Case Study

A Roadmap to the Next-Generation Technology-Enabled Learning-Centered Environments in AEC Education

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Abstract: The architecture, engineering, and construction (AEC) education communities are increasingly facing challenges caused by social, technological, economic, environmental, and political changes. Addressing these issues requires AEC educators and practitioners to systematically rethink and reform many of their current practices. Anecdotal evidence in AEC education already exists with respect to pedagogical improvements made by individual technologies such as immersive computing, artificial intelligence, robotics, big data, cyberinfrastructure, and photogrammetry. However, an effective learning-centered environment is more complex than what any single technology can accomplish. In addition, the relationship between technology-intensive learning and digital inequity in AEC education remains, to the most extent, unclear. We envision the next-generation learning-centered environment for AEC education to be technology-intensive, interdisciplinary, industry-linked, and equitable. This paper aims to present a shared vision of the next-generation learning-centered environment for AEC education. To achieve this goal, two interrelated workshops were organized with the participation of different stakeholders, including researchers, educators, and professionals from multiple disciplines of architecture, engineering, construction, computer science, learning science, education, and social sciences. This paper is based on the combined outcomes of the two workshops, organized in four themes: (1) AEC curricula and industry practice, (2) technology and learning, (3) interdisciplinary education, and (4) digital inequity. This paper contributes to the body of knowledge by creating a pathway to timely reflect on new learning strategies, new technologies, and future industry and societal needs in AEC curricula, thus producing a more adaptive AEC workforce for the 21st century. The findings of this work can be adopted by educators to develop a roadmap for creating the shared vision of the next-generation learning-centered environment for AEC education. **DOI: 10.1061/JCEECD.EIENG-1972.**

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Introduction

The evolution of technology has continuously transformed science, technology, engineering, and math (STEM) education over the last centuries (Nawari 2010). STEM education of the future faces challenges in bringing together an advanced understanding of how people learn with modern technology to create more personalized learning experiences, inspire learning, and foster creativity from an early age (Honey et al. 2020). Therefore, the rapid social and technological changes require a new vision related to the ecosystem of STEM education.

Meanwhile, the architecture, engineering, and construction (AEC) industry is one of the fastest-growing industries in the US and many parts of the world (Alizadehsalehi et al. 2020). The AEC industry constantly seeks innovative and sustainable solutions to create sustainable, healthy, and inclusive built environments while battling global challenges such as climate change, bridging social inequity gaps, and embracing technological advancements. The AEC sectors are also expected to undergo major transformations due to advances in computer-based technologies and new human experiences. Emerging technologies, such as smartphones, three-dimensional (3D) printing, mobile applications, virtual reality (VR), augmented reality (AR), and drones, are just a few game-changing examples that have impacted the industry (Shull 2018). At the dawn of the fourth industrial revolution (also called 4IR or Industry 4.0), when technology is about to disrupt many of the traditional AEC practices and higher education, the research and education communities need to answer one critical question: what will the next-generation learning environment look like for AEC education and what role or roles will emerging technologies play in shaping that environment?

Anecdotal evidence in AEC education shows that technology plays a significant role in pedagogical improvements such as building information modeling (BIM) (Wang et al. 2020), immersive computing (Vassigh et al. 2018), and 3D scanning or photogrammetry (Issa 2018). Moreover, emerging technologies such as digital twins, artificial intelligence, cyberphysical systems, and big data analytics offer sophisticated tools to create better teaching and learning experience for students that utilize smart classrooms (Bdiwi et al. 2019), smart learning environments (Kinshuk et al. 2016), and smart personalized tutors (Winkler et al. 2019). However, the implication of these and other technologies in the future of AEC

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education still remains largely unknown to the AEC research and education communities.

In particular, the impact of emerging technologies on the AEC curricula, the learning environment, and digital equity, as well as the potential of the technologies for creating new opportunities to improve AEC education, is still underexplored. A systematic investigation into the relationship among humans, learning, and technology in varied social contexts is still in the exploratory stages with respect to AEC education, especially in the aftermath of the COVID-19 pandemic, which has had a tremendous impact on the status quo. To prepare a future-ready AEC workforce, the AEC community must address these grand challenges effectively.

Goal, Scope, and Themes

Goal

The goal of this study is to create a shared vision of the next-generation technology-enabled learning-centered environment for AEC education, including its characteristics, grand challenges, and opportunities, and offer a roadmap for research and implementation. To achieve this goal, two interrelated workshops were organized with the participation of different stakeholders, including researchers, educators, and practitioners from multiple disciplines of architecture, engineering, construction, computer science, learning science, education, and social sciences. The first workshop was an extensive and intensive brainstorming session focusing on grand challenges and opportunities. The second workshop was an innovation lab focusing on developing solutions to address and materialize the shared vision developed in the first workshop. Both workshops were organized in collaboration with the ASCE and the American Society for Engineering Education (ASEE).

This article is based on the combined outcomes of the two workshops. The results of the workshops contribute to the body of knowledge by identifying a vision and a pathway to timely address new learning strategies, new technologies, and future industry and societal needs in AEC curricula, thus producing a more adaptive AEC workforce.

Scope

The central focus of this study is on the relationship and interplay between stakeholders in AEC education, technology, and lifelong learning, three key elements constituting a technology-enabled learning-centered environment. Fig. 1 shows a schematic view of the workshop scope.

These elements are now described in detail:

- Human stakeholders refer to different types of organizations and individuals in the learning-centered environment, capturing who is involved in the environment. In the context of AEC education, they are academic institutions, accreditation organizations, the AEC industry, technology industries, professional societies, undergraduate AEC students, other students (graduate students and students in professional development programs), and faculty. Among them, the main focus is given to undergraduate AEC students and their teachers to support the mission of the National Science Foundation (NSF) Improving Undergraduate STEM Education (IUSE) program. Considering the need to address lifelong learning, other types of students are also considered. Other stakeholders, such as industries and professional societies, play a role in this learning-centered environment, addressing undergraduate students' learning. Therefore, other students and stakeholders are included in the study wherever necessary.

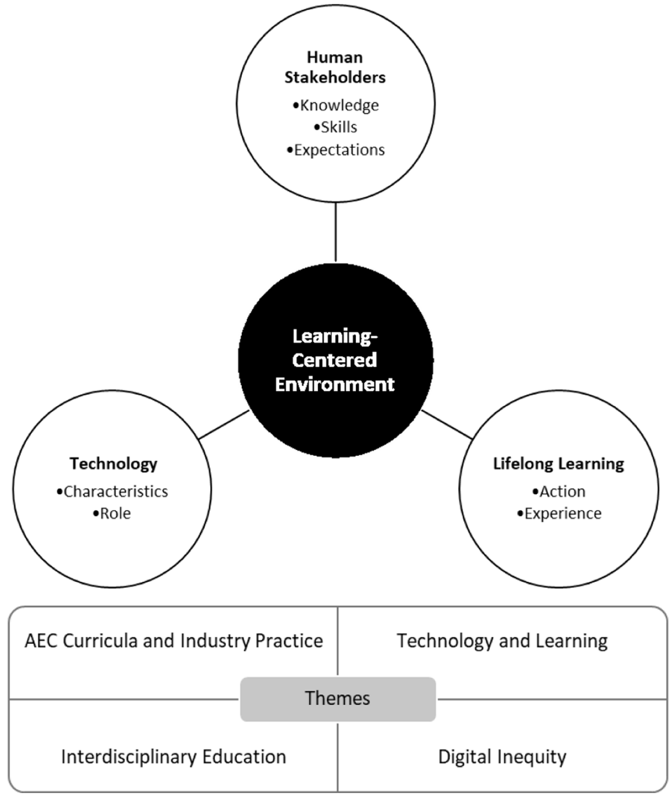

Fig. 1. Scope and themes of the workshops.

