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Towards an evidence-based framework for integrating data-driven digital solutions with academic learning modules in civil engineering education

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Abstract

Integrating emerging data-driven technological solutions into civil engineering education is essential for bridging the growing gap between conventional domain knowledge embedded in academic curricula and rapidly evolving industry practices. Although current teaching–learning systems employ rigorous frameworks for subject knowledge acquisition and separate training modules for digital skill development, learners often struggle to effectively integrate these components to emerge as well-rounded professionals. Data-driven digital solutions such as Building Information Modeling (BIM) offer the capability to converge diverse information generated across construction project operations and serve as a critical interface for informed decision-making throughout the project lifecycle. This study examines the need to realign academic delivery by embedding digitally supported activities within the core learning process of civil engineering education. The research evaluates the implementation of a six-mechanism methodology for BIM integration through a structured faculty development program conducted across affiliated colleges of a leading technological university in India. Evidence was gathered from faculty training outcomes and learner perceptions, with specific focus on design skills for engineering solution generation, workflow integration, and institutional support. The findings reveal that BIM is largely perceived as an auxiliary software skill rather than positioning it as a pedagogical instrument for integrating construction workflows, highlighting limitations in current curriculum delivery approaches. Based on these insights, the study proposes an evidence-based framework emphasizing faculty-led co-creation of BIM-integrated course modules to enhance pedagogical coherence, interdisciplinary learning, and alignment between academic training and industry requirements.

Introduction

Digital workflow systems such as Building Information Modelling (BIM) are now extensively adopted by the Architecture, Engineering, and Construction (AEC) industry for monitoring, coordination, and management of construction projects [1]. Consequently, integrating these digital systems into the curriculum design and academic learning processes of civil engineering programs has become imperative. This integration also necessitates systematic faculty training to enable educators to comprehend and adapt to this paradigm shift. Although notable transformations in teaching–learning practices have occurred following the introduction of digital workflow tools, the predominant focus has been on developing students as competent software users. As a result, effective academic instruments that meaningfully embed BIM into civil engineering education remain inadequately developed within existing academic processes [2,3].

One of the most significant barriers to BIM integration in civil engineering education is the lack of structured and effective faculty training. Moreover, the rapid pace of technological advancement demands continuous professional development programs to ensure alignment between academic practices and evolving industry requirements. The absence of a standardized faculty training framework often results in inconsistent adoption and uneven implementation of BIM education across institutions [4–6].

Several researchers have proposed frameworks and guidelines aimed at bridging the gap between industry expectations and academic preparation for the adoption of data-driven digital solutions, particularly BIM. However, comprehensive integration of BIM into tertiary education is constrained by institutional, pedagogical, and resource-related challenges, including limited faculty competency and fragmented curricula [4 - 6]. To address these challenges, various pedagogical approaches have been introduced to create realistic learning environments, such as virtual construction models that embed BIM across multiple core subjects with progressive complexity and cross-disciplinary integration, as well as problem-based learning initiatives focused on multidisciplinary coordination and data exchange[5, 7].

Among the operational strategies, [3] proposed a six-mechanism methodology to develop and consolidate BIM competencies within a civil engineering program in Peru. The proposed mechanisms include: (1) BIM integration into topics and syllabi; (2) utilization of collaborative platforms; (3) faculty training programs; (4) establishment of student organizations; (5) development of BIM application projects; and (6) area- and subject-level coordination meetings. The authors further suggested a validation process based on faculty participation, student enrolment, graduate employability, research output, curricular alignment, and student perceptions. While these mechanisms demonstrated effectiveness within a specific context, recent studies indicate that many construction project management and civil engineering programs continue to fall short in producing workplace-ready BIM practitioners. Graduates often possess only basic modeling skills, with limited proficiency in information management, project coordination, and software interoperability [4,6-7].

Furthermore, existing frameworks for integrating data-driven digital solutions into civil engineering education are largely context-specific and lack transferability across diverse institutional and regional settings. Many programs report inadequate faculty expertise in BIM and insufficient access to formal training opportunities [8]. In this context, this study examines the barriers and challenges associated with implementing the six-mechanism methodology within the Indian academic ecosystem. The study involved the design of structured learning content for construction project management, development of a systematic faculty training program to embed domain knowledge within BIM-enabled construction workflows, the selection and training of faculty members, and the post-training evaluation of faculty perceptions.

