Enhancing Construction Inspection with Augmented Reality: An Analysis of Accuracy and Observation of its Application in Training

Jeffrey Kim[1] and Darren Olsen[1]

[1]McWhorter School of Building Science, Auburn University, US
Jeff.Kim@auburn.edu, DAO0002@auburn.edu

Abstract –

The construction industry faces significant challenges, including declining quality performance, skilled labor shortages, and resistance to technological innovation. These issues have hampered the sector's operational efficiency and reputation. A critical component of quality control—accurate material placement—remains dependent on manual interpretation of 2D drawings, a task often prone to errors due to workforce inexperience. To address these concerns, this study investigates augmented reality (AR) as a tool to modernize construction inspection processes and enhance workforce training under the framework of Construction 4.0. This research evaluates the accuracy and practical utility of AR devices, including the Apple iPhone 13 Pro Max, Apple iPad Pro 12.9-inch, Trimble GPS Enabled SiteVision, and Trimble XR10 - Microsoft HoloLens 2, for inspecting the placement of underground utilities in a simulated construction environment. Thirty-two construction management students participated, using AR tools to position survey prisms at perceived utility locations. Results revealed the HoloLens achieved the highest accuracy and precision, followed by the SiteVision and iPad, with the iPhone exhibiting the largest deviations. Findings highlight AR's potential as an educational tool, enabling students to bridge theoretical knowledge with practical applications while engaging in immersive, hands-on learning. Despite limitations, including environmental variability and current technological tolerances, AR demonstrates significant promise in training future professionals and improving quality control processes. This study underscores the need for continued innovation in AR technology to advance the construction industry's efficiency, reputation, and workforce readiness.

Keywords –

Augmented Reality, Quality Control, Experiential Learning, Construction 4.0

1 Background and Rationale

The construction industry, a cornerstone of infrastructure development, is at a critical transition concerning standards in quality control. Extensive research underscores a significant decline in quality performance over recent decades. Key factors contributing to this deterioration include a persistent shortage of skilled labor [1], insufficient investment in quality management systems [2][3], and inadequate leadership in adopting technological innovations [4]. These systemic challenges have impaired the industry's competitiveness and operational efficiency. Moreover, entrenched resistance to process change and a tarnished public reputation exacerbate the sector's difficulties in adoption [5]. Concurrently, the industry is grappling with the loss of experienced professionals while relying on a less-skilled incoming workforce that requires substantial training time to achieve proficiency [6]. These intertwined issues further hinder efforts to improve productivity and public perception.

Precision in material placement is a critical aspect of construction processes. Currently, this task heavily depends on manual interpretation of two-dimensional (2D) drawings to construct three-dimensional (3D) structures. Inexperienced installers often face challenges in accurately interpreting these representations, leading to errors and delays in construction. Effective layout and quality control require practiced visualization skills typically developed through extensive field experience. However, the departure of skilled professionals has widened the expertise gap, compounding the industry’s quality control challenges and adversely affecting its reputation for reliability and customer satisfaction.

To address these issues, innovative technologies are being explored under the banner of Construction 4.0, the industry’s response to Industry 4.0 advancements. Among these, augmented reality (AR) has emerged as a transformative tool, with applications ranging from enhancing safety training [7] and improving design visualization [8] to owner training and building maintenance support [9]. AR offers a potential solution for bridging the skills gap by facilitating training and comprehension. Its potential for quality control is particularly appealing. Application of AR in quality control has been demonstrated with the verification of proper rebar installation, albeit with the assistance of laser scanners [10]. More recently, large timber installation inspections using AR has been shown to improve fastener placement for improved accuracy and safety of those installed structures [11]. Despite these past studies and others like it, none are focused on the tool for its comparable training purpose, identifying a gap in this narrowly focused viewpoint. Nevertheless, leveraging AR effectively requires a nuanced understanding of construction-specific quality control procedures.

One illustrative example is the measurement of placement tolerances for utilities embedded in concrete structures. Ensuring accurate placement is essential to prevent costly rework. Early identification of deficiencies by inspectors is crucial to maintaining quality standards. For AR to succeed in augmenting this inspection process, it must deliver consistent accuracy and precision in identifying defects. Additionally, AR's capacity to overlay virtual objects onto real-world environments must be rigorously assessed for practicality and reliability.

