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AUGMENTED REALITY (AR) IN THE MANUFACTURING PHASES OF OFF-SITE CONSTRUCTION PROJECTS

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ABSTRACT: This paper investigates the integration of Augmented Reality (AR) technology into the manufacturing phases of off-site construction projects, with a specific focus on the Canadian construction industry. Through a comprehensive systematic literature review and semi-structured interviews, the study identifies the benefits and barriers associated with adopting AR to enhance visualization, collaboration, and decision-making during project execution. The survey involves key stakeholders, including construction managers, architects, engineers, contractors, and subcontractors, capturing their experiences and perceptions of AR technology. The findings highlight significant benefits such as improved real-time collaboration, enhanced safety, reduced errors and rework, increased project efficiency, and higher client satisfaction. AR's capability to overlay precise spatial information onto real-world environments is identified as a transformative advantage in off-site construction workflows. At the same time, the study addresses notable challenges to AR adoption, including high initial investment costs, a lack of skilled personnel, compatibility issues with existing software systems, and concerns about data security and privacy. Resistance to change and the evolving maturity of AR technology are also cited as key obstacles. This paper provides a balanced perspective on the current state of AR adoption in the Canadian off-site construction industry. The findings aim to inform stakeholders and guide future strategies for integrating AR technology to improve the efficiency, safety, and quality of off-site construction projects.

Keywords: Off-site Construction (OSC), Augmented Reality (AR), Manufacturing, Correlation analysis

1. INTRODUCTION

The construction industry is undergoing a significant transformation driven by technological advancements, particularly in the realm of digital tools and immersive technologies. Among these, Augmented Reality (AR) has emerged as a promising innovation with the potential to revolutionize various phases of construction projects(Ahmed et al., 2017). Off-site construction (OSC), characterized by the prefabrication and modular assembly of building components in controlled environments, offers numerous advantages such as improved quality control, reduced construction timelines, and minimized on-site disruptions (Goulding & Rahimian, 2019). However, the complexity of coordinating manufacturing processes, ensuring precision in assembly, and maintaining effective communication among stakeholders presents ongoing challenges (Assaad et al., 2023). AR technology, which overlays digital information onto the physical environment, has the potential to address these challenges by enhancing visualization, collaboration, and decision-making

throughout different phase of project including manufacturing phases of OSC projects (Nassereddine et al., 2022).

Despite its potential, the adoption of AR and its integration with Building Information Modelling (BIM) in the construction industry, particularly in the off-site manufacturing phase, remains limited. Furthermore, the construction industry's traditional resistance to change and the evolving maturity of AR technology pose additional barriers to its widespread adoption (AL-Dhaimesh & Taib, 2023).

This paper investigates the integration of AR technology into the manufacturing phases of off-site construction projects, with a specific focus on the Canadian construction industry. The study aims to identify and assess the key benefits and barriers associated with AR adoption, drawing on insights from a comprehensive survey of industry stakeholders, including construction managers, architects, engineers, contractors, and subcontractors. By capturing their experiences and perceptions, the research provides a balanced perspective on the current state of AR adoption in the Canadian OSC sector.

2. METHODOLOGY

2.1 Research Approach

This study employs a mixed-methods research approach to evaluate the benefits and barriers of AR in the manufacturing phases of OSC projects in Canada. A combination of a systematic literature review and a structured survey was used to gather qualitative and quantitative data from industry professionals.

2.2 Systematic Literature Review (SLR) and PRISMA Framework

To systematically identify the benefits and barriers of AR in OSC, a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach was employed. The process began with the identification of relevant academic papers, industry reports, and conference proceedings from databases such as Scopus, Web of Science, and Google Scholar, using predefined search terms. An initial query (limited to articles and conference papers in English from 2015 to 2025) yielded 1,395 documents. In the screening phase, duplicates and irrelevant studies were removed based on title and abstract relevance to AR applications in construction. The eligibility stage further refined the selection based on inclusion and exclusion criteria, considering only peer-reviewed articles and high-impact industry reports. Finally, 24 studies were selected for analysis, with 6 additional articles incorporated during the review process, bringing the total to 30. A PRISMA flow diagram (Figure 1) was developed to visualize the selection process and ensure transparency in the literature review methodology.
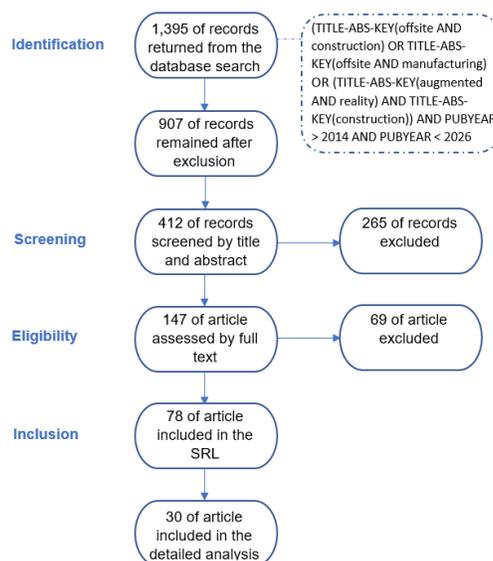

