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Leveraging AR/VR technologies to teach industry 5.0 principles to students and practitioners through learning factories

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ABSTRACT: The transition to Industry 5.0 (I5.0) marks a shift toward human-centric, sustainable, and resilient manufacturing, leveraging technologies like collaborative robots (cobots) and AR/VR to enhance inclusivity, empowerment, and safety. This study investigates how Learning Factories (LFs) can effectively convey I5.0 principles to students and professionals. A simulated production line using AR/VR allowed participants to interact with virtual cobots, assessing key pillars of safety, inclusivity, and empowerment. A survey was used to assess the impact of this immersive environment on participants' perceptions and unconscious reactions. The findings demonstrate LFs' potential to prepare a workforce that integrates human creativity with technological innovation.

KEYWORDS: industry 5.0, industry 4.0, learning factory, virtual reality, education

1. Introduction

In recent times, the speed of technological advancement has noticeably increased, influencing a variety of sectors, including manufacturing. The emergence of Industry 4.0 (I4.0) seeks to improve production efficiency by utilizing advanced technologies like automation, AI, IoT, and cyber-physical systems (Albukhitan, 2020; Brahma et al., 2020). This transition has also brought forth challenges, such as the necessity for more intricate skills among engineering graduates (Manyika et al., 2017). Building upon I4.0, Industry 5.0 (I5.0) introduces a more human-focused approach, prioritizing human welfare, sustainability, and resilience within manufacturing (Dautaj & Rossi, 2022) (Rada, 2015). It highlights the importance of a cooperative relationship between technology and human competencies, creating a work environment that boosts productivity and employee well-being (Dehbozorgi, Rossi Monica, et al., 2024). I5.0 advocates for sustainable methods, striving for an equilibrium between industrial advancement and environmental stewardship (Leng et al., 2022).

Human-Centric Manufacturing (HCM) is a fundamental component of I5.0. HCM is built on the premise that human participation in manufacturing processes is highly critical (Romero et al., 2016), which makes it essential for I5.0. First, it encourages a safe workplace through use of state-of-the-art tools such as collaborative robots (cobots) and augmented reality/virtual reality (AR/VR) with an aim to empowering employees while reducing accidents risks. Moreover, workers' perception of safety when working with cobots in industrial environments is influenced by situational awareness, which can be enhanced through augmented reality displays that inform users of the robot's movements and potential hazard zones, ultimately improving their sense of control and security in shared workspaces (San Martin et al., 2024). This makes industrial systems more accessible and adaptable to the different physical capabilities as well as experience levels within its workforce. With technology applied, this results in a more engaging and sophisticated working environment thereby increasing job satisfaction and staff retention rates. It therefore helps to narrow down the gap between labour and technology thus creating way forward for stronger/future onward industries that are sustainable (Nahavandi, 2019). Both I4.0 and I5.0 necessitate a workforce that possesses advanced technical and multidisciplinary abilities (Jerman et al., 2020; Kipper et al., 2021). Nevertheless, there are considerable discrepancies between the skills imparted in higher education and those demanded by the industry (Leow et al., 2023; Moldovan, 2019). Innovative educational frameworks, such as Learning Factories (LFs), are regarded to mitigate this gap by providing practical experience in a controlled setting (Prinz et al., 2016; Sallati et al., 2019).

LFs provide a practical, real-world setting where students can apply what they've learned in a controlled and safe environment. The outcome is the development of engineers who are not only technically proficient but also equipped with the soft skills, ethical understanding, and sustainability awareness required in the current and future industrial landscapes. A similar concept emerged in Germany in the 1980s under the term Lernfabrik and later developed in the U.S. as Teaching Factories (TFs) (Warnecke & Bullinger, 1988). These collaborative spaces bridge the gap between academia and industry, enabling practitioners to teach and share real-world factory expertise while students and faculty bring knowledge from the classroom to teach practitioners (EIT Manufacturing, 2020). This collaboration is also supported with a web conferencing platform and is an ongoing process, with regular sessions and continuous interaction between the factory and the classroom. Nowadays, the two terms are used interchangeably by defining the context, later the term was coined to pave the way for the Initiative on European Learning Factories which was later renamed International Association of Learning Factories (IALF, 2022).

