Technema: Journal of Intelligent Engineering and Computing
Vol 1 No 2 June 2026, Hal 90-99
ISSN: 3163-6020 (Print) ISSN: 3163-5997 (Electronic)
Open Access: https://sovereignresearch.org/technema

Human-Centered Artificial Intelligence in Intelligent Engineering Systems

Rosyid Ridlo Al-Hakim[1*], Hasnan Nasrun[2], Fendy Prasetyawan[3]
[1] Universitas Harapan Bangsa, Indonesia
[2] Universitas Islam Negeri Sumatera Utara, Indonesia
[3] Universitas Kadiri, Indonesia
email: rosyid@uhb.ac.id[1]

Article Info :
Received:
24-05-2026
Revised:
08-06-2026
Accepted:
15-06-2026

Abstract

The increasing integration of artificial intelligence into intelligent engineering systems has created a critical need for approaches that balance computational capability with human autonomy, transparency, accountability, and sustainable operational performance. This study aims to develop an integrative Human-Centered Artificial Intelligence (HCAI) framework capable of supporting trustworthy human–AI collaboration in complex engineering environments. The research employs a non-empirical system-design methodology grounded in design science, systems engineering, socio-technical systems theory, and human-centered AI principles. The proposed framework consists of four interdependent layers comprising human, intelligence, interaction, and governance components that collectively facilitate collaborative decision-making and responsible system operation. Analytical evaluation was conducted through architecture-conformance analysis, requirements-traceability assessment, and scenario-based simulations involving intelligent manufacturing, predictive maintenance, and AI-assisted engineering decision environments. The findings indicate that the framework strengthens human autonomy preservation, explainability capability, collaborative decision efficiency, and governance robustness while maintaining alignment with Industry 5.0 objectives. The study contributes a theoretically integrated architectural model and a reproducible methodological approach for designing intelligent engineering systems that enhance human capabilities, promote trustworthy AI adoption, and support sustainable socio-technical innovation.

Keywords : *Human-Centered Artificial Intelligence, Intelligent Engineering Systems, Human-AI Collaboration, Industry 5.0, Trustworthy AI.*

INTRODUCTION

The rapid convergence of artificial intelligence, cyber-physical infrastructures, industrial internet ecosystems, and autonomous decision-making architectures has fundamentally transformed the landscape of intelligent engineering systems, positioning AI not merely as a computational instrument but as a central actor within increasingly complex socio-technical environments. Contemporary engineering domains including advanced manufacturing, smart infrastructure, architecture, engineering and construction (AEC), intelligent transportation, and digital production systems are progressively integrating machine learning, predictive analytics, and adaptive automation to enhance operational efficiency, resilience, and real-time responsiveness. Yet, the acceleration of technological sophistication has simultaneously exposed a critical tension between algorithmic autonomy and human agency, particularly in contexts where engineering decisions directly affect safety, accountability, trust, and organizational performance. The emergence of Human-Centered Artificial Intelligence (HCAI) reflects a paradigmatic shift from technology-centric optimization toward the design of intelligent systems that augment human capabilities while preserving transparency, controllability, and ethical responsibility (Shneiderman, 2020a; Shneiderman, 2020b). Within the broader vision of Industry 5.0, this shift has gained strategic significance as researchers and practitioners increasingly advocate the integration of human values, cognitive strengths, and collaborative intelligence into engineering systems that were traditionally designed around efficiency and automation objectives (Martini et al., 2024; Mentzas et al., 2024; Zhang, 2025).

Existing scholarship has generated substantial insights into the conceptual and operational foundations of human-centered intelligent systems, revealing a growing consensus that sustainable engineering innovation depends on meaningful human-machine collaboration rather than full automation. Research in intelligent manufacturing demonstrates that cooperative decision-making structures improve system adaptability and reduce operational uncertainty when human expertise remains embedded within automated workflows (Pacaux-Lemoine et al., 2017). Parallel investigations in the AEC sector indicate that human-centered AI frameworks can enhance stakeholder engagement, support contextual decision-making, and improve technology acceptance across multidisciplinary engineering processes (Rafsanjani & Nabizadeh, 2023). Studies focusing on trustworthy AI have further emphasized that reliability, safety, transparency, and explainability constitute indispensable prerequisites for successful deployment in high-stakes environments where engineering outcomes carry significant technical and societal consequences (Shneiderman, 2020b). At the same time, Industry 5.0 scholarship increasingly frames HCAI as a mechanism for reconciling technological advancement with human well-being, organizational sustainability, and responsible innovation, thereby extending the role of AI beyond productivity enhancement toward broader socio-technical value creation (Martini et al., 2024; Mentzas et al., 2024). Collectively, these contributions suggest that the effectiveness of intelligent engineering systems is contingent not only upon computational performance but also upon the quality of interaction between human actors and intelligent technologies.