Figure 1: PRISMA flow diagram of the study

The Keyword Co-Occurrence Network, generated using VOSviewer (Figure 2), provides a structured view of key research themes on AR in construction. The network reveals AR's growing role in collaboration, precision, efficiency, and workforce training, while also highlighting gaps in technology integration, cost, and adoption. At the core of the analysis, AR stands out as the dominant theme, strongly connected to concepts such as mixed reality, virtual reality, visualization, and robotics. The presence of these connections underscores the industry's interest in integrating AR with immersive digital environments and automated systems. The construction industry emerges as another crucial node, linked to decision-making, construction sectors, and construction sites, suggesting that AR is primarily explored for its ability to improve operational efficiency, streamline communication, and enhance quality control. However, despite its potential, research on AR's practical implementation in field operations and site monitoring remains relatively limited.
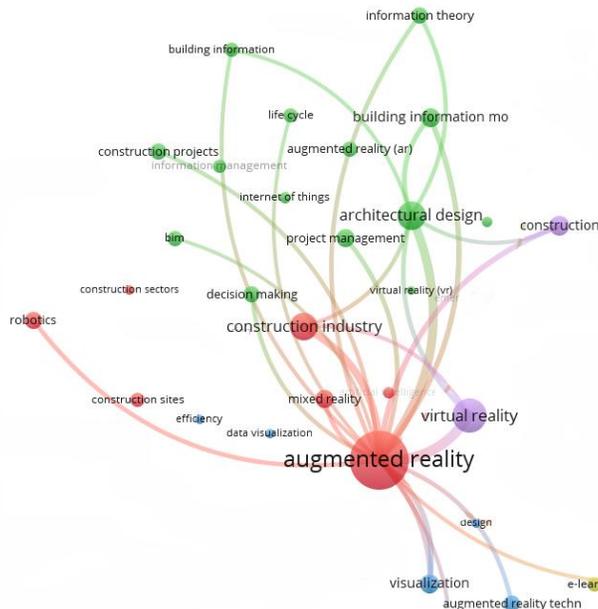

Figure 2: Keyword Co-Occurrence Network

Another key aspect revealed by the network is the connection between AR and design, with links to visualization, design processes, and e-learning. This indicates that AR is frequently studied as a tool for enhancing design accuracy, improving stakeholder communication, and facilitating educational applications within the AEC sector. In the literature, the advantages of AR implementation in the construction industry have been discussed, such as the process of mapping design to real-world construction, its use for construction quality assurance, and improving safety in construction projects (Heinzel et al., 2017). However, despite the clear advantages of AR in construction, the keyword network also reveals research gaps and challenges. Certain keywords, such as efficiency, construction sites, and data visualization, have relatively weak connections, indicating a need for more empirical studies on AR's tangible benefits in field-level operations. Additionally, aspects related to regulatory challenges, user adoption, and cost analysis are notably absent from the network, suggesting that research has predominantly focused on technological advancements rather than the financial and practical barriers to implementation.

The SLR, supported by keyword co-occurrence analysis, illustrates that while AR holds promise for enhancing construction efficiency, its integration into offsite construction still faces several hurdles. To further illustrate these findings, Table 1 summarizes the key benefits identified, highlighting AR's contributions to visualization, communication, efficiency, and safety, among others. Conversely, Table 2 presents the primary challenges and limitations that hinder its widespread adoption, including technical constraints, cost considerations, and integration difficulties. These insights provide a comprehensive understanding of AR's potential impact and the critical factors influencing its implementation in OSC manufacturing, as discussed in recent literature.

