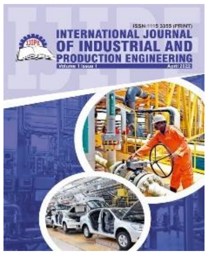

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Human-Centric Design Integration in Industry 5.0: A Framework for Resilient Smart Manufacturing

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ABSTRACT

The emergence of Industry 5.0 marks a paradigm shift from the technology-centric ethos of Industry 4.0 to a more inclusive, human-centric approach, which emphasizes collaboration between humans and intelligent systems. As manufacturing systems evolve into complex cyber-physical ecosystems, the integration of Human-Centric Design (HCD) becomes essential for ensuring not only operational efficiency but also social sustainability, resilience, and adaptability. This paper proposes a comprehensive framework for the integration of HCD principles into smart manufacturing systems, with the aim of fostering resilience and enhancement of worker well-being in the context of Industry 5.0. Through a multidisciplinary synthesis of literature spanning human factors engineering, cyber-physical systems, and organizational design, the study identifies key enablers such as collaborative robotics, AI-driven decision support, ergonomic workplace design, and adaptive human-machine interfaces. The proposed framework emphasizes the co-evolution of human and machine capabilities, promotion of shared autonomy, skill augmentation, and cognitive load management. Furthermore, it outlines mechanisms for embedding ethical considerations, inclusivity, and stakeholder participation into design processes. Case studies and recent empirical research were analyzed to validate the framework's applicability and to demonstrate its potential in the improvement of system resilience, during disruptions such as supply chain disturbances and workforce shifts. The findings underscore that a human-centric approach not only enhances technical robustness and responsiveness, but also empowers workers, and leads to higher levels of engagement, creativity, and organizational agility. This study contributes to the emerging discourse on Industry 5.0 by offering a structured pathway for aligning advanced manufacturing technologies with human values. The proposed framework serves as a strategic guide for policymakers, engineers, and organizational leaders that aim at building future-ready, human-aligned manufacturing systems.

Keywords: Industry 5.0; Smart Manufacturing; Cyber-physical Systems; Human-Machine Collaboration; Ergonomics; Adaptive systems workforce.

1. Introduction

Industry 5.0 marks the next evolutionary phase in industrial transformation, it builds upon but distinctly diverges from the automation-centric ethos of Industry 4.0. While its predecessor prioritized Cyber-Physical Systems (CPS), the Internet of Things (IoT), and Artificial Intelligence (AI) to optimize productivity and efficiency, Industry 5.0 reintroduces humans as central agents in the production ecosystem. It envisions a synergistic collaboration between advanced technologies and human creativity, intuition, and adaptability. Rather than view human labor as expendable, Industry 5.0 recognizes it as an indispensable source of innovation, personalization, and ethical oversight. Key enabling technologies such as collaborative robots (cobots), digital twins, Extended Reality (XR), and intelligent decision-support systems are designed not only to improve operational outcomes, but also to enrich human participation and well-being throughout manufacturing processes.

At the core of this transformation is Human-Centric Design (HCD), a multidisciplinary approach that places human needs, values, and capabilities at the forefront of technological development. In the context of Industry 5.0, HCD extends beyond ergonomics and usability to encompass broader socio-technical dimensions, including cognitive workload management, inclusivity, emotional engagement, and ethical accountability. Ergonomics, whose objective is aimed at the optimization of the integration of man and machine, in order to improve the work rate and accuracy, as well as the organization of daily tasks at work, entails the design of favourable workstations, as well as the enhancement of efficiency through the reduction of mental and physical strain of workers (Okpala and Ihueze, 2017, Godwin and Okpala, 2013). The integration of ergonomic considerations during the design phase such as adjustable workstations, ergonomically optimized tools, and task variability can substantially reduce the incidence of injuries in a workplace (Okpala et al., 2025a; Okpala et al., 2019).

