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Productivity of Augmented Reality for the Construction of Geometrically Complex Wall Designs

Simon Adamtey PhD[1], Muhammad Khan[2]

Associate Professor, Construction Management, Kent State University, USA[1]

Student, Construction Management, Kent State University, USA[2]

Abstract: Technological advancement has allowed the design of more complex structures consequently making the traditional method of construction inefficient. Additionally, the decline of productivity has called for the use of modern technology such as augmented reality to improved construction productivity. This study investigated the productivity of using Interactive Augmented Reality (IAR) method for the construction of complex brick wall designs. A total of 17 people with no previous bricklaying experience participated in experiments to construct three different types of brick walls with different complexities. The walls were constructed using the traditional method (no technology) and with IAR and productivities recorded. The Wilcoxon/Kruskal-Wallis non-parametric test indicated statistically significant difference in the mean productivity of the IAR (ranging from 2 to 2.5 minutes/brick) and the traditional method (ranging from 6.61 to 49.4 minutes/brick). The results indicate that the average productivity rate for placing bricks per minute using the IAR method was significantly higher than that of the traditional method.

Keywords: Interactive Augmented Reality; Microsoft HoloLens; Brick Wall; Complex Design;

I. INTRODUCTION

Many studies have suggested that productivity growth has been negative in construction, both in the United States and internationally [1] [2] [3]. This decline in construction productivity has been a cause of great concern in both the construction industry and academia [4]. Consequently, considerable research has been performed on construction productivity making it one of the most researched areas in the past decades.

To understand the cause of productivity decline, several studies have been conducted to identify the factors affecting productivity on construction sites. In 2013, a survey by [5] identified complex design as one of the significant factors affecting construction productivity in the United States [5]. In order to overcome this problem, some researchers have suggested the use of technology, which can lead to overall improvement in project productivity [6].

Technological advancement in the software industry allow architects to develop more complex designs under a new style of designing called modernism [7]. This change requires new construction methods, which not only rely on the conventional method of skilled labor but incorporate different digital tools and techniques such as industrial robots, three-dimensional (3D) printing, pre-fabrication, etc. [8].

In the late 1990's, Building Information Modelling (BIM) emerged as a new technology, which allowed both design and construction companies to use it for project design, coordination, and communication [9]. While the initial cost of BIM implementation is considered high [10], this technology has proven beneficial for overall project productivity [11]. Researchers have now started integrating BIM with other technologies, such as Augmented Reality (AR), Virtual Reality (VR), and Digital Twin, to further enhance productivity on construction sites [12]. Studies have shown that such integrations reduce project time and errors [13].

For the construction of geometrically complex designs, researchers have started exploring the use of different Interactive Augmented Reality (IAR) tools [8]. This approach is considered economical and less complicated in comparison to other approaches such as robotic fabrication and 3D printing [14]. The use of IAR could result in up to 50% increase in productivity [12]. The aim of this study is to investigate the impact of using IAR on construction productivity for geometrically complex designed brick walls construction by comparing it with the traditional construction method. The idea behind the comparison is to examine the feasibility of using IAR technology in the construction process, and its impact on time.

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II. INTERACTIVE AUGMENTED REALITY AND COMPLEX DESIGN

Interactive Augmented Reality (IAR) is a technology that allows superimposition of computer-generated holographic projections [15], such as virtual objects, text, or video, onto the real world [16]. It enhances users' perception and understanding of their surroundings by providing additional digital information through directing a device to a specific location or object in the real environment [17]. Users can view this audio-visual information using different types of devices such as glasses, headsets, mobiles, tablets, or projectors [18].

IAR can be used in the construction industry for design communications, coordination, inspection, safety training, facility management, progress tracking, quality assurances, and more. [19] conducted a thorough review of studies published between 2012 and 2020 to examine trends of IAR implementation in construction. They found most studies published for IAR were in project progress monitoring and operation, followed by quality management and task instruction. Similarly, [20] found IAR can be used for construction coordination, quality assurance and safety trainings. It can also help to improve construction productivity. [21] found that IAR can improve construction productivity through monitoring, safety training, and design information. Other studies have shown that the use of IAR can significantly improve cost and time efficiency [12].

