A NEW APPROACH TO TESTING AUGMENTED- AND VIRTUAL-REALITY TO SUPPORT TACIT KNOWLEDGE GENERATION IN DESIGN ASSESSMENT

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ABSTRACT: *Professional expertise in the architecture, engineering and construction (AEC) industry is typically developed through years of field experience. The knowledge obtained during this time consists of both explicit knowledge and tacit knowledge. Educators typically focus on presenting content to develop explicit knowledge, but both forms are required for novice students to become expert practitioners. Part of the challenge with developing tacit knowledge is that actual project experiences can be difficult to replicate in academic environments. Emerging augmented reality (AR) and virtual reality (VR) technologies may offer new abilities to provide experience that mimics on-site experiences for students. Other fields of research have developed educational approaches to support experiences that may enable tacit knowledge generation, including the Carnegie Foundation's Three Apprenticeships Model, which states that the most comprehensive learning experiences must include an emphasis on cognitive understanding, practical skills, and moral dimensions. Therefore, this paper proposes a methodology that will enable researchers to use this model as a guide in order to test the impact of AR- and VR-enabled learning in the AEC domain. This methodology includes three main parts: expert focus group interviews, VR/AR experiences with data collection throughout, and pre-post analysis to assess the impact of the technology intervention.*

KEYWORDS: *Augmented Reality, Virtual Reality, Three Apprenticeships Model, Design Assessment, Tacit Knowledge*

1. INTRODUCTION

1.1 Industry Concerns About Shortage of Skilled Workforce

In the coming decades, the architecture, engineering and construction (AEC) industry is expected to see substantial growth with labor demands growing upwards of twenty percent nationally (Henderson 2015). Although the growth is projected to increase revenues, the AEC industry as a whole is projected to struggle with meeting this demand as it continues to grapple with criticism of poor productivity (Goodrum et al. 2011; Teicholz et al. 2001) and wasted money due to interoperability issues (Chohan et al. 2007; Hwang et al. 2009; Love et al 2011). The severity of these issues are compounded by the challenges associated with entering a "labor-cliff". A labor cliff is defined as the state at which project performance is significantly affected by one or more workforce issues: labor, quantity or quality (Albattah et al. 2015). The median age of construction professionals has risen to 42.6 years of age and design professionals' median age is now 44 years old (Bureau of Labor Statistics 2017), and the lack of new professionals entering this industry is not offsetting those retiring (Gamble 2013). The confluence of these trends means the industry will continue to face challenges of training new professionals rapidly to meeting the growing workforce needs (Arditi & Mochtar, 2000; Dubois & Gadde, 2002; Schwatka, Butler, & Rosecrance, 2012).

This loss of knowledge and expertise will pose a major challenge to the AEC industry in the coming years. Knowledge is generally broken into two categories: explicit and tacit knowledge (Pathirage et al. 2008). Explicit knowledge is related to the information that can be accessed, articulated, and communicated easily. This information is typically conveyed in the form of textbooks or detailed examples (Collins 2010; Maravilhas & Martins 2018; Pathirage et al. 2008). In the AEC industry, this form of knowledge is generally taught and retained through manuals or standard operating procedures (Hizar Md Khuzaimah & Hassan 2012). However, due to the growing complexity of projects and the diverse nature of project scope within the AEC industry, a growing interest in tacit knowledge has emerged in order to better train project team members (Hizar Md Khuzaimah & Hassan 2012; Woo et al. 2004).

Unlike explicit knowledge, tacit knowledge is defined as the understanding, capabilities, skills and the experiences of individuals; often expressed in human actions in the form of thoughts, points of view, evaluation and advice (Collins 2010; Nonaka & Takeuchi 1995; Pathirage et al. 2008). Tacit knowledge has been identified as a critical element within the AEC industry and can be subcategorized further into cognitive knowledge (mental beliefs or hunches) and technical knowledge (the know-how and skills) (D'Eredita & Barreto 2006; Hizar Md Khuzaimah & Hassan 2012). By its nature, this form of knowledge is difficult to record and therefore challenging to teach to new industry members that have not had the opportunity to experience an active project jobsite in a particular situation. Typically, it is gained through years of project site experience, but the time required for this tacit knowledge generation is not conducive to meeting the industry's growing labor demands. With the current labor shortage, the industry needs a means of educating new individuals more rapidly to gain this tacit knowledge.

