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Ethical technology design for production systems: a human-centered approach at the LEONARDO learning factory

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Abstract

Industry 5.0 focuses on integrating advanced technologies with human-centric principles, aiming to empower workers rather than replace them. However, the ethical and human centric design of these technologies remains underexplored. This study addresses these gaps by applying a human-centered design (HCD) framework to three case studies involving different digital technologies, including digital twin, simulation, artificial intelligence and augmented reality. During a workshop involving participants from 12 European countries, impacts and concerns related to the design and use of these technologies on the company and society were explored. The analysis revealed key challenges, such as building trust in digital systems, ensuring alignment with human values, inclusivity across diverse user groups, and compliance with both human expertise and organizational goals, as well as covering sustainability concerns. Our research offers actionable design recommendations for creating transparent, adaptable, and inclusive technologies for production systems that align with human values. These recommendations contribute to both theory and practice, providing a roadmap for developers and engineers to design ethical, human-centric technologies that promote worker empowerment and address the risks associated with Industry 5.0 innovations.

Keywords: Industry 5.0; human-centricity; ethics; responsible research and innovation; value sensitive design

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1. Introduction

Traditional manufacturing has undergone several transformations throughout the industrial revolutions, each integrating new technologies that significantly impacted production processes. While previous industrial shifts often prioritized automation and efficiency, the advent of Industry 5.0 introduces a new paradigm centered on operator empowerment [1] and rethinking the role of technology in manufacturing [2]. Humans remain essential in industrial operations and manufacturing processes. The keyword of this evolution is "human-centricity", aiming to empower operators rather than replace them. According to the concept of Operator 4.0 [3], the human-centered approach envisions operators collaborating with enabling technologies within smart industry environments. This collaboration leverages human abilities and flexibility to adapt to changes, often with lower investment costs compared to full automation. Moreover, technology can enhance the training and performance of industry workers, amplifying their capabilities.

However, the rise of these technologies brings forth ethical concerns. Engineers and technologists must commit to upholding fundamental human rights, values, and the dignity of users and stakeholders [6]. There is a need to prioritize transparency and accountability while considering the broader societal implications of technological innovations, including sustainability and environmental impacts. Issues such as data privacy, job displacement, and the potential for over-reliance on technology necessitate careful consideration [6]. Considering these challenges, human-centered design (HCD) becomes a crucial approach [7]. HCD becomes a critical approach not only in addressing ethical concerns but also in empowering operators by ensuring that technological innovations serve their needs and enhance their capabilities. HCD enables the development of solutions that are desirable from a human perspective while also being technologically feasible and economically viable.

Despite the increasing integration of enabling technologies in industrial settings, the full realization of human-centric design remains underexplored [8]. While the potential benefits of empowering operators through technology are recognized, there is a critical gap in our understanding of how these technologies impact human experience, the work environment, and broader societal relationships. This study aims to fill that gap by employing a human centered design approach to understand the positive and negative impact of industrial digitalization through three use cases inspired by the ERASMUS+ LEONARDO project, involving different technologies aimed at empowering the human operator. Based on this, actionable recommendations are derived for the design of human-centric technologies. Our findings contribute to the discourse on ethical technology implementation and provide insights into designing human-centered technologies that empower operators while mitigating potential drawbacks.

The remainder of this paper is structured as follows. Section 2 reviews the relevant literature on technologies and HCD. Section 3 outlines the methodology. Section 4 presents the results of the analysis, highlighting problems emerging and related recommendations. Section 5 discusses the general problem that should be considered while designing technology. Finally, Section 6 concludes the paper and suggests directions for future research.

2. State of the art

Digital transformation is the change of work activities and organization as well as business processes through digital, data-based technologies [9]. This does not automatically lead to disruptive changes in work, but requires a multi-level approach, focusing on individual, group, and organizational factors to adapt to technological change and maintain competitiveness [10].

The role of humans in industry remains highly valued due to their adaptability, creativity, and problem-solving abilities. However, purely manual work has some limitations, such as fatigue, susceptibility to errors, and skill shortages. To this end, it is possible to leverage emerging digital technologies to mitigate the challenges faced by operators through technological support [11], to enhance their health, safety, working conditions and efficiency [12].