One of the major uses of IAR is in the construction of geometrically complex building structures. Designers can create complexity in brick wall design by changing any one of the following parameters: (1) shape of brick, (2) texture of brick, (3) type of bond, (4) angle of brick placements in relation to the bonding plane, and (5) mortar joint types [22]. Construction of complex designs requires skilled labor to execute tasks accurately and efficiently. The technological equipment available to laborers can be one of the crucial factors in improving productivity and reducing construction costs.

Similar studies have been conducted to explore the feasibility of IAR under different environments for complex design construction. [23] compared the conventional bricklaying construction method with augmented bricklaying for the construction of geometrically complex brick façade walls. The aim of the experiment was to make masons less dependent on drawings by using holographic images for the execution of tasks. It provided opportunities to explore possibilities of using a custom-built IAR system for feasibility, limitations, and implications during in-situ construction scenarios. [8] proposed a low-cost solution for the construction of complex design structures using a free-form modular method with a head-mounted device (HMD) to guide the user in locating and orienting each brick for wall construction. The proposed system was found 5 to 10 times less expensive than other mentioned methods [8]. [3] conducted a study in 2019 to investigate the feasibility of IAR technology for construction tasks. The aim was to enable construction managers to utilize the workforce with less experience for skilled tasks with technologically integrated workflow.

III. METHODOLOGY

To compare the productivity of constructing geometrically complex designed brick walls and examine implementation cost differences and potential cost benefits of using interactive augmented reality over the traditional construction method, three different types of walls, shown in Figure 1, were constructed using both IAR method (HoloLens 2) and the traditional method.

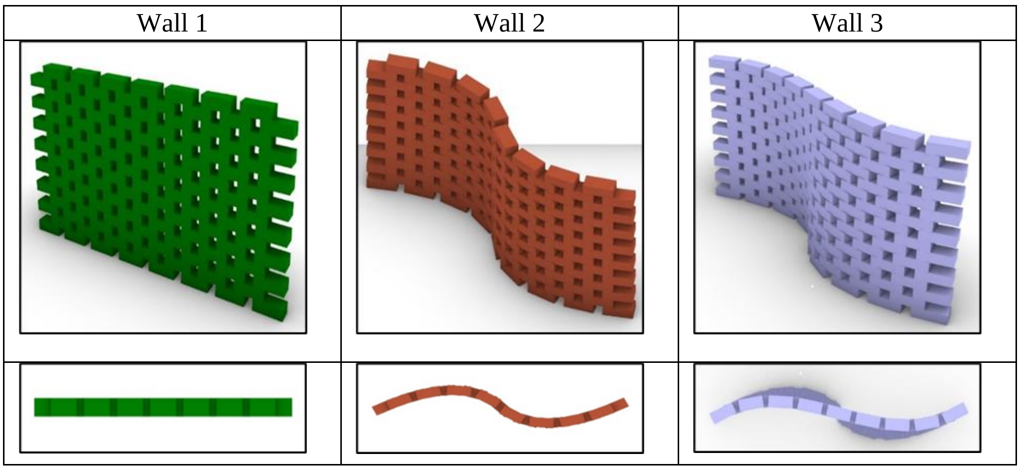

Fig. 1 Types of Brick Wall

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Table I shows the dimensions of all three walls, which were kept the same, i.e., 6 feet in length and 3 feet in height, with a running bond between courses. The total area of each wall was 18 square feet. The walls were dry built, without mortar.

TABLE I WALL CHARACTERISTICS

Wall Type	Length (ft)	Height (ft)	Type of Bond	No. of Bricks	Number of Horizontal Curves	Degree of Curves	
						Top	Bottom
1	6	3	Running Bond	135	-	1	1
2				150	2	2	2
3				160	2	2	3

Complexity in design was created by varying degree of curvature of brick placement angle on a scale from 1 to 3 degrees (see Table I). It allowed for the creation of varying levels of complexity in wall design, with the degree of curve serving as a control parameter. A degree of curvature of 1 indicated a straight wall, while a degree of 3 indicated a wall with a larger curve. A Grasshopper script was developed to generate the 3D parametric design of walls. It took the wall's start and end points from Rhinoceros 7 (Rhino) and generated a wall with pre-set brick and wall height. The degree of curvature for the top and bottom curves was also specified in the script. Rhino also allowed the export of the top view of wall layers to AutoCAD, which was used to create 2D drawings for the traditional construction method.