Table 1: Benefits of AR implementation to the manufacturing phase of OSC projects from literature review

Benefit	Reference
Enhanced Visualization	*[1], [2], [3], [4], [5], [6], [7], [8], [9], [10]
Improved Communication and Collaboration	[1], [11], [5], [6], [7], [8], [12]
Increased Productivity and Efficiency	[11], [3], [5], [7], [8], [13], [12]
Improved Design and Decision-making	[11], [7], [8], [14]
Improved Learning and Training	[4], [15], [8], [13], [16], [17]
Safety Improvements	[6], [18], [13], [10], [17], [19]
Real-time Data and Information Sharing	[2], [3], [4], [8], [10]
Error Detection and Reduction	[11], [6], [20], [13], [21], [12]
Real-time Progress Tracking	[10], [8], [9]
Cost-Effectiveness	[20], [19], [12]
Maintenance and Facility Management	[1], [3], [5], [19], [21]
Improved Inspection and Accuracy	[2], [8], [13]
Improved Task Completion and Reduced Cognitive Load	[22], [9], [23]
Simulation and Virtual Experience	[8], [24], [12]
Better Spatial Understanding and Problem-Solving	[23], [9], [12]
Enhanced Collaboration in Design and Problem-Solving	[8], [6], [16]
Project Scheduling and Tracking	[13], [14], [9], [10]
Increased Safety Awareness	[18], [10]
Improved Inventory and Resource Management	[20], [8]
Enhanced Client Feedback and Engagement	[21], [12]
Better Marketing and Customer Engagement	[12]

Table 2: Barriers of AR implementation to the manufacturing phase of OSC projects from literature review

Barrier	Reference
Technical Limitations	*[1], [11], [22], [2], [3], [20], [4], [18], [6], [12], [9], [16]
Cost of Implementation	[11], [3], [5], [18], [7], [8], [12], [19], [17], [21]
Accuracy Limitations	[11], [20], [9], [10], [8]
Device Limitations	[2], [24], [8], [9], [7], [22]
Integration with Existing Systems	[20], [7], [8], [10], [21], [12], [17]
Environmental Factors	[20], [11], [10]
Connectivity Issues	[2], [10], [8], [21]
User Acceptance	[13], [11], [6], [8], [9]
Cost and Accessibility	[1], [5], [13], [12]
Lack of Skilled Personnel	[7], [8], [12]
Marker Dependency	[1]
Limited Interaction	[3]
Complexity	[21], [12]
Cultural Resistance and Adoption	[5], [12]
Health and Safety Concerns	[22], [17]
Potential for Cognitive Overload	[23]
Lack of Industry Standards	[8]
Ergonomics and Usability Issues	[8]
Limited Market Availability	[4]
Time and Cost for Staff Training	[7]
Fragmented Nature of Construction Industry	[7]
Setup and Maintenance	[25]
Resource-Intensive Integration	[19]

*[1] Baek et al. (2019), [2] Pan et al. (2024), [3] Saar et al. (2019), [4] Proboste et al. (2023), [5] Danker et al. (2014), [6] Khan et al. (2021), [7] Nassereddine et al. (2022), [8] Tyin et al. (2024), [9] Xu et al. (2024), [10] Muñoz-La Rivera et al. (2024), [11] Chalhoub et al. (2019), [12] Alizadehsalehi et al. (2020), [13] Ahmed et al. (2019), [14] Ahmed et al. (2018), [15] Hajirasouli et al. (2022), [16] Alizadehsalehi et al. (2021), [17] Akindele et al. (2024), [18] Moore et al. (2019), [19] Xu et al. (2023), [20] Fenais et al. (2020), [21] Al-Dhaimesh et al. (2023), [22] Li et al. (2024), [23] Deshpande et al. (2018), [24] Mohammadi et al. (2024), [25] Chen et al. (2014)

2.3   Categorization of Benefits and Barriers in the Manufacturing Phase

To better understand the impact of AR in the manufacturing phase of OSC, the identified benefits and barriers were categorized based on their direct application. The categorization was established based on findings from the SLR and further refined through expert consultations. Six experts were selected based on their extensive experience in OSC, digital technologies, and AR applications. These experts included professionals from academia, industry, and research institutions, ensuring a comprehensive evaluation from multiple perspectives. This classification helps in structuring the key areas where AR influences manufacturing processes, ensuring a focused evaluation.

