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Research Article

Transforming Sustainable Construction Management Education through Artificial Intelligence: A Conceptual Pedagogical Framework for Chinese Higher Education

Yang Yi Fan[1,a], Khar Thoe Ng[2,b,*] and Peng Jia Xin[2,c]

[1]*Faculty of Engineering & Quantity Surveying (FEQS), INTI International University, Persiaran Perdana BBN, Putra Nilai, 71800 Nilai, Negeri Seremban, Malaysia; [a)]E-mail: I25037392@student.newinti.edu.my*

[2]*Faculty of Education and Liberal Arts (FELA), INTI International University, Persiaran Perdana BBN, Putra Nilai, 71800 Nilai, Negeri Seremban, Malaysia; [b),c)]E-mail: kharthoe.ng@newinti.edu.my; I25035433@student.newinti.edu.my*

([*]Corresponding Author)

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ABSTRACT: Artificial Intelligence (AI) is revolutionising teaching, curricula and the learning experience in higher education. In construction management education, the growth of sustainability, Building Information Modelling (BIM), digital twins and 'smarter' construction technologies necessitates that students be equipped to work effectively in Construction 4.0 environments. Little work has been done on how AI might facilitate pedagogic transformation and sustainable curriculum innovation in this sector, primarily in Chinese higher education.

This study used integrative literature review and conceptual framework development methodology. Relevant literature was obtained from Scopus, WoS, ScienceDirect, SpringerLink and Google Scholar, augmented with theoretical and policy literature where required. The results suggest that AI-enabled and digital construction technologies may facilitate personalised learning, experiential learning, sustainability competency, digital literacy, interdisciplinary capacity and problem-solving. Issues remain around digital readiness of educators, academic integrity, algorithmic bias, inequality of infrastructure and over-reliance on output of these systems. To this end, "Artificial Intelligence Supported Construction Pedagogy Framework" is proposed to bring together AI technologies, constructivist learning, sustainability pedagogy and Construction 4.0 competencies.

Keywords: Artificial intelligence, Digital pedagogy, Sustainable construction education, Educational innovation, Construction management education, Smart construction, Chinese higher education.

1. INTRODUCTION

Artificial Intelligence (AI) is a dynamic force driving transformation worldwide in the world of higher education. AI powered educational tools such as machine learning, intelligent tutoring systems, learning analytics and Generative AI tools ChatGPT are increasingly being utilized in the teaching repertoire to promote effective learning and engagement (Holmes *et al*., 2019; Zawacki-Richter *et al*., 2019).

At the same time, the construction industry is experiencing digitalisation at an unprecedented pace through Building Information Modelling (BIM), Internet of Things (IoT), digital twins, and smart construction (Pan & Zhang, 2021), which transforms the interface of skills professionals needed to meet the modern challenges of construction management.

The urgent demands of the sustainable development agenda press for rapid curriculum reform in construction

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management education (Ahn *et al*., 2013); construction is still one of the worst global offenders in terms of carbon emissions and environmental impact (UNEP, 2022).

In China, national projects (Education Informatization 2.0 Action Plan, Smart Education China and New Engineering Education) are promoted to achieve educational digitalization and reform following an engineering "de-carbonization"(low-carbon transition pathway) path (Ministry of Education of China, 2018). More pressingly, China's "dual carbon" objectives have accelerated the introduction of sustainable development concepts into engineering and construction education (Qi *et al*., 2024).

While previous research has addressed AI adoption and use in higher education, and also the use of digital technologies in the construction industry, fewer studies have focused on the ways in which AI can support pedagogical transformation, specifically within construction management education programmes. Often the approaches to integrating AI and digital construction technologies can be defined in instrumental terms as specific tools that can or should be adopted, rather than enacting them within a sustainability-oriented curriculum for reflective learning and professional competency development. This is particularly true in Chinese higher education institutions, which are expected to simultaneously respond to educational digitalisation, the national dual-carbon agenda, New Engineering Education, and the demand for Construction 4.0 skills.

The following research questions guide this study:

RQ1: In what ways can AI technologies facilitate pedagogical innovation in sustainable construction management education?

RQ2: What are the opportunities and challenges associated with the integration of AI into construction management curricula?

RQ3: How might AI-enhanced learning environments foster sustainability competencies within construction management students?

This study contributes to educational innovation theory by introducing the Artificial Intelligence-Supported Construction Pedagogy (AISCP) Framework, which aligns AI technology, constructivist learning principles, sustainability-oriented pedagogy, and Construction 4.0 competencies within an integrated framework. Unlike those generally concerned with AI-guided learning frameworks, the AISCP Framework is specifically concerned with construction management education where sustainability decision-making, digital construction literacy, project-based learning and Construction 4.0 readiness need to be developed in conjunction. It also extends BIM-oriented construction education by putting AI-supported reflection, sustainability judgement, interdisciplinary problem-solving and ethical governance at the core. It is therefore original in its mutual integration of technological, pedagogical, competency based and governance dimensions within the particular context of Chinese higher education.

2. METHODOLOGY

2.1. Research Design

This study uses an integrative literature review with conceptual framework development to explore the implications of Artificial Intelligence (AI) for pedagogy in sustainable construction management education. Integrative literature reviews are suitable for nascent interdisciplinary research areas, as they allow researchers to combine theoretical perspectives, identify conceptual lacunae and derive new educational frameworks from disparate bodies of literature (Snyder, 2019).

Whereas systematic reviews focus on the synthesis of quantitative evidence, integrative literature reviews allow synthesis of broader conceptual interpretations across technological, pedagogical, and sustainability studies. This approach is appropriate because the conceptual terrain where AI, sustainable construction and education meet is somewhat fragmented and underdeveloped. We synthesize literature on AI and education, and on construction pedagogy, to produce the Artificial Intelligence-Supported Construction Pedagogy (AISCP) Framework.

2.2. Literature Search Strategy

Relevant literature was collected from major academic databases: Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. Search involved mostly peer-reviewed journal articles and conference proceedings but some books and institutional reports published between 2018 and 2024 were also searched. Foundational theory and particularly relevant key documents and policy were included regardless of date (if published before 2018).

Boolean search combinations were used where helpful to create more consistent and transparent search terms. The principal item included was:

("Artificial Intelligence" OR "Generative AI" OR "AI-supported learning")

AND

("Construction Management Education" OR "Construction Education" OR "BIM Education")

AND

("Sustainability" OR "Digital Pedagogy" OR "Smart Construction")

AND

("Higher Education" OR "Chinese Higher Education")

Additional keyword combinations relating to Construction 4.0, digital transformation, sustainability-oriented engineering education, and AI-enhanced pedagogy were also applied to improve literature coverage.

2.3. Inclusion and Exclusion Criteria

The literature selection process followed predefined inclusion and exclusion criteria to ensure academic relevance and quality.

Inclusion Criteria:

Peer-reviewed journal articles and conference papers

English-language publications

Studies related to higher education and engineering education

Research focusing on AI, sustainability, BIM education, or digital pedagogy

Publications discussing educational innovation, curriculum reform, or Construction 4.0 learning environments

Exclusion Criteria:

Non-academic publications

Studies lacking educational relevance

Purely technical AI studies without pedagogical implications

Duplicate publications or inaccessible full-text studies

Research unrelated to higher education contexts

2.4. Literature Screening and Selection

While this study was not conceptualised as a systematic literature review, some principles of PRISMA-like transparency and traceability informed the screening, including: the initial database search returning 185 publications, of which 32 duplicate records were discarded; the further 153 records were screened by title, with abstract where necessary; at this stage, further 81 publications were removed as they were unrelated to higher education, wholly technical AI studies, not related to sustainability, or not published by academics; the full-text of the remaining 72 publications were reviewed and a further 26 removed as they had minimal pedagogical relevance, did not include sufficient methodological details, were lacking an accessible full text, or duplicated conceptual attempts; 46 publications were categorised in this thematic analysis. The final 46 publications were included as they were conceptually, theoretically, or methodologically relevant to at least one of the four core concerns of this study which are: AI-supported learning, construction management or engineering education, sustainability-oriented competency development, and digital construction transformation. Foundational theoretical works and significant policy documents were drawn on to support theoretical framing and contextualising where necessary.