This study investigates the integration of human-centric design principles into transformative learning environments, focusing on teaching the core concepts of HCM namely safety, inclusivity, empowerment, through VR applications. The objective is to understand how human-centric design enhances engagement with advanced technologies to promote the fusion of individuals and machines for improved productivity and well-being. A key focus of this research is to assess participants' perceptions of inclusivity, empowerment, and safety within a LF environment that integrates virtual cobots and immersive technologies. To guide this study, the following research question was formulated: "How can AR/VR technologies be leveraged within LFs to effectively convey the HCM principles to students and practitioners?" To investigate this, an immersive learning experience was developed using AR/VR technology to simulate an I5.0 production line where participants engage with a virtual cobot in the simulated environment. The study evaluates the impact of this experience through pre- and post-experience surveys, measuring changes in participants' perceptions and knowledge. The paper is structured as follows, Section 2 outlines research methodology, Section 3 covers the state-of-the-art analysis, Section 4 presents the development of the LF, Section 5 illustrates the results, Section 6 presents the discussion, and Section 7 addresses the conclusions, limitations and future research.

2. Methodology

The study began with (i) a review of the current state of the art using Scopus and Web of Science as databases, (ii) the design and development of the LF and the formulation of measurement tools for data collection and analysis. The state-of-the-art review focused on the intrinsic values of I5.0, exploring both theoretical foundations and practical applications related to LFs. This in-depth examination included academic articles, industry reports, and case studies, offering a comprehensive understanding of HCM within the context of the I5.0 paradigm. The review highlighted how HCM represents the confluence of advanced technologies and human-centered approaches, emphasizing the critical role of LF's in bridging this integration. These facilities were identified as pivotal in modernizing industrial education and training, providing immersive and practical environments that align with the evolving demands of I5.0. To address the research question, a structured LF experience was developed, simulating a modern I5.0 production line. The goal was to evaluate whether this LF effectively communicates the principles and values of I5.0. The pilot phase of the LF was conducted with the support of university professors, who refined and structured the intervention to ensure its clarity and coherence. Facilitators of the LF not only guided participants through the experience but also conducted surveys before and after the intervention to assess its impact. These surveys measured participants' perceptions, knowledge, and learning outcomes, enabling a direct comparison between their baseline understanding and post-experience insights. The surveys included both technical questions and reflections on the participants' overall learning experience. To capture immediate feedback, questions about the learning process were administered directly after the intervention. Additionally, participants engaged in a Cave Automatic Virtual Environment (CAVE), which simulated a factory floor featuring a virtual cobot. Combining both AR and VR technologies, the CAVE immerses participants in a highly interactive setting, where a cobot is projected in front of them via specialized headwear. This immersive experience aimed to enhance awareness of HCM concepts while addressing concerns about safety and reducing apprehension about working alongside collaborative robots. Since the participant group included both engineering students and industry practitioners, the evaluation focused on comparing their perceptions of HCM concepts pre and post intervention. This analysis aimed to assess differences in their understanding and acceptance of HCM principles, considering their distinct backgrounds in academic learning and practical industry experience. By examining these variations, the study provides insights into how each group engages with AR/VR-enhanced learning environments in the context of I5.0.