Research highlights AR’s efficacy in enhancing both classroom and on-site training [12][13]. With the proliferation of mobile devices, AR tools can now be deployed with minimal effort, enabling construction professionals and students to integrate these technologies seamlessly into their workflows. However, while the potential of AR for improving quality control processes is widely acknowledged, the current body of research remains speculative, emphasizing the need for empirical studies to validate its applications [8][14][15].

This study addresses these gaps through a dual focus. First, it examines students’ perceptions of AR tools as a means of teaching essential inspection and analysis skills. Second, it evaluates the accuracy of AR inspection tools in the classroom setting, hypothesizing that their effectiveness in educational contexts could translate to practical applications on construction sites. The research assumes that AR can aid students in developing foundational skills essential for future industry practitioners. Furthermore, data on the accuracy and precision of AR tools could inform their integration into real-world quality control workflows, offering practical solutions for outdated inspection practices.

By establishing a foundation for incorporating AR tools into construction education and professional practices, this research contributes to modernizing the industry. It aims to address the knowledge gap left by departing experts while enhancing productivity and reputation. These efforts signify a critical step toward an industry that struggles to embrace innovation, retain expertise, and deliver higher-quality products.

1.1 Research Rationale

How can the construction industry modernize its outdated quality control processes, improve its reputation for quality, and address the challenges posed by a declining skilled workforce? The industry's traditional mindset—relying on methods that "worked in the past"—is no longer sufficient. A paradigm shift [16] is necessary, beginning with equipping the incoming workforce with advanced training and tools to meet modern demands effectively.

This research focuses on evaluating the accuracy and potential of AR technology as a tool for construction inspections. By integrating AR into training programs, the study aims to address two critical issues: enhancing quality control and bridging the skills gap in the workforce. The research involves students from a construction management program, providing them with hands-on experience and exposure to innovative tools. Through this approach, the study seeks to demonstrate AR's capacity to improve construction processes while preparing the next generation of professionals to meet industry challenges head-on.

2 Methodology

This study employs an action research protocol, integrating insights from various disciplines to assess AR tools' effectiveness in evaluating the placement accuracy of underground utilities. By superimposing utilities over a real-world view, the study aims to prepare construction students as future professionals while connecting classroom concepts to practical applications [17].

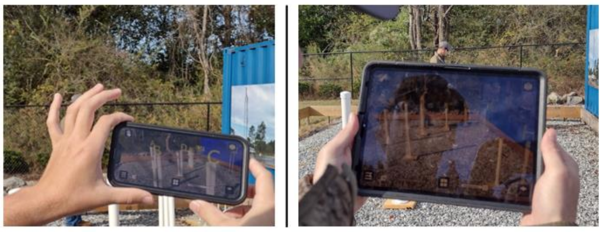
Previous research on AR accuracy and precision informs this study. Scherl et al. demonstrated error tolerances within 1.33 mm using fiducials in surgical procedures [18], while Khan et al. found object placement accuracies within 1.1 mm in virtual environments under stationary conditions and controlled lighting [19]. These findings influenced the authors' device selection and methodology, leveraging best practices to evaluate AR-assisted placement accuracy in construction.

2.1 General Participant Demographics

The study involved students from a four-year construction management program in the Southeastern United States. Participation was voluntary, and the experiment took place during a regularly scheduled class session. These students were chosen because of their foundational knowledge aligning with the study's goals and their aspirations to become project managers or superintendents in commercial construction. Most participants, aged 20 to 23, had gained hands-on experience through internships, giving them a practical understanding of construction practices and the critical role of accuracy in utility placement. This background enabled them to effectively distinguish between correctly and incorrectly placed objects, contributing to the study's credibility. Thirty-two students participated in this study.

2.2 Devices Used in this Study

Devices were selected to align the study's emphasis on accuracy and precision, as informed by the findings of Khan et al. [19] and Scherl et al. [18]. The devices chosen for the study (shown in Figures 1 and 2 below) included the Apple iPhone 13 Pro Max (iPhone), the Apple iPad Pro 12.9-inch 5th generation (iPad), and the Trimble GPS Enabled SiteVision, representing a *passive*, non-fiducial AR device category. Additionally, the Trimble XR10 - Microsoft HoloLens 2 (HoloLens) was selected as an *active*, non-fiducial AR device type. The terms "passive" and "active" refer to the level of user interactivity: the HoloLens offers a more immersive experience, placing the user into a virtual environment compared to the other devices. Additionally, the iPhone and iPad were chosen for their familiarity among students, simplifying data collection and enhancing its reliability. The HoloLens and the Trimble SiteVision were included due to their potential as cutting-edge tools for professionals, providing students with an opportunity to engage with technology that could modernize traditional inspection workflows.



a. b.