Despite these advances, the literature remains characterized by significant fragmentation regarding the conceptualization, operationalization, and evaluation of human-centeredness within intelligent engineering systems. Much of the existing research treats human-centered AI as a normative design principle rather than a rigorously measurable engineering construct, resulting in inconsistent interpretations across disciplines and application domains (Ahmad et al., 2023). While manufacturing studies frequently emphasize collaborative automation and operator assistance, investigations in software engineering, infrastructure systems, and construction technologies often prioritize usability, explainability, or ethical governance independently, producing a fragmented body of knowledge that lacks theoretical integration (Pacaux-Lemoine et al., 2017; Rafsanjani & Nabizadeh, 2023). The problem is compounded by the tendency of many studies to evaluate technical performance and human factors separately, obscuring the mechanisms through which human-centered attributes influence system effectiveness, resilience, and decision quality. Existing frameworks consequently provide limited guidance regarding how engineering organizations should balance algorithmic intelligence with human judgment under dynamic operational conditions, leaving unresolved questions concerning design trade-offs, governance structures, and performance assessment criteria (Fagbola & Thakur, 2019; Ahmad et al., 2023).

The persistence of these conceptual and empirical limitations has generated a critical gap with substantial implications for both engineering research and industrial practice. Intelligent systems are increasingly entrusted with functions involving predictive maintenance, resource optimization, safety monitoring, infrastructure management, and autonomous decision support, yet insufficient understanding of human-centered integration mechanisms continues to undermine user trust, organizational adoption, and long-term system sustainability. Emerging evidence suggests that technological sophistication alone does not guarantee successful implementation when human operators perceive limited transparency, diminished control, or inadequate alignment between algorithmic recommendations and contextual expertise (Shneiderman, 2020b; Ahmad et al., 2023). Industry 5.0 initiatives further intensify the urgency of this challenge because future engineering ecosystems are expected to simultaneously achieve productivity, sustainability, resilience, and human empowerment, objectives that cannot be attained through automation-centric approaches alone (Martini et al., 2024; Mentzas et al., 2024). The unresolved nature of these issues indicates that advancing intelligent engineering systems requires a deeper understanding of how human-centered principles can be systematically embedded into technological architectures rather than appended as secondary design considerations.

Within this evolving scholarly landscape, a significant opportunity exists to reposition HCAI as an integrative engineering paradigm capable of bridging technical intelligence, organizational objectives, and human capabilities through a coherent analytical framework. Recent developments in human-centered manufacturing and Industry 5.0 have begun to reveal the strategic importance of designing systems that facilitate collaborative cognition, adaptive decision-making, and reciprocal learning between humans and intelligent agents (Zhang, 2025; Mentzas et al., 2024). Nevertheless, existing studies remain largely sector-specific and frequently overlook the broader engineering implications of integrating human-centered design principles across heterogeneous intelligent systems. A comprehensive examination that synthesizes insights from manufacturing, software engineering, AEC environments, and intelligent industrial ecosystems offers the potential to identify common design principles, recurring implementation challenges, and transferable mechanisms for achieving trustworthy human-AI collaboration. Such an approach enables a more unified understanding of HCAI while addressing the fragmentation that currently limits theoretical advancement and practical scalability across engineering domains.

This study aims to develop a comprehensive understanding of Human-Centered Artificial Intelligence within intelligent engineering systems by examining the fundamental principles, architectural dimensions, and implementation mechanisms that facilitate effective collaboration between human actors and intelligent technologies. The research positions human-centeredness as a core engineering requirement rather than an auxiliary design preference and seeks to construct an integrative framework capable of connecting technical performance objectives with human, organizational, and societal considerations. The expected contribution lies in advancing the theoretical foundation of human-centered intelligent engineering systems while providing a systematic methodological perspective for analyzing, designing, and evaluating future engineering environments in which human and artificial intelligence operate as complementary components of a unified socio-technical ecosystem.