While the literature has extensively discussed the potential benefits of digital transformation for improving industrial efficiency [13][14], there remains significant ethical considerations and potential drawbacks. Key concerns revolve around worker rights, privacy, regulation, and the implications of increased surveillance in the workplace [5][12]. For instance, monitoring technologies might breach personal privacy or create a sense of mistrust among employees [15]. In addition to privacy concerns, the ethical debate surrounding the integration of new technologies in the workplace also includes the risk of algorithmic bias and the potential for technologies to exacerbate inequalities. For instance, biased data sets could lead to unfair decision-making processes that disproportionately impact certain groups of workers [16]. Ensuring that human-centric technologies are inclusive and ethical requires both transparency in design and active involvement of diverse user groups [17]. Therefore, while digital transformation has the potential to improve industrial operations, it is crucial to address these ethical challenges proactively to prevent exacerbating existing inequalities and violating individual rights.

To ensure that the digital workplace integration is successful, it is essential to consider human needs, abilities, and safety as primary considerations [13]. Active involvement of users to better understand the user, task, and the environment, is central to human-centricity. This approach not only promotes efficiency and precision but also ensures that processes are safe and aligned with human operational capabilities [7]. In response, HCD has emerged as a critical framework for addressing these ethical challenges by actively involving users in the design process, ensuring that technologies are aligned with human needs, values, and social norms. For example, involving users in the design process can help identify potential privacy concerns early on and develop strategies to mitigate them [18]. Moreover, HCD can lead to more inclusive designs that accommodate diverse user groups, including those with disabilities [19].

While the importance of user experience and ethical considerations has been acknowledged in the literature [14], the current body of work lacks concrete, actionable frameworks that developers and engineers can apply across different industries and cultural contexts [17]. These gaps leave a critical need for comprehensive design recommendations that integrate human-centric principles into practical applications. This research aims to fill that gap by offering comprehensive design recommendations that balance user empowerment, ethical integrity, and inclusivity.

3. Methodology

3.1. The case study

The motivation for this study was the ongoing design and development of three different technological solutions aimed at empowering operators at the LEONARDO Smart Learning Lab at the University of Calabria. The lab aims at training IEM students in the topics of human-centric production systems and providing an experimental environment for ideas. The lab is a replica of a brewing system with smart machinery, sensors and actuators installed in the system for a 4.0 management of the production process (Figure 1).

Figure 1. A schematic representation of part of the LEONARDO Smart Learning Lab at the University of Calabria.

In particular, the three case studies considered include:

- Case Study 1: an AI-based predictive analytics to improve trend identification and product quality, assisting brewers and product managers (i.e. students) in maintaining high standards and proactively addressing issues.
- Case Study 2: an AR tool to empower brewers and technicians (i.e. students) with enhanced work instructions, facilitating better performance through interactive guidance and support.

- Case Study 3: a digital twin of the production process for better monitoring and decision-making, providing process managers (i.e. students) with powerful tools to simulate and optimize operations.

3.2. Workshop and participants

The analysis was carried out during a workshop centered on ethical and responsible technology engineering at the University of Aveiro (Portugal). The workshop was led by a member of the LEONARDO project's research group and was attended by 21 Industrial Engineering and Management (IEM) students from 12 European countries. This diverse group ensured that the perspectives explored were culturally varied, which is crucial in HCD, but at the same time they all possess the technical knowledge to express useful insights.

3.3. Value sensitive design with the Tarot Cards of Tech

During the workshop, the Tarot Cards of Tech developed by the Artefact Group [20] were utilized (Figure 2) to stimulate critical thinking and encourage thorough examination of potential impacts. Rather than focusing on the predictive or mystical side of tarot, this deck is more about prompting reflection and discussion around tech innovation. It is used by designers, technologists, and anyone involved in creating products or services to consider unintended consequences, biases, and broader impacts. The deck is split into 12 categories that echo tarot's traditional suits but are adapted for modern tech themes and are designed to prompt critical thinking about technology's impact on society, allowing students to foresee unintended consequences and uncover opportunities for positive change. Each card poses a provocative question or scenario, encouraging reflection on ethical, social, and human-centric issues, guiding users through a structured brainstorming process. The cards aim to foster a human-centered approach by questioning how technology designs align with human values and needs.