Figure 1. (a.) iPhone & (b.) iPad

a. b.

Figure 2. (a.) HoloLens & (b.) SiteVision

2.3 The Experimental Space and AR Authoring Tools

The experimental case study was conducted within a simulated construction environment designed to mimic pre-concrete placement inspections commonly performed on construction sites. This phase is critical as it occurs before concrete is poured, allowing for the identification and resolution of deficiencies to avoid costly rework or delays.

The simulated site (Figure 3.a.) spanned 20 feet by 15 feet (6.1 m x 4.6 m) and was enclosed by wooden forms, creating a flat, stable surface for students to conduct observations using the AR devices described earlier (see Figures 1 and 2). Students used the devices to position a survey prism mounted on a PVC pipe supported by a tripod (Figure 3.b.), simulating the top of an underground utility pipe. The accuracy and precision of these placements were later evaluated against control points established within the simulation.

a. b.

Figure 3. (a.) Experimental Workspace & (b.) Locating

Prisim

The site was outdoors and partially shaded, reflecting typical lighting conditions encountered on construction sites. Conducting the study in natural sunlight introduced practical challenges associated with real-world inspections using AR, enhancing the study's relevance to industry applications. While outdoor lighting and weather conditions were expected to influence data collection, they were not specifically measured during this study.

The AR experience was facilitated using Trimble FieldLink MR, a platform built on Building Information Modeling (BIM) principles widely adopted in the industry [18]. A BIM model of the simulated site was initially created in Revit, then converted to a SketchUp file for seamless integration with the Trimble FieldLink MR platform (see Figure 4). This cloud-based solution ensured consistent access to the AR experience across all devices used in this study, promoting uniformity in participant interactions and data collection.

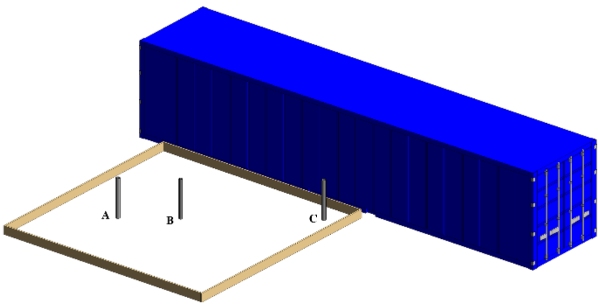


Figure 4. Rendering of the AR Display

Within the model, three virtual PVC pipes (A, B, and C) were positioned to represent utility penetrations typically encountered on construction sites. These digital proxies allowed participants to observe and assess placement accuracy before concrete placement, aligning the experiment with real-world inspection practices and ensuring practical relevance to the construction industry.

2.4 The Experimental Workflow

At the start of the study, control points were established within the simulated construction site and validated using a robotic total station. During the experiment, students navigated the simulated site (Figure 3.a.) with their assigned AR device (Figure 1 and 2), which displayed virtual pipes and their spatial positions (Figure 4). Upon identifying a virtual pipe, students positioned a survey prism stand (Figure 3.b.) at its perceived center. The robotic total station then recorded the student’s identified pipe location, capturing both northing and easting coordinates for subsequent analysis. To evaluate the accuracy of the observations, the recorded pipe coordinates from the students were compared against the control coordinates of the pipes.

3 Results and Discussion

Each pipe was individually located by students utilizing their designated AR devices, allowing every participant to make up to three positional observations specific to their assigned device.

The positional data (northing and easting coordinates) for all students were compared against the control positions of the simulated pipes using the formula outlined in Figure 5.

$$\sqrt{(N_n - N_y)^2 + (E_n - E_x)^2}$$

Figure 5. Formula for Calculating Placement Difference (Northing and Easting coordinates).

Figure 5. (N_n and E_n = pipe control coordinates and N_y and E_x = student observed coordinates)

3.1 Accuracy and Precision

A summary of the calculated error averages and standard deviations is presented in Table 1.

