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Online and blended learning in engineering education: a review of developments and impact

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ABSTRACT

Although online and blended learning have become sturdy elements of engineering education, their educational usefulness is still debatable in situations when professional competency depends on experimentation, troubleshooting, and teamwork. The data on blended and flipped instruction, remote and virtual labs, immersive technology, learning analytics, and new artificial intelligence (AI) support in engineering education is compiled in this comprehensive narrative review. The review develops the tactile-digital gap as an analytical construct, guided by the perspectives of the community of inquiry (CoI) and technological pedagogical content knowledge (TPACK): the danger that advances in digital access and conceptual practice are not matched by comparable opportunities to develop embodied technical skills and professional identity. Four requirements are shared by successful hybrid models in the literature: learning outcomes dictate the choice of modality, online activity is dynamic and feedback-rich, digital laboratory work is sequenced with real-world physical practice, and institutions offer equitable access, faculty development, and quality assurance. Long-term evidence for practical competence and professional identity is still scarce, while the best evidence is found for conceptual achievement, adaptability, and self-direction. For post-pandemic engineering education, the review offers an integrative framework and design principles. It contends that adopting technology on its own is insufficient and that pedagogically integrated hybrid ecosystems that strike a balance between flexibility, experimentation, teamwork, and professional competence are necessary for high-quality engineering education.

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1. INTRODUCTION

Engineering education is being reshaped by digitalization, changing student demographics, pressures for flexibility, and the need to prepare graduates for complex socio-technical systems. Within this context, online and blended learning have become especially significant because they offer not only alternate delivery modes, but also alternate pedagogical logics. Online learning extends instruction through networked platforms, asynchronous resources, and data-rich learning environments. Blended learning, by contrast, is best understood as the deliberate integration of online and face-to-face experiences so that each mode performs functions for which it is pedagogically well suited [1], [2]. Foundational syntheses in higher education have shown that blended approaches often outperform either fully face-to-face or fully online formats when they are intentionally designed rather than merely digitized [3], [4]. In engineering, this question has special urgency because curricula must support conceptual understanding, design thinking, teamwork, experimentation, and professional judgment simultaneously [5].

Because engineering education produces not only knowledge acquisition but also design judgment, teamwork, experimentation, and tacit problem solving, it challenges typical assertions about the efficacy of online learning. While laboratory and professional-skill goals are still more difficult to replicate through digital replacement alone [6], [7], comparative studies show that online and classroom formats can yield comparable academic achievements under suitable settings [8], [9]. As a result, findings vary more because research look at various outcomes, disciplinary contexts, and institutional preparation levels than because one modality is inherently better.

The tactile-digital gap, which is the mismatch that occurs when digital access, simulation, or automated support develops conceptual capability without comparable opportunities for physical manipulation, troubleshooting under actual uncertainty, collaborative laboratory judgement, and professional identity formation, is introduced in this review to address that variation. Throughout the review, the construct is utilized to explain why highly interactive, sequenced hybrid designs are typically more defendable than either a total rejection of digitally mediated learning or an uncritical use of technology. Three contributions are also made by the review. In order to integrate learner engagement and teaching presence to technologically and disciplinarily suitable design, it first assesses the findings using the community of inquiry (CoI) and technological pedagogical content knowledge (TPACK) perspectives. Second, it evaluates evidence in terms of practical intensity, educational stage, resource situation, and implementation before and after the epidemic. Third, it converts the tactile-digital gap into design guidelines and an integrative framework for programs in hybrid engineering. The resultant conceptual ecology is shown in Figure 1.

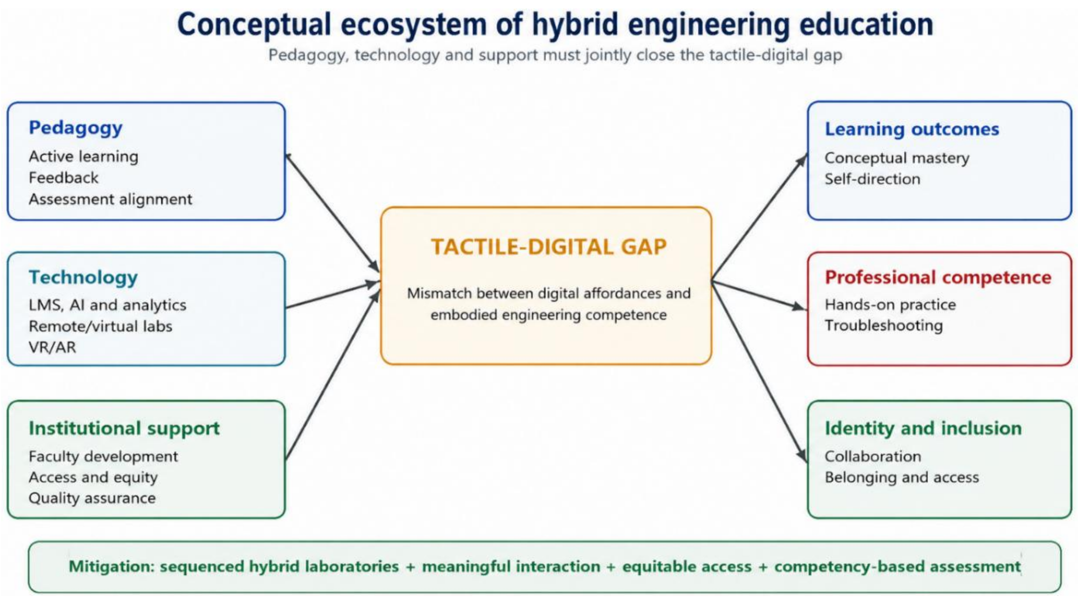

Figure 1. Conceptual ecosystem of hybrid engineering education centered on the tactile-digital gap