2.5. Thematic Analysis

The selected publications were subjected to a thematic synthesis. The first step involved identifying recurring concepts relevant to AI-supported learning, digital pedagogy, BIM education, sustainability competencies,

Table 1: Justification for Final Literature Inclusion

Inclusion criterion	Purpose in the review
Relevance to AI-supported learning or digital pedagogy	Ensured alignment with the technological and pedagogical focus of the study
Relevance to construction management or engineering education	Ensured disciplinary relevance
Connection with sustainability, BIM, digital twins or Construction 4.0	Ensured alignment with sustainable construction education
Conceptual or methodological contribution	Ensured usefulness for conceptual framework development
Full-text availability and academic credibility	Ensured transparency and reliability of review evidence

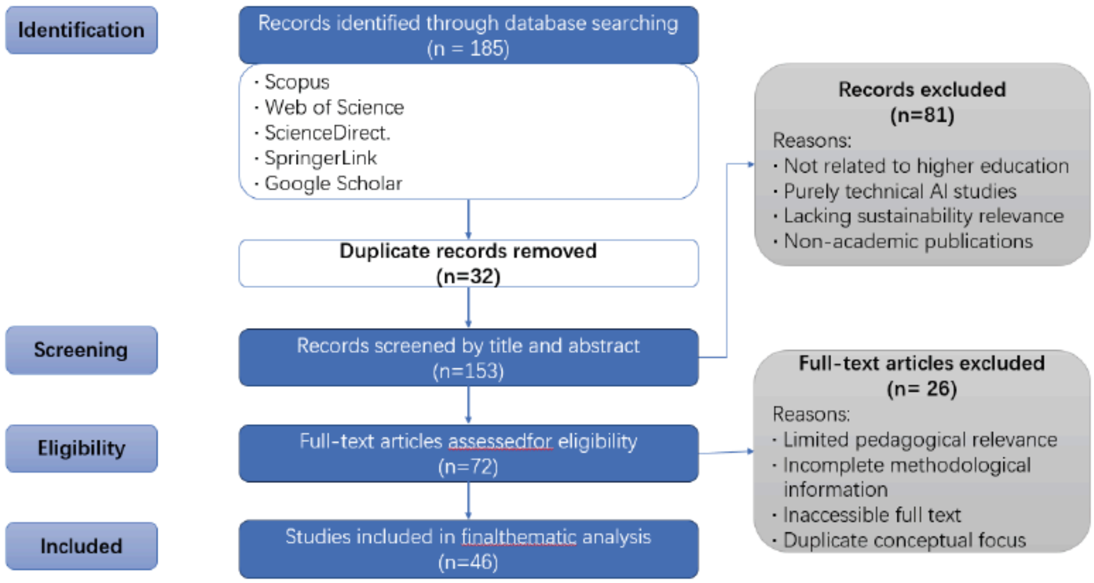

Figure 1: Literature Selection Process (PRISMA Flow Diagram).

Construction 4.0, and Chinese higher education problems identified iteratively. Concepts determined to be similar were grouped into broader categories according to conceptual relevance. These categories were then mapped to the AISCP Framework, ensuring it was informed by the literature while not simply speculative.

The review found six major themes relevant to the framework: AI supported learning environments; generative AI and educational governance; BIM education and sustainable construction; digital twins and Construction 4.0; sustainability competency development, and Chinese higher education reform. These then informed the technological, pedagogical, competency development and governance layers of the AISCP Framework.

2.6. Analytical Procedure

We undertook the analysis in three stages of coding. During the first stage, open coding, we noted the frequency of recurring concepts with respect to AI-assisted pedagogy, sustainability learning and teaching, digital construction technologies, institutional readiness and Construction 4.0 competencies. We used axial coding to classify the concepts into related buckets in the second stage. Finally, in the third stage, we undertook to order the buckets for final AISCP Framework.

To enhance methodological rigour we adopted a priori criteria for inclusion and exclusion, were transparent in our screening record and final thematic codes, and made sure to iteratively go back and forth between the themes and our research question and synthesis of literature. This robustified the final AISCP framework.

3. LITERATURE REVIEW

3.1. AI and Digital Pedagogy in Higher Education

Developments in Artificial Intelligence have had a major impact on teaching and learning in higher education.

Table 2: Mapping between Literature Themes and AISCP Framework Layers

Literature theme	Connection to the AISCP Framework
AI-supported learning environments	Technological Layer
Generative AI and educational governance	Technological Layer / Governance Layer
BIM and sustainable construction education	Technological Layer / Pedagogical Layer
Digital twins and Construction 4.0	Technological Layer / Competency Development Layer
Sustainability competency development	Competency Development Layer
Chinese higher education reform	Governance Layer / Institutional Implementation

Other studies suggest that AI applications are increasingly used to enable adaptive learning, feedback automation, learning analytics, and personalised learning pathways (Zawacki-Richter *et al*., 2019). More broadly, "AI-enhanced education" has been discussed as part of technology-enhanced learning design, adaptive learning, intelligent assessment, personalised learning environments (Bower, 2017; Hwang *et al*., 2020). More recently, recent systematic review evidence show that AI in higher education has already been widely adopted in the key areas of intelligent tutoring, assessment, and learning management and in academic prediction and AI-assisted student support (Crompton & Burke, 2023).

The rise of AI in higher education also requires a stronger focus on AI literacy and AI competency development. Research suggests that AI literacy involves both cognitive understanding and the ability to "use it, evaluate it, create with it, and navigate (one's) everyday life in relation to it" (Almatrafi *et al*., 2024). AI competency frameworks also emphasise technological understanding, ethical awareness, collaboration, self-reflection and "confidence in one's own ability to navigate AI" in educational environments (Chiu *et al*., 2024).

The rise of new Generative AI tools such as ChatGPT has further invigorated discussions relating to digital pedagogy and education transformation (Kasneci *et al*. 2023; Khalil *et al*. 2023). More generally, AI has been explored as a transformative technology in digital education in regards to intelligent learning environments, adaptive intelligent instruction, and 'teaching support' on data-rich platforms (Chassignol *et al*. 2018). In particular, Generative AI has generated concerns relating to academic writing and responsible use of technologies in education (Dwivedi *et al*. 2023). Within engineering education and construction training AI technologies can help with complex problem solving, technical writing and digital simulation and the 'construction process' (Pan & Zhang 2021; Wang *et al*. 2018). Recent engineering education research particularly points to the AI-supported system for pedagogical innovation including intelligent tutoring system, adaptive learning systems, virtual laboratory and personalized curriculum design, which can bring about learning flexibility, instructional focus and engaging students to learning (Zhang *et al*. 2024).