1.2 Potential of Emerging Technology

In the past, educators have leveraged physical design and construction projects (i.e Solar Decathlon) to enable students to attain both explicit and tacit knowledge. While this type of hands-on education may be highly valuable to the students, it is extremely time and resource intensive, which means that not all students can have this type of practical experience prior to graduation. This limits access to experience that can enable tacit knowledge generation. Augmented Reality (AR) and Virtual Reality (VR) environments may facilitate this type of education by replicating construction or design environments in a classroom setting with relatively low costs in materials. Figure 1 presents a conceptual graphic illustrating how this technology may enable similar experiences to physical presence.

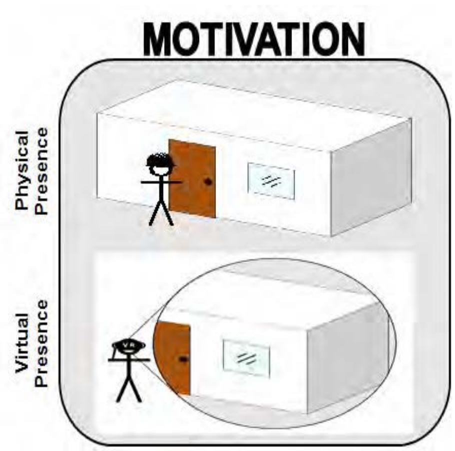

Fig. 1: Graphical representation of motivation to research

Augmented Reality (AR) and Virtual Reality (VR) environments have been suggested to provide value by allowing project teams and educators to replicate construction or design environments in a classroom setting with relatively low costs in materials (Alsafouri et al. 2017; Alsafouri & Ayer 2017; Frank & Kapila 2017; Wu et al. 2013). AR is the incorporation of both the tangible elements of the physical environment with that of the modeled virtual environment displayed simultaneously (Milgram & Kishino 1994). VR environments are where the sensation of presence is conveyed by minimizing the contact of the user with the physical world, thus differentiating from web-based VR application that are normally manipulated through a mouse and the PC display (Marini et al. 2012). AR has been identified to provide value in the early stages of a construction project by supporting decision making processes (Alsafouri et al. 2017). In addition, VR has been previously found to enable users to visualize and recognize complex workplace situations, from which the knowledge of procedures and skills could be built, and tasks in a safe and forgiving environment be carried out (Li et al. 2018). These environments are intended to simulate experiences that could only be achieved otherwise through physical experiences (Alsafouri et al. 2017; Gupta 2012; Hughes et al. 2005; Milgram & Fumio 1994). This immersion in the experience motivates the researchers to explore the extent to which these visualization environments may be able to replicate the type of tacit knowledge generation that is typically developed through years of onsite experience. Thus, the interactions with these environments lead researchers to question whether or not AR and VR can be leveraged to facilitate tacit knowledge generation.

While AR and VR offer theoretical potential to students' development of tacit knowledge, there is not currently an understanding of how tacit knowledge should be evaluated in the design and construction education domain. The Three Apprenticeships Theory offers a framework that outlines three critical components that must be embraced in order to facilitate tacit knowledge generation: head, heart, and hand (Shulman 2005). Other fields of education such as nursing have found success in the application of this learning theory in the development of better-prepared medical professionals (Taylor & Care 1999). It is possible that this same approach to learning may benefit design and construction education as well, but currently there is a lack of understanding of how it should be applied to this specific domain. Therefore, this paper aims to fill this knowledge gap by addressing the following questions: 1) *What methodological decisions facilitate the appropriate application of the Three Apprenticeships learning theory using AR/VR intervened cyberlearning environments to enable tacit knowledge generation relevant to design and construction education?* 2) *And what data should be collected during AR/VR learning activities to inform the development of relevant learning assessments in this new genre of cyberlearning?* This paper contributes a methodology to test design- and construction-related tacit knowledge generation through AR and VR-enhanced cyberlearning environments. The remainder of this paper will include a summary of the learning theory supporting the proposed methodology, along with the three-step methodology itself.

