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Human-Centered Design in Industrial Engineering: Integrating User Needs, Design Decisions, and Social Impact Assessment

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Highlights

- The paper advocates integrating Human-Centered Design (HCD) principles in industrial engineering.
- HCD helps understand user needs, leading to usable, effective, and sustainable systems.
- User research methods like ethnographic studies and usability testing inform better design decisions.
- These decisions improve safety, operator well-being, and system effectiveness.
- The paper integrates HCD and SIA for holistic, socially conscious designs.

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Abstract

Industrial engineering, with its emphasis on optimizing processes, is theoretically centered on human factors, but in practice, this focus is often underrepresented within complex systems. This paper proposes a paradigm shift by advocating for the integration of Human-centered design principles. HCD offers a robust framework for understanding user needs throughout the design process, leading to the creation of not just efficient, but also usable, effective, and ultimately, sustainable industrial systems. We argue that human-centered design transcends traditional efficiency measures. By incorporating user research methods like ethnographic studies and usability testing, industrial engineers gain deeper insights into user capabilities, limitations, and motivations. This knowledge informs design decisions that optimize not just output, but also human-system interaction, leading to improved safety, operator well-being, and ultimately, increased system effectiveness. Furthermore, the paper emphasizes the crucial role of Social Impact Assessment (SIA) within the human-centered design framework for industrial engineering. SIA encourages engineers to move beyond user-centric design and consider the broader societal implications of their creations. This ensures that industrial systems not only function flawlessly for users, but also contribute positively to the surrounding environment and communities. By outlining a potential workflow that integrates HCD and SIA, this paper proposes a holistic approach to industrial engineering project development. This approach prioritizes user research, iterative design based on user feedback, and a comprehensive evaluation of potential social impacts. By adopting this methodology, industrial engineers can redefine efficiency, creating not just productive but also user-centric, sustainable, and socially responsible systems that contribute to a more equitable future.

1. INTRODUCTION

Industrial engineering traditionally focuses on optimizing systems and processes to enhance efficiency, productivity, and cost-effectiveness [1]. This discipline integrates various resources like people, materials, and equipment, drawing from diverse engineering and scientific principles to achieve optimal outcomes [2]. Techniques like capacity studies and work studies have driven significant improvements in industries like manufacturing and healthcare [3]. However, technological advancements highlight the growing importance of user needs and social impact. Research emphasizes that understanding user perspectives is essential for developing effective digital health tools, enhancing long-term engagement and user well-being [4]. For instance, incorporating user considerations into sleep disorder apps can significantly improve their effectiveness as therapy tools [5]. Addressing complex social issues like climate change or pandemics requires a holistic and empathetic design approach [6]. This necessitates integrating societal impact considerations into the design of engineered products. For example, analyzing the social and environmental

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impact alongside economic factors when designing airships underscores the need for a comprehensive social impact metric analysis in socio-technical systems [7]. Human-centered design provides a structured framework that prioritizes user needs and experiences throughout the design process [8]. This approach fosters creativity and problem-solving through active participation, as seen in its application to create educational resources for children with learning difficulties. HCD has also proven effective in healthcare worker training [9] and in aligning bioethical considerations with the needs of disabled individuals [10].

The study provides insights into incorporating human-centered design into industrial engineering processes. By integrating user needs, design decisions, and social impact assessments, this review offers a framework for practitioners to balance operational efficiency with human well-being. It outlines methodologies that can be adopted to create more ergonomic, sustainable, and socially responsible industrial systems. Furthermore, the study highlights the role of human-centered design in mitigating the risks of technological interventions that overlook human factors, especially in the context of automation and digitalization. This review equips engineers, designers, and decision-makers with practical guidelines for embedding user-focused principles into product and system development processes, enhancing usability, safety, and overall performance. The outcomes of this research can be directly applied in industries aiming to improve worker productivity, reduce error rates, and ensure compliance with safety standards while aligning with broader sustainability goals.

