Development of an Augmented Reality Fitness Index for Contractors

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Abstract –

Construction, one of the most information-intensive industries, plays a vital role in the prosperity of nations and is expected to grow to new heights. This significant expansion, along with the increased complexity and sophistication of construction projects and rapid advances in emerging technologies, has fueled construction companies' interest in innovation as a source of competitive advantage. Augmented Reality (AR), a pillar of Industry 4.0, is an emerging technology that is gaining traction in construction. AR can be described as both an information aggregator and a data publishing platform that allows the user to (1) passively view displayed information, (2) actively engage and interact with published content, and (3) collaborate with others in real-time from remote locations. The objective of this paper is to develop an Augmented Reality Fitness Index (ARFI) to assess the suitability and applicability of AR for contractors in the construction industry. The rationale behind the proposed index is to understand the perception of stakeholders regarding the eligibility of AR in the construction industry and to investigate the potential degree of usage of AR throughout the seven phases of the lifecycle of a construction project: conceptual planning, design, pre-construction planning, construction, commissioning, operation and maintenance, and decommissioning. From the literature review, 43 AR use-cases were identified and grouped into the seven phases of a construction project. A survey was then developed to capture contractors' level of familiarity with AR in construction, level of usage of AR in construction, and perceived possible use of each AR use-cases. Next, contractors' perceived relevance of each of the 43 AR use-cases was obtained by surveying a group of subject matter experts. Using the collected data, a mathematical model was developed to compute an ARFI for each phase. The computed ARFI is used as an indication to guide the implementation of AR in construction.

Keywords –

Augmented Reality; Fitness Index; Contractors; Mathematical Model

1 Introduction

Construction, one of the most information-intensive industries, is a major contributor to the prosperity of nations and a sector that is expected to continue to grow [1]. This growth, along with the increased complexity of construction projects and rapid advances in digital technologies, heralds an increased interest by construction companies to innovate and transform their business-as-usual to remain competitive [2]–[5]. One emerging technology that is gaining interest in construction is Augmented Reality (AR). AR, a pillar of the fourth industrial revolution (Industry 4.0), both an information aggregator and a data publishing platform that allows the user to (1) passively view displayed information, (2) actively engage and interact with published content, and (3) collaborate with others in real-time from remote locations [1].

Various research efforts have investigated the potential use and impact of AR on construction projects. Some studies explored AR use-cases in specific phases of the construction project lifecycle, and others developed prototypes to investigate the impact AR on construction projects. While these efforts are critical to understanding the potential of the technology, they don't measure the degree of fitness of AR in construction. Therefore, the objective of this paper is to develop an Augmented Reality Fitness Index (ARFI) to assess the suitability and applicability of AR throughout the construction project lifecycle, using data collected from contractors.

2 Research Methodology

The methodology employed to fulfill the main goal of the research encompasses the following sub-goals. First, a comprehensive and thorough review of the existing literature is conducted to extract AR use-cases. These AR use-cases are then mapped across the project lifecycle. The lifecycle of a construction project consists of a series of phases, and the literature review showed that there is no single definition for what the phases are. The project phases adopted in this research are those introduced by [6] and are as follows: 1) Conceptual Planning, 2) Design, 3) Pre-Construction Planning, 4) Construction, 5) Commissioning, 6) Operation and Maintenance, and 7) Decommissioning. Once the AR use-cases were identified, a survey was developed and distributed to contractors to collect their perception of AR in construction. The data collected from the survey was then analyzed, and a mathematical model was developed to compute an Augmented Reality Fitness Index for each phase of the construction project lifecycle.

