

INDUSTRY 5.0 AND SMART MANUFACTURING: A HUMAN- CENTRIC, SUSTAINABLE AND INTELLIGENT TRANSFORMATION OF INDUSTRIAL SYSTEMS

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Abstract

The global manufacturing sector is undergoing a profound structural transformation driven by rapid technological advancements, shifting socio-economic priorities, environmental concerns, and increasing market volatility. Over the past decade, Industry 4.0 revolutionized production systems by integrating cyber-physical systems, automation, robotics, cloud computing, and the Internet of Things (IoT). This transformation enhanced operational efficiency, real-time data exchange, and autonomous decision-making within smart factories. However, despite its technological sophistication, Industry 4.0 faced growing criticism for its automation-centric orientation, potential workforce displacement, limited attention to sustainability, and insufficient emphasis on human values within industrial ecosystems. These limitations have paved the way for the emergence of Industry 5.0, a paradigm that redefines the relationship between humans, machines, and the environment. Industry 5.0 represents a strategic shift from purely automation-driven production toward a more human-centric, resilient, and sustainable industrial framework. Rather than replacing human labour, Industry 5.0 promotes collaboration between intelligent machines and skilled workers. It integrates advanced digital technologies with human creativity, emotional intelligence, ethical reasoning, and problem-solving capabilities. This collaborative approach enhances productivity while preserving human dignity, ensuring workplace safety, and fostering inclusive growth. The concept extends beyond technological innovation to incorporate social responsibility, environmental stewardship, and economic sustainability as integral pillars of industrial development. Smart manufacturing serves as the operational backbone of Industry 5.0. It encompasses interconnected production systems that utilize Artificial Intelligence (AI), Machine Learning (ML), IoT, big data analytics, cloud computing, edge computing, digital twins, blockchain technology, and collaborative robotics. These technologies collectively enable real-time monitoring, predictive analytics, autonomous optimization, and adaptive production planning. In contrast to traditional mass production models, smart manufacturing under Industry 5.0 facilitates mass personalization and customized product development tailored to individual consumer preferences. This shift reflects evolving market demands for flexibility, quality, and rapid responsiveness. Artificial Intelligence plays a critical role in Industry 5.0 environments by enabling intelligent decision-making processes across production cycles. AI algorithms analyse large datasets generated by connected devices to optimize scheduling, improve quality control, forecast demand, and detect anomalies. Machine learning models continuously refine performance through pattern recognition and predictive maintenance systems, reducing downtime and operational costs. Furthermore, AI enhances human-machine collaboration by supporting decision

assistance systems that augment human capabilities rather than substituting them. In conclusion, Industry 5.0 represents a holistic evolution of manufacturing systems that transcends the automation-centric paradigm of Industry 4.0. By integrating human intelligence with advanced digital technologies, it fosters collaborative production environments that prioritize sustainability, resilience, and social responsibility. Smart manufacturing technologies serve as enablers of this transformation, facilitating real-time monitoring, predictive analytics, and adaptive optimization. Although challenges related to cost, cybersecurity, workforce readiness, and ethical governance remain significant, strategic investments and supportive policy frameworks can accelerate successful adoption. Industry 5.0 thus emerges not merely as a technological upgrade but as a comprehensive socio-economic transformation shaping the future of global manufacturing ecosystems.

Keywords: Industry 5.0, Smart Manufacturing, Human-Centric Production, Artificial Intelligence, Collaborative Robots, Sustainability, Digital Transformation.

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1. Introduction:

The history of industrial development reflects a continuous process of technological advancement and structural transformation. The First Industrial Revolution (Industry 1.0), which began in the late eighteenth century, introduced mechanization through steam power and water-driven machinery. This era marked the transition from manual production systems to mechanized manufacturing processes, significantly increasing productivity and reshaping economic activities. The Second Industrial Revolution (Industry 2.0), emerging in the late nineteenth and early twentieth centuries, was characterized by electrification, the development of assembly lines, and the rise of mass production. This period enabled large-scale industrial growth, improved efficiency, and reduced production costs through standardized manufacturing.

The Third Industrial Revolution (Industry 3.0), which began in the latter half of the twentieth century, introduced automation driven by electronics, computers, and information technology. Programmable logic controllers (PLCs), robotics, and early digital systems enhanced precision and operational efficiency. Manufacturing systems became increasingly automated, reducing reliance on manual labour while improving speed and accuracy.

The Fourth Industrial Revolution, widely known as Industry 4.0, emerged in the early twenty-first century as a result of rapid advancements in digital technologies. It introduced cyber-physical systems, Internet of Things (IoT), cloud computing, artificial intelligence (AI), big data analytics, and advanced robotics into manufacturing environments. Industry 4.0 enabled the creation of smart factories, where interconnected machines communicate in real time, analyse data autonomously, and optimize production processes with minimal human intervention. The integration of physical and digital systems significantly enhanced productivity, flexibility, and global competitiveness.

