

# Industry 6.0: Redefining Intelligent And Ethical Manufacturing

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## ABSTRACT

Industry 5.0 has been conceptualized to promote close cooperation between human intelligence and cyber-physical systems, enabling personalized and demand-driven manufacturing solutions. By emphasizing human-machine collaboration, this paradigm seeks to enhance flexibility, creativity, and product customization within modern industrial environments. However, despite its advantages, Industry 5.0 encounters several limitations, including restricted scalability, challenges in reskilling the work force to effectively interact with advanced technologies, increased production costs, and growing concerns related to data privacy and security, particularly in the emerging post-quantum computing era. These constraints highlight the need for a more evolved industrial framework capable of modernizing and re-engineering industrial operations while ensuring sustainability, scalability, and resilience. Industry 6.0 emerges as a next-generation industrial paradigm characterized by ubiquitous intelligence, hyper-customer-centric manufacturing, extensive virtualization, and sustainability-driven processes. The core emphasis of Industry 6.0 lies in the realization of hyper-connected factories and adaptive, data-driven supplychains that operate seamlessly across multiple industrial verticals. In this context, the present work provides a tutorial-style survey that explores the vision, technological foundations, and recent advancements expected to shape the Industry 6.0 ecosystem. Unlike Industry 5.0, Industry 6.0 introduces novel concepts to support complex industrial applications, including supply-chain-centric production models, integrated human-robot industrial work flows, green and energy-efficient computing infrastructures, and the incorporation of generative artificial intelligence (GAI) into industrial control and decision-making processes. Key enabling technologies that underpin the Industry 6.0 vision include autonomous digital twins, metaverse-enabled virtual production environments, sixth-generation (6G) communication networks, dew computing architectures, GAI-driven collaborative robotic networks (GOBOTs), Internet-of-Anything (IoX), and quantum-assisted nano scale manufacturing technologies.

**Keywords:** paradigm, supplychains, tutorial-style, artificial intelligence, , sixth-generation.

## INTRODUCTION

The pharmaceutical sector is a complicated and determined business model of study, advancement, production, and promotion of recent chemical entities (NCEs) and bioproducts (proteins, peptides, monoclonal antibodies, vaccines, etc.) created to accentuate human well-being (Northrup 2005). “Advanced analytics” which are developed from Industry 4.0 are employed all across the value chain of pharmaceutical companies, including research and development, safety, production, and regulation. The pharmaceutical industry is a crucial segment of the healthcare system, which deals with the assembly and promotion of pharmaceuticals, biological products,

and therapeutic devices used to diagnose and treat diseases and conducts research to develop new products for human welfare. So, it would be crucial to keep up the standard of the final products to stop health hazards as many pharmaceutical products are lifesaving [1].

The pharmaceutical sector provides therapeutic agents to treat diseases. It enhances the health of the population. The pharmaceutical industry manufactures new drugs that improve patients' quality of life worldwide by researching and developing. The pharmaceutical sector is a crucial advantage to worldwide wealth. The pharmaceutical sector frequently attempts to create new therapies that

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help people live longer and healthier lives. The pharmaceutical sector contributes directly to the world gross domestic product and supports many workers by producing medical products. The pharmaceuticals are used for diagnosing and curing the disease, but sometimes it has an undesirable effect [1].

To address this gap, Industry 5.0 emerged as a human-centric paradigm that reintegrates skilled human expertise into automated industrial work flows. By fostering collaboration between humans and intelligent machines, particularly through collaborative robots (cobots), Industry 5.0 enhances flexibility, creativity, and production precision while maintaining sustainability objectives. In this paradigm, humans are responsible for complex and critical decision-making tasks, whereas repetitive and labour-intensive operations are delegated to robotic systems. AI-enabled monitoring and predictive maintenance further improve equipment reliability, reduce downtime, and support energy-efficient, low-carbon manufacturing practices [2].