2. REVIEW METHODOLOGY

This article was conducted as a structured critical narrative review rather than as a systematic review or meta-analysis. The included literature corpus comprises peer-reviewed conceptual, empirical and synthesis studies on online, blended, flipped, virtual or remote laboratory, immersive, analytics-supported and artificial intelligence (AI)-related learning in engineering education, supplemented by foundational higher-education literature required to define the theoretical lenses. The corpus is concentrated on publications from 2001 to 2025, while earlier foundational sources were retained where conceptually necessary. The review questions were:

- Which online or blended designs are associated with positive engineering learning outcomes?
- Under what practical, social and institutional conditions do results differ?
- How can hybrid design preserve the embodied and professional dimensions of engineering education?

Search descriptors represented in the corpus included engineering education with online learning, blended learning, flipped classroom, remote laboratory, virtual laboratory, immersive technology, learning analytics, generative AI, student outcomes, faculty adoption, and institutional support.

Studies were included when they examined engineering education directly, or when closely related higher-education evidence provided an essential theoretical or meta-analytic basis for interpretation. Studies were excluded from the synthesis when they did not address teaching, learning, assessment, laboratory practice, implementation or institutional implications. Sources were compared against six analytical domains: pedagogy and mode integration; student outcomes; practical authenticity; social and teaching presence; faculty and institutional readiness; and access or equity. This approach supports analytical comparison and conceptual development while avoiding unsupported claims of exhaustive retrieval or pooled effects. A reproducible database-by-database search log and screening count should be maintained before any future claim of a fully systematic review.

3. THEORETICAL AND CONCEPTUAL FRAMEWORK

The CoI framework provides a strong lens for online and blended engineering learning because it identifies cognitive presence, social presence and teaching presence as mutually necessary for meaningful educational experience [10]. In engineering settings, cognitive presence concerns reasoning through design and technical problems; social presence concerns teamwork, belonging and professional discourse; and teaching presence concerns the design, facilitation and assessment needed to connect digital activities with disciplinary outcomes. This lens explains why flexible access alone may not generate engagement or persistence when interaction and guided feedback are weak.

TPACK complements CoI by shifting attention from tools to the intersection of technological knowledge, pedagogical knowledge and engineering content knowledge [11]. A simulation, remote laboratory or AI tool is pedagogically valuable only when it is aligned with what students must understand, perform and justify. Together, CoI and TPACK position digital transformation as an instructional-design problem: technology must support presence, disciplinary reasoning and authentic competency development rather than merely increase content delivery capacity.

Within these lenses, the tactile-digital gap is defined as the discrepancy between competencies readily supported through digitally mediated learning and competencies that require embodied experimentation, physical uncertainty, informal team coordination and situated professional judgement. The gap is not an argument against digital learning. It is a diagnostic construct that guides modality selection and sequencing: the wider the gap for a learning outcome, the stronger the need for authentic laboratory, studio or field-based validation. Table 1 operationalizes the construct and identifies practical mitigation strategies.

Table 1. Dimensions and mitigation strategies for the tactile-digital gap in engineering education

Dimension	Digital affordance	Risk when used alone	Hybrid mitigation
Physical manipulation	Simulation and remote control improve preparation and repetition.	Limited equipment handling and material interaction.	Use virtual/remote preparation before supervised physical practice.
Troubleshooting and uncertainty	Digital tasks enable repeatable scenarios and feedback.	Faults may be simplified and real uncertainty removed.	Include open-ended physical fault diagnosis and design validation.
Collaboration and identity	Online teams broaden access and document work.	Weaker informal interaction and professional socialization.	Sequence online collaboration with studio/lab teamwork and reflection.
Assessment authenticity	Analytics and automated tools increase formative feedback.	Grades may over-represent conceptual or procedural proxies.	Assess observable performance, judgement and safety in authentic tasks.
Equity and access	Flexible participation can widen opportunity.	Hardware, bandwidth and specialist software burdens exclude learners.	Provide device/access support and low-bandwidth pathways.

4. HISTORICAL DEVELOPMENT

The historical evolution of online and blended learning in engineering education can be read in three overlapping phases. The first phase, emerging in the late 1990s and early 2000s, centered on web-enhanced teaching and distance delivery, especially for working professionals and geographically dispersed learners. During this period, the literature focused on equivalence questions: can online engineering instruction deliver outcomes comparable to conventional lectures [5]–[7]? The second phase shifted toward pedagogical redesign. Blended learning moved beyond simple supplementation and was framed as a transformative restructuring of time, interaction, and assessment [1]–[4]. In engineering education, this shift intersected with wider interest in active learning, project work, and learner-centered design [10]–[12]. The third phase involved ecosystem expansion: massive open online courses (MOOCs), flipped classrooms, remote laboratories, simulation platforms, and institutional learning management system (LMS) infrastructures collectively widened the repertoire of engineering teaching [13]–[19]. By the late 2010s, online and blended engineering education had become less a special format and more a strategic domain of curriculum innovation [20].

