

Article

BIM-Integrated Augmented Reality for Construction Progress Monitoring: Schedule, Economic, and Sustainability Implications

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Abstract

Construction progress monitoring is essential for controlling schedule deviations and supporting efficient resource management. Conventional field inspections remain indispensable in construction management; however, BIM-integrated Augmented Reality (AR) can provide an additional visual verification layer by relating planned digital information to observable site conditions. This study evaluates a BIM–AR framework for periodic structural construction progress monitoring in a real hospital project. BIM-based AR visualization was used during field inspections, while approved schedule information, floor-level working-day records, monthly concrete production data, and labor payment records provided the quantitative basis for progress assessment. The results identified temporary structural schedule deviations during intermediate floor construction; for example, cumulative actual progress reached 125 working days against a planned 119 days at the second-floor stage, while subsequent records indicated schedule recovery following management interventions. Cost records also revealed differences between planned and actual labor payments; however, these differences were treated as economic implications of the observed progress conditions rather than direct monetary savings attributable to AR. The benefits in terms of communication and decision support were assessed through field observations. From a sustainability perspective, the framework can support more resource-efficient construction management by facilitating earlier recognition of deviations and more informed corrective actions, with the potential to limit avoidable rework, schedule disruption, and inefficient resource use. The findings position BIM–AR as a complementary visual verification and decision-support tool for periodic construction progress monitoring.

Keywords: augmented reality (AR); building information modeling (BIM); construction progress monitoring; sustainable construction; schedule deviations; cost implications



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1. Introduction

Construction projects are frequently affected by schedule delays, cost overruns, and quality deficiencies owing to fragmented workflows, dynamic site conditions, and the involvement of multiple stakeholders. Effective construction progress monitoring is therefore essential for determining whether actual site activities are consistent with planned construction activities and for identifying deviations before they affect subsequent work. Conventional progress monitoring typically relies on site inspections, construction schedules, progress reports, photographs, quantity records, and two-dimensional drawings.

These methods remain indispensable components of construction management; however, the information required for progress assessment is often distributed across different documents and platforms, requiring project personnel to manually relate planned activities to observed site conditions. This fragmented assessment process may delay the recognition of emerging progress deviations and, consequently, limit the ability of project managers to implement timely corrective actions for schedule and cost control. Digital technologies can therefore complement conventional inspection practices by improving the accessibility, visualization, and interpretation of project information during field monitoring.

In response to these challenges, the Architecture, Engineering, and Construction (AEC) industry has increasingly adopted digital technologies to improve project planning, coordination, monitoring, and decision-making. Building Information Modeling (BIM) has become particularly important because it provides an integrated digital representation of project geometry and associated information throughout the project lifecycle. Keleş and Keleş [1] emphasized that information technologies can support the more effective management of limited construction resources, including labor, materials, equipment, and financial assets. Similarly, Aladağ [2] argued that digital transformation should extend beyond the design stage and encompass the entire project lifecycle, while Bahçeci and Polat [3] highlighted organizational and technical barriers that continue to constrain the adoption of BIM and related technologies. More recently, Koparan [4] emphasized the increasing role of BIM and emerging digital technologies in addressing growing project complexity, productivity requirements, and sustainability challenges.

Although BIM provides a comprehensive digital representation of project information, planned BIM information and physical site conditions are generally viewed through separate interfaces during construction. This requires project personnel to interpret the relationship between digital models and observable construction conditions during field inspections. AR can complement this process by superimposing BIM-based digital information onto the physical construction environment, thereby providing an additional visual verification layer during on-site inspections. Rather than replacing conventional field inspection, BIM-integrated AR can support engineers and project managers in comparing planned and observed construction conditions and interpreting potential progress deviations in conjunction with conventional project records [5–8]. The proposed BIM–AR framework should be distinguished from Digital Twin-based construction monitoring. Digital Twin systems generally involve dynamic or automated data exchange and synchronization between physical construction conditions and their digital representations, potentially enabling continuous monitoring and feedback. In contrast, the present BIM–AR framework does not provide automated bidirectional synchronization between the physical site and the BIM model. BIM information is visualized through AR during periodic field inspections, while progress conditions are subsequently evaluated using field observations and project records. Therefore, the proposed approach functions as a periodic visual verification and decision-support framework rather than a continuously synchronized Digital Twin system.

From a sustainability perspective, effective construction progress monitoring is closely related to the efficient management of project resources. Undetected or late-identified progress deviations may contribute to rework, prolonged site operations, disrupted labor and equipment utilization, and inefficient use of construction materials and time. Digital monitoring technologies can support more sustainable construction management by providing project managers with timely and interpretable information for corrective decision-making. In this context, BIM–AR integration can serve as a digital support tool for resource-efficient construction management by improving the visibility of planned–actual

discrepancies before their effects propagate to subsequent construction activities. However, the present study does not directly quantify environmental sustainability indicators such as carbon emissions, energy consumption, or material waste; rather, its sustainability relevance is considered from the perspective of resource-efficient construction management and improved progress control.

Despite the growing body of research on BIM-integrated AR, several methodological limitations remain in its application to construction progress monitoring. Previous studies have frequently focused on laboratory experiments, prototype systems, individual construction activities, or short-term demonstrations, resulting in limited validation under real construction site conditions. Furthermore, the integration of AR-assisted observations with time-based schedule information and actual cost records remains insufficiently documented, while longitudinal or periodic monitoring across successive construction stages is comparatively limited. The effectiveness of AR within progress monitoring is also not always clearly distinguished from the quantitative information provided by conventional project records, making it difficult to determine the specific contribution of AR to the monitoring process. These limitations highlight the need for field-based studies that integrate AR-assisted visualization with established schedule, production, and cost records over successive construction stages.

Accordingly, this study investigates the field implementation of a BIM-integrated AR framework for periodic structural construction progress monitoring in a real hospital construction project. The framework combines BIM-based AR visualization with approved schedule information, floor-level working-day records, structural concrete production data, and labor payment records. AR is employed as a visual verification and decision-support layer, whereas project records provide the quantitative basis for evaluating production and schedule differences. The study aims to demonstrate the practical application of BIM-integrated AR under real-world construction site conditions; to examine how AR-supported visualization can aid in identifying and interpreting deviations in structural progress when used in conjunction with conventional project records; and to assess the schedule and economic implications associated with the observed progress conditions. Through this approach, the study provides field-based evidence on BIM–AR-assisted progress monitoring and discusses its potential contribution to resource-efficient and sustainable construction management.

2. Literature Review

2.1. Digital Transformation in Construction

Digital transformation in the Architecture, Engineering, and Construction (AEC) industry has progressively shifted project management from fragmented document-based practices toward integrated digital information environments. Among these developments, BIM has become a central approach for organizing and managing geometric and non-geometric project information throughout the project lifecycle. BIM supports multidisciplinary coordination and facilitates the integration of design, scheduling, quantity, and cost information. Ofluoğlu [9] highlighted the contribution of BIM to stakeholder communication, scheduling, occupational safety, and cost control. These capabilities make BIM particularly relevant to construction progress management, where reliable and integrated project information is required to evaluate ongoing construction activities and support effective project control.

In construction progress monitoring, BIM can provide a structured digital reference for relating planned project information to construction activities. When combined with schedule, quantity, and cost records, BIM-based information can support the interpretation of construction status and facilitate progress assessment. However, progress monitoring

also depends on the collection of reliable field information through site inspections, progress reports, photographs, quantity records, and other project documentation. Therefore, BIM should not be considered a replacement for conventional field inspection; rather, it can provide an integrated information environment in which field observations and project records can be interpreted more systematically for schedule control, cost assessment, and project decision-making.

A key challenge in progress monitoring is establishing a clear relationship between planned digital information and observable construction conditions. Although BIM can integrate project information and support field-based applications, planned models, schedule records, and observed site conditions are not necessarily synchronized automatically. Consequently, project personnel may still need to interpret information from multiple sources when determining whether construction activities are consistent with the planned sequence and schedule. This limitation becomes particularly important when emerging deviations must be recognized in time to support corrective decisions related to subsequent activities, resource allocation, schedule control, and potential cost implications.

AR can complement BIM-supported progress monitoring by providing a visual interface between digital project information and the physical construction environment. By displaying BIM-based information in relation to observable site conditions, AR can assist project personnel in visually interpreting planned–actual differences during field inspections. Its role in this context is therefore not to replace conventional inspection or independently generate quantitative progress data, but to provide an additional visual verification and decision-support layer that can be used together with schedule, production, quantity, and cost records. Previous studies have highlighted the potential of BIM–AR integration for construction applications while also emphasizing the need for greater validation under actual field conditions [10–12].