Industry 5.0 faces growing challenges in addressing the future requirements of hyper-customized production, software-defined factories, large-scale digital twin integration, and fully autonomous decision-making. The increasing complexity of global supply chains and the demand for real-time orchestration across interconnected production lines necessitate a more advanced industrial framework. Industry analysts predict a rapid expansion of digital twin adoption, with global investments expected to reach trillions of dollars over the coming decades and the industrial digital twin market projected to grow substantially by the late 2020s. These trends underscore the need for near-zero-downtime operations, AI-driven predictive control, and intelligent cross-factory communication to support defect detection and process optimization in real time [3].

This uplifted the economic foundations, which swiftly progressed to Industry 2.0 in later 19th century, which is driven by electric power and assembly-line production [1]. This allowed mass-production units, which augmented productivity and distribution efficiency in manufacturing enterprises. Today, as we advance beyond Industry 4.0 and 5.0, the next frontier

— Industry 6.0 — promises a seamless fusion of human creativity, autonomous systems, and sustainable innovation, redefining the future of manufacturing.

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The limitations of Industry 5.0 make the transition toward a more advanced paradigm not optional but inevitable. Accelerated mass personalization cycles, emerging post-quantum security threats, and stringent net-zero sustainability mandates demand industrial systems capable of autonomous adaptation and resilience. Industry 6.0 therefore emerges as a foundational platform for next-generation manufacturing, enabling ultra-responsive, intelligent, and sustainable production ecosystems. This paradigm shifts the industrial focus from automation toward true autonomy, where systems can self-optimize, self-heal, and dynamically respond to changing operational conditions.

Industry 6.0 envisions hyper-connected, AI-native factories supported by next-generation communication and computing infrastructures. The development of sixth-generation (6G) wireless networks, as outlined in the ITU-R IMT-2030 framework, promises ultra-low latency, terahertz spectrum utilization, and embedded intelligence to support real-time industrial control [4].

Complementary technologies such as Open Radio Access Networks (O-RAN), Time-Sensitive Networking (TSN), and zero-touch network management further enable deterministic communication, adaptive resource allocation, and automated service orchestration across distributed manufacturing environments. By integrating intelligent automation with sustainable design principles, Industry 6.0 aims to minimize environmental impact while maximizing

Productivity there by paving the way for resilient and self-regulating industrial ecosystems aligned with long-term societal and environmental goals. The ongoing standardization of sixth generation (6G) communication services is expected to significantly

accelerate advancements in Augmented Reality (AR) and Virtual Reality (VR), enabling the creation of highly immersive and interactive environments for smart industrial applications. When coupled with ultra-reliable wireless connectivity, these technologies can seamlessly integrate with cloud platforms, IoT sensing infrastructures, and big data analytics to transform industrial training, product design, engineering workflows, and manufacturing operations [4].

### **The Vision and Technicalities**

Industry 6.0 represents the next evolutionary step in industrial transformation, extending beyond the automation and human-machine collaboration paradigms of Industry 4.0 and Industry 5.0. While earlier industrial revolutions primarily emphasized productivity, efficiency, and customization, Industry 6.0 envisions a deeply integrated industrial ecosystem that is autonomous, adaptive, intelligent, and sustainable by design. The central vision of Industry 6.0 is to establish manufacturing environments where human intelligence, artificial intelligence, and advanced at its core, Industry 6.0 aims to shift industrial systems from automation-driven to autonomy-driven operations. Unlike Industry 5.0, which reintroduced humans into the loop for creativity and decision-making, Industry 6.0 extends this collaboration by enabling systems that can self-learn, self-heal, and self-optimize while maintaining human oversight. This paradigm promotes human-in-command control, ensuring ethical, transparent, and explainable decision-making in highly autonomous industrial environments [4].

Another fundamental technical pillar of Industry 6.0 is the extensive use of digital twins and virtualized production environments. Digital twins serve as continuously updated virtual replicas of physical assets, processes, and supply chains, enabling predictive maintenance, failure analysis, and performance optimization. When combined with immersive technologies such as Augmented Reality (AR), Virtual Reality (VR), and industrial metaverses, digital twins allow engineers, operators, and customers to interact with virtual factories in real time, reducing development risks and accelerating innovation cycles [5].