The COVID-19 pandemic accelerated this trajectory dramatically, but it did not create it. Emergency remote teaching exposed the difference between planned online learning and rapid modality substitution. Studies in engineering programs during the pandemic documented both resilience and fragility: institutions were able to continue instruction at scale, yet students and staff experienced uneven readiness, reduced interaction, laboratory disruption, and psychological strain [21]–[23]. The pandemic nevertheless normalized the use of recorded microlectures, synchronous online problem-solving sessions, digital assessment tools, and remote access to experimental resources. As a result, many engineering schools moved after 2020 not back to pre-digital norms, but toward more durable hybrid configurations in which online elements were retained for flexibility, revision, analytics, and access, while in-person sessions were reserved for laboratories, teamwork, and higher-order discussion [20]–[23].

The reason for the inconsistent results is explained by comparison across time periods. Pre-pandemic research often assessed purposefully created online or mixed learning programs, emphasizing pedagogical benefits or equivalency [5]–[7], [20], [24]. Studies conducted during the pandemic period frequently assessed emergency replacement in disturbed laboratory and support conditions, which increased the reported issues of isolation, workload, and practical disruption [21]–[25]. Durable hybrid arrangements, particularly remote laboratories, analytics, and digitally enabled active learning, are increasingly being evaluated in more recent work [26]–[29]. Therefore, unfavorable emergency delivery outcomes should not be seen as conclusive evidence against planned hybrid schooling, just as favorable conceptual outcomes should not be seen as evidence that tactile professional competencies have been maintained.

5. KEY DEVELOPMENTS AND TECHNOLOGIES

One of the most consequential developments in engineering education has been the maturation of blended pedagogies rather than the mere proliferation of tools. Research on blended first-year engineering mathematics and related gateway courses indicates that structured combinations of asynchronous preparation, synchronous interaction, and targeted face-to-face support can improve continuity and learner control [24]–[30]. Flipped models are particularly prominent in engineering because they align well with disciplinary problem solving: students encounter explanatory content before class, then use contact time to apply concepts, ask questions, and work collaboratively [15], [24]–[27]. However, the literature also warns that flipped learning is not universally effective. Its success depends on preparation compliance, clarity of expectations, the quality of pre-class materials, and the design of in-class activities. When the online component is weak or excessive, the model can shift cognitive burden onto students without sufficient support [31]–[35].

A second major development concerns laboratories, long regarded as the hardest component of engineering curricula to digitize. Foundational reviews distinguished hands-on, simulated, and remote laboratories [9], while later work demonstrated that virtual and remote labs expanded rapidly and diversified technically and pedagogically [16]–[19]. Recent studies suggest that remote and virtual laboratories can support conceptual understanding, procedural learning, and access, especially when combined with active learning and structured assessment [36]–[39]. Yet, the literature remains clear that not all laboratory objectives are equally transferable. Remote experimentation can approximate instrumentation, data acquisition, and systems thinking; simulations can illuminate invisible phenomena and allow repetition without material constraints; but tactile manipulation, troubleshooting under physical uncertainty, and aspects of professional enculturation often remain better served by physical laboratories [18], [30]–[32]. The strongest evidence therefore supports complementarity rather than substitution.

A third development is the diversification of engineering-specific digital learning objects and environments. Recent literature documents the use of interactive notebooks for fluid mechanics [39], self-assessment graphical tools for computer-aided design [40], auto-graded deliberate-practice systems in chemical engineering [41], timeline-anchored social video comments [42], and student-created video artifacts in electronics and physical computing [43]. These tools matter because they shift online learning from passive content delivery toward iterative practice, immediate feedback, and social knowledge construction. They also increase the observability of learning processes, allowing instructors to identify misconceptions and participation patterns more efficiently. Nonetheless, their pedagogical value depends on integration into coherent assessment and feedback loops. Tool proliferation without curricular alignment risks producing fragmented experiences and platform fatigue.

Immersive technologies have also gained visibility. Studies in construction, fluid power, electronics, and industrial engineering report promising uses of virtual reality, augmented reality, virtual worlds, and reconfigurable virtual learning factories [36]–[38], [44]–[46]. These approaches can make abstract systems visible, simulate hazardous conditions safely, and provide repeated experiential practice without the scheduling constraints of physical labs. In engineering education, their main promise is not novelty but epistemic access: learners can inspect system behavior, spatial relations, and process flow in ways that are difficult to achieve in lectures alone. Even so, the evidence base remains uneven. Many studies report positive perceptions and local gains, but fewer provide robust longitudinal comparisons, cost-effectiveness analysis, or transfer measures to real-world performance. High-impact implementation therefore requires caution, especially where infrastructure costs and accessibility concerns are substantial [36]–[38], [44]–[46].