Current discussions are also concerned about issues of integrity, dependency on automated results, and loss of critical thinking (UNESCO, 2023; Tlili *et al*, 2023). Critical higher education research, however, indicates such discussions often circle back into vagueness, and need clearer pedagogical framing in order to not treat AI as neutral or technical as a solution (Bearman *et al*, 2023). AI-supported learning systems "may fundamentally alter how learners and instructors interact and show potential for personalised support at scale" but "how to effectively facilitate students' reliance on AI tools whilst still maintaining appropriate social boundaries, respect for learner autonomy, adhering to ethical regulations, and potentially retaining human oversight is a challenging endeavour" (Seo *et al*, 2021). As well, this suggests that universities "need inclusive policies governing the pedagogical use of AI", covering pedagogy, governance responsibilities, operational support, academic integrity, privacy, and staff development "before AI can effectively be integrated into teaching and learning" (Chan, 2023). AI "as a pedagogical issue and challenge requires urgent rethinking of educators' strategies in curriculum redesign, ethical governance, and enabling guidance" (Chan, 2023).

We undertook the analysis in three stages of coding. During the first stage, open coding, we noted the frequency of recurring concepts with regard to AI-assisted pedagogy, sustainability learning and teaching, digital construction technologies, institutional readiness and Construction 4.0 competencies. We used axial coding to classify the concepts into related buckets in the second stage. Finally, in the third stage, we undertook to order the buckets for final AISCP Framework. In our analysis we aimed for methodological rigour through a priori criteria for inclusion and exclusion, transparent – our screening record of accepted codes and final thematic codes (see above), and being sure to iteratively go back and forth between the themes and our research question and synthesis of literature. This robustified the final AISCP framework.

3.2. Sustainable Construction Education and BIM Integration

Sustainable construction management education requires students to develop interdisciplinary competencies relating to environmental sustainability, digital technologies, and project management. Conventional teaching methods often fail to make clear the associations among carbon performance, lifecycle assessment, economic constraints, and environmental decision-making. Past sustainability education research further indicates that the development of sustainability competences is highly sensitive to how well the pedagogical approach aligns with competency-oriented learning outcomes (Lozano *et al*., 2019). In sum, sustainable construction education needs pedagogical approaches that integrate technical content, sustainability thinking, and realism.

Building Information Modelling (BIM) has therefore become an increasingly important educational tool within construction management programmes. Earlier BIM education research in construction engineering, and management highlighted this need as necessary to industry ROI, curriculum design, software skills, process knowledge, and collaborative project delivery (Sacks & Pikas, 2013). More broadly, BIM offers a digital representation of building products and processes, so that project stakeholders are able to achieve better design coordination, construction planning, and facility management over the life cycle of the project (Sacks *et al*., 2018). Recent BIM-related research in the context of Chinese construction further suggests that BIM can support project design, simulation, planning, monitoring, and collaborative construction management through digital modelling and 3D/4D visualisation (Yang & Leong, 2024).

Prior work also suggests that BIM-based simulations help students better understand sustainable building design and project coordination (Lee, Y. S. *et al*., 2019). BIM education research has also cited BIM curriculum implementation challenges in construction management that include limited BIM experience, ad-hoc integration strategies, and low congruence with other construction management learning (Huang, 2018).

Nevertheless much of the BIM education literature focuses on modelling skill, coordination processes and technical software aptitude. These are important but only partially explain how students develop sustainability judgement, ethical reasoning and interdisciplinary problem solving in an AI supported Construction 4.0 setting. BIM education needs to move beyond technical modelling and become entangled with AI supported simulation, reflective learning, sustainability assessment, and ethics.

3.3. AI and Sustainability Challenges in Chinese Higher Education

China has encouraged educational digitalisation through various initiatives such as Smart Education China, and the Education Informatization 2.0 Action Plan (Ministry of Education of China, 2018). The New Engineering Education further encourages universities to integrate multidisciplinary degrees and emerging technology and sustainability-based competences into engineering courses (Zhuang & Xu, 2018).

Construction management education is therefore increasingly expected to integrate BIM technologies, AI-learning environments, and smart construction systems. However, several implementation challenges remain. Educator digital competency gaps, unequal institutional resources, and technological infrastructure disparities continue to influence the effectiveness of AI within universities.

Regional disparities across Chinese universities may further affect the implementation of AI-supported construction education. While leading universities in economically developed regions may have strong BIM laboratories, smart construction and digital infrastructure, many regional institutions struggle with technological investment, educator digital competency, and interdisciplinary curriculum. In Chinese construction management programmes, curriculum reform is driven by the interplay of engineering education accreditation, digital construction industry demand, the national dual-carbon strategy and the muddled distribution of digital teaching infrastructure. Accordingly, AI-supported sustainable construction education in China must not only relate to technology adoption, but respond to regional educator professional development and curriculum localisation. This complexity highlights the need for a pedagogical framework responsive to not only the availability of AI in the classroom, but institutional readiness and Construction 4.0 competency development.

So, the challenge in Chinese higher education is not whether AI tools are available, but whether universities have the institutional capacity to integrate them pedagogically, ethically and sustainably. Differences in digital infrastructure, staff preparedness, curriculum flexibility and regional distribution of resources could hinder the effectiveness of AI-supported construction education. So a framework could be developed to assess, not just technological adoption, but the capacity for integration, governance and localising the curriculum.

3.4. Research Gap

Existing AI-related work in construction engineering and management has primarily focused on technical applications, automation and industrial efficiency. Less attention has been paid to how AI can facilitate pedagogical transformation, sustainability-oriented curriculum design and competency development for construction management education.

Although BIM education, sustainability education and AI-supported learning has each been discussed in previous studies, these areas themselves remain fragmented; few if any have wed together AI technologies, BIM and digital twins, constructivist pedagogy, sustainability

Table 3: Major Research Themes Identified in the Literature

Theme	Key Focus	Representative Studies
AI-Supported Learning	Personalised learning, adaptive systems, learner support, AI literacy	Holmes *et al.* (2019); Zawacki-Richter *et al.* (2019); Crompton and Burke (2023); Seo *et al.* (2021); Almatrafi *et al.* (2024); Chiu *et al.* (2024)
Generative AI and Educational Governance	Academic integrity, responsible AI use, human oversight, AI policy	UNESCO (2023); Tlili *et al.* (2023); Dwivedi *et al.* (2023); Bearman *et al.* (2023); Bozkurt and Sharma (2023); Chan (2023)
BIM and Sustainable Construction Education	Simulation learning, sustainability analysis, digital construction education	Lee *et al.* (2019); Wang *et al.* (2018); Huang (2018); Sacks and Pikas (2013); Sacks *et al.* (2018); Yang and Leong (2024)
Digital Twins and Construction 4.0	Smart construction, digital twins, automation, data-driven project delivery	Boje *et al.* (2020); Sacks *et al.* (2020); Opoku *et al.* (2021); Oesterreich and Teuteberg (2016); van der Heijden (2023)
Sustainability Competency Development	Sustainability competences, systems thinking, competency-oriented pedagogy	Wiek *et al.* (2011); Lozano *et al.* (2019); Brundiers *et al.* (2021); UNESCO (2017); Qi *et al.* (2024)
Chinese Higher Education Reform	New Engineering Education, digitalisation, dual-carbon education	Zhuang and Xu (2018); Ministry of Education of China (2018); Qi *et al.* (2024)

competencies and ethical governance into a coherent framework for construction management education.

In this paper, we seek to address this gap by proposing the Artificial Intelligence-Supported Construction Pedagogy (AISCP) Framework as an integrated conceptual model for AI-supported sustainable construction management education in Chinese higher education.

The synthesis of these themes highlights the fragmented nature of current research and further demonstrates the need for an integrated pedagogical framework capable of connecting AI technologies, sustainability-oriented learning, and Construction 4.0 competency development.