- Lifelong learning is defined as "the ongoing, voluntary, and self-motivated pursuit of knowledge for either personal or professional reasons" (Department of Education and Science 2000). It refers to the process of students acquiring knowledge and skills, in particular transferable knowledge and skills, such as problem-solving and critical thinking, in postsecondary AEC education. Although the main focus of this study is on the learning of undergraduate AEC students, lifelong learning means the knowledge and skills they acquire can effectively support their training and learning needs in their professional and personal lives after graduation.
- Technology refers to information and computer technologies (ICTs) broadly. It can be a learning subject or an enabling factor of the learning environment. This part only includes technology as an enabling factor. If technology is considered a learning subject, it is included in lifelong learning.

Topical Themes

To address the goal and scope, four major topical themes related to emerging technologies have been defined to structure the workshops as follows:

- AEC Curricula and Industry Practice: There is a need to create a transformative, not disruptive, process to reform AEC education to satisfy industry needs and prepare students for future challenges. The process should transform the current AEC education toward the envisioned learning-centered environment but does not disrupt the current practices. This requires a reimagined model of academia and industry collaboration in the new context, including organizational improvements, pedagogical improvements, and knowledge transfer. Thus, it is important to answer questions that are critical to shaping the future of AEC education, e.g., what are the gaps between AEC curricula and industry practice, and what is the role of emerging technologies in creating and/or closing these gaps?

- AEC Interdisciplinary Education: Interdisciplinary education still faces curricular restrictions, logistic issues, organizational fragmentation, and varying student backgrounds. Although universities and programs try to accommodate new ideas and developments in their courses and curricula, they often face challenges such as fragmented curricula, lack of expertise, and lack of standards. In addition, each discipline has its program requirements dictated by the corresponding accreditation agency, which reduces the likelihood of developing new courses where students from all three majors can converge and benefit. Therefore, it is important to explore the opportunities offered by emerging technologies, such as new pedagogical strategies, to deliver interdisciplinary learning contents that is conducive to multiple disciplines.
- Technology and Learning: Emerging digital technologies such as digital twins (DTs), artificial intelligence (AI), cyberphysical systems (CPS), and big data are transforming AEC industry practices. In the meantime, such technologies also affect both the contents and the delivery methods of the next-generation technology-enabled learning-centered environment. One impact on AEC education is the adoption of online learning, which has been accelerated by the COVID-19 pandemic (Lee et al. 2022). Fundamental questions need to be explored related to how emerging technologies, coupled with advancements in cognitive and education sciences, form disruptive forces to improve the learning environment.
- Digital Inequity: Students and faculty possess different levels of digital literacy, and students' social, economic, and disability statuses interact with their digital literacy and digital inequity. Deficiencies in digital literacy are a hindrance to students' success. In addition, skills such as digital adaptability are a relatively new concept in AEC education. It is urgent that AEC programs foster such transferable skills of students in learning digital technologies to achieve equitable learning outcomes and develop a holistic view of digital inclusion (including physical access to digital technologies and the entire teaching and learning ecosystem). Thus, it is important to understand the extent and influence of digital inequity while creating technology-intensive learning environments and to address the challenges by developing new pedagogical strategies.

Literature Review

One of the powerful tools for brainstorming about a subject is conducting workshops where multimodal perspectives can interact with each other to generate new knowledge (Woodson et al. 2019; Ozkaynak et al. 2021; Parija and Adkoli 2020). In this regard, White et al. (2022) investigated brainstorming workshops to identify effective tools and best practices for practitioners to drive their design thinking in a remote or hybrid environment. Felder (2002) provided workshop training techniques and strategies that could be applied in brainstorming sessions, focusing on 15 workshop techniques.

Although the literature in this area indicates that many participants in brainstorming workshops only engage when they need to solve a problem, Billington et al. (2009) highlighted that there were others who desired new learning and "browsers" who were interested in gathering information. In addition, Nielsen (2012) highlighted that to enhance the effectiveness of brainstorming interaction in workshops, not only do group discussions need to be created, but also group members must be encouraged to cooperate with each other. In such an environment, participants are assisted in revealing their thoughts and engaging in a social process of clarifying, developing, and refining ideas, which will increase the effectiveness of the workshop.

Nevertheless, a successful brainstorming workshop should make the participants active learners, allowing them to be engaged instead of passive participants (Burger 2007). Therefore, facilitation of brainstorming, consisting of a high degree of forcing each group member to participate actively and contribute to the specific activity type, plays an essential role in effective brainstorming workshops. In this regard, process facilitation is essential in a brainstorming workshop, which can be defined as leadership emphasizing participation distribution and a subtle way of steering participants in a particular direction (Nielsen 2012).

In another study, Lev (2003) introduced structured networking activities, also known as "speed dating," a successful technique to enliven and improve brainstorming workshops. In the traditional format, one person speaks, and the others have to listen. After that, they will be ready for conversations during breaks. Speed dating takes these conversations further by concentrating on a specific topic of interest and recognizing that individuals fill different roles in many conversations. Thus, pairing participants with a purpose can achieve excellent learning and networking results. In addition, Kronsbein and Mueller (2019) investigated design thinking through workshops by following an action design research (ADR) approach and suggesting a practical change in the workshop format by conducting user interviews as homework before the workshop day.

To design a successful brainstorming workshop, the use of digital tools is recommended (Burger 2007). In this regard, brainstorming workshops must be compatible with and/or dependent upon digital tools that could be used in a group setting. In another study, Shaw (2006) investigated whether technology-supported "journey-making" workshops can effectively capture quality research data using problem-structuring methods (PSMs)—methods for supporting structured thinking about complex problems. Using PSM to collect participants' opinions instead of traditional tools (e.g., interviews) can address the issues of the client having access to the right stakeholders and enabling data collection using computer technologies. Although PSM applications might differ based on different workshop goals and conditions, in a journey-making workshop, participants need to discuss and even fight to indicate their opinion in brainstorming discussions.

In addition, Samiei et al. (2020) investigated the performance of virtual workshops by discussing the advantages, disadvantages, and some of the potential of the broadcast platforms (e.g., Zoom, SlidesLive, and Facebook Live) to be used in virtual workshops. They highlighted that virtual workshops could reduce costs significantly and improve engagement and participation worldwide due to the lack of need to travel.

