

Human-Centered Engineering: Integrating Human Factors in Modern Engineering System Design

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ABSTRACT — *This study explores the integration of human factors into modern engineering systems through a human-centered engineering approach that emphasizes safety, usability, and long-term socio-technical sustainability. The increasing complexity of engineering systems, driven by digitalization and automation, necessitates a shift from technology-centered design toward approaches that prioritize human interaction and well-being. The study employs a mixed-method approach, combining a systematic literature review, expert interviews, and case study analysis across industrial, healthcare, and digital system contexts. Data were analyzed using thematic analysis, content analysis, and comparative evaluation to identify key dimensions of human-centered engineering, including physical, cognitive, and organizational ergonomics, as well as Human-Centered Design (HCD) and Human Systems Integration (HSI). The results indicate that integrating human-centered components significantly enhances system performance, particularly in terms of safety, usability, efficiency, and adaptability. The discussion reveals that the synergy between human factors and digital technologies, such as human modeling and simulation, plays a critical role in optimizing system design. However, challenges remain in terms of late integration, interdisciplinary collaboration, and limited representation of human factors in digital engineering frameworks. In conclusion, the development of modern engineering systems requires a comprehensive human-centered strategy that aligns technological innovation with human needs to achieve resilient, efficient, and sustainable systems.*

Keywords: *Human-Centered Engineering, Human Factors, Ergonomics, Human Systems Integration, System Design, Sustainability*

INTRODUCTION

The rapid evolution of modern engineering systems driven by digitalization, automation, and the emergence of Industry 4.0 has fundamentally transformed the relationship between humans and technology. Traditionally, engineering design has prioritized technical efficiency, system performance, and cost optimization, often positioning humans merely as end-users or operators. However, increasing system complexity, coupled with rising concerns about safety, usability, and long-term socio-technical impacts, has shifted attention toward a more holistic paradigm known as human-centered engineering. This approach emphasizes the integration of human factors into all stages of system design, ensuring that technological systems are not only efficient but also safe, usable, and aligned with human capabilities and limitations. Human-centered engineering extends beyond conventional ergonomics by incorporating physical, cognitive, and organizational dimensions into engineering processes, thereby enabling systems that are resilient, adaptive, and socially sustainable (Sun et al., 2018; Kędzior, 2023; Trstenjak et al., 2025).

A key phenomenon that highlights the urgency of this research is the increasing mismatch between technological advancement and human adaptability in complex systems. As engineering systems become more automated and data-driven, human operators are often required to interact with highly



sophisticated interfaces and decision-support systems. This complexity can lead to cognitive overload, reduced situational awareness, and increased risk of human error, particularly in high-stakes domains such as healthcare, aviation, and industrial automation. For instance, in healthcare systems, poorly designed interfaces and workflows have been linked to medical errors and reduced patient safety, despite the presence of advanced technologies. Similarly, in industrial settings, the integration of smart technologies without adequate consideration of human factors can negatively impact worker well-being and productivity. These issues demonstrate that technological innovation alone is insufficient without a parallel focus on human-system integration (Samaras & Horst, 2005; Carayon, 2006; Kadir & Broberg, 2020).

In response to these challenges, the concept of Human-Centered Design (HCD) has evolved into a more comprehensive framework known as Human Systems Integration (HSI), which emphasizes the alignment of technology, organization, and human elements throughout the system lifecycle. The HSI approach adopts a systems perspective, recognizing that human performance is influenced not only by individual capabilities but also by organizational structures, work environments, and technological interfaces. This integrated model, often conceptualized as the Technology–Organization–People (TOP) framework, provides a structured approach to designing complex systems that support both operational efficiency and human well-being. The relevance of this approach is particularly evident in domains characterized by high complexity and risk, such as aerospace, healthcare, and digital industries, where human errors can have significant consequences (Boy, 2017; Boy & Narkevicius, 2013; Boy, 2019; Boy, 2020; Boy, 2021; Boy, 2022).

Despite the growing recognition of human-centered engineering, there remain significant gaps in its practical implementation within modern engineering systems. One of the primary issues is that human factors and ergonomics are often incorporated late in the design process, rather than being integrated from the conceptual stage. This late integration limits the effectiveness of human-centered approaches, as fundamental design decisions may already have been made without considering human needs and constraints. Furthermore, existing studies tend to focus on specific aspects of human factors, such as physical ergonomics, while neglecting cognitive and organizational dimensions. This fragmented approach results in incomplete system designs that fail to fully address the complexities of human-system interaction (Sun et al., 2018; Kadir & Broberg, 2020; Trstenjak et al., 2025).