4. THEORETICAL FOUNDATION

4.1. Constructivist Learning Theory

Constructivist Learning Theory posits that learners build knowledge by experience, reflection, and interaction instead of being passive recipients (Piaget & Inhelder, 1969). In sustainable construction topics, students find it challenging to grasp the abstractions behind the notion of carbon neutrality, lifecycle assessment, and sustainability trade-offs in traditional lecture-format approaches. AI-supported simulations, BIM environments, and experiential learning activities allow students to develop further understanding by having their theoretical knowledge applied to actual project features at hand. This fits with wider studies of AI-supported higher education specifically in relation to AI intelligent learning environments and "personalisation, interaction, and data-informed education practices" (Ouyang *et al.*, 2022). "Through interactive learning environments, students are able to scrutinise sustainability bridging decisions and see their environmental, economic and operational decisions play out". For this reason, experiential learning approaches are suitable for also facilitating collaborative problem solving and reflective records of learning. It also follows the same tie to experiential learning theory, whereby the development of knowledge relies on concrete experience, reflection, conceptualisation and active experimentation (Kolb, 1984).

4.2. Technology Acceptance Model (TAM)

Developed originally for business information systems, the Technology Acceptance Model (TAM) describes how users are accepting and adopting technology via perceived usefulness and perceived ease of use (Davis, 1989). Educator readiness to use AI systems, student digital literacy and institutional availability and support of the technology may influence if immersive AI supported learning environments are adopted within construction management education.

If the AI systems are viewed as useful to learn about sustainability and gain industry readiness, acceptance of the technology is likely to increase. However, if these are perceived as overly complex, adoption may fall, leading to poorly integrated AI technology in the classroom. Successful integration of AI technologies within higher education will depend upon technology availability, but also educator confidence, training and institutional expectations of use.

4.3. Theoretical Integration

Constructivist Learning Theory and the Technology Acceptance Model provide the theoretical foundation for the Artificial Intelligence-Supported Construction Pedagogy (AISCP) Framework. Constructivist learning explains how students build their sustainability knowledge through active learning, experiential learning, reflection, and learner-learner interaction. Based upon Davis's (1989) Technology Acceptance Model, perceived usefulness and perceived ease of use in turn shape educators' and learners' acceptance of AI-supported learning technology. These two theoretical perspectives combined explain how AI-enhanced learning environments can foster sustainability competency development and Construction 4.0 readiness in construction management education.

5. CONCEPTUAL FRAMEWORK DEVELOPMENT

5.1. Distinctiveness of the AISCP Framework

5.2. Technological Layer

Figure **2** illustrates the proposed Artificial Intelligence-Supported Construction Pedagogy (AISCP) Framework integrating AI technologies, pedagogical transformation, sustainability competency development, and ethical governance within Construction 4.0 learning environments.

The pedagogical level of AI is conceptualised not only as a tool for enhancing these competencies but also as a

Table 4: Comparison between AISCP and Existing Pedagogical Models

Existing model/framework	Main focus	Limitation for this study	AISCP contribution
General AI-enhanced learning frameworks	Adaptive learning, intelligent tutoring, learning analytics and personalisation	Often too broad and not tailored to construction management learning tasks	Contextualises AI within construction project learning, sustainability decision-making and Construction 4.0 readiness
Digital pedagogy frameworks	Technology-enhanced learning design and student engagement	Limited attention to construction-specific competencies and professional judgement	Links digital pedagogy with construction management education and sustainability-oriented project learning
BIM education models	BIM modelling, coordination and software proficiency	Often software-oriented and insufficiently connected with sustainability reflection	Extends BIM education through AI-supported simulation, digital twins and reflective sustainability learning
Sustainability education frameworks	Systems thinking and sustainability competencies	Limited integration with AI, BIM and digital construction tools	Embeds sustainability competencies into AI-supported construction management learning
Engineering pedagogy models	Problem-based learning, experiential learning and professional skills	Often lack explicit AI governance and institutional readiness dimensions	Adds ethical governance, human oversight, faculty preparedness and implementation requirements

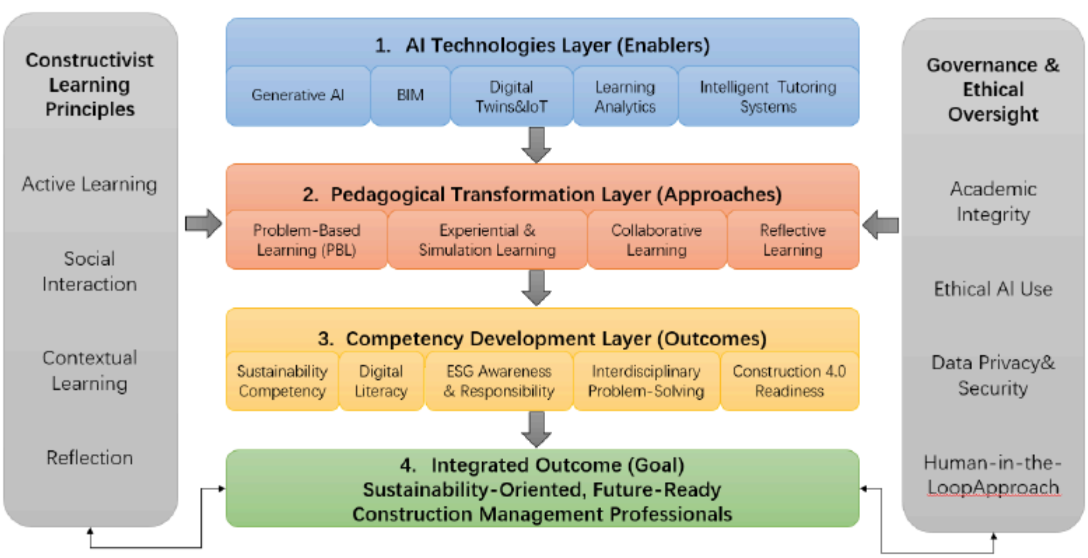

Figure 2: Artificial Intelligence-Supported Construction Pedagogy (AISCP) Framework.

driver of sustainability learning, interdisciplinary collaboration, and professional competencies.

The technological layer of the AISCP Framework also incorporates Generative AI, Building Information Modelling (BIM), digital twins, learning analytics, and intelligent tutoring systems.

These technologies enable the construction of pedagogical environments that are interactive and can be explored in a personalised manner, simulated from a sustainability angle, made collaborative, or made data-driven. Generative AI tools such as ChatGPT may provide technical insights, sustainability tips, and project-based learning assistance to students. Research proposes the AI academic guidance agent, which could serve as a green educational support assistant capable of providing personalised academic knowledge, increasing the efficiency of decision-making, and guiding academic learners through personalised self-service learning environments (Qiu *et al*., 2024). BIM and digital twins support visual learning, lifecycle simulation and sustainability-oriented project exploration.

Learning analytics may also assist educators in tracking student engagement, pinpointing learner difficulties, and providing a customised experience (Siemens & Long, 2011).

5.3. Pedagogical Layer

Following the principles of Constructivist Learning Theory, the Pedagogical layer of the AISCP Framework aims to use AI-supported technologies as cognitive scaffolding rather than allowing them to merely act like information delivery devices. As students can explore the environmental and economic trade-offs of their construction proposals via BIM 5D and digital twins using iterative simulations and real-time scenario analysis, they will be able to reveal the more tacit aspects of construction technology, behaviours and decisions. Within this layer, students gain knowledge of sustainable construction not as mere recipients, but by grappling with problem-based experiences, meaningful reflection, and interacting with digital technologies.