The study is motivated by the need to optimize industrial systems by considering human well-being and operational efficiency. Industrial engineering has been increasingly incorporating approaches that consider the interaction between technological innovation and user-centered methodologies. Human-centered design integrates user needs into the design process to ensure socially responsible decisions. The adoption of automation and digital tools in Industry 4.0 has led to a marginalization of the human factor in industrial systems. This review aims to address this gap by examining how user needs and social impact assessments can be systematically integrated into design decisions. The objective is to highlight strategies for harmonizing ergonomic principles, usability, and broader societal impacts, thus promoting sustainable industrial practices. The review aims to provide a comprehensive overview to inform future design processes in industrial engineering with a strong human-centered ethos by synthesizing existing studies.

2. USER RESEARCH METHODS IN HCD FOR INDUSTRIAL ENGINEERING

In the field of industrial engineering, there is a clear trend towards human-centered design, which prioritizes understanding user needs to develop systems that are not only efficient but also user-friendly and effective [11-13]. Various HCD methodologies, such as personas and user studies, have been employed in industrial contexts to identify user requirements, particularly in the context of digitalization and human-machine collaboration [14-15] (Table 1). Experts have stressed the importance of integrating human aspects into engineering design processes to enhance human performance and operational efficiency in manufacturing environments. By applying HCD concepts and methods, industrial engineering projects can develop systems that are not only efficient but also tailored to end users' needs and preferences, leading to improved overall performance and user satisfaction. Understanding user interactions with existing systems is a crucial first step in human-centered design, and this is achieved through various user observation techniques. Ethnographic studies, as described in Adam et al. [16], involve researchers immersing themselves in the user's work environment to study daily routines, challenges, and interactions with existing systems, providing valuable contextual data on user needs and pain points, which enhances the design process (Table 1). Additionally, first-person research methods, as outlined in Ellen & Perlman [17], can help improve understanding of user experiences and preferences. Combining these approaches with human-centered design principles enables designers to create more effective and user-friendly solutions that genuinely address end-user needs. Contextual inquiries, as described in Chafi and Cordero [18], are a valuable strategy in which researchers observe users performing specific tasks in their workplace, offering insights into user thought processes and issues with the current system. Furthermore, first-person research approaches, such as autoethnography and autobiographical design, as discussed in Lucero et al. [19], provide a unique perspective by involving the researcher in data collection. Observational tests, as detailed in Walter et al. [20], emphasize the quantification of human observations using advanced technical means, enabling the development of software for observational testing and analysis (Table 1).

Observation methods provide industrial engineers with valuable insights into user interactions with systems in their natural environments. This is evident in numerous research articles [21-25] (Table 1). By studying user behaviors and actions, engineers gain a comprehensive understanding of user workflows, allowing them to identify bottlenecks, inefficiencies, and areas for system modifications to better support user tasks and processes. Analyzing user interactions with technology and systems enables engineers to enhance designs that align with user needs and preferences. Observation approaches offer insights that surpass what users can articulate. By observing users interacting with technologies in their natural environment, industrial engineers gain a deeper understanding of user preferences and pain points. These techniques allow engineers to observe user frustration or challenges with specific actions, indicating unmet needs and highlighting opportunities to enhance system usability. Engineering tools like heuristic evaluation, surveys, user interviews, gesture log analysis, and video analysis can help identify crucial flaws. These flaws can be in error messages, system responses, feedback mechanisms, and user interactions with the interface [26-31] (Table 1). This leads to improved user-centered system designs. Observation approaches provide industrial engineers with valuable information that users may not be able to communicate themselves. By observing individuals in their natural environments, engineers can gain a deeper understanding of unexpected user interactions, identifying potential design flaws or areas for improvement. This approach facilitates the identification of unexpected user interactions during the design process, emphasizing critical areas that could enhance the user experience and system performance. Systematically studying user interactions with technologies enables engineers to obtain a more comprehensive understanding than traditional user input. This leads to better design decisions and improvements [21,32-34] (Table 1).