Defined as a way of thinking that places the people and other important stakeholders at the center of a design, innovation and implementation process, HCD principles is based on the understanding of user needs, preferences, and cognitive abilities in designing interfaces that facilitate natural and intuitive interaction (Okpala et al., 2023; Okpala and Udu, 2025). By embracing HCD principles, organizations can foster a more meaningful integration of humans in smart manufacturing environments. This includes augmentation of human decision-making, promotion of adaptive interactions between workers and machines, and ensuring that technological advancement does not come at the cost of worker empowerment or psychological well-being. Moreover, HCD supports long-term sustainability goals through the alignment of industrial innovation with the United Nations Sustainable Development Goals (SDGs), particularly those related to decent work, equality, and inclusive economic growth.

In parallel, the growing complexity, uncertainty, and interconnectedness of global manufacturing systems have made resilience a defining characteristic of future-ready smart factories. Resilience which is the capacity to anticipate, absorb, adapt to, and recover from disruptions is critical not only for the maintenance of operational continuity, but also for enabling adaptive responses to shifting human and technological requirements. Human-centric technologies such as context-aware AI, emotionally intelligent robotics, and adaptive user interfaces enhance this resilience by supporting real-time decision-making under stress and enabling agile system behavior. These innovations allow smart factories to respond more holistically to disruptions whether they stem from supply chain volatility, cyber-security threats, or workforce instability by leveraging the strengths of both human and machine collaborators.

This paper proposes a structured framework for the integration of Human-Centric Design into Industry 5.0-enabled smart manufacturing systems, with the goal of enhancement of resilience, adaptability, and inclusiveness. It systematically reviews recent developments in HCD and Industry 5.0, outlines essential design components such as human-machine collaboration, cognitive support, and ethical system architectures, and presents illustrative case applications from diverse manufacturing sectors. By addressing the intersection of technological capability and human agency, the framework offers actionable insights for practitioners, system architects, and policymakers that seek to cultivate manufacturing ecosystems that are not only digitally advanced, but also deeply attuned to human values.

2. Literature Review

The transition from Industry 4.0 to Industry 5.0 reflects a paradigmatic shift in manufacturing, where the focus expands from technological automation to human-machine collaboration. Industry 4.0 which deals with the applications of intelligent products and production process represents a new era in manufacturing, and characterized by the fusion of digital technologies with traditional industrial processes (Igbokwe et al., 2024; Okpala et al., 2025b). While Industry 4.0 harnessed technologies such as the Internet of Things (IoT), cyber-physical systems (CPS), and Artificial Intelligence (AI) to build flexible, data-driven, and automated smart factories (Mourtzis et al., 2022; Ono et. al., 2024), its strong emphasis on efficiency and productivity often overlooked human values (Mgbemena et.al. 2023; Onuoha et.al., 2022; Okeagu & Mgbemena 2022). While firms can achieve better organization, technological management, agility, and customer-centric product and service tailoring by leveraging IoT (Igbokwe et al., 2024b; Udu et al., 2025a; Chukwumuanya et al., 2025), AI is defined as an array of technologies that assist computers to achieve different complex functions like the capacity to perceive, understand, assess and decode both verbal and written languages, evaluate and predict data, make proposals and suggestions, and much more (Udu et al., 2025b; Okpala et al., 2025c; Udu et al., 2025c).

The global disruptions triggered by the COVID-19 pandemic exposed critical vulnerabilities in purely automated systems, prompting the re-evaluation of technology-centric models. The COVID-19 outbreak disrupted nearly all human activities, including education, research, sports, entertainment, transportation, worship, social interactions, economy, business, and politics (Okpala et all., 2024). In response, Industry 5.0 articulated by the European Commission (2021), places humans back at the center of industrial systems, prioritizing sustainability, inclusivity, and resilience (Ghobakhloo & Fathi, 2023). This shift redefines smart manufacturing as not only technology-enabled, but also human-driven, as it establishes a foundation for the integration of Human-Centric Design (HCD).

Human-Centric Design is an interdisciplinary approach grounded in ergonomics and design thinking that prioritizes the needs, capabilities, and limitations of human operators in industrial environments. As Zarte et al. (2020), explained, its core principles include accessibility for diverse physical and cognitive abilities, participatory co-creation, cognitive augmentation via AI and AR/VR, and the ethical treatment of workers with regard to privacy and dignity. Far from being a mere design philosophy, HCD is now regarded as a strategic imperative for ensuring sustainable competitiveness and adaptability in complex manufacturing systems (Schumann et al., 2017). The growing complexity of digital tools necessitates systems that empower human workers rather than marginalize them, especially as they interact with increasingly intelligent and autonomous technologies.

