International Journal of Advanced Engineering and Technology
www.allengineeringjournal.com
ISSN: 2456-7655
Received: 28-02-2026, Accepted: 31-03-2026, Published: 15-04-2026
Volume 10, Issue 2, 2026, Page No. 9-13

A socio-technical framework for AI-driven cognitive ergonomics: Harmonizing human-centricity with Industry 5.0

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Abstract

The transition from Industry 4.0 to Industry 5.0 marks a shift from purely technological optimisation to a value-driven paradigm that emphasises human-centeredness, sustainability, and resilience. Despite the widespread adoption of artificial intelligence (AI) in industrial operations, existing implementations often focus predominantly on operational efficiency, neglecting the cognitive load, psychological well-being, and decision-making capacities of human operators. To address this critical gap, this study proposes a multi-layered Socio-Technical Framework for AI-Driven Cognitive Ergonomics, designed to integrate human-centred design principles with intelligent automation systematically. Building upon advancements in Human Digital Twins (HDTs), neurophysiological sensing (EEG and eye-tracking), wearable health devices (smartwatches, biosensing patches, smart rings, and EEG-enabled headbands), and collaborative robotics, the framework integrates both real-time physiological data streams and operators' historical health records stored in enterprise databases to deliver personalised cognitive support. Organised into two interconnected tiers — the Human-Centric Tier and the Organisational-Management Tier — the framework demonstrates how AI can harmonise individual cognitive support, human-cobot collaboration, and management-level decision-making through adaptive interfaces, real-time feedback mechanisms, and dynamic task allocation strategies. A conceptual application in a collaborative assembly scenario illustrates the framework's practical relevance, highlighting how Operator 5.0 maintains situational awareness, control, and trust through explainable AI (XAI) and shared mental models. Simulation and analytical evaluations indicate that integrating cognitive ergonomics with AI-assisted systems enhances productivity, reduces operator workload, and improves team coordination. By aligning AI capabilities with human factors, the proposed framework delivers actionable guidance for designing socially sustainable, human-centred smart factories. These findings underscore that the successful realisation of Industry 5.0 depends not solely on automation but also on the deliberate harmonisation of AI with human cognitive and ergonomic needs, ensuring that industrial workplaces remain resilient, adaptive, and fundamentally people-centred.

Keywords: Industry 5.0, cognitive ergonomics, human-centred design, socio-technical framework, explainable ai, wearable health monitoring, operator health data

Introduction

Over the past decade, Industry 4.0 has transformed manufacturing by incorporating advanced technologies such as the Industrial Internet of Things (IIoT), big data analytics, and cyber-physical systems to enhance efficiency, productivity, and operational precision [1, 2]. These technologies enable the development of smart factories in which machines, sensors, and digital systems communicate and exchange data in real time to optimize industrial operations [2]. While these technologies have automated numerous industrial processes, they have often treated human operators as passive supervisors or secondary contributors, exposing them to increased cognitive demands, mental fatigue, and reduced situational awareness [3]. As industrial environments become increasingly complex and information-intensive, the cognitive workload of operators continues to grow, highlighting the need for systems that actively support and enhance human decision-making [4].

Industry 5.0 represents a shift toward a more human-centric production paradigm, emphasizing the integration of human creativity, adaptive reasoning, and problem-solving with advanced automation [5]. Unlike previous frameworks focused primarily on efficiency and technological optimization, this approach recognizes humans as central actors whose skills must be complemented rather than replaced by intelligent systems [6]. A critical aspect of this transition is cognitive ergonomics, which examines how mental processes, including attention, perception, memory, and decision-making, interact with complex industrial systems to influence performance, safety, and overall well-being [7]. The introduction of artificial intelligence (AI) in modern factories has further reshaped operational dynamics, enabling predictive analytics, adaptive automation, and intelligent decision support [8]. However, the primary focus of many AI implementations remains on optimizing efficiency, precision, and throughput, with limited attention given to the cognitive and ergonomic needs of human operators [4]. Effectively harmonizing human capabilities with AI-driven systems therefore requires design approaches that enhance cognitive functions, adaptability, and collaboration between humans and machines [3]. By integrating human-centred design principles with AI-enabled cognitive support, industrial environments can maintain operator engagement, improve situational awareness, and foster organizational resilience. Such approaches create workplaces that are not only productive but also adaptive, sustainable, and fundamentally centred on human well-being, supporting the vision of Industry 5.0 as a socially responsible and human-focused industrial paradigm [5].