MOOCs and large-scale digital platforms represent another strand of development. Systematic review evidence suggests that MOOCs in engineering education have primarily been used to widen access, support lifelong learning, and feed hybrid campus models [14], [47]–[49]. More recent work on MOOC-based flipped classrooms shows that open or semi-open digital content can be repurposed effectively for on-campus engineering courses when embedded in local facilitation and assessment structures [47]. This has strategic significance for engineering schools seeking scalable pre-class content, outreach pathways, or continuing professional education. Yet completion, interaction quality, and contextualization remain persistent concerns. In engineering, where prerequisite chains and disciplinary coherence matter, large-scale platforms are most effective when integrated into local curriculum rather than treated as standalone replacements for programs [14], [47]–[49]. Figure 2 illustrates conceptual overview of major developments shaping contemporary engineering education, including blended and flipped pedagogies, virtual/remote/physical laboratories, digital learning objects and environments, immersive technologies, and MOOCs or large-scale digital platforms.

In all of these advances, there is no one single technology that seems to be superior to all other uses of engineering. Blended and flipped models are most effective when knowledge application and coached problem solving can be structured around the pre-class preparation [24]–[28], [33], [34]. Virtual and remote laboratories are best suited to expression of visualization, rehearsal, instrumentation access and continuity, while those requiring physical manipulation, troubleshooting and professional enculturation are still best supported by hybrid or in-person validation [18], [30]–[32] While visualization and feedback can be extended through immersive technologies and tools supported by AI, their educational value will largely rely on the validity of the assessment tool, access, and faculty capabilities [36]–[38], [44]–[46], [50]. So, the effectiveness of technology depends on the learning outcome and on whether or not it crosses the tactile-digital gap directly or not.

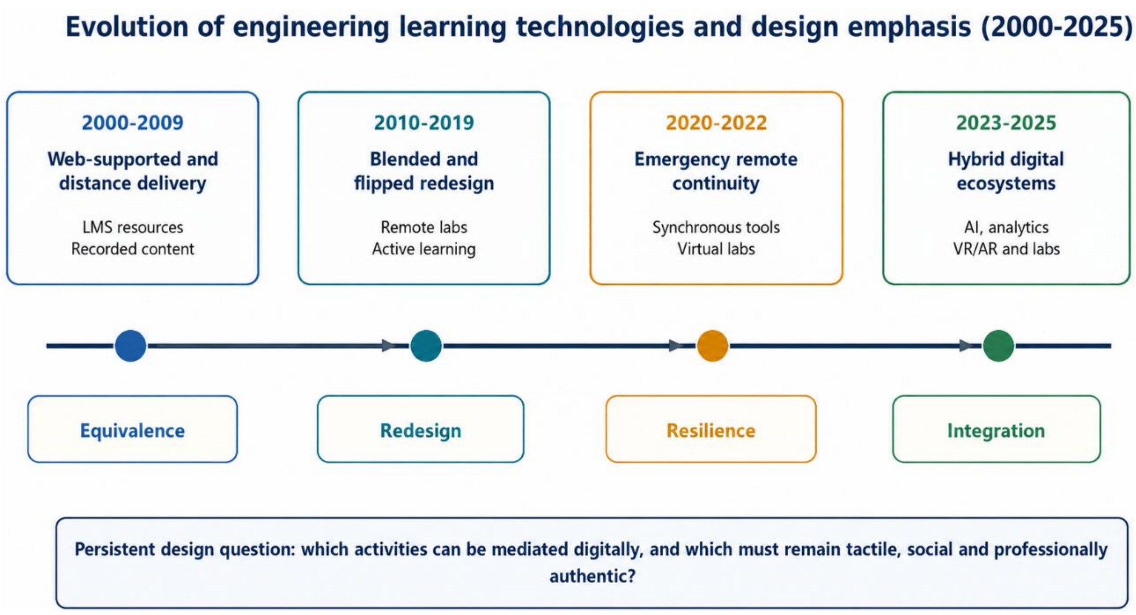

Figure 2. Evolution of engineering learning technologies and hybrid design emphasis (2000-2025)

6. IMPACT ON STUDENT LEARNING OUTCOMES

The impact of online and blended learning on student outcomes in engineering education is best understood as conditional rather than universal. Broad meta-analytic work in higher education indicates that blended learning often yields better outcomes than purely online or purely face-to-face delivery [3], [4].

Within engineering education, studies of blended and flipped courses often report improvements in academic performance, course outcome attainment, or conceptual engagement when online preparation is coupled with active in-class work [24], [25], [33], [34]. Cross-institutional evidence also suggests that blended implementations can strengthen self-direction and learner agency, particularly when students are given structured autonomy rather than unbounded flexibility [28]. These findings support a central conclusion of the field: modality is less predictive than design quality. Engineering students appear to benefit most when online environments are used to extend practice, provide timely feedback, and free synchronous time for coached problem solving.

Student engagement, however, is multidimensional. Online and blended formats often increase flexibility, replayability of explanations, and control over pacing, which many students value in concept-heavy engineering subjects [21], [22], [24], [27]. They can also increase participation from students who are reluctant to speak in crowded lecture halls but are more comfortable engaging through forums, chats, annotations, or staged asynchronous tasks [42]. At the same time, multiple studies reports reduced social connectedness, weaker peer interaction, and challenges in sustaining motivation during heavily online periods [22], [23], [27], [50]. This tension is especially salient in engineering, where belonging, collaborative identity, and persistence are linked to interaction-rich environments. Thus, positive effects on convenience and content access do not automatically translate into stronger community or persistence. Well-designed blended learning mitigates this by intentionally engineering contact, team-based activity, and visible instructor presence.