Drawing on reflections from faculty training outcomes, student feedback, and industry expert validation, this study identifies key implementation challenges and proposes contextually grounded recommendations to overcome them. These insights collectively contribute towards an evidence-based understanding of how data-driven digital solutions can be more effectively integrated into civil engineering education, with particular attention to faculty competency, student proficiency and industry alignment. Rather than presenting a prescriptive framework, this study offers a reflective, practice-informed roadmap for institutions seeking to embed BIM within undergraduate civil engineering curricula.

Methodology

The program aimed at integrating data-driven processes such as Building Information Modeling (BIM) was designed and implemented at A.P.J Abdul Kalam Technological University,I Kerala, India for civil engineering faculty from its affiliated colleges, with the objective of bridging skill gaps within the academic curriculum. Participation was invited through an open call circulated to all 142 affiliated colleges under the University. A total of 30 faculty members participated in the program, and no additional screening or elimination was carried out beyond the application stage.

The training content was designed with a strong emphasis on foundational theoretical concepts in construction project management, complemented by a brief exposure to site working conditions to facilitate understanding of real-world construction processes. This was followed by structured training on digital workflows, culminating in hands-on sessions on Building Information Modeling. The distribution of the training content is summarized in Figure 1.

Prior to the BIM-focused sessions, faculty participants were provided with theoretical inputs on project management principles and digital workflows in construction management. These sessions were intended to enable faculty members to understand how BIM tools can be meaningfully embedded within academic teaching–learning processes.

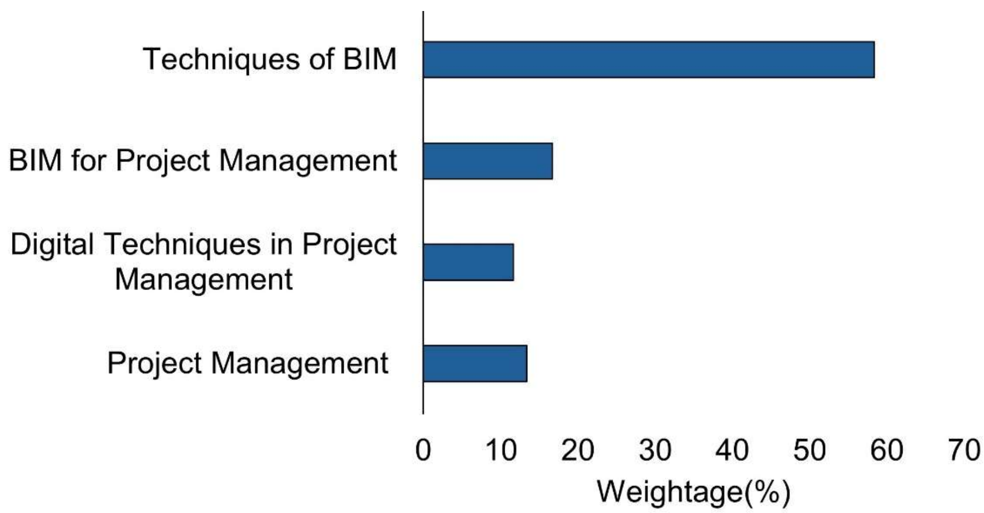

Figure 1. Percentage weightage of training content in the BIM-integrated faculty development program.

The training cohort comprised 48% male and 52% female participants, with an average teaching experience of 10 years. Although all faculty members who applied were admitted to the program, prior familiarity with at least one civil engineering drafting software was specified as a mandatory prerequisite for participation. The program was designed to achieve the following objectives: (1) to develop a comprehensive understanding of BIM concepts and tools; (2) to provide practical, hands-on experience using industry-standard BIM software; and (3) to discuss effective pedagogical practices for teaching BIM, thereby equipping students with industry-relevant competencies.

The program was conducted in-person over a five-day period at Indian Institute of Infrastructure and Construction Kollam Kerala, following a project-based learning approach. The knowledge and skills acquired by the participating faculty members are expected to be transferred to students within their respective institutions through curriculum integration and instructional practice.

Results

The BIM-assisted curriculum places significant emphasis on skill development within the teaching–learning process. The academic knowledge acquired by faculty participants is operationalized through digital workflows, which constitute a core skill component of BIM-based education. Furthermore, students are expected to apply these acquired skills across multiple subject domains in an integrated manner, rather than in isolated courses. Consequently, BIM-based pedagogy necessitates the acquisition of new competencies by learners while simultaneously reinforcing the importance of lifelong learning in adapting to evolving professional practices.

