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The Integration of Generative AI, Robotics, and IoT in Industry 6.0: A Conceptual Framework for Human-Centric and Sustainable Manufacturing

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Abstract: *Industry 6.0 is emerging as a next-generation manufacturing paradigm that extends Industry 5.0 by integrating advanced intelligence, human-centric design, and sustainable industrial ecosystems. Key enabling technologies such as Generative Artificial Intelligence (GenAI), collaborative robotics, and the Industrial Internet of Things (IIoT) are driving this transformation through intelligent decision-making, adaptive automation, and real-time connectivity.*

However, existing research mainly focuses on these technologies in isolation, and a unified integration framework for Industry 6.0 remains limited. To address this gap, this paper proposes the Integration Framework for Human-Centric Sustainable Manufacturing (IF-HCSM), a conceptual model that integrates GenAI, robotics, and IIoT within a layered industrial architecture.

The proposed framework consists of five layers: sensing and data acquisition, intelligent inference, human–machine collaboration, adaptive execution, and sustainability governance. It demonstrates how IIoT enables real-time data collection, GenAI supports intelligent decision-making, and collaborative robotics enhances safe and flexible human–machine interaction. The framework also incorporates cybersecurity, ethical AI, and sustainability as core enablers.

The proposed study provides a structured foundation for developing intelligent, resilient, and sustainable Industry 6.0 manufacturing systems and identifies key challenges and future research directions..

Keywords: Industry 6.0, Generative Artificial Intelligence, Industrial Internet of Things (IIoT), Collaborative Robotics, Human-Centric Manufacturing, Sustainable Manufacturing, Smart Manufacturing, Digital Twin, Explainable AI, Cyber-Physical Systems

I. INTRODUCTION

The manufacturing industry has experienced continuous transformation through successive industrial revolutions, each driven by disruptive technological innovations. Industry 1.0 introduced mechanization through steam power, Industry 2.0 enabled mass production through electrification, Industry 3.0 incorporated automation and digital computing, and Industry 4.0 leveraged cyber-physical systems, artificial intelligence, cloud computing, and the Industrial Internet of Things (IIoT) to create interconnected smart factories [1], [3]. While Industry 4.0 significantly improved productivity, efficiency, and automation, concerns regarding environmental sustainability, workforce well-being, and industrial resilience prompted the emergence of Industry 5.0 [2].

Industry 5.0 shifts the focus from purely technology-driven manufacturing toward a human-centric, sustainable, and resilient industrial ecosystem. The European Commission defines Industry 5.0 as a paradigm that places human well-being at the center of industrial transformation while simultaneously addressing environmental and societal challenges [2]. Recent studies have emphasized the importance of human–robot collaboration, sustainable production systems, ethical artificial intelligence, and resilient supply chains as key characteristics of Industry 5.0 [7], [9], [10], [27]. Although

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Industry 5.0 represents a significant advancement beyond the automation-centric vision of Industry 4.0, emerging technological developments indicate the need for a more intelligent, adaptive, and autonomous industrial paradigm.

In this context, Industry 6.0 has begun to emerge as a conceptual vision for the future of manufacturing. Industry 6.0 extends the principles of Industry 5.0 by integrating advanced artificial intelligence, collaborative robotics, ubiquitous connectivity, digital intelligence, and sustainability-oriented governance into a unified manufacturing ecosystem [4]. Rather than replacing human workers, Industry 6.0 seeks to augment human capabilities through intelligent systems that support decision-making, creativity, safety, and productivity. The paradigm envisions manufacturing environments where autonomous technologies and human expertise coexist to achieve operational excellence while maintaining social and environmental responsibility.

Among the technologies expected to drive this transformation, Generative Artificial Intelligence (GenAI), collaborative robotics, and the Industrial Internet of Things (IIoT) play a central role. Generative AI has demonstrated remarkable capabilities in content generation, industrial knowledge discovery, predictive analytics, process optimization, and intelligent decision support [11], [12], [13]. Large language models and other generative architectures have the potential to revolutionize industrial operations by enabling natural-language interaction, automated engineering design, and adaptive production planning. Simultaneously, collaborative robots (cobots) have evolved beyond conventional industrial automation to support safe, flexible, and efficient human–robot collaboration in manufacturing environments [6], [16], [17], [18], [34]. These systems enhance productivity while preserving the critical role of human expertise in complex industrial processes.

The Industrial Internet of Things provides the communication and sensing infrastructure necessary for intelligent manufacturing systems. Through interconnected sensors, machines, and devices, IIoT enables real-time data collection, monitoring, analytics, and process control across the manufacturing lifecycle [6], [18], [24]. When integrated with Generative AI and collaborative robotics, IIoT creates a data-driven ecosystem capable of supporting adaptive and autonomous industrial operations. Furthermore, technologies such as digital twins, cyber-physical systems, edge computing, and industrial metaverse platforms further strengthen the capabilities of future manufacturing environments [19], [28], [35].

Despite growing research on Generative AI, robotics, and IIoT, existing studies primarily investigate these technologies independently or within the frameworks of Industry 4.0 and Industry 5.0. The literature reveals a lack of comprehensive conceptual frameworks that systematically integrate these technological pillars within an Industry 6.0 context while simultaneously addressing human-centricity, sustainability, cybersecurity, explainability, and ethical governance. This gap limits the ability of researchers and practitioners to understand how these technologies can collectively contribute to the development of future manufacturing ecosystems.