3 Augmented Reality Use-Cases

Research studies by [7]–[35] were reviewed, and 43 AR use-cases were identified and grouped into the seven AR phases, as shown below. *P1* is Conceptual Planning, *P2* is Design, *P3* is Pre-Construction Planning, *P4* is Construction, *P5* is Commissioning, *P6* is Operation and Maintenance, and *P7* is Decommissioning:

P1 Real-time visualization of conceptual projects
P1 Overlaying 4D content into real-world (or physical objects) such as traffic flow, wind flow, etc.
P1 An understanding of how the desired project connects with its surroundings
P2 Overlay of 3D models over 2D plans (i.e. Design [or project] visualization in the office over 2D plans)
P2 Design (Project) visualization at full scale on-site
P2 Virtual tours for clients while on-site or in the office (AR walk-through)
P2 Real-time design change (material selection, design functionalities)
P3 Clash detection
P3 Early identification of design errors
P3 Constructability Reviews during design
P3 Full-scale site logistics (virtually locate equipment, trailers, laydown areas, storage, etc.)
P3 Space Validation and Engineering Constraints Checks (collaboratively locate and operate virtual construction equipment, such as cranes)
P3 Virtual planning and sequencing
P3 Safety orientation (do safety orientation in an augmented virtual environment)
P3 AR-simulation based safety training programs for workers
P4 Visualizing layout and integration of prefab components in the shop
P4 Site layout without physical drawings
P4 4D Simulations on-site (augmented simulated construction operations)
P4 Monitoring the progression of workflow and sequence
P4 Visualization of augmented drawings in the field
P4 On-site inspections
P4 Remote site inspection
P4 Visualization of underground utilities
P4 Visualization of the proposed excavation area
P4 Visualization of the construction systems/work (i.e. MEP, structural, etc.)
P4 Planning the positioning and movement of heavy/irregular objects/equipment
P4 Real-time support of field personnel
P4 On-site safety precautions (site navigation and in-situ safety warning)
P4 Augmented Mock-ups
P4 Construction progress visualization and monitoring
P4 On-site material tracking
P4 Create design alternatives on-site
P4 Visualization of augmented work instructions/manuals/procedures in the field
P4 Real-time visualization, review, and analysis of data associated with a particular worker, equipment, construction system, etc.
P5 On-site inspection/Punchlists
P5 Remote site inspection
P6 Availability of Maintenance information
P6 Locate building systems that need maintenance without destructive demolition or further survey work
P6 Refurbishment visualization
P6 Real-time support of engineers and technicians
P6 Training for maintenance and repair
P7 Remodeling visualization
P7 Evaluation of the new facility/installations over the existing one

4 Data Collection

4.1 Survey

Once the 43 AR use-cases were identified, a survey was developed, tested, and distributed to contractors. The survey was designed to capture the following data:

1. Respondent's level of familiarity of AR in the context of the construction industry measured on the following scale: (0) never heard of it; (1) vaguely heard of the term before; (2) basic understanding; (3) good understanding; and (4) very good understanding.
2. Respondent's level of usage of AR in the context of the construction industry measured on the following scale: (0) have not experienced AR before and not interested in the technology; (1) have not

experienced AR before but interested in the technology; (2) explored/ exploring AR applications; (3) tested/ testing AR applications; and (4) have used AR on at least one construction project.

3. Contractor's approximate average annual revenue in the last three years (measure in U.S. dollars).
4. Respondent's perceived level of usage of each of the 43 AR use cases measured on a five-point Likert scale of (1) very low; (2) low; (3) moderate; (4) high; and (5) very high. Respondents could also select "N/A" (coded as 0) if they don't think an AR use-case will be used.

4.2 Data Characteristics

A total of 46 responses were collected. Survey results showed that 13% of respondents had vaguely heard of AR, 2% had a basic understanding, 14% had a good understanding, and the remaining 17% had a very good understanding of the technology. When asked about their usage of AR in construction, 13% indicated that they had not experienced AR before but are interested, 8% stated that they had explored/are exploring AR applications, 11% mentioned that they had tested/are testing AR application, and the remaining 14% reported that they had used AR on at least one construction project. It should be noted that none of the respondents indicated that they had not heard of AR before or are not interested in the technology, proving that AR is a promising technology in construction.

