Global Research Journal in Engineering, Science, Technology and Management (GRJESTM)
Volume 02, Issue 01 (January-February) 2026, pp. 309-316
GRJESTM :: An odaswa™ Journal
ISSN : 3107-3611 (Online)

REVIEW ARTICLE

Industry 5.0: Human-Centric Engineering and Its Implications for Organizational Management

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Abstract. Industry 5.0 represents the next evolution of industrial development, extending beyond the automation and connectivity principles of Industry 4.0 by placing human well-being, sustainability, and resilience at the center of technological innovation. While Industry 4.0 primarily emphasized cyber-physical systems, artificial intelligence, the Internet of Things (IoT), cloud computing, and smart manufacturing, Industry 5.0 promotes collaboration between humans and intelligent machines to create more adaptive, sustainable, and socially responsible production systems. Human-centric engineering seeks to combine advanced digital technologies with human creativity, ethical decision-making, and cognitive capabilities, thereby improving productivity while enhancing employee satisfaction and organizational resilience. Emerging technologies such as collaborative robots (cobots), artificial intelligence, digital twins, edge computing, augmented reality, and intelligent decision-support systems are transforming organizational structures, workforce management, and industrial operations. This review examines the fundamental principles of Industry 5.0 and explores its implications for organizational management with emphasis on human-centered engineering, sustainable manufacturing, workforce transformation, and digital innovation. The paper discusses the technological foundations of Industry 5.0, human–machine collaboration, organizational adaptability, leadership, skill development, and future challenges. By analyzing these concepts, the review provides insights into how Industry 5.0 can contribute to resilient organizations, sustainable industrial growth, and responsible technological advancement.

Keywords: Industry 5.0, human-centric engineering, organizational management, collaborative robots, sustainable manufacturing, digital transformation

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1. Introduction

Industrial development has progressed through successive technological revolutions that have continuously transformed manufacturing processes and organizational management. The First Industrial Revolution introduced mechanized production using water and steam power, while the Second Industrial Revolution enabled mass production through electricity and assembly-line manufacturing. The Third Industrial Revolution brought computers, automation, and information technology into industrial operations. More recently, Industry 4.0 integrated cyber-physical systems, artificial intelligence (AI), cloud computing, big data analytics, and the Internet of Things (IoT) to create highly connected and intelligent manufacturing environments [1], [2].

Although Industry 4.0 significantly improved productivity, efficiency, and automation, it also raised concerns regarding workforce displacement, ethical use of AI, cybersecurity, and the reduced involvement of human expertise in decision-making [3]. These challenges demonstrated that technological progress alone is insufficient for sustainable industrial development. Modern industries require a balanced approach that combines technological innovation with human values, environmental responsibility, and organizational resilience.

Industry 5.0 has emerged as this new industrial paradigm. Rather than replacing human workers with intelligent machines, it emphasizes collaboration between humans and advanced technologies. The European Commission defines Industry 5.0 through three fundamental pillars: human-centricity, sustainability, and resilience, highlighting that technological innovation should ultimately improve societal well-being while supporting economic growth [4]. This approach recognizes that creativity, critical thinking, ethical judgment, and emotional intelligence remain uniquely human capabilities that complement intelligent automation.

Human-centric engineering forms the core of Industry 5.0. It focuses on designing technologies that enhance human capabilities instead of replacing them. Collaborative robots (cobots), AI-assisted decision-support systems, augmented reality (AR), wearable devices, and digital twins enable workers to perform complex tasks more safely, efficiently, and accurately [5]. These technologies reduce repetitive workloads, improve workplace safety, and allow employees to concentrate on innovation, problem-solving, and strategic decision-making.

Sustainability is another defining characteristic of Industry 5.0. Manufacturing industries consume significant amounts of energy and natural resources while contributing to greenhouse gas emissions. Intelligent monitoring systems, predictive maintenance, circular economy practices, and AI-based resource optimization enable organizations to improve operational efficiency while reducing environmental impacts [6]. Consequently, Industry 5.0 supports both industrial competitiveness and sustainable development objectives.