In this context, real-time visualization, real-time data acquisition, and periodic progress monitoring should be clearly distinguished. AR may provide real-time visualization of BIM information during an individual site inspection; however, this does not necessarily imply continuous or real-time acquisition of construction progress data. In the present study, formal progress observations were conducted periodically. Accordingly, AR was used for on-site visualization and visual comparison during individual inspections, whereas construction progress assessment was performed using periodic field observations and corresponding project records.

The proposed BIM–AR framework should also be distinguished from Digital Twin-based construction monitoring. Digital Twin systems generally involve dynamic data updating and synchronization between physical assets or processes and their digital representations, potentially supporting continuous monitoring and feedback. In contrast, the framework adopted in this study does not involve automated or bidirectional synchronization between the physical construction site and the BIM model. BIM information is visualized through AR during periodic field inspections, while progress conditions are evaluated using observations and project records. Therefore, the proposed approach should be understood as a BIM–AR-assisted periodic visual verification and decision-support framework rather than a continuously synchronized Digital Twin system.

2.2. Applications of AR in Construction

Extended Reality (XR) technologies provide different forms of interaction between digital information and physical environments. Within this spectrum, Virtual Reality (VR) immerses users in computer-generated environments, whereas AR overlays digital information onto the physical environment without isolating users from real-world

conditions [5–14]. This characteristic makes AR particularly relevant to construction activities that require simultaneous interaction with digital project information and observable site conditions.

Advances in mobile computing, computer vision, sensors, and wearable technologies have increased the accessibility of AR in construction. AR applications can be implemented through smartphones, tablets, smart glasses, and head-mounted displays, while different tracking and registration approaches are used to align digital information with physical environments [15–17]. The reliability of this alignment depends on the tracking method, environmental conditions, and system configuration; therefore, marker- or image-based tracking should not be assumed to guarantee accurate model registration under all field conditions. An example of image-based AR visualization is presented in Figure 1.

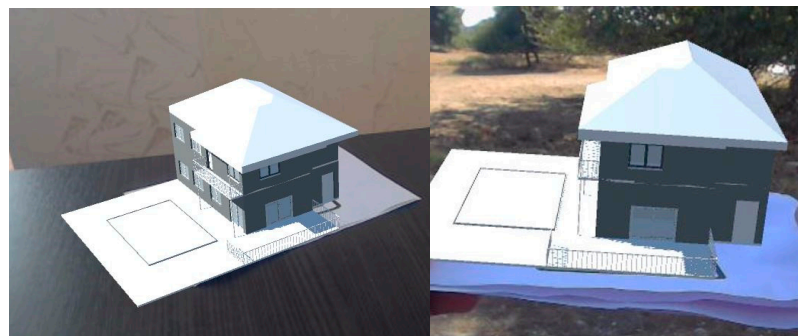


Figure 1. Marker-based AR visualization using QR-code image recognition.

In construction, the integration of AR with BIM enables digital project information to be visualized in relation to physical site conditions. This integration can support field inspection, planned–actual comparison, progress interpretation, and coordination by providing an additional visual layer during site activities. Importantly, real-time visualization of BIM information during an individual AR inspection should be distinguished from real-time data acquisition or continuous progress monitoring. AR can provide an immediate visual representation during an inspection, whereas the frequency of progress assessment depends on the data-collection protocol adopted for a particular application.

Previous studies have demonstrated the potential of BIM–AR integration for construction management, while also identifying limitations in field-based validation. Alkan and Başağa [10] emphasized the integration potential of BIM and AR but noted the prevalence of laboratory or controlled applications. Similarly, Nassereddine et al. [11] and El Kassis et al. [12] highlighted the need for further evaluation under actual construction site conditions. Accordingly, the following subsections review AR applications with particular emphasis on their relevance to field verification, construction progress monitoring, planned–actual comparison, and project decision-making.

2.2.1. Design Visualization and Communication

Visualization is one of the principal functions of AR in construction because it enables digital project information to be viewed in relation to physical site conditions. When integrated with BIM, AR can support field personnel in interpreting model information directly within the construction environment and can facilitate visual comparison between planned elements and observable construction conditions. Previous studies have demonstrated the value of AR for design visualization, collaborative review, and on-site interaction [18–20]. In the context of construction progress monitoring, however, its primary relevance lies in supporting field verification and improving the interpretation of planned–actual conditions rather than visualization as an independent objective.

AR-assisted visualization can also support communication and coordination by providing project participants with a shared visual reference during field inspections. Relating BIM-based information to observable site conditions can help engineers and site personnel discuss identified discrepancies, interpret their implications for ongoing activities, and support decisions concerning subsequent construction work. Accordingly, the contribution of AR to progress monitoring can be summarized in four interrelated functions: field visualization, visual verification, progress interpretation, and coordination support. These functions complement conventional project records and field inspection practices rather than replacing them, while quantitative progress and schedule assessments remain dependent on the corresponding project data.

2.2.2. Construction Progress Monitoring

Construction progress monitoring is a key application area of AR, as effective project control requires planned construction information to be systematically related to observable site conditions. Conventional progress monitoring commonly relies on site inspections, photographs, progress reports, schedules, quantity records, and two-dimensional drawings. AR-assisted approaches complement these conventional sources by enabling BIM-based information to be visualized in relation to physical construction conditions during field inspections. Across the literature, BIM models and schedule information are commonly used as representations of planned conditions, whereas field observations, site images, and spatial data provide information on actual construction status [21–24].

Existing approaches differ in terms of data acquisition, registration, and planned–actual comparison methods. In relatively straightforward applications, BIM geometry is visually compared with observable construction conditions to support progress verification and the identification of discrepancies. More advanced approaches incorporate spatial localization and mapping techniques, such as Visual Simultaneous Localization and Mapping (VSLAM), to support model registration and field inspection [24]. These approaches indicate that AR can provide a useful visual interface between planned digital information and physical site conditions; however, the reliability of progress interpretation depends not only on AR visualization but also on registration accuracy, the quality and currency of the underlying BIM and schedule information, and the reliability of the field data used for comparison.

Monitoring frequency also varies considerably among AR-based construction applications. A distinction should therefore be made between real-time AR visualization and real-time construction progress monitoring. AR can display BIM-based information and facilitate immediate visual comparison during an individual field inspection, but this capability does not necessarily mean that construction progress data are acquired, updated, and evaluated continuously. Progress monitoring becomes real-time only when actual site information is continuously or near-continuously captured, synchronized, and evaluated against planned information. In contrast, approaches based on observations conducted at predefined intervals should be regarded as periodic monitoring. In the present study, formal progress observations were conducted periodically; therefore, AR provided visualization and visual verification during individual inspections, while the overall progress assessment remained periodic rather than continuous or real-time.

Previous studies suggest that AR-assisted monitoring can support planned–actual verification, progress interpretation, coordination, and field decision-making [7,8]. Nevertheless, important methodological limitations remain. The accuracy of AR-assisted assessment may be affected by registration and tracking errors, environmental conditions, model quality, and differences between the timing of digital information updates and actual site changes. Furthermore, visual identification of a discrepancy does not by itself

constitute a quantitative measurement of construction progress; where progress quantities or completion rates are manually interpreted or derived from conventional project records, the assessment may remain dependent on human judgment and the quality of the underlying data. These limitations are particularly important when AR-assisted observations are used to support schedule or economic interpretation and should therefore be considered when evaluating the effectiveness of AR-based progress monitoring. A methodological comparison is presented in Table 1.

Table 1. Methodological Comparison.

Study	Project Type	AR/BIM Integration Method	Data Source	Research Limitations
[21]	Construction site monitoring	AR-based integration of BIM models with on-site visualization	BIM model and site information	Validation was limited to a specific application context, restricting broader generalization to different construction environments.
[22]	Modular construction	AR-assisted visualization for construction progress monitoring	Digital model and construction progress information	The application was focused on modular construction, limiting validation across different project types and construction processes.
[23]	Construction inspection	BIM-integrated AR for visual comparison of planned and as-built conditions	BIM information and observed site conditions	The assessment primarily focused on visualization and discrepancy identification, with limited evaluation across broader construction management processes.
[8]	Construction management	BIM–AR integration for visualization and construction management	BIM and digital project information	Field-based quantitative validation of the identified operational benefits was limited.
[7]	Construction management	Review and synthesis of AR applications in construction	Published literature	As a review-based study, the findings were synthesized from existing literature rather than validated through longitudinal implementation in a construction project.
[24]	Construction inspection	BIM–AR integration supported by VSLAM for spatial registration and inspection	BIM and spatial/site inspection data	The evaluation primarily addressed inspection and registration performance within the investigated application context.

2.2.3. Quality Inspection and Defect Detection

Quality inspection is relevant to construction progress monitoring because defects, incomplete work, dimensional inconsistencies, and installation errors can affect whether a construction activity can be considered satisfactorily completed and may lead to corrective work or rework that influences subsequent project activities. In this context, BIM-integrated AR can support field verification by allowing inspectors to relate planned model information to observable construction conditions. Previous applications involving reinforcing steel

inspection, timber wall installation, rebar tying, and infrastructure inspection have demonstrated the potential of AR to support the identification and interpretation of construction discrepancies during field activities [25–28].