4.3 Data Analysis

Researchers indicated that the perception of users of a technology is influenced by the users' familiarity and degree of usage of the technology [36], [37]. Therefore, before developing the mathematical model, the relationship between:

1. The respondent's perception of an AR use-case and the respondent's familiarity with AR
2. The respondent's perception of an AR use-case and the respondent's usage of AR

were evaluated using the Kruskal-Wallis H test and Kendall's tau-b. Additionally, the impact of the economic volume of the respondents (i.e. average annual revenue) on the respondent's perception of an AR use-case was also investigated using Kruskal-Wallis H test.

The analysis of these three relationships resulted in significant p-values, providing statistical evidence at the 95% confidence level that the respondent's perceived level of usage of each AR use-case differs across the different levels of familiarity and usage of AR and the economic volume of the company.

5 Augmented Reality Fitness Index (ARFI)

The objective is to develop an Augmented Reality Fitness Index (ARFI) to assess the suitability and applicability of AR in the construction industry using contractors' data. Using the data collected for the survey and the statistical relationships that were identified in the previous sections, this section outlines the steps undertaken to develop the mathematical model.

5.1 Motivation

ARFI is a proposed measure on a normalized scale from 0 to 1 of the usage potential of AR in a particular construction phase and throughout the lifecycle of a construction project. The rationale behind the proposed index is to understand the perception of contractors regarding the eligibility of AR in the construction industry and to investigate the potential degree of usage of AR throughout the seven phases of the lifecycle of a construction project. ARFI in each phase is computed as a weighted average of the usage potential of the technology's identified use-cases in that phase and based the perceived relevance of each use-case.

The usage potential (UP_j) of an AR use-case j is calculated as a weighted average of the perceived possible use of this use-case in its corresponding phase obtained from the survey. However, this variable is subjective by nature and differs among respondents. To reduce the influence of this subjectivity, the perceived possible use of an AR use-case j is, therefore, subsequently weighted based on three variables: familiarity with AR, current usage of AR, and economic volume of the respondent. These three variables are combined into one variable, namely the response weight (w_i), which is used to weigh the perceived possible use of an AR use-case corresponding to respondent i.

Contractors' perceived relevance of an AR use-case j was obtained by surveying a group of subject matter experts on each of the 43 identified use-cases.

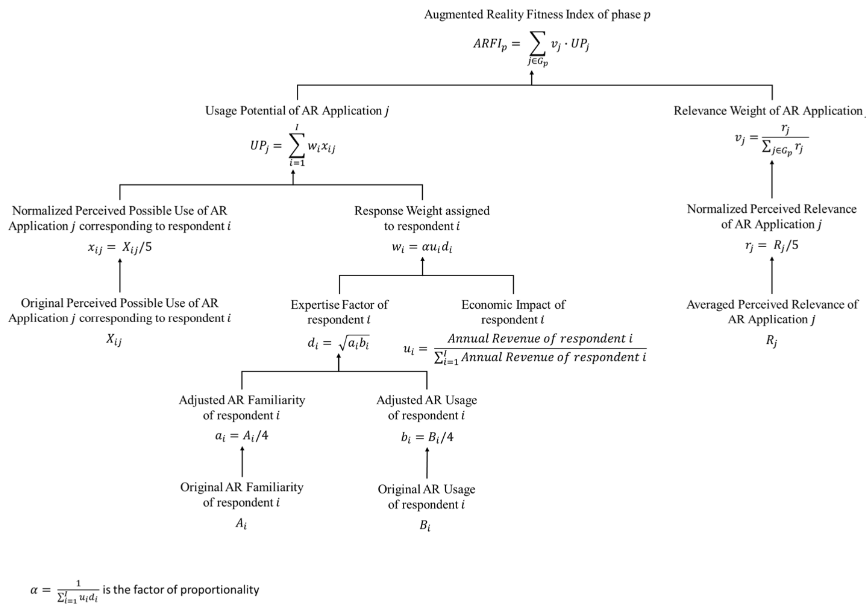

Figure 1. Breakdown of the Augmented Reality Fitness Index Mathematical Model

5.2 Mathematical Formulation

The model computes for each phase p of the lifecycle of a construction project a corresponding Augmented Reality Fitness Index, $ARFI_p$.