Table 3: Categorization of AR Benefits in the Manufacturing Phase of Off-Site Construction

Category	Benefits
Collaboration & Workflow Integration	Real-time collaboration, improved stakeholder communication, enhanced decision-making in the manufacturing process
Quality & Precision	Enhanced visualisation, Reduced errors and rework, improved documentation, enhanced spatial cognition, design error detection
Production Efficiency	Streamlined workflows, increased manufacturing efficiency, reduced fabrication timelines, improved automation and scheduling
Safety & Training	Virtual workforce training, error detection before physical assembly, enhanced ergonomic assessment for workers

Table 4: Categorization of AR Barriers in the Manufacturing Phase of Off-Site Construction

Category	Barriers
Technology & Infrastructure	Compatibility issues with manufacturing software, lack of standardized AR hardware, insufficient IT resources, reliance on AR specialists
Cost & Investment	High initial investment in AR tools for manufacturing, maintenance costs, cost of integrating AR into production lines
Workforce & Training	Shortage of skilled personnel for AR operation, time and cost of training manufacturing staff, resistance to adopting AR for fabrication processes
Adoption & Maturity	Limited real-world applications in OSC manufacturing, uncertainty about AR's benefits in prefabrication, immaturity of AR technology for large-scale fabrication

2.4   Survey Design

A structured survey was developed to capture the perceptions of key stakeholders in the OSC industry regarding AR technology. The survey aimed to validate and assess the identified benefits and challenges of AR adoption through participant responses. The questionnaire was divided into three main sections:
- Participant Information: Collected demographic and professional background data, including roles in the construction industry, years of experience, and familiarity with AR technology.
- Benefits of AR in Off-Site Construction: Evaluated respondents' perceptions of AR's advantages in OSC using a five-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree).
- Barriers to AR Adoption: Assessed potential challenges in implementing AR using a five-point Likert scale (1 = Not a Barrier, 5 = Significant Barrier).

Prior to answering the survey, participants were provided with a video demonstration showcasing a real-world use case of AR in manufacturing phase of OSC to ensure a consistent understanding of the technology's application.

2.5   Participant Selection

The survey targeted professionals from various disciplines within the construction industry, including construction managers, architects, engineers, contractors, and subcontractors. Participants were selected based on their involvement in OSC projects and their potential exposure to AR technologies.

2.6   Data Analysis

Quantitative data from the survey were analyzed using descriptive statistics to identify trends and patterns in respondents' perceptions. The mean and standard deviation were calculated for each benefit and barrier statement to determine the overall agreement levels. Additionally, qualitative responses from open-ended questions were thematically analyzed to capture insights into real-world AR applications and challenges. To assess the correlation between the perceived benefits and barriers of AR adoption in the manufacturing phase, Spearman's correlation was used. The analysis was conducted using Python, specifically the "*scipy.stats*" library. Given that the survey data primarily consists of ordinal Likert scale responses, Spearman's correlation was chosen as it measures the strength and direction of monotonic relationships between ranked variables. The Spearman's rank correlation coefficient (ρ) is calculated using the equation (Eq. 1):

[1] $\rho = 1 - \dfrac{6 \sum d_i^2}{n(n^2 - 1)}$

where:
- d_i is the difference between the ranks of corresponding values,
- n is the number of observations.

To evaluate the internal consistency and reliability of the survey instrument, Cronbach's alpha test was conducted. This test measures the degree to which survey items that intend to measure the same construct produce consistent results. The Cronbach's alpha coefficient (α) is calculated using the equation (Eq. 2):

[2] $\alpha = \dfrac{k}{k-1}\left(1 - \dfrac{\sum \sigma^2_i}{\sigma^2_t}\right)$

where:
- k is the number of items,
- σ^2_i is the variance of each individual item,
- σ^2_t is the total variance of all items combined.

A Cronbach's alpha value above 0.7 was considered acceptable for reliability. The mean and standard deviation were calculated for each benefit and barrier statement to determine the overall agreement levels. Additionally, qualitative responses from open-ended questions were thematically analyzed to capture insights into real-world AR applications and challenges.

3. RESULT AND DISCUSSION

A total of 28 valid expert responses were analyzed to evaluate AR's benefits and barriers in OSC manufacturing. The ranking of these factors, serves as a foundation for developing strategies to maximize AR's effectiveness in OSC.

3.1   Key Benefits of AR in OSC Manufacturing:

Survey findings confirm that AR significantly enhances multiple aspects of the OSC manufacturing phase, particularly in collaboration, quality assurance, and production efficiency. The ranked benefits are as follows:

3.1.1 Collaboration & Workflow Integration (Highest-Ranked Benefit)

Real-time collaboration and enhanced stakeholder communication were rated as the most valuable AR applications. By overlaying digital information in real time, AR facilitates immediate feedback loops, improving decision-making and coordination across project teams.