### **Industry6.0: An Applicative Technical Landscape**

While Industry 5.0 focuses on human-centric and collaborative manufacturing, Industry 6.0 extends this vision by enabling seamless human-machine coexistence within intelligent and autonomous ecosystems. It incorporates advanced technologies such as quantum computing, nanotechnology, biotechnology, and cognitive AI, thereby pushing the boundaries of automation, personalization, and sustainability. Based on its functional capabilities, Industry6.0 applications can be broadly categorized into four major dimensions: (i) enhanced efficiency and productivity, (ii) hyper customization and mass personalization, (iii) sustainable and responsible manufacturing, and (iv) human-centric industrial systems [6]. Another foundational pillar of Industry 6.0 is artificial intelligence (AI) and machine learning (ML), which constitute the cognitive layer of future industries. These technologies empower systems to extract knowledge from vast datasets, predict outcomes, and autonomously refine operational strategies. AI-driven analytics enable predictive maintenance, intelligent demand forecasting, adaptive production scheduling, and real-time quality assurance, thereby reducing downtime and improving operational efficiency [6]. Additive manufacturing, commonly known as 3D printing, emerges as a transformative enabler within the Industry 6.0 ecosystem. By allowing on-demand fabrication and rapid prototyping of complex components, additive manufacturing facilitates mass customization, shortens product development cycles, and enhances design flexibility. This capability supports agile manufacturing models and accelerates innovation across multiple industrial sectors [7].

In addition, blockchain (BC) technology ensures secure, transparent, and tamper-resistant data exchange within Industry 6.0 environments. Through decentralized ledgers and smart contracts, blockchain enhances trust among stakeholders, enables secure supply chain traceability, and supports automated transactional processes. These features are particularly valuable in distributed manufacturing networks and multi-stakeholder industrial ecosystems [8].

### **Enhanced Efficiency and Productivity**

Industry 6.0 significantly improves industrial efficiency through autonomous and self-optimizing systems. AI-enabled robots and collaborative robots (cobots) are expected to independently execute complex tasks while working alongside humans in shared environments. These systems enhance productivity by combining machine precision with human decision-making capabilities. Predictive and proactive maintenance becomes feasible through continuous monitoring using real-time sensor data and intelligent algorithms, enabling early fault detection and optimized maintenance scheduling. Additionally, AI-driven feedback mechanisms continuously analyse production data to self-adjust operational parameters, ensuring consistent quality, reduced waste, and improved resource utilization [9].

### **Hyper-Customization and Mass Personalization**

A defining feature of Industry 6.0 is the ability to deliver highly personalized products at scale. Advanced AI systems combined with additive manufacturing enable real-time, on-demand production tailored to individual customer preferences. This paradigm supports flexible manufacturing without compromising efficiency. The adoption of digital and virtual product twins allows manufacturers to simulate, test, and optimize products in virtual environments before physical realization. These digital replicas facilitate collaborative design, accelerate innovation cycles, and significantly reduce development costs. Moreover, AI-driven adaptive supply chains dynamically respond to demand fluctuations, ensuring optimal inventory management and timely delivery [10].

### **Sustainable and Responsible Manufacturing**

Sustainability is a central objective of Industry 6.0. Intelligent systems enable closed-loop resource management by optimizing material usage, minimizing waste, and promoting recycling practices. Advanced bio-inspired materials, nanotechnology-based solutions, and bio-manufacturing techniques further support environmentally responsible production.

Decentralized manufacturing models, including micro factories powered by renewable energy sources,

reduce transportation-related emissions and strengthen local production capabilities. These approaches collectively contribute to circular economy principles and long-term industrial sustainability [11].

### **Human-Centric Approach**

Despite increasing automation, Industry 6.0 maintains a strong emphasis on human-centricity. Workforce transformation through continuous upskilling and reskilling enables humans to transition toward creative, analytical, and strategic roles. AI systems act as decision-support tools, augmenting human expertise rather than replacing it.