$ARFI_p$ is based on the evaluation of the weighted usage potential of a set of AR use-cases in phase p. In the following, J denotes the total number of AR use-cases ($J = 43$), and G_p (with $1 \leq p \leq 7$) denotes the disjoint sets of AR use-cases within a phase p, with:
$G_1 \cup G_2 \cup G_3 \cup G_4 \cup G_5 \cup G_6 \cup G_7 = \{1, 2, 3, \dots, 43\}$,
where:
$G_1 = \{1, 2, 3\}$, $G_2 = \{4, 5, 6, 7\}$, $G_3 = \{8, 9, \dots, 15\}$, $G_4 = \{16, 17, \dots, 33\}$, $G_5 = \{34, 35\}$, $G_6 = \{36, 37, \dots, 41\}$, and $G_7 = \{41, 42\}$ represent the sets of AR use-cases in the Planning Phase, Design Phase, Pre-Construction Phase, Construction Phase, Commissioning Phase, Operation and Maintenance Phase, and Decommissioning Phase, respectively.

The model used to calculate $ARFI_p$ is defined as:

$$ARFI_p = \sum_{j \in G_p} v_j \cdot UP_j \tag{1}$$

where:

- p denotes the number of phases of the lifecycle of a construction project ($1 \leq p \leq 7$),
- UP_j denotes the usage potential of AR use-case j, and
- v_j denotes the relevance weight of AR use-case j, with $v_j \geq 0$ and $\sum_{j \in G_p} v_j = 1$.

The underlying assumption here is that the index $ARFI_p$ solely depends on the AR use-cases in phase p. To compute this index, we need to determine the values of UP_j and v_j.

5.2.1 Usage Potential of AR Use-case *j*

The Usage Potential of AR of use-case j is defined as:

$$UP_j = \sum_{i=1}^{I} w_i x_{ij} \tag{2}$$

where:

- I denotes the number of respondents,
- x_{ij} denotes the normalized perceived possible use of an AR Use-case j corresponding to respondent i. These normalized values are calculated using $x_{ij} = X_{ij}/5$, with X_{ij} being the original perceived impact of a barrier k corresponding to respondent i, where $X_{ij} \in \{0, 1, 2, 3, 4, 5\}$. And,
- w_i is a response weight assigned to respondent i, with $\sum_{i=1}^{I} w_i = 1$.
- w_i is computed based on the following four variables, A_i, B_i, and u_i, where:
- A_i is the AR familiarity of respondent i, with $A_i = \{0, 1, 2, 3, 4\}$,
- B_i is the AR Usage of respondent i, with $B_i = \{0, 1, 2, 3, 4\}$, and
- u_i is the economic impact of respondent i, with

$$u_i = \frac{Annual\ Revenue\ of\ respondent\ i}{\sum_{i=1}^{I} Annual\ Revenue\ of\ respondent\ i}$$

It should be noted that none of the respondents selected 0, and therefore, original values did not need to be adjusted to account for zeroes. Original values were normalized, and as a result, the following variables are defined:

- a_i is the adjusted AR familiarity of respondent i, where $a_i = A_i/4$, so $a_i \in \{0.25, 0.5, 0.75, 1\}$, and
- b_i is the adjusted AR Usage of respondent i, where $b_i = B_i/4$, so $b_i \in \{0.25, 0.5, 0.75, 1\}$.