To address this challenge, this paper proposes the Integration Framework for Human-Centric Sustainable Manufacturing (IF-HCSM), a conceptual Industry 6.0 framework that integrates Generative AI, collaborative robotics, and IIoT into a unified architecture. The framework consists of five interconnected layers: sensing and data acquisition, intelligent inference, human–machine collaboration, adaptive execution, and sustainability governance. Through these layers, the framework demonstrates how intelligent technologies can support efficient, adaptive, sustainable, and human-centered manufacturing operations.

The major contributions of this paper are summarized as follows:

- To analyze the evolution from Industry 4.0 and Industry 5.0 toward the emerging Industry 6.0 paradigm.
- To examine the role of Generative AI, collaborative robotics, and IIoT as key enabling technologies for next-generation manufacturing systems.
- To propose the Integration Framework for Human-Centric Sustainable Manufacturing (IF-HCSM) for Industry 6.0 environments.
- To identify critical challenges related to cybersecurity, interoperability, workforce transformation, ethical AI governance, and sustainability.

- To outline future research directions involving digital twins, explainable AI, autonomous industrial systems, and sustainable manufacturing ecosystems.

The remainder of this paper is organized as follows. Section II presents the literature review and research gap analysis. Section III describes the conceptual research methodology adopted for framework development. Section IV discusses the core technological pillars of Industry 6.0. Section V introduces the proposed IF-HCSM framework. Section VI presents the framework analysis and implications. Section VII discusses challenges and future research directions. Finally, Section VIII concludes the paper.

II. LITERATURE REVIEW AND RESEARCH GAP ANALYSIS

The evolution of manufacturing from Industry 4.0 to Industry 6.0 has been driven by advancements in artificial intelligence, robotics, Industrial Internet of Things (IIoT), and digital technologies. Recent studies emphasize the need for intelligent, human-centric, and sustainable manufacturing systems that integrate these technologies to improve productivity, resilience, and environmental performance. This section reviews the key literature related to Industry 6.0 and identifies the research gaps addressed by the proposed framework.

A. Evolution from Industry 4.0 to Industry 6.0

Industry 4.0 introduced cyber-physical systems, cloud computing, AI, and IIoT for smart manufacturing [3], [7]. Industry 5.0 expanded this vision by emphasizing sustainability, resilience, and human-centricity [2], [8], [32]. Building on these developments, Industry 6.0 is emerging as a paradigm that integrates intelligent automation, collaborative robotics, GenAI, and sustainable manufacturing ecosystems [4], [33].

B. Generative AI in Manufacturing

Generative AI has demonstrated significant potential in engineering design, process optimization, predictive maintenance, and intelligent decision-making [5], [12], [14]. Recent research highlights its capability to support autonomous manufacturing systems and sustainable industrial operations. However, comprehensive integration with robotics and IIoT remains limited [12].

C. Collaborative Robotics and Human–Robot Collaboration

Collaborative robots (cobots) enhance workplace safety, flexibility, and productivity by enabling effective human–machine interaction [6], [17], [18]. Human–robot collaboration is increasingly recognized as a critical component of future manufacturing systems. Nevertheless, current studies mainly focus on operational performance rather than intelligent ecosystem integration [34].

D. Industrial Internet of Things (IIoT)

IIoT enables real-time connectivity, data acquisition, predictive maintenance, and digital manufacturing through interconnected industrial devices [7], [28]. It also serves as the foundation for digital twins and cyber-physical systems. However, cybersecurity, interoperability, and governance challenges remain significant barriers to large-scale deployment [19], [28].

E. Sustainable and Human-Centric Manufacturing

Human-centricity and sustainability are fundamental principles of Industry 5.0 and Industry 6.0 [10], [22], [32]. Recent studies emphasize ethical AI, workforce empowerment, environmental responsibility, and resilient production systems [11], [23]. However, these principles are often studied independently from technological integration frameworks.

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F. Comparative Literature Analysis

Table I presents a comparative analysis of major studies related to Industry 6.0, Generative AI, Robotics, IIoT, and Sustainable Manufacturing.

Table I. Comparative Literature Review

No.	Paper Title (Year)	Technology Domain	Key Contribution	Research Gap
1	Industry 5.0 or Industry 6.0? A Review of Enabling Technologies and Potential Applications (2022)	Review of emerging Industry 6.0 technologies	Identified AI, robotics, IoT, digital twins, block chain, and quantum computing as key enablers of future intelligent manufacturing.	Did not provide a practical framework for technology integration.
2	Industry 4.0 and Industry 5.0—Inception, Conception and Perception (2021)	Evolution of Industry 4.0 and Industry 5.0	Demonstrated the transition from automation-driven production to human-centric and sustainable manufacturing systems.	Industry 6.0 concepts and implementation strategies were not discussed.
3	Industry 5.0: Prospect and Retrospect (2022)	Analysis of Industry 5.0 principles	Highlighted sustainability, resilience, and human well-being as core dimensions of next-generation manufacturing.	Limited discussion on Generative AI and autonomous intelligence.
4	Generative Artificial Intelligence in Manufacturing: Opportunities for Actualizing Industry 5.0 Sustainability Goals (2024)	Applications of GenAI in manufacturing	Showed that GenAI can improve process planning, predictive maintenance, resource optimization, and sustainability performance.	Lack of integration with robotics and industrial IoT systems.
5	Deep Generative Models in Engineering Design: A Review (2022)	Generative design and product development	Demonstrated that generative models accelerate product innovation and reduce design cycle time.	Focused mainly on engineering design rather than shop-floor manufacturing.
6	Toward Human-Centric Smart Manufacturing: A Human-Cyber-Physical Systems Perspective (2022)	Human-centered manufacturing architecture	Proposed a Human-Cyber-Physical System (HCPS) model for improving worker interaction and decision-making.	Did not incorporate Generative AI technologies.
7	Human–Robot Collaborations in Smart Manufacturing Environments: Review and Outlook (2023)	Human–robot collaboration	Reported improvements in workplace safety, productivity, and operational flexibility through collaborative robots.	Sustainability and AI-driven autonomous adaptation were not addressed.
8	Collaborative Robots in Manufacturing and Assembly Systems: Literature Review and Future Research Agenda (2024)	Collaborative robotics applications	Identified emerging trends in adaptive robotics, sensing technologies, and intelligent automation.	Limited discussion on integration with AI and IoT ecosystems.
9	Industrial Internet of Things: Challenges, Opportunities, and Directions (2018)	Industrial IoT architecture	Established IIoT as a foundation for real-time monitoring, predictive maintenance, and data-driven manufacturing.	Predates Industry 5.0 and Industry 6.0 developments.
10	Cybersecurity for Industrial IoT (IIoT): Threats,	Security of industrial IoT systems	Identified major cyber threats including ransomware, data	Human-centric governance and AI