3. State of the art

I5.0 was introduced by Rada in 2015, emphasizing industrial upcycling and environmental preservation. Unlike earlier models that displaced workers, I5.0 fosters collaboration between humans and machines, enhancing individual contributions while preserving job opportunities (Rada, 2015). The I5.0 vision advocates for a symbiotic relationship where technology supports human creativity, driving productivity and innovation without sacrificing employment prospects. This idea builds on the principles established by I4.0 but signifies a significant change by highlighting the significance of employee well-being throughout the manufacturing process, anchored in three fundamental pillars: Human Centricity, Sustainability, and Resilience (Rada, 2015). It encourages a system focused on humans (Dehbozorgi, Rossi Monica, et al., 2024), acknowledging that the adoption of advanced technologies should not undermine the human workforce. Rather, I5.0 promotes a more cooperative relationship where human expertise and technological advancements work together, boosting productivity while prioritizing the welfare of workers. This approach promotes a holistic integration of social, environmental, and economic considerations for a sustainable and inclusive industrial future (Nahavandi, 2019). The I5.0 approach seeks to establish a harmonious relationship between humans and technology, emphasizing that the future of manufacturing must prioritize the human aspect. This entails not only safeguarding the physical and mental well-being of employees but also cultivating a workplace that encourages their advancement and development. The overarching aim of I5.0 goes beyond mere economic growth and job creation; it includes a wider social goal of fostering sustainable development (Leng et al., 2022). Literature is currently formalizing the key components that make up a Human Capital Management (HCM) system, with several models proposing the following major dimensions
(Dautaj et al., 2023; Lu et al., 2022):

- ***Safety:*** Employees perceive safety across three aspects: emotional (feeling valued and being part of a team), professional (job security, ensuring that one's role is not at risk), and physical safety (ergonomic and healthy workplace equipped with appropriate tools and furnishings).
- ***Inclusivity:*** Within the framework of HCM, inclusivity is interpreted in two ways of personal (the acceptance of inherent characteristics such as age, gender, etc.) and work-related inclusivity (importance of diverse skills among employees, which is vital when job roles evolve or when new team members are introduced).
- ***Empowerment:*** The two perceived dimensions of empowerment are individual (having confidence in one's skills and decisions) and structural empowerment (strategies that promote power distribution, decision-making, and control over resources).

Several studies highlight a persistent gap between knowledge (factual and procedural) and practical know-how among practitioners, leading to employability challenges and mismatches between employer needs and the qualifications of engineering graduates. Higher education institutions (HEIs) play a critical role in addressing these deficiencies by equipping the future workforce with essential skills (Leow et al., 2023; Musariwa & Tinonetsana, 2023), enabling graduates to support companies in maintaining competitiveness within I4.0 and I5.0. (Moldovan, 2019) emphasizes the digital transition in the European Union's manufacturing sector, highlighting the need for engineers proficient in designing, maintaining, and supervising intelligent machines, which requires a blend of basic, soft, and technical skills that current education systems often inadequately provide. Moreover, as the workforce undergoes significant transformations due to digital advancements, it is crucial to equip both emerging professionals—such as university graduates—with foundational AI competencies before entering the job market, and to reskill or upskill the existing workforce to meet the evolving demands of Industry 4.0 and 5.0, ensuring sustainable industrial growth and competitiveness (Dehbozorgi, Rossi, et al., 2024).
A promising solution is the integration of LFs into academic curricula. LFs offer hands-on experience with industrial processes and technologies in a secure environment, bridging the gap between theory and

practice. This approach is especially relevant as I5.0 developments are explored alongside the ongoing implementation of I4.0 in businesses (Longo et al., 2020). LFs have demonstrated their effectiveness in preparing future engineers, providing practical understanding and skills aligned with real-world industrial environments (Prinz et al., 2016; Sallati et al., 2019), and serving as a vital tool for education and skill development in the rapidly evolving industrial landscape.

Moreover, the literature defines three elements for the structuring of a LF starting from a manufacturing workshop for training purposes, based on three elements: didactic, integrative, and engineering. A focus on the didactic pillar confirms the importance of taking the learning strategy and educational goal into consideration along with the target group. (Abele et al., 2019) states that the physical learning factories can be supported by means of digital factory systems and tools (ERP, MES, etc.); most physical learning factories have digital systems implemented. The physical value streams can be expanded virtually. LFs can be categorized by scale or degree of the presence of a physical environment. Moreover, the use of modern technologies to support and enhance learning. This could include VR, AR, 3D printing, IoT, Robots, AI, Wearable devices, Virtual laboratories, and other technological tools that help bridge the gap between theoretical knowledge and practical application in a controlled, educational setting (Hernandez-de-Menendez, Escobar Díaz, et al., 2020).