Methodology

In order to create a shared vision of the next-generation technology-enabled learning-centered environment for AEC education, we used the brainstorming workshop technique (Woodson et al. 2019; Ozkaynak et al. 2021; Parija and Adkoli 2020). The brainstorming workshop is used, first, to identify the needs, challenges, and solutions for creating such a shared vision, and then to build consensus regarding the identified needs, challenges, and solutions to create a roadmap to achieve the shared vision. To allow enough analysis time after identifying the needs, challenges, and solutions to be used for building consensus, two separate workshops were used, Workshop 1 and Workshop 2. As shown in Fig. 2, Workshop 1 was

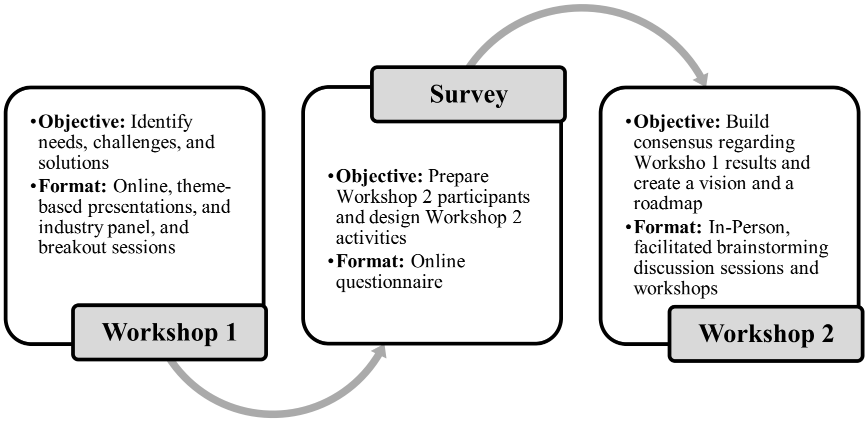

Fig. 2. Major steps of the project.

followed by a survey questionnaire, the responses to which influenced the design of Workshop 2.

In Workshop 1, we organized presentations and an industry panel, and conducted brainstorming facilitation in the format of parallel breakout discussion sessions. The objective was to identify the needs of the AEC education community, the challenges facing the community, and the proposed solutions. The breakout sessions were audio recorded. The recording was transcribed and manually reviewed by the organizing committee members. During the review, the focus was given to identifying the needs, challenges, and solutions as outcomes of Workshop 1. Workshop 1 was entirely virtual over Zoom, allowing participation from different locations and recording of all the information presented. It was performed over 3 consecutive days (a total of 15 h, including the breaks).

According to the design thinking approach, these outcomes were structured into a survey questionnaire distributed to Workshop 2 participants before the event. The goal of this survey was not only to introduce the Workshop 2 participants to the identified challenges and solutions to ensure knowledge transfer, but also to use the results of the survey questionnaire to develop the content and organize Workshop 2 in a more effective way.

Workshop 2 involved a consensus-building process to create a shared vision and a roadmap for creating a next-generation AEC education learning-centered environment. Applying the Six Sigma SIPOC (suppliers, inputs, process, outputs, customers) approach (Yeung 2009; Eryarsoy et al. 2022), a trained facilitator facilitated the process to ensure the active engagement of all participants and to reach a common goal at the end of the process. In addition, several digital tools were integrated into the workshops to ensure achieving consensus during the workshop. In Workshop 2, several digital tools were used to capture the generated data and share it with the participants after the workshop. Workshop 2 was conducted in person over 1.5 days (a total of 17 h, including the breaks).

Workshop Information

Workshop 1 was an online event (to mitigate the risks of the COVID-19 pandemic) that took place on November 15–17, 2021. Workshop 1 had several elements, including a keynote speech, topical presentations on each theme, an industry discussion panel (with industry professionals from AEC industries and a professional construction organization), and several breakout sessions to facilitate discussion and brainstorming. The goal of Workshop 1 was to create a list of challenges and actions toward creating the next-generation learning-centered environment with a focus on the role of emerging technologies.

Workshop 2 was built upon the outcome of Workshop 1 and was held on June 24–25, 2022, in Minneapolis, on the sidelines of the annual ASEE conference. In addition to a keynote speech, group discussions and consensus-building sessions were the main activities of the workshop. The goal of Workshop 2 was to use the generated knowledge in Workshop 1 (e.g., challenges and actions) to create a roadmap toward creating a next-generation AEC education learning-centered environment with a focus on the human-technology frontier in AEC education.

Workshop 1 had 37 participants (17 of whom presented in several sessions while participating in breakout sessions). The participants' fields of expertise included 14% architecture, 38% engineering (civil, mechanical, and so on), 30% construction, and 19% education (education science, engineering education, and so on). Workshop 2 had 30 participants (of which eight were from Workshop 1), with fields of expertise of 23% architecture, 31% engineering, 19% construction, and 27% education. The demographic information of the participants in both workshops is provided in Tables 1 and 2.

Table 1. Demographic information of participants

Categories	Workshop 1	Workshop 2	Total
Total number of participants	37	30	63
Field of expertise			
Architecture	5 (13.5%)	6 (20.0%)	10 (15.9%)
Engineering	14 (37.8%)	8 (26.7%)	21 (33.3%)
Construction	11 (29.7%)	9 (30.0%)	20 (31.7%)
Education	7 (18.8%)	7 (23.3%)	12 (19.1%)
Type of institution			
Academic (R1)	27 (73.0%)	26 (86.7%)	49 (77.8%)
Academic (non-R1)	6 (16.2%)	4 (13.3%)	10 (15.9%)
Industry	4 (10.8%)	0 (0.0%)	4 (6.3%)
Affiliation			
Instructor/Designer	1 (2.7%)	2 (6.6%)	3 (4.8%)
Assistant Professor	12 (32.4%)	13 (43.3%)	25 (39.7%)
Clinical Assistant Professor	1 (2.7%)	1 (3.3%)	2 (3.2%)
Associate Professor	7 (18.9%)	6 (20.0%)	12 (19.0%)
Professor	10 (27.0%)	7 (23.3%)	15 (23.8%)
Industry practice	4 (10.8%)	0 (0.0%)	4 (6.3%)
Other	2 (5.4%)	1 (3.3%)	2 (3.2%)
Gender			
Female	21 (56.8%)	12 (40.0%)	29 (56.0%)
Male	16 (43.2%)	18 (60.0%)	34 (54.0%)
Minority serving institution	2	2	3

Table 2. Demographic information of participants of the survey

Area of expertise	No. of participants
Architecture	3
Engineering	11
Construction	5
Education	2
Total	21

In addition, a survey was administered to Workshop 2 participants. The survey questions are related to the needs of the stakeholders, challenges facing the AEC education community, and solutions identified in Workshop 1. Likert scales of 1 (strongly disagree), 2 (disagree), 3 (neutral), 4 (agree), and 5 (strongly agree) were applied to elicit participants' degree of agreement with the identified needs, challenges, and solutions. The purpose of the survey is to prepare the participants for Workshop 2 and help organizers design workshop activities. A total of 21 participants partook in the survey.