From a progress-monitoring perspective, the relevance of quality-related discrepancies lies primarily in their potential implications for the status and sequencing of construction activities rather than in quality assessment as an independent performance dimension. When defective, incomplete, or inconsistent work is identified during field verification, the corresponding activity may require correction or rework before subsequent work can proceed, potentially affecting recorded progress and schedule interpretation. Therefore, in the present study, quality-related observations are considered complementary information for interpreting construction progress rather than a separate quantitative measure of overall project quality. The study does not evaluate dimensional inspection accuracy or project-level quality performance; instead, AR-assisted visual verification is used to support the interpretation of observed construction conditions in conjunction with project records. Table 2 lists representative studies on AR applications in the field of quality control and defect detection.

Table 2. Representative Studies on AR Applications for Quality Inspection and Defect Detection.

Ref.	Area	Main Contribution	Identified Limitation
[25]	Reinforcing steel inspection	Improved inspection accuracy using AR visualization	Limited to reinforcement inspection
[26]	Timber wall installation	Increased assembly precision and construction quality	Evaluated a single construction activity
[28]	Rebar tying	Reduced installation errors through real-time AR guidance	Focused on operational accuracy rather than project performance
[27]	Underground utility installation	Improved comparison between digital models and field conditions	Did not evaluate schedule or cost impacts
[8]	BIM–AR integration	Enhanced quality management and reduced rework potential	Primarily conceptual and operational evaluation

2.2.4. Occupational Safety and Training

Occupational safety and workforce training represent established application areas of AR in construction. Previous studies have shown that AR can support hazard visualization, safety training, equipment operation, and construction education by presenting contextual digital information within physical or simulated environments [29–33]. These applications demonstrate the broader potential of AR to support site-based information delivery and interaction. However, occupational safety and training are not direct analytical dimensions of the present study, which focuses specifically on BIM–AR-assisted construction progress monitoring. Accordingly, this application area is included only to provide concise context regarding the broader use of AR in construction and is not considered an outcome evaluated by the proposed framework.

2.2.5. Synthesis of Previous AR Applications in Construction

AR applications in construction have been investigated across a broad range of activities that can be synthesized into three principal domains: production and assembly, field monitoring and visualization, and inspection, maintenance, and rehabilitation. In production and assembly, AR has been applied to bricklaying, panel production, machine setup, construction robotics, wood-frame and complex masonry assembly, timber construction, rebar tying, and formwork installation, demonstrating its potential to provide task-specific visual guidance and support construction accuracy [26–41].

A second group of studies is more directly related to the scope of the present research and addresses field monitoring, visualization, information exchange, and construction support. These applications include construction site and modular progress monitoring, underground infrastructure visualization, construction data exchange, architectural review, on-site interaction, construction machinery visualization, planning support, road construction, infrastructure networks, bridge engineering, and residential construction [18–49]. Collectively, these studies demonstrate the relevance of AR for relating digital project information to observable field conditions, supporting progress interpretation, and facilitating field-based coordination.

The third domain includes inspection, maintenance, rehabilitation, and heritage-related applications, such as reinforcing steel inspection, post-earthquake reinforcement, district heating installation, pipe maintenance, infrastructure management, and architectural heritage conservation [25–56]. These applications further demonstrate the capacity of AR to provide context-specific visual information for verifying, maintaining, or interpreting physical assets.

Overall, the literature demonstrates the technical versatility of AR across construction activities; however, its relevance to construction progress monitoring depends on how AR visualization is integrated with project information and field data. From the perspective of the present study, the most relevant applications are those that combine digital models with observable site conditions to support planned–actual interpretation and progress verification. Nevertheless, existing approaches vary considerably in their application scope, field validation, data sources, and integration with project records.

2.2.6. Research Gaps and Research Positioning

Despite the growing body of research on AR in construction, several interconnected methodological and empirical gaps remain regarding its application to construction progress monitoring. First, field validation remains limited. Many existing studies have been conducted in laboratory environments, controlled settings, prototype applications, or task-specific demonstrations, while comparatively fewer studies have examined BIM–AR-assisted monitoring through repeated observations under actual construction site conditions [10–12]. Consequently, although the technical feasibility and visualization capabilities of AR are well established, evidence regarding its practical use as a complementary field-verification tool during project execution remains comparatively limited.

Second, existing studies differ considerably in their monitoring approaches, data sources, comparison procedures, and observation frequencies. Much of the literature has emphasized visualization performance, usability, user experience, or task-specific inspection, frequently relying on qualitative observations, perception-based assessments, or individual demonstrations. Although AR can provide immediate visualization and facilitate planned–actual comparison during a field inspection, this capability should be distinguished from continuous or real-time construction progress monitoring. Relatively limited evidence is available from studies that combine periodic AR-assisted field verification with actual project records to systematically interpret progress deviations over time.

Third, integration between AR-assisted observations and schedule- and cost-related project information remains insufficiently developed. Previous studies frequently report operational benefits such as improved visualization, communication, discrepancy identification, and potential rework reduction; however, these benefits do not by themselves demonstrate improvements in schedule or cost performance. In particular, limited field-based evidence is available on how visually identified progress deviations can be interpreted together with actual schedule, production, and cost records to assess their potential

scheduling and economic implications. This distinction is important because differences between planned and actual project records cannot be attributed causally to AR without an appropriate counterfactual or causal evaluation design.

Finally, existing applications are often task-specific, focusing separately on visualization, assembly, inspection, maintenance, or other construction activities. Consequently, there remains a need for field-based implementation frameworks that clearly define how BIM information, AR-assisted visual verification, periodic field observations, and conventional project records can be combined within a construction progress-monitoring process. Such frameworks are particularly relevant for determining the practical role of AR as a complementary decision-support mechanism rather than as a replacement for conventional inspection and project-control practices.

Against this background, the present study investigates a BIM-integrated AR framework for periodic structural construction progress monitoring in a real hospital construction project. The framework combines BIM-based AR visualization with periodic field observations and project records, including schedule information, structural concrete production data, working-day records, and labor payment records. AR is employed as a visual verification and decision-support layer, while the project records provide the quantitative basis for interpreting progress and schedule differences. Accordingly, the study does not attempt to establish a causal cost-saving effect attributable to AR; rather, it examines the potential schedule and economic implications associated with the observed progress deviations. This positioning provides field-based evidence on how BIM–AR-assisted visualization can be integrated with conventional project records to support periodic construction progress monitoring under actual site conditions. The identified research gaps and the corresponding positioning of the present study are summarized in Table 3.

Table 3. Research Gaps Identified in Previous Studies and the Positioning of the Present Study.

Research Gap	Limitation Identified in Previous Research	Positioning of the Present Study
Field validation	Limited validation through repeated observations under actual construction site conditions	Application in a real hospital construction project
Monitoring methodology	Limited integration of AR visualization with periodic progress assessment and actual project records	Field observations combined with BIM–AR visual verification and project records
Schedule and economic interpretation	Limited integration of identified progress deviations with schedule, production, and cost-related records	Interpretation of observed deviations using schedule, production, working-day, and labor payment records
Integrated implementation	Limited field-based frameworks combining BIM, AR visualization, field observations, and conventional project-control data	BIM–AR-assisted periodic progress-monitoring framework integrating visual verification with conventional project records

3. Materials and Methods

3.1. Research Design

This study adopts a case study approach to investigate the applicability of a BIM-integrated AR framework for periodic structural construction progress monitoring under real construction site conditions. The case study approach enables the proposed framework to be evaluated within an actual project environment, where construction activities, site conditions, and project records can be considered together.

The research workflow consists of six sequential stages. In the first stage, a comprehensive literature review was conducted to identify the current applications and method-

ological limitations of AR-assisted construction progress monitoring and to establish the research scope. In the second stage, the architectural and structural project information was used to develop a three-dimensional BIM model representing the planned structural construction. In the third stage, the BIM model was integrated into an AR environment to enable on-site visualization and visual verification of planned structural elements.

In the fourth stage, periodic field inspections were conducted during the structural construction phase. During these inspections, BIM-based AR visualization was used as a complementary visual verification layer to support the comparison and interpretation of planned and observed construction conditions. The AR application provided immediate visualization during each inspection; however, the progress-monitoring process itself was periodic rather than continuous or real-time.

In the fifth stage, periodic field observations were combined with project records, including the approved construction schedule, floor-level working-day records, structural concrete production data, and labor payment records. These records provided the quantitative basis for assessing structural construction progress and interpreting planned–actual differences, while photographs and AR visualization records supported the documentation of observed site conditions.