Table 1. Error Calculations

PIPE		DEVICE TYPES			
		HoloLens	**SiteVision**	**iPhone**	**iPad**
A	Average	2.47	3.05	7.51	3.30
	SD	1.23	1.85	4.22	1.95
	n	8	8	8	8
B	Average	2.73	3.60	5.97	3.66
	SD	1.69	2.40	2.80	1.17
	n	8	8	8	8
C	Average	4.65	3.91	5.30	3.79
	SD	1.34	2.53	1.43	1.39
	n	8	8	8	8

Note: All error measurements are represented in (SI) inches.

Analyzing the results for each AR device—the HoloLens, SiteVision, iPhone, and iPad—reveals notable variations in performance. The HoloLens consistently demonstrated the highest placement accuracy, with an overall average error of 3.28 inches across all three pipes (A, B, and C). In comparison, the SiteVision recorded an average error of 3.52 and the iPad recorded a near similar average error of 3.59 inches. The iPhone exhibited the largest error, averaging 6.26 inches. Precision, assessed through standard deviation, further underscored the HoloLens' reliability, as it had the lowest standard deviation of 1.42, followed closely by the iPad at 1.50. The SiteVision and iPhone trailed with a standard deviation of 2.26 and 2.82 respectively.

These findings align with the expectations set by Trimble's whitepaper [21], affirming the superior performance of the HoloLens' WLT technology compared to devices lacking such features. Similar to Trimble's conclusions, the HoloLens excelled in anchoring virtual elements to the real-world environment. It should be noted, however, that this study differed methodologically by excluding fiducials and stationary observers, leading to accuracy results that diverged from prior research [19][18]. These deviations were anticipated, given the experimental conditions.

The iPad and the SiteVision emerged as a practical alternatives to the HoloLens, with accuracy and precision closely mirroring those of the HoloLens. Despite this, the iPad offers a less immersive experience, as its AR interface relies on a handheld screen. In contrast, the HoloLens provides a more engaging, hands-free experience by overlaying virtual elements directly onto the user's field of view via a headset. This hands-free operation enhances mobility and safety, whereas the need to hold the iPhone or iPad can restrict movement and increase safety risks [22]. Consequently, the decision to use these devices should balance factors such as cost, immersion, and safety. The SiteVision accommodates for this ergonomic consideration by providing a handle for operation, but it too is a device that requires the use of at least one of the operator's hands.

While the observed tolerances in this study indicate that the current AR tools may not meet the precise standards required in many construction industry applications—where tolerances often range between 1/8" and 1/4"—they nonetheless highlight the potential of AR as a valuable educational tool. The technology's ability to bridge theoretical learning with practical applications makes it a promising resource for advancing industry training and education.

3.2 Practicality for Academic and Industry Use

The AR tool proves to be a highly valuable educational resource, especially as a training platform for aspiring inspectors. While its accuracy may not yet align with industry standards, its immersive nature offers a unique opportunity for hands-on learning. Through interactive simulations and practical exercises, trainees can refine their ability to detect and address construction deficiencies, gaining a deeper understanding of inspection processes. Participant feedback highlights the AR tool's potential as a transformative educational aid. As one student expressed in their open-ended comments:

"The experience was enjoyable and gave me a better grasp of how to inspect for construction errors."

Anecdotally, this feedback reflects a broader trend of positive student engagement and impactful learning experiences when action research is implemented [23]. Research supports the effectiveness of active, experiential learning strategies in improving educational outcomes, particularly when cognitive load is managed effectively [12][24].

These findings underscore the AR tool's promise as a teaching aid within the construction field. By leveraging its immersive capabilities to foster active participation, the tool not only enhances practical competencies but also encourages a culture of ongoing learning and innovation. The study's results suggest that the AR tool positively transforms the educational experience, signalling a shift toward more dynamic and interactive training methods in the industry.

3.3 Considerations for the Future of this Research

While this study sought to manage key variables influencing outcomes, certain factors arose that merit consideration in future investigations.

Firstly, environmental conditions, such as sunlight and weather, were not controlled. This approach aimed to mimic real-world variability on construction sites, ensuring practical relevance for industry applications. However, during the experiment, delays occurred as researchers waited for optimal sunlight to continue, given that poor lighting could compromise the HoloLens experience and overheating issues were noted with the iPhone and iPad. These challenges led to the loss of several data points, requiring rework to maintain study integrity.