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	Countermeasures, Challenges and Future Directions (2023)		breaches, and network attacks in IIoT environments.	security aspects were not explored.
11	Digital Twin in Industry: State-of-the-Art (2019)	Digital twin technologies	Demonstrated how digital twins improve monitoring, simulation, and production optimization.	Did not address Generative AI-enabled decision support.
12	Industry 5.0 Implications for Inclusive Sustainable Manufacturing: An Evidence-Knowledge-Based Strategic Roadmap (2023)	Sustainable manufacturing transformation	Proposed strategic actions for achieving inclusive and sustainable industrial growth.	Lacked a unified technology integration framework.
13	Human-Centered and Sustainable Artificial Intelligence in Industry 5.0: Challenges and Perspectives (2024)	Ethical and sustainable AI	Emphasized transparency, fairness, and responsible AI deployment in industrial systems.	Limited practical implementation guidelines.
14	The Industry 5.0 Framework: Viability-Based Integration of the Resilience, Sustainability, and Human-Centricity Perspectives (2023)	Industry 5.0 framework development	Integrated resilience, sustainability, and human-centricity into a unified industrial model.	Did not include GenAI, digital twins, or IIoT integration.
15	From Industry 4.0 Digital Manufacturing to Industry 5.0 Digital Society: A Roadmap Toward Human-Centric, Sustainable, and Resilient Production (2024)	Future manufacturing roadmap	Presented a strategic roadmap for transforming manufacturing into human-centric digital ecosystems.	No implementation model for Industry 6.0 technologies.

G. Research Gap Analysis

The reviewed literature demonstrates significant advancements in Generative AI, collaborative robotics, IIoT, digital twins, and sustainable manufacturing. However, three major gaps remain. First, most studies investigate these technologies independently rather than as an integrated ecosystem. Second, existing frameworks are primarily designed for Industry 4.0 or Industry 5.0 environments, while Industry 6.0 implementation models remain limited. Third, current research lacks a unified framework that simultaneously addresses intelligent automation, human-centricity, sustainability, cybersecurity, and responsible AI governance. Therefore, there is a clear need for a unified Industry 6.0 framework capable of integrating Generative AI, collaborative robotics, and IIoT while simultaneously supporting human-centricity, sustainability, cybersecurity, explainability, and ethical governance. Addressing this gap constitutes the primary motivation for the proposed IF-HCSM framework.

III. RESEARCH METHODOLOGY

A. Research Approach

This study employs a conceptual research methodology to develop the Integration Framework for Human-Centric Sustainable Manufacturing (IF-HCSM) for Industry 6.0 environments. Conceptual research is appropriate when emerging domains lack established theoretical models and require the synthesis of existing knowledge into a coherent framework. Since Industry 6.0 remains an evolving paradigm, a conceptual approach enables the integration of Generative Artificial Intelligence (GenAI), collaborative robotics, and the Industrial Internet of Things (IIoT) into a unified manufacturing architecture.

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The methodology is based on a systematic review and synthesis of prior studies related to Industry 4.0, Industry 5.0, Industry 6.0, intelligent manufacturing, digital twins, human–robot collaboration, sustainability, and ethical AI. Through this process, key technological capabilities, implementation challenges, and research gaps were identified and subsequently incorporated into the proposed framework.

B. Framework Development Methodology

The IF-HCSM framework was developed through a five-stage methodology designed to ensure theoretical consistency and alignment with Industry 6.0 principles.

1) Literature Identification

Relevant journal articles, conference papers, industrial reports, and policy documents published between 2018 and 2025 were systematically reviewed. The literature search was conducted using major academic databases including IEEE Xplore, Scopus, ScienceDirect, SpringerLink, and Google Scholar. The review focused on Industry 4.0, Industry 5.0, Industry 6.0, Generative AI, collaborative robotics, IIoT, digital twins, cybersecurity, sustainability, and human-centric manufacturing [2], [4], [12], [22].

2) Technology Analysis

The identified literature was analyzed to evaluate the capabilities, opportunities, and limitations of GenAI, collaborative robotics, and IIoT. These technologies were selected because they consistently emerged as the most influential enablers of intelligent, adaptive, and connected manufacturing systems [6], [12], [16].

3) Research Gap Identification

A comparative analysis of existing studies revealed three major gaps: (i) limited integration among GenAI, robotics, and IIoT; (ii) lack of Industry 6.0 implementation frameworks; and (iii) insufficient consideration of sustainability, cybersecurity, explainability, and ethical governance within existing manufacturing architectures.

4) Framework Design

Based on the identified gaps, a layered conceptual architecture was designed. The framework organizes manufacturing functions into five interconnected layers: Sensing and Data Acquisition, Intelligent Inference, Human–Machine Collaboration, Adaptive Execution, and Sustainability Governance.