Improved workplace safety is achieved through collaborative robots, intelligent monitoring systems, and advanced ergonomic designs that reduce physical strain. This harmonious integration of human intelligence and machine autonomy fosters improved working conditions and enhanced job satisfaction. Across application domains such as agriculture, manufacturing, energy, governance, finance, and healthcare, Industry 6.0 promises transformative impacts. Precision agriculture leverages AI and IoT to optimize resource utilization and increase crop yields. Smart factories integrate real-time data analytics and automation for streamlined production. In finance, decentralized finance (DeFi) and blockchain-based systems enable secure, frictionless transactions. Healthcare benefits from personalized medicine, early disease detection, telemedicine, and data-driven diagnostics. Intelligent energy grids optimize renewable energy distribution, while governance systems gain transparency through blockchain and AI-enabled citizen engagement.

Overall, Industry 6.0 envisions a future where intelligent technologies and human values converge to create a sustainable, efficient, and resilient industrial ecosystem. By balancing innovation with ethical responsibility, Industry 6.0 has the potential to reshape how societies live and work across all sectors [12].

### **Key Enablers of Industry 6.0**

Industry 6.0 is enabled by a convergence of advanced technologies that collectively support human-centricity, intelligence, sustainability, and resilience.

The following subsections outline the most critical enablers.

### **Automated Digital Twins**

Automated digital twins act as real-time virtual counterparts of physical systems, continuously updated using IoT and sensor data. Unlike static simulation models, automated twins evolve dynamically through AI-driven parameter learning and adaptation. They enable predictive maintenance, process optimization, and rapid validation of operational changes, forming the backbone of intelligent Industry 6.0 systems [3].

### **Metaverse**

The industrial metaverse enables immersive interaction between humans, machines, and data within shared virtual environments. It supports collaborative design, operator training, and remote monitoring by integrating digital twins, AR/VR, and real-time analytics. In Industry 6.0, metaverse platforms enhance situational awareness and accelerate innovation cycles [4].

### **6G Networks**

6G networks are expected to deliver ultra-reliable low-latency communication (uRLLC), massive connectivity, and native AI support. These features are critical for cyber-physical-social systems (CPSS), enabling real-time control, holographic communication, and large-scale cobot coordination. 6G also introduces quantum-resistant security mechanisms, ensuring robust industrial communication [4].

### **Dew Computing**

Dew computing extends cloud-edge paradigms by enabling local autonomous operation even during connectivity loss. It reduces latency, communication costs, and energy consumption while supporting real-time industrial decision-making. Dew computing is particularly valuable in safety-critical and remote industrial environments [13].

### **Internet of Anything (IoX)**

IoX extends IoT by integrating machines, humans, materials, digital twins, and environmental entities

into a unified network. This hyper-connectivity enables real-time supply chain tracking, predictive maintenance, and adaptive production planning, supporting the complex ecosystems envisioned in Industry 6.0 [14].

### **Blockchain**

Blockchain strengthens Industry 6.0 by enabling decentralized trust, secure data sharing, and automated smart contracts. It enhances supply chain traceability, asset tokenization, and compliance auditing, ensuring integrity across interconnected industrial systems [15].

### **Quantum Computing**

Quantum computing offers unprecedented computational power for optimization, cryptography, and machine learning acceleration. In Industry 6.0, quantum-enhanced algorithms support complex scheduling, secure communication, and high-precision sensing, although challenges related to scalability and error correction remain [16].

### **Industry 6.0 Components**

Industry 6.0 integrates a diverse set of advanced digital and physical technologies to create an intelligent, adaptive, and sustainable industrial framework. At its foundation, cloud computing serves as the computational backbone, enabling scalable storage, real-time data processing, and seamless interoperability across industrial platforms. Cloud infrastructures support high-volume analytics and facilitate collaboration among geographically distributed stakeholders.