Figure 2. Example of cards involved in the workshop.

3.4. Experimental setup

The workshop participants were divided into three teams (one per each case study). They were given one hour to brainstorm on the specific assigned tech solution using the 12 cards. Considerations and thoughts were collected using Google Form. At the end, a qualitative thematic analysis was conducted to identify patterns and themes within the resulting considerations in the survey (Figure 3).

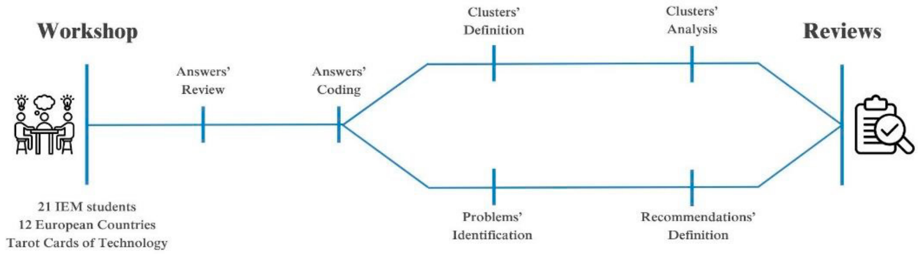

Figure 3. Methodology adopted in this study.

First, all collected considerations were reviewed to gain a comprehensive understanding of the discussions. Then, the data were coded by assigning labels to segments of text corresponding to specific topics or concepts, with codes developed inductively from the data itself. These codes were used to identify the general problem emerging from each card to develop suggestions for the human-centric design of technologies. The codes were grouped into broader categories to form overarching themes representing key areas of interest, such as trust and adoption, usability and accessibility, cultural and social impact, ethical and security considerations, balance between technology and human expertise, workforce implications, environmental sustainability. The themes were reviewed and refined to ensure they accurately captured the essence of the data. Overlapping themes were combined, and distinctions between themes were clarified to enhance clarity and coherence. The clusters were analyzed to uncover common aspects that derive from the introduction of new technologies in an industrial environment, independent from the technology adopted.

4. Results

The results reveal specific challenges and actionable insights for achieving a HCD in industrial environments. Across all cases, trust, inclusivity, and ethical considerations were consistently highlighted, underlining the need for technological designs that are transparent, accessible, and aligned with human values. In Case Study 1 (Table 1), participants focused mainly on the impact that the introduction of AI-based systems may have on the role of the operator and its skills. Besides the accuracy and the trustworthiness of this kind of system, participants focused on the loss of creativity and critical thinking skills, as well as a decrease in team collaboration and communication for the workers using it. Recommendations included improving data quality for AI models, tailoring systems to user needs through co-creation, and balancing AI insights with human expertise to foster proactivity.

Table 1. List of problems and recommendations for case study 1 “Improving trend identification and product quality with AI-based predictive analytics”.

Problem	Recommendation
Inaccurate, cumbersome, or non-intuitive AR systems can lead to user frustration, reluctance to adopt new technologies, and potential financial losses, ultimately eroding trust in the product.	Improve the AI model's accuracy by using high-quality data and robust validation processes, while reducing manual effort by leveraging existing operational data to match real situations. Simplify the user interface to enhance usability and provide practical training that highlights immediate benefits to motivate users. Involve users in the development and testing phases to tailor the system to their needs. Establish accessible feedback mechanisms for continuous improvement and allow experienced users to customize settings to better fit their workflows.
Overreliance on AI can diminish users' proactivity and creativity. Resistance from certain user groups, such as older employees, may hinder adoption. Additionally, the product might alter existing cultural practices by introducing new workflows that don't align with users' backgrounds or experiences.	Tailor the AI system to accommodate different cultural contexts and user needs, through customized training programs to address varying levels of familiarity with AI, reducing resistance and overreliance. Implement change management strategies that promote balanced use of AI, encouraging users to combine AI insights with their own expertise to maintain proactivity and creativity.
Workers with disabilities or stakeholders in the value chain will be excluded. This could result in missed opportunities to enhance productivity, collaboration, and overall quality of work life for these groups.	Incorporate features that assist workers with disabilities or learning difficulties. Extend the system's capabilities to include stakeholders along the value chain to enhance collaboration and reduce inefficiencies.
Misses opportunities to align the product with customer preferences, foster cross-departmental collaboration, and encourage innovation through controlled experimentation.	Incorporate feedback from end consumers into the AI system to ensure the product evolves with customer desires. Engage other departments to utilize the AI system for broader analysis and improvements across production processes.