Literature Review

Contemporary research on industrial ergonomics identifies several critical themes shaping the evolution of human-centred manufacturing in the context of Industry 5.0. These themes include the interaction between automation and human work, cognitive workload management, trust and transparency in artificial intelligence, and the development of Human Digital Twins (HDTs) as socio-technical enablers within smart factories [3, 4].

1. The Automation Paradox and the Ironies of Automation

A key insight in ergonomics research is that automation does not simply replace human labour but fundamentally transforms the nature of the tasks humans perform. The concept commonly referred to as the Ironies of Automation suggests that as systems become increasingly reliable and automated, human operators are primarily required to intervene only during rare system failures [11]. These interventions can be cognitively demanding because operators may be under-practiced or have limited situational awareness of the system's internal processes, which increases the likelihood of operational errors [11, 12].

In response to these challenges, modern manufacturing paradigms emphasize redefining the role of the operator within highly automated environments. The concept of Operator 4.0 and the emerging Operator 5.0 promotes a symbiotic relationship between humans and intelligent machines, where operators collaborate with advanced technologies such as artificial intelligence, wearable devices, and collaborative robots to improve decision-making and operational performance [9]. This approach allows human workers to focus on complex problem-solving, creativity, and strategic decision-making while routine or repetitive tasks are managed by automated systems.

2. Cognitive Load and Neurophysiological Monitoring

Cognitive ergonomics in industrial systems increasingly focuses on real-time monitoring of mental workload. High levels of information density and complex user interfaces can exceed human cognitive processing capacity, resulting in reduced performance, higher error rates, and increased stress among operators [13]. To address these challenges, researchers are integrating neurophysiological sensing technologies, such as electroencephalography (EEG) and eye-tracking systems, into smart manufacturing environments [14].

These sensing technologies enable the development of adaptive human–machine interfaces capable of dynamically adjusting information displays, system alerts, or task allocations based on the operator's real-time cognitive state. By responding to variations in mental workload and attention levels, such systems improve operational safety, reduce fatigue, and enhance human performance within complex industrial environments.

3. Trust, Transparency, and Explainable AI

The effectiveness of human-AI collaboration largely depends on the level of trust operators place in automated systems. Many AI algorithms operate as black-box models, meaning their decision-making processes are difficult for human users to interpret. This lack of transparency can lead to reduced trust, over-reliance on automation, or inappropriate system usage [15].

To address these challenges, recent research emphasizes the importance of Explainable Artificial Intelligence (XAI). XAI systems provide transparent and interpretable explanations of algorithmic decisions, allowing operators to understand how conclusions are reached and to verify system outputs when necessary [16]. By improving transparency and interpretability, explainable AI enhances human-machine collaboration, supports shared mental models, and promotes responsible deployment of intelligent systems in industrial environments.

4. Human Digital Twin (HDT) as a Socio-Technical Enabler

The concept of the Human Digital Twin (HDT) represents an advanced integration of digital technologies with human-centered design principles. Unlike traditional digital twins that replicate machines or production processes, HDTs create digital representations of human operators by modelling their physiological, cognitive, and behavioural characteristics [17].

By continuously monitoring the operator's physical and cognitive states, HDTs enable adaptive interventions that improve both performance and well-being. For example, these systems can adjust workload distribution, recommend ergonomic corrections, or provide haptic and robotic feedback to reduce physical strain and fatigue. In addition, HDTs support inclusive and sustainable workforce strategies by accommodating diverse worker capabilities, including aging populations. As a result, Human Digital Twins play a critical role in enabling socially sustainable and adaptive manufacturing systems within the Industry 5.0 paradigm.