Workshop Findings

In the following, we first present the results of an analysis of the transcribed text of Workshop 1 materials. Then, participants' views on the current status, challenges, and actions concerning the four themes are presented.

Text Mining Analysis

Due to the online format of Workshop 1, we were able to record and transcribe all the presentations and breakout sessions on each theme. Using the generated transcripts, we applied text mining to investigate keywords used in the workshop under different themes. This analysis provided an informative overview of the topics discussed on each theme. First, a list of the most frequent keywords used in the workshop was collected. The words "learner(s)," "tool(s)," "environment," "perspective," "design(ing)," and "class(room)" were the most repeated keywords during Workshop 1, with a repetition of more than 300 times. Fig. 3 presents a word cloud highlighting the most repeated phrases based on frequency. This word cloud provides a simple visual insight that can lead to more in-depth analyses of the phrases used during Workshop 1.

Fig. 3. (Color) Word cloud of the most repeated phrases in Workshop 1.

After identifying the most frequent phrases used in each theme (i.e., AEC curricula and industry practice, technology and learning, interdisciplinary education, and digital inequity), we performed a multidimensional scaling (MDS) analysis to generate a two-dimensional point map of distances between the identified most frequent phrases. Each point represents a phrase in this point map, and the distance between points represents how often these phrases are used under the same theme. Using this point map, we discovered the relationship of each phrase to the other phrases. Next, the frequency of each phrase was integrated into the point map to generate a three-dimensional rating map of the identified phrases.

The result of the MDS analysis and the three-dimensional point map is shown in Fig. 4. As it is stated, the distance between phrases shows their similarity of use in each theme (for example, the words on the right-hand side are used mostly in the digital inequity theme, which is why they are closer together and far from the others) In addition, the size of the circles represents the frequency of use of each word in Workshop 1. Moreover, this map is color-coded; for example, the light red circles are mostly used in the interdisciplinary education theme. The mixed colors show the utilization of that phrase in different themes.

As shown in Fig. 4, EC Curricula & Industry Practice (light red cluster), Technology & Learning (light green cluster), and Interdisciplinary Education (light purple cluster) are located on the left-hand side of the map, whereas Digital Inequity (light blue cluster) is located on the right-hand side. It indicated that there are more interrelationships between the concepts covered in the three themes of AEC Curricula & Industry Practice, Technology & Learning, and Interdisciplinary Education compared with Digital Inequity. Particularly, the Digital Inequity theme, with keywords such as information literacy, digital adaptability, digital equity, affordability, disability, and universal design, is further away from the center of the map (toward the right-hand side), and the shared phrase "learning" connects these terms to the left-hand side of the map. Considering the two keywords of "learning" and "students" as the most repeated terms in all four themes as the core concept of the map, digital inequity is an essential element in students' learning in the next-generation technology-enabled learning-centered environment in the AEC education.

On the other hand, the Technology & Learning theme, with keywords such as online learning, performance, mental workload, and work engagement, is mostly toward the left bottom side of the map, whereas the Interdisciplinary education theme with keywords such as collaboration, data, and disciplines is mostly toward the left top side of the map. These two themes are connected through the AEC Curricula & Industry Practice theme, with keywords such as real word, BIM, knowledge, and idea (mostly located on the left-center side of the map), illustrating how the AEC industry practice and designed curricula based on that can link the interdisciplinary education to technology in the education in the next-generation learning-centered environment in the AEC education. Finally, these three themes are linked to the right-hand side of the map using the shared phrase "students," surrounded by "classroom," "system," "future," "stakeholders," and "lifelong learning."

Overall, this map can help educators understand the essential concepts and the interrelations between the themes for the next-generation technology-enabled learning-centered environment in AEC education. It also helps to explain the interrelationships between the designed workshop themes to better delineate the future needs and requirements in creating the shared vision of such a learning-centered environment.

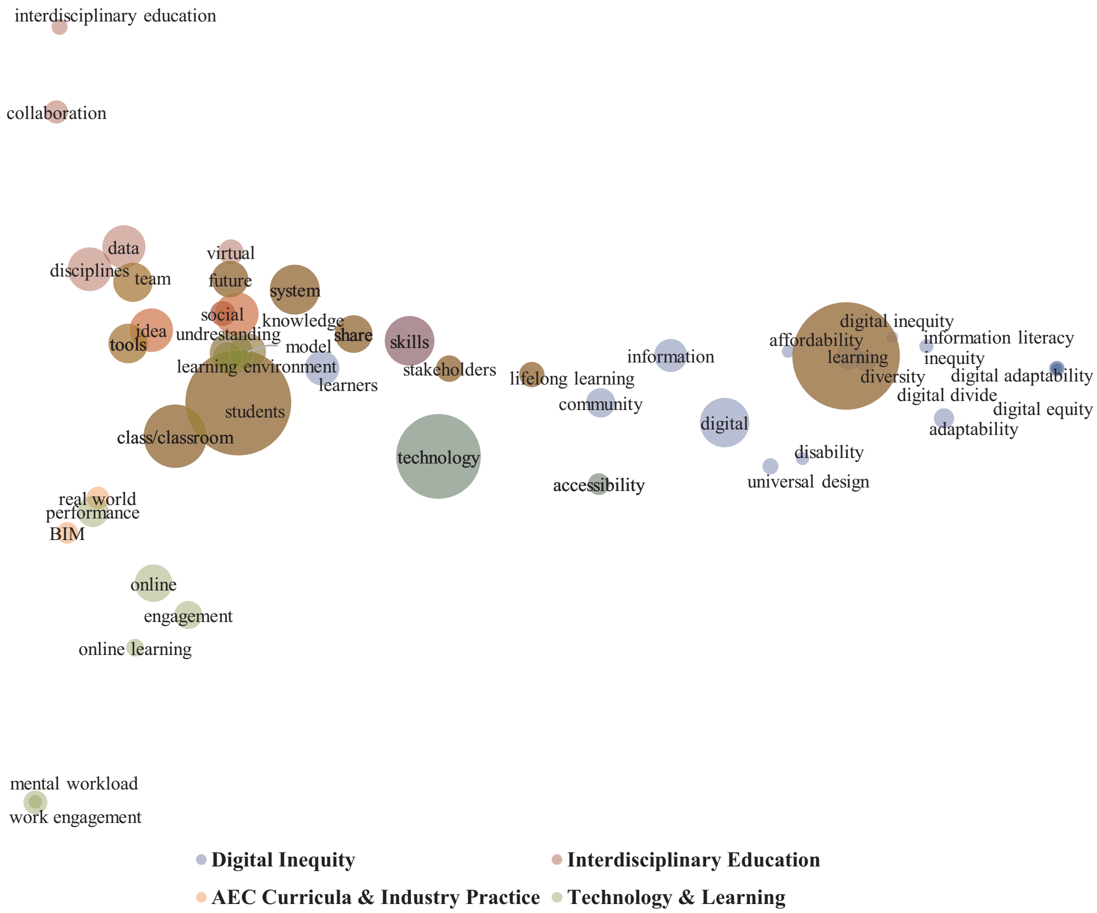

Fig. 4. (Color) Three-dimensional point map of the frequently used phrases in Workshop 1.