The resilience of smart manufacturing systems is becoming a critical priority as organizations face dynamic market demands, supply chain disruptions, and the need for rapid customization. At the core of smart manufacturing lies the integration of advanced technologies such as IoT, AI, and Machine Learning (ML), alongside traditional manufacturing processes (Nwankwo et al., 2024). ML enables computers to study and learn from data and thereby make decisions or predictions even when it is not clearly programmed to do so (Aguh et al., 2025; Udu and Okpala, 2025; Okpala et al., 2025d). However, resilience extends beyond machine capability, it includes the ability to absorb disruptions, adapt to novel tasks, and recover with minimal downtime. Human involvement enhances this resilience through qualities that are difficult to replicate algorithmically: adaptability, creativity, and contextual judgment. For instance, when faced with ambiguous data or unexpected ethical dilemmas, human operators can rapidly adjust processes or make informed decisions that machines may not be equipped to handle.

Although several models have attempted to incorporate human roles within smart manufacturing such as RAMI 4.0, the Human Digital Twin (HDT), and the European Commission's Industry 5.0 guidelines most fall short in operationalizing HCD principles at the ground level. While RAMI 4.0 includes human components, it positions them in ancillary roles with limited influence on system-level decision-making. Similarly, the Human Digital Twin (HDT) framework emphasizes individual safety and productivity but falls short in addressing broader ethical considerations and organizational integration. Recent work by Bucci et al., (2024), highlighted the potential of digital twins to bridge this gap through the alignment of human needs with system capabilities. Nonetheless, there remains a significant opportunity to develop a holistic, modular framework that integrates technological, psychological, and ethical dimensions that offer a truly resilient, human-centered smart manufacturing model for Industry 5.0.

Comparison Between Industry 4.0 and Industry 5.0 Characteristics

The transition from Industry 4.0 to Industry 5.0 represents a significant paradigm shift from a focus on automation, efficiency, and technology-driven processes to a framework that is centered on human-centricity, resilience, and sustainability. This evolution redefines smart manufacturing through the integration of ethical considerations, human well-being, and sustainable development. Table 1 provides a detailed comparison of the characteristics of Industry 4.0 and Industry 5.0. it emphasizes on the shift towards collaborative human-machine interaction and also highlighted the changing priorities that shape the future of resilient and inclusive industrial innovation.

Table 1: Comparison between the characteristics of Industry 4.0 and Industry 5.0

Characteristic	Industry 4.0	Industry 5.0
Primary Focus	Automation and efficiency	Human-centricity and resilience
Technology Orientation	Cyber-Physical Systems (CPS), IoT, Big Data, AI	Human-AI collaboration, personalization, sustainability
Role of Humans	Minimizing human intervention	Empowering human creativity and decision-making
Production Paradigm	Mass customization	Hyper-personalization and co-creation
Design Philosophy	Technology-driven	Human-centric and value-driven
Workforce Role	Operators as system overseers	Operators as co-creators and value contributors

Sustainability Focus	Efficiency and waste reduction	Sustainable development and circular economy integration
Resilience Orientation	Reactive to disruptions	Proactive, adaptive, and resilient to change
Ethical Considerations	Often secondary to performance	Core component (ethics, wellbeing, diversity, inclusion)
Governance and Policy Integration	Technological regulations and standards	Socio-technical policies including ethics and human values

Table 1 offers a comprehensive comparison between the core characteristics of Industry 4.0 and Industry 5.0, it illustrates the evolution from a technology-centric to a human-centric industrial paradigm. While Industry 4.0 emphasizes automation, efficiency, and cyber-physical integration, Industry 5.0 introduces a more holistic approach that prioritizes human well-being, creativity, and ethical values. It fosters synergy between humans and intelligent systems, and aims at resilience, personalization, and sustainability. It also underscores how Industry 5.0 redefines smart manufacturing by embedding social, environmental, and ethical dimensions into industrial innovation and decision-making.

