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Review

Framework for the Use of Extended Reality Modalities in AEC Education

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Abstract: The educational applications of extended reality (XR) modalities, including virtual reality (VR), augmented reality (AR), and mixed reality (MR), have increased significantly over the last ten years. Many educators within the Architecture, Engineering, and Construction (AEC) related degree programs see student benefits that could be derived from bringing these modalities into classrooms, which include but are not limited to: a better understanding of each of the subdisciplines and the coordination necessary between them, visualizing oneself as a professional in AEC, and visualization of difficult concepts to increase engagement, self-efficacy, and learning. These benefits, in turn, help recruitment and retention efforts for these degree programs. However, given the number of technologies available and the fact that they quickly become outdated, there is confusion about the definitions of the different XR modalities and their unique capabilities. This lack of knowledge, combined with limited faculty time and lack of financial resources, can make it overwhelming for educators to choose the right XR modality to accomplish particular educational objectives. There is a lack of guidance in the literature for AEC educators to consider various factors that affect the success of an XR intervention. Grounded in a comprehensive literature review and the educational framework of the Model of Domain Learning, this paper proposes a decision-making framework to help AEC educators select the appropriate technologies, platforms, and devices to use for various educational outcomes (e.g., learning, interest generation, engagement) considering factors such as budget, scalability, space/equipment needs, and the potential benefits and limitations of each XR modality. To this end, a comprehensive review of the literature was performed to decipher various definitions of XR modalities and how they have been previously utilized in AEC Education. The framework was then successfully validated at a summer camp in the School of Building Construction at Georgia Institute of Technology, highlighting the importance of using appropriate XR technologies depending on the educational context.

Keywords: virtual reality; augmented reality; mixed reality; AEC education; immersive

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1. Introduction

A career in Architecture, Engineering, and Construction (AEC) fields can be extremely rewarding, not only financially but also because it allows one to make a difference in thousands of people's lives by building their homes, schools, hospitals, parks, and so on. Bankrate's 2021 Ranking listed Architectural Engineering as the most valuable college major, and Construction scored second place on the list. The ranking is based on the unemployment rates and average income of American workers according to the subject of their undergraduate studies [1]. Over the last ten years, the educational applications of extended reality (XR) modalities have increased significantly, and many educators within AEC-related degree programs wish to bring these innovative technologies to the classroom, given the visual/3D nature of these disciplines' subject matter and increasing use of these applications in the building/construction industry. The potential benefits from increased use of XR modalities include improved recruitment, retention, and enhanced engagement and learning.

Perhaps the most significant potential for educational XR use is student recruitment. The career options in AEC are often not well understood by precollege and early college (first and second year) students [2]. Further, construction management and engineering fields are surrounded by stigmas that make it difficult to attract a diverse group of college-bound teenagers to this field [3]. Architecture is perhaps the best-understood career among AEC fields due to popular culture and a longer history for the term. Still, there can be erroneous impressions about what architects do or how it compares to construction management and engineering careers for income and career progression. Given the relatively fewer challenges to recruitment and retention of students in architecture programs and for a manageable scope for this paper, henceforth, only Architectural Engineering and Construction Management fields will be discussed, and the AE/C abbreviation will be used.

In contrast to Architecture, when thinking about a career in construction, most people immediately relate it to the physical labor during construction; and do not think of construction managers, superintendents, virtual design and construction (VDC) managers, or other professional/leadership positions that have little-to-no physical work expectations but are professional careers only possible with college degrees. This lack of knowledge or erroneous perception can be a challenge for recruiting high-school students to construction management and related degrees in universities. Similarly, engineering is viewed as an extremely challenging education and career; and self-identities formed early in life (e.g., I am not good in math and science; girls or Black and Hispanic people do not choose engineering, etc.) or lack of examples and roles models, can limit consideration of engineering programs in college choices. As a result, both construction management and engineering are traditionally white-male-dominated fields [4,5].

Other challenges in AE/C education relate to retention and enhanced learning outcomes for the students who chose one of these majors but may be struggling to persist. AE/C fields are very visual and create tangible products: buildings and infrastructure. Despite that fact, the traditional college education in related engineering fields (Architectural Engineering, Structural Engineering, Civil Engineering) can be vastly word/text/calculation and lecture-based. This emphasis on theory can make it difficult for first and second-year students to connect the equations and concepts learned in the classroom to real-life building applications until they persist enough to enroll in higher-level design-based classes and participate in internships. One way to make education in AE/C degrees more engaging and interactive is by implementing cutting-edge visualization/simulation technologies in classes. Many previous studies demonstrated that extended reality (XR) modalities such as virtual reality (VR), augmented reality (AR), and mixed reality (MR) can be powerful tools to motivate and engage AE/C students in their classes [2,6–10].

As mentioned before, AE/C education still relies heavily on teacher-centered traditional instructional methods and has been slow to adopt the technologies that have been recently developed when compared to other scientific and other engineering fields [11]. Further, in the past few years, a major change has been observed in the AE/C industry, where many large general contractors and construction firms have been adopting AR, VR, and MR, for various applications, such as safety training, specialty training, inspections, simulations, coordination, clash detection, and others. On the education side, the uses of these modalities in classrooms are increasingly being experimented with, and positive outcomes are reported, such as improving student engagement, motivation, and satisfaction, for example [6,8–10]. Still, it is also acknowledged that these initiatives present new challenges in terms of aligning educational objectives with the appropriate technology applications, especially because learning and employing XR technologies can be very time-consuming for the faculty and costly for the schools [7,12–14]. In addition, there is a variety of XR modalities, and new technologies are continuously developed. As a result, there is confusion about the definitions of these XR modalities in both technical and popular literature. Finally, and most importantly, there is no guidance in the literature that grounds the selection of an XR-based intervention in educational applications within a theoretical framework or pedagogy.

The goal of this paper is to address this significant gap in the literature and to provide a decision-making framework for the use of XR modalities in AE/C education. To achieve this goal, first, pertinent literature is carefully examined to decipher the often conflicting terminology of currently available technologies that fall under the XR umbrella (VR, AR, and MR). Then, another round of literature review is conducted to identify case studies where XR has been applied in AE/C education. Grounded in this knowledge base and the educational framework of the Model of Domain Learning (MDL), a decision-making framework is proposed. The proposed decision-making framework considers a variety of factors that affect learning, engagement, interest, and motivation. This study contributes to the body of STEM education research by considering possible AEC education objectives with respect to a variety of factors that must be considered for the appropriate, meaningful, equitable, and scalable use of these technologies. A pilot application and validation of the proposed framework are briefly introduced through a summary of student reflections related to various XR interventions utilized at the inaugural Georgia Tech School of Building Construction summer camp.