AEC Curricula and Industry Practice

The human-technology frontier in AEC workplaces is changing in many fundamental aspects, particularly due to the unprecedented COVID-19 pandemic. In order to shape the future of AEC education, we aimed to identify the gaps between AEC curricula and industry practice while highlighting the role of emerging technologies in creating and/or closing these gaps.

Current Status

The words fragmented and disintegrated can best describe the AEC curricula and their relationship with the industry. First, the existing setup of AEC curricula, a legacy of Industrial Revolution 2.0 to a large extent, places their focus on specialization and does not encourage collaboration among architecture, engineering, and construction disciplines. Secondly, major gaps between AEC curricula and industry practice clearly exist. Problems, in reality, are complex; however, such problems are often tamed when presented to students. For example, the course assignments in engineering education often do not resemble the real-world problems facing industries.

Thirdly, although many AEC schools and departments benefit from sustained communication and dialogues with industry partners such as their industry advisory boards, trends and changes in the AEC industries are not timely reflected in AEC curricula. Finally, the current accreditation of AEC programs has a strong disciplinary focus. The role of accreditation in shaping future AEC curricula is not fully explored concerning AEC curriculum integration, industry-academia collaboration, disciplinary and cross-disciplinary communication skills, and fundamental skills and knowledge to deal with ever-changing technological progress.

Challenges and Actions

One of the main challenges in shaping the future of AEC education will be to bridge gaps between AEC curricula and industry practices. To address this challenge, participants of the two workshops proposed a hierarchy of actions. In addition, we generated a map of the proposed actions addressing the identified challenges. The list of proposed actions based on their importance in implementation and their connection to the identified challenges is shown in Fig. 5. Actions on the top of the triangle have higher importance according to the ratings.

Based on the findings, the most important actions were identified as follows:

- Improve cross-training and foster skill sets needed to understand scientific methods, human behavior, material science, and ecology, in addition to computational thinking, communication skills, business savviness, and digital literacy.
- Identify connecting concepts between disciplines to support deep integration of disciplinary knowledge and include those concepts in teaching.
- Identify specific gaps in the industry to realize IR4.0 or the implication of IR4.0 to the AEC industry and decide the role of AEC education. Address questions on how AEC education communities can bridge the gaps and refocus AEC education on transferable skills, enabling toolsets, and a growth mindset.

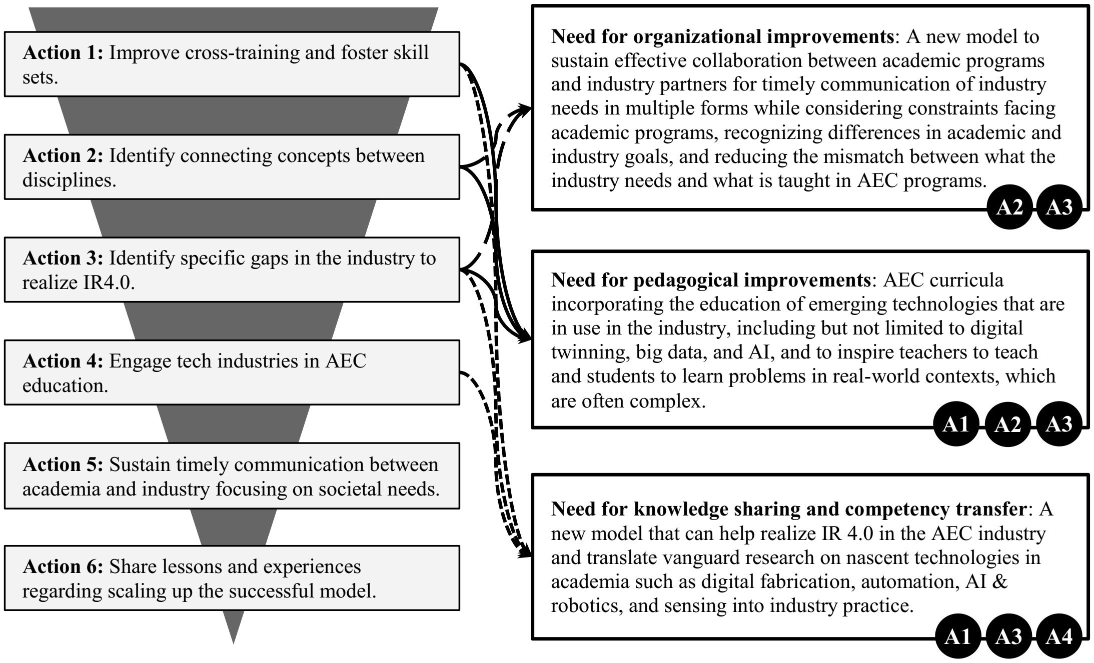

Fig. 5. Map of actions and challenges in AEC curricula and industry practice.

In addition, based on the number of actions linked to each challenge, it can be concluded that pedagogical improvements and knowledge and competency transfer challenges are mostly addressed by the proposed actions. Action 6 was identified, but participants did not map it to any challenges.

Interdisciplinary Education

Multidisciplinary teamwork and communication are essential skills for AEC students. We aimed to explore the opportunities offered by emerging technologies, such as new pedagogical strategies to deliver interdisciplinary learning content that is conducive to multiple disciplines.

Current Status

Interdisciplinary education for AEC students has long been recognized as a necessity. Workshop participants cited examples from many AEC programs (Zolin et al. 2000; Abdirad and Dossick 2016; Hu 2019) that have practiced multi/interdisciplinary courses with various delivery formats. Nevertheless, today's siloed AEC education curriculum hampers the true interdisciplinary programs focusing on disciplinary collaboration rather than cooperation. In addition, AEC programs mainly focus on in-depth knowledge development in their own discipline, with a secondary focus on balancing the need for interdisciplinary and disciplinary education.

Challenges and Actions

One of the main challenges in shaping the future of AEC education will be to bridge gaps within AEC curricula through synergy at the knowledge and organization levels among AEC disciplines, including foundational and transferable knowledge/skills related to learning new technologies and working across disciplinary lines. To address these challenges, a hierarchy of actions was proposed by participants of the two workshops. In addition, we generated a map of the proposed actions addressing the identified challenges. The list of proposed actions based on their importance of implementation and their connection to the identified challenges is shown in Fig. 6. Actions on the top of the triangle have higher importance according to the ratings.

The results illustrate that the most important actions are as follows:

- Foster an interdisciplinary collaboration mindset.
- Investigate the role of emerging technologies in creating a better interdisciplinary learning environment, such as a cloud-based intelligent immersive platform (responsive environment, dynamic feedback, and experiential learning) and adaptive learning systems operated by AI algorithms for developing a learner profile (individual scaffolding and learning path for students of different disciplines).
- Explore a new model to balance between depth and breadth for curriculum design (professor's mindset, depth versus breadth, problem-solving skills, multidisciplinary lifelong learning skills, coding/programming, data/statistical capabilities, and cognitive skills). Determine if a curriculum can be effectively designed and implemented as a reversed T with extension to other disciplines (breadth).