Prior to the training intervention, reflections from faculty, students and industry experts consistently underscored the need for structured digital upskilling. A faculty participant noted the tension between industry demands and institutional readiness, "*Students need to be trained for current industry need. But the convenience of the faculty and resource support need for quality training are not discussed effectively*". While student perceptions revealed a limited understanding of BIM's integrative potential, with one student stating "*BIM is a good modeling tool for buildings. I am not very sure that it can integrate different operations in a construction project*." Industry experts corroborated these concerns, with one stating "*Students need to have good knowledge on construction engineering. But they approach BIM learning with affirm belief that they are able to overcome the engineering knowledge gap through BIM training*". These pre-training perspectives collectively reinforced the need for a structured practice-oriented training intervention.

This section presents the outcomes of faculty training program based on post-training survey responses. Of the 30 faculty participants, 24 completed the post training survey, representing an 80% response rate. The initial set of questions aimed to capture participants' perceptions and motivations for engaging in the training program. When asked to provide a single response reflecting their primary perspective on BIM, 45% of respondents perceived BIM primarily as an advanced software tool for modelling building systems, while an equal proportion (45%) viewed BIM as a cutting-edge tool capable of enhancing student employability. Only 10% identified BIM primarily as a workflow management system, indicating that a limited proportion of participants initially recognized BIM beyond its modelling capabilities. Faculty were also asked to identify the primary learning objective for students through a single-response question. The majority of respondents (58%) identified improving professional competence as the most important objective, followed by acquiring additional software-related knowledge (30%), suggesting a stronger orientation toward employability and practice-oriented outcomes.

With respect to the time invested by faculty in additional self-learning through asynchronous online components (Figure 2), 50% reported spending more than 25 hours, 25% spent less than 25 hours, while the remaining 25% were unable to devote additional time beyond the in-person training sessions. In terms of subsequent student training conducted by faculty (Figure 2), 46% reported spending more than 25 hours, 25% between 10 and 25 hours, and 13% less than 10 hours, while 16% were unable to conduct any student training following the program.

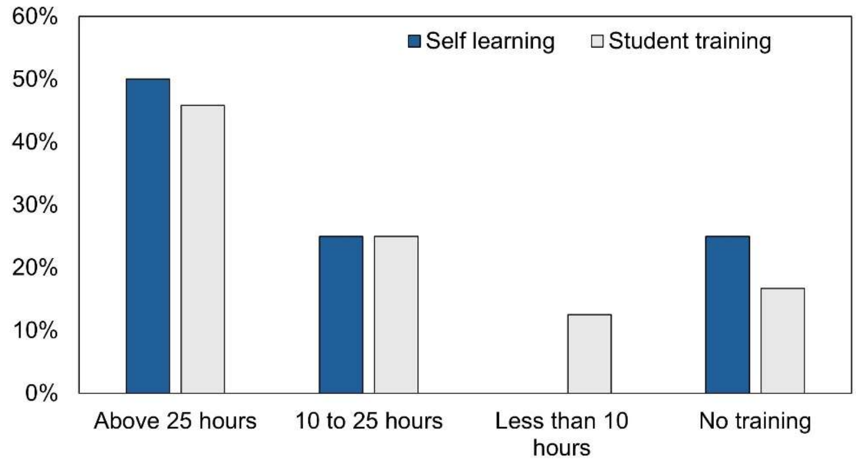

Figure 2. Time spent by faculty on self-learning and training students (% of respondents).

Faculty perceptions regarding institutional responsibility for student training revealed varying levels of support. While 38% reported that institutions expected faculty to independently manage student training initiatives, an equal proportion (38%) received additional institutional support beyond individual effort. However, 24% reported receiving no instructional support, attributing either to institutional indifference or to the absence of adequate laboratory infrastructure required for effective BIM training.

Faculty perceptions on BIM training for students were further examined through four single-response questions, Q1) Do you think more intense software training is required? Q2) Do you believe faculty competence in BIM is not essential because it is primarily a software tool? Q3) Do you think students in the future will learn BIM independently, making specific training sessions unnecessary? Q4) Do you think introducing BIM as a course would replace or compromise other important courses? The results are as presented in Figure 3. A substantial majority (75%) agreed that more intensive software training is required, while 21% remained neutral, indicating a strong consensus on the need for enhanced technical training. Additionally, 59% disagreed with the assertion that faculty competence in BIM is non-essential because it is primarily a software tool, although 21% agreed with this view, reflecting mixed perceptions regarding the pedagogical role of faculty expertise. Most participants (63%) disagreed with the notion that students would independently acquire BIM skills in the future, highlighting the continued importance of structured academic guidance. Opinions were divided on whether introducing BIM as a standalone course would compromise other essential subjects; while 38% agreed or strongly agreed with this concern, 46% disagreed or strongly disagreed, suggesting that many participants did not perceive BIM integration as detrimental to curricular balance.