The evidence on practical and professional skills is more mixed. Remote and virtual labs can effectively support conceptual understanding, experimental planning, interpretation of results, and familiarity with instrumentation interfaces [17], [18], [29]–[32], [46]. They may also broaden access by allowing repetition, off-hours experimentation, and participation by students who cannot always be physically present. However, some studies indicate that students still perceive differences between virtual or remote laboratories and in-person labs in terms of embodied manipulation, troubleshooting under physical constraints, and the realism of uncertainty [18], [30], [31]. This does not invalidate digital laboratories; rather, it clarifies their best use. For introductory exposure, pre-lab preparation, systems visualization, and continuity during disruption, they are highly valuable. For advanced psychomotor practice and tacit professional behaviors, many programs still need physical laboratory experiences or carefully designed hybrid lab sequences.

Four boundary conditions are found through analytical comparison. First, compared to laboratory-intensive courses, less equipment-intensive areas like engineering mathematics, programming, and systems analysis can frequently benefit from a bigger online component. Second, compared to more seasoned postgraduate or professional learners, undergraduate students might need greater scaffolding, social presence, and organized laboratory sequencing. Third, compared to universities with limited bandwidth or equipment, high-resource institutions are better equipped to implement remote hardware, immersive systems, and device support. Fourth, it is important to distinguish emergency remote delivery from post-pandemic hybrid models that were purposefully created. When taken as a whole, these factors explain why research with seemingly contradictory results may really be compatible rather than contradictory [20]–[32], [37]–[47], [51]–[55]. Another important outcome domain is equity. Online and blended learning can widen access for working students, commuters, caregivers, and geographically distributed learners [5], [14], [53]. New online engineering degrees and modular pathways suggest that digital delivery may diversify participation in the field [53]. Yet access gains can be undermined by the digital divide, uneven home study environments, differential self-regulation, and hidden costs of connectivity and devices [21]–[23]. In engineering education, these equity issues are amplified when laboratory software, specialized hardware, or high-bandwidth immersive platforms are required. The literature therefore supports an equity-by-design stance: accessibility, device burden, bandwidth assumptions, and inclusive participation structures should be treated as core design variables rather than afterthoughts. Without that, online flexibility can mask new forms of exclusion.

Lastly, research indicates that coherence, communication, and assistance have a greater impact on student satisfaction than the nominal manner of delivery. According to recent research on online engineering education, satisfaction increases when there are fewer technical obstacles, meaningful interactions, fast feedback, and clear objectives [55]. On the other hand, when students encounter platform fragmentation, ambiguous workload redistribution, or an inconsistency between online assignments and evaluation, their discontent increases. Because contentment is frequently addressed casually, this finding is significant. In engineering education, satisfaction is important not just as an emotive metric but also as a mediator of effort, perseverance, and desire to participate in challenging problem-solving sequences. Thus, orchestration is necessary for effective blended learning. The effects of blended and online learning on engineering education student learning outcomes are summarized in Table 2.

Table 2. Summary of the impact of online and blended learning on student learning outcomes in engineering education

Outcome domain	Positive impacts reported	Challenges/negative impacts	Key implication for engineering education	Key refs
Academic performance and knowledge acquisition	Blended learning often outperforms fully online or fully face-to-face formats. Improved grades, course outcome attainment, and conceptual understanding are frequently reported when pre-class online learning is combined with active in-class problem solving.	Gains are inconsistent when courses simply digitize lectures without redesign. Poor alignment between online tasks and assessment can reduce effectiveness.	Design quality matters more than modality. Best results occur when online tools extend practice, feedback, and preparation, while class time is used for coached application.	[3], [4], [24], [25], [33], [34]
Self-direction and learner agency	Structured autonomy can improve self-regulation, responsibility for learning, time management, and independent study habits.	Excessive flexibility without scaffolding may overwhelm students with weak self-management skills.	Use guided autonomy with milestones, progress checks, and clear expectations rather than unlimited flexibility.	[28]
Student engagement and participation	Greater flexibility, replayability of lectures, pacing control, and alternative participation channels (forums, chats, annotations) can increase engagement, especially in concept-heavy courses.	Convenience does not automatically create deep engagement. Passive content consumption may replace active participation if poorly designed.	Combine asynchronous resources with interactive tasks, participation prompts, and instructor presence.	[21], [22], [24], [27], [42]
Social connectedness and belonging	Well-designed blended models can sustain peer interaction through teamwork, discussion spaces, and visible instructor support.	Reduced sense of community, weaker peer interaction, isolation, and lower motivation are common in heavily online settings.	Social presence should be intentionally designed through group work, live interaction, mentoring, and collaborative projects.	[22], [23], [27], [50]
Practical laboratory skills	Remote and virtual labs can support conceptual understanding, experimental planning, data interpretation, and familiarity with instruments. They also improve access and allow repetition.	Students may perceive limitations in hands-on manipulation, troubleshooting physical systems, and experiencing real uncertainty.	Digital labs are highly effective for preparation and continuity, but advanced psychomotor competencies often still require physical or hybrid labs.	[17], [18], [29]–[32], [46]
Professional and tacit skills	Some blended environments support teamwork, communication, and digital collaboration skills relevant to modern engineering practice.	Tacit professional behaviors, embodied teamwork, and informal learning may be harder to replicate online.	Use hybrid experiences combining digital collaboration with in-person design, teamwork, and studio/lab experiences.	[18], [30], [31]
Equity and access	Flexible delivery benefits working students, commuters, caregivers, remote learners, and lifelong learners. Can broaden participation through online degrees and modular pathways.	Digital divide, poor study environments, connectivity costs, device limitations, and software/hardware requirements may create new inequities.	Adopt equity-by-design principles: accessible platforms, low-bandwidth options, device support, inclusive scheduling, and flexible participation models.	[5], [14], [21]–[23], [53]
Student satisfaction	Satisfaction improves when communication is clear, interaction is meaningful, feedback is timely, and technical systems work reliably.	Dissatisfaction rises with fragmented platforms, unclear workload shifts, weak support, or misaligned assessments.	Satisfaction depends more on coherence and support than on delivery mode itself.	[55]
Overall conclusion	Online and blended learning can substantially enhance engineering education outcomes when intentionally designed.	No modality is universally superior; weak implementation can reduce quality.	The central determinant of success is pedagogical orchestration, not technology alone.	[3], [4], [28], [55]