The Pedagogical layer encompasses AI-supported technologies alongside Problem-based learning, Experiential Learning, Simulation Learning and Collaborative Learning approaches. AI technologies become learning supports that enable students to explore sustainability trade-offs and project scenarios, engaging in reflection.

Simulation-based learning environments may enhance students' understanding of sustainability concepts; for instance, tying design decisions to their environmental and financial implications. Students might adjust construction materials or energy systems or project schedules in BIM simulations and observe their ramifications on carbon emissions, performance and life-cycle costs in real-time.

These pedagogical approaches promise more engaged, active learning spaces as compared to lecture-based instruction.

5.4. Competency Development Layer

Competency development layer: for this layer of the AI framework, sustainability competencies, digital literacy, interdisciplinary problem-solving, ESG awareness and Construction 4.0 readiness (these competencies are drawn from existing literature). From the perspective of the Technology Acceptance Model (TAM), the successful cultivation of these core competencies depends on students' perceived usefulness and perceived ease of use of AI supported learning instruments. When construction management students feel that generative AI personal tutors and intelligent tutoring systems can reduce the complexity of Life Cycle Assessments (LCA), their behavioural intention to use sustainable decision-making models may improve, and they may have improved green construction readiness by achieving better mastery.

As common competency goals, Wiek *et al* (2011) stated that it has been shown that systems thinking, anticipatory thinking, normative competence, strategic competence, and interpersonal competence lie in the dimensions of sustainability learning. More recently, research in sustainability education has expanded on the competency frameworks, citing the importance of functions such as intrapersonal competence, implementation competence, and integration competence to drive sustainability transformations into higher education (Brundiers *et al* 2021). In another review, UNESCO's Education for Sustainable Development framework also states that sustainability learning should incorporate cognitive learning goals as well as socio-emotional and behavioural learning objectives, all aligned with the Sustainable Development Goals (UNESCO 2017).

Through an AI supported learning environment, students may develop skills to assess sustainability performance, risk analysis, and digital technology use in construction management practice. The framework therefore, proposes an environmentally green digitally competent construction professional in a smart construction environment. AI supported learning environments may demand students display promise decision makers through a better blend of Technical knowledge with sustainability thinking and project management skills.

5.5. Governance and Ethical Layer

The roll out of AI-supported construction education too will need the accompanying ethical governance and institutional oversight.

Higher education will need to established clear guidelines regarding ethical governance, responsible use of AI, data governance, and human oversight, as human-in-the-loop and student sovereignty remain key priorities in construction management education. Students will need to continue developing their own critical thinking, engineering judgement, and ethical judgement and decision-making capacity. Universities must ensure that AI technologies are used responsibly as part of the educational experience.

Without sufficient governance, excessive consumption of AI-generated outputs may erode students' critical thinking abilities and meaningful learning opportunities.

5.6. Mechanism of the AISCP Framework

The AISCP Framework proceeds through a series of iterative interactions between AI-supported technologies, pedagogy, competencies, and governance.

“AI-supported technologies” such as Generative AI, BIM simulations, digital twins, and intelligent tutoring systems provide students’ interactive data-driven approach to the learning process, sparking experiential and collaborative pedagogical approaches that engage students into processes of sustainability-oriented problem-solving.

By repeatedly entering into a process of reflecting on AI-supported simulations and project-based learning scenarios, students gradually construct sustainability cognition, interdisciplinary decision-making ability, and Construction 4.0 competencies. Governance and ethical mechanisms operate to maintain sufficient levels of responsible AI usage, academic integrity, and human-centred critical reasoning.

Figure **3** illustrates the operational mechanism through which AI-supported learning environments facilitate sustainability cognition, reflective learning, and professional competency development within construction management education.

The mechanism highlights that the educational value of AI does not emerge solely from technological adoption

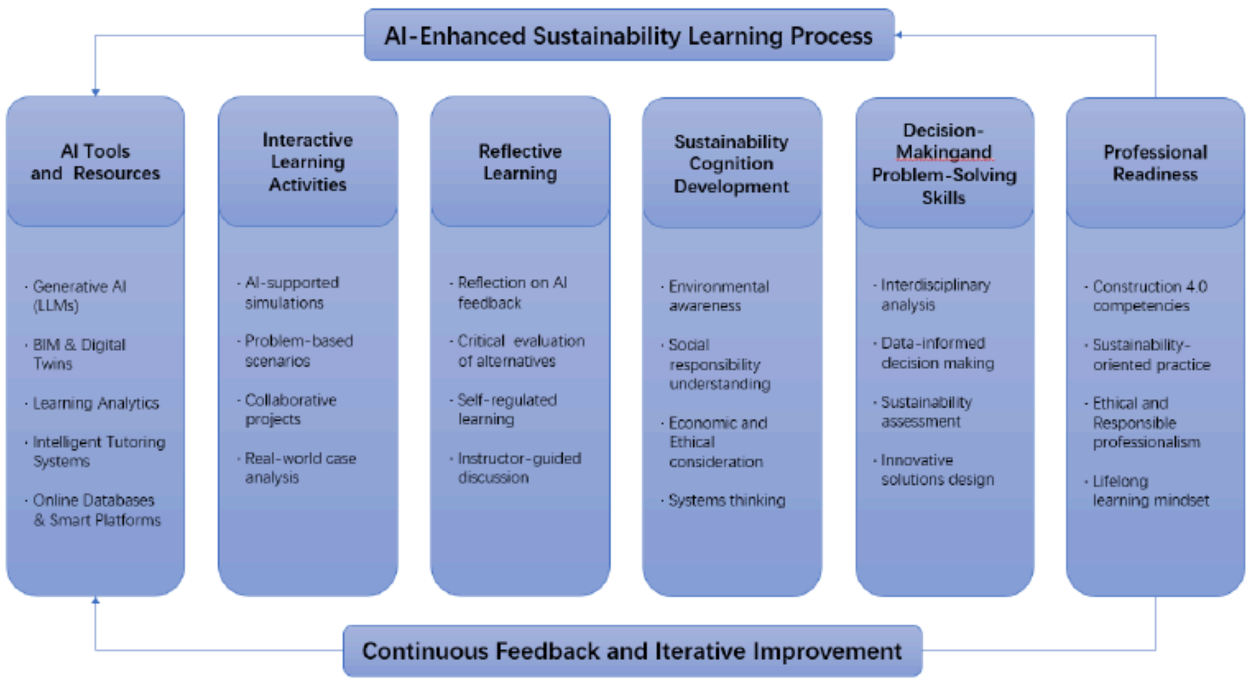

Figure 3: Mechanism of AI-Enhanced Sustainability Learning in Construction Management Education.

Table 5: Operationalisation of the AISCP Framework in Construction Management Education

AISCP layer	Curriculum integration	Teaching strategy	Required resources	Assessment evidence	Expected outcome
Technological Layer	Integrate generative AI, BIM, digital twins and learning analytics into construction management modules	AI-supported simulation and digital modelling	AI tools, BIM laboratory, project datasets and digital platforms	BIM model, simulation output, AI-use log	Digital construction literacy and AI awareness
Pedagogical Layer	Embed project-based and problem-based sustainability tasks into coursework	Group project, scenario analysis, reflective learning and instructor-guided inquiry	Case projects, collaborative learning platform and tutor guidance	Reflective journal, group report and project presentation	Active, experiential and reflective learning
Competency Development Layer	Include sustainability, ESG, lifecycle thinking and Construction 4.0 skills in learning outcomes	Carbon-cost comparison, stakeholder analysis and sustainability decision-making	Sustainability assessment tools, rubric and construction project data	Portfolio, design justification and oral defence	Sustainability competency and professional readiness
Governance Layer	Establish AI-use policy and ethical assessment requirements	AI disclosure, human-in-the-loop review and responsible-use guidance	Institutional AI policy, academic integrity rules and data governance guidelines	AI-use declaration, ethical reflection and assessment checklist	Responsible, ethical and critical AI use

This operationalisation table suggested that AISCP will not be achievable simply by the addition of AI tools to existing modules. It expected coherence between curriculum design, teaching strategy, institutional resources and assessment evidence and anticipated learning outcomes.

itself, but from continuous interaction between AI-supported learning activities, reflective inquiry, sustainability-oriented cognition, and human-centred pedagogical guidance.