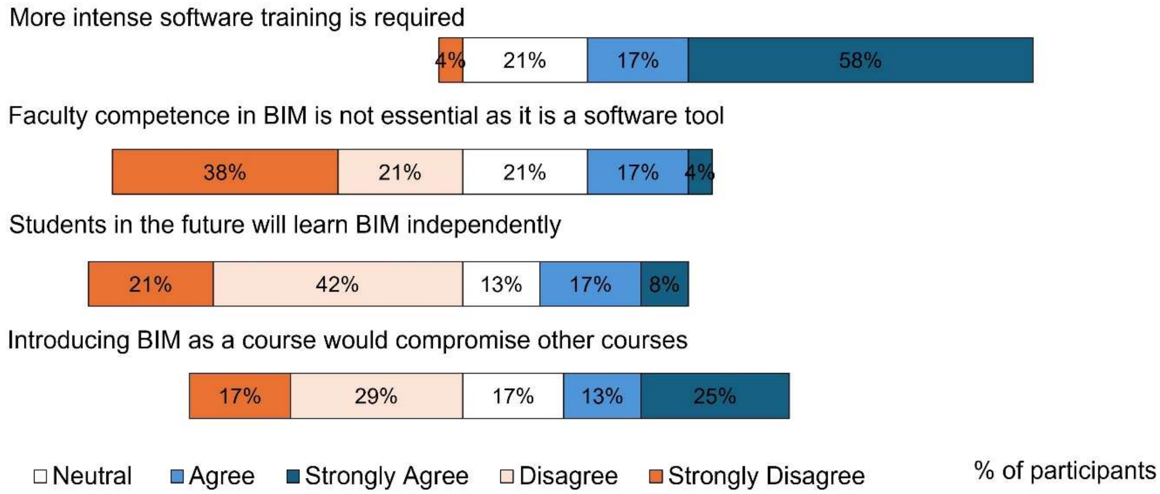

Figure 3. Faculty perceptions on BIM training for students.

Institutional support for BIM implementation was assessed through four single-response questions, Q1) Do you think colleges view BIM as a valuable professional skill for students Q2) Do you believe colleges promote such programs to enhance students learning opportunities? Q3) Do you think colleges are effectively addressing the need to improve faculty competency in BIM? Q4) Do you think colleges need to provide more institutional support – time and resources- to hep faculty implement skills gained through FDPs? The results are as illustrated in Figure 4. A majority of respondents (63%) believed that colleges recognize BIM as a valuable skill for students, indicating a generally positive institutional outlook. Furthermore, 71% reported that colleges actively promote BIM-related initiatives to enhance student learning opportunities. However, while 50% felt that institutions are addressing faculty competency in BIM, a considerable proportion expressed neutrality (33%) or disagreement (16%), suggesting inconsistencies in institutional capacity-building efforts. Notably, 75% of respondents agreed that additional institutional support is required to enable faculty to effectively implement the skills acquired through Faculty Development Programs (FDPs).