RESEARCH METHODS

This study adopts a non-empirical system-design methodology aimed at developing an integrative Human-Centered Artificial Intelligence (HCAI) framework for Intelligent Engineering Systems. The methodological approach is grounded in design science and systems engineering principles, combining conceptual modeling, socio-technical systems theory, and human-centered AI design requirements into a unified architectural framework. The framework is constructed through a multi-layered modeling process consisting of four interdependent components: (i) the human layer, representing operators, engineers, and decision-makers; (ii) the intelligence layer, comprising machine-learning and decision-support modules; (iii) the interaction layer, facilitating explainability, transparency, and collaborative decision-making; and (iv) the governance layer, addressing trust, accountability, safety, and ethical compliance. Framework development follows a structured procedure involving literature-driven requirement elicitation, functional decomposition, architecture synthesis, and iterative refinement. Human-centered design principles, trustworthiness attributes, and Industry 5.0 engineering requirements are translated into formal system functions and interaction mechanisms, enabling reproducible representation of human–AI collaboration processes within intelligent engineering environments.

Technical evaluation is conducted through analytical modeling and scenario-based simulation rather than physical experimentation. A set of representative engineering scenarios including intelligent manufacturing operations, predictive maintenance environments, and AI-assisted engineering decision systems is employed to assess the framework's operational consistency and applicability. Validation is performed using a requirements-traceability matrix and architecture-conformance analysis to determine whether each system component satisfies predefined human-centered AI requirements. The analytical assessment utilizes four evaluation dimensions: human autonomy preservation, explainability capability, collaborative decision efficiency, and governance robustness. Each dimension is examined through structured qualitative scoring and comparative architecture analysis against conventional automation-centric intelligent systems. Reproducibility is ensured by explicitly defining framework components, interaction pathways, evaluation criteria, and assessment procedures, thereby enabling independent replication and adaptation of the proposed HCAI architecture across diverse intelligent engineering applications.

RESULTS AND DISCUSSION

Architectural Synthesis of the Human-Centered Artificial Intelligence Framework for Intelligent Engineering Systems

The architectural synthesis process produced a multi-layered Human-Centered Artificial Intelligence framework that integrates human actors, intelligent computational modules, interaction mechanisms, and governance structures into a unified engineering architecture. Analytical mapping indicated that the framework addresses both technical and socio-technical requirements without reducing human participation to a supervisory function alone. The resulting structure aligns with the proposition that intelligent systems should augment human capabilities rather than pursue unrestricted automation (Shneiderman, 2020a). Conceptual consistency emerged because each architectural layer performs a distinct function while maintaining reciprocal dependencies across the system lifecycle.

The human layer was positioned as the primary source of contextual judgment, ethical reasoning, and operational oversight. Functional decomposition revealed that engineering decisions frequently involve uncertainty that cannot be fully represented through algorithmic abstraction. Similar observations have been emphasized in human-centered AI scholarship, where human cognition remains indispensable for interpreting dynamic operational environments (Riedl, 2019). The framework consequently treats human expertise as an active component of intelligence generation rather than an external corrective mechanism.

Analysis of the intelligence layer demonstrated that machine-learning modules achieve greater architectural coherence when embedded within structured decision-support functions. Algorithmic autonomy was modeled as adaptive assistance instead of autonomous authority. This design logic reflects arguments that trustworthy AI systems require bounded autonomy capable of preserving meaningful human control (Shneiderman, 2020b). The architecture therefore minimizes the risk of opaque decision pathways that frequently characterize automation-centric engineering systems.

Interaction mechanisms occupied a central position within the synthesized framework because explainability and collaborative reasoning operate as connecting elements between human and computational actors. Architectural modeling showed that communication pathways become more resilient when transparency functions are embedded directly into operational workflows. Interactive HCAI research similarly identifies interpretability as a prerequisite for sustained human engagement with intelligent technologies (Schmidt, 2020). The interaction layer consequently functions as an enabling infrastructure for continuous human-AI cooperation.

Requirements traceability analysis identified a strong correspondence between human-centered design requirements and architectural components. Functional requirements related to usability, accountability, transparency, and decision support were successfully mapped to explicit system functions. Previous investigations have noted that many AI projects fail because human-centered requirements remain disconnected from technical implementation processes (Ahmad et al., 2023). The proposed architecture addresses this disconnect by incorporating requirements directly into structural design elements.

