Guidelines for Designing Engineering Education in the Context of Industry 4.0 and 5.0

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Abstract. This paper presents a set of guidelines to facilitate in the design of engineering education in the context of I4.0 and I5.0. Based on current trends, the paper examines the evolving expectations for engineering competencies, considering technological changes and a shift towards more human-centric, sustainable, and resilient industrial systems. Through the integration of a Learning Factory and experiential learning, the authors propose a pedagogical framework tailored to the expectations of higher education and modern industry. Through a multifaceted learning domain, interdisciplinary skills, digital fluency, and soft skills, such as creativity and collaboration, are fostered to prepare engineers for the complexities of future industrial work. The guidelines are informed by literature analysis and practical insights drawn from academic-industry collaborations, to bridge the gap between theoretical education and real-world application.

Keywords: Industry 4.0 · Industry 5.0 · Learning Factories · Engineering Education · Experiential Learning · Higher Education · Guidelines

1 Introduction

The accelerating pace of technological advancement, exemplified by Industry 4.0 (I4.0) and subsequently Industry 5.0 (I5.0), has transformed the skills demand for new engineering graduates [1]. This shift requires individuals to be not only technically proficient but also capable of adapting, collaborating, and working in a multi-dimensional team to problem-solve [2]. In the light of the transformative goals of I5.0, it is necessary to ensure engineering students possess the requisite skills and competencies to navigate the challenges of this new industrial paradigm. While I5.0 is a relatively recent development, the discussion on aligning education with technological trends has been ongoing for many years [3]. Similar educational challenges were encountered during the transition to I4.0, where organizations faced increased complexity in manufacturing systems and more demanding qualification requirements for engineering graduates entering the workforce. Innovations and the broader digital industrial transformation

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have the potential to affect nearly every aspect of industry, necessitating heightened skills, and a stronger conceptualization of the interconnections and complexity in work processes [4]. As a result, a revised educational approach and pedagogical model is needed to meet the needs of industry and meet the expectations of students [5].

1.1 Research Motivation

The transition toward I4.0 and I5.0 introduces profound changes in workforce requirements, challenging traditional educational models. Existing curricula often lack integration of the multidisciplinary skills and experiential learning necessary to equip students with competencies like advanced digital literacy, human-technology collaboration, and resilience—competencies essential in I4.0 and I5.0 environments. Considering these demands, higher education institutions (HEIs) are increasingly expected to redesign their programs to produce graduates who are both technologically literate and human-centred in their approach. Traditional lecture-based, content-heavy instruction models no longer suffice; instead, learning environments must become flexible, immersive, and closely aligned with real-world industrial practices [6]. However, rapid technological advancement challenges standard educational delivery, while tight budgets and high costs of advanced technology impede effective skill integration [7]. Learning Factories (LFs) offer a viable solution, providing secure, regulated environments for hands-on experience with industrial processes and emerging technologies [8]. This experiential learning is critical for preparing engineers amidst the ongoing development of I5.0 alongside I4.0 implementation [9]. LFs bridge the gap between theoretical knowledge and real-world industrial demands, fostering both intellectual and practical skills essential for deeply intertwined digital-physical systems [10].

This paper advances beyond theoretical framing to practical application, addressing how effective learning experiences can be designed. It develops guidelines for HEIs to incorporate in the designing of learning spaces, formulation of pedagogical strategies, and deployment of enabling technologies. Drawing on empirical research, expert interviews, and literature reviews, it provides concrete recommendations to enhance curriculum delivery, improve engagement, and foster future-proof skills.

2 Context and Research Objectives

The acquisition of knowledge and the development of skills are downstream in the educational path that the students navigate throughout their career, even being considered the main outcome of the overall learning experience according to some approaches [11]. Addressing the challenge presented above, thus, requires an understanding of three key factors that shape students' learning experience: the contents (knowledge and skills) that students should possess, the way in which these contents are learned and should be taught, and the way in which the spaces where learning takes place should be designed [12]. In a study by Dehbozorgi et al. [2], the integration of key educational components namely pedagogy, learning spaces, and technology support the development of future-ready engineers. That research resulted in a conceptual framework that provided a high-level understanding of how learning experiences can be structured to meet the demands of

I4.0 and I5.0 (see Fig. 1). Central to that exploration was the role of LFs experiential learning environments that simulate real industrial conditions to bridge the gap between classroom learning and workplace application [13].