In the final stage, the collected information was comparatively evaluated to identify structural progress and schedule deviations and to examine their potential scheduling and economic implications. AR was therefore employed as a visual verification and decision-support component of the framework, whereas quantitative assessments were based on the corresponding project records. The study does not attribute observed schedule or cost differences causally to AR. The overall research workflow is illustrated in Figure 2. The graphic summary was created with the help of artificial intelligence. A generative artificial intelligence (GenAI) tool was used solely to assist in the visual preparation of the Graphical Abstract. The tool was used to generate and/or refine graphical elements based on author-provided descriptions of the study framework.

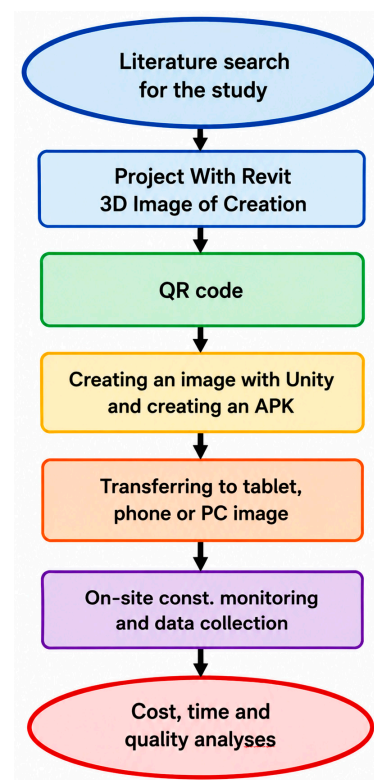


Figure 2. Overall research methodology adopted in the present study.

3.2. BIM–AR System Architecture

The proposed BIM–AR framework was structured to integrate digital model information, AR-assisted field visualization, and conventional project records within a periodic structural construction progress-monitoring process. The system architecture consists of three interconnected components: (i) the BIM information layer, (ii) the AR-assisted field visualization and verification layer, and (iii) the project-record-based evaluation layer. This structure was designed to distinguish the visual verification function of AR from the quantitative assessment of construction progress.

The BIM information layer represents the planned structural configuration of the project and provides the three-dimensional digital information required for field visualization. Architectural and structural project information was used to prepare the BIM models, which were subsequently transferred to the AR environment. The models were organized according to building levels so that the relevant structural information could be accessed during field inspections.

The AR-assisted field visualization and verification layer enables BIM-based structural information to be displayed within the physical construction environment using a mobile device. During each field inspection, the relevant BIM model was accessed through the AR application and used to support visual comparison between planned structural elements and observable site conditions. Accordingly, AR functions as a complementary visual verification and decision-support layer rather than as an automated progress-measurement system. The visualization available during an individual inspection is immediate, whereas the overall construction progress-monitoring process is based on periodic field observations.

The project-record-based evaluation layer provides the quantitative information required to interpret structural progress and schedule differences. This layer includes the approved construction schedule, floor-level working-day records, structural concrete production data, and labor payment records. These data were evaluated together with the documented field observations to interpret planned–actual progress differences and their potential scheduling and economic implications. Thus, quantitative progress assessment was derived from project records rather than directly generated by the AR application.

The interaction between these three components establishes a clear separation between visual verification and quantitative evaluation. BIM–AR supports the interpretation of observed construction conditions during field inspections, while conventional project records provide the numerical basis for progress and schedule assessment. The framework therefore complements established construction monitoring practices rather than replacing them and does not involve automated bidirectional synchronization between the physical construction site and the BIM model.

3.3. BIM Model Preparation and AR Application Development

The BIM–AR application was developed through a sequential process involving BIM model preparation, transfer of the digital model to the AR development environment, configuration of the visualization functions, and deployment of the application to a mobile device. The architectural and structural project drawings were first used to develop a three-dimensional BIM model in Autodesk Revit. The model represented the structural configuration of the hospital project and was organized according to building levels to facilitate the visualization of the relevant structural elements during field inspections.

Following BIM model preparation, the three-dimensional models were transferred to the Unity development environment for integration with AR functionality. Vuforia Engine was incorporated into Unity to enable image-based tracking and model visualization. QR-code-based markers were assigned to the relevant building levels, allowing the

corresponding BIM model to be accessed and visualized during field inspections. The required application functions and interactions were implemented using C# scripts within the Unity environment.

After the AR environment was configured, the application was compiled as an Android Package Kit (APK) and deployed to a tablet computer for field use. The application enabled the relevant BIM model to be displayed during site inspections, allowing project personnel to visually relate planned structural information to observable construction conditions. To improve field usability, the floor-level models were incorporated into a single application, enabling users to access the required model without installing separate applications for individual floors.

The developed application was used as a visualization and visual-verification tool within the proposed monitoring framework. It did not automatically measure construction quantities, calculate progress percentages, or synchronize field conditions with the BIM model. Instead, the AR application supported the interpretation of planned and observed structural conditions during periodic field inspections, while quantitative progress and schedule assessments were performed using the corresponding project records. The BIM model preparation and AR application development process is illustrated in Figure 3.



Figure 3. Office-based BIM development and on-site implementation of the proposed AR system: (a) Office-based; (b) On-site.

Software used in the study:

- Autodesk Revit: Three-dimensional drawings of the project were created. (<https://www.autodesk.com/tr/products/revit/overview> (accessed on 1 August 2026))
- Vuforia-Unity: This program was used to capture the AR image via a trigger (marker). (<https://developer.vuforia.com/home> (accessed on 1 August 2026))
- Unity: Used for APK and visualization. (<https://unity.com/> (accessed on 1 August 2026))

A 3D rendering of the property has been created in Revit. Figure 4 shows the floor plan of the property drawn in Revit and the 3D rendering details for that floor; Figure 5 shows the front elevation of the rendering completed in Revit; and Figure 6 shows the views of the column-beam and floor slab systems. Upon examining Figure 4, a 2D floor plan for each floor is shown on the left, and 3D visuals for the same floor are displayed on the right.

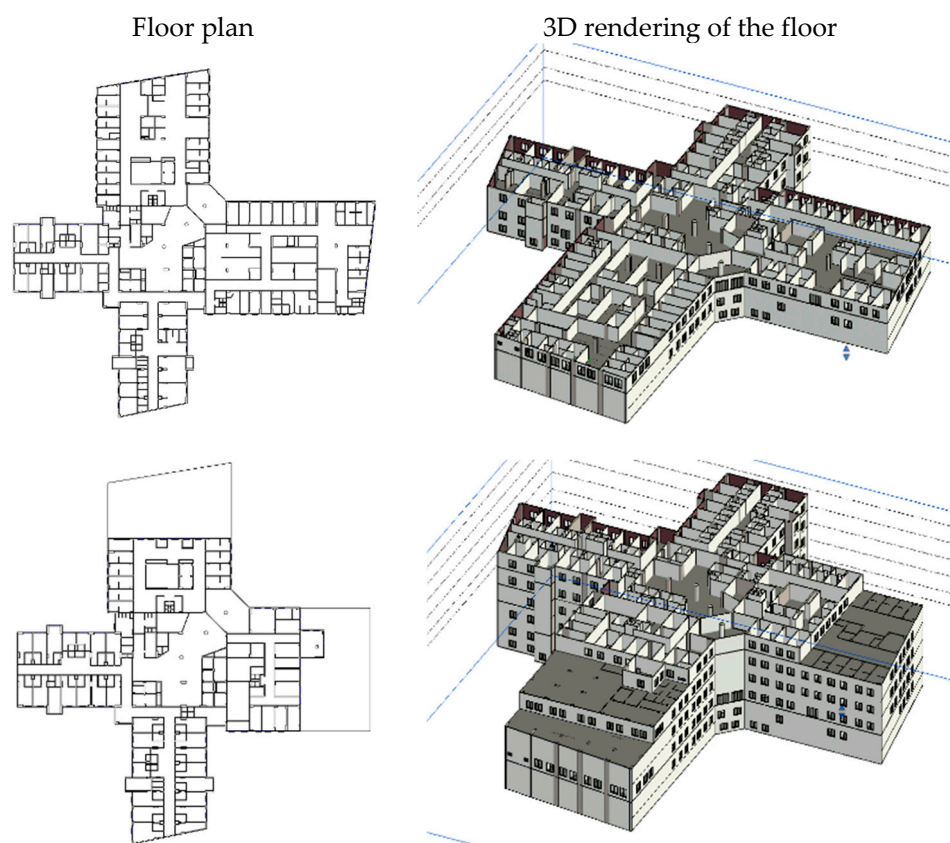


Figure 4. Images captured in the Revit environment by floor and in 3D.