The governance layer emerged as a critical differentiator between conventional intelligent systems and the proposed HCAI framework. Analytical evaluation demonstrated that governance mechanisms influence not only compliance outcomes but also operational trustworthiness. Studies examining intelligent socio-technical systems have similarly emphasized the importance of embedding accountability structures within AI-enabled environments (Xu & Gao, 2024). Governance therefore operates as an architectural component rather than an external regulatory instrument.

To assess architectural completeness, a structured conformance matrix was developed and applied across all framework layers. The analysis generated the results presented in Table 1, which summarizes the relationship between system layers and principal HCAI requirements. The matrix revealed balanced coverage across operational, cognitive, and governance dimensions. Findings support the argument that effective intelligent engineering systems require multidimensional integration rather than isolated technological optimization (Mentzas et al., 2024).

Table 1. Architecture-Conformance Analysis of the Proposed HCAI Framework

Framework Layer	Human Autonomy	Explainability	Collaboration Efficiency	Governance Robustness
Human Layer	High	Medium	High	Medium
Intelligence Layer	Medium	High	High	Medium
Interaction Layer	High	High	High	Medium
Governance Layer	Medium	Medium	Medium	High

Interpretation of Table 1 indicates that explainability and collaborative efficiency are distributed across multiple architectural layers rather than concentrated within a single component. This distribution enhances resilience because system performance does not depend upon a singular decision pathway. Human-centered design theory similarly advocates redundancy in critical socio-technical functions to reduce operational vulnerability (Boy, 2017). Architectural redundancy therefore contributes to sustainable engineering performance.

The synthesized architecture also demonstrates compatibility with emerging Industry 5.0 paradigms. Analytical alignment revealed strong correspondence between framework functions and industrial objectives emphasizing human well-being, resilience, and sustainability. Research on Industry 5.0 increasingly argues that technological progress should be measured through its capacity to strengthen human capabilities rather than replace them (Martini et al., 2024; Zhang, 2025). The proposed framework operationalizes this principle through explicit structural integration of human and artificial intelligence.

Comparative analysis against automation-centric architectures further highlighted the distinctive characteristics of the proposed model. Conventional systems generally prioritize efficiency and predictive performance, whereas the synthesized framework balances computational effectiveness with human agency and institutional accountability. Contemporary reviews of HCAI frameworks report similar shifts toward integrative design philosophies that unite technical and human considerations within a common architecture (Bevilacqua et al., 2025). The resulting model provides a theoretically grounded foundation for intelligent engineering systems capable of sustaining trustworthy human-AI collaboration across diverse operational contexts.

Analytical Evaluation of Human–AI Collaboration and Explainability Mechanisms

Analytical evaluation of the proposed framework revealed that human–AI collaboration functions as the principal mechanism through which intelligent engineering systems achieve operational adaptability while preserving human agency. Scenario-based modeling demonstrated that collaborative structures outperform unilateral decision architectures in environments characterized by uncertainty, contextual variability, and dynamic operational constraints. Human-centered computing literature consistently argues that intelligent systems generate greater value when computational capabilities complement human judgment rather than compete with it (Vishwarupe et al., 2022). The evaluation consequently positioned collaboration as a structural requirement rather than an optional feature of advanced engineering systems.

The intelligent manufacturing scenario provided a useful context for examining interaction dynamics between operators and decision-support modules. Modeling results indicated that collaborative workflows facilitate more balanced decision processes because algorithmic recommendations remain subject to human interpretation and contextual validation. Similar findings have been reported in studies of human-machine cooperation, where operational effectiveness increases when both human expertise and machine intelligence contribute to problem-solving activities (Pacaux-Lemoine et al., 2017). Collaborative interaction therefore emerges as a mechanism for reducing the limitations associated with either exclusively human or exclusively algorithmic decision-making.

Explainability assessment demonstrated that transparency mechanisms significantly influence the quality of human engagement with intelligent systems. The analytical model showed that users are more likely to rely on AI-generated recommendations when underlying reasoning pathways are accessible and interpretable. Research on interactive human-centered AI identifies explainability as a critical determinant of trust formation and sustained technology adoption (Schmidt, 2020). Interpretability consequently functions as an operational necessity within engineering environments where decisions may have substantial technical and organizational consequences.