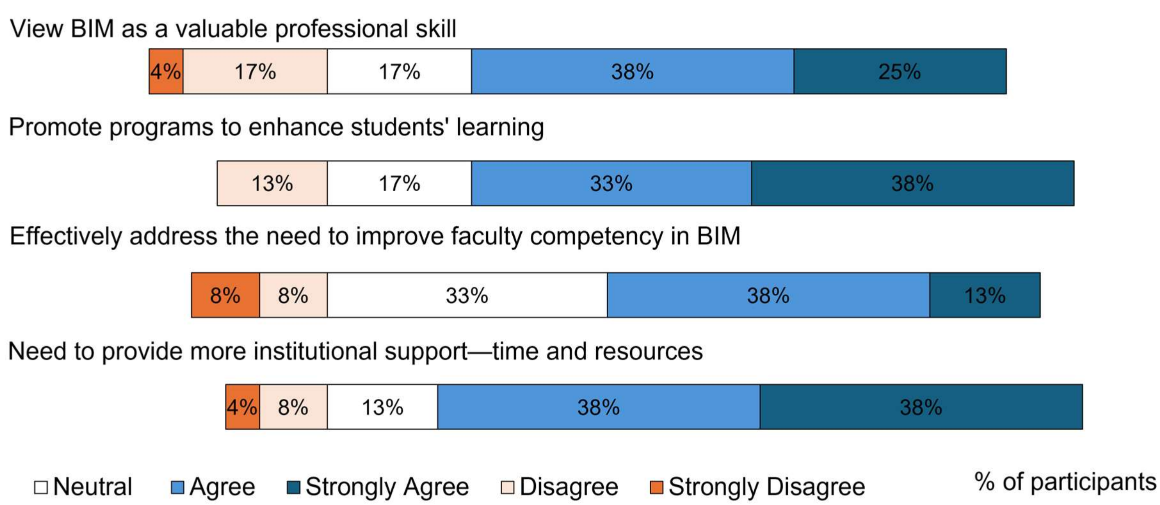

Figure 4. Faculty perceptions on institutional support for BIM training.

Participants were asked to provide multiple responses regarding the skill gaps they expected the training program to address. The majority identified software competency and industry-relevant skills as critical gaps (67% each), followed by design competency (25%) and broader civil engineering proficiency (12%). Similarly, when asked about preferred approaches for delivering BIM training to students, 42% supported the introduction of a dedicated BIM laboratory course, while 25% advocated external training beyond the formal curriculum. Another 25% suggested restructuring the curriculum to embed BIM across multiple courses, and an equal proportion recommended a well-structured certification program to enhance student employability.

Finally, when asked to identify the primary application or role of BIM, 84% of respondents agreed that BIM functions as a comprehensive platform integrating key engineering sub operations such as planning, analysis, design, and construction. In open-ended responses, participants highlighted several implementation challenges, including short academic semesters, heavy teaching workloads, ineffective online training during regular college hours, lack of technical support for software issues, and limited access to computer laboratories due to scheduling constraints. Suggested improvements included introducing BIM as a standalone laboratory course, offering offline or hybrid training modes, scheduling training during periods of reduced academic load, providing refresher training for faculty, enhancing institutional support mechanisms, and formally embedding BIM within the curriculum. Participants also emphasized the need for periodic program monitoring, designated points of contact for updates, and certification for students to improve placement opportunities. Despite these challenges, respondents consistently acknowledged BIM as a valuable initiative for enhancing both faculty capability and student readiness for industry practice.

Discussions

Ensuring the professional relevance of emerging technological solutions within engineering curricula is a continuous requirement across conventional engineering programs. Many contemporary technologies are oriented toward improved material and manpower utilization, sustainability, data driven decision-making, and the integration of artificial intelligence dimensions that were not explicitly emphasized in earlier curricular frameworks. In civil engineering practice, construction projects typically follow a sequential workflow comprising land-use planning, architectural design, material selection, structural design, estimation and costing, construction management, sustainability assessment, and post-construction operations such as maintenance and rehabilitation. Traditionally, engineering education has mirrored this structure by treating each stage as a discrete activity, where outputs from one stage serve as inputs for the next, with limited emphasis on cross-stage information continuity.

Building Information Modeling (BIM) fundamentally alters this paradigm by capturing and integrating information across all stages of the construction lifecycle and enabling seamless information exchange among stakeholders. This capability supports uninterrupted project execution and improved coordination. Consequently, academic training in BIM involves two distinct but interrelated components: (i) acquiring technical proficiency in BIM tools, and (ii) learning to overlay these tools within the teaching–learning processes of core engineering knowledge domains. Under this paradigm, conventional engineering systems are no longer viewed as isolated physical entities but as components of an information-driven operational ecosystem. As learners attain the required competency levels, they develop the ability to identify the information generated at each stage of construction and to understand the interconnectedness of data across the entire workflow.