5) Conceptual Validation

The conceptual validation process involved mapping each framework layer against key Industry 6.0 requirements identified in the literature, including intelligence, adaptability, human-centricity, sustainability, resilience, cybersecurity, and ethical governance. This mapping ensured theoretical consistency between the proposed framework and the foundational principles of Industry 6.0.

C. Research Workflow

The overall workflow adopted in this study is illustrated in Fig. 1. The process begins with a comprehensive literature review and progresses through technology analysis, research gap identification, framework development, and conceptual validation. The resulting framework provides a structured foundation for future empirical investigations and industrial implementation studies.

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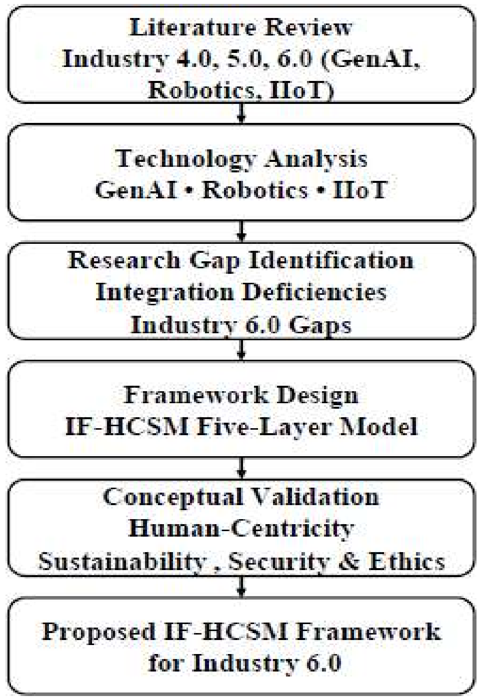

Fig. 1. Research Methodology Workflow for IF-HCSM Framework Development

D. Methodological Contribution

The methodological contribution of this study lies in its systematic integration of technological, human, and sustainability perspectives within a single Industry 6.0 framework. Unlike existing studies that primarily focus on individual technologies, the proposed methodology combines GenAI, collaborative robotics, IIoT, digital twins, explainable AI, and sustainability governance into a unified conceptual architecture.

The resulting IF-HCSM framework provides a theoretical reference model for researchers and practitioners seeking to design intelligent, resilient, and sustainable manufacturing ecosystems. Furthermore, it establishes a foundation for future empirical validation through simulation studies, industrial case analyses, and real-world implementation projects. Unlike existing studies that focus on isolated technological domains, the proposed methodology provides a structured approach for integrating Generative AI, collaborative robotics, IIoT, digital twins, sustainability governance, and human-centric design principles within a unified Industry 6.0 framework.

IV. CORE TECHNOLOGICAL PILLARS OF INDUSTRY 6.0

The Industry 6.0 manufacturing paradigm is driven by three foundational technological pillars: Generative Artificial Intelligence (GenAI), Collaborative Robotics, and the Industrial Internet of Things (IIoT). When integrated, these technologies enable intelligent, adaptive, and sustainable industrial operations.

A. Generative Artificial Intelligence (GenAI) in Manufacturing

Generative AI extends beyond conventional AI by enabling autonomous generation of designs, process plans, and decisions based on learned industrial knowledge [11]. Applications of GenAI in manufacturing include engineering design optimization, predictive maintenance, process planning, and natural-language human–machine interaction through large language models (LLMs) [12], [13]. GenAI also contributes to sustainability by identifying energy-efficient

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production strategies and minimizing material waste [12]. However, challenges related to model interpretability, data quality, and computational overhead must be addressed through responsible AI governance frameworks [11].

B. Collaborative Robotics and Human–Robot Collaboration

Collaborative robots (cobots) are designed to work alongside human operators in shared workspaces, enhancing productivity, safety, and operational flexibility [6], [16], [17], [18], [34]. Equipped with force-torque sensors, computer vision, and proximity detection, cobots dynamically adapt to human presence and support physically demanding or precision-intensive tasks without replacing human cognitive contributions [16]. When integrated with GenAI, cobots can receive natural-language instructions, interpret production goals, and autonomously generate execution plans [5]. In Industry 6.0, collaborative robotics further supports sustainability through optimized material handling, energy-efficient operation, ergonomic task execution, and accurate quality inspection [17], [18], [34]. Key challenges include safety certification, workforce reskilling, and ethical task allocation between humans and machines [16].

C. Industrial Internet of Things (IIoT)

IIoT forms the connective backbone of intelligent manufacturing by enabling real-time data collection, monitoring, and analytics across interconnected industrial devices, sensors, and machines [6], [18], [24]. IIoT data feeds support predictive maintenance, quality assurance, energy management, and supply chain visibility. When combined with GenAI, these real-time data streams enable accurate, situation-aware decision-making [12]. Digital twins, powered by continuous IIoT data, create virtual replicas of physical assets that support simulation-driven production planning and performance optimization [19], [28]. Edge computing further enhances IIoT by enabling low-latency AI inference closer to data sources [28], while emerging 5G and industrial metaverse platforms extend real-time connectivity and immersive human–machine interaction [35]. Major challenges include cybersecurity threats, protocol interoperability, and data governance across heterogeneous industrial environments [19], [28].

Collectively, Generative AI, collaborative robotics, and IIoT constitute the technological foundation of Industry 6.0 manufacturing systems. Their convergence enables intelligent decision-making, adaptive automation, human-centric collaboration, and sustainability-oriented operations. These technological pillars therefore serve as the primary enablers of the proposed IF-HCSM framework presented in the following section.