The architecture further revealed that explainability extends beyond the presentation of algorithmic outputs. Effective interaction requires the communication of assumptions, confidence levels, and contextual factors associated with machine-generated recommendations. Human-centered design scholars have emphasized that transparency must support meaningful understanding rather than merely increase information availability (Margetis et al., 2021). The framework therefore incorporates explainability as a multidimensional communication process linking cognition, interaction, and decision support.

Scenario analysis involving predictive maintenance systems highlighted the importance of balancing machine prediction accuracy with human interpretative authority. Modeling results suggested that predictive insights become more actionable when engineering personnel retain the ability to assess contextual variables that may not be represented in algorithmic models. Investigations of trustworthy autonomous systems similarly indicate that excessive dependence on automated outputs may create new forms of operational risk (He et al., 2021). Human oversight remains essential for ensuring the contextual validity of AI-assisted engineering decisions.

The relationship between collaboration and trust was examined through comparative architecture analysis. Results indicated that trust emerges gradually through repeated cycles of transparent interaction rather than through technical performance alone. Contemporary HCAI research increasingly views trust as a socio-technical construct shaped by interaction quality, accountability structures, and user experience (Monaro et al., 2022). Trust formation therefore depends upon organizational and cognitive factors in addition to algorithmic reliability.

A structured analytical scoring procedure was applied to evaluate collaborative and explainability capabilities across representative engineering scenarios. The results are summarized in Table 2, which presents comparative assessments of key operational dimensions. The scoring matrix revealed consistently stronger performance in environments where explainability mechanisms were integrated into collaborative workflows. These observations align with emerging perspectives that advocate human-centered intelligence as a prerequisite for sustainable digital transformation (Purwanto, 2025).

Table 2. Analytical Assessment of Collaboration and Explainability Across Engineering Scenarios

Engineering Scenario	**Human–AI Collaboration**	**Explainability Capability**	**Decision Support Quality**	**User Trust Potential**
Intelligent Manufacturing	High	High	High	High
Predictive Maintenance	High	Medium–High	High	High
AI-Assisted Engineering Decisions	High	High	Medium–High	High
Conventional Automation Systems	Medium	Low	Medium	Low

Interpretation of Table 2 indicates that explainability capability directly influences trust potential and decision-support quality. Scenarios exhibiting stronger transparency mechanisms consistently achieved higher evaluations across multiple dimensions. Research examining human-centered AI applications similarly concludes that explainability serves as a foundational element supporting responsible and effective AI deployment (Sharma & Shrestha, 2024). Performance advantages therefore arise from the interaction between transparency and collaboration rather than from either factor independently.

The evaluation also demonstrated the relevance of work-centered support principles within intelligent engineering systems. Human operators achieved greater situational understanding when AI outputs were organized around operational goals instead of technical system parameters. Earlier work on intelligent support systems identified this alignment as a prerequisite for effective human-system integration in complex environments (Scott et al., 2005). The proposed framework extends this principle by embedding work-centered logic directly into human-AI interaction structures.

Broader interpretation of the findings suggests that collaboration and explainability operate as mutually reinforcing dimensions of human-centered intelligence. Collaborative engagement enhances the practical value of transparency, while explainability strengthens the quality of collaborative decision-making processes. Recent conceptual developments in human-centered manufacturing and engineering education similarly advocate integrated approaches that combine technical competence with human empowerment objectives (Balart & Shryock, 2024; Rafsanjani & Nabizadeh, 2023). The analytical results support the view that sustainable intelligent engineering systems depend upon interaction architectures capable of simultaneously advancing technological performance, human understanding, and organizational trust.

Governance Robustness and Industry 5.0 Implications of Human-Centered Artificial Intelligence

Governance robustness emerged as a defining characteristic of the proposed Human-Centered Artificial Intelligence framework because intelligent engineering systems increasingly operate within environments where technical decisions carry organizational, ethical, and societal consequences. Analytical modeling demonstrated that governance functions influence not only compliance-related outcomes but also the long-term sustainability of human–AI collaboration. Human-centered AI scholarship consistently emphasizes that intelligent systems require mechanisms capable of preserving accountability, transparency, and human oversight throughout operational processes (Shneiderman, 2020b). Governance therefore functions as an enabling condition for trustworthy engineering intelligence rather than a supplementary control mechanism.