2. Definitions of XR Modalities and Platforms

Articles related to definitions of XR modalities and platforms were comprehensively reviewed as follows: 337 articles were extracted from search engines, including Google Scholar, Web of Science, and ScienceDirect, combining the search keywords XR, VR, AR, and definition. Afterward, duplicated articles were removed, retaining 213 articles. Then, irrelevant articles were screened out by examining the titles and abstracts of the 213 articles, and as a result, 82 articles were reviewed. Out of this group, 49 articles were found the most relevant to this study after examining the entire contents of the articles and are cited in this work. The inclusion criteria for the articles were that they are peer-reviewed and original articles written in English, and they contain content associated with the definition of XR modalities and platforms.

2.1. Definition of XR Modalities

A variety of terms are used to describe different virtual reality and related technologies, which are simulations created using computers and wearables [15,16]. XR is an umbrella term that refers to all types of real and virtual combined environments. VR, AR, and MR are different modalities with different characteristics, but it is difficult for non-experts to distinguish them clearly because their definitions are often inconsistent and used interchangeably. To better apply XR in AE/C education, first, a baseline understanding should be established by clearly identifying the nuances of different XR modalities. To this end, the authors identified key definitions of XR terminology based on a comprehensive literature review. Further, VR applications are classified into non-immersive virtual reality (nIVR) and immersive virtual reality (IVR); then, each of the terms (nIVR, IVR, AR, and MR) are defined with a focus on technological aspects and user experience. These definitions are presented in Table 1, and detailed descriptions of each term are provided in the following sections.

Table 1. Definitions of XR Modalities.

	Definition	Current Hardware	Current Software
Non-Immersive virtual reality (nIVR)	nIVR is a computer-generated virtual environment accessed through 2D-display devices in that users feel a sense of presence based on a vivid and interactive experience.	2D-display device (PC, smartphone, tablet)	Mozilla Hubs, Gather, Roblox, etc.
Immersive virtual reality (IVR)	IVR is a computer-generated environment that can provide a more immersive experience and a higher sense of presence than nIVR by using immersive display devices.	Cave automatic virtual environment, Head-mounted display (Oculus quest 2, HTC VIVE PRO 2, HP reverb G2, Google Cardboard, Samsung Gear VR, etc.)	Spatial, Mozilla Hubs, Meta Horizons, etc.
Augmented Reality (AR)	AR is a virtual-real combined environment where virtual elements are overlayed in the user's view to enhance the real-world experience.	2D display device (smartphone, PC, tablet), Optical head-mounted display	Pokémon Go, IKEA place, etc.
Mixed Reality (MR)	MR is a virtual-real combined environment that can provide a more immersive and interactive experience than AR by enabling users to interact with real and virtual elements simultaneously.	Optical head-mounted display (Magic Leap, Microsoft HoloLens, Google glasses, etc.)	Mirage, Holomeeting 2, HoloAnatomy, etc.

2.1.1. Virtual Reality

From a technical perspective, VR refers to a simulated environment generated by a computer [17]. An essential concept for understanding user experience in VR is a presence moderated by vividness and interactivity [18]. Presence is a concept emerging with the development of VR, which indicates that users perceive themselves to be in a different physical space than they actually are in the VR environment [19]. Vividness refers to the extent of the richness of sensory information and the presentation quality of the mediated environment [20], and interactivity refers to the extent to which users can interact with the mediated environment in real-time [21,22]. VR can deliver multiple sensory information, such as visual and acoustic information, and allows users to interact with mediated environments using controllers such as keyboards, mouses, joysticks, and body trackers [23]. As a result of vividness and interactivity, users can sense the experience the phenomenon of presence, which was explained above.

VR applications can be further classified into non-immersive and immersive, nIVR and IVR, depending on the device type used to represent VR [24]. nIVR represents VR through 2D-display devices such as smartphones, tablets, and PC and allows users to interact with VR by using keyboards, mouses, and user interfaces on smartphones and tablets [25]. nIVR can be used with software allowing access to VR using 2D-display devices, such as Mozilla Hubs, Gather, and Roblox. IVR, on the other hand, requires use of immersive display devices. Currently, these devices/environments available include a cave automatic virtual environment (CAVE) and a head-mounted display (HMD) [26]. CAVE is a physical space (room) and includes large screen walls that project VR and provides an interactive VR experience to users by getting behavioral information such as body position, hand gestures, and eye movement through tracking sensors [27]. In CAVE, users can be secluded from the real world and interact with full-scale VR, thereby having a more immersive and realistic experience than when using nIVR. HMDs are typically goggles-type devices consisting of a stereoscopic display and controllers [28,29]. HMDs also provide immersive and realistic experiences by enveloping users' views with a stereo-scope display and enabling users to navigate a full-scale VR using controllers [30]. In recent years, various HMDs have emerged, including high-end HMDs such as Oculus quest 2, HTC VIVE PRO 2, and HP reverb G2, and low-budget HMDs such as Google Cardboard and Samsung Gear VR [21]. Since HMDs are much less expensive and more convenient to use than CAVE, it is the more widely used version of the IVR applications. IVR can be used with software that allows access to VR using HMDs, such as Spatial, Mozilla Hubs, and Meta Horizons.

2.1.2. Augmented Reality

AR refers to overlaying virtual information and objects (hereafter, virtual elements) generated by computers onto the real world in real-time [31,32]. Azuma [33] defined AR based on three characteristics which are (1) a combination of reality and virtuality, (2) ability to be interactive with virtual elements in the real world, and (3) three-dimensional registration of real and virtual elements. In terms of user experience, the most significant difference between AR and VR is that while VR allows users to experience a computer-generated virtual world only (and obscures any view of the real environment of the user), AR allows users to experience a real world where virtual elements are overlaid with the real environment [34,35]. In other words, virtuality is the center of user experience in VR, but in AR, virtuality is used to enhance the real-world experience of users [36].

AR can be used with an optical head-mounted display (OHMD), a type of HMD equipped with a see-through display that allows users to see the real world with superimposed virtual elements [37]. However, since OHMDs are expensive, AR is mainly used with 2D-display devices such as smartphones and tablets, which are more convenient to use and already owned by many people (Figure 1). The most known and representative example of an AR application is Pokémon Go, a mobile game that allows users to interact with virtual creatures called Pokémon augmented in reality [38]. In addition, many furniture companies, such as IKEA, Wayfair, Overstock, and Target, are using AR to allow consumers to place virtual furniture in their rooms before making purchase decisions [39].

Figure 1. 2D-display AR application created and used by the authors.