V. THE PROPOSED IF-HCSM FRAMEWORK

A. Framework Overview

The Integration Framework for Human-Centric Sustainable Manufacturing (IF-HCSM) is proposed as a conceptual architecture for Industry 6.0 manufacturing environments. The framework integrates Generative AI, collaborative robotics, and IIoT within a five-layer hierarchical structure that supports intelligent, adaptive, human-centric, and sustainability-oriented industrial operations. Each layer performs distinct functions while maintaining bidirectional communication with adjacent layers, ensuring seamless data flow, intelligent inference, and coordinated execution across the entire manufacturing ecosystem. The framework also incorporates cybersecurity, ethical AI governance, and sustainability as cross-cutting enablers embedded throughout all layers [2], [4].

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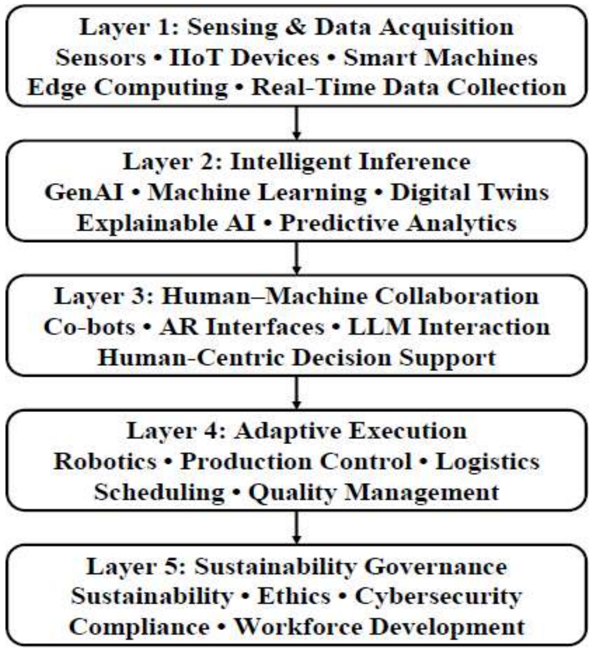

Fig. 2. Proposed IF-HCSM Framework Architecture for Industry 6.0 Manufacturing

B. Layer 1 – Sensing and Data Acquisition

The foundation of the IF-HCSM framework is the sensing and data acquisition layer, which is responsible for collecting real-time operational data from the physical manufacturing environment. This layer comprises industrial sensors, actuators, embedded controllers, smart machines, and IIoT-connected devices that continuously monitor production parameters including temperature, pressure, vibration, energy consumption, and machine status [6], [18], [24].

Data collected at this layer is transmitted through industrial communication protocols such as OPC-UA, MQTT, and 5G wireless networks to edge nodes and cloud platforms for further processing. Edge computing infrastructure deployed at this layer reduces transmission latency and enables time-critical local processing, ensuring rapid system responsiveness for real-time manufacturing operations [28]. This layer serves as the primary data source for all intelligent functions performed in the layers above.

C. Layer 2 – Intelligent Inference

The intelligent inference layer processes the data acquired from Layer 1 and applies advanced AI techniques to generate actionable insights and decisions. GenAI models, machine learning algorithms, and large language models (LLMs) operate at this layer to support predictive maintenance, process optimization, anomaly detection, quality forecasting, and autonomous production planning [11], [12], [13].

Digital twin platforms integrated at this layer create virtual replicas of physical assets and processes, enabling simulation-driven decision-making and scenario evaluation before physical implementation [19], [28]. Explainable AI (XAI) mechanisms ensure that AI-generated decisions are transparent, interpretable, and auditable by human operators, which is essential for responsible and ethical AI deployment in industrial environments [11]. This layer continuously refines its models based on new data streams from Layer 1, enabling adaptive and self-improving intelligence across the manufacturing system.

D. Layer 3 – Human–Machine Collaboration

The human–machine collaboration layer serves as the primary interface between intelligent systems and human workers within the Industry 6.0 environment. This layer enables safe, intuitive, and productive interaction between human operators and AI-driven collaborative robots [5], [16], [29].

Cobots deployed at this layer receive task instructions generated by the intelligent inference layer and execute them in coordination with human workers. Natural-language interfaces powered by LLMs allow operators to communicate with robotic systems and production platforms using conversational commands, reducing the technical barrier to human–machine interaction [13]. Augmented reality interfaces and industrial metaverse environments further enhance situational awareness and collaborative decision-making between humans and machines [35].

Human well-being, cognitive load management, and workforce empowerment are prioritized at this layer in alignment with the human-centric principles of Industry 5.0 and Industry 6.0 [2], [7], [9], [10]. Safety monitoring systems continuously assess the shared workspace and dynamically adjust robotic behavior to prevent accidents and ensure occupational health standards are maintained [16],[17],[18], [34].

E. Layer 4 – Adaptive Execution

The adaptive execution layer is responsible for translating intelligent decisions and human–machine collaborative outputs into physical manufacturing actions. This layer governs production scheduling, robotic task execution, supply chain coordination, quality control, and logistics management [5], [24].

AI-driven control systems at this layer continuously monitor production performance against predefined targets and dynamically adjust operational parameters in response to real-time feedback from Layers 1 and 2 [12], [18]. Collaborative robots execute physical tasks with high precision and flexibility, adapting their behavior based on changing production requirements, human instructions, and environmental conditions [16], [17], [18], [34]. This adaptive capability enables manufacturing systems to maintain operational continuity in the face of disruptions, demand variability, and supply chain uncertainties, directly supporting the resilience objectives of Industry 6.0 [4], [33].