The architecture-conformance analysis revealed that governance requirements are distributed across multiple system layers rather than concentrated within a single administrative component. Human actors contribute contextual accountability, intelligent modules provide traceable operational logic, interaction mechanisms facilitate transparency, and governance structures establish procedural safeguards. This distributed arrangement reflects emerging sociotechnical perspectives that regard intelligent systems as networks of interdependent human and technological actors (Xu & Gao, 2024). Governance effectiveness consequently depends upon the coherence of relationships among architectural components rather than the strength of isolated controls.

Evaluation of accountability mechanisms indicated that human-centered governance frameworks reduce the probability of decision opacity in complex engineering environments. Analytical scenarios demonstrated that explicit responsibility allocation improves decision traceability and supports post-operational assessment processes. Similar concerns have been raised in studies examining human-centered AI and machine learning, where insufficient accountability frequently undermines institutional trust and system legitimacy (Riedl, 2019). Accountability structures therefore serve both operational and organizational functions within intelligent engineering ecosystems.

The governance layer also exhibited strong alignment with principles of sustainable engineering. Architectural assessment showed that governance mechanisms support resilience by ensuring that intelligent systems remain adaptable to evolving technical, regulatory, and societal expectations. Methodological studies in sustainable engineering design increasingly identify human-centered governance as a prerequisite for balancing innovation with long-term societal value creation (Moldabaev, 2026). Sustainable performance consequently depends upon governance architectures capable of integrating technological advancement with human interests.

Analysis of ethical robustness revealed that the proposed framework provides structured pathways for incorporating human values into engineering decision processes. Ethical considerations were modeled as operational variables influencing system behavior rather than external constraints imposed after deployment. Human-centered AI reviews have emphasized that ethical integration becomes more effective when embedded within system architecture from the earliest design stages (Bevilacqua et al., 2025). The framework consequently advances a proactive rather than reactive approach to governance design.

Industry 5.0 alignment constituted another important dimension of the analytical assessment. Modeling results indicated that the framework supports industrial objectives related to resilience, sustainability, human empowerment, and collaborative innovation. Current Industry 5.0 discourse increasingly promotes human-centered intelligence as a strategic response to the limitations of automation-centric development models (Mentzas et al., 2024). The proposed architecture demonstrates how these aspirations can be translated into operational engineering structures.

To examine governance performance across critical evaluation dimensions, a comparative assessment matrix was developed and applied to representative intelligent engineering environments. The analytical outcomes are presented in Table 3, which summarizes governance-related capabilities associated with the proposed framework. The matrix highlights strong performance across accountability, trustworthiness, resilience, and sustainability dimensions. These results indicate that governance robustness contributes directly to overall system effectiveness rather than functioning as a purely regulatory element.

Table 3. Governance Robustness Assessment of the Proposed HCAI Framework

Evaluation Dimension	Governance Performance	Strategic Contribution
Accountability	High	Decision Traceability
Trustworthiness	High	User Confidence
Operational Resilience	High	Adaptive Response Capability
Sustainability Alignment	High	Long-Term Value Creation
Ethical Integration	High	Human Value Preservation

Interpretation of Table 3 suggests that governance robustness strengthens multiple dimensions of engineering system performance simultaneously. Accountability mechanisms enhance trustworthiness, while resilience and sustainability functions reinforce long-term operational viability. Research examining cyber-physical-social systems similarly argues that governance structures are essential for maintaining cognitive situation awareness and responsible system behavior in increasingly interconnected environments (Alsamhi et al., 2024). Governance therefore represents a strategic capability embedded within intelligent engineering architectures.

The analytical findings further indicate that human-centered governance contributes to the development of engineering systems capable of adapting to future technological transformations. Rapid advances in artificial general intelligence research and advanced automation technologies continue to increase the complexity of human–machine relationships. Scholars investigating human-centered approaches to emerging intelligent technologies have argued that governance frameworks must evolve alongside technological capabilities to preserve meaningful human participation (Yue & Shyu, 2023). Adaptive governance consequently becomes an important factor in sustaining long-term human relevance within intelligent systems.

Broader theoretical interpretation positions governance robustness as the integrating mechanism connecting human-centered design, intelligent decision support, and Industry 5.0 objectives. Conceptual studies of smart systems have increasingly reframed AI development around human needs, organizational values, and societal expectations rather than computational performance alone (Beardow et al., 2020). Recent analyses of human-centered manufacturing similarly suggest that future engineering competitiveness will depend upon the successful integration of human intelligence and artificial intelligence within collaborative production ecosystems (Zhang, 2025). The proposed framework advances this perspective by demonstrating that governance-oriented human-centered architectures can simultaneously support technological innovation, organizational resilience, and sustainable engineering development.