5.7. Operationalisation of the AISCP Framework

5.8. Illustrative Application in a Construction Management Module

The following example is illustrative rather than an empirical case study.

5.9. Assessment and Evaluation Mechanisms

6. DISCUSSION

6.1. Comparison with Existing Pedagogical Models

Compared with more general AI-enhanced learning models, the AISCP Framework is more discipline-specific because it links AI-supported learning with construction management tasks, sustainability decision-making and Construction 4.0 competency development.

Table 6: Illustrative Application of AISCP in a Sustainable Construction Management Module

Stage	Learning activity	AI-supported tool	Student output	AISCP layer
Problem framing	Analyse a construction sustainability problem	Generative AI-assisted inquiry	Problem statement and sustainability objectives	Pedagogical / Competency
Digital modelling	Develop alternative project solutions	BIM and digital simulation	Alternative BIM models	Technological
Sustainability analysis	Compare carbon, cost and lifecycle implications	AI-supported simulation or analytics	Carbon-cost comparison report	Competency
Reflection and discussion	Critically evaluate AI-generated suggestions	AI-use log and reflective journal	Reflection on assumptions and limitations	Governance / Pedagogical
Final assessment	Present and defend a construction management solution	Instructor and peer feedback	Group presentation and portfolio	Competency / Governance

Compared with BIM education models, the AISCP Framework shifts the emphasis away from software proficiency toward AI-supported simulation, reflective learning and sustainability-oriented decision-making.

Compared with sustainability education frameworks, AISCP offers a more technology-integrated pathway for competency development through its linking of sustainability competencies with AI tools, digital construction technologies, constructivist pedagogy and governance mechanisms.

6.2. Educational Opportunities

The implications of this research are that the educational potentials of AI for construction management education does not lie simply in the existence or availability of digital tools, but in how these tools are pedagogically contextualized into sustainability learning activities. Within the AISCP Framework, AI-supported technologies can support experiential learning via how students might interrogate construction project scenarios, weigh the sustainability tradeoffs and reflect on how they might make professional decisions.

Compared to conventional PowerPoint slide delivery lectures, AISCP encourages students to wrestle with construction management problems via simulation, inquiry, collaboration and reflection, which help to support bridging the divide of theory of sustainability abstractness to professional construction management practice. Particularly, that AI-supported BIM simulations, digital twins and learning analytics might help students to understand how carbon performance, lifecycle cost, project scheduling, stakeholder needs, and environmental decision-making are interrelated.

But these educational opportunities are dependent on curricular design rather than technology adoption alone. AI tools meaningfully contribute to construction management education only when paired with structured learning outcomes, instructor mediation, reflective assessment and ethical governance. In this sense the AISCP Framework situates AI in pedagogical redesign rather than as a technology in itself.

6.3. Institutional Challenges

Regardless of these benefits, several institutional challenges also remain. Educator digital competency gaps, equal technological infrastructure access issues, interdisciplinary curriculum mixing limitations might mitigate the impact of AI supported education transformation. In particular, less developed university programmes may have common difficulties with funding, digital infrastructure and requirements of technology investment. Such imbalances may also play a role in exposure to BIM laboratories, advanced simulation systems and AI supported learning systems.

Educator adaptations however caution against such optimism. Many construction management educators draw upon significant existing technical expertise due to their technical training via traditional engineering disciplines, yet may be inexperienced in AI supported learning environments or digital pedagogies. Borne from the inertia of traditionalist engineering faculty, the TAM anchors itself in the established protocol of educational institutions. Many educators exhibit a significant low perceived ease of use (PEOU) towards smart learning analytics and automated grading dashboards. Institutions may therefore require an AI-TPACK training component to correct low attitudes, ease of use and intentions to use.

6.4. Ethical and Pedagogical Risks

The rapid rise of Generative AI in higher education introduces challenges surrounding academic honesty, algorithmic bias, and cognitive dependency (Tlili *et al.*, 2023). Students may employ AI-built project reports, sustainability evaluations, and other products without interrogating assumptions. This cognitive dependency will activate a further “fast food” approach to learning rather than develop independent problem-solving.

We can limit risks of cognitive dependency by having higher education align generative AI uses with constructivist approaches. In the AISCP Framework, AI is not the technology that gives right (and “fast food”) engineering answers or project solutions. It can be a dialogic learning partner - one that encourages collaborative reflection, problem-based inquiry, and human-in-the-loop decisions. Generative AI should likewise edge us towards human centred learning design (rather than the dominant automated learning) so that educators still give customised mentoring, pedagogical care, and critical oversight rather than accept the automated system (Bozkurt & Sharma, 2023). Moreover, AI-enabled sources can be inaccurate, biased and incomplete - in construction management contexts, these failures can happen in students’ understanding of sustainability assessments, and engineering calculations or project management processes. AI technologies should think of pedagogical supports, not principal (also in the ways it affects students learning and learning strategies) replacing independent human reasoning.

Human-AI collaboration must be balanced if we are to keep the quality of education, as well as the development of competency for the evolving industry.

6.5. Future Transformation of Construction Education

Education for the future construction manager should embrace balanced human-AI collaboration, interdisciplinary learning, sustainable competency development and ethical governance. AI-supported educational reshaping should not only be about technology, but about long-term curriculum development and student-centred learning.

As Construction 4.0 technologies continue development, universities may need to invest more effort into building sustainability-influenced digital competencies within construction management. Construction 4.0 is described as encompassing automation, digitisation and data-driven project delivery technology, as well as cyber-physical systems, organisational change and wider changes to the construction industry (Oesterreich & Teuteberg, 2016). One recent review paper suggests that Construction 4.0 is best understood through discussion of the social, environmental, governance and humane aspects (van der Heijden, 2023).

How the higher education ecosystem could change in order to fulfil the needs for the sustainable construction of the future, remains an open question.

7. IMPLICATIONS

7.1. Implications for Educators

Of note for educators, the AISCP Framework has implications for construction educators. First, educators should use AI as a form of cognitive and pedagogical support rather than teaching, judgement or students reasoning instead of. In an AI supported learning environment, educators can set problem based construction tasks where students can use generative AI, BIM based simulation, digital twins or learning analytics to explore sustainability problems, compare project alternatives and justify construction management decisions. Second, educators should help students "lean into" AI consciously and responsibly. Students should not just generate the AI supported outputs, but also evaluate how reliable they were, what assumptions and limitations are inherent in them. Reflective journals, "AI-use" logs and oral defence can let students explain how they interpreted, checked and improved AI supported information. This holds promise in reducing the 'crutch' behaviour and in supporting independent judgement. Third, educators need clearer AI literacy and pedagogical confidence ourselves. Our AI literacy needs to include not just AI tools and their general evaluation, but recognition of bias, guidance for data privacy interaction, and support for others to use responsibly. This is similar to recent discussions of AI literacy and AI competency in the postsecondary context (Almatrafi *et al*., 2024; Chiu *et al*., 2024).