The experiment involved 17 random participants comprising of 7 females and 10 males. None of the participants had previous bricklaying experience. Participants were provided a brief training for the construction process. In the IAR session, participants learned how to load a 3D model in Fologram, establish a connection between HoloLens 2 and Fologram, navigate the software, and load an on-site model as shown in Figure 2.

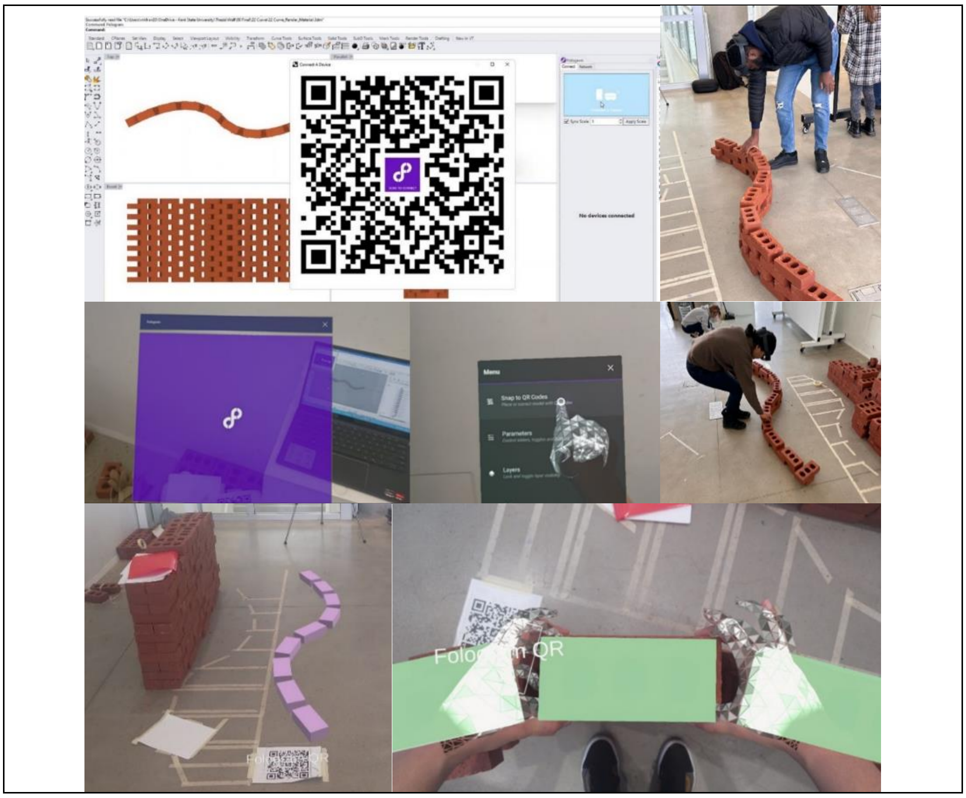

Fig. 2 IAR Construction Method

The traditional method session, on the other hand, focused on layout marking, establishing the origin for angles, and using construction tools like a bubble level and a measuring tape. The experiment was conducted in an indoor environment as shown in Figure 3. The process of construction was recorded for analysis.

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Fig. 3 Traditional Construction Method

The productivity of participants was calculated based on how many minutes were used by a participant to place a single brick for both the traditional and IAR methods (see Equation 1). During the initial testing of Fologram and HoloLens 2 for the experiment, it was observed that constructing an-18 square feet brick wall using HoloLens 2 took an average of 30 minutes. As a result, a ten-minute time window was selected, during which an average of three data points was generated from one complete process. A total of 40 data points was collected from the 17 participants to perform statistical analysis.

$$\text{Productivity}\ \left(\frac{\text{mins}}{\text{brick}}\right) = \frac{\text{Time consumed (minutes)}}{\text{Per brick (brick)}}\ \text{... Eq. 1}$$

There are several factors which can influence the productivity of participants. It would be practically impossible to specify and run analysis on all factors. As a result, only six factors that had an impact on the participant's performance were taken into consideration: (1) prior experience, (2) design complexity, (3) work environment, (4) task clarity, (5) accuracy of the technology, and (6) construction methods. However, since all participants lacked prior bricklaying experience, the effect of experience on productivity was assumed to be the same for both methods. Additionally, the experiments were performed in an indoor environment with the same HoloLens 2 device. The effect of environment on productivity was also considered the same for both methods. Each participant was also given brief training on the use of HoloLens 2 and other tools, thereby eliminating the influence of task clarity. The only remaining factors were design complexity (wall type) and construction method.