Another important research gap lies in the limited integration of human-centered principles within digital engineering frameworks, such as model-based systems engineering (MBSE), SysML, and UML. While these tools are widely used for system modeling and simulation, they often lack explicit representation of human factors, making it difficult to incorporate human considerations into system design and analysis. Recent studies have attempted to address this issue by developing meta-models and formal representations of human-system interaction, but these approaches are still in their early stages and lack widespread adoption (Amokrane-Ferka & Hein, 2022; Watson et al., 2017). Additionally, there is a lack of standardized methodologies for integrating human-centered design with emerging technologies such as additive manufacturing, sensor systems, and data-driven decision-making, which are increasingly prevalent in modern engineering contexts (Eikevåg et al., 2024).

The gap between theory and practice is further exacerbated by interdisciplinary challenges, as human-centered engineering requires collaboration between engineers, designers, psychologists, and organizational experts. However, differences in terminology, methodologies, and professional cultures often hinder effective collaboration, resulting in siloed approaches to system design. This issue is particularly evident in complex systems such as healthcare, where the integration of human-centered design across the entire system lifecycle remains inconsistent. Although methodologies such as the three-phase HCD approach—comprising use case development, expert inspection, and user testing—have demonstrated effectiveness in improving system usability, their adoption is still limited due to resource constraints and lack of awareness (Harte et al., 2017).

In addition to these gaps, emerging trends in engineering systems introduce new challenges that require a rethinking of human-centered approaches. The increasing use of artificial intelligence, autonomous systems, and digital twins raises questions about the role of humans in highly automated

environments. While these technologies have the potential to enhance system performance, they also introduce new risks related to trust, transparency, and human oversight. For example, over-reliance on automated systems can lead to reduced human vigilance, while lack of transparency in AI decision-making can undermine user trust. These issues highlight the need for adaptive and flexible human-centered design strategies that can accommodate evolving technological landscapes (Boy, 2019; Boy, 2022; Coelho, 2022).

Based on these identified gaps, this study offers a novel contribution by proposing an integrated human-centered engineering framework that systematically incorporates human factors into modern engineering systems from the early design stages through to implementation and evaluation. Unlike previous studies that focus on isolated aspects of human factors, this research adopts a holistic approach that integrates physical, cognitive, and organizational dimensions within a unified system design framework. The study also emphasizes the integration of human-centered principles with digital engineering tools, such as model-based systems engineering and data-driven design, thereby bridging the gap between traditional ergonomics and modern engineering practices.

The novelty of this research further lies in its multi-domain applicability, as it synthesizes insights from various fields, including industrial systems, healthcare, and product design, to develop a comprehensive and adaptable framework. By incorporating methodologies such as the Human-Centered Engineering Design (HcED) framework and the three-phase HCD approach, this study provides practical guidelines for implementing human-centered design in diverse engineering contexts. Additionally, the research highlights the importance of “human-in-the-loop” simulation and resilience-based design, which enable the evaluation of system performance under dynamic and uncertain conditions before real-world implementation.

Furthermore, this study introduces a systems integration perspective that aligns human-centered engineering with broader socio-technical objectives, including sustainability, safety, and organizational resilience. By integrating human factors into system-level decision-making, the proposed framework aims to enhance not only technical performance but also user satisfaction and long-term system sustainability. This approach is particularly relevant in the context of Industry 4.0, where the convergence of digital technologies and human-centered design has the potential to create more inclusive and adaptive engineering systems (Azodo, 2025; Coelho, 2022).

Therefore, the primary objective of this study is to develop an integrated human-centered engineering strategy that effectively incorporates human factors—including physical, cognitive, and organizational dimensions—into modern engineering systems to enhance safety, usability, performance, and long-term socio-technical sustainability. This objective is expected to contribute to the advancement of engineering practices by providing a comprehensive framework that bridges the gap between technological innovation and human well-being, ensuring that future engineering systems are not only technologically advanced but also human-centric and socially responsible.