5. Wearable Health Technologies in Industrial Contexts

Recent advances in wearable health technologies have significantly expanded the ability to monitor operator well-being in industrial environments beyond traditional neurophysiological tools. Devices such as smartwatches, biosensing patches, smart rings, and EEG-enabled headbands now provide continuous, non-invasive streams of biometric data, including heart rate variability, skin conductance, blood oxygen saturation, and sleep quality that are closely correlated with cognitive performance and stress levels [19]. When these real-time biometric streams are integrated with operators' historical health records held in enterprise databases, AI systems can generate contextually personalised interventions rather than generic alerts. This data fusion approach enables the Human Digital Twin to evolve dynamically, reflecting not just current physiological state but longitudinal health trajectories [17]. Such personalised, data-driven support is a cornerstone of the Operator 5.0 vision and is central to the extended framework presented in this study.

Methods

This study employs a conceptual and simulation-based methodology to design and evaluate a multi-layered Socio-Technical Framework for AI-Driven Cognitive Ergonomics. The methodology integrates literature synthesis, framework development, and scenario-based validation.

1. Conceptual Framework Development

Insights from cognitive ergonomics, HDTs, wearable health technologies, neurophysiological monitoring, collaborative robotics, and human-AI interaction are synthesized to construct a framework comprising two interconnected tiers:

1.1 **Human-Centric Tier:** Encompasses individual operator cognitive state monitoring (via EEG, eye-tracking, wearable devices, and historical health records) alongside human-human and human-cobot coordination. AI-driven adaptive interfaces, XAI tools, and smart devices support real-time decision-making and task allocation.

1.2 **Organisational-Management Tier:** Ensures AI deployment is aligned with safety protocols, ethical standards, production objectives, and ergonomic policies. Management receives AI-assisted decision support through smart dashboards and alert systems, enabling systemic oversight and adaptive workflow governance.

2. Simulation and Conceptual Validation

The framework is evaluated through scenario-based simulations of a collaborative assembly process. Operator cognitive load, task completion time, error rates, and situational awareness are assessed under adaptive AI-supported workflows.

3. Analytical Approach

Both qualitative and quantitative metrics, decision accuracy, response time, cognitive load indices, and team coordination efficiency, are used to assess the framework's performance, comparing adaptive interventions with conventional processes.

4. Design Principles

The framework emphasizes human-centred adaptively, explainability, multi-scale integration, and social sustainability, ensuring ergonomic, ethical, and resilient industrial operations.

Design of the Socio-Technical Framework

Building on insights from cognitive ergonomics, human–AI collaboration, and Human Digital Twins (HDTs), this study proposes a multi-layered Socio-Technical Framework designed to harmonize human-centred design with AI-driven industrial systems. The framework emphasizes the active participation of the Operator 5.0, ensuring that humans remain central within complex intelligent production environments [3, 18]. By integrating technological, cognitive, and organisational dimensions, the framework aims to enhance operator performance, safety, well-being, and system resilience. The architecture recognizes that effective Industry 5.0 systems must balance technological efficiency with human capabilities, enabling adaptive interactions between operators and intelligent machines [5, 4].

1. Framework Architecture

The proposed framework is organized into two interconnected tiers, each addressing a distinct dimension of human–AI collaboration within industrial environments.