3. Proposed Framework for Human-Centric Design in Industry 5.0

The proposed framework presents a comprehensive, human-centric model that integrates Industry 5.0 capabilities with the principles of HCD to enhance resilience, adaptability, and worker well-being in smart manufacturing systems. Structured around four interdependent dimensions collaboration, cognition, ergonomics, and ethics, the model aims to align human strengths with advanced technologies through a socio-technical systems approach. Within this architecture, human workers and digital agents such as AI, cobots, and digital twins co-create value through physical and digital layers that are interconnected by data pipelines, sensors, and human-machine interfaces. Crucially, human feedback loops are embedded at all operational levels which include planning, execution, and optimization, in order to ensure inclusive and responsive decision-making (Dani et al., 2020). The framework's objectives are fourfold: enhancement of human-machine synergy, supporting of contextual and adaptive decision-making, prioritization of safety and inclusion, as well as embedding of ethical governance into technology adoption processes.

In Industry 5.0 environments, human-machine collaboration transcends passive oversight, evolving toward dynamic, shared control systems. Collaborative robots (cobots) now operate alongside human workers, and respond in real time to gestures, voice commands, and force feedback. These systems are equipped with AI-driven perception algorithms that interpret human intent, thereby promoting seamless and safe interaction (Mukherjee et al., 2024). Human-Machine Interfaces (HMIs) such as adaptive dashboards, gesture recognition tools, and voice-activated controls are central to this interaction, and provide intuitive, personalized communication channels that align with users' cognitive profiles. The benefits include reduced cognitive overload, improved situational awareness, and faster anomaly detection and resolution. Furthermore, the cognitive demands of complex smart factories necessitate real-time support through AI-powered systems that are capable of data-driven decision support, predictive diagnostics, and fault alerts. Augmented Reality (AR) and Virtual Reality (VR) tools extend these capabilities through the offering of immersive training modules and maintenance simulations, which facilitate skill transfer, error reduction, and collaborative design of production processes (Tsamis et al., 2021). In this model, workers retain centrality in decision-making, even within highly automated systems.

Human-centric design in manufacturing further requires attention to both physical and cognitive ergonomics. Smart manufacturing systems must adapt to a diverse workforce, and also accommodate a range of physical abilities, body types, and cognitive preferences. Ergonomic enhancements such as exoskeletons, height-adjustable workstations, and motion-assist devices serve to reduce fatigue and injury risk, while multimodal interaction methods (e.g., touch, voice, gesture) and customizable interfaces address neurodiversity and linguistic diversity. Inclusive design not only supports safety and comfort, but also fosters greater engagement and retention among workers (Bonilla et al., 2023). Successful HCD implementation also depends on evolving organizational structures. This includes the integration of interdisciplinary teams such as engineers, psychologists, ethicists, participatory design practices that involve frontline workers, and adaptive workflows that preserve human autonomy. Ethical imperatives such as data privacy, transparency, and algorithmic fairness must be embedded into governance mechanisms. The European Commission's Industry 5.0 agenda and the European Parliament's 2020 Resolution call for ethics-by-design, full human oversight, and accountability in AI systems. This includes addressing consent in biometric monitoring, mitigating bias in AI-driven HR tools, and the provision of digital literacy and reskilling for displaced roles (Ashraf & Mustafa, 2024). Ultimately, the framework serves as a blueprint for a resilient, inclusive, and ethically grounded evolution of smart manufacturing.

Interaction Model of Human, Machine, and Environment in Smart Manufacturing

The interaction model of human, machine, and environment in smart manufacturing illustrates the dynamic relationships that are essential for the attainment of resilience and adaptability in Industry 5.0. This model emphasizes seamless collaboration, real-time data exchange, and contextual awareness, through the integration of human intuition with machine intelligence within environmentally responsive and sustainable production systems. Figure 1 illustrates the Interaction Model of Human, Machine, and Environment in smart manufacturing, which emphasizes their interconnected roles in Industry 5.0. The model highlights collaborative intelligence, adaptive feedback loops, and contextual integration, and showcases how human-centric design enhances resilience, efficiency, and sustainability in next-generation manufacturing ecosystems.