2.1.3. Mixed Reality

The traditional definition of MR is based on the Reality–Virtuality continuum of Milgram et al. [35]. In the Reality–Virtuality continuum, MR refers to a virtual and reality combined environment represented in a display, and AR is included in MR. However, as Microsoft developed HoloLens in 2016 and called it an MR device, which can provide a completely different user experience from existing VR and AR; MR has established itself as a unique concept [40]. Although MR is becoming increasingly popular and actively used in research, its definition is inconsistent, including a hybrid of AR and VR, a synonym with AR, immersive AR using OHMDs, and an enhanced version of AR [41–43]. According to Speicher et al. [44], the definition of MR differed from study to study, and even experts defined MR differently. Therefore, it is necessary to acknowledge that the definition of MR in this paper may be inconsistent with some of the previous publications.

In this paper, MR is defined as a different concept from AR. MR, similar to AR, overlays virtual elements into the real world, showing users a virtual-real combined environment. However, in terms of user experience, MR provides a more immersive and interactive experience than AR because MR allows users to interact with virtual and physical elements simultaneously on the same display [45,46]. For example, if there is a virtual object in MR, we can see it and anchor it to the physical surface in the real world, which is impossible in AR (Figure 2). In addition, MR allows users to interact with virtual elements more intuitively and naturally than AR by using advanced technologies such as eye and gesture tracking, which also enhance the level of interactivity and immersion of user experience [47,48]. Several MR devices were developed, such as Magic Leap, Microsoft HoloLens series (1 and 2), and Google glasses [49]. Among the MR devices, the Microsoft HoloLens series is undoubtedly the most representative device for MR and was used in most studies referring to MR in their XR application [46,47,50,51]. In recent years, various MR software using the HoloLens series, such as Mirage, HoloMeeting 2, and HoloAnatomy, has been developed.

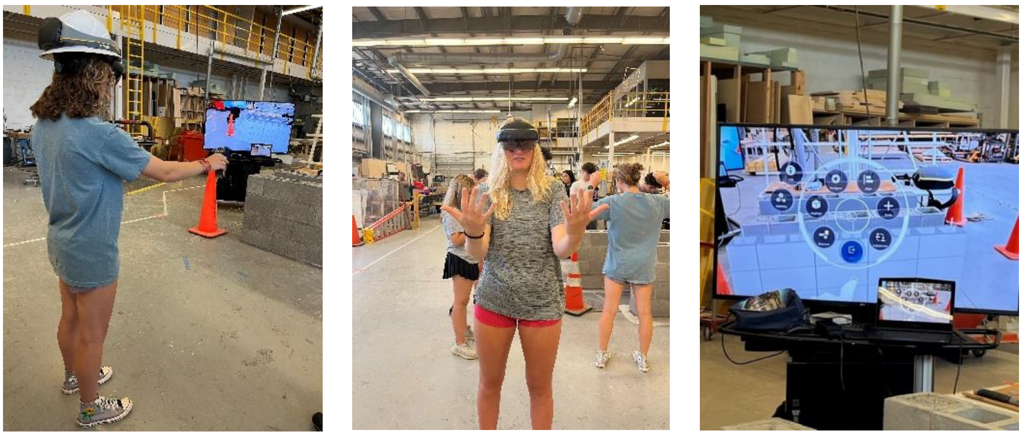

Figure 2. MR application using OHMDs where Georgia Tech summer camp students can place the Revit model of a masonry wall in front of a physical one to compare dimensions and measure both.

2.2. Multi-User Virtual Environment

A definition is provided for multi-user virtual environments (MUVE), which is an important term associated with XR modalities [52,53]. MUVE is a platform where multiple users can access a computer-generated virtual environment simultaneously by representing themselves through avatars. In MUVE, users can communicate with each other while interacting with the virtual context in real-time [54]. MUVE is not a new concept, but it has received more and more attention with the advances in XR technologies, such as the development of affordable HMDs and improvement in computer graphic techniques [55]. One of the most famous MUVEs is Second Life, developed in 2003 by Linden Lab [56]. In Second Life, users create avatars to represent their identity and interact with other users while conducting various activities as if in the real world [57]. Following the Second Life, various MUVEs such as Roblox, The Sandbox, Mozilla Hubs, Spatial, and Meta Horizons were developed.

MUVE has significant potential as an educational platform augmenting classroom-based learning and as a more engaging alternative to traditional online education because of its pedagogical benefits [2,43,58,59]. First, MUVE has been shown to improve students' interest and engagement in learning by creating a collaborative learning atmosphere where students actively interact while performing experiential tasks together using VR [60,61]. This collaborative and task-oriented learning can potentially help students have a deeper understanding and better learning outcomes [62]. In addition, MUVE can improve students' communication skills and social connection by eliminating certain inequalities observed in classroom-based learning, such as the hierarchical relationship between tutors and students and social status differences among students, which can negatively impact collaboration [63].

3. AE/C Educational Objectives and XR Use Cases

This paper is a part of a larger National Science Foundation-funded research project in which the Model of Domain Learning (MDL) is used as the theoretical framework to connect various AE/C educational objectives with the use of XR modalities [64]. Three categories of program objectives are identified where XR modalities can be used to achieve them: Recruitment, Retention, and Subject Matter Specific Learning objectives (Figure 3).