The initial phase of human-centered design involves understanding user interactions with existing systems. Various user observation methods exist to achieve this. Ethnographic investigations, as proposed by van Velsen et al. [35], offer valuable contextual data. Researchers can study user interactions within the broader work environment and social dynamics using this method. However, Wang and Babaian [29] highlight the time-consuming nature of such studies and the need for advanced researcher skills to interpret findings accurately. Mandolfo et al. [36] suggested that in-depth exploration of user interactions through screen capture recordings can support ethnographic research. These recordings can illustrate the ease of learning new interfaces and how users overcome challenges, potentially leading to improved interface design. Integrating these diverse approaches enhances the overall understanding of user interactions and effectively informs the design of usable systems (Table 1). Furthermore, combining various observation technologies can lead to comprehensive data collection, guiding the development of user-centered eHealth innovations and improving the entire design process. Contextual inquiries offer advantages like targeted data collection for specific tasks and real-time questioning [25]. However, they may miss capturing the broader context of user work, potentially overlooking unexpected interactions [37] (Table 1). To address these limitations, incorporating additional approaches such as questionnaires can provide valuable insights into user needs and satisfaction levels, aiding in usability evaluation and design decision-making [38]. By strategically combining these observation technologies, design teams can enhance the development of user-centered eHealth innovations while improving the overall design process.

The concept of Human-centered design extends beyond simple observation and encompasses various user research methods like interviews, questionnaires, and usability testing. Tosi et al. [37] highlight interviews as a valuable tool for users to express their needs and challenges in detail. Surveys, as conducted by Kanev et al. [39], are beneficial for gathering feedback from a larger user pool but may offer less specific insights. Chomiak-Orsa et al. [40] emphasize the importance of usability testing, where users interact with prototypes to identify errors and provide feedback for design improvements. These methods complement user observation by diving deeper into user needs, collecting broader user feedback, and refining designs through direct user engagement, making them crucial components of a comprehensive HCD approach. By integrating human-centered design principles, industrial engineers can develop user-centered systems that meet various criteria. HCD, incorporating human factors/ergonomics (HF/E) knowledge, focuses on understanding user needs and improving usability, safety, and sustainability [41-45] (Table 1). This allows for the design of straightforward systems that minimize errors and enhance user satisfaction while ensuring both ease of use and effectiveness. Safety remains a priority by addressing user needs to minimize hazards and create a safe work environment. Additionally, aligning user preferences with broader social and environmental concerns leads to more sustainable systems, resulting in positive long-term impacts through accountability and efficiency. This comprehensive approach directly benefits users while aligning with ethical and environmental considerations, making industrial systems more holistic and impactful [41-45] (Table 1)

Table 1. *Categorization of Studies on Human-centered design Methodologies and Observation Techniques in Industrial Engineering*

Study Focus	Key Concepts/Findings	Authors
Human-centered design Trends	Focuses on the trend towards HCD in industrial engineering to develop efficient, user-friendly systems.	[11-13]
HCD Methodologies	HCD methodologies like personas and user studies are used to identify user requirements, particularly in digitalization and human-machine collaboration.	[14,15]
Ethnographic Studies	Ethnographic studies involve researchers immersing themselves in user environments to understand routines, challenges, and interactions, providing contextual data for better designs.	[16]
First-Person Research	First-person research methods, such as autoethnography and autobiographical design, help in understanding user experiences and preferences.	[17,19]
Contextual Inquiries	Contextual inquiries involve observing users performing tasks in their workplaces to gain insights into user thought processes and system issues. Provides targeted data but may miss broader work context.	[18,35,37]
Observation Methods	Observation methods provide valuable insights into user interactions with systems in their natural environments, identifying inefficiencies, bottlenecks, and areas for improvement to align with user needs and preferences.	[20-25,27,30]
User Interaction Analysis	Engineering tools like heuristic evaluation, gesture log analysis, and video analysis help identify system flaws, such as error messages, feedback mechanisms, and user interactions, which can be improved for better user-centered system designs.	[26,28-31]
Usability Testing	Usability testing, where users interact with prototypes, identifies design errors and allows for feedback, improving designs through direct user engagement.	[39,40]
Screen Capture and Ethnography	Screen capture recordings support ethnographic research, revealing how users learn and adapt to new interfaces, leading to improved design.	[30,36]
Interviews & Surveys	Interviews allow users to express detailed needs and challenges, while surveys gather broader feedback. These methods complement observation and usability testing, adding depth to user-centered design.	[37-39]
Safety & Usability	HCD methods integrate human factors/ergonomics knowledge to enhance usability and safety while addressing user preferences, social, and environmental concerns, leading to more sustainable and holistic industrial systems.	[41-45]
Usability Testing Limitations	Highlight the challenges, such as time-consuming nature of in-depth observation and advanced skills required for interpretation, emphasizing the need for supplementary methods like questionnaires.	[30]
Combining HCD Methods	Combining various user observation and usability testing approaches enables comprehensive data collection, guiding the development of user-centered innovations, particularly in sectors like eHealth.	[41-45]