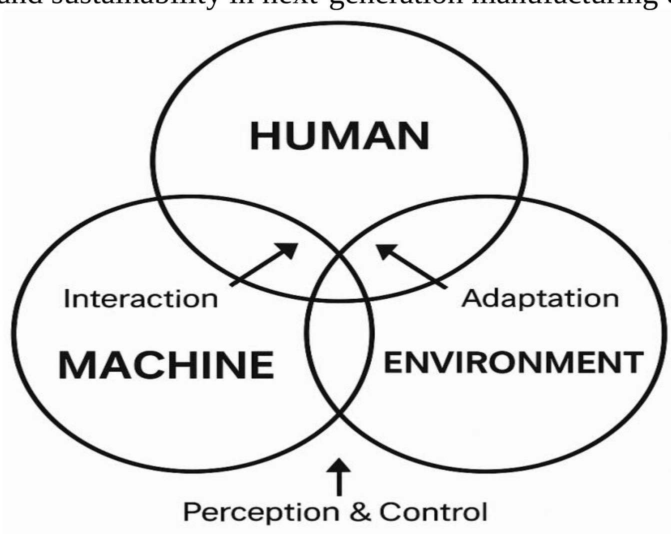

Figure 1: The interaction model of human, machine, and environment in smart manufacturing

This model demonstrates a synergistic relationship where humans, intelligent machines, and the surrounding environment continuously interact to foster resilience, adaptability, and sustainable production. Humans are positioned as active collaborators, bringing creativity, ethical judgment, and contextual awareness, while machines contribute precision, computational power, and data-driven insights. The environment encompassing physical, digital, and ecological dimensions acts as both a constraint and enabler, and influences system behavior and feedback mechanisms. Real-time communication and adaptive feedback loops between all entities allow for responsive decision-making and continuous improvement. This triadic interaction promotes a balanced ecosystem where human values guide technological application, and leads to safer, more inclusive, and environmentally conscious manufacturing processes. Ultimately, the model illustrates how the integration of human-centric design enhances system robustness, responsiveness, and long-term sustainability in smart manufacturing environments.

4. Application Scenarios and Case Studies

The proposed HCD framework for Industry 5.0 is highly adaptable across diverse manufacturing sectors that faces increasing complexity, customization demands, and workforce diversification. Real-world and conceptual case scenarios from automotive, healthcare, and electronics manufacturing underscore how the integration of HCD principles enhances resilience, adaptability, employee well-being, and operational efficiency. In the automotive sector, BMW's deployment of collaborative robots (cobots) on production lines exemplifies adaptive human-machine collaboration. As highlighted by Oyekunle et al., (2024), cobots assist with complex tasks such as wiring and component installation while ensuring worker safety and efficiency. Human workers maintain control over decision-critical points, while cobots handle precision and repetition. HCD elements implemented include ergonomically optimized workstations, voice-activated HMIs, and AR-based cognitive support tools. The outcomes include reduced injury rates, improved customization flexibility, and heightened worker satisfaction which demonstrate how the shift from operator to collaborative decision-maker supports both system agility and human well-being.

In the healthcare manufacturing domain, particularly in personalized prosthetic development, Industry 5.0 principles enable mass customization that is guided by human oversight. Companies such as Össur utilize AI and digital twins to generate individualized prosthetic designs, which enhances patient outcomes while preserving autonomy (Green & Clayton, 2021). However, final refinements rely on human expertise, including tactile feedback and direct patient interaction, ensuring empathy and precision in production. HCD applications in this context include inclusive design that is tailored to physiological and cultural diversity, AI-driven systems that simulate mobility and stress conditions, and AR-enhanced training modules for technicians. The impact is evident in improved fit and usability, reduced production lead time, and a shift from batch production to personalized solutions. This scenario illustrates the fusion of human empathy with advanced technology, which drives both innovation and social value in sensitive manufacturing domains.

Electronics manufacturing, particularly semiconductor assembly, showcases how adaptive cyber-physical systems can be integrated with HCD to handle micro-scale precision. Leading firms such as TSMC are adopting wearable-assisted technologies that enable technicians to work in tandem with vision-guided robots for chip placement (Ashraf & Mustafa, 2024). These systems exemplify the balance between automation and ethical human-centric oversight. Innovations include wearable exoskeletons and gloves for enhanced dexterity, multilingual HMIs to accommodate a global workforce, and real-time cognitive monitoring to detect fatigue and anomalies. These measures result in improved throughput, reduced human error, and sustained productivity even during labor shortages or disruptions, such as those caused by the COVID-19 pandemic.