However, despite its technological achievements, Industry 4.0 has faced criticism for prioritizing automation and efficiency over human welfare and environmental sustainability. The heavy emphasis on machine autonomy raised concerns about job displacement, skill redundancy, cybersecurity vulnerabilities, and widening socio-economic inequalities. Additionally, increased industrial activity and digital infrastructure expansion contributed to environmental pressures, including higher energy consumption and electronic waste generation. These limitations highlighted the need for a more balanced and inclusive industrial framework.

2. Objectives of the Study:

- 1. To examine the core technologies enabling smart manufacturing**, including AI, IoT, collaborative robotics, digital twins, and big data analytics.
- 2. To analyse sustainability and resilience aspects**, emphasizing environmental responsibility and adaptive industrial systems.
- 3. To identify challenges and future research opportunities**, including technical, organizational, ethical, and policy-related considerations.

3. Review of Literature:

The concept of Industry 5.0 has gained significant academic and policy attention in recent years as a progression beyond Industry 4.0. While Industry 4.0 focused primarily on automation, digitalization, and efficiency through cyber-physical systems, the emerging literature on Industry 5.0 emphasizes human-centricity, sustainability, and resilience. Researchers across disciplines have examined technological, social, economic, and environmental dimensions of this evolving industrial paradigm.

3.1 Foundations in Industry 4.0 Research:

The theoretical roots of Industry 5.0 are closely connected to the extensive body of research on Industry 4.0. Early studies on Industry 4.0 emphasized smart factories, machine-to-machine communication, Internet of Things (IoT), and advanced robotics. Scholars highlighted the role of artificial intelligence (AI), big data analytics, and cloud computing in enabling real-time decision-making and predictive maintenance. These technologies were considered essential for improving operational efficiency, reducing downtime, and enhancing global competitiveness.

However, several researchers also identified limitations within the Industry 4.0 model. Concerns were raised regarding workforce displacement due to automation, lack of human involvement in decision-making processes, cybersecurity vulnerabilities, and growing energy consumption. Some studies argued that an excessive focus on technological efficiency neglected social responsibility and environmental sustainability. These criticisms laid the groundwork for the development of a more balanced industrial framework, ultimately leading to the conceptualization of Industry 5.0.

3.2 Emergence of Industry 5.0 Concept:

The term “Industry 5.0” began appearing in academic discourse as scholars explored the integration of human intelligence with advanced technologies. Unlike Industry 4.0, which primarily focused on autonomous systems, Industry 5.0 emphasizes collaboration between humans and machines. The literature describes Industry 5.0 as a paradigm that restores the human role in manufacturing by combining human creativity and problem-solving abilities with machine precision and computational speed.

Several authors argue that Industry 5.0 should not be viewed as a replacement for Industry 4.0 but as its extension. According to this perspective, Industry 5.0 leverages the digital infrastructure developed during the Industry 4.0 era while embedding social and environmental objectives into industrial strategies. This integration creates production systems that are technologically advanced yet ethically responsible.

A key contribution of Industry 5.0 literature is the emphasis on personalization and mass customization. Researchers note that modern consumers increasingly demand customized products. Human-machine collaboration enables flexible production systems capable of delivering personalized goods efficiently. Thus, Industry 5.0 supports both economic competitiveness and customer-centric innovation.

3.3 Human-Centric Manufacturing and Human-Robot Collaboration:

One of the central themes in Industry 5.0 research is human-robot collaboration (HRC). Traditional industrial robots were designed to operate in isolated environments due to safety concerns. In contrast, collaborative robots are developed to work safely alongside human workers. Studies highlight that cobots enhance productivity by performing repetitive or hazardous tasks while humans focus on complex, creative, and decision-intensive activities.

Researchers emphasize that human-centric manufacturing improves job satisfaction, reduces workplace injuries, and enhances overall organizational performance. However, literature also identifies challenges such as workforce resistance, need for skill development, ergonomic design considerations, and ethical concerns related to monitoring and data privacy.

Theoretical frameworks in this domain often draw from socio-technical systems theory, which stresses the interdependence between social and technical elements within organizations. Scholars argue that successful Industry 5.0 implementation requires balancing technological innovation with workforce empowerment and training.

3.4 Smart Manufacturing Technologies:

Smart manufacturing remains a fundamental pillar of Industry 5.0. Numerous studies have explored enabling technologies such as Artificial Intelligence, IoT, digital twins, cloud computing, and additive manufacturing.

Artificial Intelligence has been extensively studied for its ability to optimize production scheduling, detect defects, forecast demand, and enable predictive maintenance. Machine learning algorithms process large volumes of production data to identify patterns and improve decision-making accuracy. Researchers highlight that AI-driven analytics reduce operational inefficiencies and enhance competitiveness.

The Internet of Things (IoT) facilitates real-time connectivity among machines, sensors, and systems. Studies show that IoT-enabled factories improve transparency, enhance resource utilization, and support decentralized decision-making. Integration of IoT with cloud computing further enhances scalability and remote monitoring capabilities.