Usability testing is an essential element in industrial engineering, significantly enhancing user experience and system efficiency. By employing various methodologies, such as eye tracking and the System Usability Scale (SUS), usability testing allows engineers to evaluate and optimize interfaces effectively. Recent studies emphasize its critical role in both web and industrial environments, demonstrating how it identifies usability issues and informs design improvements. As industries increasingly adopt digital transformations, integrating human-centered design principles becomes vital to ensure that systems meet user needs while promoting productivity and safety. This introduction sets the stage for a detailed exploration of usability testing methods, their applications in industrial settings, and the importance of incorporating social impact assessments into the design process (Table 2).

Table 2. *Overview of Usability Testing and Human-Centered Design Studies in Industrial Engineering*

Focus Area(s)	Relevance to Industrial Engineering	Author(s)
Eye Tracking: Analyzing user interactions and identifying areas of confusion on interfaces.	Eye tracking applied in usability testing for industrial HMI and web interfaces, helping improve design efficiency and user satisfaction.	[46,47]
System Usability Scale (SUS): Quick usability assessments showing significant score improvements after iterative testing.	SUS employed to assess user satisfaction and usability, providing a measure of design improvement in industrial settings.	[46,48]
Human-Machine Interfaces (HMI): Iterative prototyping and optimization techniques (e.g., Fitts's Law).	Usability testing for HMIs is crucial for designing systems that operators can interact with efficiently and safely, enhancing ergonomics.	[49]
Digital Transformation: Balancing automation and human roles, ensuring intuitive interfaces.	Highlights the role of usability testing in the integration of AI and IoT, improving productivity and user experience in industrial contexts.	[50]
Human-centered design: User involvement, iterative prototyping, virtual reality (VR), cognitive assistance systems.	HCD enhances design effectiveness and worker satisfaction, focusing on continuous prototyping and user feedback in industrial environments.	[51-53]
Usability Testing: Enhancing product effectiveness by identifying barriers and improving user experience	Usability testing improves system efficiency by identifying flaws, with visualizations clarifying results for industrial stakeholders.	[54]
Social Life Cycle Assessment (SLCA): Structured methodology for evaluating socioeconomic impacts.	SLCA assesses the social impacts of industrial products, guiding decision-making with precise indicators.	[55,56]
Social Impact Assessment (SIA): From regulation to management, emphasizing stakeholder engagement.	SIA's evolving role in industrial settings ensures social acceptance and community engagement are key factors in project success.	[56]
Social Impacts in Design: Incorporating social measures during design, using prompt questions for evaluation.	Social factors influence design parameters, with prompt questions aiding in identifying and evaluating social impacts in industrial products.	[57,58]

3. UNCOVERING USER NEEDS FOR HUMAN-CENTERED INDUSTRIAL ENGINEERING

In the field of industrial engineering, Human-centered design prioritizes understanding user needs to create effective and efficient systems. The concept of Human-centered design surpasses mere observation and encompasses a variety of user research methodologies including interviews, questionnaires, and usability testing. Tosi et al. [37] emphasize interviews as a means for users to articulate their requirements and challenges in detail. Surveys, as noted by Kanev et al. [39], effectively gather feedback from a larger user sample but may offer fewer specific insights. Chomiak-Orsa et al. [40] underscore the significance of usability testing, which involves users interacting with prototypes to identify faults and provide feedback for iterative design enhancements. These approaches complement user observation by delving deeper into user needs, gathering feedback from a broader audience, and refining design through direct user engagement, making them crucial elements of a comprehensive HCD approach. By integrating Human-centered design principles, industrial engineers can develop user-centered systems that meet multiple criteria. HCD, incorporating Human Factors/Ergonomics (HF/E) knowledge, focuses on understanding user demands and enhancing usability, safety, and sustainability [41-45]. We engineer straightforward systems to eliminate errors and enhance user satisfaction, ensuring usability and effectiveness. Safety is prioritized by addressing user needs to minimize hazards and establish a secure working environment. Furthermore, by aligning user preferences with broader social and environmental concerns, these systems become more sustainable, resulting in a positive long-term impact through responsibility and efficiency. This comprehensive approach directly benefits users while also aligning with ethical and environmental considerations, making industrial systems more holistic and impactful [42-45,59].