Security vulnerabilities and ethical misuse are significant risks, both in the programming, operational and post operation phases	Implement robust security measures and ethical guidelines to prevent misuse and protect data integrity
Excessive use may hinder creativity, innovation, and critical thinking	Encourage balanced use of AI as an assistant, promoting human oversight and decision-making
Passionate users would leverage the AI to augment their capabilities while valuing human expertise	Foster a community that views AI as a tool for empowerment, providing training and resources to maximize its benefits
The product could both isolate users, decreasing communication and collaboration.	Design features that promote collaboration and shared learning experiences among users
Potential for reputational damage due to failures led to wrong data or ethical issues	Prioritize quality assurance, ethical standards, and crisis management plans to mitigate risks. Keep human reasoning in the loop to oversee the process.
Scaling up brings challenges like maintaining quality, preserving innovation, and managing workforce impacts. Also, scaling the process need new resources to train the model	Develop strategies for sustainable scaling, including resource management and supporting innovation
Risk of displacing valuable human roles and processes	Balance automation with preserving essential human expertise and creative processes
The product can both positively and negatively impact the environment	Optimize AI models for energy efficiency and focus on sustainable practices in product development

Case Study 2 (Table 2) highlighted usability barriers in AR systems, especially for those unfamiliar with technology, which could lead to exclusion. Participants highlighted more the technical impact on the worker, such as the usability aspect and its integration in the daily task, specifically attention was posed to the adaptability of the system to the level of knowledge of the workers using it. Recommendations include simplifying interfaces, ensuring inclusive design for diverse users, and integrating AR with traditional methods to ease adoption.

Table 2. List of problems and recommendations for case study 2 “Empowering brewers and technicians with AR-based digital work instructions”.

Problem	Recommendation
AR systems may be unreliable due to the quality and quantity of information showcased. Ease of use based on the user's aversion to technology, quality and interface of the output and technical limitation.	Simplify and enhance the AR interface for better usability and reliability. Ensure accurate alignment between AR visuals and reality, and provide comprehensive training to help users adapt confidently to the new technology.
AR adoption may be challenging for those unfamiliar with new technology or those who take pride in their hard working reputation	Integrate AR in a way that complements traditional methods, highlighting benefits without replacing existing practices. Offer intuitive interfaces and training to ease adoption, and encourage collaboration between experienced and new users.
Without inclusive design, the AR system may exclude users with disabilities or language barriers.	Design the AR system with inclusivity in mind by incorporating multi-language support and accessibility features to accommodate diverse user needs.
Certain groups may be unable to use the AR system due to technological barriers or disabilities, leading to exclusion.	Provide alternative instruction methods and additional support to include those unable to use AR, ensuring the system is accessible to all users.
The AR system may be exploited by bad actors, leading to security breaches or unethical use.	Implement strong security measures and ethical guidelines to protect against misuse. Educate users on safe practices and monitor for unauthorized activities.
Excessive reliance on AR technology may negatively impact users' social interactions and well-being.	Promote balanced use of AR by encouraging regular breaks and emphasizing the importance of real-world engagement alongside technology use.
While enthusiastic users enhance product success, overuse may have adverse effects on individuals.	Engage superfans constructively by involving them in community activities and product development, while promoting healthy usage habits.
Social dynamics can influence how users adopt and perceive the AR system.	Include collaborative features that enhance shared experiences and allow personalization to accommodate different user preferences, fostering positive social interactions.
Mistakes from inaccurate AR guidance could cause serious incidents, harming the company's reputation.	Ensure AR instructions are accurate and safe through rigorous testing and quality control measures to prevent errors and maintain trust.
Scaling up may bring challenges in data management and maintaining system quality.	Plan for scalability by ensuring the system can handle increased users and data volume. Use insights from the expanded user base to continuously improve the AR experience.
The technology could displace jobs and create legal uncertainties regarding liability for mistakes.	Address potential job impacts by retraining staff for new roles within the AR ecosystem. Establish clear legal guidelines and responsibilities to manage liabilities.
AR devices and systems may have negative environmental implications if not designed sustainably.	Use sustainable materials in devices and adopt eco-friendly design practices to minimize environmental footprint, aligning the product with environmental responsibility.