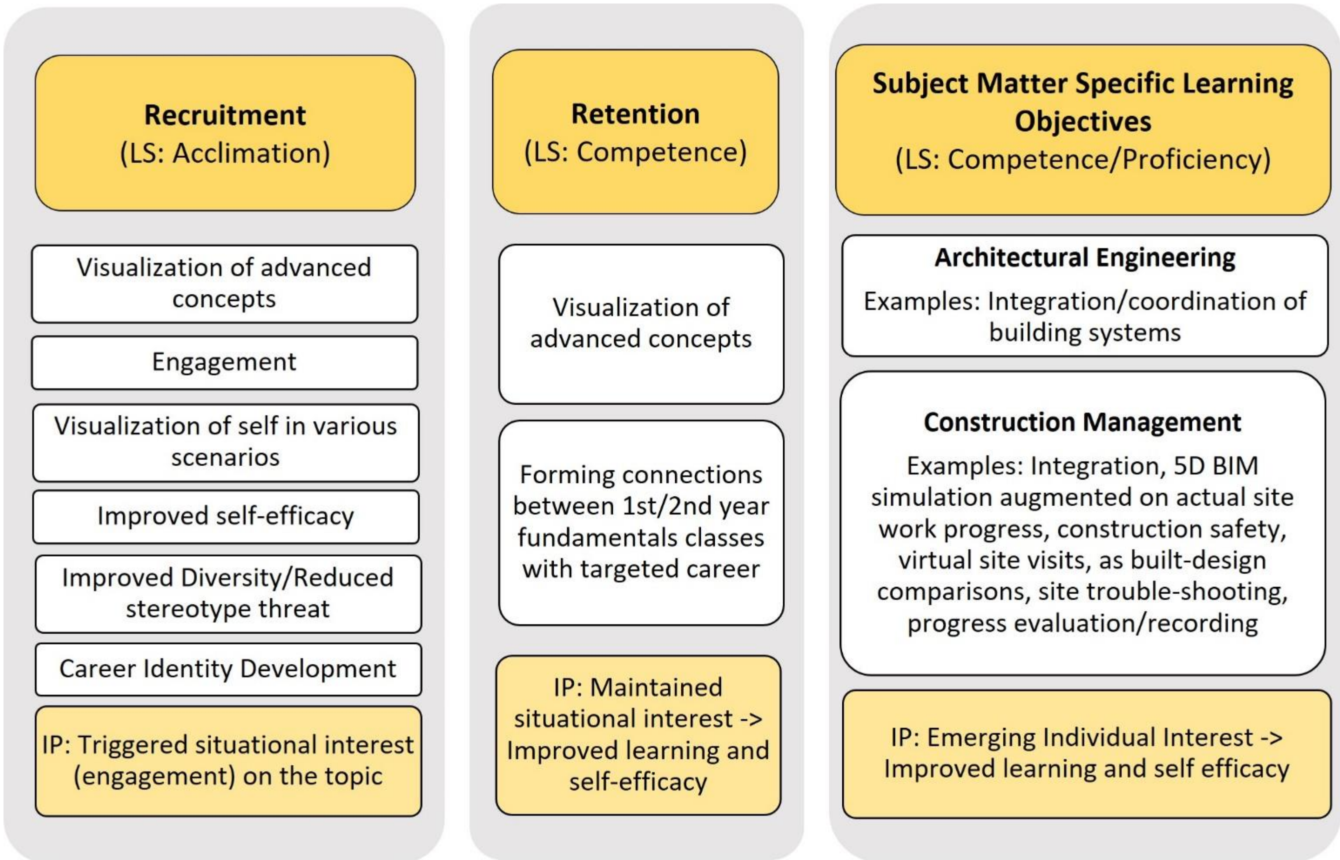

Figure 3. General categories for the educational objectives within Architectural Engineering and Construction education. (LS: Learning stage, IP: Interest Phase per MDL framework).

The following sections will first explain the learning and interest stages based on MDL and then provide examples from the literature for applications of XR modalities associated with these program objectives. The literature related to the applications of XR in AE/C education was comprehensively reviewed using the following methodology: a list of relevant peer-reviewed articles was obtained from the Georgia Tech library database and Google Scholar combining the words/expressions of VR, AR, MR, and XR with AEC, construction, and architectural engineering education. Titles and abstracts of the 82 articles were reviewed, and 37 relevant studies were selected. Out of the 37 studies, a literature review table was developed to summarize the technology described, methods, sample size, educational context (e.g., summer camp, class intervention, etc.), and key findings. Based on the level of relevance to the goals of this paper, ultimately, 21 educational studies were included in this paper. The main inclusion criteria were that the papers are peer-reviewed and original articles written in English and containing content associated with the applications of XR in AE/C education.

3.1. Model of Domain Learning

MDL is a theoretical framework for the study of students' academic development in domains (i.e., subject areas or fields of study) [65]. The model comprises three primary components: knowledge, interest, and strategies/strategic processing. Among these components, knowledge and strategies are considered cognitive variables, and interest is described as a motivational variable.

In the area of knowledge, learning is defined as a three-stage progression from acclimation to competence to proficiency. In MDL literature, it is suggested that few students progress to proficiency because individuals who represent this state not only have rich structures of knowledge but are also knowledge generators. It is also suggested that competence is the longest and most complex of the three stages, and it may be divided into three sub-stages: early, middle, and late competency.

In the area of strategic processing, two types are defined that are linked to the level of knowledge of the individual. Surface-processing strategies (e.g., repetitive practice) are those that do not require much cognitive effort or prior knowledge but are necessary to build confidence in a domain. Deep-processing strategies (e.g., design) require learners to expend a significant amount of cognitive energy and utilize a large volume of knowledge. They are, therefore, more appropriate for competency and expertise levels.

Finally, the motivational variable, i.e., interest, is found to significantly impact what students will learn [66]. Two main types of interest are defined. Individual Interest is a deep-seated and long-term motivational commitment to learn about a domain. Situational Interest has a short timescale and is characterized by spontaneous arousal and often does not result in sustained domain learning unless prolonged educational activities are employed to maintain the triggered interest. In fact, interest development has been conceived of as occurring in four phases: triggered situational interest, maintained situational interest, emerging (less-developed) individual interest, and well-developed individual interest [67,68]. Many complex factors play into one's individual interest development in a particular domain, as explained in the social cognitive career theory (SCTT), such as predispositions, gender, race/ethnicity, disability/health status, background, learning experiences, and expectations from the individual [69]. MDL's phases of interest fit nicely in the larger SCTT context, and it further suggests that via well-designed educational activities, a new interest can be triggered and developed despite a lack of initial and deep-seated interest from one's background.

While there can be an infinite topic or course-specific learning objectives within the umbrella of AE/C education, we identified three general categories (Figure 3) based on a comprehensive literature review on the use of XR modalities in AE/C education through the lens of the MDL framework. Three stages of knowledge (Learning Stage (LS): acclimation, competency, and proficiency) and three phases of interest (Interest Phase (IP): triggered situational interest, maintained situational interest, and emerging individual interest) are considered to categorize possible applications of XR modalities into three buckets: Recruitment activities (K-12 students and community colleges), Retention activities (1st and 2nd year in AE/C programs), and deeper learning activities

(3rd–5th year discipline-specific design, analysis, and capstone courses). The authors believe, in alignment with the developers of the MDL framework, that the highest phase of interest (i.e., well-developed individual interest) typically occurs after college education when one practices the application of the knowledge in daily applications.

AE/C Education has been slowly but positively embracing XR technologies. There are many studies on how immersive and non-immersive VR, AR, and MR have been used to engage students for recruitment, retention, and enhanced subject matter learning purposes. The next sections provide examples from the literature organized into the aforementioned three categories (Figure 3).

3.2. Uses of XR in Recruitment

Precollege programs, such as explorer programs and summer camps, are commonly used recruitment tools by many universities as an opportunity to excite high school students. There are various programs in AE/C-related fields with a variety of durations and activities. All have one major goal in common, which is to generate interest in their domain. This is done by presenting career options with that degree, helping them visualize themselves in these careers, and fighting the stigmas and deep-seated perceptions about AE/C fields [70–73].