It is apparent that most of those actions can be mapped to the fragmented curricula challenge; however, the lack of expertise and the lack of standards are also very important to be addressed.

Technology and Learning

Technology-mediated environments, including technology-generated artifacts like 3D design models or construction site images, affect learning. We aimed to explore the role of emerging technologies, coupled with advancements in cognitive and education sciences, to form disruptive forces to improve the learning environment.

Current Status

There are two distinctive topics under this theme. The first involves skills and knowledge related to technologies that the AEC industry applies, and the second is related to technologies that

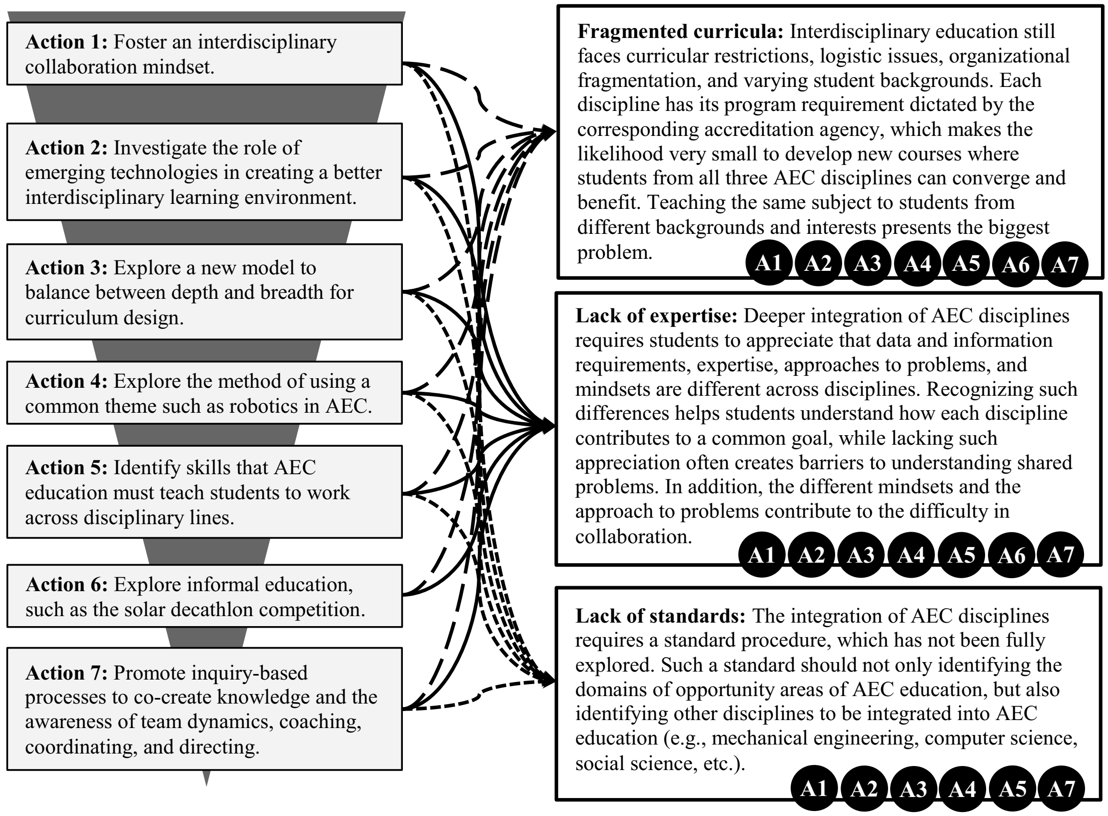

Fig. 6. Map of actions and challenges in interdisciplinary education.

support teaching and learning. The impact of emerging technological advancements on the AEC industry is profound. For example, a recent article in *Forbes* (Rutkowski 2021) noted that, in the foreseeable future, the industry would embrace new concepts, practices, and technologies such as DT, AI, sustainability, resilient systems, big data, and the changing nature of engineering (i.e., how engineers perform their tasks changes over time). In addition, the 2021 Educause Horizon Report named AI, hybrid learning, learning analytics, microcredentialing, open educational resources, and quality online learning as key technologies that will significantly impact future teaching and learning (Pelletier et al. 2022). Such technological progress will transform AEC education in terms of both the contents and the methods of delivering those contents.

Challenges and Actions

The main challenge in shaping the future of AEC education will be to transform AEC education with emerging digital technologies by means of integrating digital technologies into AEC education, affecting both the contents and the delivery methods of the next-generation learning-centered environment. However, emerging digital technologies can create new challenges, including transforming AEC technological practices, lack of protocols and standards, and technology adoption. These challenges, along with a list of proposed actions and their connection to the identified challenges, are shown in Fig. 7. The actions on the top of the triangle have higher importance according to the ratings.

Our findings highlight the most important actions as follows:

- Consider the limitation of faculty knowledge, create pathways for faculty professional development, and provide effective incentives and rewards for faculty to incorporate new technologies into teaching or the curriculum.
- Have a better understanding of the role of emerging technologies such as AI and DT and their potential in AEC education, including resolving conflicts among design, engineering, and construction and simulating in-person integrations. In the meantime, explore their implications on educational practices, such as data privacy and security.
- Explore a new T-shaped education model across AEC disciplines and determine potential overlaps or connectivity among disciplines.

Most of those actions are mapped to the transforming AEC technological practices challenge. The lack of protocol and standards in technology adoption is also addressed by most actions. Action 6 was identified, but participants did not map it to any challenges.

Digital Inequity

The AEC education communities have widely embraced the use of computer technologies in both in-person and online learning. Thus, we aimed to investigate the extent and influence of digital inequity while creating technology-intensive learning environments and address grand challenges by developing new pedagogical strategies.

Current Status

According to the National Digital Inclusion Alliance (NDIA 2022), digital equity is "a condition in which all individuals and communities have the information technology capacity needed for full participation in our society, democracy, and economy." To date, the digital divide, educational inequality, and digital inequity remain significant societal problems in the US and around the world. Unfortunately, because the digital divide cannot be closed completely, it also affects social inequity. Identified factors contributing