Case Study 3 (Table 3) presented more balanced concerns on the impact of the use of digital twins. Insights revealed that this case study can have a better impact on the environment than the other two already presented. The digital twin leaves more space for environmental consideration in the design phase. Other aspects highlighted are about mistrust in digital twin results and the exclusion of operators with lower levels of technological proficiency, the so-called non-tech-savvy staff. Solutions emphasized engaging experts in development to enhance accuracy, providing tailored training, and ensuring that digital twins complement human decision-making rather than displacing expertise.

Table 3. List of problems and recommendations for case study 3 "Enhancing process monitoring and decision making with a simulation based digital twin".

Problem	Recommendation
The digital twin may lead to unreliable and unclear results that do not match with the expert knowledge, causing mistrust among users and hindering its adoption.	Improve the digital twin's accuracy and clarity by involving technicians and experts in its development. Provide clear, understandable feedback and results, establish continuous updates and feedback loops, and offer training to help users effectively interpret and justify simulation outcomes.
Cultural habits may resist adopting the digital twin, as traditional operators and customers distrust standardized, technology-driven processes.	Integrate the digital twin in a way that complements traditional methods, involving the experts in the implementation. Provide culturally and linguistically tailored training and support, demonstrating how technology enhances rather than replaces traditional practices.
Without intentional design, the digital twin may not fully empower underserved populations, missing opportunities for greater accessibility.	Design the digital twin to be user-friendly and accessible, accommodating varying expertise and physical abilities. Include remote working capabilities to involve those unable to be physically present, broadening career opportunities
The digital twin may exclude non tech-savvy staff and operational workers, leading to missed opportunities for improvement and inclusion.	Include operational workers in the digital twin's development and use. Provide training and support to non tech-savvy staff, creating accessible interfaces to ensure all users can contribute their expertise to process optimization.
The digital twin could be misused to favor profit over quality and sustainability, harming reputation and ethical standards.	Establish guidelines within the digital twin that balance efficiency with quality and sustainability goals. Implement oversight mechanisms to prevent misuse and ensure decisions align with ethical and environmental standards.
Excessive trust in the digital twin may cause users to overlook physical systems and security, risking quality and confidentiality.	Promote balanced use by encouraging regular checks with physical systems. Train users to critically assess simulations and maintain focus on quality and security alongside efficiency gains.
Superfans may unintentionally expose proprietary data, risking confidentiality and homogenizing products.	Implement clear policies on data confidentiality and acceptable sharing. Provide secure, internal collaboration platforms to prevent public disclosure of sensitive information while fostering innovation.
Poor communication and differing approaches among users can lead to conflicts, affecting teamwork and decision-making.	Enhance collaboration by integrating communication tools within the digital twin. Provide training on teamwork and conflict resolution, and encourage sharing best practices to align methods and goals among users.
Adoption of the digital twin could cause job losses, security risks, and quality issues, leading to scandals that harm reputation and industry stability.	Mitigate job displacement through retraining programs and new roles. Implement robust cybersecurity measures to prevent hacking. Ensure consistent use to maintain quality, and engage with industry stakeholders to responsibly manage market impacts.
Widespread adoption may reduce innovation and competitiveness due to over standardization and underutilization of skilled personnel.	Encourage customization and flexibility within the digital twin. Invest in developing users' data interpretation skills, promoting innovation through diverse applications of the technology.
The digital twin may render traditional methods obsolete, leading to job losses and impacting cultural heritage.	Integrate traditional practices with the digital twin to preserve cultural methods while enhancing processes. Provide opportunities for technicians to upskill and transition into new technology-supported roles.
Without careful use, the digital twin might harm the environment, but it also offers opportunities to enhance sustainability.	Leverage the digital twin to optimize for environmental sustainability by including impact metrics in simulations. Encourage sustainable sourcing and simulate processes that reduce waste and energy consumption, aligning efficiency with ecological responsibility.