The use of VR technology, particularly immersive systems, has been associated with various physical, physiological, and psychological side effects, including simulator sickness, visual strain, and postural discomfort, highlighting the need for proper ergonomic design, user training, and safety guidelines to mitigate potential health risks (Costello, 1997). While VR technology presents significant advantages for safety-relevant training by allowing users to experience hazardous scenarios in a controlled environment, careful consideration must be given to potential issues such as simulator sickness, physical discomfort, and cognitive overload, which can impact both the effectiveness and safety of its application (Stefan et al., 2023).

4. Development of the Learning Factory

As outlined in Section 2, the literature has guided the development of LFs toward integrating real-world industrial environments with learning spaces, creating a model that effectively simulates authentic industrial settings. It was envisioned as a dynamic environment that supported learning to take place both formally, informally, with emphasis on practical application of knowledge and solving real-world problems. The design process incorporated the integration of cobots, VR/AR technologies, and interactive modules to create an immersive, hands-on educational experience, as illustrated in (Figure 1). This LF model brought together theoretical knowledge and practical skills to bring greater understanding of HCM technologies and how they are applied within I5.0. Moreover, the article addresses the aforementioned research by developing a systematic approach to the workshop based on a didactical-technological approach (Tisch et al., 2016) (Dehbozorgi, Rossi Monica, et al.,2024). This methodology facilitates the structured formulation of the conceptual tiers: 'Learning Objectives' (macro), 'teaching module' (meso), and 'learning situation' (micro).

- Macro Level: The macro-level perspective highlights the key goals of a HCM, focusing on raising industry awareness and educating professionals about integrating I5.0 principles into manufacturing. The workshop method aims to tackle the challenge of embracing HCM principles while promoting a shift towards a more human-focused approach in manufacturing.
- Meso Level: The meso level highlights the strategies needed to promote HCM principles during design. This level emphasizes the use of specialized technological tools such as AR/VR which shows that the technology is used as a medium to convey the message of I5.0.
- Micro Level: The micro level is demonstrated through a workshop with practitioners and academics, where participants were introduced to a CAVE environment, simulating a factory floor with a virtual cobot. Section 5 of the paper analyses the results, showing the effectiveness of LFs in conveying the principles of I5.0.

The experience is carefully divided into two distinct phases, each designed to achieve a specific objective within the broader research framework. The “Before Experience” phase focuses on establishing baseline knowledge and perceptions of participants regarding HCM technologies. Participants are surveyed through a comprehensive questionnaire to assess their familiarity with HCM principles, prior experiences with collaborative robots, safety beliefs of such technologies, and exposure to VR/AR technologies.

Following the initial questionnaire, participants entered the CAVE for an immersive activity guided by a technical engineer. Wearing VR headwear, they interacted with a virtual assembly line featuring a cobot. The intervention included two scenarios: in the first, the cobot moved rapidly toward the participant, prompting either a startled reaction or a virtual collision, assessing their initial fear response. In the second, the cobot detected human presence and halted its movement, evaluating perceptions of safety in a collaborative setting. This intervention aimed to measure participants' trust and confidence in working alongside cobots in I5.0 environments. The "After Experience" phase evaluates the impact of an immersive educational experience conducted in a digital cave setting. Participants engage in interactive, risk-free sessions designed to deepen their understanding and comfort with HCM technologies. A modified version of the initial survey is used to measure changes in participants' perceptions, including shifts in safety beliefs, reduction in fear or anxiety, and improved perceptions of the accessibility and usability of HCM tools. Additionally, this phase assesses participants' sense of empowerment and confidence when interacting with advanced technologies. By comparing data from before and after the intervention, the study offers a comprehensive analysis of how immersive learning impacts participants' understanding and engagement with HCM technologies. This two-phase design ensures a systematic evaluation of both baseline conditions and the transformative effects of educational interventions in the context of I5.0.