Secondly, the limited size of the student cohort may have constrained the breadth of the findings. A larger participant pool could provide a more comprehensive dataset, yielding deeper insights into the effectiveness of the AR tool.

Lastly, the requirement for students to work in pairs to record virtual pipe locations introduced an additional variable. Those using the iPhone and iPad faced limitations due to the need to hold their devices, leaving only one free hand for marking tasks. Conversely, HoloLens users had the advantage of hands-free operation, potentially influencing the overall results. Those using the SiteVision were afforded more flexibility since the device was equipped with a handle and wrist strap to precent dropping the device. While theses discrepancy likely impacted the study, no specific data was collected to confirm its effect.

These considerations point to areas where future research can refine methodologies, address limitations, and further explore the AR tool's potential to enhance learning and professional development in the construction industry.

4 Conclusion

The findings from this research reveal the transformative potential of AR as both an educational tool and a technology capable of modernizing quality control practices in the construction industry. With construction increasingly defined by its challenges—such as a declining skilled workforce, a need for higher-quality outcomes, and resistance to technological change—AR offers a pathway to innovation and improvement.

Through this study, AR tools demonstrated their ability to bridge the gap between theoretical learning and practical application, particularly in training students on critical inspection and analysis skills. The immersive and interactive nature of AR facilitates experiential learning, enabling students to practice identifying construction errors within a controlled, simulated environment. Feedback from participants underscores this value, with many noting increased engagement and comprehension. Active, hands-on learning methodologies, supported by the AR platform, align with established educational research, which emphasizes the importance of reducing cognitive load to optimize learning outcomes.

From a technical perspective, the study highlighted the relative strengths and limitations of AR devices, such as the HoloLens, SiteVision, iPhone, and iPad, in achieving placement accuracy for simulated utilities. While the HoloLens emerged as the most precise tool, with accuracy levels surpassing other devices, the findings suggest that current AR technology may not yet meet the stringent tolerances required in some industry-specific applications. However, these tools show significant promise as cost-effective and accessible alternatives for training purposes. The hands-free operation of the HoloLens was shown to enhance user mobility and safety, offering an additional layer of practicality for both educational and field applications.

This research contributes to the growing body of evidence supporting AR's integration into construction practices. It highlights AR's dual role in addressing pressing industry challenges: by equipping the next generation of professionals with advanced skills and by improving workflows in quality control. These outcomes position AR as an instrumental technology for advancing the goals of Construction 4.0, fostering innovation, and enhancing the reputation and productivity of the construction sector [25].

In conclusion, this study demonstrates that augmented reality represents a significant opportunity for the construction industry to modernize its approaches to education and quality control. By fostering a culture of innovation and continuous learning, AR has the potential to mitigate the challenges associated with a declining skilled workforce while enhancing the quality and efficiency of construction processes. As the industry continues to evolve, embracing technologies like AR will be critical to building a future characterized by greater resilience, adaptability, and excellence in construction practices.

References

[1] Allen, S., 1985. Why Construction Industry Productivity is Declining. Macroeconomics eJournal. https://doi.org/10.2307/1924811.

[2] Rosenfeld, Y., 2009. Cost of quality versus cost of non‐quality in construction: the crucial balance. Construction Management and Economics, 27, pp. 107 - 117. https://doi.org/10.1080/01446190802651744.

[3] Arditi, D., & Gunaydin, H., 1997. Total quality management in the construction process. International Journal of Project Management, 15, pp. 235-243. https://doi.org/10.1016/S0263-7863(96)00076-2.

[4] Wright, R., 1989. Technology for competitiveness of the U.S. construction industry. . https://doi.org/10.6028/nist.ir.89-4099.

[5] Moraru, G., & Popa, D., 2021. Potential Resistance of Employees to Change in the Transition to Industry 5.0. MATEC Web of Conferences. https://doi.org/10.1051/matecconf/202134307005.

[6] Welfare, K., Sherratt, F., & Hallowell, M., 2021. Perceptions of Construction Work: Views to Consider to Improve Employee Recruitment and Retention. Journal of Construction Engineering and Management. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002057.

[7] Li, X., Yi, W., Chi, H., Wang, X., & Chan, A., 2018. A critical review of virtual and augmented reality (VR/AR) applications in construction safety. Automation in Construction, 86, pp. 150-162. https://doi.org/10.1016/J.AUTCON.2017.11.003.