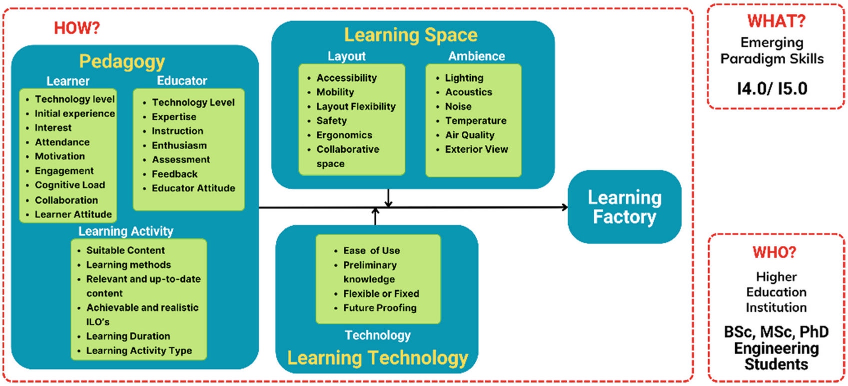

Fig. 1. Holistic view of the conceptual framework [2]

2.1 Research Approach

The preliminary literature review has helped identify key research objectives and gaps. Table 1 provides a visual representation of the proposed research approach.

Table 1. Structured Research Approach

Research Gap (G)	Research Objective (O)	Research Question (RQ)
G1: Ineffective Higher Education Strategies for Imparting Critical Skills [14] G2: Lack of Integration of Experiential Learning into Engineering Curricula [15]	O1: Develop guidelines for designing effective learning environments in engineering education, particularly for emerging I4.0/I5.0 paradigms	RQ1: What are the key guidelines for designing effective learning environments in engineering education that meet the demands of I4.0 and I5.0 paradigms?
Methodology: Scoping Review, Empirical Research: Learning Factory Session		
Expected Outcomes		
1. Comprehensive guidelines for designing learning environments that foster essential competencies and prepare students for future challenges	2. Enhanced understanding of how experiential learning improves student engagement, motivation, and knowledge retention, and concrete guidelines for integrating such approaches into curricula	

The research question was formulated to address the critical need for effective design strategies in engineering education that can bridge the gap between theoretical knowledge and practical skills, particularly in the evolving contexts of I4.0 and I5.0, where technological advancements and human-centric approaches demand new pedagogical frameworks. The methodology focuses on investigating learning environments that simulate Industry 5.0 production settings, enabling empirical analysis of how experiential learning, technology integration, and flexible spaces support competency development aligned with I4.0 and I5.0 requirements.

3 Methodology

To empirically investigate effective engineering education approaches aligned with Industry 5.0, a LF experience was designed to simulate a modern I5.0 production line. The pilot session took place at the MADE Competence Center in Milan and involved engineering students who engaged in three key technologies: virtual product development, Lean 4.0 and smart assembly, and collaborative robots with exoskeletons. The primary goal was to assess the significance of various factors influencing participants' overall learning experience and to analyse the impact of each component within this simulated environment. The pilot was conducted in close collaboration with university faculty, who played a critical role in refining the LF intervention to ensure clarity, coherence, and strong educational value. During the session, trained technical engineers guided students through hands-on activities and subsequently administered a post-experience survey to collect immediate feedback. Empirical data gathered through this approach supports a comprehensive exploration of how learning experiences can be effectively designed in the context of emerging industrial technologies and pedagogical paradigms. Data was collected through a structured questionnaire, allowing participants to access the survey immediately after completing the LF session. The survey was carefully constructed based on key variables outlined in Fig. 1, encompassing pedagogy, learning technology, and space dimensions. These variables addressed learner and educator characteristics, teaching methods, and environmental factors influencing the learning process. Responses were measured using a five-point Likert scale to capture participants' perceptions and shifts in their attitudes toward these factors. To ensure the reliability and validity of the survey, potential biases, including response bias and social desirability bias, were carefully considered and measures were taken to minimize priming effects and literature bias.