3.1.2 Quality & Precision

Enhanced visualization and improved documentation were recognized as critical benefits. AR significantly reduces errors and rework by providing precise, interactive visual guidance, improving spatial cognition and design accuracy.

3.1.3 Safety & Training

AR enables virtual workforce training, allowing workers to practice complex tasks before physical assembly, minimizing risks and improving ergonomic assessments. Error detection before fabrication contributes to a safer work environment and enhances overall operational reliability.

3.1.4 Production Efficiency (Lowest-Ranked Benefit)

While not as highly ranked as other benefits, streamlined workflows and reduced fabrication timelines were noted as key advantages. AR supports automation and scheduling, leading to process optimization.

3.2 Challenges and Barriers to AR Adoption

Despite its clear advantages, several critical barriers hinder the widespread adoption of AR in OSC manufacturing. The ranked barriers are as follows:

3.2.1 Technology & Infrastructure (Primary Barrier)

Compatibility issues with existing manufacturing software and reliance on AR specialists were the most frequently cited technical constraints.
The lack of standardized AR hardware and insufficient IT infrastructure further complicate seamless integration into current workflows.

3.2.2 Workforce & Training

Resistance to adopting AR, coupled with a shortage of skilled personnel, poses a major challenge.
The time and cost required for training staff on AR tools remain significant obstacles to workforce readiness.

3.2.3 Adoption & Maturity

Uncertainty regarding AR's benefits in prefabrication and its limited real-world applications contribute to slow adoption.
The immaturity of AR technology for large-scale fabrication reinforces skepticism among industry stakeholders.

3.2.4 Cost & Investment (Lowest-Ranked Barrier)

The high initial investment in AR tools, along with maintenance costs, remains a substantial concern.
Financial constraints continue to limit AR's adoption, particularly for small and mid-sized enterprises in the OSC sector.

3.3 Correlation analysis

The internal consistency and reliability of the responses were tested using Cronbach's alpha, calculated with Equation 2 for both benefits and barriers. The Cronbach's alpha value for benefits was 0.750, and for barriers, it was 0.780, both considered acceptable for internal consistency and reliability. Figure 3 and

Figure 4 shows the Spearman correlation analysis for the benefits and barriers of AR application in the manufacturing phase of OSC projects.
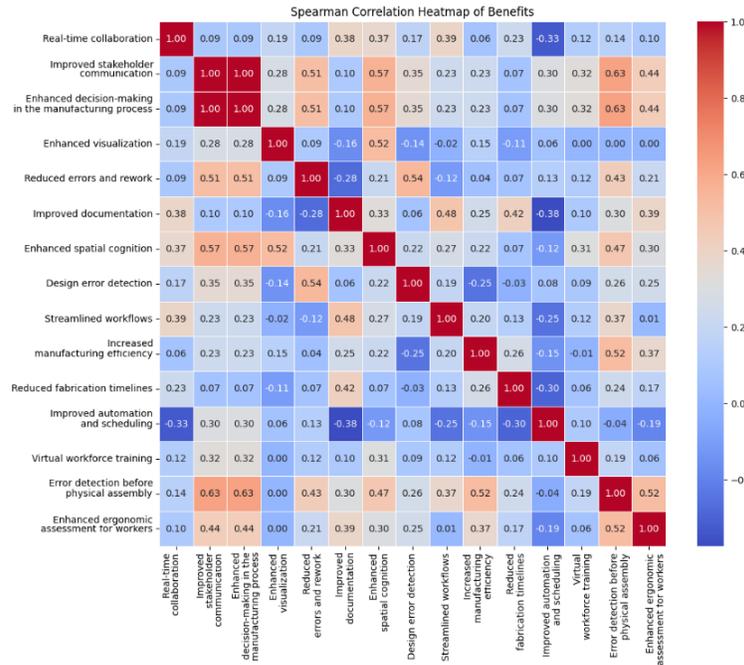