F. Layer 5 – Sustainability Governance

The sustainability governance layer represents the highest level of the IF-HCSM framework and is responsible for overseeing environmental performance, ethical AI compliance, cybersecurity management, and regulatory adherence across all underlying layers [2], [10], [22], [23].

At this layer, sustainability dashboards monitor key performance indicators related to energy consumption, carbon emissions, material efficiency, and waste generation, enabling manufacturers to track and improve their environmental footprint in real time [12], [32]. Ethical AI governance mechanisms ensure that all AI-driven decisions comply with principles of fairness, transparency, accountability, and human oversight [11], [23]. Cybersecurity frameworks protect IIoT networks, AI systems, and production data from unauthorized access, ransomware, and data breaches [19], [28].

Workforce development programs and human-centric policies are also governed at this layer, ensuring that the transition to intelligent automation enhances rather than diminishes the role of human workers in Industry 6.0 environments [2], [9], [10]. This layer provides the governance foundation that ensures all manufacturing operations remain socially responsible, environmentally sustainable, and ethically compliant.

G. Framework Integration and Cross-Cutting Enablers

The five layers of the IF-HCSM framework operate as an integrated system with continuous bidirectional data flow and feedback loops. IIoT provides the real-time data foundation, GenAI enables intelligent decision-making and autonomous optimization, and collaborative robotics ensures safe and flexible physical execution in coordination with human workers [5], [6], [11], [12]. Cybersecurity, explainable AI, digital twins, and sustainability governance serve as cross-cutting enablers that are embedded across all layers, ensuring the framework operates with resilience, transparency, and ethical responsibility [19], [23], [28].

The proposed IF-HCSM framework establishes a closed-loop intelligent manufacturing architecture in which real-time sensing, AI-driven intelligence, human expertise, and adaptive execution continuously interact to support resilient, sustainable, and human-centric industrial operations. The framework therefore provides a conceptual foundation for the realization of Industry 6.0 manufacturing ecosystems.

VI. FRAMEWORK ANALYSIS AND IMPLICATIONS

A. Addressing the Identified Research Gaps

The literature review revealed several limitations in existing Industry 4.0, Industry 5.0, and emerging Industry 6.0 research. Although significant progress has been achieved in intelligent manufacturing, most studies investigate Generative Artificial Intelligence (GenAI), collaborative robotics, and Industrial Internet of Things (IIoT) technologies independently rather than within a unified manufacturing architecture. Furthermore, existing frameworks frequently emphasize automation and digitalization while providing limited consideration for sustainability, ethical governance, cybersecurity, and human-centric collaboration [4], [8], [9], [22].

The proposed IF-HCSM framework addresses these shortcomings by integrating GenAI, collaborative robotics, and IIoT into a comprehensive Industry 6.0 architecture. Unlike conventional approaches, the framework establishes a continuous interaction among physical manufacturing systems, intelligent decision-making mechanisms, and human operators. Through its five-layer structure, the framework supports intelligent automation while maintaining human oversight, sustainability objectives, and operational resilience [4], [16], [22], [33].

Moreover, the incorporation of cybersecurity, explainable artificial intelligence, digital twins, and sustainability governance as cross-cutting enablers distinguishes the IF-HCSM framework from many existing manufacturing models. These elements ensure that technological advancement is aligned with responsible innovation principles and long-term industrial sustainability goals [15], [19], [23], [30].

B. Theoretical Contributions of the IF-HCSM Framework

The proposed framework contributes to the growing body of Industry 6.0 research in several important ways. First, it extends the human-centric and sustainability-oriented principles of Industry 5.0 by incorporating advanced AI-driven intelligence capable of supporting autonomous yet explainable decision-making processes [2], [8], [16].

Second, the framework integrates concepts from Human-Cyber-Physical Systems (HCPS), digital twins, intelligent manufacturing, and sustainable production systems into a unified conceptual architecture. Previous studies have discussed these concepts independently; however, the proposed model demonstrates how they can operate collectively to support future manufacturing ecosystems [16], [20], [21], [25], [26].

Third, the framework introduces sustainability governance as an architectural layer rather than treating sustainability as a secondary outcome. This design choice emphasizes the importance of embedding environmental responsibility, ethical AI principles, and cybersecurity management directly within industrial decision-making processes [11], [22], [23].

Finally, the IF-HCSM framework provides a theoretical foundation for future empirical investigations, simulation-based validation studies, and industrial implementation research. The framework can serve as a reference model for researchers and practitioners seeking to design Industry 6.0 manufacturing environments that balance technological innovation with human and environmental considerations [4], [22], [33].

C. Industrial Implications

The proposed framework has significant implications for manufacturing organizations pursuing digital transformation initiatives. Through the integration of IIoT-enabled sensing technologies, AI-driven analytics, and collaborative robotic systems, manufacturers can achieve higher levels of operational efficiency, process visibility, and production flexibility [6], [7], [12], [34].

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The Intelligent Inference Layer enables proactive decision-making by utilizing predictive analytics, digital twins, and GenAI models to anticipate operational disruptions and optimize production activities. Consequently, organizations can reduce machine downtime, improve product quality, and enhance resource utilization [12], [20], [21].

From a workforce perspective, the Human–Machine Collaboration Layer promotes worker empowerment rather than workforce replacement. Human operators remain central to decision-making processes while intelligent systems provide real-time recommendations, assistance, and automation support. This approach aligns with the human-centric philosophy advocated by Industry 5.0 and emerging Industry 6.0 research [2], [10], [16].