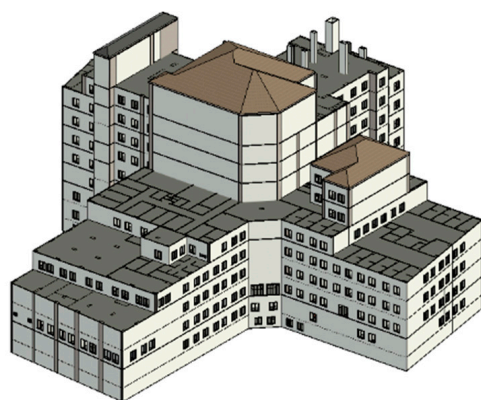


Figure 5. View of the front facade generated upon completion of the Revit drawing.

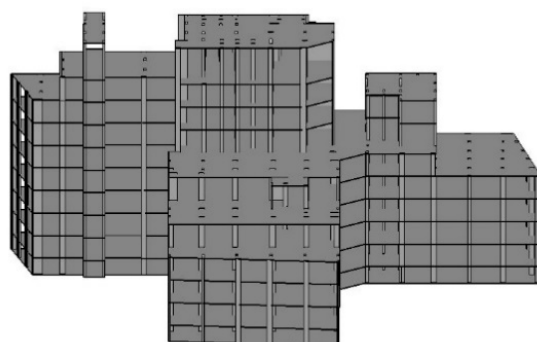


Figure 6. View of the column-beam and floor system upon completion of the Revit drawing.

Figure 7 shows both the 3D renderings of the property created using Revit and the renderings created in Unity and tested in an office environment. The table includes images of the entire property as well as separate renderings for column-beam and floor details and for each floor. The images on the left were generated using Revit, while those on the right were created using Unity in an office environment. The first images show the entire property, while the other photos feature column, beam, and floor details.

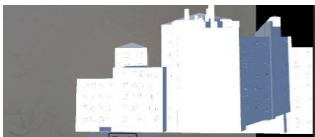
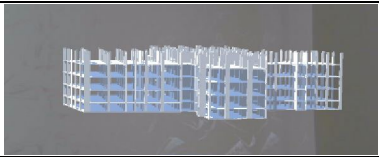
	Front view	Image of the mezzanine	Image of the mezzanine
Images captured in the Revit environment			
AR visuals in the Unity environment			

Figure 7. A comparison of structural components created using BIM during construction with AR visualization.

The image obtained from the APK file installed on the tablet was tested in an office environment, and the resulting image is shown in Figure 8. An APK file was created for the images generated in Unity, and the resulting APK file was transferred to an Android-based tablet. When the tablet screen is positioned over the QR code, the desired visuals related to the property appear on the screen. An important point to note in this study is that the Android version of the tablet selected in Unity must be compatible with the operating system of the device (tablet, phone, etc.) to which the APK file will be transferred. In the office environment, test studies were also conducted using layered visuals. The desired layer can be selected from the same screen. Since each APK reduces device capacity and can cause slowdowns during program operation, this approach allows for inspection using a single APK. During each construction monitoring session, the planned view appears on the screen during site visits and can be compared with the current status. Diversifying the images loaded into the APK will also enable inspections on various topics.

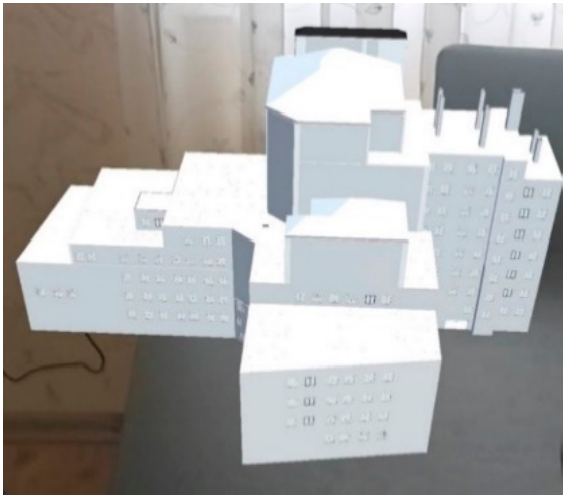


Figure 8. Screenshot taken on the tablet screen.

3.4. Data Collection and Progress Monitoring Procedure

Data collection was structured to combine periodic BIM–AR-assisted field observations with conventional project records. Field inspections were conducted periodically at predefined structural construction stages based on the planned floor-level concrete casting dates provided by the contractor. Prior to each inspection, the expected structural construction level corresponding to the scheduled inspection date was determined using the approved project information and planned construction sequence.

All field inspections were conducted by the same two-person inspection team throughout the monitoring period in order to maintain consistency in the observation procedure. During each inspection, the BIM–AR application was used as a visual verification tool to display the relevant structural BIM model within the physical construction environment. The observable construction status at the corresponding site locations was then compared with the predefined expected structural condition. Photographs and AR screenshots were also recorded to document the observed site conditions and support subsequent interpretation.

A planned–observed discrepancy was identified when the structural condition observed at the relevant location did not correspond to the construction level expected for the inspection date. This assessment involved human interpretation supported by BIM–AR visualization and was not performed automatically by the AR application. Accordingly, AR was used to support the visual recognition and interpretation of potential discrepancies, while the existence and magnitude of quantitative progress or schedule differences were subsequently evaluated using the corresponding project records.

The quantitative data sources comprised the approved construction schedule, floor-level working-day records, structural concrete production data, and labor-related payment records. The approved schedule provided the planned timing and sequence of structural activities, while working-day records were used to evaluate floor-level construction durations. Structural concrete production data were used specifically as an indicator of reinforced-concrete structural production and were not treated as a measure of overall project progress. Labor-related payment records were included as cost-related project information to support the interpretation of the potential economic implications associated with observed progress conditions.

The same inspection and interpretation procedure was applied throughout the monitoring period to provide a consistent basis for planned–observed comparison. The monitoring process therefore consisted of four sequential steps: (1) determination of the expected structural condition for the scheduled inspection date, (2) BIM–AR-assisted visual comparison with the observable site condition, (3) identification of potential discrepancies through human interpretation, and (4) verification and quantitative interpretation using the corresponding schedule, working-day, and production records. BIM–AR therefore functioned as a complementary visual verification and decision-support layer rather than as an automated progress-measurement system. Table 4 lists the functional capabilities of the developed BIM-integrated AR system during site monitoring.

Table 4. Functional Capabilities of the Developed AR System During Field Monitoring.

Data Source	Role in the Study
Approved construction schedule	Planned timing and schedule comparison
Floor-level working-day records	Evaluation of structural activity durations and schedule deviations
Structural concrete production records	Quantitative indicator of structural construction progress
Labor payment records	Cost-related information for interpreting potential economic implications

3.5. Progress, Schedule, and Economic Evaluation Method

The evaluation method was designed to assess structural construction progress and schedule deviations by combining periodic field observations with the corresponding project records. The analysis was conducted at the floor level, allowing planned and observed construction conditions to be compared across successive stages of structural construction. AR-assisted visualization was used to support the identification and interpretation of planned–observed differences during field inspections, whereas quantitative evaluation was based on the approved schedule, working-day records, structural concrete production data, and labor payment records.

Schedule performance was evaluated by comparing the planned timing of structural activities with the corresponding actual construction records. Floor-level working-day differences were examined to identify whether structural activities were completed within, ahead of, or beyond the planned durations. These comparisons were used to characterize the magnitude and temporal distribution of schedule deviations across the monitored structural construction stages.

Structural concrete production was evaluated as a quantitative indicator of structural construction progress. Planned concrete quantities derived from the project documentation were compared with recorded concrete production for the corresponding structural stages. Concrete volume was not used as an indicator of overall project progress because it does not represent non-structural activities such as mechanical and electrical installations, façade works, or architectural finishes. Accordingly, the concrete-based assessment was explicitly limited to the structural construction scope examined in this study.

The economic assessment was conducted using labor payment records as cost-related project information and was interpreted in conjunction with the observed structural progress and schedule differences. Planned and actual payment-related records were compared to examine the economic conditions associated with the monitored construction periods. In this context, AR-assisted visual verification may support the earlier recognition and interpretation of emerging progress deviations, providing project managers with an opportunity to implement corrective actions before such deviations propagate to subsequent construction activities. Earlier intervention may, in turn, help limit potential additional labor requirements, prolonged site operations, rework, and other cost consequences associated with unresolved progress deviations. However, differences between planned and actual payment records were not interpreted as cost savings directly generated by the AR system, since such differences may also result from variations in construction pace, quantities, workforce deployment, or other project-specific factors. Therefore, the analysis does not establish a causal relationship between AR implementation and cost savings; rather, it examines the potential economic implications of the observed progress deviations and discusses how AR-assisted early visual recognition may contribute to reducing exposure to additional costs through more timely corrective decision-making.