Digital twin technology has emerged as a transformative innovation. Literature suggests that digital twins allow manufacturers to simulate production processes, predict failures, and optimize performance before physical implementation. This capability improves resilience and reduces operational risks.

Additive manufacturing, commonly known as 3D printing, supports customization and reduces material waste. Scholars identify it as a key driver of sustainable production in Industry 5.0.

4. Conceptual Framework of Industry 5.0:

Industry 5.0 builds upon Industry 4.0 technologies but shifts the focus toward three pillars:

4.1 Human-Centric Approach:

Unlike Industry 4.0, which emphasized automation and efficiency, Industry 5.0 promotes human creativity, critical thinking, and emotional intelligence alongside machines. Workers collaborate with AI systems and robots to enhance productivity.

4.2 Sustainability:

Industry 5.0 integrates environmental responsibility into production processes. It supports circular economy principles, energy efficiency, waste reduction, and carbon neutrality.

4.3 Resilience:

The COVID-19 pandemic exposed vulnerabilities in global supply chains. Industry 5.0 promotes resilient manufacturing systems capable of adapting to disruptions through digital monitoring and predictive analytics.

5. Smart Manufacturing- Definition and Core Principles:

Smart manufacturing refers to technology-driven production systems that use interconnected devices, data analytics, and intelligent automation to improve efficiency and flexibility.

Core Principles:

- Real-time data acquisition and analysis
- Interoperability between machines and systems
- Autonomous decision-making
- Predictive maintenance
- Customization and flexibility

Smart manufacturing acts as the operational framework through which Industry 5.0 is implemented.

6. Enabling Technologies of Industry 5.0:

6.1 Artificial Intelligence (AI) and Machine Learning-

AI enables predictive analytics, quality inspection, demand forecasting, and intelligent scheduling. Machine learning algorithms process vast datasets to optimize production lines.

6.2 Internet of Things (IoT)-

IoT connects sensors, machines, and software platforms to create an integrated network. Real-time data enhances operational transparency and performance monitoring.

6.3 Collaborative Robots (Cobots)-

Unlike traditional industrial robots, cobots work safely alongside humans. They assist in repetitive or hazardous tasks while allowing human workers to focus on complex decision-making.

6.4 Digital Twins-

A digital twin is a virtual replica of a physical asset or system. It allows simulation, predictive analysis, and system optimization before physical implementation.

6.5 Big Data and Cloud Computing-

Cloud-based systems enable data storage and analysis at scale. Big data analytics helps in identifying patterns, reducing downtime, and improving resource allocation.

6.6 Additive Manufacturing (3D Printing)

Supports customization and small-batch production, aligning with Industry 5.0's personalized manufacturing approach.

7. Industry 4.0 vs Industry 5.0: A Comparative Perspective:

Dimension	Industry 4.0	Industry 5.0
Focus	Automation & Efficiency	Human-Centric Collaboration
Workforce Role	Replacement/Reduction	Augmentation & Empowerment
Sustainability	Secondary	Core Objective
Customization	Mass Customization	Personalized Production
Resilience	Moderate	High

8. Human-Robot Collaboration (HRC):

Human-Robot Collaboration is central to Industry 5.0. It combines human intelligence with robotic precision.

Benefits:

- Improved productivity
- Reduced workplace injuries
- Enhanced job satisfaction
- Greater production flexibility

Challenges:

- Safety protocols
- Skill gaps
- Worker resistance
- Ethical considerations

9. Sustainability and Circular Economy:

Industry 5.0 promotes:

- Energy-efficient machinery
- Waste minimization
- Sustainable supply chains
- Lifecycle assessment of products
- Recycling and remanufacturing

Smart manufacturing systems track energy usage and carbon emissions in real time, enabling green production.

10. Resilience and Risk Management:

Resilient smart manufacturing systems use:

- Predictive maintenance
- AI-based risk assessment
- Real-time supply chain tracking
- Digital twins for scenario planning

These tools reduce operational disruptions and improve crisis response.

11. Implementation Challenges:

11.1 Technical Barriers

- High investment cost
- Integration complexity
- Cybersecurity risks

11.2 Organizational Barriers

- Resistance to change
- Lack of skilled workforce
- Training requirements

11.3 Ethical and Social Issues

- Data privacy
- Workforce displacement concerns
- Digital divide

12. Future Research Directions:

Future studies should explore:

- Ethical AI governance models
- Advanced human-machine interface design
- Quantum computing in manufacturing
- Blockchain integration in smart supply chains
- Measuring social sustainability in Industry 5.0

13. Conclusion;

Industry 5.0 represents a paradigm shift toward intelligent, sustainable, and human-centered manufacturing systems. By integrating advanced technologies with human creativity, it addresses the limitations of Industry 4.0 and builds resilient industrial ecosystems. Smart manufacturing serves as the operational engine of this transformation, enabling real-time data-driven decisions and sustainable practices. Although implementation challenges exist, strategic investments in technology, workforce development, and policy frameworks can facilitate successful adoption. Industry 5.0 is not merely a technological evolution but a socio-economic transformation shaping the future of global manufacturing.

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