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Feasibility Studies of Augmented Reality for the Construction of Geometrically Complex Wall Designs

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Abstract: This study investigated the financial feasibility of using Augmented Reality in the construction of geometrically complex brick wall designs. Implementation Cost Analysis was conducted to determine the Cost Benefit Ratio (CBR) of AR use. The study involved the installation of three different brick walls with different curvature using AR and the traditional method. The results showed that the use of AR is financially feasible for geometrically complex brick walls. The CBR for Wall Type 1 (which was a straight wall) was 0.04, indicating the unfeasibility of using AR in the construction process. For the more complex walls (Wall Type 2 and Wall Type 3), the CBR increased almost ten times from Wall Type 2 (2.81) to Wall Type 3 (13.28), indicating that AR method is more feasible for more geometrically complex brick walls. The study found that using the AR construction method for the most geometrically complex brick wall (Wall Type 3) resulted in potential savings of $490.09 ($27.22/square feet) in the construction cost. Based on these findings, it is recommended to use AR in the construction of geometrically complex brick walls for cost savings. However, AR was found unfeasible for straight walls.

Keywords: Augmented Reality; Implementation Cost Analysis; Cost-Benefit-Analysis; Complex Design; HoloLens; Brick Wall.

I. INTRODUCTION

Augmented Reality (AR) has become more popular and commercially available. The research on AR applications has attracted significant interest since the mid-1990s, owing to the development of key enabling technologies, such as tracking, display, and interaction [1]. In recent years, several studies have focused on AR application in the construction industry [2] [3]. But as with any new technology, the adoption in the construction industry is not widespread compared to other industries such as manufacturing [4]. The full potential of virtual models, especially in the construction and operation phases, is largely unrealised [5] [6].

High initial and implementation costs have been mentioned as barriers to the widespread use of AR in construction [7]. Thus, the development of methods for estimating costs and the assessment of cost-benefit-ratios can help companies and stakeholders effectively make financial decisions of their investments in AR. One of such cost estimating methods is Implementation Cost Analysis, which involves identifying, measuring, and analyzing the expenses associated with introducing a new system, process, and technology including direct and indirect costs, to assess their impact on an organization's budget and overall effectiveness.

One area in construction where AR can have significant impact is in the construction of geometrically complex building structures. These designs are difficult to construct with traditional methods because they often require specialized fabrication techniques, precise detailing, and often involve non-standard materials and construction methods, leading to increased costs and potential challenges in execution. The ability of AR to use the existing environment and superimpose digital or virtual elements to appear as if both are together at the same time can potentially reduce or eliminate this difficulty [3].

To assist stakeholders and companies in deciding on the use of AR in the construction of complex designs, it is important to assess the ICA of AR application. In sum, this research seeks to empirically investigate the feasibility of using AR for the construction of geometrically complex designed brick walls using ICA.

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II. AUGMENTED REALITY IN CONSTRUCTION

Augmented Reality (AR) refers to superimposing computer-generated virtual objects over real objects/scenes to produce a mixed world. Users can acquire additional information of real world by rendering this mixed overlay in devices such as head mounted displays, see through glasses, and handheld monitors [8]. AR technologies have been used in various disciplines and arenas, e.g. engineering, construction, entertainment, aerospace, medicine, military, and automotive industry, as a frontline technology to meet visualization difficulties in their specific domain.

AR can be used in the construction industry for design communications, coordination, inspection, safety training, facility management, progress tracking, quality assurances, and more. [3] conducted a thorough review of studies published between 2012 and 2020 to examine trends of AR implementation in construction. They found most studies published for AR were in project progress monitoring and operation, followed by quality management and task instruction. Similarly, [9] found AR can be used for construction coordination, quality assurance and safety trainings. It can also help to improve construction productivity. [10] found that AR can improve construction productivity through monitoring, safety training, and design information. Other studies have shown that the use of AR can significantly improve cost and time efficiency [10].

One of the uses of AR 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 [11]. 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. Researchers had explored feasibility of AR under different environments for the complex design brick construction. [12] 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 AR system for feasibility, limitations, and implications during in-situ construction scenarios. [13] 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 [13].

[14] studied the application of AR in the Architecture, Engineering, and Construction (AEC) industry and have suggested its feasibility. They identified AR application areas in industrial construction based on suitability of AR technologies. In order to successfully explore suitability of AR, the paper assesses work tasks from the viewpoint of human factors regarding visual information requirements to find rationale for the benefits of AR in work tasks. The comprehensive map reveals that eight work tasks (layout, excavation, positioning, inspection, coordination, supervision, commenting, and strategizing) out of 17 classified work tasks may potentially benefit from AR support [14].