Findings from the faculty training program indicate that participants invested significant time in mastering BIM software skills, and institutional management also made concerted efforts to provide the necessary infrastructure and resources to support skill-development initiatives. Faculty motivation to participate in the training was largely driven by the need to enhance software competency and student employability. However, the role of BIM as a comprehensive workflow management and pedagogical integration tool was not fully realized by many participants. This highlights the need for deliberate alignment between academic course content and BIM-enabled workflows, ensuring that BIM applications correspond directly to the construction stages addressed within classroom instruction. Such alignment is essential for translating academic learning outcomes into effective industrial practice.
Stakeholder reflections across all three groups reveal a convergent yet distinctly positioned set of challenges for BIM integration. Faculty strongly agreed to incorporate BIM in academic learning process but faces serious challenges in the absence of a general framework of learning integration. This results in generating added stress of equipping themselves with the skills needed to train students and in identifying appropriate training spaces within the curriculum. Industry stakeholders urgently need a large number of trained BIM professionals, with the immediate priority being the creation of datasets for digital workflow management of construction processes. The absence of a trainer pool within academic institutions directly affects the number of trained professionals in the market. Students are aware of BIM as a tool but perceive it as an added skill set above their core engineering education. This is not entirely incorrect given current employment opportunities where onsite and BIM-based roles exist as separate job profiles. This perception prevents students from achieving the understanding of BIM as embedded skill in civil engineering knowledge domain.

The responses further reveal concerns that excessive emphasis on BIM training, if treated as a standalone activity, could adversely affect learning outcomes in other core courses. As a result, many faculty members and institutions currently perceive BIM training as an additional or supplementary learning exercise rather than an integral component of curriculum delivery. This underscores the necessity of adopting a synergistic approach that balances established academic content with emerging technological competencies to meet industry expectations for professional proficiency in BIM. While most faculty members believe that laboratory-based instruction or certified training program can address skill gaps, they also strongly disagreed with the notion that faculty competence in BIM is unnecessary or that students can independently acquire BIM expertise outside structured academic environments.

These perspectives indicate a clear demand for strategic academic planning to enable effective BIM integration while addressing existing misconceptions. Although the faculty development program discussed in this study enhanced participants' understanding of BIM's versatility, it also revealed the need for advanced training focused on using BIM as a pedagogical instrument across construction engineering domains, including planning, design, management, and post construction operations. Such an approach would ensure comprehensive representation of construction workflows throughout the building lifecycle.

Accordingly, a critical implication of this study is that the co-creation of a pedagogical framework for BIM integrated curriculum delivery by engaging faculty members is essential. Taken together, stakeholder reflections point to a systematic misalignment where faculty lack integration framework, industry lacks a trained educator pool, and students lack conceptual positioning to view BIM as a core engineering competency rather than an additional software skill. Addressing any one of these challenges in isolation is insufficient. Collective design of course delivery strategies fosters ownership, consistency, and scaffolded learning across the curriculum, thereby enabling students to progressively build competencies aligned with industry practices. Existing BIM implementation frameworks can become truly effective only when faculty collaboratively develop and adopt BIM-enabled teaching methodologies, ensuring coherent integration across courses and sustained learning benefits for students.

Conclusion

This study examined the impact of implementing the six-mechanism methodology for integrating Building Information Modeling (BIM) into the civil engineering curriculum with the objective of developing professional competency among undergraduate students throughout their course of study. The findings provide a comprehensive reflection of prevailing perceptions within the teaching–learning community across a leading technological university in India. Evaluation across the six mechanisms indicates a strong need for deeper and more systematic integration of learning components to establish an effective pedagogical structure for BIM competency development. The results highlight that addressing the identified challenges and barriers requires targeted interventions, particularly through faculty training programs focused on pedagogical redesign. Such programs must move beyond software proficiency and explicitly demonstrate how emerging digital solutions can enhance the efficiency of conventional civil engineering workflows through integrated information management. In the case examined, trained faculty members largely perceived BIM not merely as a standalone digital skill but as an added learning layer that complements existing domain knowledge and supports the integration of multiple construction workflows. However, the findings also reveal that both faculty members and institutions tend to focus predominantly on the resource and infrastructure requirements associated with BIM skill training, rather than on ensuring deeper academic competency and conceptual integration within regular coursework. This underscores the need to reposition BIM from an auxiliary skill-based exercise to a core pedagogical instrument embedded within course delivery. Accordingly, the study concludes that co-creation of BIM-integrated course modules by faculty teaching interconnected subjects is critical for ensuring curricular coherence and meaningful learning outcomes. Such collaborative curriculum design enables a shared pedagogical vision, reduces fragmentation, and facilitates the effective exploration of the broader benefits of emerging digital solutions within civil engineering education. This approach is essential for achieving sustainable integration of BIM and for aligning academic training with evolving industry practices.

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