1.1 Human-Centric Tier

The Human-Centric Tier addresses both individual cognitive support and collaborative interactions between human operators as well as between operators and collaborative robots (cobots). AI systems continuously read operators' historical health records stored in enterprise databases, including prior physiological baselines, chronic condition indicators, and occupational health history, and compare these longitudinal profiles against real-time biometric data streamed from wearable devices such as smartwatches, biosensing patches, smart rings, and EEG-enabled headbands [19]. This comparison enables personalised, context-aware interventions: for instance, an operator whose live heart rate variability deviates from their historical norm under moderate workload may receive an automatic task redistribution prompt or a rest recommendation via their smart device. Human Digital Twins are continuously updated through this dual data stream, maintaining an evolving digital representation of each operator's cognitive and physiological state [17]. Within this tier, AI also supports human-cobot coordination, dynamically allocating physically demanding or repetitive tasks to cobots when sensor data indicates operator fatigue or declining situational awareness. Shared dashboards and XAI-enabled explanations ensure that operators retain understanding and control throughout [16].

1.2 Organisational-Management Tier

The Organisational-Management Tier integrates AI capabilities with organisational governance, ensuring that human-centred practices are embedded in broader production strategies and management processes. Management receives AI-generated insights through smart decision-support dashboards, enabling real-time monitoring of team performance, workload distribution, and safety compliance across the factory floor. Adaptive workflow management tools allow supervisors to rebalance task assignments and resource allocation in response to operator health flags or production disruptions. By aligning AI deployment with ethical standards, ergonomic protocols, and workforce well-being policies [6], this tier supports long-term organisational resilience and sustainable Industry 5.0 operations.

2. Design Principles

The proposed framework is guided by four key design principles that support effective human-AI collaboration:

2.1 Human-Centred Adaptivity

Industrial systems dynamically respond to operator cognitive states, preferences, and capabilities through adaptive automation and intelligent interfaces.

2.2 Explainability and Transparency

AI systems provide interpretable outputs and decision explanations, enabling operators to understand system behaviour and maintain trust in automated processes.

2.3 Integration Across Scales

The individual, team, and organizational layers operate as an integrated socio-technical ecosystem, ensuring seamless information flow and coordinated decision-making.

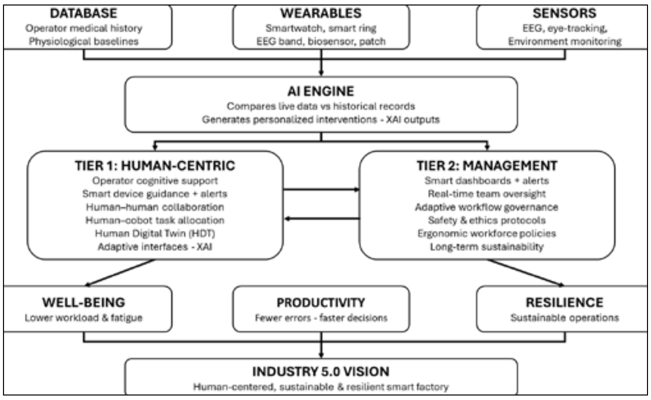
2.4 Sustainability and Resilience

Ergonomic support, workload balancing, and inclusive workforce strategies promote physical, cognitive, and social well-being while maintaining long-term system adaptability.

3. Operationalization

Implementation of the proposed framework involves embedding Human Digital Twins, neurophysiological monitoring systems, and adaptive AI interfaces into industrial workflows. In practical applications, operators interact with intelligent agents that regulate information flows, provide contextual guidance during critical events, and support decision-making processes. These systems continuously analyse operator workload and environmental conditions to dynamically adjust automation levels and task assignments.

Simulation studies within collaborative assembly environments indicate that integrating cognitive monitoring with adaptive AI technologies can significantly reduce cognitive overload, improve team coordination, and enhance operator autonomy [17]. By aligning technological innovation with human-centred design principles, the framework supports the development of resilient and socially sustainable manufacturing systems consistent with the goals of Industry 5.0.



Results and Discussion

The proposed multi-layered Socio-Technical Framework demonstrates significant potential to enhance human-AI collaboration, cognitive ergonomics, and overall system resilience in Industry 5.0 environments. Conceptual application and simulation studies in collaborative assembly scenarios indicate improvements across three major dimensions: individual performance, team coordination, and organizational outcomes.