[15] provided a detailed review of AR in the AEC industry, and gave a review of several major research efforts prior to 2009 and categorizes various AR technologies with their advantages and disadvantages [15].

The above listed studies indicate studies have been conducted on the application of AR in different areas of construction. However, the application of AR in construction is still at its infancy stage. This paper adds to the existing literature by reviewing the financial feasibility of AR application in the construction of geometrically complex designs.

III. IMPLEMENTATION COST ANALYSIS

Despite the many potential benefits of using AR, high implementation cost is still considered as one of the major barriers in the adoption of the technology [9]. Researchers suggest that the cost savings and benefits, in terms of both time and money, that can be achieved by using AR should be demonstrated through field experiments and case studies [7]. Till this date, there is a research gap for analyzing the implementation cost of using AR with that of traditional method for the construction of geometrically complex designed structures.

IV. METHODOLOGY

To examine implementation cost differences and potential cost benefits of using AR over the traditional construction method, three different types of walls, shown in Figure 1, were constructed using both AR method (HoloLens 2) and the traditional method. The AR technology used in this study was Fologram and HoloLens 2.

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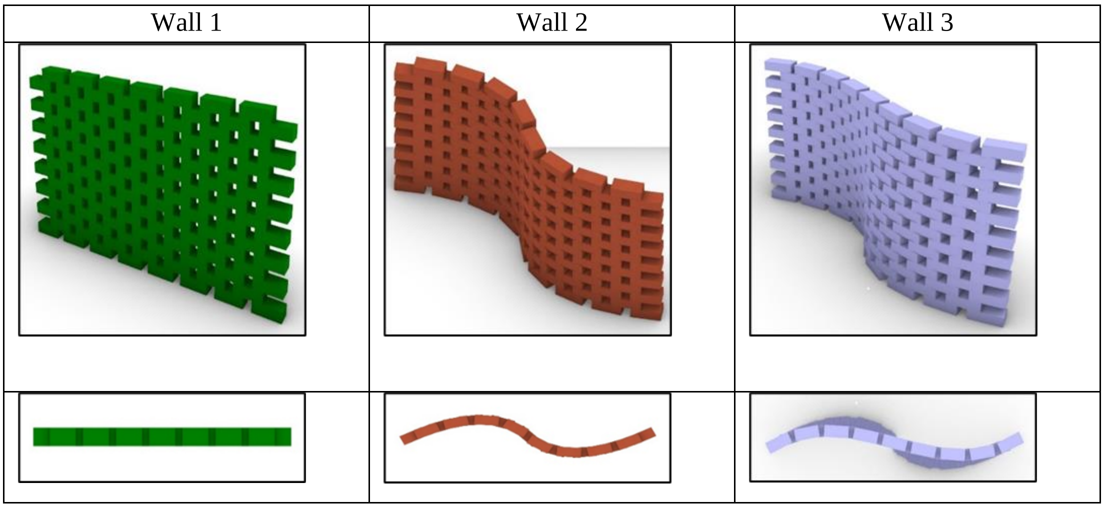

Fig. 1 Types of Brick Wall

The dimensions of all three walls were kept the same, i.e., 6 feet in length and 3 feet in height, with a running bond between courses (see Table I). 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 1 above). 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 AR session, participants learned how to load a 3D model in Fologram, established a connection between HoloLens 2 and Fologram, navigated the software, and loaded an on-site model.

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. The process of construction was recorded for analysis.

The number of minutes used by a participant to place a single brick for both the traditional and IAR methods was recorded. During the initial testing of the AR 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 of the study, 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.

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V. INSTALLATION DURATIONS

Table II illustrates the total durations for the completion of the walls using AR and traditional method. For Wall Type 1, it was observed that the total durations of the traditional and AR methods were relatively close at 30 minutes (0.50 hours) and 25.8 minutes (0.43 hours) respectively. Initially, the AR 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.

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 AR method. The traditional method had a longer initial learning curve as participants spent more time on bricklaying compared to the AR method. 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 AR 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 AR 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.