4 Scoping Literature Review

To address the research question, this paper employed a mixed-method approach consisting of a scoping literature review and empirical research. This dual approach ensured both theoretical breadth and practical depth, allowing for the development of comprehensive, evidence-based design guidelines for future-oriented learning environments. Given the multi-dimensional nature of learning experience design namely pedagogy, space, and technology. This method allowed for greater flexibility in capturing relevant educational, technological, and industrial design insights. The references for this review were identified through comprehensive searches conducted in Scopus and Web of Science. The inclusion criteria for this review as seen in Table 2, were as follows: (a) original research articles; (b) published within the last decade; (c) published in English; and (d) alignment with the conceptual framework of this study. The exclusion criteria were: (a) articles not published in English; (b) commentaries or editorials; and (c) other review articles. Initial screening involved reviewing titles and abstracts, followed by a detailed full-text assessment of potentially relevant articles. The initial search retrieved 237 articles. After removing 115 irrelevant or duplicate records, 122 articles remained. Of these, 51 were excluded based on relevance and eligibility criteria, resulting in 71 studies included in this review. Search Strings Used in Scopus and Web of Science:

(TITLE-ABS-KEY ("learning space" OR "learning place*" OR "learning activity*" OR "learning experienc*" OR "learning factory" OR "teaching factory") AND TITLE-ABS-KEY ("higher education" OR "industrial engineering") AND TITLE-ABS-KEY ("technology*" OR "industry* 4.0" OR "digital transformation" OR "industry* 5.0′′)) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA, "ENGI")) AND (LIMIT-TO (LANGUAGE, "English")).*

Table 2. Phases of the article selection based on the PRISMA [16]

Stage	Description	Number of Articles
Identification	Articles Reviewed from Scopus and WoS	237
Screening	Articles screened on title, keywords and abstract	122
Eligibility	Full-text articles assessed for eligibility	71
Included	Articles included in the Scoping Review	71

This section establishes comprehensive guidelines for creating effective learning experiences, drawn from an extensive review of relevant literature. These guidelines are designed to help educators, instructional designers, and institutions develop engaging, flexible, and future-oriented learning environments that meet the evolving demands of both students and the engineering industry. The design of learning spaces, pedagogy, and the use of technology are essential for creating effective educational environments. Well-designed learning spaces enhance engagement and collaboration [17]. Pedagogy focuses on active learning approaches [18], while learning technologies, facilitate experiential learning and skill development [19]. Learning theories transitioned from behaviourism to constructivism and connectivism, emphasizing collaboration, interaction, and self-regulation [20]. Learning environments shifted from traditional classroom setups to project-based and flexible learning spaces to support active social learning [21]. A study by Wang et al. [22] delved into how game elements in Kahoot! particularly points and audio, influence student engagement. The study suggested that audio, when combined with the use of points, has the most significant impact on student interaction. In contrast, Chaiyo et al. [23] examined the effects of three different gamification tools on student engagement, enjoyment, concentration, perceived learning, satisfaction, and motivation in lessons. Moreover, motivation is particularly crucial, and designing tools that engage students is essential for success. Flexibility is also critical, allowing students to adapt their learning to fit their individual styles and needs. By focusing on learner-centric approaches, educators can better address the diverse preferences of students, ultimately improving the effectiveness of the learning process [24]. The design of the physical learning environment also plays a key role in supporting collaboration and student comfort. Drawing inspiration from co-working spaces, the space was designed to transcend a traditional classroom. This shift in atmosphere fosters a more welcoming and comfortable space for collaboration [25]. Design choices to support communication and teamwork such as the technology selection, and placement of lounges and whiteboards in visible areas. Additionally modern lighting and exposed industrial ceilings gave the space a creative, open feel [17]. These design elements support well-known educational practices that emphasize active learning, student interaction, and collaboration. One widely recognized framework is the Seven Principles for Good Practice in Undergraduate Education [26], which highlights the importance of engagement, peer collaboration, and timely feedback. The design of learning spaces has become a key area of focus in higher education research, with various scholars proposing frameworks to enhance the connection between physical environments and student experiences. [27] examine how educational environments interact with the individuals who use them, emphasizing that learning spaces reflect the collective characteristics of their users. Their work highlights the importance of both physical and social aspects in shaping these environments, and how these factors influence user interaction and engagement. [28] extend this perspective by proposing a set of design principles that incorporate emotional and cultural dimensions of space. Their principles include comfort, aesthetics, flow, equity, blending, affordances, and repurposing. These elements acknowledge the diverse needs of learners and consider how physical and virtual resources, such as technology and spatial flexibility, impacts students' mental and physical well-being. [29] also contributes to the conversation by outlining guiding principles that support student-centred learning.