1. Human-Centric Tier Outcomes

At the human-centric level, integration of wearable biometric devices, neurophysiological sensing, and Human Digital Twins (HDTs) enables real-time monitoring of cognitive workload, attention, and fatigue. By comparing live biometric data against each operator’s historical health records, the AI system distinguishes transient workload spikes from chronic fatigue patterns, allowing more precise and personalised interventions. Adaptive interfaces adjust information presentation, task pacing, and automation levels based on this dual data input, effectively mitigating cognitive overload and preserving situational awareness. Within the same tier, AI-assisted cobot coordination ensures that physically demanding or high-risk sub-tasks are dynamically reassigned when operator health flags are detected. Simulations reveal that operators supported by these interventions maintain higher situational awareness, faster decision-making, and lower error rates compared to conventional systems, while human-cobot teams demonstrate improved workflow fluency and reduced fatigue accumulation.

2. Organisational-Management Tier Outcomes

At the organisational level, management receives actionable, AI-synthesised alerts and performance summaries through smart devices and dashboards, supporting real-time decision-making without requiring constant manual monitoring. Adaptive workflow management tools enable supervisors to rebalance workload assignments in response to operator health data, production demands, or unexpected disruptions. Alignment of AI deployment with safety standards, ethical guidelines, and ergonomic protocols ensures that automation serves human needs rather than undermining them. Observed outcomes include improved resource allocation decisions, reduced managerial response time during disturbances, and stronger compliance with occupational health standards across diverse workforce demographics.

3. Implications for Industry 5.0

The results underscore that successful implementation of Industry 5.0 requires deliberate harmonisation of human and machine capabilities across both tiers. The two-tier architecture demonstrates that productivity, efficiency, and safety are not mutually exclusive: when AI interventions are designed with cognitive ergonomics and personalised health data in mind, operators remain empowered, engaged, and resilient. By integrating wearable health monitoring, historical data analytics, adaptive support, explainable decision-making, and management-level oversight, and industrial systems can achieve human-centred, sustainable, and adaptive production environments that fully realise the principles of Industry 5.0.

Conclusion

This study presents a multi-layered Socio-Technical Framework for AI-Driven Cognitive Ergonomics that integrates human-centred design principles with intelligent automation to address the evolving demands of Industry 5.0. By synthesizing insights from cognitive ergonomics, neurophysiological monitoring, collaborative robotics, and Human Digital Twins (HDTs), the framework emphasizes the active role of the Operator 5.0 within complex industrial environments.

The framework demonstrates that real-time cognitive and physiological support within the Human-Centric Tier — powered by wearable devices, historical health data, and AI-driven cobot coordination — coupled with AI-assisted management decision-support in the Organisational-Management Tier, can simultaneously enhance operator performance, situational awareness, trust, and overall system resilience. Simulation studies indicate that adaptive interfaces, personalised workload balancing, and transparent AI decision-making reduce cognitive overload, improve decision accuracy, and strengthen human-AI collaboration. At the organisational scale, the framework ensures that production processes remain sustainable, socially responsible, and resilient to variability or unexpected disruptions.

These findings underscore that the successful realization of Industry 5.0 requires more than automation efficiency; it demands a deliberate harmonization of human cognitive and ergonomic needs with machine intelligence. By maintaining human centrality while leveraging AI capabilities, the framework fosters workplaces that are adaptive, productive, and supportive of well-being, reflecting the core principles of human-centric industrial transformation.

Future research can extend this framework through empirical implementation in industrial environments, evaluating performance across diverse operational contexts and workforce demographics. Integration with emerging technologies such as augmented reality, predictive analytics, and advanced robotics may further enhance adaptive cognitive support and collaborative efficiency. Further investigation into privacy-preserving architectures for handling sensitive operator health records, and standardisation of wearable data protocols in industrial settings, will be important for translating the proposed framework into deployment-ready solutions. By bridging socio-technical principles with AI-driven ergonomics, this study contributes a foundational model for designing resilient, human-centred, and ethically aligned smart factories that exemplify the vision of Industry 5.0.

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