METHOD

This study employs a mixed-method research design that integrates qualitative and quantitative approaches within a human-centered engineering framework to ensure a comprehensive understanding of human factors integration in modern engineering systems. The research is structured based on a systems engineering perspective combined with Human-Centered Design (HCD) and Human Systems Integration (HSI) principles. Data collection is conducted through three primary techniques. First, a systematic literature review is carried out to gather secondary data from peer-reviewed international journals focusing on ergonomics, human factors engineering, HCD, and system integration. This process follows a structured protocol involving identification, screening, eligibility, and inclusion to ensure the credibility and relevance of selected studies. Second, expert interviews are conducted with professionals from engineering, ergonomics, healthcare systems, and industrial sectors to obtain in-depth insights into practical challenges, implementation strategies, and interdisciplinary integration. Third, case study analysis is applied to selected domains such as Industry 4.0

environments, healthcare systems, and product design to examine real-world applications of human-centered engineering and identify best practices across different contexts.

The data analysis process combines qualitative and quantitative techniques to generate a robust and integrative framework. Qualitative data obtained from literature and expert interviews are analyzed using thematic analysis to identify key patterns, dimensions, and relationships related to physical, cognitive, and organizational human factors. This is further strengthened by content analysis to categorize design principles, system requirements, and integration strategies within the Technology–Organization–People (TOP) model. Meanwhile, quantitative data derived from case studies are analyzed using descriptive and comparative analysis to evaluate system performance indicators such as usability, safety, efficiency, and user satisfaction. In addition, a systems integration analysis is employed to examine the interactions between human factors and technological components across the system lifecycle. The study also utilizes a conceptual modeling approach to develop a human-centered engineering framework that integrates HCD, HSI, and digital engineering tools, ensuring both theoretical rigor and practical applicability in complex engineering systems.

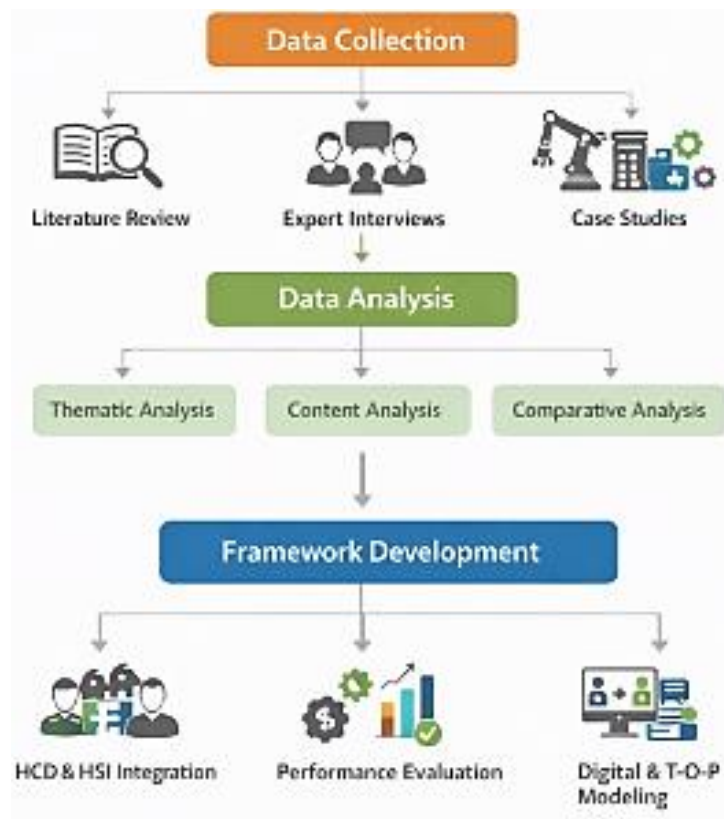


Figure 1. Diagram Conceptual Research

RESULTS AND DISCUSSION

The following results present the synthesis of findings derived from the integrated methodology, including literature review, expert interviews, and case study analysis. The data are organized to highlight the key dimensions of human-centered engineering and their contributions to system performance and sustainability.