Collectively, these case examples affirm the value of the proposed HCD framework in supporting resilient, adaptive, and inclusive manufacturing systems. By embedding ergonomic, cognitive, and ethical considerations into advanced technological deployments, organizations can achieve both operational excellence and enhanced workforce well-being.

Performance Indicators for Resilience and Human-Centric Metrics

Performance indicators that integrate resilience and human-centric metrics are essential for the evaluation of Industry 5.0 manufacturing systems. These metrics assess operational robustness, adaptability, and human factors, which ensures that smart manufacturing can effectively respond to disruptions, while promoting worker well-being, collaboration, and sustainability. Table 2 presents key performance indicators that comprehensively measure both system resilience and human-centered outcomes, and also provide a framework to guide the design and implementation of inclusive, sustainable, and resilient smart manufacturing processes aligned with Industry 5.0 principles.

Table 2: Performance indicators for resilience and human-centric metrics

Category	Indicator	Description
Operational Resilience	System Recovery Time	Time required to restore normal operations after a disruption.
	Process Flexibility	Ability to adapt to changes in production volume or product types.
	Supply Chain Responsiveness	Speed and efficiency of supply chain adjustments in response to disruptions.
Technological Adaptability	Human-Machine Interaction Efficiency	Effectiveness of collaboration between workers and intelligent systems.
	Data-Driven Decision-Making	Degree to which real-time data informs operational decisions.
Social Sustainability	Workforce Inclusivity	Extent of diversity, equity, and inclusion in the workplace.
	Training and Upskilling	Availability and effectiveness of employee development programs.
	Employee Participation in Innovation	Level of employee engagement in suggesting and implementing process improvements.
Psychological Well-being	Job Satisfaction	Overall satisfaction of employees with their roles and responsibilities.
	Stress and Fatigue Levels	Monitored levels of psychological and physical strain in the workforce.
	Work-Life Balance	Perceived balance between professional duties and personal life.
Environmental Integration	Eco-Efficiency	Resource use and environmental impact per unit of output.
	Adaptive Facility Management	Ability of physical infrastructure to support flexible and sustainable operations.

These indicators as highlighted in Table 2, span operational resilience, technological adaptability, social sustainability, psychological well-being, and environmental integration. By assessing factors such as system recovery time, human-machine interaction, workforce inclusivity, job satisfaction, and eco-efficiency, this framework ensures a balanced approach to performance measurement. It emphasizes not only the ability of systems to adapt and recover from disruptions, but also the importance of human well-being and sustainable practices in the attainment of resilient and inclusive industrial growth.

5. Discussion

The application of the proposed human-centric framework across diverse industrial sectors such as automotive assembly, personalized healthcare manufacturing, and high-precision electronics demonstrates its versatility and impact. These cases validate the framework's central premise that embedding Human-Centric Design (HCD) within smart manufacturing systems enhances resilience, adaptability, and long-term sustainability. Key insights include the strengthening of human-machine synergy through technologies like cobots and intelligent interfaces, which foster collaborative workspaces where value is co-created. Ergonomic design and cognitive support tools alleviate physical and mental strain, and promotes a healthier, more engaged workforce. Crucially, human adaptability and decision-making capacity act as a safeguard against the limitations of automation, and also enable systems to respond dynamically to disruptions. Thus, manufacturing resilience is reframed not as a byproduct of technological redundancy, but as a function of social adaptability, trust, and flexible collaboration.

The proposed framework aligns closely with the European Commission's Industry 5.0 vision, which emphasizes human-centricity, sustainability, and resilience as the foundations of future industrial development. By prioritizing worker autonomy, inclusive design, and participatory engagement, the framework positions people as active agents within smart manufacturing environments rather than passive operators. Technologies that support mass customization and reduce material waste contribute to ecological sustainability, while workplace ergonomics and well-being initiatives enhance social sustainability by lowering injury rates, turnover, and burnout. The framework's "human-in-the-loop" models embody the flexibility demanded by rapid technological, social, or environmental changes. Beyond immediate operational improvements, this approach aligns organizations with evolving policy expectations and societal values, and offers a path to long-term regulatory compliance and public trust.