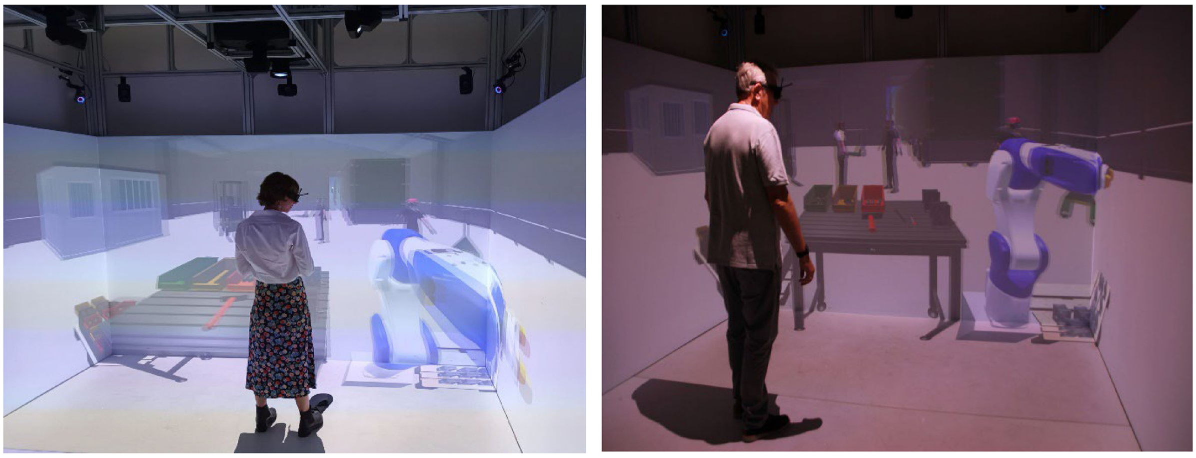

Figure 1. Participants inside a digital cave environment

5. Results and observations

The pilot workshop was conducted at MADE Competence Center in Milan with 52 participants from academia (engineering students) and industry (a mix of roles and sectors). The majority of the participants were males with about 65.3% males and 34.6% females. Regarding the age, the population were 28.8% between 18 and 24 years old, 42.3% between 25 and 34 years old, and 28.8% above the age of 35 years old. The students were also divided based on their academic degree: 5.7% of participants were currently enrolled in a bachelor's degree, 32.6% were enrolled in a master's degree and the remaining 11.5% were pursuing a PhD degree. Consequently, 45% of the participants were students, while 55% were industry practitioners. The involvement of different age groups and both genders greatly added to the research, hence rendering balanced and inclusive outcomes. The demographic features of the respondents are of importance in relation to the understanding of the broader applicability and effectiveness of human-centered design in the transformative learning factories framework of I5.0.
For data collection, a survey was administered through a series of questionnaires given to participants during their experiences in various LFs. Each respondent was required to complete two questionnaires before and after the LF experience. The surveys were distributed via a QR code, which participants could scan to access the google forms hosting the questions. To assess participants' perceptions of HCM in I5.0, a 12-question survey was designed, covering prior knowledge, safety, inclusivity, empowerment, and confidence in using AR/VR and cobot technologies. Questions on safety, inclusivity, and empowerment were strategically framed to evaluate the effectiveness of immersive learning in reinforcing these principles. Responses were collected using a five-point Likert scale, chosen for its ability to capture perception shifts. However, potential biases, such as response and social desirability bias, were considered (Heo et al., 2022). Efforts were made to minimize priming effects and literature bias, ensuring

an unbiased assessment of AR/VR-enhanced learning factories in fostering I5.0 competencies. The results of the questionaries are presented below (Table 1). For result analysis, qualitative data were converted into quantitative data for descriptive statistical analysis.

Table 1. Analysis of survey results based on respondent feedback

	How do you rate the safety associated with the use of cobots?		How do you rate the safety associated with the use of VR?		How does virtual design influence your confidence in creating new products/processes?		How accessible are these technologies to diverse backgrounds and professional profiles?		How simple is it to Implement VR Technologies in an industrial setting?	
Students										
	Before	After	Before	After	Before	After	Before	After	Before	After
Mean	3.48	4.57	3.61	4.35	3.54	3.83	3.17	3.57	2.22	2.91
Std	1.06	0.82	1.05	1.00	0.91	1.17	1.05	1.21	0.72	1.44
Median	3	5	3	5	3	3	3	3	2	3
Practitioners										
Mean	3.38	4.17	3.21	4.17	3.69	3.79	2.93	3.66	2.69	3.48
Std	1.06	0.99	1.00	0.99	0.95	1.13	1.05	1.09	1.02	0.97
Median	3	5	3	5	3	3	3	3	3	3
Overall										
Mean	3.42	4.35	3.38	4.25	3.54	3.81	3.04	3.62	2.48	3.23
Std	1.06	0.94	1.04	1.00	0.95	1.14	1.06	1.15	0.93	1.23
Median	3	5	3	5	3	3	3	3	2.5	3