7. FACULTY ADOPTION AND CHALLENGES

Faculty adoption remains one of the decisive determinants of success in online and blended engineering education. Engineering faculty are often willing to use digital tools, but willingness does not guarantee pedagogical transformation. Studies of staff perceptions during and after the pandemic show that instructors frequently recognized the utility of online learning for continuity and flexibility while also expressing concern about interaction quality, laboratory authenticity, academic integrity, and workload [49], [54]. Other reports from engineering courses taught during emergency and post-emergency conditions show that active learning online is possible, but it requires deliberate redesign of facilitation, participation norms, and feedback structures rather than simple transfer of lecture habits into video-conferencing environments [52]. In short, faculty adoption is not a binary matter of acceptance versus resistance; it is a question of whether institutions enable instructors to redesign teaching at the level of pedagogy, assessment, and course architecture.

Three recurring challenges dominate the literature. The first is workload. High-quality online and blended courses require front-loaded investment in instructional design, media production, assessment revision, and digital support materials [49], [54]. The second is pedagogical confidence. Many engineering academics are disciplinary experts with limited formal training in online pedagogy, social presence, or digital facilitation [50], [51]. The third is evaluative uncertainty: faculty may be unsure how to assess teamwork, laboratory competencies, or higher-order reasoning in digital environments without increasing plagiarism risk or surveillance burden [22], [49]. These challenges help explain why some engineering programs achieved effective hybrid redesign while others produced fragmented, stressful, or overly content-heavy online experiences. Faculty training, therefore, must go beyond tool tutorials toward evidence-based course design and discipline-specific assessment literacy.

Faculty adoption also varies over time. Emerging evidence from electrical and computer engineering suggests that instructors' approaches to online laboratories evolved across the pandemic period, indicating that adoption is developmental rather than static [54]. Early emergency solutions often privileged access and continuity, whereas later iterations focused more on alignment, interactivity, and assessment quality. This temporal dimension matters because some negative findings about online engineering education reflect crisis conditions rather than mature practice. Even so, the literature cautions against assuming that adaptation alone solves structural problems. Without recognition in promotion criteria, workload models, and technical support, adoption can remain individualized and unsustainable. Long-term success depends on converting individual improvisation into institutional capability.

Finally, the financial burden of hardware requirements is a recurring equity concern in online and blended engineering education. Students from low-income backgrounds may have trouble obtaining dependable laptops, specialized software, high-performance devices, or stable internet connectivity, which can directly limit their participation in design-based activities, laboratory simulations, and other digitally intensive learning experiences. According to TPACK, faculty adoption is defined as the ability to integrate digital technologies with engineering-specific education and reliable competency assessment, rather than just being willing to use platforms. According to the CoI lens, social interaction design and intentional teaching presence are also necessary. Therefore, institutions that just offer software access fail to fulfill the core educational task, whereas professional development that focuses on inclusive participation, authentic evaluation, and hybrid laboratories is more likely to promote sustainable adoption [49], [52], [54].

8. INSTITUTIONAL STRATEGIES AND SUPPORT

Institutional strategy has become increasingly central as engineering schools move from episodic digital initiatives to systemic hybrid provision. Successful institutions tend to combine instructional technology platforms, remote access infrastructure, course design support, staff development, and revised quality assurance processes [20], [21], [53]. The literature suggests that the most effective institutional responses do not treat online learning as a temporary emergency overlay. Instead, they embed digital design into program review, accreditation mapping, student support, and capital planning. In engineering, this includes decisions about remote or virtual lab investment, software licensing, device lending, learning analytics governance, and the sequencing of campus-intensive versus online-intensive activities across curricula [20], [53].

Institutional support also shapes whether online and blended learning broaden access meaningfully. Online engineering degrees and hybrid master's pathways demonstrate that institutions can use digital delivery to serve non-traditional learners, regional industry partners, and lifelong learning needs [20], [53]. MOOC-supported and stackable models may further allow engineering schools to build outreach pipelines and flexible progression routes [47], [48]. However, the literature also shows that scaling is not simply a matter of enrollment growth. Institutions must provide advising, academic support, onboarding to digital study practices, and psychologically safe channels for participation, particularly in high-cognitive-load engineering courses [55]. Where institutional strategy emphasizes platform deployment without support ecology, student frustration and attrition are more likely.