Human-centered design plays a crucial role in influencing design decisions throughout the entire Information Engineering (IE) process, including the aspect of design for inclusion by considering the accessibility needs of diverse users during the design phase. Research emphasizes the importance of involving users in all phases of the design process to create educational resources that address lifelong learners' needs [60]. Additionally, the exploration of design decision competence in Participatory Design projects highlights the significance of users developing competence to actively participate in design decisions, particularly through experiences with materials and prototypes that showcase technical possibilities [61]. Furthermore, in the context of AI-assisted decision-making, the potential biases that can arise from design decisions, such as problem formulation and data selection, underscore the necessity of a critical examination of AI technologies in decision-making contexts to ensure fairness and equity, especially in disability-related settings [62].

4. HUMAN-CENTERED DESIGN: SHAPING USER-CENTERED DECISIONS IN INDUSTRIAL ENGINEERING

The Human-centered design approach significantly influences design decisions in Industrial Engineering (IE), particularly in task analysis to enhance user tasks [63,64]. Understanding users' decision-making habits and experiences is crucial for customizing designs efficiently, especially at the intersection of user experience (UX) design and behavioral intervention technologies. In the context of machine learning and Industry 4.0, architectural design decisions underscore the importance of modeling current practices and integrating knowledge to support decision-making processes [60,65]. Applying HCD principles to task analysis enables designers to enhance overall user experience and system efficiency. The creation of low-fidelity and high-fidelity prototypes facilitates user feedback and iterative idea development [60,66,67]. Prototypes serve as tangible representations of designers' mental models, facilitating effective communication with stakeholders and end users [68]. Additionally, exploratory prototyping techniques are essential for developing new interactive features and eliciting human responses early in the design process, emphasizing flexibility, design insights, and subjective incubation over controlled experiments [69]. Through HCD methodologies, designers can ensure that their solutions are reliable, user-centered, and tailored to individual user demands and preferences. By integrating HCD principles into their approaches, industrial engineers can develop solutions that are not only efficient but also user-friendly and customized to the specific demands of the target population. The combination of HCD and Human-in-the-Loop Simulation (HITLS) capabilities allows for the early creation of virtual prototypes, facilitating activity analysis, agile development, and certification [43]. The integration of HCD and Systems Engineering (SE) throughout a system's lifecycle yields Human Systems Integration (HSI), a multidisciplinary approach that fuses hard sciences with human and social sciences to enhance engineering problem-solving and solution delivery [70]. Furthermore, the amalgamation of TRIZ and HCD techniques offers a customer-focused approach to product development, prioritizing usability and innovation based on a deep understanding of customer demands [71]. Ultimately, by incorporating HCD concepts, industrial engineers can ensure that their solutions prioritize both efficiency and user-friendliness [72,73].

The frameworks for evaluating the social impact of technologies developed through industrial engineering projects involve various methodologies, including Social Life Cycle Assessment (SLCA) to analyze the social and environmental impacts of a product or system throughout its lifecycle. Evaluations of social impacts in projects like smart cities emphasize human-centered design, stakeholder inclusion, and citizen engagement, highlighting the need for coherent and analytical approaches to comprehend impacts before, during, and after projects [74]. In Argentina, the Social Technological Development Project (PDTS) incorporates an evaluation system based on Quality and Relevance to recognize technological activities with social impact, considering ethical aspects, environmental respect, and political guidelines like the Sustainable Development Goals [75]. The broader evaluation framework for generative AI systems defines categories such as bias, privacy, and labor costs, aiming to assess societal impacts like trustworthiness, inequality, and environmental concerns [76]. These diverse approaches underscore the importance of comprehensive evaluations to understand and mitigate the social implications of industrial engineering projects. Evaluating the social impact of technologies developed through industrial engineering projects involves assessing various aspects. The frameworks for evaluation encompass considerations such as social return on investment (SROI), which quantifies the social benefits and value generated by a technology in relation to its economic costs. This evaluation process extends beyond economic factors to include social implications, ethical considerations, and environmental impacts. Studies emphasize the importance of evaluating social impacts in smart city projects, incorporating human-centered design, stakeholder engagement, and sustainability principles [74]. Additionally, in Argentina, the Social Technological Development Project (PDTS) serves as an instrument for recognizing technological activities with social impact, emphasizing ethical aspects, environmental respect, and adherence to national and international guidelines [75]. Engineering internships also highlight the need for intentional development of connections between engineering work and social impact considerations to equip students with the necessary tools for evaluating social impacts [77].