The effectiveness of the implementation of AE/C precollege programs has been tested through surveys and discussed by many researchers. For example, Redden and Simons [71] reported that the Auburn University 2017 Building Construction Summer Camp successfully expanded the students' interest in a career in construction management and positively impacted their perceptions about the construction field as a career path. Yilmaz et al. [72] concluded that the activities performed during the Texas A&M University–Kingsville 2008 Summer Camp increased the students' satisfaction and interest in engineering disciplines. The survey responses from the students revealed the effectiveness of the program in attracting students to engineering professions. Gaedicke, Shahbodaghlou and Guiney [73] indicated that the Construction Management and Engineering Summer Camp hosted by California State University benefited 60 students by promoting student comprehension of AE/C as an attractive career path. Their study results also concluded that the students are highly interested in the use of technologies, and emphasizing the technological applications in construction management is one way to promote AE/C.

Furthermore, intending to engage the students to increase recruitment in the AE/C education arena, and in line with the literature reviewed, a few research groups are exploring the applications of XR modalities in AE/C precollege programs like Georgia Institute of Technology (Figure 2), Colorado State University (CSU), Auburn University, and Florida International University [74–77]. CSU's website mentions that IVR and MR technologies were applied for visualization and inspection of a construction project [78]. However, the specific use of those technologies was not described on the other programs' websites. Since the application of XR technologies in precollege AE/C programs is a recent possibility being investigated in many universities, not many papers have been published on these experiments yet.

3.3. Uses of XR in Retention

The majority of the course content in postsecondary institution classes, in general, is presented by the educators to the students through lecture-based traditional teaching methods. Stains et al. [79] performed a massive study that analyzed over 2000 science, technology, engineering, and mathematics (STEM) classes in 25 institutions across the United States and Canada and reported that 55% of the STEM classes observed consist of a passive group of students being lectured by the instructor at least 80% of the time and 27% of the classes are lecture-based complemented by group activities. More alarmingly, only 18% of the classes are noted to be taught in a student-centered style. Considering that every student acquires knowledge, skills, and abilities in their own unique way, and people are heterogeneous in their instructional needs, the classroom outcomes are positively affected if various educational activities and methods are explored by the educators [80].

The literature suggests that the traditional methods could be positively complemented by the of XR modalities, because they can help accommodate different learning styles, engage the students, and provide enjoyment [6,8,81]. Students' feedback on various activities that applied XR modalities reported that the students' engagement and satisfaction increased during the activities and that they not only enjoyed the experiences, but the use of XR acted as a motivator for learning [6,8–10]. Erdogmus et al. [2] reported on the pilot application of XR-based activities in two different institutions' 1st year Introduction to Architectural Engineering courses. This study reported that the students agreed that they are more likely to stay in the architectural engineering major and earn their degree and they are more confident in their abilities to succeed after being exposed to these nIVR experiences.

Kim and Irizarry [13] investigated whether a non-immersive AR tool using iPads would improve construction management students' spatial skills learning. The 254 participants were divided into control and test groups. Then, the participants performed a group lab assignment where they were asked to solve spatial practical problems. The test group had access to an AR software to help them perform the lab assignment, control group did not have access to this 3D visualization. After the lab-assignment, both groups performed a post-assessment to measure their improvements, and also post-surveys to access the perceived effort by the students in performing the assignment and to obtain the students' perceptions regarding their experiences using AR as a learning tool. The mean score in the pre-assessment were 55.5 and 60.5 for the control and test groups, respectively, and 65.9 and 70.8 in the post-assessment, which represents similar improvements in both groups. However, the survey completed by the test group revealed that the students' perceived effort was lower and satisfaction, enjoyment and confidence in their learning were increased due to using AR which provided them with a better learning experience even though their assessment scores were similar to the control group.

Lucas and Gajjar [82] experimented with a non-immersive web-based VR simulation application to test whether this would enhance the students' understanding of the sequence of wood frame construction. The results from this case study with 77 participants showed that there was no statistical difference in the overall scores between the students that used nIVR and the students that only had traditional classroom instructions about wood frame construction. However, the students' survey responses on the use of the nIVR show they support the use of this type of technology to complement traditional classroom learning and that they believe the application allowed for an active and engaging learning environment.

These studies highlight an important differentiation that must be considered in educational research and the educational applications of XR. While these case studies do not necessarily show significant improvements in learning outcomes related to spatial visualization, there seem to be evident gains in enjoyment which can be and should be leveraged for retention purposes within the framework of triggering situational interest and maintaining situational interest in a particular career. Further, with a more thoughtful framework behind the design of learning activities, XR applications in spatial visualization can be better utilized to complement the traditional teaching methods to aid the students visualize structures and components in environments that are not easily accessible or make the AE/C education more accessible to students with disabilities.

Hence, by facilitating the visualization of complex concepts and by keeping the students interested and motivated in their majors, the expectations are that fewer students will change out of AE/C related majors and consequently improve the retention rates in those programs that are implementing XR modalities.

3.4. Uses of XR in Subject Matter-Specific Learning Objectives

This bucket of use cases for XR in AE/C education is intended to explain the benefits of the technology in enhancing one's learning in higher level subject matters and teaching/demonstrating use cases that are also actively used or experimented with in the AE/C industry. Hence, the emphasis shifts from triggering and maintaining interest to emerging individual interest and moving one from the acclimation stage of learning to competency (and in some occasions proficiency) stage. Use of XR can provide particularly beneficial learning opportunities for topics that are either too difficult to explain without 3D visualization or if real-life experiential activities can pose risks to health and well-being.

One of the most common applications of XR technology in both industry and education is construction safety training. The obvious benefit of applying XR technology in this scenario is that the students and/or workers can learn about the risks in the construction site in a risk-free environment. A prototype system was developed by Pedro, Le, and Park [7] to integrate nIVR safety scenarios into construction curricula to improve learners' safety knowledge and hazard recognition ability. The system was then implemented through a series of lectures and its success was evaluated through questionnaires and interviews in a class (n = 25). The participants described the nIVR software as fun, engaging and capable of effectively transferring safety information. The research results also state that the nIVR software improved the students' ability to identify hazards and supported active learning by engaging and motivating students. Bin et al. [83] developed an interactive multiuser IVR experience using HDM, hand controllers, and a vibration platform to simulate a construction site. The IVR construction safety training system designed allows multiple users to be physically, visually, and tactfully present at the same time. In the virtual scene of a construction accident safety hazard, the user completes the consciousness migration that correlates the virtual scene to the real scene, thereby avoiding the safety accident in the real construction.