Data and assessment are the last institutional concern. According to recent engineering studies of online learning data and self-directed learning [28], [29], [41], digital environments provide opportunity to assess participation, performance trajectories, and interaction patterns. However, there are still insufficiently strong institutional evaluation frameworks in the literature that link analytics to professional competence, equity, and disciplinary outcomes. Therefore, in addition to additional data, engineering schools need to ask better questions, such as which learning outcomes are enhanced by online flexibility. Which call for embodied practice? Which students benefit or suffer from hybrid structures? Instead of depending on snap decisions made during a crisis, institutional maturity in online and hybrid engineering education will depend on the capacity to consistently respond to such questions. Key institutional tactics and support systems for successful online and blended learning in engineering education are compiled in Table 3.

Table 3. Key institutional strategies and support mechanisms for effective online and blended learning in engineering education

Strategic domain	Key institutional actions	Expected benefits	Risks if neglected	Supporting references
Digital Infrastructure	Implement robust LMS, video platforms, cloud collaboration tools, and secure digital ecosystems	Reliable course delivery, scalable access, improved continuity, enhanced communication	Platform failure, fragmented learning experience, poor user satisfaction	[20], [21], [53]
Remote and virtual laboratory capacity	Invest in remote labs, simulation tools, virtual labs, and hybrid practical environments	Expanded laboratory access, flexible scheduling, continuity during disruption, improved conceptual learning	Limited practical skill development, reduced experimental authenticity, inequitable access	[20], [53]
Course design support	Provide instructional design teams, media production support, and evidence-based curriculum redesign services	Higher-quality online courses, stronger alignment of outcomes and assessment, better student engagement	Content digitization without pedagogy, weak interaction design, poor learning outcomes	[20], [21], [53]
Faculty development	Deliver continuous training in online pedagogy, digital assessment, student engagement, and technology use	Greater faculty confidence, better teaching quality, sustainable innovation culture	Faculty resistance, burnout, ineffective technology adoption	[20], [21], [53]
Quality assurance and accreditation	Integrate online learning into program review, accreditation mapping, benchmarking, and continuous improvement systems	Maintained academic standards, compliance, stronger institutional credibility	Inconsistent standards, accreditation gaps, reputational risk	[20], [53]
Student access and inclusion	Offer device lending, internet support, accessibility tools, flexible scheduling, and inclusive learning design	Wider participation, reduced barriers, improved equity and retention	Digital divide, exclusion of disadvantaged learners, higher dropout rates	[20], [53], [55]
Academic and pastoral support	Provide advising, tutoring, onboarding to digital learning, counseling, and safe participation channels	Better transition, stronger persistence, improved wellbeing and satisfaction	Isolation, anxiety, disengagement, increased attrition	[55]
Flexible pathways and lifelong learning	Develop online degrees, hybrid master's programs, stackable credentials, and MOOC-supported progression routes	Serves working professionals, regional learners, and lifelong learners; expands institutional reach	Limited market relevance, missed recruitment opportunities	[20], [47], [48], [53]
Learning analytics and data governance	Use dashboards, engagement tracking, progression analysis, and ethical governance of learner data	Early identification of risk, evidence-based intervention, continuous enhancement	Misuse of data, privacy concerns, decisions based on weak metrics	[28], [29], [41]
Strategic evaluation and continuous improvement	Evaluate which outcomes suit online delivery, which need physical practice, and which student groups benefit most	More mature hybrid models, targeted investment, improved long-term effectiveness	One-time crisis decisions, inefficient spending, persistent inequities	[28], [29], [41]

9. FUTURE TRENDS AND RECOMMENDATIONS

The next phase of online and blended engineering education is likely to be shaped by convergence among three streams: intelligent support, immersive environments, and modular program design. Virtual learning factories, virtual and augmented reality (VR/AR) -enhanced experimentation, and hybrid laboratory ecosystems are already moving engineering education toward digital twins of industrial contexts [37], [38], [44]–[46]. At the same time, generative AI is introducing new possibilities for tutoring, feedback, drafting, code support, and adaptive explanation, alongside significant concerns related to epistemic dependence, assessment validity, and ethics [56], [57]. The future is therefore unlikely to be defined by a single dominant technology. More plausibly, engineering programs will assemble layered digital ecologies in which AI supports practice and feedback, immersive systems support visualization and safe experimentation, and campus experiences concentrate on collaboration, fabrication, and professional judgment.

Future adoption decisions are reframed by the tactile-digital gap: technology should be chosen based on the authentic experience it cannot replace and the skill it can effectively assist. In situations where competency is embodied, safety-sensitive, or socially located, physical laboratory and collaborative design experiences are still crucial, but AI-supported feedback and immersive visualization may enhance preparation and reflection. Therefore, the goal is evidence-based orchestration of digital and physical learning rather than maximal digitalization. Several evidence-based recommendations follow from the reviewed literature. First, programs should adopt pedagogy-first design. Technology selection should begin from learning outcomes, especially the distinction between conceptual, procedural, collaborative, and psychomotor goals [8]–[12], [17], [18]. Second, blended learning should be treated as curricular architecture rather than a collection of add-ons; online preparation, synchronous activity, laboratory experiences, and assessment should be explicitly sequenced [1]–[4], [24], [28]. Third, engineering schools should invest in hybrid lab strategies that combine simulations, remote access, and physical practice rather than framing digital labs as total replacements [18], [30]–[32], [46]. Fourth, faculty development should address design, facilitation, and assessment not merely platform operation [49], [52], [54]. Fifth, institutions should adopt equity-by-design principles that reduce device, bandwidth, scheduling, and accessibility barriers [21]–[23], [53], [55]. Sixth, future research should prioritize longitudinal and comparative studies that examine not only grades and perceptions, but transfer, retention, teamwork, professional identity, and post-graduate readiness [58], [59].