IV. PRODUCTIVITY ANALYSIS

The data for the wall type and construction method were in categorical form whereas productivity was in continuous form (see Table II).Wall type and construction method were the independent variables, and productivity was the dependent variable.

TABLE II DATA CATEGORIES

Variable	Categories		
Wall Type	Wall Type 1	Wall Type 2	Wall Type 3
Construction Method	Traditional	Interactive Augmented Reality (IAR)	

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Wilcoxon Signed Rank Non-Parametric Test was used to examine the mean differences in the productivity of the participants. The level of significance (α) for statistical analysis was kept at 0.05 with a confidence interval of 95%. Initially, the continuous dependent variable data were checked for significant outliers, as shown in Figure 4. The analysis revealed no significant outliers in the dataset.

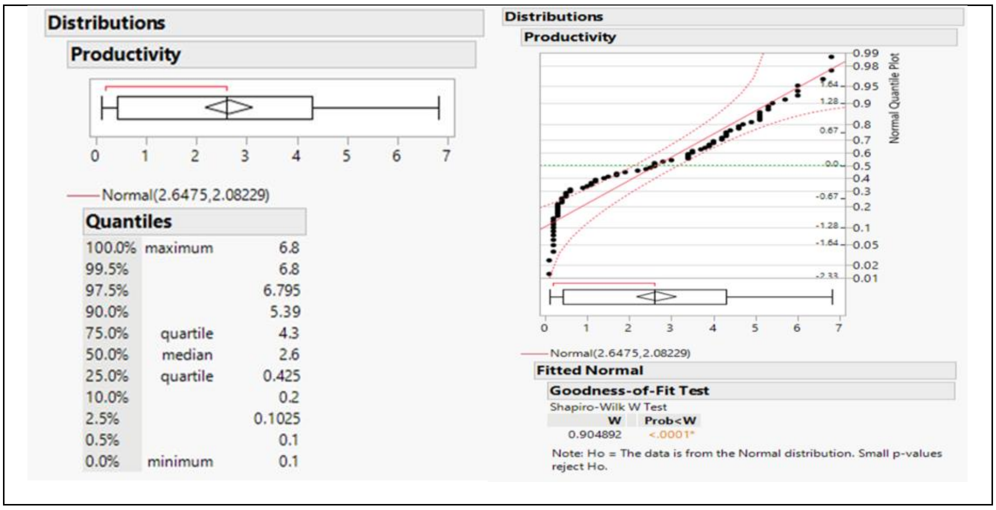

Fig. 4 Check for significant outlier and normal distribution

After evaluating significant outliers, the productivity data was tested using the Shapiro-Wilk test to determine the conditions for normality. A p-value less than a significance level (α = 0.05) indicates non-normal distribution. Figure 5.1 shows the p-value for the test as 0.001, which is less than the level of significance (i.e., α = 0.05). This indicated that the data does not follow a normal distribution. The Q-Q plot also supported the conclusion of non-normality, as the points deviate significantly from the expected values for a normal distribution, especially on the left (see Figure 5). Welch's test was used for the comparison of the homogeneity of variances (homoscedasticity) among the different groups. Homoscedasticity implies equal variance of a dependent variable across different levels of an independent variable. The p-value (p = 0.001) obtained from the Welch test was lower than the significance level (0.005). This indicated that the variances of groups were not homogenous (see Figure 5). Hence, the condition of homogeneity was also not satisfied.