Industrial engineers play a crucial role in ensuring that their designs have positive impacts on society while minimizing negative consequences by incorporating social impact assessments [78,79]. The lack of standard methods for considering social impacts in engineering highlights the importance of integrating social impact evaluations into the design process [80,81]. By utilizing tools and methodologies to assess social impacts, engineers can enhance sustainability benefits and address urgent societal issues effectively. The consideration of social impacts alongside economic and environmental factors in the design phase is essential for creating products that not only meet technical requirements but also contribute positively to society as a whole, emphasizing the need for a holistic and empathetic approach to design.

5. OPTIMIZING INDUSTRIAL HCD: CHALLENGES AND OPPORTUNITIES FOR EFFECTIVE INTEGRATION

The integration of Human-centered design into existing Information Engineering (IE) workflows poses challenges related to time constraints, financial considerations, and the necessity for cultural change within engineering teams [82]. Additionally, barriers to the adoption of new technologies like Electronic Health Records (EHRs) in healthcare settings include high initial setup costs, a lack of computer skills among healthcare personnel, and inadequate maintenance culture [83]. Furthermore, difficulties in workflow integration during EHR adoption lead physicians to devise workarounds, highlighting the importance of enhancing functionality to improve workflow efficiency and reduce alert fatigue [84]. Moreover, challenges in implementing Computerized Clinical Decision Support (CDS) emphasize the need for interoperability standards to facilitate sharing across healthcare systems while minimizing resource-intensive modifications at specific sites [85]. Effectively addressing these issues requires a comprehensive strategy that considers resource management, long-term planning, and organizational readiness to implement HCD principles successfully. Adapting existing approaches to meet industrial project constraints represents an opportunity to advance Human-centered design methods tailored for industrial engineering applications. By adopting a use-centered approach to method development, the industrial viability of HCD techniques can be enhanced, leading to a more significant impact in industrial contexts [86]. Furthermore, integrating human-centered design techniques into industrial machine design can yield products with enhanced usability and a more positive user experience, addressing the current focus on functional requirements over usability in industrial design [87]. Feedback from industrial practitioners underscores the need for future HCD methods to be adjustable, explicit, systematic, inspiring, and adaptable for multidisciplinary teams, with an emphasis on transparency, measurable outcomes, and integration into the development process [88]. By addressing these issues, HCD methods can be refined to better align with the distinctive objectives and challenges of industrial engineering applications, thereby improving product development processes and outcomes [89].

6. CHALLENGES AND LIMITATIONS OF HCD IN INDUSTRIAL ENGINEERING

Industrial projects often have tight deadlines due to contracts, production schedules and market requirements. However, implementing human-centered design, which includes prototyping, iterative testing, and in-depth user research, can be time-consuming. Balancing detailed design processes with the urgency of product release can limit the effectiveness of HCD methods. Additionally, the need for skilled labor and the costs associated with redesign, prototyping, and user testing can add up. Due to budget constraints, it is often difficult to allocate enough money for these ventures [90]. Access to prototyping tools, usability testing software, and end users may not always be easy in industrial environments. A strong commitment to traditional practices and distrust of novel approaches such as HCD are common in industrial settings, perhaps due to a misconception about the benefits of HCD or the belief that it is unnecessarily complex and expensive [91]. Designing and understanding industrial products often requires specialized knowledge due to their complex and technological nature. In addition, strict regulatory requirements can limit the flexibility of the design process. Incorporating user feedback is difficult in the legal framework due to regulatory constraints [92]. HCD techniques are easier to apply in smaller initiatives, and scaling these techniques to large industrial projects with numerous stakeholders and complex supplier lines can be challenging. Coordinating iterative design and user research across departments and geographic regions adds another layer of complexity [93].