The variables a_i, and b_i are then combined into a new variable, d_i, which represents the "expertise factor" of respondent i. d_i is calculated as the geometric mean of a_i and b_i, i.e.

$$d_i = \sqrt{a_i b_i}.$$

As shown in Figure 2 the geometric mean (right) gives smaller weights to respondents with lower expertise in comparison to the arithmetic mean (left).

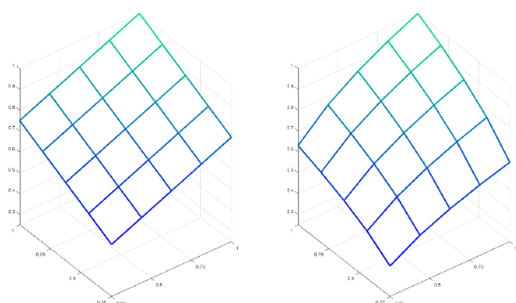

Figure 2. Effect of Using geometric mean on the expertise factor, d_i, for $a_i = 1$

For each respondent i, w_i is then assumed to be proportional to u_i (their economic impact) and d_i (their expertise factor). Therefore:

$$w_i = \alpha u_i\, d_i$$

α is then calculated by:

$$1 = \sum_{i=1}^{I} w_i = \alpha \sum_{i=1}^{I} u_i d_i.$$

Thus,

$$\alpha = \frac{1}{\sum_{i=1}^{I} u_i d_i}$$

and,

$$w_i = \frac{u_i d_i}{\sum_{i=1}^{I} u_i d_i} = \frac{u_i \sqrt{a_i b_i.}}{\sum_{i=1}^{I} u_i \sqrt{a_i b_i.}} \quad (3)$$

5.2.2 Perceived Relevance of AR Use-case *j*

The Usage Potential of an AR use-case j, UP_j, obtained from equation (2) is then weighted using the perceived relevance of that AR use-case j. R_j denotes the perceived relevance of each AR Use-case j obtained by averaging the responses of a group of 10 subject matter experts, where $0 \le R_j \le 5$. These rates were then normalized to r_j, with $0 \le r_j \le 1$. Therefore, for each AR use-case j, $r_j = R_j/5$.

For each AR use-case j, the relevance weight v_j is assumed to be proportional to r_j. Therefore, $v_j = \beta r_j$, and similar to α, β is calculated by:

$$\beta = \frac{1}{\sum_{j \in G_p} r_j}$$

thus,

$$v_J = \frac{r_j}{\sum_{j \in G_p} r_j} \quad (4)$$

Consequently,

$$ARFI_p = \sum_{j \in G_p} \frac{r_j}{\sum_{j \in G_p} r_j} \sum_{i=1}^{I} \frac{u_i \sqrt{a_i b_i.}}{\sum_{i=1}^{I} u_i \sqrt{a_i b_i.}} x_{ij} \quad (5)$$

5.3 Model Validation

The objective of the mathematical model is to reduce the subjectivity of the data by adjusting the answers of the respondents based on their level of familiarity and usage of AR in construction. An important question arises as to how to prove that the methodology employed to develop the model is effective. [38] noted that simulations provide a powerful technique for answering this question. Therefore, a simulation study was designed to evaluate the mathematical model developed and to compare it to competing approaches, i.e. using the arithmetic mean instead of geometric. The objective of the simulation is to prove that the values computed from the model are more representative than the observed raw data collected from the survey.

The Latin-Hypercube Sampling (LHS) experimental design technique in Python was used to run the simulation 1,000 times in a Monte Carlo Fashion.

Four datasets are generated in this simulation: the assumed *true* dataset, the *observed* dataset, the *arithmetic-based modeled* dataset, and the *geometric-based modeled* dataset. The *observed* dataset was generated by adding noise to the *true* dataset, and it represents the data collected from the survey. The *arithmetic-based modeled* dataset was generated by adjusting the *observed* dataset using the arithmetic mean (i.e. $d_i = \frac{a_i+b_i}{2}$). The *geometric-based modeled* dataset was generated by adjusting the *observed* dataset using the geometric mean (i.e. $d_i = \sqrt{a_i b_i}$).