TABLE II. COMPLETION DURATIONS

	Wall Type 1	Wall Type 2	Wall Type 3
AR (HoloLens)	25.8 minutes	30 minutes	39 minutes
Traditional	30 minutes	127.2 minutes	619.2 minutes

VI. IMPLEMENTATION COST ANALYSIS

The purpose of the ICA was to investigate the feasibility of using an AR for constructing geometrically complex designed brick walls. The analysis consisted of three steps: data collection, data evaluation, and the calculation of the cost-benefit ratio (CBR). The CBR is the ratio of the potential cost savings achieved through reduced working hours and the implementation cost of the AR for the construction of geometrically complex designed brick walls. In this study, Fologram, a relatively new software, was used to transmit 3D models designed in Rhino to the HoloLens 2.

The process of creating 3D models using Rhino is the same for both the traditional and AR methods. Loading time into Fologram was considered as part of the construction time for the AR method. Therefore, the design durations for both the traditional and AR methods were the same. Hence, the ICA was focused on the construction phase. The cost data for the ICA was collected from various sources. Currently, the HoloLens 2 device can be rented at a monthly rate of 749 USD. Additionally, the Fologram monthly subscription costs 199 USD [16]. These costs were converted into hourly costs for analysis based on 50 working weeks and 40 working hours per week in a calendar year (i.e., 166.67 hours).

- MHC = Per hour HoloLens 2 cost = 4.49 ($/hr)
- SC = Per hour Fologram subscription cost = 1.19 ($/hr)
- OC = Other equipment required for traditional construction = 0.00 ($/hr)

According to the Bricklayers Union on Indeed.com, one of the largest job listing platforms, the average hourly wage for a Brick Mason in the United States is 23.28 $/hr, with a high of 42.50 $/hr [17] (BrickLayers Union, 2023). The average hourly wage for a Brick Mason helper in the United States is 16.00 $/hr [18].

Thirty percent of fringe benefits were added to the labor cost per hour. It was assumed that tool charges like measuring tape, bubble level, and angle reader required for traditional construction were included in the labor cost.

- LC = Labor and helper cost = 23.28 + 16.00 = 39.28 ($/hr)
- 30% Fringe Benefits = LC + (30% * LC) = 51.06 ($/hr)

Table III represents the construction cost, total time, and total construction cost for all three wall types built using traditional and AR methods.

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TABLE III. TOTAL CONSTRUCTION COST AND TIME

Description	Wall 1			
	C_{TM}	T_{TM}	C_{AR}	T_{AR}
Cost for traditional construction method: $C_{TM} = LC + OC$	51.06 ($/hr)	0.50 (hr)		
Cost for IAR method: $C_{IAR} = LC + MHC + SC + OC$			56.75 ($/hr)	0.43 (hr)
Total Cost for traditional construction method: $TC_{TM} = C_{TM} \times T_{TM}$	25.53 ($)			
Total Cost for IAR method: $TC_{AR} = C_{AR} \times T_{AR}$			24.40 ($)	
	Wall 2			
	C_{TM}	T_{TM}	C_{AR}	T_{AR}
Cost for traditional construction method: $C_{TM} = LC + OC$	51.06 ($/hr)	2.12 (hr)		
Cost for IAR method: $C_{AR} = LC + MHC + SC + OC$			56.75 ($/hr)	0.50 (hr)
Total Cost for traditional construction method: $TC_{TM} = C_{TM} \times T_{TM}$	108.26 ($)			
Total Cost for IAR method: $TC_{AR} = C_{AR} \times T_{AR}$			28.38 ($)	
	Wall 3			
	C_{TM}	T_{TM}	C_{AR}	T_{AR}
Cost for traditional construction method: $C_{TM} = LC + OC$	51.06 ($/hr)	10.32 (hr)		
Cost for IAR method: $C_{IAR} = LC + MHC + SC + OC$			56.75 ($/hr)	0.65 (hr)
Total Cost for traditional construction method: $TC_{TM} = C_{TM} \times T_{TM}$	526.98 ($)			
Total Cost for IAR method: $TC_{IAR} = C_{AR} \times T_{AR}$			36.89 ($)	

- T_{TM} = Time consumed to complete the task using traditional method (in hours).
- T_{IAR} = Time consumed to complete the task using AR method (in hours).
- C_{TM} = Per hour cost for traditional method
- C_{AR} = Per hour cost for AR method

The time difference (T_{Δ}) between traditional method (T_{TM}) and AR method (T_{AR}) represents potential work hours reduced by using the HoloLens 2. The C_{Δ} represents the per hour labor cost difference between traditional (C_{TM}) and AR (C_{AR}) construction method (see Table IV).