Building Information Modelling (BIM) plays a crucial role by providing comprehensive digital representations of physical and functional assets. BIM enhances lifecycle management by supporting planning, simulation, construction, and operational optimization, while improving coordination among design, engineering, and manufacturing teams. When integrated with IoT-enabled sensors, BIM systems allow real-time monitoring of asset health and performance. Robotic automation and collaborative robots (cobots) significantly enhance productivity by performing repetitive, precision-intensive tasks while safely interacting with human operators. These

systems are powered by AI and machine learning algorithms, which enable autonomous decision-making, process optimization, predictive maintenance, and adaptive control. AI-driven analytics further support demand forecasting, anomaly detection, and operational intelligence.

Immersive technologies such as Augmented Reality (AR) and Virtual Reality (VR) bridge the gap between digital planning and physical execution. These technologies facilitate workforce training, virtual prototyping, remote maintenance, and real-time visualization of complex assembly processes. Digital twins, acting as dynamic virtual replicas of physical systems, allow simulation-driven optimization, fault diagnosis, and performance evaluation throughout the production lifecycle.

Sustainability is embedded as a core component through advanced data analytics, enabling efficient energy management, waste reduction, and carbon footprint monitoring. The convergence of these technologies forms a cohesive and intelligent Industry 6.0 ecosystem capable of self-optimization, resilience, and environmentally responsible operation [3][4].

### **Challenges, Future Directions, and Opportunities for Industry 6.0**

Industry 6.0 represents a transformative leap toward autonomous, intelligent, and sustainable industrial ecosystems. While its vision promises unprecedented efficiency and human-machine synergy, its realization is accompanied by significant technical, organizational, and regulatory challenges. This section discusses the major barriers to adoption, outlines emerging research directions, and highlights the opportunities enabled by Industry 6.0.

#### **Potential Challenges**

One of the foremost challenges in Industry 6.0 is information security, driven by the extensive interconnectivity of cyber-physical systems, cloud infrastructures, and IoT-enabled devices. The increased reliance on distributed data exchange exposes industrial environments to advanced cyber threats, including ransomware, data manipulation, and supply-chain attacks. Consequently, robust cryptographic mechanisms, zero-trust architectures,

multi-factor authentication, and continuous threat monitoring are essential to ensure system resilience. Blockchain-based solutions have emerged as promising tools for securing supply-chain traceability and ensuring data immutability, thereby reducing risks associated with fraud and tampering [4].

Another significant obstacle is data management, characterized by the volume, velocity, and heterogeneity of industrial data. Efficient storage, processing, and real-time analytics require scalable architectures such as distributed data lakes, edge analytics platforms, and AI-driven data orchestration. Ensuring data quality, interoperability, and accessibility across heterogeneous systems remains a nontrivial task, particularly in large-scale industrial deployments.

The integration of emerging technologies, such as quantum computing and advanced AI models, introduces additional technical complexity. While quantum computing offers powerful optimization and simulation capabilities, it also necessitates the development of quantum-safe cryptography and specialized expertise. Similarly, deploying AI systems at scale requires addressing model robustness, explainability, and lifecycle management.

From an organizational perspective, legacy system integration represents a major barrier. Existing industrial equipment often relies on proprietary protocols and siloed architectures, making seamless interoperability with modern platforms costly and fragile. Furthermore, the high capital expenditure associated with private 5G/6G networks, edge infrastructures, and AI orchestration platforms demands new investment strategies and cloud-native operational models.

Beyond technical concerns, data governance, regulatory compliance, and ROI assessment remain challenging. Cross-border data sharing, privacy regulations, and sector-specific compliance requirements complicate the deployment of federated learning and shared analytics platforms. Additionally, quantifying the economic value of benefits such as sustainability gains, resilience, and hyper-customization remains an open research challenge [3][4][5].

## Future Directions

The evolution toward Industry 6.0 opens new research avenues centred on ultra-low latency communication, intelligent autonomy, and computational convergence. Edge computing combined with advanced wireless technologies enables real-time decision-making by processing data close to its source, reducing latency and bandwidth consumption. This paradigm is particularly critical for autonomous manufacturing lines, robotics, and mission-critical industrial applications.