Finally, the results obtained from AR-assisted field verification and the quantitative project records were interpreted together to provide an integrated assessment of structural construction progress. This approach enabled visually identified progress conditions to be examined alongside schedule, production, working-day, and labor payment information while maintaining a clear distinction between the visual decision-support role of AR and the quantitative evidence provided by conventional project records.

3.6. Schedule Deviation and Cost Implication Assessment

The evaluation method was designed to distinguish between visual verification, structural production progress, and schedule performance, as these dimensions represent different aspects of construction progress monitoring. BIM–AR-assisted field observa-

tions were used to visually compare the expected structural condition with the observable site condition, while quantitative assessment was conducted using conventional project records. Accordingly, AR did not independently calculate progress percentages or schedule deviations.

Structural concrete production data were used as a quantitative indicator of reinforced-concrete production progress during the monitored structural phase. Periodic and cumulative planned and actual concrete quantities were compared to examine differences in structural production over successive construction stages. However, concrete volume was not interpreted as a direct measure of schedule performance or overall project progress. Equal cumulative concrete quantities at the end of the structural phase may coexist with temporary delays at intermediate construction stages; therefore, production quantities and temporal schedule performance were evaluated separately.

Schedule performance was assessed using the approved construction sequence and floor-level planned and actual working-day records. The relationship between BIM–AR observations and quantitative project records was evaluated sequentially. When a potential planned–observed discrepancy was visually identified during a field inspection, the corresponding structural stage was subsequently examined using the relevant working-day, schedule, and production records. Thus, BIM–AR provided a visual indication of a potential discrepancy, whereas conventional project records provided the quantitative basis for determining whether a measurable production or schedule difference existed. This distinction was maintained throughout the analysis to avoid attributing quantitatively observed deviations directly to the AR system.

Concrete production and working-day data were therefore interpreted as complementary rather than interchangeable indicators. Concrete quantities described the production output achieved during the structural phase, whereas working-day records represented the temporal performance of the corresponding floor-level structural stages. Although the approved construction sequence was considered when relating observations to individual floors and structural stages, detailed Critical Path Method (CPM) information linking each monitored element to critical or non-critical activity status was not available. Consequently, the study does not infer whether individual observed deviations affected the overall project critical path.

Economic interpretation was conducted separately using labor-related payment records. Planned and actual payment values were compared to examine the cost-related conditions associated with the observed structural progress. These differences were not interpreted as direct savings or economic benefits generated by BIM–AR because the study did not include an AR-free control scenario or a counterfactual cost model. Instead, the economic assessment was limited to discussing the potential economic implications of earlier discrepancy recognition and subsequent management intervention. Accordingly, BIM–AR was evaluated as a complementary visual verification and decision-support mechanism rather than as an independent source of quantitative schedule or cost performance.

4. Case Study

4.1. Case Study Description

The BIM–AR-assisted progress monitoring framework was implemented in a hospital construction project selected as the case study. The project was considered suitable for field implementation because of its relatively large construction area, multiple interconnected blocks, varying building heights, and phased structural construction process. These characteristics provided an appropriate setting for examining the application of BIM–AR-assisted visual verification across successive structural construction stages under actual site conditions.

The project site covers an area of 15,230 m², has a nearly rectangular geometry, and is located on relatively flat terrain. The site is bordered by roads on three sides and by a park area along its southern boundary.

The hospital project has a total construction area of 49,195 m², comprising a 39,472.65 m² hospital building and a 9721.44 m² parking structure. The project consists of seven adjacent reinforced-concrete blocks with different numbers of floors. Blocks A and C comprise two basement levels, a ground floor, and seven standard floors; Block D comprises two basement levels, a ground floor, and six standard floors; Block E comprises two basement levels, a ground floor, and four standard floors; Block B comprises two basement levels, a ground floor, and three standard floors; Block B* comprises two basement levels, a ground floor, and two standard floors; and the parking block comprises two basement levels and a ground floor. The blocks are constructed as adjacent structures with varying building heights. Cross-sectional views of the hospital project are presented in Figure 9.

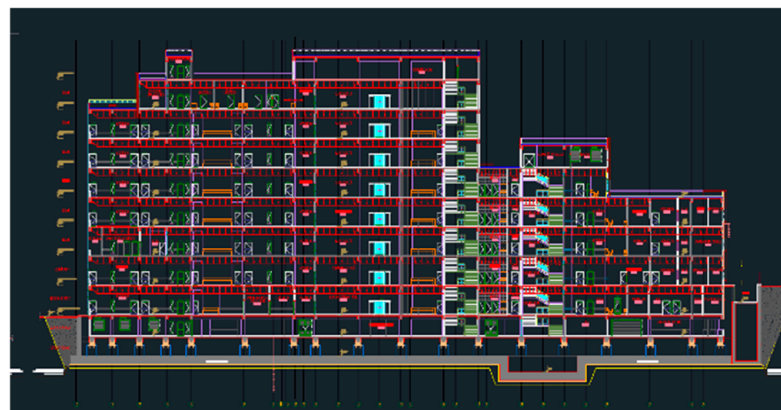


Figure 9. Cross-sectional views of the hospital project.

4.2. On-Site BIM–AR Implementation

Following the development of the BIM–AR application described in Section 3.3, the system was deployed on the hospital construction site during the structural construction phase. The application was operated on a tablet computer, enabling the BIM-based structural models to be visualized directly within the physical construction environment during field inspections. The relevant floor-level model was accessed through the corresponding QR-code-based marker, allowing the planned structural configuration to be viewed in relation to the observable site conditions.

During on-site implementation, the AR visualization was used as a complementary visual verification tool to support the comparison between BIM-based planned structural information and the construction conditions observed at the time of inspection. This enabled the research team to visually examine whether the structural elements represented in the BIM model corresponded with the observable construction status and to identify locations where planned and observed conditions required further interpretation using the corresponding project records.

Particular attention was given to maintaining a clear distinction between AR-assisted visualization and quantitative progress assessment. The AR application provided immediate visualization during each site inspection but did not automatically determine construction completion percentages, quantify schedule deviations, or calculate cost differences. Instead, visually observed conditions were documented and subsequently interpreted together with the approved schedule, working-day records, structural concrete production data, and labor payment records, as described in Sections 3.4 and 3.5.

The on-site implementation also provided a common visual reference for discussing observed construction conditions among project personnel. By relating the BIM-based planned configuration to the physical construction environment, AR-assisted visualization supported the interpretation of progress conditions and the communication of identified discrepancies during field inspections. Where emerging deviations could be visually recognized at an earlier stage, the system could support more timely consideration of corrective actions before their effects extended to subsequent construction activities. However, this function was treated as decision support rather than evidence of a causal improvement in schedule or cost performance. Representative images obtained during the on-site implementation of the BIM–AR application are presented in Figure 10.

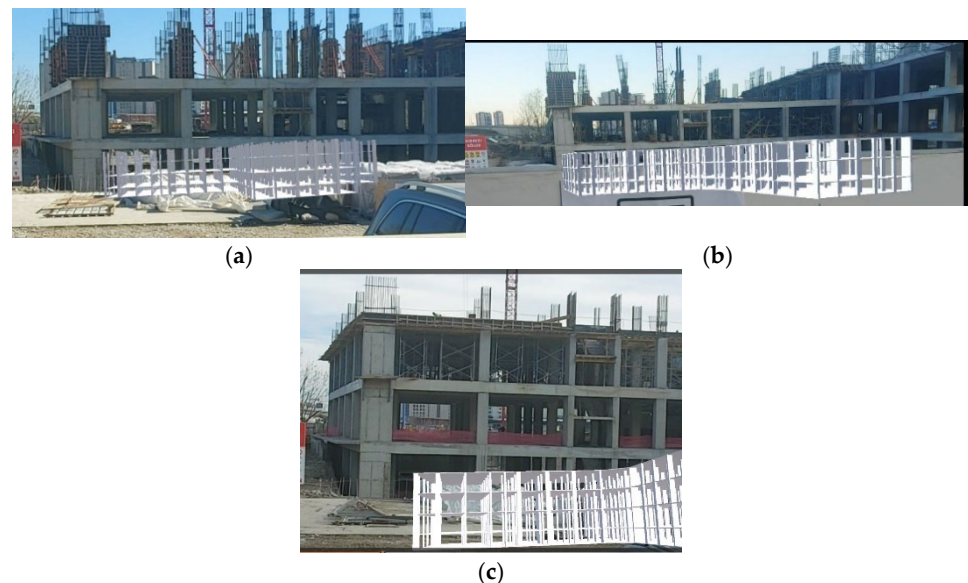


Figure 10. Images from the field investigations. (a) First image; (b) Second image; (c) Third image.

4.3. Periodic Field Monitoring

Following the on-site deployment of the BIM–AR application, periodic field monitoring was conducted throughout the monitored structural construction period of the hospital project. Site observations were performed at periodic intervals, providing successive observation points for examining the development of structural construction over time. At each observation, the construction status of the relevant building levels was documented and compared with the corresponding planned structural information.