5. Discussion

Each card used in the critical thinking workshop prompted discussions on multiple topics represented in Figure 4. For example, when discussing the introduction of AI-based predictive analytics, there was a stronger focus on its impact on the workforce. Specifically, workforce-related concerns emerged in five out of the twelve cards, reflecting issues such as changes in skill requirements, job displacement, or the effect on collaboration and creativity.

This diversity of responses across different technologies, whether AI, AR, or digital twins, highlighted that each technology brought up distinct concerns. This variation allowed us to group the topics into 7 broad categories or clusters of macro ethical problems. These clusters represent key themes that arise from introducing new technologies in industrial environments. By identifying these clusters, we can generalize the findings and use them as a foundation for designing human-centered technological solutions. Each cluster provides insight into recurring issues that should be carefully addressed when developing or deploying new technologies to ensure they align with human values, capabilities, and needs.

1.1. Trust and adoption

A predominant theme was the critical importance of accuracy and reliability in technologies. Any inaccuracies, errors, or unrealistic outputs could lead to a significant loss of trust among users. For instance, technologies that provide incorrect outputs may cause users to question their validity and revert to traditional methods. Trust is foundational and is built when technologies consistently perform as expected.

1.2. Usability and accessibility

Complex or non-intuitive designs, overcomplicated instructions, and a lack of guidance are barriers to adoption. Technologies should align closely with users' existing workflows and cognitive models, otherwise, users may become frustrated and abandon it. Moreover, technologies might inadvertently exclude certain user groups, such as non-tech-savvy individuals, the elderly, or those with disabilities. For example, technologies that rely heavily on visual interfaces may not be accessible to visually impaired users. Without appropriate accommodation or alternative modalities, these users may feel overwhelmed or marginalized, leading to decreased morale and engagement.

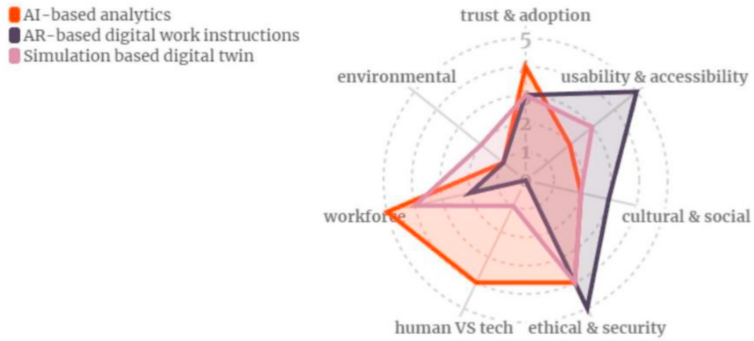

Figure 4. Distribution of the impact area cluster in the three case studies.

Conversely, technologies that provide clear instructions, support multiple languages, or offer remote access can enable individuals without prior expertise or those with physical limitations to participate more fully in industrial processes, reducing barriers to entry. Furthermore, technologies need to be adaptable and flexible, accommodating diverse user preferences and evolving requirements. Customizable interfaces, adjustable settings, and modular designs can cater to individual needs and promote broader adoption.

1.3. Cultural and social impact

Cultural habits and traditional practices play a significant role in technological adoption. Different categories may resist the adoption of new technologies. This resistance is often rooted in a fear of devaluing their expertise or losing the personal touch associated with traditional practices. The introduction of technology must, therefore, be sensitive to these cultural dynamics. Also, the integration of technologies can alter social interactions and collaboration within the workplace. Overreliance on technology might reduce communication among team members, leading to isolated work practices. This shift could potentially harm interpersonal relationships and diminish teamwork, which are essential components of a productive work environment.

6.1. Ethical and security consideration

One of the most pressing concerns surrounding emerging technologies is the risk of misuse by malicious actors. Threats such as unauthorized access, data manipulation, or unethical practices, such as compromising product quality for financial gain, can lead to severe consequences for both businesses and users. To mitigate these risks, it is essential to implement robust security measures that protect sensitive information and prevent harmful activities.