In order to evaluate the effectiveness of each model, the squared deviations between 1) *observed* and *true* values, 2) *arithmetic-based modeled* and *true* values, and 3) *geometric-based modeled* and *true* values were calculated. Results showed that the deviation between the *geometric-based modeled* and *true* values is statistically significantly less than the other two deviations, justifying the use of the geometric mean.

6 Discussions

ARFI in each phase is computed using equation (5), and the values are displayed in Table 1 and illustrated in Figure 3.

Table 1. $ARFI$ values for each phase

Phase	ARFI
Conceptual Planning	0.743
Design	0.768
Pre-Construction Planning	0.719
Construction	0.709
Commissioning	0.589
Operation and Maintenance	0.701
Decommissioning	0.646

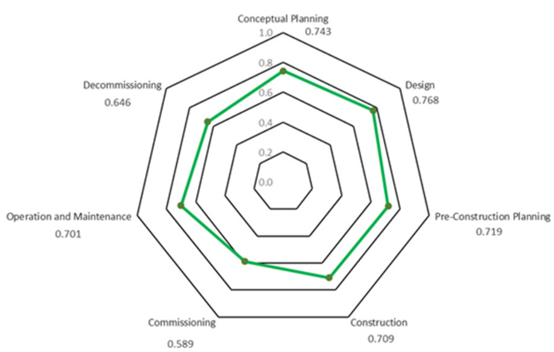

Figure 3. A radar chart of $ARFI$ values throughout the construction project lifecycle

It can be shown from Table 1 and Figure 3 that all ARFI values are greater than 0.5 indicating the potential of AR in construction. According to contractors, AR is perceived as the highest fitness index in Design (0.743), followed by Conceptual Planning (0.743), Pre-Construction Planning (0.719), Construction (0.709), Operation and Maintenance (0.701), Decommissioning (0.646), and finally commissioning (0.589).

These results highlight the importance of integrating AR throughout the entire lifecycle, placing a greater emphasis on early phases. Although the ARFI values were computed from the perspective of contractors, the construction phases – which traditionally is the most relevant phase for contractors – did not have the highest ARFI value. This shows that contractors are aware of the need to integrate AR early in the project for the later project phases to reap the benefits. The results also suggest that the construction industry is shifting the traditional delivery systems as contractors' involvement and engagement in the early phases of the project is increasing.

7 Conclusions

AR is a promising technology in the construction industry. While previous research efforts have investigated specific AR use-cases, this paper investigated the fitness and applicability of AR throughout the seven phases of the construction project lifecycle. Forty-three AR applications were identified from the extant literature and were grouped into the seven phases. Next, a survey was developed to collect contractors' perceptions of the potential of AR in construction, and 46 responses were collected. Data summary showed that all respondents had some level of familiarity with AR in the context of the construction industry, and the majority had previously used the technology to some extent. Statistical analyses showed that the respondent's perception of the potential use of an AR use-cases depends on three variables: 1) the respondent's familiarity with AR, 2) the respondent's usage of AR, and 3) the company's economic volume. A mathematical model, ARFI, was then developed to compute an AR fitness score between 0 and 1 for each phase of the project lifecycle. The calculated ARFI values were all greater than 0.5, indicating that AR can be well integrated into all phases. Additionally, while ARFI was developed using contractors' data, construction did not have the highest ARFI value. Early project phases, namely design, conceptual planning, and pre-construction planning, had an ARFI score slightly higher than construction, indicating contractors' awareness of the potential of AR and increased involvement in early phases. Future work can survey other stakeholders, including Architect/Engineers, subcontractors, facility managers, and owners, and investigate variations of stakeholders' perceptions of the fitness of AR.

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