When developing technical solutions to improve productivity and minimize resource consumption, the focus is often on efficiency. However, with this focus on efficiency, ease of use is not always at the forefront. For example, highly automated devices can be effective but difficult for operators to understand and use [94]. Sometimes simplifying complex processes for the purpose of user understanding can hinder operational efficiency. Limited budgets can lead to compromises in user-centered design, as extensive user testing, high-quality materials, and iterative design processes can significantly increase costs. To reduce costs, companies may opt for cheaper solutions with fewer features, which may impact the overall user experience [95]. In industrial environments, safety is paramount and is often subject to strict regulations. However, some security features, such as protective devices or emergency stop buttons, which inadvertently make usability more difficult. Placing controls in a location convenient to the user can result in unintentional compromise of those controls [92]. When considering design, it is crucial to find the balance between efficiency, ease of use, cost and security.

In highly specialized industries, it can be challenging to involve end users in the device design process. User research can be ineffective if users lack technical knowledge and cannot provide useful input. For example, complex medical devices and aircraft parts require expertise that end users may not have [95]. Strict regulations can also limit the incorporation of user feedback into product development, particularly in highly regulated sectors such as aviation and medicine [92]. Managing user research in large industrial projects can be expensive and complex [93], especially when involving numerous stakeholders, teams in different locations, and complex supply chains. In fast-moving industries like technology, there may not be enough time for extensive user research and design revisions. Companies may prioritize rapid time-to-market over extensive user testing, potentially leading to usability issues [90].

One significant challenge in human-centered design is user diversity. HCD must cater to a wide range of users with unique needs and preferences, making it difficult to design solutions that are universally effective. For example, HCD methodologies designed for workers in developed economies may fail to account for the specific needs of workers in low-resource environments, potentially leading to the exclusion of key segments of the population [35]. Considerations for users with special needs further complicate HCD application, especially when designing for users with disabilities. For instance, designing tools for factory workers with dyslexia or other cognitive challenges requires significant adaptations, which can elongate the design process and create additional layers of complexity [96]. In industrial sectors with dynamic work environments, such as mining and transportation, the need for constant redesign presents another challenge. Safety considerations, evolving user tasks, and changes in the physical environment require HCD processes that are adaptive. For example, underground mining operations demand tools and interfaces that can quickly adapt to new safety regulations and operational contexts, adding pressure to the HCD process [97]. A pressing limitation is the technological integration challenge. As industries adopt more automated systems, there is a growing tension between automation and human-centric design. While automation improves efficiency, it can inadvertently marginalize the human element, leading to designs that are less intuitive or even hazardous to workers [98]. Contextual and temporal constraints also play a critical role in limiting the scope of HCD. Designs often fail to account for long-term environmental changes or broader contextual shifts. For example, a user-centered design for ergonomic workstations may overlook how seasonal changes in lighting or temperature within a factory affect workers' performance and comfort, limiting the practical application of such designs over time [35].

7. ALTERNATIVE PERSPECTIVES ON INDUSTRIAL ENGINEERING METHODOLOGIES

Traditional industrial engineering (IE) methods focus on optimizing systems, processes and products to improve efficiency, productivity and cost effectiveness. IE techniques prioritize streamlining workflows, reducing waste, and continuous improvement through methods such as just-in-time production (JIT) and value stream mapping [99]. Data-driven strategies are used to reduce variation and improve quality, while DMAIC ((Define, Measure, Analyze, Improve, Control)) technique is used to resolve errors. The aim of these methods is to standardize work processes and increase work productivity. They are particularly effective in high volume manufacturing and standardized processes as they help reduce waste and maximize productivity. In industries such as aerospace and automotive, accuracy and reliability are critical, and methodologies such as Six Sigma play an important role in improving quality and reducing errors. Traditional IE methods are also valuable in industries such as automotive, where cost control and manufacturing efficiency are paramount. By optimizing processes, industries can ensure consistent compliance with quality and safety standards, resulting in significant cost and performance reductions. Integrating Human-centered design principles with classic IE techniques can provide a holistic solution. Lean approaches take user feedback into account to ensure that efficiency gains and waste reduction do not compromise the user experience [100]. Combining traditional IE continuous improvement cycles with HCD iterative design cycles can improve both efficiency and user experience in each iteration.