Effectively addressing these ethical concerns requires clear and well-defined policies to ensure responsible use of technology. Such policies must focus on protecting users' rights and maintaining public trust by addressing key issues, including data privacy, consent, accountability, and transparency. Strong security protocols are also critical for safeguarding against threats like hacking, unauthorized access, and data breaches. Additionally, fostering user awareness and education on security practices is essential for promoting a proactive defense against potential risks.

6.2. Balance between technology and human experience

Depending on technologies might lead users to neglect their skills and critical thinking abilities. This could result in a workforce that is less adaptable and less capable of addressing unforeseen challenges without technological assistance. Maintaining a balance between technological aid and human expertise is essential. It is important to keep humans actively involved in decision-making processes. Technologies should be designed to require human oversight and input, ensuring that users remain engaged and that their judgment is integrated into technological outputs. This approach promotes accountability and preserves the human element in industrial operations.

6.3. Workforce implication

Certain roles, such as skilled artisans, technicians, and instructors, might be threatened by new technologies. This possibility could lead to resistance from employees worried about job security, negatively affecting morale and hindering adoption. On the other hand, technology could create new job opportunities. Roles in technology maintenance, data analysis, and user support may emerge, requiring different skill sets. To mitigate the negative impacts of technological change, companies should adopt reskilling and upskilling programs to help workers transition into these new positions. Furthermore, technologies could foster communities of practice, where users share insights, best practices, and innovations. Such collaboration can drive continuous improvement and collective problem-solving. However, the risks associated with knowledge sharing are linked to the potential for intellectual property leaks or homogenization of products and processes. To maximize benefits and minimize risks, secure platforms for collaboration that protect proprietary information while encouraging open communication are needed. In this way, the value of cultivating a culture that supports innovation and learning, leveraging the collective expertise of users to enhance technology effectiveness is emphasized.

6.4. Environmental sustainability

The implementation of technologies could have adverse environmental effects. Increased energy consumption, electronic waste from hardware devices, and the carbon footprint associated with manufacturing and operating these technologies are serious concerns. Considering environmental sustainability in the design and deployment of new technologies could have the potential to enhance environmental sustainability. By optimizing processes, reducing waste, and improving resource efficiency, these technologies can contribute to more sustainable industrial practices.

7. Conclusion

This study has explored the ethical and human-centered dimensions of Industry 5.0, focusing on the integration of enabling technologies such as AI-based predictive analytics, AR, and digital twin systems in industrial environments. By employing a HCD approach, we examined both the positive and negative impacts of these technologies across three distinct case studies. The findings highlight several key challenges, ranging from issues of trust, usability, and inclusivity to concerns over worker autonomy, data privacy, and potential job displacement. Our case studies revealed actionable recommendations, including improving data quality, ensuring inclusivity by tailoring technologies to diverse user groups, fostering collaboration between human expertise and automated systems, and addressing the ethical risks of surveillance and over-reliance on technology.

From a theoretical perspective, this research contributes to the growing body of literature on HCD by identifying specific gaps in existing frameworks, particularly concerning the inclusivity of marginalized or non-tech-savvy workers, cross-cultural adaptability, and the need for a balance between technology and human oversight. We propose that ethical design principles should be at the forefront of technological development, ensuring transparency, accountability, and alignment with human values. Practically, this research offers concrete design recommendations for developers and engineers to adopt human-centered principles in their technology creation. These guidelines can help mitigate ethical risks, ensure that digital tools are intuitive and accessible, and promote an ethical industrial environment. By implementing the strategies outlined in this study, organizations can foster greater trust and engagement, ultimately facilitating smoother adoption of Industry 5.0 technologies.

Despite its contributions, this study has certain limitations. The participant sample, though culturally diverse, consisted of students rather than experienced industry professionals, which may affect the generalizability of the findings to real-world industrial settings. Future research should involve industry professionals to further validate the applicability of the recommendations. Additionally, while this study focused on the European context, expanding the scope to include perspectives from other regions would enhance the global relevance of the findings.

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