Building on previous work, [38] proposed a design approach based on the National Survey of Student Engagement (NSSE) themes. While not covering all variables in broader models, it offers practical guidance for linking physical spaces with educational goals. The approach outlines five principles for exemplary learning environments. The first, Academic Challenge, emphasizes spaces that encourage deep engagement with course material through flexible furniture, accessible infrastructure, and supportive lighting and colour. Learning with Peers highlights spaces for both individual and collaborative learning, featuring movable seating, writable surfaces, and effective acoustics. Moreover, studies emphasize the integration of environmental factors like lighting, acoustics, and air quality, which are crucial for creating comfortable and productive learning atmospheres that support focus and minimize distractions [30]. To complement the literature, an experimental study was conducted as a LF session simulating a modern I5.0 production line. This allowed students to engage with advanced manufacturing technologies in a controlled, hands-on setting. Such experiments effectively capture real-time learning behaviours and the impact of pedagogical and environmental factors [10]. This approach is widely recognized in educational research for validating theoretical frameworks and guiding practical design in engineering education [31].

5 Results

The pilot LF session was conducted at MADE Competence Center with 32 engineering students where they were invited to perform the LF on 3 main technologies of virtual product development, lean 4.0 and smart assembly, collaborative robots and exoskeletons. The majority of the participants were males, with about 69.7% males and 30.3% females. The participant group comprised 7 bachelor's (21.21%), 17 master's (51.52%), and 9 PhD students (27.21%, with the age distribution of participants showed that 48.48% were between 25–34 years old, 45.45% were between 18–24, and 6.06% were within the 35–44 age range. The guidelines were developed by first surveying students during the empirical LF session to identify the variables they considered most important for their learning experience. The most emphasized variables were then synthesized and transformed into design guidelines for effective learning, particularly in the context of I4.0 and I5.0. These guidelines serve as a practical toolkit for educators and institutional leaders seeking to implement or enhance experiential learning models, particularly within engineering and technical programs. Importantly, they are not prescriptive, but rather modular and scalable, allowing institutions to tailor implementation according to their resources, student demographics, and program goals. Additionally, these findings offer insights for reflection on the structuring of the specific Learning Activities (LA). These guidelines are organized in tables below. The guidelines are categorized based on literature and empirical research findings. Pedagogical guidelines are presented in Table 3, and Table 4, space-related guidelines in Table 5 and Table 6, and technological guidelines in Table 7, and Table 8.

Table 3. Pedagogical Guidelines – Direct Literature

Learning Approach	
Guidelines	Direct Literature
Experiential Learning	Engage students in practical, hands-on experiences where they apply theoretical knowledge in real-world scenarios. Encourage internships, mentoring, workshops, learning factories, and collaborative projects to foster experiential learning [32]
Active Pedagogy	Incorporate active learning techniques such as project-based learning, problem-solving, flipped classrooms, and game-based pedagogy. This encourages engagement and participation from learners [18]
Gamification	Use gamification tools (e.g., Kahoot!, Quizizz) to increase engagement, motivation, and enjoyment in learning activities. Implement elements like audio and point systems to enhance student interaction [22]

(*continued*)

Table 3. (*continued*)