Additionally, the Sustainability Governance Layer supports environmental and social responsibility by continuously monitoring sustainability indicators, regulatory compliance requirements, and cybersecurity risks. This capability enables organizations to pursue economic growth while simultaneously reducing environmental impact and strengthening organizational resilience [11], [22], [32].

D. Comparison with Existing Manufacturing Frameworks

The IF-HCSM framework differs from existing Industry 4.0 and Industry 5.0 models in several important aspects. Industry 4.0 frameworks primarily focus on automation, connectivity, and data exchange through cyber-physical systems and IoT technologies [1], [3]. While these frameworks significantly improve operational efficiency, they often provide limited support for human-centricity and sustainability objectives.

Industry 5.0 frameworks shift attention toward human well-being, resilience, and sustainability; however, many existing models do not fully address the integration of emerging technologies such as Generative AI, large language models, explainable AI, and advanced collaborative robotics within a unified industrial architecture [2], [8], [9].

The proposed IF-HCSM framework extends these earlier paradigms by incorporating intelligent autonomy, adaptive decision-making, collaborative human–robot interaction, sustainability governance, cybersecurity management, and ethical AI oversight into a single framework.

Consequently, the model provides a more comprehensive representation of the expected characteristics of Industry 6.0 manufacturing environments [4], [22], [23], [33].

E. Expected Benefits of the Proposed Framework

The implementation of the IF-HCSM framework is expected to generate multiple benefits across operational, human, and environmental dimensions. By leveraging Generative AI and advanced analytics, manufacturers can improve decision accuracy, accelerate problem-solving, and optimize production planning processes [5], [12].

The integration of collaborative robotics enables flexible automation while maintaining active human participation in manufacturing operations. This capability improves productivity, workplace safety, and workforce satisfaction [6], [17], [18], [34].

Furthermore, real-time IIoT monitoring combined with digital twin technologies enhances visibility across manufacturing processes and facilitates continuous process improvement [7], [20], [21]. Sustainability governance mechanisms support energy optimization, waste reduction, carbon footprint management, and compliance with environmental regulations [11], [22], [32].

Collectively, these capabilities contribute to the development of intelligent, resilient, sustainable, and human-centric manufacturing ecosystems. Therefore, the proposed IF-HCSM framework represents a promising conceptual foundation for realizing the vision of Industry 6.0 and supporting the next generation of industrial transformation [4], [11], [16], [22], [33].

VII. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

A. Technical Integration Challenges

Despite the significant potential of the proposed IF-HCSM framework, several technical challenges must be addressed before its large-scale industrial adoption. The framework relies on the seamless integration of Generative Artificial

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Intelligence (GenAI), collaborative robotics, Industrial Internet of Things (IIoT), digital twins, and cloud-edge computing infrastructures. However, these technologies often originate from different vendors and operate using heterogeneous communication protocols, data formats, and software architectures [7], [28].

Interoperability limitations can create communication bottlenecks, increase implementation complexity, and reduce system scalability. Achieving standardized data exchange and seamless integration among diverse industrial platforms remains a major challenge for future Industry 6.0 environments [33]. Furthermore, the computational requirements of large language models and advanced AI systems may impose significant infrastructure costs, particularly for small and medium-sized enterprises (SMEs) [5], [12].

B. Cybersecurity and Data Privacy Concerns

The increasing connectivity of industrial systems exposes manufacturing environments to a growing range of cybersecurity threats. IIoT devices, cloud platforms, AI models, and digital twin systems continuously exchange large volumes of sensitive operational data, creating potential attack surfaces for cybercriminals [19], [28].

Cyberattacks such as ransomware, data manipulation, industrial espionage, and unauthorized system access can disrupt manufacturing operations and compromise organizational security. Additionally, Generative AI systems may introduce new vulnerabilities, including model manipulation, prompt injection attacks, and unauthorized access to proprietary industrial knowledge [12].

Future implementations of the IF-HCSM framework must therefore incorporate robust cybersecurity mechanisms, including zero-trust architectures, encryption techniques, intrusion detection systems, and secure AI governance policies to ensure operational resilience and data protection [19], [27], [30].

C. Ethical and Responsible AI Challenges

Although Generative AI offers substantial opportunities for intelligent manufacturing, its deployment raises important ethical concerns. AI-generated decisions may be affected by data bias, limited transparency, or insufficient explainability, potentially reducing trust among workers and managers [15], [23].

Maintaining human oversight over AI-driven decision-making processes is essential to prevent excessive automation and ensure accountability. Ethical considerations related to fairness, transparency, privacy, and decision responsibility must be incorporated into industrial AI governance frameworks [23], [27], [30].

Moreover, organizations must establish clear guidelines defining the roles and responsibilities of human operators and intelligent systems within Industry 6.0 environments to ensure responsible technology adoption.

D. Workforce Transformation and Skills Development

The successful implementation of Industry 6.0 technologies depends not only on technological advancement but also on workforce readiness. The integration of GenAI, collaborative robotics, and intelligent automation will significantly transform job roles, required competencies, and workplace interactions [2], [10].

Employees will increasingly require multidisciplinary skills that combine manufacturing knowledge with expertise in artificial intelligence, data analytics, robotics, cybersecurity, and digital technologies. Organizations must therefore invest in continuous training, workforce reskilling, and human-centered change management strategies to facilitate the transition toward intelligent manufacturing systems [16], [24]. Ensuring that technological innovation enhances rather than replaces human capabilities remains a critical objective of Industry 6.0 development.

E. Sustainability and Regulatory Challenges

Although Industry 6.0 aims to promote sustainable manufacturing, achieving sustainability objectives remains challenging. Advanced AI models, cloud infrastructures, and large-scale data processing systems consume substantial computational resources and energy, potentially increasing environmental impacts if not managed appropriately [11], [22].