Students showed a significant increase in their perception of safety with collaborative robots (3.48 → 4.57) and Virtual Reality (3.61 → 4.35) after the LF experience, with median values shifting from 3 to 5. Their confidence in virtual design and belief in technology accessibility also improved, though less dramatically. The biggest improvement was seen in their perception of how simple it is to implement VR in an industrial setting, increasing from 2.22 to 2.91, suggesting that hands-on experience enhanced their understanding of VR's practicality. Practitioners also reported improvements across all categories, but to a lesser extent compared to students. Their perception of cobot safety increased from 3.38 to 4.17, and VR safety from 3.21 to 4.17. Their view on VR accessibility and implementation ease improved more moderately, indicating that while the immersive experience was beneficial, prior industry exposure may have tempered their initial skepticism less than in students. The combined results show a positive shift in all areas, with safety perceptions (3.42 → 4.35 for cobots, 3.38 → 4.25 for VR) showing the highest improvement. The biggest challenge remains the perceived ease of implementing VR in industry, which, despite an increase from 2.48 to 3.23, still lags behind other categories. This suggests that while immersive learning is effective in enhancing safety perceptions and empowerment, more exposure or industry case studies may be needed to convince participants of the feasibility of integrating VR into real-world manufacturing processes.
The comparison between students and practitioners reveals that students exhibited a greater improvement in their perceptions of safety, inclusivity, and empowerment after the LF experience. Students showed a larger increase in confidence with collaborative robots (3.48 → 4.57) and VR safety (3.61 → 4.35) compared to practitioners (3.38 → 4.17 and 3.21 → 4.17, respectively). Similarly, their views on the ease of implementing VR in industry improved more significantly (2.22 → 2.91) compared to practitioners (2.69 → 3.48). This suggests that students, being less exposed to industry settings, had more room for perception shifts, making them more receptive to AR/VR-enhanced learning. The promising side is with students, as their increased confidence and openness to technology indicate a strong potential for future industry adaptation, whereas practitioners, while benefiting from the experience, showed a more gradual shift, likely due to their prior exposure and practical industry constraints.
Moreover, Table 1 shows positive shifts in perceptions and confidence regarding VR technologies. Initially, many respondents had little to no VR experience, but exposure improved views on safety, inclusivity, and empowerment. More participants rated VR as highly safe and accessible, while

confidence in using VR for designing products and industrial applications increased. When completing tasks in the CAVE environment, most reported high confidence. These findings highlight the learning factories' success in fostering understanding of HCM principles.

Table 2. Additional pre and post experience questions

	Pre-Experience			Post-Experience		
	How familiar are you with the concept of HCM?	Have you worked with Collaborative Robots before?	Have you worked with VR/AR before?	How would you rate your level of fear when interacting with the collaborative robot?	How would you rate your level of fear when the collaborative robot collided with you?	How confident did you feel using these technologies to successfully complete the task within the Cave?
Students						
Mean	2.65	1.57	1.96	4.22	1.61	4.48
Std	1.05	0.88	0.95	1.32	0.97	0.88
Median	2	1	2	5	1	5
Practitioners						
Mean	2.62	1.38	2.00	4.10	1.62	4.17
Std	0.81	0.61	1.08	1.35	1.00	0.99
Median	2	1	2	5	1	5
Overall						
Mean	2.63	1.46	1.98	4.15	1.62	4.31
Std	0.92	0.75	1.03	1.34	0.98	0.95
Median	2	1	2	5	1	5

As shown in Table 2, students and practitioners showed similar trends, but students exhibited greater adaptability to AR/VR technologies. Practitioners had slightly more prior familiarity with HCM, Cobots, and VR/AR, yet both groups had limited hands-on experience. Students reported higher initial fear (4.22 vs. 4.10), but both groups had similarly low fear (1.61 vs. 1.62) after the cobot crash scenario, indicating improved safety perception. Students felt more confident (4.48 vs. 4.17) in using AR/VR technologies, suggesting they were more receptive to immersive learning, while practitioners remained more cautious despite improvements.