[8] Hajirasouli, A., Banihashemi, S., Drogemuller, R., Fazeli, A., & Mohandes, S., 2022. Augmented reality in design and construction: thematic analysis and conceptual frameworks. Construction Innovation. https://doi.org/10.1108/ci-01-2022-0007.

[9] Chi, H. L., Kim, M. K., Liu, K. Z., Thedja, J. P. P., Seo, J., & Lee, D. E. (2022). Rebar inspection integrating augmented reality and laser scanning. Automation in Construction, 136, 104183. https://doi.org/10.1016/j.autcon.2022.104183

[10] Fazel, A., & Adel, A. (2024). Enhancing construction accuracy, productivity, and safety with augmented reality for timber fastening. Automation in Construction, 166, 105596. https://doi.org/10.1016/j.autcon.2024.105596

[11] Harikrishnan, A., Abdallah, A., Ayer, S., Asmar, M., & Tang, P., 2021. Feasibility of augmented reality technology for communication in the construction industry. Adv. Eng. Informatics, 50, pp. 101363. https://doi.org/10.1016/J.AEI.2021.101363.

[12] Kim, J. and Irizarry, J., 2021. Evaluating the use of augmented reality technology to improve construction management student's spatial skills. International Journal of Construction Education and Research, 17(2), pp.99-116.

[13] Olbina, S. and Glick, S., 2023. Using integrated hands-on and virtual reality (VR) or augmented reality (AR) approaches in construction management education. International Journal of Construction Education and Research, 19(3), pp.341-360.

[14] Adebowale, O., & Agumba, J., 2022. Applications of augmented reality for construction productivity improvement: a systematic review. Smart and Sustainable Built Environment. https://doi.org/10.1108/sasbe-06-2022-0128.

[15] Delgado, J., Oyedele, L., Beach, T., & Demian, P., 2020. Augmented and Virtual Reality in Construction: Drivers and Limitations for Industry Adoption. Journal of Construction Engineering and Management-asce, 146, pp. 04020079. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001844.

[16] Kuhn, Thomas S. The structure of scientific revolutions. Vol. 962. Chicago: University of Chicago press, 1997.

[17] Zuber‐Skenitt, O., 1993. Improving Learning and Teaching Through Action Learning and Action Research. Higher Education Research & Development, 12, pp. 45-58. https://doi.org/10.1080/0729436930120105.

[18] Scherl, C., Stratemeier, J., Karle, C., Rotter, N., Hesser, J., Huber, L., Dias, A., Hoffmann, O., Riffel, P., Schönberg, S., Schell, A., Lammert, A., Affolter, A., & Männle, D., 2020. Augmented reality with HoloLens in parotid surgery: how to assess and to improve accuracy. European Archives of Oto-Rhino-Laryngology, 278, pp. 2473 - 2483. https://doi.org/10.1007/s00405-020-06351-7.

[19] Khan, F., Muvva, V., Wu, D., Arefin, M., Phillips, N., & Swan, J., 2021. Measuring the Perceived Three-Dimensional Location of Virtual Objects in Optical See-Through Augmented Reality. 2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), pp. 109-117. https://doi.org/10.1109/ismar52148.2021.00025.

[20] Sacks, R., Eastman, C., Lee, G. and Teicholz, P., 2018. BIM handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers. John Wiley & Sons.

[21] Trimble White Paper on Accuracy of the Trimble XR-10, October 2020.

[22] Alzhrani, A., Cook, M., Johnstone, K., & Cooper, J., 2018. Handheld Mobile Devices—How Do We Use Them at Work? A University Case Study. Advances in Intelligent Systems and Computing. https://doi.org/10.1007/978-3-319-96083-8_16.

[23] Zuber‐Skenitt, O. (1993). Improving learning and teaching through action learning and action research. Higher education research and development, 12(1), 45-58. https://doi.org/10.1080/0729436930120105

[24] Sweller, J., 2020. Cognitive load theory and educational technology. Educational Technology Research and Development, 68(1), pp.1-16.

[25] Sawhney, A., Riley, M. and Irizarry, J., 2020. Construction 4.0: Introduction and overview. In Construction 4.0 (pp. 3-22). Routledge.