Learning Approach	
Guidelines	Direct Literature
Reflection and Emotional Investment	Design learning activities that personally resonate with students, fostering emotional engagement. This deeper involvement enhances motivation, retention, and overall learning impact [33]
Collaborative Learning	Design activities that encourage peer-to-peer learning and foster meaningful relationships between learners and instructors. Include group projects and discussions to enhance collaboration [34]
Multi-disciplinary Learning	Incorporate interdisciplinary approaches that reflect real-world industrial systems, blending subjects such as IT and industrial engineering [35]
Problem-Based Learning	Encourage learners to tackle real-world problems, promoting critical thinking and problem-solving skills [36]
Project-Based Learning	Focus on real-world applications through project-based activities, simulations, and collaborative projects [37]
Motivation & Engagement	Prioritize activities that enhance student motivation and engagement. Design learning tasks that are intrinsically interesting and foster curiosity [38]
Learning Style Accommodation	Design learning experiences that accommodate various learning styles and cultural backgrounds [39]
Diverse Content Delivery	Use multimedia, including text, video, and audio, to cater to diverse learning preferences [40]
Student Engagement	Research on active participation through discussions, peer interaction, and projects [41]
Cultural Sensitivity	Acknowledge and plan for diversity in cultural communication and educational values, ensuring inclusivity for all learners [39]
Student Contribution	Create meaningful opportunities for learners to engage with the content, their peers, and instructors. This could be through discussions, interactive sessions, or hands-on projects [36]
Instructor's Role	Instructors should act as facilitators, providing guidance while allowing students the freedom to explore and solve problems independently. Educators should foster a safe, judgment-free space to encourage experimentation and creativity [42]

(*continued*)

Table 3. (*continued*)

Learning Approach	
Guidelines	Direct Literature
Assessment & Feedback	Incorporate multiple forms of assessment, including projects, quizzes, presentations, and self-assessment. Continuous feedback should be provided to guide students in their learning journey [43]
Flexible Learning	Ensure the flexibility of learning, allowing students to adapt to their individual learning styles, needs, and preferences. Flexibility in time management and learning pace is essential [44]
Reflection & Self-Regulation	Encourage students to reflect on their learning processes and experiences. Provide spaces conducive to self-regulation, including quiet zones to avoid distractions [20]
Personalized Learning Paths	Design learning activities that cater to individual students' learning preferences, cultural backgrounds, and language differences. Personalized learning systems should allow students to navigate their own educational experiences [39]
Project-Based Learning	Broader perspectives on how project-based learning enhances skills like collaboration and innovation [45]
Student Engagement	Broader studies suggesting interactive sessions help learners engage more meaningfully with content [46]
Cultural Sensitivity	Studies discuss the importance of acknowledging and adapting to cultural differences in education [47]

Table 4. Pedagogical Guidelines – Empirical Research

Learning Approach	
Guidelines	Empirical Research
Achievable Outcomes	Design learning activities with clear, realistic goals to provide learners with a sense of progress and accomplishment
Interest in Learning Activities	Ensure that learning activities are aligned with students' interests and relevant to real-world applications, particularly in engineering, where complex concepts need sustained attention

(*continued*)

Table 4. (*continued*)

Learning Approach	
Guidelines	Empirical Research
Industry-Relevant Content	Ensure that the learning content is current and aligned with industry standards to prepare students for future job market demands
Motivation & Engagement	Create relevant, hands-on activities that align with students' interests to boost motivation. Use interactive tools and achievable challenges to maintain focus and engagement throughout the learning process
Clarity in Explanation	Educators should focus on delivering clear explanations, especially when covering complex technical content. This ensures learners can follow along and grasp critical concepts
Enthusiasm and Passion	Instructors should convey enthusiasm and passion for the subject matter, as this creates a more dynamic, interactive learning environment and encourages greater student participation

Table 5. Learning Space Guidelines – Direct Literature

Layout	
Guidelines	Direct Literature
Flexible and Adaptable Layout	Design spaces with movable furniture, such as round tables, movable chairs, and whiteboards. Flexible seating arrangements, such as U-shaped desks or sofas, enable various configurations based on the activity [48]
Collaborative Zones	Include multipurpose open areas divided into zones with adaptable furniture for group work, informal meetings, and individual study. This helps create a collaborative learning atmosphere [49]
Informal Learning Spaces	Incorporate "third places" such as cafés, libraries, lounge areas, and social seating arrangements to support informal learning and social interaction [30]
Personal Learning Spaces	Design quiet, enclosed areas for focused individual work with minimal distractions. This should include individual carrels and noise-free environments [50]
Technology-rich Environments	Equip classrooms and learning spaces with work surfaces for advanced technology, including projectors, personal screens, digital whiteboards, and collaborative tools such as LMS (Learning Management Systems) [44]

(*continued*)

Table 5. (*continued*)