The growing complexity of global supply chains and recent disruptions caused by pandemics, geopolitical conflicts, and climate-related events have also highlighted the importance of organizational resilience. Advanced technologies such as digital twins, predictive analytics, and real-time monitoring allow organizations to anticipate risks, optimize resource allocation, and respond rapidly to changing operational conditions [7]. These capabilities strengthen business continuity and improve long-term organizational adaptability.

Industry 5.0 extends beyond technological transformation and significantly influences organizational management. Modern organizations increasingly adopt collaborative leadership, continuous learning, interdisciplinary teamwork, and employee empowerment to maximize the benefits of digital transformation. Managers are expected to integrate technological expertise with human resource development, ethical governance, and sustainability strategies to create innovative and resilient workplaces [8]. At the same time, employees require new competencies in digital technologies, data analytics, AI-assisted decision-making, and collaborative problem-solving, making lifelong learning an essential component of organizational success [9].

Understanding the principles of Industry 5.0 is therefore essential for organizations seeking to remain competitive in the evolving digital economy. Human-centered engineering, intelligent automation, sustainability, and organizational resilience collectively provide the foundation for modern industrial systems capable of balancing technological advancement with human well-being.

This paper reviews the fundamental principles of Industry 5.0 and examines their implications for organizational management. It discusses the evolution from Industry 4.0, human-centric engineering, enabling technologies, human–machine collaboration, workforce transformation, and organizational sustainability. The review aims to provide a comprehensive understanding of how Industry 5.0 can support responsible innovation and resilient organizational development.

2. Principles of Industry 5.0

Industry 5.0 builds upon the technological achievements of Industry 4.0 while shifting the focus from automation-driven manufacturing to human-centered, sustainable, and resilient industrial systems. Rather than viewing intelligent machines as replacements for human workers, Industry 5.0 promotes collaboration between humans and advanced technologies to achieve higher productivity, innovation, and societal well-being. This paradigm integrates engineering, management, artificial intelligence, and sustainability to create manufacturing systems that balance economic performance with environmental and social responsibility [10].

2.1. Evolution from Industry 4.0 to Industry 5.0

Industry 4.0 introduced digital manufacturing through technologies such as cyber-physical systems, IoT, cloud computing, artificial intelligence, and big data analytics. These technologies enabled smart factories capable of autonomous monitoring, predictive maintenance, and real-time production optimization [2]. However, excessive dependence on automation raised concerns regarding workforce displacement, ethical AI, cybersecurity, and organizational resilience [11].

Industry 5.0 addresses these concerns by recognizing that human intelligence and machine intelligence are complementary rather than competing capabilities. The European Commission identifies human-centricity, sustainability, and resilience as the three pillars of Industry 5.0, emphasizing that technological innovation should enhance human well-being while supporting sustainable economic growth [4]. Consequently, organizations increasingly design production systems that combine digital automation with human creativity, judgment, and problem-solving abilities.

2.2. Human-Centric Engineering

Human-centric engineering is the defining principle of Industry 5.0. It focuses on designing technologies that support workers instead of replacing them. Industrial systems are developed with consideration for ergonomics, occupational safety, employee well-being, and cognitive capabilities, allowing humans to remain central participants in manufacturing processes [12].

Collaborative robots (cobots) illustrate this concept by working safely alongside human operators. Unlike conventional industrial robots that operate within isolated environments, cobots share workspaces with employees and assist in repetitive, physically demanding, or hazardous tasks. Human workers continue to perform activities requiring creativity, critical thinking, quality assessment, and complex decision-making, while robots provide precision, speed, and consistency [13].

Human-centric engineering also incorporates intuitive human–machine interfaces, wearable sensors, augmented reality (AR), and virtual reality (VR) systems that improve productivity, reduce workplace injuries, and simplify complex maintenance and training procedures. These technologies enhance employee satisfaction while increasing operational efficiency [14].

2.3. Human–Machine Collaboration

Effective collaboration between humans and intelligent machines is a fundamental objective of Industry 5.0. Artificial intelligence is increasingly employed as a decision-support tool rather than an autonomous decision-maker. AI systems analyze large volumes of production data, identify anomalies, predict equipment failures, and recommend operational improvements, while final decisions remain under human supervision [15].