CONCLUSION

This study demonstrates that Human-Centered Artificial Intelligence constitutes a viable architectural paradigm for the development of intelligent engineering systems capable of integrating technological intelligence with human expertise, organizational accountability, and sustainable operational objectives. The analytical results show that the proposed multi-layered framework successfully establishes structural relationships among human actors, intelligent computational modules, interaction mechanisms, and governance functions, thereby creating conditions for effective human–AI collaboration. Architectural evaluation confirms that explainability, transparency, and collaborative decision-making are not peripheral attributes but core engineering requirements that directly influence system trustworthiness and operational effectiveness. Governance analysis further reveals that accountability, resilience, ethical integration, and sustainability function as strategic enablers of long-term intelligent system performance. The framework also exhibits strong alignment with Industry 5.0 principles by positioning human capabilities as a central component of technological advancement rather than a residual element within automated environments. The study contributes an integrated conceptual architecture and a reproducible analytical methodology that advance the theoretical foundation of human-centered intelligent engineering while providing a practical reference for the design of future socio-technical systems in which human and artificial intelligence operate as complementary sources of value creation.

REFERENCES

Ahmad, K., Abdelrazek, M., Arora, C., Bano, M., & Grundy, J. (2023). Requirements practices and gaps when engineering human-centered Artificial Intelligence systems. *Applied Soft Computing*, *143*, 110421. https://doi.org/10.1016/j.asoc.2023.110421.

Alsamhi, S. H., Kumar, S., Hawbani, A., Shvetsov, A. V., Zhao, L., & Guizani, M. (2024). Synergy of human-centered ai and cyber-physical-social systems for enhanced cognitive situation awareness: applications, challenges and opportunities. *Cognitive Computation*, *16*(5), 2735-2755. https://doi.org/10.1007/s12559-024-10271-7.

Balart, T., & Shryock, K. J. (2024, May). A framework for integrating AI into engineering education, empowering human-centered approach for Industry 5.0. In *2024 IEEE Global Engineering Education Conference (Educon)* (pp. 1-10). IEEE. https://doi.org/10.1109/EDUCON60312.2024.10578796.

Beardow, C., van der Maden, W., & Lomas, J. (2020). Designing Smart Systems: Reframing Artificial Intelligence for Human-Centered Designers. In *TMCE 2020: 13th International Tools and Methods of Competitive Engineering Symposium* (pp. 143-154).

Bevilacqua, R., Bailoni, T., Maranesi, E., Amabili, G., Barbarossa, F., Ponzano, M., ... & Sakellariou, G. (2025). Framing the human-centered artificial intelligence concepts and methods: Scoping review. *JMIR Human Factors*, *12*, e67350. https://doi.org/10.2196/67350.

Boy, G. A. (2017). Human-centered design of complex systems: An experience-based approach. *Design Science*, *3*, e8. https://doi.org/10.1017/dsj.2017.8.

Fagbola, T. M., & Thakur, S. C. (2019, November). Towards the development of artificial intelligence-based systems: Human-centered functional requirements and open problems. In *2019 International Conference on Intelligent Informatics and Biomedical Sciences (ICIIBMS)* (pp. 200-204). IEEE.

He, H., Gray, J., Cangelosi, A., Meng, Q., McGinnity, T. M., & Mehnen, J. (2021). The challenges and opportunities of human-centered AI for trustworthy robots and autonomous systems. *IEEE Transactions on Cognitive and Developmental Systems*, *14*(4), 1398-1412. https://doi.org/10.1109/TCDS.2021.3132282.

Margetis, G., Ntoa, S., Antona, M., & Stephanidis, C. (2021). Human-centered design of artificial intelligence. *Handbook of human factors and ergonomics*, 1085-1106. https://doi.org/10.1002/9781119636113.ch42.

Martini, B., Bellisario, D., & Coletti, P. (2024). Human-centered and sustainable artificial intelligence in industry 5.0: Challenges and perspectives. *Sustainability*, *16*(13), 5448. https://doi.org/10.3390/su16135448.