2. THEORETICAL UNDERPINNINGS

2.1 The Three Apprenticeships Model

The “Three Apprenticeships Model” provides the theoretical underpinnings for the proposed methodology of this paper. The results of a multi-year, multi-institutional study conducted by the Carnegie Foundation for the Advancement of Teaching (2007) describe the current state of undergraduate engineering education in the U.S. and provide recommendations for improving curriculum to align with the professional demands of the field. The study found that within engineering fields, curricula are primarily focused on the technical or explicit knowledge within the related field, though there is a need for more integrated learning experiences that involve knowledge (Head), skills (Hand), and professional judgment (Heart) (Sheppard et al. 2009). In theory, these experiences should provide a more well-rounded approach to facilitating the development of more robust forms of explicit and tacit knowledge among new professionals.

The Three Apprenticeships approach is informed by the insights of many contributors. John Dewey, a professor and education researcher, argued that teachers not only need to be educated on theory, but also practical application (Shulman 2004). Later, Shulman expanded on Dewey’s theory with his perspective on the three apprenticeships. Shulman theorized that professional education is composed of three apprenticeships: cognitive, practical, and moral (Shulman 2005). The cognitive dimension focuses on the knowledge professionals should possess, the practical dimension focuses on the skills a professional must exhibit, and the moral dimension focuses on the attitudes, values, and ethics that are commonly associated with the profession of interest. Following this line of research, the Transformative Sustainable Learning (TSL) theory was created to ensure that certain values were imparted in education to ensure a sustainable future that will continue to progress our society (Sipos et al. 2008). Sipos and colleagues (2008) echoed the sentiments of Dewey and Shulman through their work, and continued to argue that the head, hand, and heart should be implemented into inter- and trans-disciplinary education. While the combination of the three constructs are interchangeably referred to as both Transformative Sustainable Learning and Three Apprenticeships in existing scholarship, the authors will refer to them as the “Three Apprenticeships” in this paper for continuity. The proposed methodology of this paper aims to address the need for more diverse learning integration in design curricula through the application of a Three Apprenticeships approach to educating future design and construction professionals.

3. PROPOSED METHODOLOGY

The proposed methodology involves a three-step procedure based on the Three Apprenticeships theory to test design- and construction-related tacit knowledge generation through AR and VR environments. The intention of this methodological approach is to provide researchers and educators a method to test tacit knowledge generation with visualization technologies so that they may be able to understand the extent each technology may be used to recreate experiences that elicit behaviors relating to tacit knowledge gain. The first step of the methodology includes expert interviews to identify particular use cases and desired research questions that need to be addressed in relation to the targeted apprenticeship. The second step involves the development of pre- and post-learning activity assessments that will help educational researchers to evaluate the impacts of technology interventions. The third step involves the development of the actual AR/VR-enabled learning experience based on the targeted learning outcomes. These steps are outlined in Figure 2 and detailed in the subsequent sections.