The integration of HCD into Industry 5.0 also has profound implications for workforce development. As traditional roles evolve, workers must transition from routine operators to collaborative problem-solvers that are capable of interacting with AI, digital twins, and cyber-physical systems. This shift demands a blend of digital literacy, adaptive thinking, and ethical judgment. To support this transition, organizations must invest in reskilling initiatives, microlearning platforms, and continuous on-the-job training. Upskilling is essential not only for technological competence, but also for fostering ethical and human-centered innovation. The attainment of the full potential of human-centric design requires the cultivation of a culture of participation and co-creation, where cross-functional teams spanning HR, engineering, and operations collaboratively design systems that enable both performance and human fulfillment.

The Triple Impact of Human-Centric Design

The triple impact of human-centric design in manufacturing addresses operational efficiency, social responsibility, and psychological well-being, which reflects a holistic approach to Industry 5.0. Through the integration of human needs across these dimensions, this design paradigm enhances productivity, fosters inclusive and supportive workplaces, and promotes mental health. Figure 2 visually represents this framework, illustrating how operational, social, and psychological factors collectively contribute to resilient and sustainable smart manufacturing systems. This comprehensive focus enables industries to achieve long-term adaptability and human-centered innovation.

Figure 2: The triple impact of human-centric design in manufacturing

Figure 2 illustrates the triple impact of human-centric design in manufacturing, it emphasizes its integral role in Industry 5.0's resilient smart manufacturing framework. The operational dimension focuses on the enhancement of productivity, efficiency, and process optimization by aligning technologies with human capabilities. The social dimension highlights the fostering of inclusive, collaborative workplaces that promote diversity, equity, and social responsibility. The psychological dimension addresses employee well-being, motivation, and mental health, it recognizes their critical influence on performance and innovation. Together, these interconnected impacts create a balanced, sustainable manufacturing ecosystem where human needs are central, and also enables adaptability, resilience, and long-term success in smart industrial environments.

6. Challenges and Future Research Directions

As the industrial landscape transitions towards Industry 5.0, the integration of HCD into smart manufacturing presents a complex array of challenges that extend beyond technological innovation. The convergence of advanced technologies such as AI, collaborative robotics, digital twins, and Augmented Reality (AR) with human-centered objectives necessitates a multidimensional approach. Despite rapid technological advancements, legacy infrastructure remains a significant impediment, which often lack compatibility with emerging digital tools and frameworks like the Asset Administration Shell (AAS), that standardizes data exchange for system interoperability (Zielstorff et al., 2023). In parallel, latency issues and underdeveloped Human-Machine Interfaces (HMIs) hinder real-time interaction between humans and machines (Mihai et al., 2022). Cyber-physical integration further introduces pressing concerns around data privacy and biometric monitoring. For Small and Medium-Sized Enterprises (SMEs), the high cost of the implementation of ergonomic, cognitive, and personalized technologies raises the risk of deepening digital divides, particularly in less-resourced sectors (Nagar & Eaves, 2024).

As highlighted in Table 3, the development of adaptive interfaces and collaborative robotics, establishment of ethical frameworks for data governance, as well as research on lifelong learning systems and digital reskilling are some of the future research directions in human-centric design for industry 5.0.

Table 3: Challenges and future research directions in human-centric design for industry 5.0

Challenge	Description	Future Research Directions
Human-Machine Collaboration	Ensuring seamless interaction between humans and intelligent machines	- Development of adaptive interfaces and collaborative robotics (cobots) - Studies on trust and transparency in AI decision-making - Personalization of user experience in cyber-physical systems
Data Privacy and Ethics	Managing the ethical use of worker-related data in hyper-connected environments	- Establishing ethical frameworks for data governance - Designing privacy-preserving AI algorithms - Legal and regulatory studies in human-data interaction
Skills Gap and Workforce Readiness	Aligning human skills with technological advances	- Research on lifelong learning systems and digital reskilling - Human-AI teaming training methodologies - Role of immersive technologies (AR/VR) in skill development
Psychosocial Impact	Addressing mental health, job satisfaction, and social well-being in digital workplaces	- Investigating the impact of automation on worker identity - Measuring human well-being in smart factories - Designing supportive organizational policies
Integration Complexity	Incorporating human-centric design across diverse legacy and digital systems	- Interoperability frameworks between human-in-the-loop systems - Use of digital twins for human-centric simulation - Scalable integration models for SMEs
Trust in Intelligent Systems	Building user confidence in autonomous and semi-autonomous decision-making	- Human-centric explainable AI (XAI) - User perception studies in decision support systems - Transparent AI model development frameworks
Customization vs. Standardization	Balancing personalized user needs with production efficiency	- Flexible manufacturing systems (FMS) for human customization - Mass customization enabled by AI and additive manufacturing - User-centered product configuration models