7.2. Implications for Curriculum Designers

For curriculum designers the AISCP Framework notes that AI should not simply be bolted onto construction management programmes as further digital entities, but that learning supported by AI should be integrated into curriculum development through expressive learning outcomes, project-based activities and sustainable development assessment.

Construction management modules contain generative AI, BIM, digital twins, lifecycle thinking, carbon assessment, ESG awareness and Construction 4.0 competencies. Moving the focus of training away from software-centred delivery towards competency-based one is called for. BIM and digital construction users should be employed in data modelling skills development but also in sustainability judgement, interdisciplinary dialogue and reflexive decision.

Curriculum designers will find scope in aligning course contents with corresponding learning activities and assessment methodology. Students may be required to assess carbon performance, lifecycle cost, project scheduling and stakeholder needs in some imagined construction project, which[7]may liken up technical management and sustainability issues as environmental, economic, managerial and ethical.

7.3. Implications for Academic Administrators and Policy Makers

For academic administrators, the implementation of the Framework will require institutional support: universities need to provide appropriate digital infrastructure, access to AI and BIM-related learning resources, faculty development programmes and interdisciplinary teaching support. Involvement than may result in AI supported construction education increasing the inequalities between institutions with lots of digital resources and those with little.

Closely related are also institutional policies for responsible AI, those that are clear around acceptable for teaching and assessment purposes, disclosure, academic integrity, data governance and human oversight. Recent discussions about AI policy for generative AI in higher education talk about the importance of clear institutional guidance being a first step integrated responsibly into teaching and learning (Chan, 2023; UNESCO, 2023).

This is an undertaking in which policy makers can assist, by investment in digital infrastructure, regional resource sharing and curriculum reform for AI-integrated sustainable construction education, particularly in the Chinese higher education landscape where digital resources are generally unevenly spread in schools with differing degrees of digitalisation, BIM laboratory access, educator preparation and degrees of institutional readiness.

7.4. Theoretical Implications

Theoretically, this study contributes to the body of literature regarding educational innovation by transitioning discussion of AI in higher eduation beyond the digital adoption literature and into areas of pedagogical transformation and sustainability-oriented curriculum development. The AISCP Framework offers a conceptual model for understanding how AI-supported technologies, constructivist learning principles, sustainability competencies and ethical governance can intersect with construction management education.

The framework transitions existing discussions of digital pedagogy and Construction 4.0 learning awareness from a purely technological intervention perspective towards understanding AI supported education as a pedagogical and institutional process. By bringing together Constructivist Learning Theory and the Technology Acceptance Model, we offer a theoretical approach to understanding both student centred learning and educator acceptance of AI supported construction pedagogy.

8. CONCLUSION

8.1. Summary of Findings

In this study, the authors explored the potential of Artificial Intelligence to support pedagogical innovation and sustainability-oriented curriculum reform in construction management education, focusing on Chinese higher education. Using an integrative literature review and conceptual framework development approach, the authors proposed the Artificial Intelligence-Supported Construction Pedagogy (AISCP) Framework. Integrating AI-supported technologies, constructivist learning principles, sustainability competency development and ethical governance, the framework argues that the educational value of AI is not derived solely from technology adoption but from the synergies between digital tools, active learning, sustainability-oriented judgement, professional competency, and institutional support. The authors identified challenges including educator preparedness, digital infrastructure inequality, academic integrity, over-reliance on AI-generated outputs, and the need for responsible governance, concluding that AI-supported construction management education requires human-centred pedagogy, proper assessment design, and institutional policy support.

8.2. Limitations

This study looked at how Artificial Intelligence might support pedagogical innovation and sustainability-oriented curriculum reform in construction management education, focusing on Chinese higher education. They conducted an ‘integrative literature review ’ and development of ‘conceptual frameworks’ to produce the Artificial Intelligence-Supported Construction Pedagogy (AISCP) Framework.

Integrating AI-supported technologies and pedagogy with constructivist learning principles, sustainability competency development and ethical governance, the framework suggests that the educational value of AI comes not from technology adoption but the potential of synergies between digital tools, active learning, sustainability-oriented judgement, professional competency, and institutional support. Issues of educator preparedness, digital infrastructure inequality, academic integrity, over-reliance on AI-generated outputs, and the need for responsible governance, and argue that AI-supported construction management education requires human-centred pedagogy, proper assessment design and institutional policy support.

8.3. Future Research Directions

Future work might pilot the AISCP Framework in construction management modules to consider its usability in practice. Further empirical studies might survey, interview, plough through learning analytics, assess student learning portfolios or carry out classroom observation to judge its impact on sustainability competency development, AI literacy and/or Construction 4.0 readiness. Later comparative studies of initiative undertaken at different universities, with respect for a region or national context, might touch upon the meaning of institutions and cultures in implementation. Finally, it could longitudinal studies aiming to measure the long-term impact of AI-supported learning environments on the professional readiness of construction students and their sustainable construction decision-making.

DECLARATION OF CONFLICT OF INTEREST

The author(s) declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AUTHOR CONTRIBUTIONS

Yang YiFan was responsible for conceptualisation, literature review, methodology design, framework development, original draft preparation, and manuscript revision. Khar Thoe Ng contributed to supervision, critical review, editing, academic guidance, and final approval of the manuscript. Peng JiaXin contributed to literature organisation, manuscript formatting, language checking, and revision support. All authors have read and approved the final manuscript.

REFERENCES

[1] Ahn, Y. H., Pearce, A. R., Wang, Y., & Wang, G. (2013). Drivers and barriers of sustainable design and construction. International Journal of Sustainable Building Technology and Urban Development, 4(1), 35-45. https://doi.org/10.1080/2093761X.2012.759887

[2] Lee, S., Lee, J., & Ahn, Y. (2019). Sustainable BIM-based construction engineering education curriculum for practice-oriented training. Sustainability, 11(21), 6120. https://doi.org/10.3390/su11216120

[3] Bower, M. (2017). Design of Technology-Enhanced Learning. Emerald Publishing. https://doi.org/10.1108/9781787141827

[4] Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Quarterly, 13(3), 319-340. https://doi.org/10.2307/249008

[5] Dwivedi, Y. K., et al. (2023). “So what if ChatGPT wrote it?” Multidisciplinary perspectives on opportunities, challenges and implications of generative conversational AI for research, practice and policy. International Journal of Information Management, 71, 102642. https://doi.org/10.1016/j.ijinfomgt.2023.102642

[6] Holmes, W., Bialik, M., & Fadel, C. (2019). Artificial Intelligence in Education: Promises and Implications for Teaching and Learning. Center for Curriculum Redesign.

[7] Hwang, G. J., Xie, H., Wah, B. W., & Gašević, D. (2020). Vision, challenges, roles and research issues of AI in education. Computers and Education: Artificial Intelligence, 1, 100001. https://doi.org/10.1016/j.caeai.2020.100001

[8] Kasneci, E., et al. (2023). ChatGPT for good? On opportunities and challenges of large language models for education. Learning and Individual Differences, 103, 102274. https://doi.org/10.1016/j.lindif.2023.102274

[9] Khalil, M., et al. (2023). Exploring the potential and challenges of ChatGPT in higher education. Smart Learning Environments, 10(1), 43.

[10] Kolb, D. A. (1984). Experiential Learning. Prentice Hall.