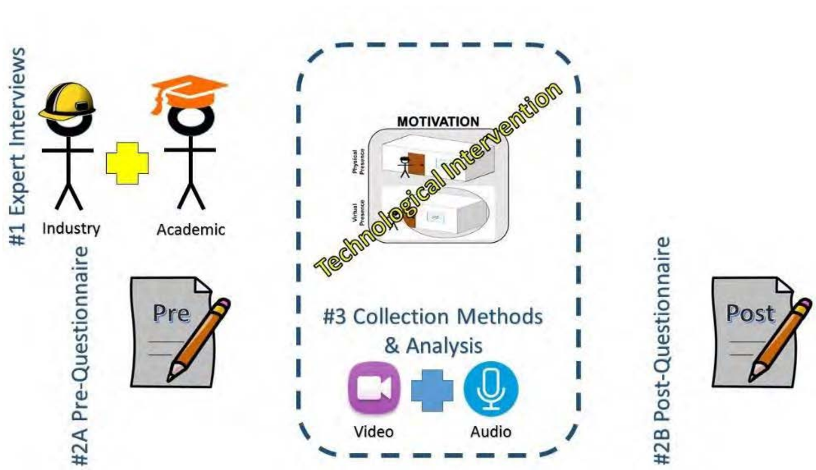

Figure 2: Graphical Overview of Proposed Methodology

3.1 Expert Interviews

Different forms of assessment allow for gathering evidence of different forms of knowledge. Thus, in order to evaluate each of the three apprenticeships in relation to design assessment, educators and researchers must strategically target each apprenticeship using a variety of forms of data collection and analysis. Although tacit knowledge is gained through the combination of the three apprenticeships, by separating each apprenticeship into separate evaluations, it allows researchers to identify specific characteristics of each apprenticeship that may be manipulated to promote greater tacit knowledge gain. Once a targeted apprenticeship is established amongst the research team, the first step within the methodology would be to identify which experiences would best replicate career situations within the industry that call for that particular apprenticeship. To do this the research team must first gain insights about the real world situations faced throughout the design industry and the associated decision processes industry professionals take to be successful in each situation. To establish this understanding and provide a framework for replicating an experience in a testing environment, researchers should first conduct interviews with subject matter experts targeted at understanding the decision processes or elements of knowledge they dwell upon when coming up with solutions. Subject matter experts are those assumed to have prolific working experience within the industry or a content expert in an academic setting.

To obtain the most beneficial commentary amongst industry professionals, it is suggested to develop an interview protocol specifically focusing on how experts and novices differ in their processes for acquiring knowledge and how they represent knowledge (e.g., domain-specific vs. general knowledge) (Popovic 2000). Interview questions should be based upon the working knowledge and work experience each expert faces in their careers. The questions should allow for open-ended discussion from the interviewee to reflect upon previous experiences and decision-making processes that were used to remedy the discussed situation. Dependent upon which apprenticeship is targeted, interview questions should be refined to accommodate each dimension in order to encourage interviewees to have more attuned perspectives and answers to the apprenticeship. For example, sample questions developed for application with the heart dimension or moral apprenticeship are provided in Table 1. Through these interviews, researchers should be able to identify specific career experiences in relation to design assessment that can be recreated in a virtual and/or augmented environment. Each interview protocol should be piloted and refined as necessary in order to allow researchers to target meaningful responses from interviewees.

Table 1: Sample Expert Interview Protocol Questions

1	Tell me a little about how long you have worked in this industry and what you currently do.
2	Based on the following four options, which phase do you have the most impact on as part of your day-to-day job: planning, design, build, or operate?
3	Can you give me example of a time when you needed to design or build a facility (or component) for individuals with needs different from your own? Please keep this example in mind throughout the rest of the interview.
4	What is your approach for designing/constructing a facility that is mindful of a diverse group of individuals (e.g., age, disability/ability, etc.)?
5	How do you evaluate different design/construction options to support the group of individuals? (Prompt: What information is useful for completing this evaluation?)

3.2 Technological Intervention

Once an experience can be identified through the situational content provided by the expert interviewees, researchers can then address how to best recreate the experience through visualization technologies. Table 2 presents examples of defined career experiences and the associated targeted apprenticeship. In order to target a particular apprenticeship, it is necessary to develop a strategy for replicating, recording, and analyzing tacit knowledge generation for the intended career experience researchers would like to evaluate.

Table 2: Example Experiences Associated With Each Apprenticeship

Apprenticeships:	Example Experience Use-Case:	Experience Justification:
Cognitive (Head)	Building Code Evaluation	To test industry specific knowledge participants should possess through the use current building codes required for a space
Moral (Heart)	Handicap Accessibility	To generate empathy among participant by placing them in a design scenario requiring of a user with different needs than their own
Practical (Hand)	Window Frame Assembly	To challenge participants use of skills by defining a set of means and methods that can be built by hand

Assuming that a physical experience is not available for assessment on an active project that would exactly replicate the identified situation or experience, researchers must artificially create this experience. For this, a technological intervention may be able to facilitate the environment. The authors of this paper have refrained from explicitly detailing development strategies for the technological intervention. The intent of this methodological approach is to have a wide applicability to test tacit knowledge across various construction use-cases or career experiences of which researchers and educators may require different development needs in creating the immersive experience. Therefore, general guidelines and suggestions are presented in order to develop the technological intervention to be tested. The technological intervention to create this environment should represent the intended career experience in a manner that conveys enough detail and immersion so that it is comparable to the physical world experiences that students would face in their eventual career. From previous work, visualization technologies such as AR and VR have been identified to be effective means of communication and creating immersive environments that mimic the physical world. AR and VR have been reported to support better decision-making that traditionally had only been reported through physical mock-ups or experience (Alsafouri et al. 2017). AR allows for the users to physically walk around or interact with a space while simultaneously interacting with the developed virtual model. Where physical exploration of a virtual space is not required, VR can be used to allow participants to be fully immersed in a developed virtual model. The close approximation of experience through the use of these technologies may provide users enough of an immersive experience to facilitate tacit knowledge generation