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In addition, emerging regulations governing artificial intelligence, industrial data management, privacy protection, and cybersecurity continue to evolve globally. Organizations implementing Industry 6.0 technologies must ensure compliance with relevant regulatory frameworks while maintaining operational efficiency and innovation capabilities [27], [29], [30]. Future research should investigate mechanisms for balancing technological advancement with environmental responsibility, ethical compliance, and long-term sustainability goals.

F. Future Research Directions

Several promising research opportunities emerge from the proposed IF-HCSM framework.

First, future studies should focus on empirical validation of the framework through industrial case studies, pilot implementations, and simulation-based experiments. Such investigations would provide practical evidence regarding the effectiveness and feasibility of the proposed architecture [20], [21]. Second, researchers should explore advanced trust-aware and explainable AI mechanisms capable of improving transparency and human acceptance of AI-generated decisions in manufacturing environments [15], [23].

Third, future work may investigate the integration of emerging technologies such as industrial metaverse platforms, trust-aware federated learning, quantum computing, and autonomous multi-agent systems within Industry 6.0 architectures. Such technologies have the potential to enhance distributed intelligence, privacy-preserving analytics, and collaborative decision-making across geographically distributed manufacturing ecosystems. [31], [35]. Fourth, quantitative sustainability assessment models should be developed to evaluate the environmental, economic, and social impacts of intelligent manufacturing systems. Such models would support evidence-based decision-making and sustainability optimization [11], [22], [32].

Finally, future research should examine the development of standardized interoperability frameworks, cybersecurity protocols, and governance mechanisms capable of supporting secure and scalable Industry 6.0 ecosystems across diverse industrial sectors [19], [28], [33].

G. Summary of Challenges and Future Directions

While the IF-HCSM framework demonstrates significant potential for enabling intelligent, sustainable, and human-centric manufacturing, its successful implementation requires addressing technical, organizational, ethical, cybersecurity, and regulatory challenges. Future research efforts focused on validation, standardization, explainable AI, sustainability assessment, and secure industrial integration will play a crucial role in advancing the realization of Industry 6.0 manufacturing systems.

VIII. CONCLUSION

The manufacturing sector is undergoing a significant transformation driven by advances in artificial intelligence, robotics, and digital connectivity. While Industry 4.0 emphasized automation and smart manufacturing, and Industry 5.0 introduced human-centricity, sustainability, and resilience, the emerging concept of Industry 6.0 seeks to establish a more intelligent, adaptive, and responsible industrial ecosystem. However, existing research remains fragmented, with limited studies providing a comprehensive framework that integrates Generative Artificial Intelligence (GenAI), collaborative robotics, and the Industrial Internet of Things (IIoT) within a unified Industry 6.0 architecture.

This paper addressed this research gap by proposing the Integration Framework for Human-Centric Sustainable Manufacturing (IF-HCSM), a conceptual architecture designed to support the development of next-generation manufacturing systems. The framework integrates three key technological enablers—GenAI, collaborative robotics, and IIoT—within a five-layer structure consisting of the Sensing and Data Acquisition Layer, Intelligent Inference Layer, Human–Machine Collaboration Layer, Adaptive Execution Layer, and Sustainability Governance Layer. Together, these layers establish a closed-loop manufacturing ecosystem capable of intelligent decision-making, adaptive automation, real-time monitoring, and continuous improvement.

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The proposed framework contributes to Industry 6.0 research by extending the principles of human-centric manufacturing and sustainable industrial development beyond the capabilities of existing Industry 4.0 and Industry 5.0 models. Unlike traditional manufacturing architectures that primarily focus on automation and connectivity, the IF-HCSM framework incorporates explainable artificial intelligence, digital twins, cybersecurity management, ethical AI governance, and sustainability monitoring as integral components of the industrial ecosystem. This holistic approach enables the coordination of human expertise, intelligent systems, and physical manufacturing resources while maintaining transparency, resilience, and environmental responsibility.

The analysis presented in this study demonstrates that the integration of GenAI, collaborative robotics, and IIoT can significantly enhance manufacturing intelligence, operational flexibility, workforce empowerment, and sustainability performance. Furthermore, the framework highlights the importance of maintaining human oversight in AI-driven environments, ensuring that technological advancement complements rather than replaces human capabilities. By embedding governance, security, and ethical considerations throughout the architecture, the framework supports the development of trustworthy and responsible Industry 6.0 systems.

Despite its contributions, this study has certain limitations. The proposed IF-HCSM framework is conceptual in nature and has not yet been validated through industrial implementation, simulation studies, or empirical experimentation. Consequently, the operational effectiveness, scalability, and performance of the framework require further investigation in real-world manufacturing environments.

Future research should focus on the practical validation of the framework through industrial case studies, digital twin simulations, and pilot deployments across diverse manufacturing sectors. Additional studies may also explore the integration of emerging technologies such as federated learning, industrial metaverse platforms, quantum computing, and autonomous multi-agent systems within the proposed architecture. Furthermore, quantitative models for evaluating sustainability performance, human–robot collaboration effectiveness, and AI trustworthiness should be developed to support evidence-based Industry 6.0 implementation strategies.

In conclusion, the proposed IF-HCSM framework provides a comprehensive conceptual foundation for integrating Generative AI, collaborative robotics, and IIoT in Industry 6.0 manufacturing environments. By combining intelligent automation, human-centric collaboration, sustainability governance, and adaptive decision-making within a unified architecture, the framework offers a strategic pathway toward the realization of resilient, sustainable, trustworthy, and human-centered manufacturing ecosystems for the next generation of industrial transformation.

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