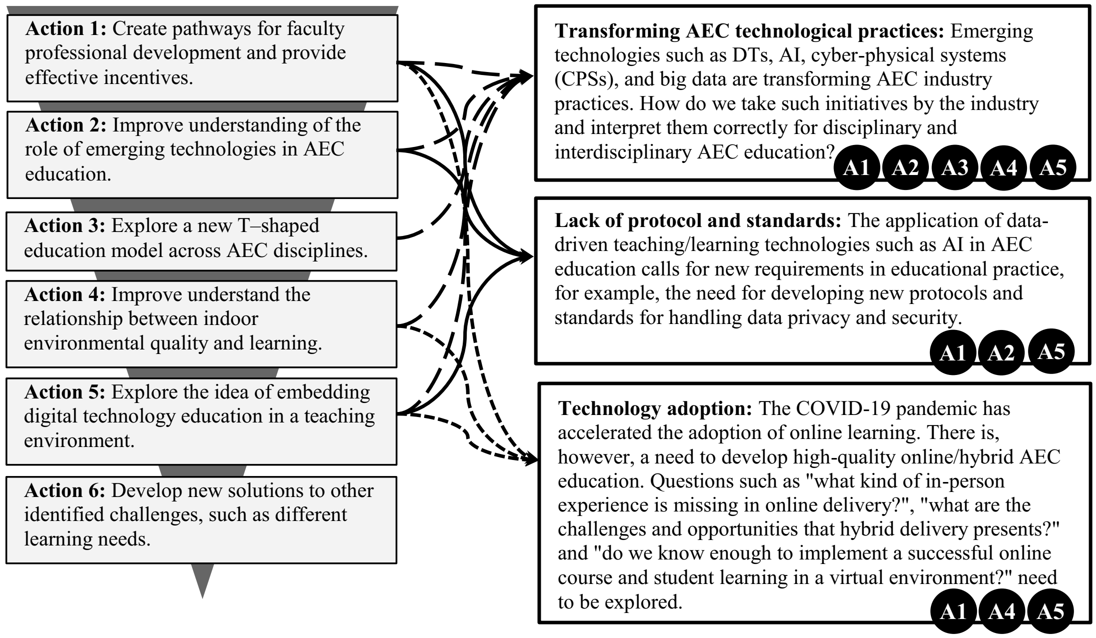

Fig. 7. Map of actions and challenges in technology and learning.

to digital inequality include cost, internet access, parent education, mobile devices, lack of information and/or digital literacy, socioeconomic status, race, and ethnicity.

Current digital divide policies and discussions focus on students' physical access to digital technologies such as the Internet. Nevertheless, it is clear that the digital divide and digital inequity are defined by physical access and other technology-related factors such as conditions of access, skills, uses, personal and social consequences of internet use, as well as personal factors such as disabilities and socioeconomic status. The issue of digital inequity and its impact on AEC students are significantly underexplored in AEC education.

Challenges and Actions

The main challenge in shaping the future of AEC education will be to create an inclusive learning environment by recognizing that students and faculty possess different levels of digital literacy and that students' social, economic, and disability statuses interact with their digital literacy and digital inequity. Fostering students' transferable skills in learning digital technologies to achieve equitable learning outcomes and developing a holistic view of digital inclusion are urgent. To this end, the key challenges that need further investigation are technological readiness, digital adaptability, and digital inclusion. These challenges, the list of proposed actions, and their connection to the identified challenges are shown in Fig. 8, Actions on the top of the triangle have higher importance according to the ratings.

The results illustrate that the most important actions are as follows:

- Develop students' transferable skills and self-learning capability to deal with constant changes in technologies and mitigate the potential digital divide.
- Create pedagogically sound approaches to support lifelong learning, for example, supporting learners with microcredentials and offering technology-enabled learning opportunities for such learners.
- Explore concepts, theories, and methods for building AEC learners' digital inclusion, digital fluency, and digital adaptability.
- Create an inclusive community of practice and learning. Apply principles such as user-centered design (UCD) to change what we teach and how we teach, for example, the involvement of underserved students in ideation, assessment, and testing alternatives. Individualize teaching/learning delivery according to the conditions of each student.

The digital adaptability challenge was addressed mostly by voted actions, followed by a tie between challenges of technological readiness and digital inclusion. Action 7 was identified but not mapped to any challenges.

Discussion and Limitations

The qualitative results of the two workshops suggest that the next-generation learning-centered environment in AEC should be viewed as a technology-enabled, learner-focused, and evolving ecosystem. In summary, a shared vision of the next-generation learning-centered environment for AEC education can be summarized in four theme-based statements as follows:

- AEC Curricula and Industry Practice. This theme aims to inspire students in the AEC programs to learn emerging technologies, develop transferable skills such as cross-disciplinary skills and skills to learn emerging technologies, foster a growth mindset, and develop the ability to help the AEC industry transform into Construction 4.0. The role of technology in supporting these learning activities needs to be explored. The learning activities need the support of (1) a new model of collaboration and communication to reduce the mismatch between what the industry needs and what is taught in AEC programs, (2) inspired and capable teachers, (3) relevant policies and guidelines at academic institutions to encourage curricula improvement, and (4) the involvement of accreditation organizations.
- Interdisciplinary Learning. This theme aims to create a better integrated AEC curriculum model that fosters an interdisciplinary mindset and prepares students with balanced depths and breadth to be able to work across disciplinary lines. The role

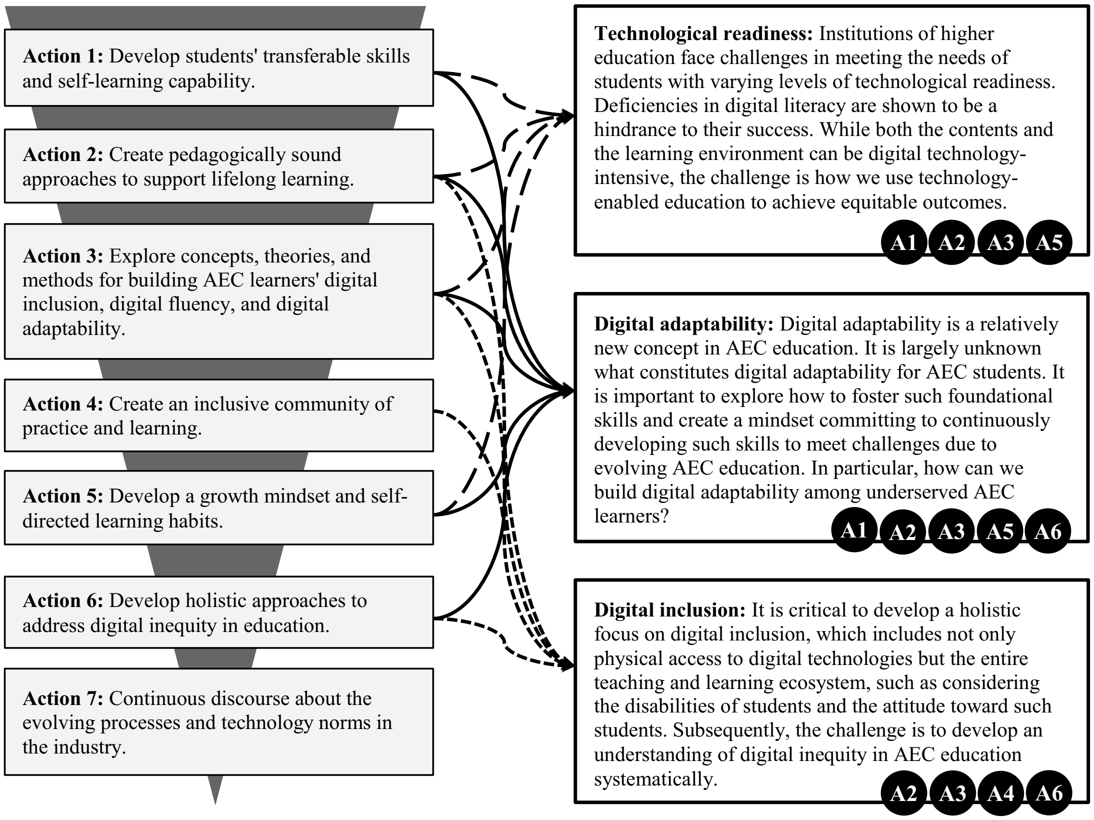

Fig. 8. Map of actions and challenges in digital inequity.

of technology in supporting these learning needs is to be explored. It is also essential that there is inspired faculty.