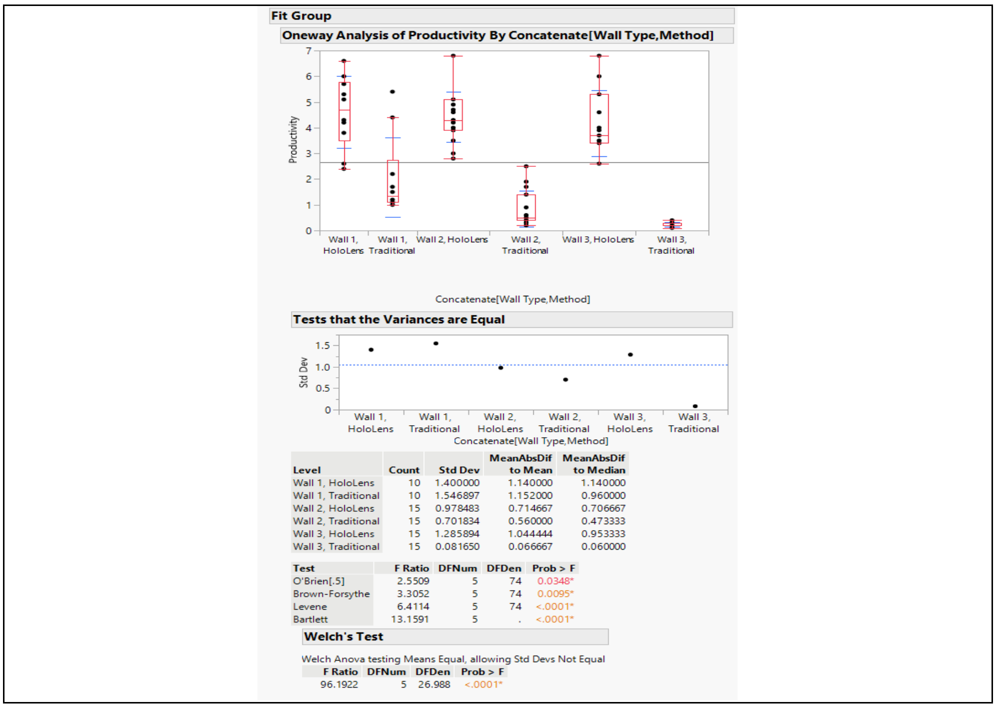

Fig. 5 Homogeneity of Variances

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Before conducting the Wilcoxon Signed Rank Non-Parametric Test, an effect test was performed to determine whether each independent variable (wall type and construction method) had any significant impact on the dependent variable (productivity) [24]. The effect test shown in Figure 6 depicts that wall type and construction method have a significant impact on productivity with the value of p (0.0017) and p (0.0001), respectively. They are both less than the level of significance (0.05). The results showed an R-squared value of 0.75 (see Figure 6), indicating that 75% of the productivity data was influenced by the wall type and construction method while the remaining 25% could be due to other factors not included in the model [25].

Response Productivity

Whole Model

Summary of Fit

RSquare	0.758513
RSquare Adj	0.742197
Root Mean Square Error	1.05727
Mean of Response	2.6475
Observations (or Sum Wgts)	80

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Wall Type	2	2	15.51883	6.9416	0.0017*
Method	1	1	216.00343	193.2364	<.0001*
Wall Type*Method	2	2	6.25200	2.7965	0.0675

Fig. 6 Effect Test and Summary of Fit

Additionally, the test revealed no interaction effect between groups of wall type and construction method (see Figure 7) with a p-value higher than the significance threshold (0.067 > α) (see Figure 7). We can separate the effects of two variables to analyze the differences in the mean productivity of groups using the Wilcoxon Signed Rank Test [24].

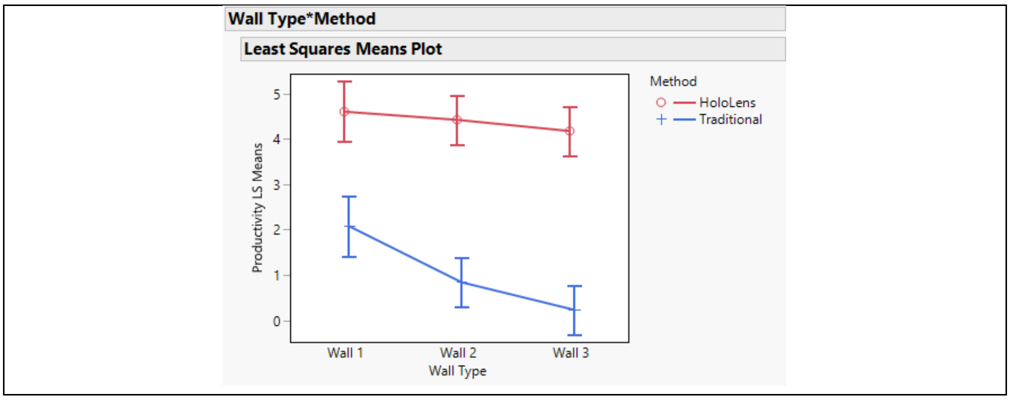

Fig. 7 Interaction effect between groups

The p-values for Wall Type 1, Wall Type 2, and Wall Type 3 were 0.004, 0.0001, and 0.0001, respectively, which were less than the level of significance (α = 0.05). This indicated a statistically significant difference in the mean productivity between participants building a wall with and without the use of HoloLens 2/IAR, leading to the rejection of the null hypothesis. Therefore, the alternative hypothesis is accepted.