Layout	
Guidelines	Direct Literature
Inclusivity in Space Design	Ensure that learning spaces follow the principles of Universal Design, making them accessible to all students, including those with disabilities. Integrate digital tools and assistive devices to accommodate diverse learners [51]
Sustainable Design	Adopt sustainable practices in the design of learning spaces, considering energy-efficient technologies, environmentally friendly materials, and responsible waste management [52]
Scalability and Future Flexibility	Ensure that learning spaces are designed with scalability in mind, allowing for future adaptations based on technological advancements or changing educational needs [53]
Integration with Campus Master Plan	Learning spaces should fit within the larger campus infrastructure, enabling seamless transitions between formal and informal learning spaces [54]
Hybrid Learning Spaces	Support the development of hybrid learning spaces that combine both physical and virtual elements, enabling students to participate in a dynamic and flexible learning environment [55]
Acoustics	Ensure the learning space has controlled sound zones, with appropriate acoustic design to minimize distractions from both inside and outside the environment [30]
Lighting and Colours	Use adjustable lighting and colour schemes to create an environment conducive to different learning tasks. Appropriate lighting is crucial for maintaining focus, while colours can be used to define different functional areas [56]
Air Quality and Temperature	Provide a comfortable learning atmosphere with regulated air quality, lighting, and temperature to ensure that learners remain comfortable and focused [57]
Physical and Sensory Environment	Include comfortable furniture, appropriate noise levels, and ergonomic designs to ensure that students feel comfortable in their learning spaces. Integrating aesthetic elements like decoration and colour can also improve motivation [46]

Table 6. Learning Space Guidelines – Empirical Research

Layout	
Guidelines	Empirical Research
Physical Safety	Prioritize physical safety in the design of learning spaces, particularly in hands-on environments where students may interact with machinery or technical equipment
Ergonomics	Ensure the space is ergonomically designed to enhance student comfort and reduce fatigue, which supports longer engagement and better concentration
Pedagogical Foundation	Ensure the space is ergonomically designed to enhance student comfort and reduce fatigue, which supports longer engagement and better concentration
Thermal Quality	Maintain optimal thermal conditions to avoid discomfort and distractions, thus enhancing learners' focus during technical activities
Cleanliness	Keep the learning environment clean and hygienic, as this fosters a conducive and healthy atmosphere that supports learning and engagement

Table 7. Technology Guidelines – Direct Research

Technology	
Guidelines	Direct Literature
Integration of Smart Technologies	Utilize smart classrooms that include tools like smart boards, interactive displays, virtual and augmented reality to enhance the learning experience [58]
Learning Management Systems (LMS)	Provide tools like LMS, virtual studios, and mobile learning apps that support both synchronous and asynchronous learning [59]
Virtual LFs	Provide virtual environments for students to experience real-world industrial processes digitally, enhancing their skills in experimentation, data gathering, and problem-solving [60]
Interactive Platforms	Employ tools like virtual labs, digital whiteboards, and mobile collaboration devices to support active learning beyond the classroom [61]

(*continued*)

Table 7. (*continued*)

Technology	
Guidelines	Direct Literature
Use of Emerging Technologies	Explore new technologies such as IoT, augmented reality, artificial intelligence, and immersive environments to create innovative learning experiences [62]
Ubiquitous Learning Spaces	Use technology to create a learning environment that is accessible from any location, integrating wireless networks, mobile devices, virtual labs, and digital learning platforms
Adaptive Learning Systems	Implement adaptive learning platforms that adjust content based on learner performance and preferences, helping personalize the learning experience [63]
Flexible Technology Use	Offer flexible access to technology, such as laptops, tablets, and 3D printers, to enable personalized and dynamic learning

Table 8. Technology Guidelines – Empirical Research

Technology	
Guidelines	Empirical Research
Future-Proof Technology	Select technologies that are adaptable and scalable to future trends in engineering, minimizing the need for constant updates while staying relevant
Ease of Use	Choose user-friendly technologies that are intuitive for both learners and educators, reducing the cognitive load associated with using the tools and allowing more focus on learning