6. Discussion

We have gained valuable insights into how various stakeholders perceive and engage with the core principles of human-centered design in manufacturing. From the individual worker's perspective, HCM is associated with enhanced safety, confidence, empowerment, and inclusivity, aligning with the pillars of collaboration and symbiosis, empowerment and inclusivity, and safety and ergonomics. This highlights the benefits of prioritizing human well-being and capabilities in production processes. Specifically, the study discovered that following their encounters with Cobots and VR/AR technologies, individuals showed noticeably higher levels of confidence, and greater perceptions of safety and accessibility. From the organizational perspective, HCM principles promote staff retention, job satisfaction, and productivity, aligning closely with the pillars of empowerment and inclusivity and collaboration and symbiosis, reinforcing the idea that a supportive workforce drives organizational success. From the business perspective, HCM fosters creativity, adaptability, and flexibility, aligning with the pillars of safety and ergonomics, and collaboration and symbiosis. This underscores the importance of balancing technological advancements with human ingenuity to sustain competitiveness. At the societal level, HCM contributes to sustainable development, social inclusion, and well-being, aligning with the pillar of empowerment and inclusivity, emphasizing the broader societal benefits of ethical and human-focused manufacturing. Additional discussion can be seen below (Table 3).
The table shows the percentage of participants with positive perceptions before and after the learning factory experience for the three HCM pillars: safety, inclusivity, and empowerment. The % increment column highlights the improvement in perceptions, with Empowerment showing the largest increase

(44.23%), followed by Inclusivity (32.69%) and Safety (13.46%). This demonstrates the success of the learning factories in enhancing participants' understanding and confidence regarding the core principles of HCM linked to I5.0.

Table 3. Participants' perceptions of HCM principles pre and post LF experience

Pillar	Positive Before (%)	Positive After (%)	Change (%)
Safety	59.62%	73.08%	13.46%
Inclusivity	48.08%	80.77%	32.69%
Empowerment	42.31%	86.54%	44.23%

7. Conclusions, limitations and future works

This study effectively addressed the research question by demonstrating how AR/VR technologies can enhance LFs to teach HCM principles of I5.0 namely safety, inclusivity, and empowerment. The results showed that immersive experiences significantly improved participants' confidence in using cobots, understanding safety, and perception of technology accessibility. Students exhibited greater adaptability than industry practitioners, highlighting the potential of AR/VR-based education in preparing future professionals for human-centric smart manufacturing. One key limitation is the evaluation of VR safety primarily from the user perspective, introducing potential biases in experience-based assessments. However, since users are central to implementation, their perceptions remain critical in assessing VR's practical impact. Additionally, the study was limited in sample size and short-term evaluation, affecting generalizability and long-term learning assessment. Lastly, skepticism about VR's feasibility in real industrial environments indicates the need for further exploration of cost, infrastructure, and integration challenges. Further studies should explore the long-term effects of AR/VR training on job readiness, adaptive learning systems, and cross-sector applications. Integrating mixed reality and AI-driven learning could enhance engagement. Ethical considerations of prolonged VR exposure should also be addressed to ensure inclusive and safe industrial education. Additionally, future studies should aim to expand the participant pool to improve the generalizability of findings and incorporate a more diverse demographic. Further quantitative analyses, such as measuring participants' physical reactions to fear stimuli in the CAVE, can provide deeper insights. Comparative studies focusing on fear and empowerment when interacting with collaborative versus non-collaborative robots are recommended, as well as longitudinal analyses to evaluate the long-term retention of I5.0 concepts. Finally, exploring broader applications of AR/VR for teaching other industrial concepts could extend the impact of this research.

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