TABLE IV. TOTAL TIME AND COST DIFFERENCE

Description	Wall 1	Wall 2	Wall 3
$T_{\Delta} = TC_{TM} - TC_{AR}$	0.07 (hr)	1.62 (hrs)	9.67 (hrs)
$C_{\Delta} = C_{AR} - C_{TM}$	5.69 ($/hr)	5.69 ($/hr)	5.69 ($/hr)

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VII. RESULTS AND ANALYSIS

The benefits of using AR for complex design construction were estimated in terms of total savings. There were two factors taken into consideration to calculate the potential total savings (TS). First, the AR method allowed significant reduction in construction time in comparison to the traditional method. This is cost obtained by multiplying total time (T_Δ) difference with per hour traditional method cost (C_{TM}). Second, the AR method reduced the construction time indicating potential savings. However, on other hand it is more expensive than the traditional method. The cost difference between the AR and traditional method was deducted from the total time (T_Δ) difference with per hour traditional method cost (C_{TM}) to obtain potential savings. The cost difference was calculated by multiplying time consumed to complete the construction using AR method (T_{AR}) with cost difference between two methods (C_Δ). The final cost (TS) is the potential savings of using the AR method of construction over the traditional method (see Table V).

TABLE V. TOTAL SAVINGS

Total Savings	Wall 1	Wall 2	Wall 3
TS = ($T_\Delta \times C_{TM}$) – ($T_{IAR} \times C_\Delta$)	1.13 ($)	79.88 ($)	490.09 ($)

The total savings were then divided by the total cost of implementing AR construction method to determine the CBR. The value of a CBR less than 1.0 indicates an unfeasible investment, a value equal to 1.0 indicates a break-even for an investment, and a value greater than 1.0 indicates that investment benefits are more than the investment cost.

Table VI represents the CBR of implementing AR for complex design construction for all the three wall types. The CBR value for Wall Type 1 is less than 1.0, which shows that it is not feasible for contractors to use AR method for the construction of Wall Type 1. This may be because Wall Type 1 was a straight wall that could be built without necessarily using technology. The CBR values for Wall Type 2 and 3 were 2.81 and 13.28, respectively. The CBR value for Wall Type 2 (2.81) indicates that the potential benefits of using AR method is more than twice the cost, while the CBR value for Wall Type 3 (13.28) indicates that the potential benefits are thirteen times the cost [19]. This result showed that the feasibility of using AR construction method increases with increase in complexity of the wall design.

TABLE VI. COST-BENEFIT RATIO

Cost-Benefit Ratio	Wall 1	Wall 2	Wall 3
CBR = Total Saving (TS) ÷ Total Cost of AR Construction (TC_{AR})	0.04	2.81	13.28

VIII. CONCLUSIONS AND RECOMMENDATIONS

The aim of this study was to perform a financial feasibility of using AR method in the construction of geometrically complex wall designs. ICA was conducted to determine the CBR of AR use in the study.

The results showed that the use of AR method is financially feasible for geometrically complex brick walls. The CBR for Wall Type 1 (which was a straight wall) was 0.04, indicating the unfeasibility of using AR in the construction process. Also, the total construction time for both methods were close to each other, 0.50 hours for AR method and 0.43 hours for traditional method. This may be attributed to the fact that Wall Type 1 was a straight wall that did not require the use of AR method. For the more complex walls (Wall Type 2 and Wall Type 3), the CBR increased almost ten times from Wall Type 2 (2.81) to Wall Type 3 (13.28), indicating that AR method is more feasible for more geometrically complex brick walls. The study found that using the IAR construction method for the most geometrically complex brick wall (Wall Type 3) resulted in potential savings of $490.09 ($27.22/square feet) in the construction cost. The total time to complete the Wall Type 3 with AR method was less than one hour in comparison to the traditional method, which was more than 10 hours. Based on these findings, it is recommended to use AR in the construction of geometrically complex brick walls for improved productivity, time efficiency, and cost savings. However, the technology use was found unfeasible for straight walls.

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.

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While this study focused on brick wall construction, future research should also investigate the use of AR for constructing other building materials, including drywall and elements such as columns. This would expand the potential use cases of AR in the construction industry. Future research should also consider developing a predictor model based on the ICA findings, which indicate that the financial feasibility of the technology increase with the complexity of the brick wall designs.

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