A final recommendation concerns how the field frames evidence. Too much of the literature still contrasts "online" with "face-to-face" as if these were stable, homogeneous categories. Engineering education needs more studies of design patterns, implementation conditions, and program-level ecosystems. It also needs more cost analyses, workload accounting, and research from underrepresented regions and institutions. The central question is no longer whether engineering can be taught online at all. The more productive question is which combinations of online, blended, and in-person experiences best support different forms of engineering learning, for whom, and under what conditions. That reframing would move the field beyond emergency narratives and toward mature pedagogical strategy. Figure 3 illustrates conceptual synthesis of emerging directions and evidence-based recommendations for the next phase of engineering education. The figure highlights the convergence of intelligent support, immersive environments, and modular program design into layered digital learning ecologies that combine AI-supported feedback, immersive visualization, experimentation, and campus-based professional learning.

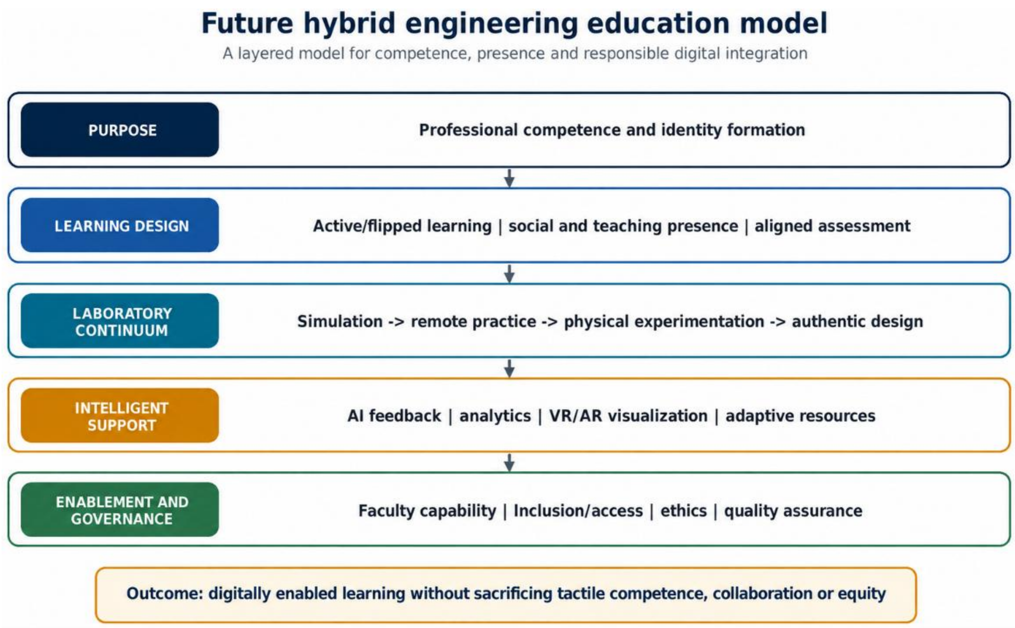

Figure 3. Future hybrid engineering education model for digitally enabled professional competence

10. CONCLUSION

When online and blended learning are focused on discipline objectives rather than technology accessibility, they can enhance engineering education. For conceptual achievement, flexibility, feedback, and self-direction, the examined evidence most consistently supports properly planned hybrid learning; but it is still more conservative when it comes to tactile laboratory skill, collaborative professional judgement, and long-term competence. This review's conceptual contribution is the tactile-digital gap, as understood from the viewpoints of TPACK and the CoI. The paradigm shows why persistent cognitive, social, and instructional presence as well as technological decisions that are in line with engineering content and real-world performance criteria are key to the success of digitally mediated learning. In practical engineering programs, digital preparation, remote or virtual experimentation, and physical validation should be arranged in a fair, assessment-aligned hybrid curriculum. Priorities for study include responsible evaluation of learning enabled by AI and immersive technologies, comparative evidence across resource contexts, and longitudinal assessment of practical competence and professional identity.

This review is limited in four ways. First, neither PRISMA-style screening nor comprehensive database retrieval are claimed; instead, it is a structured critical narrative evaluation. Second, transferability to resource-constrained contexts may be limited since English-language studies and institutions with adequate digital infrastructure dominate the accessible literature. Third, judgments on developing systems should be seen as tentative since technology and policy are changing quickly, especially with regard to generative AI and immersive tools. Fourth, compared to longitudinal measures of tactile competence, professional identity, and graduation preparation, the evidence base is still stronger for accomplishment, engagement, and perceptions. Future research must be comparative, longitudinal, and context-sensitive due to these limitations.

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Hamza Abu Owida	✓	✓		✓	✓	✓	✓		✓	✓		✓	✓	
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this paper.

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