For Wall Type 1, the mean productivity of using the IAR method was recorded as 2.41 minutes/brick compared to the traditional method which was recorded as 6.61 minutes/brick. The mean productivity for Wall Type 2 construction using the IAR method was recorded as 2.37 minutes/brick, while the traditional method yielded 20.70 minutes/brick.

Similarly, the mean productivity for Wall Type 3 construction using the IAR method was recorded as 2.60 minutes/brick, while the traditional method yielded 49.40 minutes/brick. See Figure 8 for the mean productivities. It was noted that as the wall design became more complex, the mean productivity to place a single brick using traditional construction method significantly increased from 6.61 minutes per brick to 49.4 minutes per brick. However, for the IAR method, the mean productivity for all wall types remained within the range of 2 to 2.5 minutes per brick.

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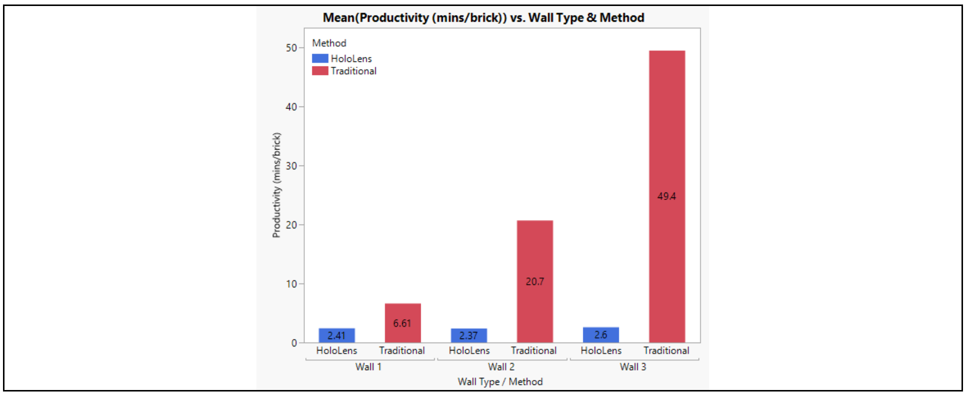

Fig. 8 Mean productivity of groups

It was also observed that for Wall Type 1, the total durations of the traditional and IAR methods were relatively close at 30 minutes (0.50 hours) and 25.8 minutes (0.43 hours) respectively. Initially, the IAR method was faster than the traditional method. However, the times for both methods became close to one another once the participants had passed the learning curve (see Figure 8). For Wall Type 2, the total construction time using the traditional method was recorded as 127.2 minutes (2.12 hours) and 30 minutes (0.50 hours) using the IAR method. The traditional method had a longer initial learning curve as participants spent more time on bricklaying compared to the IAR method (see Figure 8). This could be because the first two courses of Wall Type 2 had different brick placement angles, which consumed more of the construction time for the traditional method. However, the rest of the wall followed the same pattern. As participants became familiar with the design, both the IAR and traditional methods' productivity came relatively close to each other. For Wall Type 3, the total time was 619.2 minutes (10.32 hours) for the traditional method and 39 minutes (0.65 hours) for the IAR method. Interestingly, for Wall Type 3, the construction time initially increased for the traditional method as the wall height increased but eventually flattened out. This could be due to the wall design, as it has a bigger curve on the base than the top, which increased the construction time for the starting courses in the traditional method (see Figure 8).