Virtual site visits present another focus that is being considered in AE/C education as the technologies evolve and allow this type of activity. This is an extremely powerful tool for educators in AE/C, given the logistical challenges of arranging an in-person site visit as well as costs and personal safety considerations [6]. It also affords students with disabilities to participate in a virtual site visit that enables them to have a very similar experience as the in-person site visit. Behzadan and Kamat [11] developed an interactive and immersive MR virtual site visit. On a large screen, a real-time video of a construction job site was streamed to the students. Using an AR HMD and a connected device that allowed to track finger motion, the students interacted with the scene and augment relevant information on the HMD by scanning an AR Book with QR codes. In another study, intending to promote a site experience to the students, Kim [84] created an IVR experience to visualize a 360° image of a construction site using HMD and hand controllers. Participants (n = 81) were divided into control and test groups to visualize a static 360° image of a music auditorium under construction. The control group had access only to the image. The test group had textual, video, and quiz annotations in addition to the same image. The student's self-reported scores demonstrated a higher perceived learning performance by the test group students in eight out of nine categories. The annotated 360° photographs provided a better-perceived learning experience for the test group. Still, the data suggest that the non-annotated 360° images used for the control group were also significant as a learning tool.

Besides spatial visualization, safety training, and virtual site visits, there are many course-specific applications of XR technology in AE/C education. Kandi et al. [85] studied the impact of an interactive IVR game on 94 architecture students in a classroom setting. The students were divided into control and test groups and were asked to find design mistakes in two treatment conditions: 2D drawings and IVR experience. The students were tested after each activity. The study results showed that the IVR game resulted in a higher number of design mistakes correctly identified by the students. Fauzi, Ali and Amirudim [86] performed a study intending to measure the effectiveness of using AR as a tool to enhance the students' comprehension of the construction process of a pad foundation. The students (n = 41) performed a test where they were asked to list the components and materials and explain and sketch the construction process of a pad foundation. The test results showed that 68% of the students had improvements in their understanding of the concepts based on a comparison of their pre-test and post-test scores. The authors claim that these study results demonstrate the effectiveness of the use of AR for enhanced competency based on their observations compared to the previous offerings of the class. The study did not conduct the experiment with a control group. Moreover, the survey results confirmed that the students appreciate the use of AR in AE/C education, and the practice also satisfied the students' expectations for how AR can enhance their learning process. The authors also reported that the students participated and engaged more in the class when using AR.

Erdogmus et al. [2] shared the results of the implementation of Virtual/Augmented-Reality-Based Discipline Exploration Rotations (VADERs) with first-year students of an AE course. While the primary goal of the experiment was centered around retention, the activities also aimed to increase students' comprehension of each of the AE/C subdisciplines and how they need to be integrated to realize the design and construction of a building. The students were able to experience virtual rotations through the five sub-disciplines of AE/C (acoustics, lighting/electrical, mechanical, structural, and construction management) as interns working toward the design of a small healthcare clinic. They were asked to complete traditional engineering tasks, such as applying equations, for example, in addition to performing the virtual experiential tasks, such as listening to sound through walls with different sound transmission classes or observing various degrees of glare. The students were then asked to weigh the pros and cons of how each subdiscipline would be affected by their design decision. The study outcomes indicate that student learning was positively impacted by the use of the non-immersive VR modality.

As can be seen, the case studies in the literature support the hypothesis that implementing XR as a complement to traditional teaching methods is beneficial to enhance both the interest and the competency level of the students. However, adopting these ever-evolving XR modalities can be a daunting task for traditionally trained educators. In the next section, a decision-making framework is developed to compare the potential outcomes of each technology for different educational goals and priorities.

4. Decision-Making Framework for the Use of XR in AEC Education

A novel framework for applying XR modalities to AEC education is proposed based on the definitions, literature review, and educational context presented in Sections 1–3. In this section of the paper, architecture is also included, and the AEC acronym is used. The decision-making framework for use of XR in AEC education comprises of three steps (illustrated in Figure 4). In step 1, educators are encouraged to identify their educational objectives for applying XR as well as the priorities associated with their educational intervention. The framework includes the previously explained three educational contexts (retention, recruitment, and subjective matter-specific learning) and the MDL-based theoretical framework: whether the goal is to trigger/maintain interest, increase comprehension, or both. Six priority areas are identified as linked to achieving common educational objectives in AEC, including visualization of concepts and tasks, interest generation, interactivity of tasks, accessibility and scalability, risk on students, and risks of performing the same tasks in the real world. In step 2, XR technologies are recommended based on the ranking of these educational objectives and priorities for the use case. The specifications for the six educational priorities and recommended XR technologies are as follows:

1. Visualization of task: Educators need different levels of visual aids depending on their educational objectives, which in turn can prompt use of a different XR modality. For example, if one aims to teach impact of lighting design in the built environment; some educators may provide a visualization through an XR using a 2D display device, and yet others may use immersive display devices to provide a more realistic experience for students. In this regard, visualization level desired for the task is closely related to the subject matter specific learning objectives. When higher level of visualization is the priority of the XR application, MR and IVR are recommended because the XR using immersive displays can provide more realistic and immersive visualizations to students.