This collaborative approach combines the complementary strengths of both humans and machines.

Human capabilities include:

- Creativity and innovation
- Ethical reasoning
- Critical thinking
- Strategic decision-making
- Emotional intelligence

Machine capabilities include:

- High-speed computation
- Continuous monitoring
- Precision and repeatability
- Data analytics
- Real-time optimization

The integration of these capabilities improves production quality, reduces operational risks, and enhances organizational flexibility. Explainable Artificial Intelligence (XAI) further strengthens collaboration by making AI-generated recommendations more transparent and understandable, thereby increasing trust among employees and managers [16].

2.4. Enabling Technologies of Industry 5.0

Industry 5.0 is supported by several advanced digital technologies that enable intelligent, sustainable, and resilient manufacturing systems. Artificial Intelligence (AI) enables predictive maintenance, production scheduling, quality inspection, supply chain optimization, and intelligent decision support. Machine learning algorithms continuously improve system performance by learning from operational data [17]. Collaborative Robots (Cobots) perform repetitive and physically demanding tasks while safely interacting with human workers. Their flexibility makes them suitable for customized manufacturing and small-batch production environments [13].

Digital Twins create virtual representations of physical equipment and manufacturing systems. By integrating real-time sensor data with simulation models, digital twins enable predictive maintenance, process optimization, and scenario analysis before physical implementation [18]. The Internet of Things (IoT) connects machines, sensors, and production systems through continuous data exchange. IoT enables real-time monitoring of equipment performance, inventory levels, energy consumption, and environmental conditions, improving operational visibility and responsiveness [19].

Cloud and Edge Computing provide scalable computational resources for processing industrial data. While cloud platforms support centralized data storage and analytics, edge computing performs low-latency processing near production equipment, enabling rapid responses in time-critical applications [20]. Augmented Reality (AR) and Virtual Reality (VR) support employee training, equipment maintenance, remote technical assistance, and product design visualization. These technologies reduce training time, improve maintenance accuracy, and facilitate knowledge transfer within organizations [21].

Together, these technologies establish an intelligent manufacturing ecosystem that enhances productivity while preserving human involvement and supporting sustainable industrial development.

2.5. Implications for Organizational Management

Industry 5.0 requires organizations to rethink traditional management practices. Leadership increasingly emphasizes employee empowerment, interdisciplinary collaboration, continuous learning, and innovation rather than hierarchical control [22]. Managers must balance technological investment with workforce development, ethical governance, and sustainability objectives.

Workforce transformation is another major organizational implication. Employees require competencies in digital technologies, AI-assisted decision-making, data analytics, cybersecurity, and collaborative problem-solving. Consequently, organizations are investing in continuous professional development, reskilling, and lifelong learning initiatives to prepare employees for rapidly evolving industrial environments [9].

Table 1. Industry 4.0 vs 5.0

Feature	Industry 4.0	Industry 5.0
Primary Focus	Automation	Human-centered collaboration
Objective	Productivity	Productivity with well-being
Human Role	System operator	Strategic collaborator
AI Function	Automation	Decision support
Sustainability	Secondary consideration	Core principle
Manufacturing	Smart factories	Human-centric smart factories
Organizational Goal	Operational efficiency	Resilience and sustainability

Industry 5.0 also strengthens organizational resilience by enabling flexible production systems, intelligent supply chain management, predictive maintenance, and rapid adaptation to market changes or external disruptions. These capabilities improve long-term competitiveness while supporting responsible and sustainable business practices [7].