Quantum computing is expected to play a transformative role by addressing optimization and simulation problems beyond the reach of classical computing. Future research focuses on developing practical quantum algorithms for applications such as logistics optimization, materials discovery, and drug development, alongside hybrid quantum-classical frameworks that ensure near-term usability [3][4][5][6].

The continued evolution of autonomous systems and CPS will further reduce human intervention in routine operations while improving safety and adaptability. AI-enhanced CPS are expected to enable predictive maintenance, adaptive control, and self-healing industrial processes, forming the backbone of resilient Industry 6.0 ecosystems

## Generative AI for Industry 6.0

Generative Artificial Intelligence (GAI) has emerged as a cornerstone technology for Industry 6.0, enabling advanced automation, decision support, and intuitive human-machine interaction. Large Language Models (LLMs) are increasingly applied to generate design specifications, automate documentation, and facilitate natural-language interaction with industrial systems and collaborative robots. These models transform unstructured operational data into actionable insights, significantly reducing downtime and knowledge silos across global production sites.

In distributed and privacy-sensitive environments, federated learning frameworks enable collaborative model training without exposing raw data, preserving confidentiality while improving model robustness. Complementing LLMs, Small Language Models (SLMs) provide lightweight, low-latency inference

suitable for edge deployment, supporting tasks such as log summarization, workflow automation, and semantic search in resource-constrained settings. Together, these generative AI paradigms enhance scalability, explainability, and responsiveness in Industry 6.0 deployments.

## CONCLUSION

This survey presents one of the earliest comprehensive and forward-looking investigations into Industry 6.0, offering a holistic perspective on its vision, enabling technologies, and transformative potential. Through a systematic analysis of existing literature and relevant industrial reports, the study highlights the rapid evolution of technological paradigms that collectively shape the foundation of the next industrial revolution. The findings demonstrate that Industry 6.0 is not merely a continuation of prior industrial phases, but a paradigm shift driven by the convergence of intelligent automation, advanced connectivity, and human-centric innovation. The survey extensively examined the role of emerging enablers such as 6G communication networks, quantum computing, dew and edge computing paradigms, and generative artificial intelligence (GAI) within the Industry 6.0 ecosystem. These technologies collectively enhance operational efficiency, ultra-low latency connectivity, and intelligent automation, while simultaneously supporting sustainability and adaptive manufacturing. Their integration enables industries to move toward highly interconnected, autonomous, and resilient systems capable of responding dynamically to real-time demands and uncertainties.

Empirical insights drawn from the reviewed studies indicate a growing adoption of smart, sustainable, and precision-driven manufacturing practices. The Industry 6.0 architectural framework discussed in this survey illustrates how advanced data analytics, AI-driven decision-making, and cyber-physical-human systems can significantly improve productivity, energy efficiency, and resource utilization. These advancements underline the potential of Industry 6.0 to substantially reduce the environmental footprint of industrial operations while maintaining high levels of performance and scalability. Furthermore, the increasing synergy between human intelligence and machine intelligence fosters decision-making

environments that are both data-driven and intuitively human-centered, reinforcing the core philosophy of Industry 6.0. In addition, this work presented representative case studies that demonstrate the practical feasibility of Industry 6.0 concepts, along with a detailed discussion of existing challenges, open research directions, and emerging opportunities. Key challenges include system interoperability, cybersecurity risks, ethical considerations, workforce adaptation, and the need for standardized frameworks capable of supporting large-scale deployments.

Looking ahead, future research should focus on addressing the integration complexity and scalability of Industry 6.0 technologies across diverse industrial sectors. Particular attention must be given to socio-technical challenges, evolving regulatory landscapes, and ethical implications associated with increased autonomy and AI-driven decision systems. Moreover, as advancements in artificial intelligence and automation continue to accelerate, longitudinal studies will be essential to assess their long-term impacts on workforce dynamics, supply chain resilience, and global trade ecosystems. Such continued exploration is vital to ensure that Industry 6.0 not only accelerates industrial growth but also contributes meaningfully to a sustainable, inclusive, and human-centric global industrial future.

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