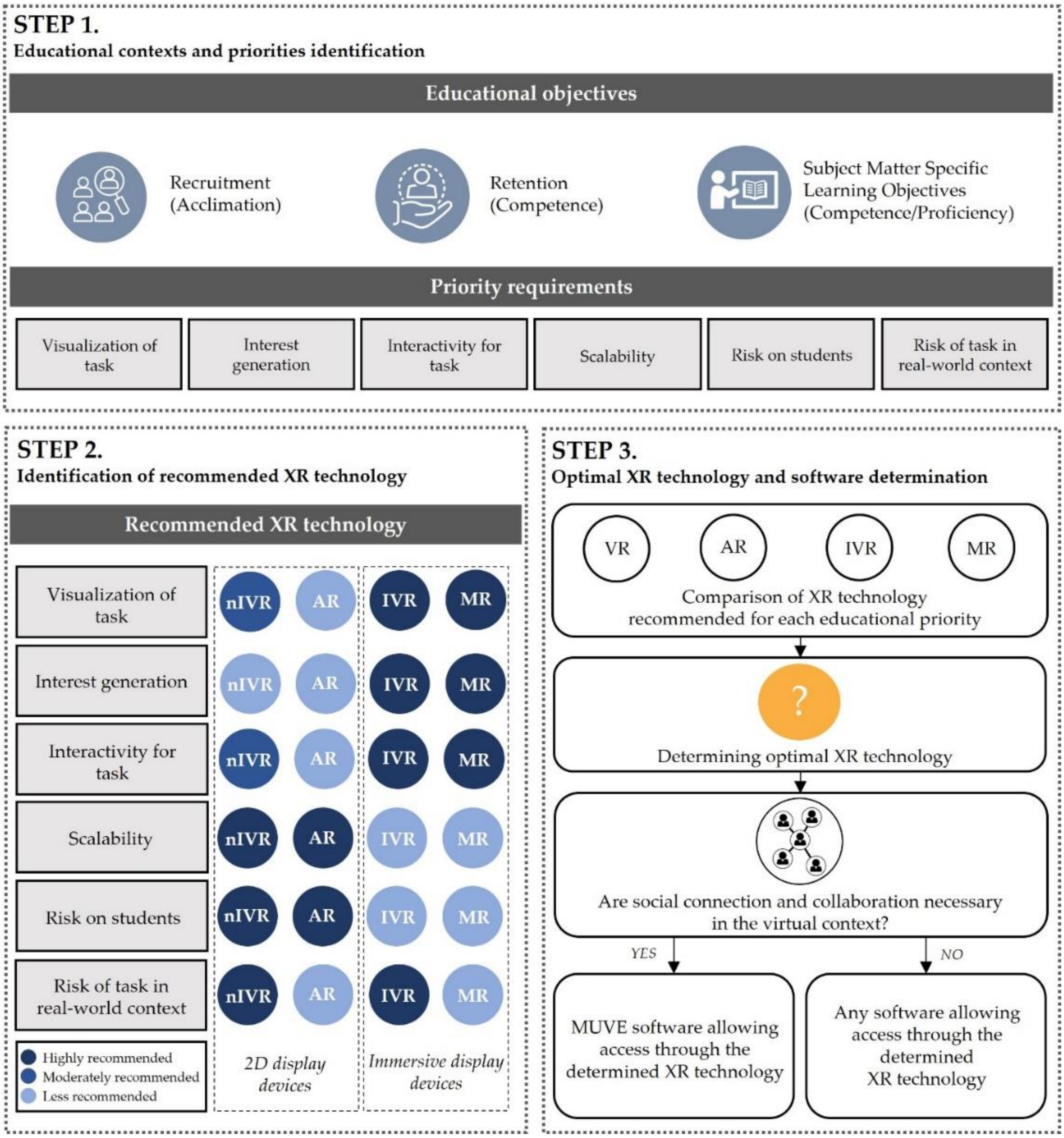

Figure 4. Decision-making framework guide for AE/C educators' application of XR technologies.

2. Interactivity for task: Educators need different levels of interactivity for different educational tasks. Some tasks can be performed simply by visualizing whole or partial built-environment elements in 2D or 3D, while more complex topics may benefit immensely from students' ability to manipulate the virtual elements using controllers or hand gestures directly (e.g., changing/testing design configurations, sizing different building elements). In this regard, interactivity for a task is closely associated with the subject matter specific learning objectives. For learning situations where interactivity is a high priority, MR and IVR are recommended because these technologies provide a higher level of interactivity than nIVR and AR.
3. Interest generation: Interest generation is essential, especially for recruitment level, but also for retention and enhanced subject matter learning, given the strong links between interest/motivation and learning. Interest triggered while participating in XR-based activities can translate into persistence in an otherwise difficult curriculum. For this educational priority, IVR and MR are recommended since XR using immersive

displays can arouse more interest from users than 2D display devices because of their immersive and interactive features.

4. Scalability/Accessibility: The term accessibility can be defined in three ways in this context. It can mean access to the technology, which allows an educational activity to be distributed widely across large classes and institutions without the need for expensive and specific equipment and software. It can also imply that the use of technology allows those with a variety of disabilities can access activities via XR that are otherwise not available to them. Design of digital media for accessibility is yet another possible definition, and it is an emerging topic in its own right. Ideally, any XR activity would accommodate visual, auditory, physical, learning, or other disabilities, but in reality, specific design steps need to be taken to make this possible and without dedicated expertise, it may not be possible. In this paper, only the first two descriptions of accessibility are considered, and they are generally referred to as "scalability" in Figure 4. Scalability here implies wider access to technology (i.e., scalability to larger groups with minimal cost) and allowing access to environments otherwise inaccessible (e.g., for those with mobility issues, remote campuses). As such, if scalability is a priority in the considered educational application, the selected XR modality's ease of use and cost may override other desires (e.g., immersion and interactivity). IVR and MR can be perceived as more challenging to use than 2D display devices because most students are not used to employing immersive display devices. Immersive display devices, especially OHMDs for using MR, are also relatively expensive, while nIVR and AR can be used with smartphones, tablets, and PC, which are already owned by many students. Therefore, when scalability is a priority in AEC education applications, nIVR and AR may be more desirable than IVR and MR.
5. Risk on students: Using IVR and MR can pose some health risks to students due to the use of immersive display devices. IVR can cause cybersickness in users with various physical symptoms such as dizziness, nausea, and eye strain, especially when used for a long time [87]. In addition, as most educators realized during the recent COVID pandemic, the use of MR and IVR can bring up cleaning and maintenance issues because students would need to share HMDs and OHMDs within the timeframe of a single class by many students due to their expensive cost. Accordingly, if educators consider the risk to students as a high priority and the class sizes are very large, AR and nIVR applications using 2D display devices are recommended over IVR and MR.
6. Risk of task in real-world context: Perhaps the most obvious benefit of a virtual world is the ability to experience environments and activities which may be dangerous or hazardous in real life. Teaching students about the repercussions of violating construction safety rules or explaining failure progression of a wall during an earthquake are just two examples among many. Educators can apply XR to demonstrate dangerous or impossible tasks in real-world. In these cases, nIVR and IVR are recommended over AR and MR because these XR technologies allow students to perform various tasks without any risk in a virtual environment. Caution should be employed, however, with too-realistic virtual environments that may trigger past-trauma related risks to the student. For example, for someone who has been in an actual collapsing building during an earthquake in the past, the trauma risk to the student may be greater than the benefits of visualizing the structural behavior of the wall in an immersed matter.

In step 3, optimal XR technology is determined by comparing recommended XR technologies identified in Step 2 and weighing the various priorities given the particular application. For example, if educators consider visualization for task and accessibility as higher priority requirements, then nIVR can be the most appropriate method. Once the optimal XR technology is identified, the type of software is determined depending on the necessity of social connection and collaboration in the virtual context. The educators may aim for an asynchronous activity, synchronous activity, or a mix of both, depending on the context. When social connection and collaboration are desired, MUVE software allowing access to the determined optimal XR technology, can be used. The software can be developed by educators suitable to their application scenarios if they have computational abilities by using game engines such as Unity and Unreal Engine. However, if educators are unable to develop software for XR application, commercial platforms can be used which allow easy access using various types of XR technologies, such as Mozilla Hubs and Spatial.

5. Discussion and Pilot Validation of Proposed Framework

Architectural Engineering and Construction Management fields are surrounded by misperceptions that make it difficult to recruit a diverse group of high-school students to these programs. Increasing capabilities of technologies related to various XR modalities present opportunities to help students visualize themselves in these career paths without risk of failure. The comprehensive literature review presented in this paper shows an increasing trend in use of XR modalities in recruitment and outreach events in AEC education, but three significant research gaps are also identified: (1) the terminology and definitions for various XR modalities are not consistent, (2) none of the research on XR interventions in AEC education explains clearly how and why these educators chose a particular XR intervention, (3) most of the XR interventions are not grounded in a theoretical or educational framework, (4) there is very limited evidence-based research that measures the impact of different XR modalities on particular educational outcomes.