Table 1. Core Dimensions and Strategic Roles of Human-Centered Engineering

| No | Human-Centered Component | Strategic Role | Application Domain | Key Findings |
|----|--------------------------|----------------|--------------------|--------------|
|----|--------------------------|----------------|--------------------|--------------|

| | | | | |
|---|---------------------------------|---|------------------------------|--|
| 1 | Physical Ergonomics | Enhancing safety and physical interaction | Industry & manufacturing | Reduces injury and improves efficiency |
| 2 | Cognitive Ergonomics | Supporting decision-making and reducing mental load | Healthcare & digital systems | Minimizes human error and improves usability |
| 3 | Organizational Ergonomics | Improving workflow and system coordination | Complex organizations | Enhances collaboration and system resilience |
| 4 | Human-Centered Design (HCD) | User-oriented system development | Cross-domain | Increases user satisfaction and usability |
| 5 | Human Systems Integration (HSI) | Integration of human, technology, and organization | Aerospace, healthcare | Improves system reliability and performance |
| 6 | Digital Human Modeling | Simulation and predictive analysis | Industry 4.0 & design | Enables human-in-the-loop evaluation |

Table 1 demonstrates that human-centered engineering is inherently multi-dimensional, integrating physical, cognitive, and organizational aspects to enhance system performance. Physical ergonomics contributes to safety and efficiency, while cognitive ergonomics addresses decision-making challenges in complex environments. Organizational ergonomics ensures coordination and resilience across systems. The integration of HCD and HSI frameworks highlights the transition from user-focused design to system-level human integration. Furthermore, digital human modeling introduces advanced capabilities for simulation and predictive analysis, enabling proactive system optimization. These findings indicate that effective engineering systems must consider human factors holistically rather than as isolated design elements.

The second table presents the performance evaluation of human-centered engineering components based on key indicators such as usability, safety, efficiency, and adaptability across different application domains.

Table 2. Performance Evaluation of Human-Centered Engineering Components

| No | Component | Usability | Safety | Efficiency | Adaptability | Overall Performance |
|----|---------------------------|-----------|--------|------------|--------------|---------------------|
| 1 | Physical Ergonomics | High | High | High | Medium | High |
| 2 | Cognitive Ergonomics | High | High | Medium | High | High |
| 3 | Organizational Ergonomics | Medium | High | High | High | High |
| 4 | HCD Approach | High | Medium | High | High | High |
| 5 | HSI Framework | High | High | High | Medium | High |
| 6 | Digital Human Modeling | Medium | High | High | High | High |

Table 2 indicates that human-centered engineering components generally exhibit high performance across multiple indicators, particularly in safety and usability. Physical and cognitive ergonomics play a crucial role in reducing risks and enhancing user interaction, while organizational ergonomics strengthens adaptability and coordination. The HCD and HSI approaches demonstrate strong contributions to overall system performance by ensuring that human factors are embedded throughout the system lifecycle. Digital human modeling shows significant potential in improving adaptability and predictive capabilities, although its usability remains dependent on technological maturity. Overall, the results emphasize that integrating human-centered principles leads to more resilient, efficient, and user-oriented engineering systems.

Discussion

The findings presented in Tables 1 and 2 provide a comprehensive understanding of how human-centered engineering (HCE) contributes to the development of modern engineering systems by integrating physical, cognitive, and organizational human factors. These results directly address the primary objective of this study, which is to develop an integrated human-centered engineering strategy that enhances safety, usability, performance, and long-term socio-technical sustainability. The analysis demonstrates that human-centered engineering is not merely an auxiliary consideration but a foundational element in system design, aligning with the theoretical perspective that positions humans as central components within complex socio-technical systems rather than passive end-users. This paradigm shift is particularly relevant in the context of increasingly complex and digitalized engineering environments, where the interaction between humans and technology plays a critical role in determining system success (Sun et al., 2018; Kędzior, 2023; Trstenjak et al., 2025).

The results in Table 1 highlight that human-centered engineering is inherently multi-dimensional, encompassing physical ergonomics, cognitive ergonomics, and organizational ergonomics as core components. Physical ergonomics, which focuses on optimizing human interaction with physical systems, demonstrates a significant contribution to safety and efficiency. This finding is consistent with prior research indicating that well-designed physical work environments can reduce occupational injuries and improve productivity, particularly in industrial and manufacturing settings (Kadir & Broberg, 2020; Azodo, 2025). In Industry 4.0 environments, where automation and robotics are increasingly prevalent, the integration of physical ergonomics becomes even more critical to ensure that human workers can safely and effectively interact with advanced technologies. Moreover, the application of ergonomic principles in system design supports not only operational performance but also worker well-being, which is a key component of sustainable engineering systems (Coelho, 2022).