Beyond technical limitations, the human-centricity championed by Industry 5.0 is fundamentally an ethical mandate. As AI increasingly influences operational and strategic decision-making, principles of transparency, fairness, and accountability become vital to ensure responsible deployment (Meduri et al., 2024). Assistive technologies such as emotion-sensing wearables, while potentially empowering, also risk becoming tools of surveillance if misused. Inclusive design must account for workforce diversity including age, gender, physical ability, and cultural background and requires intentional integration of fairness-aware algorithms and bias mitigation techniques (Shams et al., 2023). Moreover, while collaborative technologies may boost productivity, they can also precipitate job displacement or resistance among workers that are unprepared for digital transformation. To mitigate such outcomes, ethical adoption strategies should include transparent transition planning, continuous reskilling opportunities, and participatory design processes that foster workforce engagement and trust.

Institutional inertia and organizational fragmentation further complicate the integration of HCD in Industry 5.0. Siloed structures across engineering, human resources, and IT departments impede the interdisciplinary collaboration required for successful implementation. The ability to transition from hierarchical control models to participatory leadership remains both culturally and structurally demanding. The establishment of AI Ethics Boards and governance frameworks, as advocated by Manda et al. (2024), can foster accountability and alignment with societal values. Continuous stakeholder engagement and lifecycle monitoring are equally crucial for the maintenance of ethical standards (Meduri et al., 2024). However, many organizations lack internal advocates or mature frameworks to spearhead this transformation. Furthermore, existing performance metrics remain narrowly focused on efficiency and output, which often neglect qualitative indicators such as well-being, adaptability, and trust. The ability to address these gaps requires a forward-looking research agenda that emphasizes the co-development of adaptive AI systems, ethical design from inception, and simulations to test HCD's impact on system resilience during crises. Structured learning mechanisms like gamified training, mentorship, and participatory job redesign should underpin workforce evolution. Ultimately, standardized metrics that assess cognitive load, emotional well-being, and human trust in automation will be essential for the evaluation of the success of human-centric Industry 5.0 systems.

7. Conclusion

This paper has provided a comprehensive examination of how Human-Centric Design can be effectively integrated into the emerging paradigm of Industry 5.0 to foster resilient, adaptive, and sustainable smart manufacturing systems. While departing from the automation-centric ethos of Industry 4.0, the proposed framework emphasizes the centrality of human well-being, collaboration, and creativity in shaping future industrial ecosystems. Key contributions include the development of a structured, human-centric model that incorporates advanced technologies such as collaborative robots, AI-enabled decision support, and inclusive Human-Machine Interfaces while addressing ethical, ergonomic, and organizational dimensions. Practical case studies from the automotive, healthcare, and electronics sectors demonstrate the framework's versatility in the enhancement of operational adaptability, safety, and employee satisfaction. Furthermore, the framework aligns with broader policy goals, particularly the European Union's Industry 5.0 agenda, which reinforces human-centric innovation as both a strategic advantage and an ethical imperative. The study also identified critical challenges and proposed pathways for advancement of interdisciplinary research and practice.

As industries confront rising complexity, uncertainty, and social responsibility, embedding Human-Centric Design into digital transformation strategies is no longer optional, but essential. The next generation of smart manufacturing must be built not only for efficiency, but for inclusivity, resilience, and human empowerment. The ability to realize this vision requires coordinated action, therefore industry leaders must champion cultural change that values human input, technology developers should design adaptive and inclusive tools, policymakers and educators must promote digital literacy and lifelong learning, while researchers must pursue cross-disciplinary collaboration to develop solutions that are both technologically robust and socially responsible.

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