8. STRENGTHENING THE THEORETICAL FRAMEWORK

8.1. Theoretical Foundations in Human-centered design

Human-centered design is a methodology that prioritizes the creation of user-friendly systems while deeply considering the needs and capabilities of end users. Don Norman's model highlights the importance of understanding user goals, actions, and feedback when interacting with a system. This includes setting goals, taking actions, and interpreting results [94]. Norman and Draper advocate creating systems that are easy to use and effectively meet users' needs. To ensure user satisfaction, this approach recommends involving users at every stage of the design process [101]. Vygotsky first developed this model and later extended it with the help of Engeström to examine how people's behavior is influenced by their social and cultural environment. This highlights the importance of understanding the broader context of user interactions with technologies [102]. Participatory design (PD) involves the active participation of the user in the design process and has its origins in Scandinavia. This approach ensures that the design meets the needs and perspectives of users [103].

8.2. Theoretical Foundations in Industrial Engineering (IE)

The main goal of Industrial Engineering (IE) is the optimization of complex processes and systems. This field is based on various established theories and frameworks. Scientific management, introduced by Frederick Taylor, emphasizes the use of scientific methods to evaluate and improve work processes. To achieve the most effective methods of performing tasks, time and motion studies must be conducted [104]. Developed at Toyota by Taiichi Ohno and Eiji Toyoda, lean manufacturing focuses on reducing waste and improving productivity. It includes concepts such as value stream mapping, kaizen (continuous improvement), and just-in-time (JIT) (Womack & Jones, 1997). Originating at Motorola, Six Sigma is a data-driven method for improving quality by identifying and eliminating defects. The core of this approach is the DMAIC framework, which stands for Define, Measure, Analyze, Improve, Control [105]. The Theory of Constraints (TOC), introduced by Eliyahu Goldratt, focuses on identifying and resolving bottlenecks that limit system performance. The emphasis is on systematic problem solving and continuous improvement [106].

8.3. Integrating HCD and IE: Theoretical Synergies

Integrating Industrial Engineering (IE) and Human-centered design can lead to a more comprehensive approach to design and optimization. By combining these two disciplines, we emphasize the cooperative optimization of both the technological and social aspects of work systems. This approach is consistent with industrial engineering's focus on productivity and efficiency as well as the emphasis on user needs in human-centered design [107]. An integrated approach that prioritizes both overall system performance and human well-being combines the principles of Human-centered design and Industrial Engineering (IE). Consistent with the principles of human-centered design, ergonomics includes user research, usability testing, and iterative design [108]. When user-centered design is combined with lean manufacturing principles, it can result in higher productivity and higher user satisfaction. Integrating user-centered design and lean manufacturing ensures that user feedback is incorporated into ongoing development efforts and that process improvements do not impact usability [100].

9. CONCLUSION

This review emphasizes the need for a fundamental change in industrial engineering (IE) by promoting the combined use of Human-centered design principles with traditional optimization methods. HCD provides a strong framework for user-focused research, allowing for the collection of detailed user data throughout the design process. This data guides iterative design choices that not only improve system efficiency but also prioritize ergonomic factors for better human-system interaction. By incorporating usability testing approaches, HCD helps to identify and address potential human errors, resulting in improved operator well-being and system performance. Additionally, the paper highlights the crucial role of Social Impact Assessment (SIA) within the HCD framework for IE. SIA encourages engineers to go beyond user-centric thinking by considering the broader societal and environmental impacts of their designs. This comprehensive approach ensures that industrial systems not only work well for users but also have positive effects on communities and the environment. By outlining a potential workflow that integrates HCD and SIA, this paper suggests a comprehensive engineering paradigm. This paradigm focuses on user research, iterative design based on user input, and a thorough assessment of potential social impacts. By adopting this approach, IE professionals can redefine efficiency, shifting their focus from creating simply productive systems to developing user-centered, sustainable, and socially responsible solutions that contribute to a fairer and more environmentally conscious future.

CONFLICTS OF INTEREST

No conflict of interest was declared by the author.

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