3.2.1 Data Collection Methods & Analysis

As tacit knowledge is gained through experience, researchers are interested in both the verbal and non-verbal behaviors demonstrated within the modeled experience and how that may relate to the decisions of professionals. In order to evaluate the user within the modeled experience and test the possible tacit knowledge gain in relation to the targeted apprenticeship, it is necessary to record the interaction both visually and audibly. This data can be used to conduct future behavioral analysis. Researchers are interested in both expert demonstrated behaviors within the modeled experience as well as novice behaviors. By having both expert and novice behavioral data, statistical comparisons (i.e. one-sample t-tests) to evaluate the ability of novices to meet the standard set forth by experts.

Multiple video and an audio recording devices are suggested to collect this information. The use of multiple video camcorders allows researchers to fix the cameras in key locations and different angles around the experiment to record all physical interaction with the modeled experience. An audio recording device can be fixed on or near the test subject to record user's answers to posed scenarios and communication while interacting with the modeled experience. Assuming the testing space is sufficiently small, video camcorders can be used alone to record the interaction if background noise is of no concern.

To facilitate verbal communication of participants, it is suggested that researchers develop a think-aloud protocol to lead subjects through the experience and inquire about the subject's decision-making process without bias. A think-aloud protocol is a tool typically used in psychology and cognitive human factors fields that has been suggested to be one of the most effective ways to assess higher level thinking processes which involve working memory (Joe et al. 2015; Olson 1983). It is a tool used to establish verbal communication of the problem-solving strategies of participants (Joe et al. 2015). The protocol should first sufficiently introduce the test subject to the experience or use case they are virtually being placed into and establish the task the user is to complete. Researchers should avoid the use of prompting test subjects past the point of introducing the experience as to not introduce bias. During the experiment, researchers should attune the think-aloud protocol to have little to no involvement by the research team and only use open ended questions with regard to the experience or use case. The questions should not suggest a right or wrong answer, but rather ask “how” and “why” the participant made the decisions they did. The answers to the questions can be later used for video behavioral analysis and qualitative analysis.

Once the video and audio data are collected, a behavioral coding scheme can be developed to identify and quantitatively evaluate the verbalized answers and key physical interactions. By assigning codes to each identified answer or interaction, researchers are able to assign a numeric value to the interactions the users are demonstrating that can later be used for statistical analysis (Alsafouri et al. 2017; Liston et al 2001). This can be done in numerous types of video analysis software such as BORIS. The coding scheme is dependent upon the experience and apprenticeship the research team is targeting within the experiment. Depending on which data points are of most interest to analyze or provide the greatest value with regard to meaningful inference, the coding scheme can be rearranged as necessary to accommodate the experiment. Example codes are provided below in Table 3 for an experiment in relation to handicap design assessment. Behavioral codes can be assigned to collect different information from the experiment. Time and duration information can be collected by monitoring the beginning, end, or time stamp of a certain interaction or communication. This information can be used to conduct productivity statistics of participants and identify the order of which information is identified. Counted instances of coded elements can be used for rubric-based evaluation or for comparison against different sampled groups (i.e. novice and expert).

Table 3: Example Behavioral Codes for Video Analysis

Code:	Behavior:	Data Collected for Statistical Analysis:
Begin Assessment	Moment when participant acknowledges the start of their assessment or when the first comment is given	Duration : Beginning timestamp of activity
End Assessment	Moment when participant acknowledges the end of their assessment or when participant states they have no additional comment	Duration : Ending timestamp of activity
Countertop Height	Participant comment stating the height of any countertop needs to be adjusted to fit the height of someone in a wheelchair	Point : Counted event
Movement Through Model	Active movement in wheelchair by participant in model	Duration & Point: Can assign start/ stop codes to collect timestamps or counted event

3.3 Perceptual Analysis – Pre & Post Questionnaires

To understand and evaluate the impacts of intervention on participants before and after the modeled experience, a pair of pre and post-test surveys (known more generally as a repeated-measures design) can be used to collect quantitative data (Dugard & Todman 1995). The perceptual content gathered can be used for statistical analysis (e.g. one-sample t-test) to determine if there is any significant change in perception and/or knowledge due to the introduction of the intervention. A main advantage of using pre- and post-test design is that the associated repeated-measures statistical analyses tend to be more powerful, and thus require considerably smaller sample sizes than other types of analyses (Brogan & Kutner 2012).