[11] Zhuang, T., & Xu, X. (2018). “New Engineering Education” in Chinese higher education: Prospects and challenges. Tuning Journal for Higher Education, 6(1), 69-109. https://doi.org/10.18543/tjhe-6(1)-2018pp69-109

[12] Ministry of Education of China. (2018). Education Informatization 2.0 Action Plan.

[13] Pan, Y., & Zhang, L. (2021). Roles of artificial intelligence in construction engineering and management: A critical review and future trends. Automation in Construction, 122, 103517. https://doi.org/10.1016/j.autcon.2020.103517

[14] Piaget, J., & Inhelder, B. (1969). The Psychology of the Child. Basic Books.

[15] Siemens, G., & Long, P. (2011). Penetrating the fog: Analytics in learning and education. EDUCAUSE Review, 46(5), 30-40.

[16] Snyder, H. (2019). Literature review as a research methodology. Journal of Business Research, 104, 333-339. https://doi.org/10.1016/j.jbusres.2019.07.039

[17] Tlili, A., Shehata, B., Adarkwah, M. A., Bozkurt, A., Hickey, D. T., Huang, R., & Agyemang, B. (2023). What if the devil is my guardian angel: ChatGPT as a case study of using chatbots in education. Smart Learning Environments, 10, 15. https://doi.org/10.1186/s40561-023-00237-x

[18] UNEP. (2022). 2022 Global Status Report for Buildings and Construction. United Nations Environment Programme.

[19] UNESCO. (2023). Guidance for Generative AI in Education and Research. UNESCO Publishing.

[20] Wang, P., Wu, P., Wang, J., Chi, H.-L., & Wang, X. (2018). A critical review of the use of virtual reality in construction engineering education and training. International Journal of Environmental Research and Public Health, 15(6), 1204. https://doi.org/10.3390/ijerph15061204

[21] Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Artificial intelligence applications in higher education. International Journal of Educational Technology in Higher Education, 16(1), 39. https://doi.org/10.1186/s41239-019-0171-0

[22] Qi, S., Jiang, P., & Zhou, M. (2024). Enhancing sustainable development competence in undergraduates: Key determinants in the context of “dual-carbon” targets. Sustainability, 16(21), 9208. https://doi.org/10.3390/su16219208

[23] Chassignol, M., Khoroshavin, A., Klimova, A., & Bilyatdinova, A. (2018). Artificial intelligence trends in education: A narrative overview. Procedia Computer Science, 136, 16-24. https://doi.org/10.1016/j.procs.2018.08.233

[24] Ouyang, F., Zheng, L., & Jiao, P. (2022). Artificial intelligence in online higher education: A systematic review of empirical research from 2011 to 2020. Education and Information Technologies, 27, 7893-7925. https://doi.org/10.1007/s10639-022-10925-9

[25] Zhang, N., Leong, W. Y., Zhang, T., & Wei, C. (2024). Artificial intelligence in engineering education: A review of pedagogical innovations. INTI Journal, 2024(46), 1-10. https://doi.org/10.61453/INTIj.202446

[26] Qiu, Y., Khan, M. H., Zhu, S., Chen, S., & Chan, C. (2024). Enhancing sustainability in academic guidance: Develop an AI-driven agent for Education 5.0. INTI Journal, 2024. https://doi.org/10.61453/INTIj.202440

[27] Yang, F., & Leong, W. Y. (2024). Application and challenges of BIM technology in China’s integrated utility tunnels. INTI Journal, 2024(41), 1-14. https://doi.org/10.61453/INTIj.202441

[28] Crompton, H., & Burke, D. (2023). Artificial intelligence in higher education: The state of the field. International Journal of Educational Technology in Higher Education, 20, 22. https://doi.org/10.1186/s41239-023-00392-8

[29] Bearman, M., Ryan, J., & Ajjawi, R. (2023). Discourses of artificial intelligence in higher education: A critical literature

review. Higher Education, 86, 369-385. https://doi.org/10.1007/s10734-022-00937-2

[30] Seo, K., Tang, J., Roll, I., Fels, S., & Yoon, D. (2021). The impact of artificial intelligence on learner-instructor interaction in online learning. International Journal of Educational Technology in Higher Education, 18, 54. https://doi.org/10.1186/s41239-021-00292-9

[31] Bozkurt, A., & Sharma, R. C. (2023). Challenging the status quo and exploring the new boundaries in the age of algorithms: Reimagining the role of generative AI in distance education and online learning. Asian Journal of Distance Education, 18(1), i-viii.

[32] Wiek, A., Keeler, L., & Redman, C. (2011). Key competencies in sustainability: A reference framework for academic program development. Sustainability Science, 6(2), 203-218. https://doi.org/10.1007/s11625-011-0132-6

[33] Lozano, R., Barreiro-Gen, M., Lozano, F. J., & Sammalisto, K. (2019). Teaching sustainability in European higher education institutions: Assessing the connections between competences and pedagogical approaches. Sustainability, 11(6), 1602. https://doi.org/10.3390/su11061602

[34] Huang, Y. (2018). A review of approaches and challenges of BIM education in construction management. Journal of Civil Engineering and Architecture, 12(6), 401-407. https://doi.org/10.17265/1934-7359/2018.06.001

[35] Almatrafi, O., Johri, A., & Lee, H. (2024). A systematic review of AI literacy conceptualization, constructs, and implementation and assessment efforts (2019-2023). Computers and Education Open, 6, 100173. https://doi.org/10.1016/j.caeo.2024.100173

[36] Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. Automation in Construction, 114, 103179. https://doi.org/10.1016/j.autcon.2020.103179

[37] Brundiers, K., Barth, M., Cebrián, G., Cohen, M., Diaz, L., Doucette-Remington, S., Dripps, W., Habron, G., Harré, N., Jarchow, M., Losch, K., Michel, J., Mochizuki, Y., Rieckmann, M., Parnell, R., Walker, P., & Zint, M. (2021). Key competencies in sustainability in higher education—toward an agreed-upon reference framework. Sustainability Science, 16(1), 13-29. https://doi.org/10.1007/s11625-020-00838-2

[38] Chan, C. K. Y. (2023). A comprehensive AI policy education framework for university teaching and learning. International Journal of Educational Technology in Higher Education, 20, 38. https://doi.org/10.1186/s41239-023-00408-3

[39] Chiu, T. K. F., Ahmad, Z., Ismailov, M., & Sanusi, I. T. (2024). What are artificial intelligence literacy and competency? A comprehensive framework to support them. Computers and Education Open, 6, 100171. https://doi.org/10.1016/j.caeo.2024.100171

[40] Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. Computers in Industry, 83, 121-139. https://doi.org/10.1016/j.compind.2016.09.006

[41] Opoku, D.-G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. Journal of Building Engineering, 40, 102726. https://doi.org/10.1016/j.jobe.2021.102726

[42] Sacks, R., & Pikas, E. (2013). Building information modeling education for construction engineering and management. I: Industry requirements, state of the art, and gap analysis. Journal of Construction Engineering and Management, 139(11), 04013016. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000759

[43] Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems. Data-Centric Engineering, 1, e14. https://doi.org/10.1017/dce.2020.16

[44] Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). BIM handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers (3rd ed.). Wiley. https://doi.org/10.1002/9781119287568

[45] UNESCO. (2017). Education for Sustainable Development Goals: Learning objectives. UNESCO. https://doi.org/10.54675/CGBA9153

[46] van der Heijden, J. (2023). Construction 4.0 in a narrow and broad sense: A systematic and comprehensive literature review. Building and Environment, 244, 110788. https://doi.org/10.1016/j.buildenv.2023.110788