6 Discussion and Conclusion

The findings presented in this study contribute directly to addressing two of the most persistent challenges in contemporary engineering education: the lack of strategic frameworks for critical skill development (Gap 1) and the insufficient integration of experiential learning models into formal curricula (Gap 2). By developing a set of empirically informed and literature-supported guidelines, this research offers a strategic response to Gap 1, enabling HEIs to systematically design learning experiences that go beyond traditional instructional models. These guidelines provide educators and instructional designers with actionable tools to structure learning environments that are both academically rigorous and practically relevant. Rather than treating pedagogy, space, and technology as separate concerns, the proposed framework promotes an integrated approach that aligns these dimensions with the competencies demanded by I4.0 and I5.0. Some guidelines, including Project-Based Learning, Motivation & Engagement, and Student Engagement, overlap between the literature review and empirical research findings, reinforcing their importance in engineering education. However, other guidelines contribute unique, complementary perspectives that broaden the understanding of designing effective learning environments. In relation to Gap 2, the study repositions experiential learning, particularly through LFs, from being a supplemental or peripheral activity to a core pedagogical strategy. LFs act as catalysts for skill development by offering real-world, simulated environments where students can apply theoretical knowledge, make decisions, collaborate in teams, and engage with emerging technologies. These experiences bridge the divide between academic knowledge and industrial application, effectively blending the conceptual with the practical. The pedagogical value of experiential learning lies in its ability to contextualize content, promote reflection, and develop higher-order thinking skills. Unlike conventional classroom settings, LFs provide students with the opportunity to engage in problem-solving within authentic, consequence-driven scenarios. This aligns closely with the needs of modern industry, where engineers must be capable of working in complex, uncertain, and technology-rich environments. Moreover, survey and empirical data highlight the effectiveness of experiential learning, technology use, and adaptable learning spaces in developing the competencies demanded by I4.0 and I5.0. Notably, students showed increased engagement and motivation when interacting with I5.0-relevant technologies such as collaborative robots and smart assembly systems, underscoring the importance of integrating these elements into the engineering curricula. In sum, the guidelines presented here serve not only as a response to existing gaps but also as a forward-looking framework that empowers educational institutions to innovate their teaching practices. They promote a shift from static, content-heavy instruction to dynamic, learner-centred ecosystems capable of preparing students for a workforce increasingly shaped by digitalization, sustainability, and human-centric values.

6.1 Actionable Recommendations

To move beyond descriptive summaries, we have prioritized and synthesized the most impactful guidelines into a set of actionable recommendations. By contextualizing these recommendations with examples and practical considerations, we provide educators and institutions with a clearer roadmap to implement meaningful improvements aligned with I4.0 and I5.0.

1. Redesign at least one core course per semester using project- or problem-based learning frameworks linked to real industry challenges.
2. Repurpose underused physical areas (e.g., lounges, seminar rooms) into flexible collaboration zones with whiteboards and movable seating.
3. Adopt a "flipped classroom" model for key technical courses to free up class time for collaborative, hands-on sessions.
4. Form faculty-industry pairs to co-design and co-deliver course modules that reflect current industrial practices.
5. Create low-cost simulation labs or virtual LF environments using free/open-source tools where physical Learning Factories are not feasible.

6. Implement learning analytics via LMS platforms to track engagement and adapt instruction dynamically.
7. Introduce "design sprints" or hackathons once per semester as immersive, short-term experiential learning events.
8. Establish a student feedback loop that continuously refines space design and technology adoption based on usability and impact.
9. Provide micro-credentials or badges for competencies gained through LF activities and interdisciplinary collaboration.
10. Benchmark student outcomes annually against the competencies demanded by emerging I4.0/I5.0 job profiles to validate relevance.

6.2 Limitations and Future Works

Future research should focus on piloting the proposed guidelines across diverse higher education institutions to evaluate their adaptability in varying academic and cultural contexts. Additionally, longitudinal studies are recommended to assess the long-term impact of experiential learning environments, such as LFs on student skill development, employability, and post-graduation performance. These efforts will help refine the framework, ensuring its relevance, scalability, and effectiveness in shaping future-ready engineering education. Moreover, the research identified the need for continuous updates to the guidelines developed in this study, particularly as technology evolves. While the conceptual framework was validated, further empirical research is recommended to validate and refine the guidelines, ensuring they remain relevant to the ever-changing demands of industries driven by I4.0 and I5.0.

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