Table 2. Organizational benefits of 5.0

Technology	Organizational Benefit
Artificial Intelligence	Better decision-making
Collaborative Robots	Improved worker safety
Digital Twins	Predictive maintenance
Internet of Things	Real-time monitoring
Edge Computing	Faster operational response
Augmented Reality	Efficient workforce training
Machine Learning	Process optimization
Big Data Analytics	Strategic planning

Table 1 and 2 describe the advantages of 4.0 over 5.0 and organizational benefits of 5.0

2.6. Summary

Industry 5.0 extends the capabilities of Industry 4.0 by placing human well-being, sustainability, and resilience at the center of industrial innovation. Human-centric engineering encourages collaboration between employees and intelligent technologies rather than replacing human expertise. Emerging technologies such as artificial intelligence, collaborative robots, digital twins, IoT, and augmented reality enable organizations to improve operational efficiency while supporting workforce development and sustainable manufacturing. These principles provide a strong foundation for future organizations seeking to balance technological advancement with social responsibility and long-term competitiveness.

3. Conclusion

Industry 5.0 represents a significant evolution in industrial development by shifting the focus from technology-driven automation to human-centered, sustainable, and resilient manufacturing systems. While Industry 4.0 established the foundation for intelligent factories through cyber-physical systems, artificial intelligence, IoT, and big data, Industry 5.0 recognizes that long-term industrial success depends on effective collaboration between humans and intelligent technologies rather than complete automation. This paradigm combines technological innovation with social responsibility, environmental sustainability, and employee well-being to create more adaptive and competitive organizations.

The review highlights that human-centric engineering enables organizations to design production systems that enhance human capabilities through collaborative robots, AI-assisted decision support, digital twins, and intelligent interfaces. These technologies reduce repetitive and hazardous tasks while allowing employees to contribute through creativity, innovation, ethical reasoning, and strategic decision-making. As a result, organizations can achieve higher productivity without compromising workforce engagement and job satisfaction.

The integration of advanced digital technologies also strengthens organizational resilience and operational efficiency. AI-driven analytics, predictive maintenance, IoT-based monitoring, and real-time data processing enable industries to respond rapidly to market changes, supply chain disruptions, and evolving customer demands. At the same time, sustainability initiatives supported by intelligent resource management and circular economy practices contribute to reduced environmental impact and responsible industrial growth.

The major contributions of Industry 5.0 to organizational management can be summarized as follows:

- Places human well-being at the center of technological innovation.
- Promotes collaboration between employees and intelligent machines rather than workforce replacement.
- Enhances productivity through AI-assisted decision-making and automation.
- Improves workplace safety using collaborative robots and ergonomic system design.
- Supports sustainable manufacturing through efficient energy and resource utilization.
- Strengthens organizational resilience against operational disruptions and supply-chain uncertainties.
- Encourages continuous learning and workforce reskilling to meet emerging technological demands.
- Facilitates data-driven strategic management through AI, IoT, digital twins, and predictive analytics.
- Improves innovation and product customization by combining human creativity with intelligent automation.
- Aligns industrial development with environmental and social responsibility, supporting long-term business sustainability.

Despite its significant potential, several challenges remain before Industry 5.0 can be fully implemented. Organizations must address issues related to cybersecurity, data privacy, ethical AI governance, interoperability among digital systems, workforce resistance to technological change, and the substantial investment required for digital transformation. In addition, educational institutions and industries must collaborate to develop multidisciplinary skills that combine engineering, data science, artificial intelligence, management, and sustainability.

Future research should focus on developing explainable and trustworthy AI systems, improving human–robot interaction, integrating digital twins with real-time decision support, advancing sustainable manufacturing technologies, and establishing international standards for Industry 5.0 implementation. Emerging technologies such as quantum computing, edge intelligence, autonomous systems, and generative AI are expected to further strengthen human–machine collaboration and organizational adaptability.

In conclusion, Industry 5.0 represents a transformative industrial paradigm that balances technological advancement with human values, sustainability, and organizational resilience. By integrating human-centric engineering with intelligent digital technologies, organizations can achieve greater innovation, operational excellence, and long-term competitiveness while contributing to sustainable economic and societal development.

Acknowledgement

The authors sincerely acknowledge the guidance and support of the faculty members of their institution for their valuable insights and encouragement throughout this study. Special thanks are extended to the library and research staff for providing access to relevant resources. The authors also express gratitude to colleagues and peers for their constructive feedback and motivation during the completion of this work.

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