- Technology and learning. This theme relates to enhancing AEC learning environment using data-driven and AI/machine learning technologies, including emerging technologies for disciplinary and interdisciplinary education.
- Digital inequity. This theme articulates the need to produce AEC students with digital fluency, digital adaptability, and a growth mindset to cope with the evolving technological environment in the AEC industry and AEC education. AEC programs systematically develop an understanding of digital inequity in AEC education, not just physical access to digital technology but other factors such as considering disability and attitude toward such students.

The identified actions constitute major steps on the roadmap for creating the shared vision of the next-generation learning-centered environment for AEC education. The top three actions in each theme are summarized in Table 3.

It needs to be noted that several main factors limit the discussions and findings. First, the number and categories of participants are limited. Due to funding and resource limitations, including additional participants with different pedagogical experiences and perspectives was impossible. For example, the study can benefit from the perspective of academic administrators. Secondly, the design of the two-workshop format may create a knowledge gap. To improve knowledge transfer, we planned an overlap of core participants in both workshops, in addition to providing Workshop 1 results (including the identified challenges and solutions for creating the shared vision) to Workshop 2 participants prior to the beginning of the workshop. However, there is no guarantee that participants of Workshop 2 had the same understanding and interpretation of the Workshop 1 results as the Workshop 1 participants. It is impossible to identify potential misunderstandings of the intention or context of the recommendations of Workshop 1 by Workshop 2 participants. Thus, it is difficult to know if such misunderstandings have impacted the findings. Finally, the qualitative nature of the study can be subjective, and the results may be susceptible to different interpretations.

Conclusion and Future Directions

The goal of this study was to create a shared vision of the next-generation learning-centered environment for AEC education, including its characteristics, grand challenges, and opportunities, and offer a roadmap for research and implementation. In this regard, we organized two interrelated workshops with the participation of different stakeholders, including researchers, educators, and practitioners, in collaboration with the ASCE and ASEE. The workshops had three main elements, i.e., human stakeholders, lifelong learning, and technology, in four themes, i.e., AEC curricula and industry practice, AEC interdisciplinary education, technology and learning, and digital inequity. A total of 63 experts participated in the workshops (37 in Workshop 1 and 30 in Workshop 2) from multiple disciplines of architecture, engineering, construction, computer science, learning science, education, and social sciences. Participants explored relevant questions on topics such as a vision for the next-generation AEC education learning-centered environment and the role of emerging technologies in shaping that environment.

The outcome of this series of workshops illustrated that a systematic effort is needed to implement the actions and realize the shared vision and the contribution of all stakeholders. To solve this complex challenge, the AEC education community needs to take the lead in pedagogical and curriculum reform and professional

J. Civ. Eng. Educ., 2024, 150(3): 05024002

Table 3. Roadmap for creating the shared vision of the next-generation learning-centered environment for AEC education

Theme	Actions
AEC curricula and industry practice	• Improve cross-training and foster skill sets needed to understand scientific methods, human behavior, material science, and ecology, in addition to computational thinking, communication skills, business savviness, and digital literacy. • Identify connecting concepts between disciplines to support deep integration of disciplinary knowledge and include those concepts in teaching. • Identify specific gaps in the industry to realize IR4.0 or the implication of IR4.0 to the AEC industry and decide the role of AEC education. Address questions on how AEC education communities can bridge the gaps and refocus AEC education on transferable skills, enabling toolsets, and a growth mindset.
Interdisciplinary education	• Foster an interdisciplinary collaboration mindset. • Investigate the role of emerging technologies in creating a better interdisciplinary learning environment, such as a cloud-based intelligent immersive platform (responsive environment, dynamic feedback, and experiential learning) and adaptive learning systems operated by AI algorithms for developing a learner profile (individual scaffolding and learning path for students of different disciplines). • Explore a new model to balance between depth and breadth for curriculum design (professor's mindset, depth versus breadth, problem-solving skills, multidisciplinary lifelong learning skills, coding/programming, data/statistical capabilities, and cognitive skills). Determine if a curriculum can be effectively designed and implemented as a reversed T with extension to other disciplines (breadth).
Technology and learning	• Consider the limitation of faculty knowledge, create pathways for faculty professional development, and provide effective incentives and rewards for faculty to incorporate new technologies into teaching or the curriculum. • Have a better understanding of the role of emerging technologies such as AI and DT and their potential in AEC education, including resolving conflicts among design, engineering, and construction and simulating in-person integrations. In the meantime, explore their implications on educational practices, such as data privacy and security. • Explore a new T-shaped education model across AEC disciplines and determine potential overlaps or connectivity among disciplines.
Digital equity	• Develop students' transferable skills and self-learning capability to deal with constant changes in technologies and mitigate the potential digital divide. • Create pedagogically sound approaches to support lifelong learning, for example, supporting learners with microcredentials and offering technology-enabled learning opportunities for such learners. • Explore concepts, theories, and methods for building AEC learners' digital inclusion, digital fluency, and digital adaptability. • Create an inclusive community of practice and learning. Apply principles such as user-centered design (UCD) to change what we teach and how we teach, for example, the involvement of underserved students in ideation, assessment, and testing alternatives. Individualize teaching/learning delivery according to the conditions of each student.

development, share and promote the vision with a larger audience, such as professional societies and accreditation agencies, and explore new models to maintain effective communication with the industries. Today, many specific activities by individual faculty can already contribute to the vision, such as incorporating technology-related content in various AEC courses, sharing experiences with colleagues, and researching the effectiveness of new technologies in learning. However, the complexity of challenges requires a convergence approach that the AEC community is not yet prepared to create due to factors such as curriculum fragmentation and faculty readiness. Therefore, it is urgent that the AEC community explore mechanisms to create synergy among the stakeholders and share a common vision.

Future research may explore the role of emerging technologies in the pedagogy of cross-training, curriculum integration, and fostering students' transferable skills. In addition, the digital adaptability of students needs research attention as it is an essential skill of lifelong learning. As technologies evolve, the confidence and abilities of students to learn and use new technologies in the digital age are critical to the success of their lives. Future research may also address the lack of protocol and standards in technology adoption in different contexts, such as curriculum integration, balance between depth and breadth for curriculum design, and the needs of diverse student populations, including those with disabilities.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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