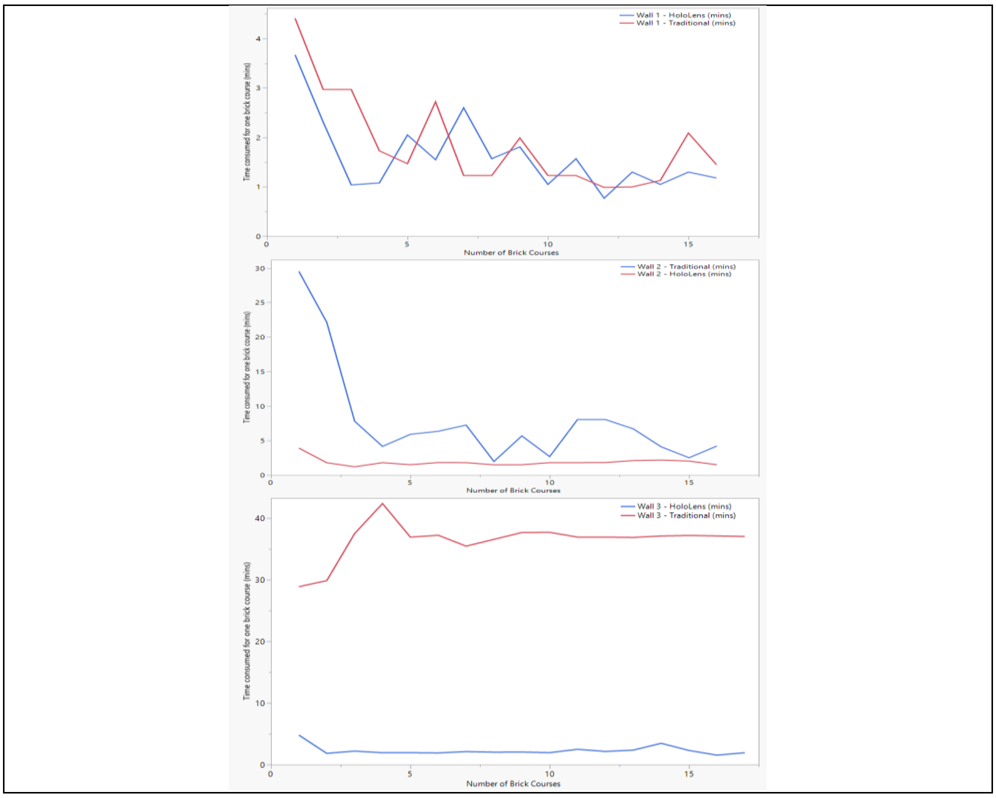

Fig. 8 Learning curve for construction

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V. CONCLUSION AND RECOMMENDATION

The aim of this study was to compare the productivity of constructing geometrically complex brick walls using traditional and IAR methods. Initially, a two-way ANOVA was chosen to examine the difference in the mean productivity of the traditional method and IAR method. However, the data violated assumptions of normality and homoscedasticity, and the effect test showed no interaction effect between wall type and construction method. Therefore, the effects of the two variables were separated and the mean productivity differences were analyzed using the non-parametric Wilcoxon Signed Rank Test. The test results showed that there was a statistically significant difference in productivity between the traditional and IAR construction methods. It was observed that the mean productivity decreased for both methods as the complexity of the wall design increased. However, the difference in mean productivity of the traditional construction method for the different walls was noticeably larger, varying from 6.61 minutes/brick to 49.4 minutes/brick, in comparison to the IAR method, which remained within the range of 2.0 to 2.5 minutes/brick. This could be because Wall Type 1 was much simpler and easier to build than Wall Type 3, in which every brick had a different angle of placement. The average productivity rate for placing bricks per minute using the IAR method was higher than that of the traditional method.

To improve the applicability of the study findings, it would be beneficial to replicate the experiment in outdoor environments and involve experienced personnel. This would eliminate accuracy issues due to participants' lack of experience and provide more robust results regarding the feasibility of using the device for constructing geometrically complex brick walls. While this study focused on brick wall construction, future research should also investigate the use of IAR for constructing other building materials, including drywall and elements such as columns. This would expand the potential use cases of IAR in the construction industry.

One of the primary constraints of this study was the definition of wall design complexity. [22] proposed five factors that could be manipulated to create different brick wall patterns. Designers could vary these factors to generate diverse design patterns with varying degrees of complexity. However, in this study, only the angle of brick placements in relation to the bonding plane was taken into account to introduce complexity in the design. Future studies should aim to develop a design that considers all five factors in order to validate the feasibility of using IAR for varying levels of complexity.

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