This paper addressed these research gaps by deciphering the terminology on various XR modalities and most importantly, providing a novel decision-making framework grounded in model of domain learning theory.

First, based on the comprehensive literature review, this paper defined each of the currently available XR technologies to help educators in AE/C field better understand their options. This methodological study of XR modalities also provide better clarity on the advantages and disadvantages of each:

- IVR can provide an immersive and realistic experience to users compared to nIVR. However, IVR is costlier than nIVR to implement in classes because it requires individual immersive display devices to be purchased for each user or requires an efficient sharing system or lab setup.
- MR is the most advanced XR modality, as it captures the advantages of both VR and AR [40]. Specifically, it can provide users with a high level of interactive and immersive virtual experience in a real-world-like context. Accordingly, MR has potential in various applications by enabling experiential tasks which are difficult through VR and AR [88]. However, MR is even further cost-prohibitive.
- nIVR and AR have limited ability to provide a highly immersive and interactive experience compared to IVR and MR due to their technological features. However, nIVR and AR can be employed with 2D display devices that are widely accessible to many students and educators and are, therefore, the most scalable.

After this study, as well as anecdotal knowledge, authors offer the following reasons why XR applications in education are still scarce: (1) the task of implementing these emerging technologies and the various XR modalities in classes can be a daunting task for educators. (2) There can be a certain level of faculty resistance to the application of XR technologies in their classrooms due to the added burden of learning how to operate, maintain, or program highly technological devices. For someone who is just starting to consider these technologies, even knowing where to start and what each modality has to offer can be overwhelming. XR technologies are also known to be costly investments, require lots of maintenance, and may create hygiene issues or other risks to students [7,8,14]. (3) Another area of resistance among faculty may be the belief that XR technologies might "dilute" content delivery. According to the literature, this fear is not unfounded because while almost all studies report an increase in student enjoyment, several also report minimal to no impact on improvements in subject-matter learning [6–10]. As a result, it is not surprising that the main course delivery mode for AE/C degree programs is still traditional lectures. However, traditional lectures do not take advantage of the highly visual nature of these fields, may not work for all learner types, and are not always engaging for the students. It is therefore suggested herein that the solution is not choosing one or the other but complementing traditional teaching methods with well-designed XR interventions grounded in educational theory frameworks.

This paper proposed a framework to guide educators in AEC fields to select optimal XR modalities as well as the types of software and hardware, depending on their educational objectives and their own ranking of various factors. Importantly, this framework organizes the often-daunting process of deciphering these XR modalities, their advantages/limitations, and available types of software that can be used in conjunction with the selected hardware. Grounded in the Model of Domain Learning framework's learning stages and interest phases, the proposed framework can help educators better align their learning objectives and priorities before selecting a particular XR modality.

While a systematic validation of the proposed framework is out of the scope of this study, two different projects provided the basis for the proposed framework and can be offered as preliminary validation data. The first project is the pilot application of the VADERs modules in Fall 2020. The VADER intervention was designed and implemented by Erdogmus et al. [2] to increase retention among first-year Architectural Engineering students in two different institutions. Initially, the determined educational priorities were: (1) visualization of tasks and interest generation to engage the students for retention and (2) socialization among the two groups of students. Based on the proposed framework, the first priority would suggest the use of IVR or MR; however, the desire to make this easily accessible to a large group of students in two different universities was deemed more important ultimately, tipped the priority scale toward nIVR and browser-based MUVE applications. Finally, the implementation of this intervention coincided with the height of the COVID-19 pandemic and as such, risk to students (hygiene, lack of safe access to labs/gadgets) immediately became the highest priority, and the modality selected was nIVR using Mozilla Hubs. Survey results, as well as student reflections, showed that the intervention was successful in helping students better understand the AEC subdisciplines and visualize themselves in this career path, and achieve the increased engagement goal [2].

The second preliminary validation comes from the 2022 Georgia Tech summer camp, where various XR modalities were introduced, and students' perceptions of these modalities were tested both via individual after-activity surveys as well as pre- and post-camp surveys. Clearly, the educational goal of this camp was recruitment. As such, the generation of interest was the highest priority. Students were offered: (1) an MR activity using OHMDs (HoloLens 2), (2) an AR activity using an iPad, and (3) an IVR activity using HMDs (Oculus Quest 2). While the participants (n=14) scored enjoyment of all three activities highly, some students noted physical discomfort (nausea and dizziness) with wearing HMDs both in MR and IVR modalities. Some noted they also did not feel safe while using these modalities. Two participants who had these physical issues even noted they were less interested in a career in construction after participating in the IVR activity. These preliminary findings show that when inclusivity and scalability in education are considered, nIVR and AR applications should be preferred; or at the very least, educators should always consider offering non-immersive XR modalities as an alternative [88].

Several limitations of this paper must be noted and considered for future research. First, additional and more specific educational objectives can be identified for the application of XR in AEC education. Further, the sampled case studies are not exhaustive, and other examples from other disciplines can be found. In addition, it is acknowledged that while this study is up-to-date in terms of available technologies at the time of its writing and will serve many educators in a variety of ways, XR technologies are advancing very rapidly, and new modalities and capabilities may be available before too long. Thus, follow-up studies to update the suggested framework according to the development of technologies are required.

6. Conclusions

Various conclusions can be drawn from this paper:

- After an in-depth review of terminology related to these emerging technologies, authors suggest the use of extended reality, XR, as the umbrella term to be adopted when a variety of modalities or devices/applications are implied. Similarly, the most important aspect of these technologies from an application point of view is whether they are immersive or not, and this differentiation is also important. That said, technology language is fluid, and as new technologies are developed, it is expected that the language will also evolve.
- Pertinent literature on XR use case studies in AEC education show clear findings that these interventions always increase student interest, enjoyment, and, therefore, engagement; however, contributions to improved learning are harder to achieve and measure. Educational research on validated learning assessment tools before and after XR interventions, as well as with control groups, is needed.
- The proposed decision-making framework considers the complexity of competing priorities in an educational setting and offers a road map for instructors to make informed decisions when they design XR interventions for their classes.
- The preliminary validation case studies confirm that the proposed decision-making framework simplifies the process even under conditions that change the priority rankings unexpectedly.

Ultimately, the authors of this paper suggest that the goal of using XR interventions should not be to entirely substitute the traditional teaching methods, such as lectures that educate on fundamentals, in-person site visits, and any other tools the educators may use that already achieve successful educational outcomes. However, if the intervention is designed thoughtfully and pedagogically, as suggested through the framework proposed herein, these interventions are more likely to increase the engagement, self-efficacy, and, ultimately, learning of students.

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