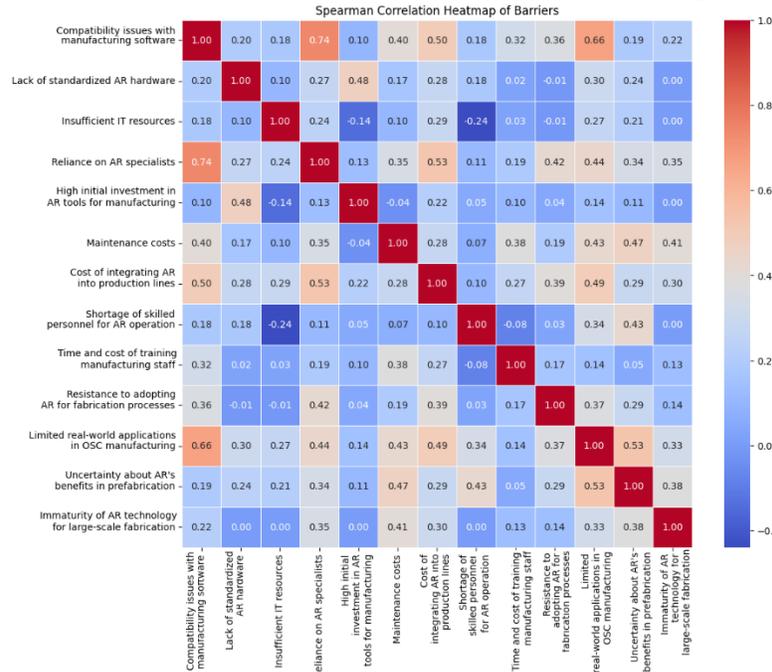Figure 3: Heat map matrix of the benefits of AR in the manufacturing phase of OSC

Figure 4: Heat map matrix of the barriers of AR in the manufacturing phase of OSC

The heat map matrix (Figure 3) of benefits demonstrates how AR in the manufacturing phase of OSC leads to significant improvements in various areas. Interpretation of the highest correlations is as follows:

- Improved Stakeholder Communication and Enhanced Decision-Making: These two benefits are highly correlated, suggesting that enhanced communication among stakeholders directly contributes to better decision-making in the manufacturing process.

- Enhanced Visualization and Design Error Detection: The strong correlation here indicates that improved visualization capabilities of AR lead to a reduction in design errors, which is crucial for improving manufacturing efficiency and reducing rework.
- Real-time Collaboration and Enhanced Spatial Cognition: Real-time collaboration is strongly related to the improvement in spatial understanding, likely due to AR's ability to provide real-time, interactive, and 3D representations of the work, which helps in understanding spatial relationships on-site.

In addition, the correlation analysis of barriers (Figure 4) shows the following understanding:
- Cost-Related Barriers: Strong correlations are visible between High Initial Investment, Maintenance Costs, and Cost of Integrating AR into Production Lines. These highlight those financial constraints and high upfront costs are tightly linked as major barriers to the adoption of AR.
- Skilled Personnel: The correlation between Shortage of Skilled Personnel and Time and Cost of Training indicates that the lack of expertise in AR technology correlates significantly with the time and resources needed to train personnel, making it a substantial challenge.
- Resistance to Adopting AR and Uncertainty About AR's Benefits are strongly correlated. This suggests that skepticism about the value and effectiveness of AR plays a central role in hindering its widespread adoption in manufacturing.

The findings highlight the substantial potential of AR to improve various aspects of OSC manufacturing, particularly in enhancing collaboration, precision, and safety. However, significant barriers, primarily in technology, workforce readiness, and cost, must be addressed for successful integration. The high initial investment and maintenance costs, along with a lack of skilled personnel and resistance to AR adoption, are central challenges hindering AR's widespread use in the sector.

4. CONCLUSIONS

This study investigates the integration of AR into the manufacturing phases of OSC projects, emphasizing its potential to enhance collaboration, improve quality control, and streamline workflows, ultimately boosting efficiency and safety. The research offers a meaningful contribution to both academia and industry by delivering a comprehensive analysis of AR applications in OSC manufacturing. Through a systematic literature review and empirical survey, it provides actionable insights into the tangible advantages and persistent barriers to AR adoption, addressing key knowledge gaps and offering guidance for practitioners. Notably, the study identifies critical areas for advancement, including improved collaboration, precision, and training, while also acknowledging challenges such as integration hurdles and workforce preparedness.

Nevertheless, significant obstacles remain, including high implementation costs, technical compatibility concerns, skill shortages, and resistance to change within the industry. The study's limitations include a relatively small sample size, which, while reflective of key stakeholders, may not fully represent the broader spectrum of construction professionals. Additionally, the absence of a detailed cost-benefit analysis limits its immediate utility for decision-makers. Future research should focus on large-scale pilot projects to validate AR's sustained impact on OSC. Further investigations into cost-effectiveness, digital tool interoperability, and workforce development strategies will be essential to support broader adoption..

5. ACKNOWLEDGMENTS

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