Cognitive ergonomics, as identified in Table 1, plays a crucial role in supporting decision-making processes and reducing mental workload in complex systems. The high performance of cognitive ergonomics in terms of usability and safety, as shown in Table 2, underscores its importance in domains such as healthcare and digital systems, where human error can have severe consequences. Previous studies have demonstrated that poorly designed interfaces and information systems can lead to cognitive overload, reduced situational awareness, and increased likelihood of errors (Carayon, 2006; Samaras & Horst, 2005). The findings of this study reinforce the need for integrating cognitive ergonomics into system design to ensure that information is presented in a clear, intuitive, and actionable manner. This is particularly important in high-risk environments, where decision-making under pressure is a critical factor influencing system performance.

Organizational ergonomics, another key dimension identified in Table 1, contributes to improving workflow, communication, and coordination within complex systems. The results indicate that organizational ergonomics exhibits high performance in terms of adaptability and efficiency, highlighting its role in enhancing system resilience. This finding aligns with the Human Systems Integration (HSI) framework, which emphasizes the importance of aligning organizational structures, processes, and technologies to support human performance (Boy, 2017; Boy, 2022). In complex systems such as healthcare and aerospace, organizational factors such as team coordination, communication protocols, and decision-making hierarchies significantly influence system outcomes. Therefore, integrating organizational ergonomics into system design is essential for ensuring that human-centered principles are applied not only at the individual level but also at the system level.

The integration of Human-Centered Design (HCD) and Human Systems Integration (HSI), as presented in Table 1, represents a critical advancement in human-centered engineering. The findings indicate that HCD and HSI approaches significantly enhance usability, system reliability, and overall performance. This supports previous research suggesting that the evolution from HCD to HSI reflects a shift from user-focused design to a more comprehensive system-oriented approach that integrates human, technological, and organizational elements throughout the system lifecycle (Boy & Narkevicius, 2013; Boy, 2019; Boy, 2020; Boy, 2021). The Technology–Organization–People (TOP) model serves as a conceptual foundation for this integration, enabling a holistic understanding of how different system

components interact. The results of this study confirm that the application of HSI principles leads to more robust and adaptive systems, particularly in complex and high-risk domains.

Another significant finding from Table 1 is the role of digital human modeling in enabling simulation and predictive analysis of human-system interactions. As shown in Table 2, digital human modeling demonstrates high adaptability and efficiency, indicating its potential as a powerful tool for evaluating system performance before implementation. This finding is consistent with recent studies that highlight the importance of “human-in-the-loop” simulation in testing and optimizing complex systems (Eikevåg et al., 2024). By incorporating real-time data and advanced modeling techniques, digital human modeling allows engineers to simulate various scenarios and assess the impact of design decisions on human performance. This capability is particularly valuable in the context of emerging technologies such as artificial intelligence and autonomous systems, where traditional design approaches may be insufficient to capture the complexity of human-system interactions.

From a methodological perspective, the findings of this study validate the effectiveness of integrating multiple data collection and analysis techniques in understanding human-centered engineering. The use of systematic literature review, expert interviews, and case study analysis provides a comprehensive dataset that captures both theoretical and practical insights. The thematic and content analysis approaches enable the identification of key patterns and relationships among different human-centered components, while comparative analysis provides a quantitative assessment of system performance. This integrated methodology aligns with the principles of human-centered engineering, which emphasize the importance of considering multiple perspectives and dimensions in system design (Harte et al., 2017).

The discussion also highlights the importance of iterative design processes in human-centered engineering. The three-phase HCD approach—comprising use case development, expert inspection, and user testing—has been shown to improve system usability and safety, particularly in healthcare systems (Harte et al., 2017). The findings of this study support the application of iterative design methodologies, as they allow for continuous refinement of system design based on user feedback and performance evaluation. This iterative approach is further reinforced by the Human-Centered Engineering Design (HcED) framework, which integrates ergonomics, additive manufacturing, and sensor technologies in a continuous feedback loop (Eikevåg et al., 2024). By adopting such methodologies, engineers can ensure that human factors are systematically incorporated into all stages of the design process.