During each field observation, the relevant BIM model was visualized through the AR application and examined in relation to the observable site conditions. This process provided a visual reference for identifying and interpreting differences between the structural elements expected according to the planned construction stage and those observable on site. Photographs and AR screenshots were recorded to document the conditions observed during the inspections and to support subsequent comparison across monitoring periods.

Following each field observation, the visual information was evaluated together with the corresponding project records. The approved construction schedule and floor-level working-day records were used to examine the timing and duration of structural activities, while structural concrete production data provided a quantitative indicator of structural construction progress. Labor payment records were considered as cost-related project information when interpreting the potential economic implications associated with the observed progress deviations. The monitoring process therefore combined AR-assisted visual verification with schedule, production, working-day, and payment-related records, rather than deriving quantitative progress measures directly from the AR application.

The successive periodic observations enabled changes in structural construction status to be examined across different monitoring periods and supported the identification of emerging planned–actual progress differences. Where a discrepancy was visually recognized during an inspection, the corresponding project records were subsequently examined to determine whether the observed condition was associated with a schedule or production deviation. In this way, AR served as a complementary mechanism for visual recognition and interpretation, while the existence and magnitude of quantitative deviations were determined from the corresponding project data.

It should be emphasized that the monitoring procedure was periodic rather than continuous or real-time. Although the AR application enabled immediate visualization of BIM information during individual field inspections, observations were formally conducted at periodic intervals. Accordingly, the results presented in the following sections represent periodic snapshots of structural construction progress rather than continuous digital tracking of site activities.

4.4. Case-Specific Progress and Schedule Assessment

Following the periodic field monitoring process, the structural construction progress of the hospital project was assessed by comparing the observed site conditions with the corresponding schedule and production records. The assessment was conducted at the floor level and across successive monitoring periods, enabling the temporal development of structural construction to be examined in relation to the approved construction schedule. AR-assisted visualization supported the recognition and interpretation of planned–observed differences during field inspections, while the existence and magnitude of quantitative deviations were determined from the corresponding project records.

Schedule assessment was based on the comparison of planned and actual working days for the monitored structural construction activities. Floor-level working-day records were examined to determine whether the corresponding structural stages were completed within the planned duration or experienced schedule deviations. This comparison provided a quantitative basis for identifying the timing and magnitude of delays across the monitored building levels and for relating the field observations to the recorded construction schedule.

In parallel, planned and actual structural concrete quantities were compared for the corresponding construction stages. Concrete production was used specifically as an indicator of structural construction progress, since reinforced-concrete activities represented the principal production scope monitored during the study period. The analysis was therefore limited to the structural phase and was not intended to represent overall project progress, which would also require consideration of mechanical and electrical installations, façade works, architectural finishes, and other non-structural activities.

The combined interpretation of working-day records, structural concrete production data, and AR-assisted field observations enabled progress deviations to be examined from both temporal and production perspectives. Where the AR-supported field inspection indicated a difference between the planned structural configuration and the observable construction status, the corresponding schedule and production records were reviewed to determine whether the visually identified condition was supported by quantitative evidence of a progress deviation. This approach prevented visual observations alone from being treated as quantitative evidence of delay.

The assessment further provided a basis for considering the management implications of identified deviations. Earlier visual recognition of emerging discrepancies through BIM–AR-assisted inspection may enable project personnel to investigate the underlying conditions and consider corrective actions before delays propagate to subsequent structural

activities. However, the analysis does not establish that AR itself prevented or reduced the recorded schedule deviations; rather, it evaluates AR as a complementary visual decision-support mechanism within the broader progress-monitoring process.

During site visits, the project manager compared the previously targeted concrete pour volumes with the actual concrete pour volumes at each floor level. Table 5 lists the targeted, actual, and cumulative concrete volumes on a periodic basis. In August, the targeted and actual concrete pour volumes were 3348.60 m³; in September, 1583.40 m³, in October 4932.00 m³, in November 4932.00 m³, in December the target was 7937.20 m³ while the actual volume was 6602.20 m³, in January the target was 4387.15 m³ while the actual volume was 6239.95 m³, in February, 3879.45 m³ was targeted but 3566.40 m³ was achieved, and in March, 2581.20 m³ was targeted but 2376.45 m³ was achieved.

Table 5. Planned and Actual Concrete Pouring by Month and Cumulatively.

	Cubic Meters			
	Targeted	Completed	Cumulative Target	Cumulative Completed
Aug. 24	3348.60	3348.60	3348.60	3348.60
Sep. 24	1583.40	1583.40	4932.00	4932.00
Oct. 24	4932.00	4932.00	9864.00	9864.00
Nov. 24	4932.00	4932.00	14,796.00	14,796.00
Dec. 24	7937.20	6602.20	22,733.20	21,398.20
Jan. 25	4387.15	6239.95	27,120.35	27,638.15
Feb. 25	3879.45	3566.40	30,999.80	31,204.55
Mar. 25	2581.20	2376.45	33,581.00	33,581.00

Figure 11 shows a graph comparing the planned and actual concrete pour volumes by month. Findings indicate that concrete pour volumes up to the first floor were in line with the plan, while work on column pours between the second and third floors concrete production remained below the planned level. However, starting with the third-floor slab—that is, from mid-January onward—the planned concrete pouring volumes were met, and in some periods, actual concrete production exceeded the planned level. For this project, the number of workers on-site was increased starting in late December.

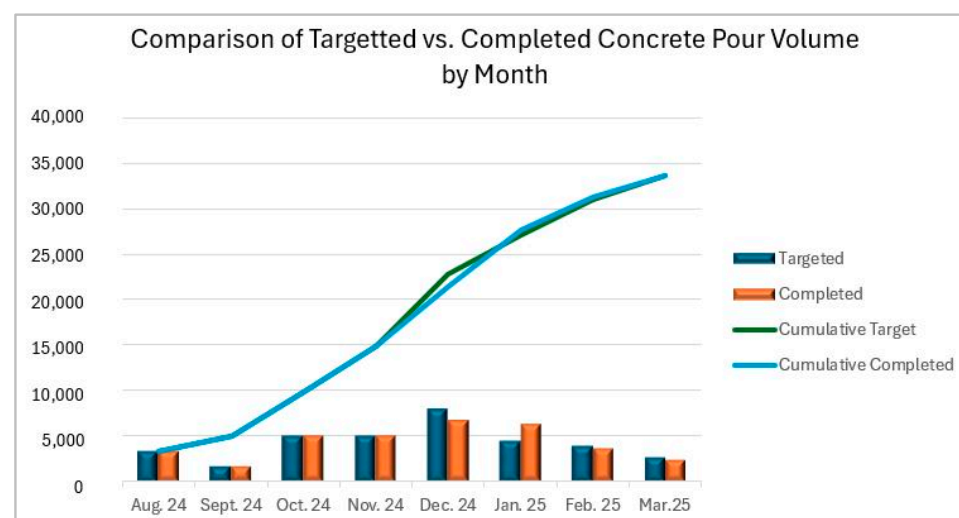


Figure 11. Comparison of Planned and Actual Concrete Pour Volume by Month.

To avoid attributing the subsequent schedule recovery directly to the BIM–AR system, the observed process was analytically separated into four stages: deviation recognition, management decision-making, corrective intervention, and subsequent schedule recovery. BIM–AR supported the visual recognition of the potential deviation, whereas conventional project records provided the quantitative basis for evaluating the observed progress condition. The subsequent workforce increase represented a management intervention, and the improvement observed thereafter should therefore be interpreted as following this corrective action rather than as a direct causal effect of AR. Table 6 summarizes the sequence of events.

Table 6. Sequence of events.

Stage	Timing	Evidence/Action	Interpretation
Deviation recognition	December 2024	A potential planned–observed discrepancy was visually recognized during BIM–AR-assisted field inspection.	BIM–AR supported visual recognition of the potential deviation.
Record-based verification	December 2024	The observed condition was evaluated using corresponding working-day and concrete production records.	Conventional project records provided the quantitative basis for confirming the progress condition.
Management decision	Late December 2024	The observed progress condition was communicated to project management and corrective action was considered.	Decision-making remained a management responsibility and was not performed by the AR system.
Corrective intervention	Late December 2024 onward	Workforce resources were increased to support structural production.	Workforce increase constituted the direct management intervention intended to improve production performance.
Observed recovery	Mid-January 2025 onward	Subsequent working-day and production records indicated improvement in structural progress.	Recovery followed the management intervention and cannot be attributed causally to AR alone.

Table 7 presents the number of workdays planned for each floor, broken down by both floor and cumulatively, showing both target and actual figures. Figure 12 graphically illustrates the target and actual workdays and their cumulative totals by floor; it is evident that deviations began as early as the first floor, delays persist up to the column level between the 2nd and 3rd floors; however, from the 3rd floor level to the 6th floor level, construction is concrete production exceeded the planned level compared to the target, and similar progress to the target is observed at other levels.