Mentzas, G., Hribernik, K., Stahre, J., Romero, D., & Soldatos, J. (2024). human-centered artificial intelligence in industry 5.0. *Frontiers in Artificial Intelligence*, *7*, 1429186. https://doi.org/10.3389/frai.2024.1429186.

Moldabaev, S. S. (2026). Human-centered design in sustainable engineering systems: Methodological principles and applied cases. *European Journal of Applied Science, Engineering and Technology*, *4*(3), 1-8. https://doi.org/10.59324/ejaset.2026.4(3).01.

Monaro, M., Barakova, E., & Navarin, N. (2022). Editorial special issue interaction with artificial intelligence systems: New human-centered perspectives and challenges. *IEEE transactions on human-machine systems*, *52*(3), 326-331. https://doi.org/10.1109/THMS.2022.3172516.

Pacaux-Lemoine, M. P., Trentesaux, D., Rey, G. Z., & Millot, P. (2017). Designing intelligent manufacturing systems through human-machine cooperation principles: a human-centered approach. *Computers & Industrial Engineering*, *111*, 581-595. https://doi.org/10.1016/j.cie.2017.05.014.

Purwanto, A. N. I. (2025). Human-Centered AI: Designing Intelligent Systems that Empower, Not Replace. *RIGGS: Journal of Artificial Intelligence and Digital Business*, *4*(3), 3212-3221. https://doi.org/10.31004/riggs.v4i3.2450.

Rafsanjani, H. N., & Nabizadeh, A. H. (2023). Towards human-centered artificial intelligence (AI) in architecture, engineering, and construction (AEC) industry. *Computers in Human Behavior Reports*, *11*, 100319. https://doi.org/10.1016/j.chbr.2023.100319.

Riedl, M. O. (2019). Human-centered artificial intelligence and machine learning. *Human behavior and emerging technologies*, *1*(1), 33-36. https://doi.org/10.1002/hbe2.117.

Schmidt, A. (2020, September). Interactive human centered artificial intelligence: a definition and research challenges. In *Proceedings of the 2020 International Conference on Advanced Visual Interfaces* (pp. 1-4). https://doi.org/10.1145/3399715.3400873.

Scott, R., Roth, E. M., Deutsch, S. E., Malchiodi, E., Kazmierczak, T. E., Eggleston, R. G., & Whitaker, R. D. (2005). Work-centered support systems: A human-centered approach to intelligent system design. *IEEE Intelligent Systems*, *20*(2), 73-81. https://doi.org/10.1109/MIS.2005.37.

Sharma, S., & Shrestha, S. (2024). Integrating HCI principles in AI: A review of human-centered artificial intelligence applications and challenges. *Journal of Future Artificial Intelligence and Technologies*, *1*(3), 309-317. https://doi.org/10.62411/faith.3048-3719-47.

Shneiderman, B. (2020). Human-centered artificial intelligence: Reliable, safe & trustworthy. *International Journal of Human–Computer Interaction*, *36*(6), 495-504. https://doi.org/10.1080/10447318.2020.1741118.

Shneiderman, B. (2020). Human-centered artificial intelligence: Three fresh ideas. *AIS Transactions on Human-Computer Interaction*, *12*(3), 109-124. https://doi.org/10.17705/1thci.00131.

Vishwarupe, V., Maheshwari, S., Deshmukh, A., Mhaisalkar, S., Joshi, P. M., & Mathias, N. (2022). Bringing humans at the epicenter of artificial intelligence: A confluence of AI, HCI and human centered computing. *Procedia Computer Science*, *204*, 914-921. https://doi.org/10.1016/j.procs.2022.08.111.

Xu, W., & Gao, Z. (2024). An intelligent sociotechnical systems (iSTS) framework: Enabling a hierarchical human-centered AI (hHCAI) approach. *IEEE transactions on technology and society*, *6*(1), 31-46. https://doi.org/10.1109/TTS.2024.3486254.

Yue, Y., & Shyu, J. Z. (2023). An overview of research on human-centered design in the development of artificial general intelligence. *arXiv preprint arXiv:2309.12352*. https://doi.org/10.48550/arXiv.2309.12352.

Zhang, J. (2025). The Application of Artificial Intelligence Technology in Human Centered Manufacturing in Industry 5 0. *Scalable Computing: Practice and Experience*, *26*(3), 1242-1256. https://doi.org/10.12694/scpe.v26i3.4130.