems, and drive continuous optimization to maintain competitive advantage in today's dynamic manufacturing environment.

Future research will focus on validating the proposed framework through comprehensive case studies, pilot projects, and simulations across various manufacturing sectors to ensure its practical applicability and sector-specific adaptability. Key priorities include advancing AI, machine learning, and digital twin technologies to enhance predictive analytics and real-time optimization; developing effective organizational change strategies to foster leadership, innovation, and workforce readiness; and strengthening cybersecurity to safeguard interconnected systems. Additionally, emphasis will be placed on workforce upskilling to meet evolving digital demands, refining sustainability metrics to better assess environmental impact and resource efficiency, and conducting economic evaluations to ensure cost-effectiveness and return on investment. These efforts will collectively support the implementation of resilient, sustainable, and human-centric smart manufacturing systems, enabling organizations to maintain a competitive advantage and drive industry transformation.

Abbreviations

Abbreviation	Full Term
AI	Artificial Intelligence
Automation	The use of technology to perform tasks without human intervention
Big Data	Large, complex datasets that require advanced analysis
Cyber-Physical Systems	Integrations of computation, networking, and physical processes
IIoT	Industrial Internet of Things

Abbreviation	Full Term
IoT	Internet of Things
LCC	Life Cycle Cost
ML	Machine Learning
MRO	Maintenance, Repair, and Overhaul
OEE	Overall Equipment Effectiveness
PdM	Predictive Maintenance
Robotics	The technology and use of robots in manufacturing and automation
SMEs	Small and Medium Enterprises
TPM	Total Productive Maintenance

Conflict of interest

The authors declare no conflict of interest.

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