The pre- and post-test surveys aim to collect quantitative data, in addition to the qualitative data collected using the think-aloud protocol, to address the following research questions:

I. How do participants respond to the technology intervention itself, including the experience and potential knowledge gains?
II. How do participants perform in the experiment, i.e. conducting design and constructability review, in the technology-intervened environment?
III. How other factors, including the demographics (e.g. prior working knowledge and experience) of the participants and the two different visualization technology (i.e. VR and AR), may influence their performance in the modeled experience?

3.3.1 Pre & Post Activity Questionnaire Design

The pre-test survey questionnaire should collect the demographics information of the participants, including their prior working knowledge and experience with: 1) design and constructability review; and 2) visualization technology (VR & AR) used in the research activity. Perceptions and expectations towards performing the tasks in the experiment with different visualization technology are also measured using 5-point Likert-type scales. The post-test survey questionnaire collects data on participants' perceived experience with the design and constructability review activities in both VR and AR intervened environments. To help understand the usability difference perceived by participants in the two environments should integrated into the questionnaires as well. The ten-item attitude Likert scales, i.e. the System Usability Scales (SUS) developed by Brooke (1996), are suggested to be used to quantify this information. In order to keep data consistent, the questionnaires should be linked via the use of identifier questions to allow direct comparison of responses by the same participants before and after the activity. In order to limit bias, identifying questions should be prompted in a fashion that does not directly identify the participant within the activity. The medium of which the questionnaire is distributed, whether it be a paper or electronic questionnaire, is not important. Though in order to allow participants to have the best recall of the activity, it is imperative that the pre-questionnaire be given immediately before the activity and the post questionnaire immediately after the activity.

Corresponding to the research questions, the following analyses can be performed:

I. Comparing the usability of the two visualization technology-intervened environments, using one-sample t-test;
II. Comparing the expected with experienced results of design and constructability review in the VR- and AR-intervened environments using one-sample t-test; and
III. Evaluating if the above analyses are dependent on prior working knowledge and experience (i.e. novice vs. experts) using Pearson's chi-square test.

4. LIMITATIONS & DISCUSSION

The authors provide a methodological approach to test new and emerging technological interventions' impacts on tacit knowledge generation based on the Three Apprenticeships model. While the methodology has a theoretical basis, it has not yet been empirically tested, so the authors cannot claim the extent to which this mode of education impacts student learning.

As the proposed methodology does not call for an evenly distributed sampling of expert interviewees, generalizability among diverse population may be limited. The experiences and replicated environments in AR or VR are based on the situational content provided by expert interviews which are assumed to be regionally centered in experience. This may lead to developed experiences that may not be practical for replication in other research or curricula.

The authors aim to create this methodology to support learning experiences enabled by AR or VR technologies. It is possible that other researchers will want to explore the impacts of different technologies. If so, they may find that certain aspects of the proposed methodology must be changed to accommodate the different technology. It is likely that this would only impact the technological intervention data collection activities, but the authors recognize the potential limitation that this poses to broad application of this methodology.

5. CONCLUSION

This research presents a methodological approach for testing and assessing tacit knowledge generation for design and construction education according to the Three Apprenticeships model. The specific methodology developed aims to provide a means for assessing tacit knowledge generation through the use of AR- and VR-intervened cyberlearning environments. The use of video and audio recordings of users in simulated environments translated into coded information allows researchers to objectively compare both student novices and practitioner experts to understand the similarities or differences in the behaviors related to tacit knowledge. This work contributes to the current body of knowledge by providing an approach that allows researchers to perform objective and empirical future work to test the applicability of using these technologies to facilitate experiences that would otherwise be difficult or impossible to replicate in a classroom setting.

If the methodology provided is leveraged by other researchers, it may provide an effective way for educators to develop a more comprehensive understanding of how the Three Apprenticeships learning theory supports design and construction education. This will not only advance the theoretical understanding of cyberlearning for the AEC domain, but it may also allow educators and practitioners to train new individuals to more rapidly develop the critical tacit knowledge that traditionally has required years to develop. This would provide a mechanism to address some of the pressing needs for skilled workforce in the AEC industry while supporting the personal development of the future industry leaders.

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