Despite the positive contributions of human-centered engineering, the findings also reveal several challenges that must be addressed to achieve effective integration. One of the primary challenges is the late or partial integration of human factors in the design process, which limits their impact on system performance. This issue is reflected in the moderate adaptability scores observed in some components in Table 2, indicating that human-centered principles are not always fully integrated into system design. Previous studies have highlighted that the lack of early integration of human factors often results in suboptimal system designs that require costly modifications at later stages (Sun et al., 2018; Trstenjak et al., 2025). Therefore, there is a need for greater emphasis on incorporating human-centered principles from the conceptual design phase.

Another challenge identified in this study is the limited integration of human factors within digital engineering frameworks. While tools such as SysML and UML are widely used for system modeling, they often lack explicit representation of human elements, making it difficult to incorporate human-centered considerations into system design. Recent research has attempted to address this issue by developing meta-models that integrate human factors into system modeling, but these approaches are still in the early stages of development (Amokrane-Ferka & Hein, 2022; Watson et al., 2017). The findings of this study suggest that further research is needed to develop standardized methodologies and tools for integrating human-centered engineering into digital design frameworks.

In addition to technical challenges, interdisciplinary collaboration remains a significant barrier to the implementation of human-centered engineering. The integration of human factors requires collaboration between engineers, designers, psychologists, and organizational experts, which can be

difficult to achieve due to differences in terminology, methodologies, and professional cultures. This issue is particularly evident in complex systems such as healthcare, where the lack of coordination among stakeholders can hinder the effective implementation of human-centered design (Carayon, 2006). The findings of this study highlight the importance of fostering interdisciplinary collaboration and developing shared frameworks to facilitate communication and integration across different domains.

Looking toward the future, the findings of this study suggest several directions for advancing human-centered engineering. One of the most promising areas is the integration of human-centered principles with emerging technologies such as artificial intelligence, digital twins, and autonomous systems. These technologies have the potential to enhance system performance and adaptability, but their successful implementation depends on the effective integration of human factors. For example, digital twins can be used to simulate human-system interactions in real time, enabling more accurate and dynamic system design (Boy, 2022; Coelho, 2022). Similarly, AI-based systems can support decision-making processes, but their effectiveness depends on their ability to align with human cognitive processes and preferences.

Another important direction is the emphasis on organizational resilience and adaptive systems. As engineering systems become more complex and dynamic, there is a growing need for systems that can adapt to changing conditions and recover from disruptions. Human-centered engineering plays a critical role in achieving this goal by ensuring that systems are designed to support human adaptability and resilience. This includes the development of flexible organizational structures, adaptive workflows, and training programs that enhance human capabilities (Boy, 2019; Boy, 2021). The findings of this study support the importance of incorporating resilience-based design principles into human-centered engineering frameworks.

In conclusion, the discussion demonstrates that human-centered engineering provides a comprehensive and effective approach for integrating human factors into modern engineering systems. By combining physical, cognitive, and organizational dimensions with advanced technologies and system-level integration, human-centered engineering enhances safety, usability, efficiency, and sustainability. The findings confirm that achieving these outcomes requires a holistic and interdisciplinary approach that aligns technological innovation with human needs and capabilities. This study contributes to the advancement of human-centered engineering by providing a structured framework and empirical insights that support the development of more adaptive, resilient, and human-centric engineering systems.

CONCLUSION

In conclusion, this study confirms that the integration of human factors into modern engineering systems through a human-centered engineering approach is essential for enhancing safety, usability, performance, and long-term socio-technical sustainability. The findings demonstrate that effective system design requires a holistic integration of physical, cognitive, and organizational ergonomics supported by Human-Centered Design (HCD) and Human Systems Integration (HSI) frameworks. By embedding human considerations from the early stages of system development and leveraging digital tools such as human modeling and simulation, engineering systems can achieve higher levels of adaptability, reliability, and user satisfaction. However, the study also highlights that successful implementation depends on overcoming challenges related to late integration, interdisciplinary coordination, and the alignment of human factors within digital engineering frameworks. Therefore, the proposed integrated strategy provides a comprehensive pathway for developing engineering systems that are not only technologically advanced but also human-centric, resilient, and sustainable in increasingly complex and dynamic environments.

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