Table 7. Planned and Actual Workdays By Floor.

	Target Workday	Cumulative Target Workday	Actual Working Day	Cumulative Actual Working Day
Second basement level				
First-second basement	20	20	20	20
First basement	25	45	25	45
Ground-First basement	15	60	15	60
Ground floor	13	73	13	73
1st Floor-Ground	10	83	10	83
1st Floor	13	96	17	100
2nd-1st Floor	10	106	11	111
2nd Floor	13	119	14	125

Table 7. Cont.

	Target Workday	Cumulative Target Workday	Actual Working Day	Cumulative Actual Working Day
3rd-2nd Floor	10	129	5	130
3rd Floor	13	142	11	141
4th-3rd Floor	8	150	8	149
4th Floor	10	160	10	159
5th-4th Floor	8	168	8	167
5th Floor	10	178	10	177
6th-5th Floor	7	185	7	184
6th Floor	8	193	9	193
7th-6th Floor	6	199	6	199
7th Floor	5	204	5	204

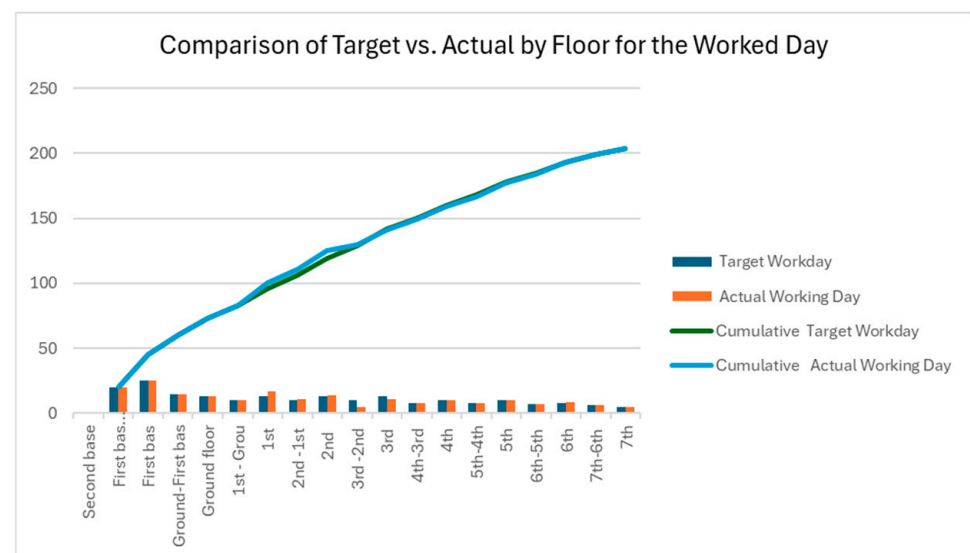


Figure 12. Comparison of Planned and Actual Workdays by Floor.

4.5. Economic Interpretation of Observed Progress Deviations

Although the primary focus of the case study was structural construction progress and schedule monitoring, the observed deviations also have potential economic implications. Delays in structural activities can extend the duration of site operations, increase labor and equipment requirements, disrupt subsequent construction activities, and increase the risk of rework. Therefore, the economic interpretation in this study focuses on the potential cost consequences associated with unresolved progress deviations rather than on attributing direct cost savings to the BIM–AR system.

Labor payment records were examined as cost-related project information and interpreted together with the observed structural progress and schedule conditions. Differences between planned and actual labor-related payments were considered in relation to variations in construction duration, workforce deployment, and production conditions during the monitored periods. These records provided an additional economic perspective for interpreting the consequences associated with progress and schedule deviations; however, they were not used to calculate a direct return on investment or a monetary saving attributable to AR.

Within this context, the potential economic contribution of BIM–AR lies primarily in its ability to support the earlier visual recognition and interpretation of emerging progress discrepancies. When a planned–observed difference becomes visible during an AR-assisted field inspection, project personnel can examine the corresponding schedule and production records and consider corrective measures before the deviation propagates to subsequent activities. Earlier intervention may help limit additional labor requirements, prolonged site operations, disruption of construction sequencing, rework, and other cost consequences associated with unresolved progress deviations.

Accordingly, the relationship between AR-assisted monitoring and economic performance should be interpreted as an indirect and potential contribution rather than a demonstrated causal cost-saving effect. The BIM–AR system provides a visual decision-support mechanism that may improve the timeliness with which progress-related problems are recognized and communicated, while the resulting economic outcome depends on the corrective actions subsequently taken by project management and on other project-specific factors.

From this perspective, the economic value of BIM–AR-assisted progress monitoring is associated with improving the conditions for proactive project control. By supporting earlier recognition of deviations and more timely corrective decision-making, the approach may contribute to reducing exposure to avoidable additional costs and inefficient resource use. This potential is also relevant to sustainable construction management, since improved control of labor, time, materials, and rework can support more resource-efficient project delivery. Nevertheless, the present case study does not quantify environmental impacts or establish direct monetary savings attributable to AR; these aspects require further investigation through dedicated cost–benefit and sustainability assessments.

During the monitored structural construction period, reinforcement works accounted for a total of 8830 man-days over 216 working days. The average workforce varied across the monitoring periods, reaching its highest level in January 2025. Based on the recorded reinforcement quantity of 5,854,290 kg, the corresponding labor productivity was approximately 663 kg per man-day. These workforce records were used as contextual information for interpreting changes in structural production and schedule performance rather than as direct evidence of an AR-induced productivity improvement. Table 8 presents the periodic workforce and labor input for reinforcement works during the monitored structural construction period, including the number of man-days, working days, and average workforce employed in each monitoring period.

Formwork activities accounted for a total of 6920 man-days over 159 working days during the monitored period. The average workforce varied between monitoring periods and increased notably during January 2025. Considering the total recorded formwork quantity of 117,485.44 m², the corresponding labor productivity was approximately 16.98 m² per man-day. Similar to the reinforcement records, these data were used to characterize workforce deployment and production conditions during the monitored structural construction period and were not interpreted as productivity gains directly attributable to the BIM–AR application. Table 9 presents the periodic workforce and labor input for formwork works during the monitored structural construction period, including the number of man-days, working days, and average workforce employed in each monitoring period.

Table 8. Periodic Workforce and Labor Input for Reinforcement Works.

Rebar Monthly Wages	Number of Man-Days	Working-Day	Number of Workers
Jul. 24	819	23	35.6
Aug. 24	918	23	39.9
Sep. 24	973	24	40.5
Oct. 24	1050	26	40.4
Nov. 24	1100	26	42.3
Dec. 24	1059	24	44.1
Jan. 25	1201	24	50
Feb. 25	900	23	39.1
Mar. 25	810	23	35.2
	8830	216	40.8
	5,854,290.00	kg of rebar	
	663	kg per worker	

Table 9. Periodic Workforce and Labor Input for Formwork Works.

Formwork Daily Wages	Number of Man-Days	Working-Day	Number of Workers
Jul. 24	610	16	38.1
Aug. 24	672	16	42
Sep. 24	795	18	44.2
Oct. 24	850	20	42.5
Nov. 24	880	19	46.3
Dec. 24	800	18	44.4
Jan. 25	915	17	53.8
Feb. 25	797	19	41.9
Mar. 25	601	16	37.6
	6920	159	43.4
	117,485.44	sqm formwork	
	16.98	sqm per worker	

Based on all reviews, it can support the interpretation of time- and cost-related project conditions affecting the project. According to the reviews, while the planned payment as of July 2024, was \$735,150.12, the actual payment as of July 2024, amounted to \$803,184.55.

The difference of USD 68,034.43 (8.5%) represents the difference between planned and actual labor-related payment records and should not be interpreted as a monetary saving or economic benefit generated by the BIM–AR application. The observed difference may reflect multiple project-specific factors, including workforce deployment, construction pace, production quantities, and other operational conditions. BIM–AR supported the visual recognition of potential deviations between the expected and observed structural conditions during field inspections, while the existence and magnitude of these deviations were subsequently evaluated using the corresponding project records. Table 10 compares the payment records related to planned and actual labor costs throughout the construction period under review. The differences presented in the table show the variations between planned and actual labor costs.

Table 10. Comparison of Planned and Actual Labor-Related Payment Records.

Cost-Related Record	Planned Amount (USD)	Actual Amount (USD)	Difference (USD)	Difference (%)
Payment status at the reference date	735,150.12	803,184.55	68,034.43	8.5%
Total calculated payment	811,799.97	889,830.51	78,031.00	8.8%

The payment differences presented in Table 10 cannot be causally attributed to the BIM–AR application, as they may also reflect variations in construction pace, workforce deployment, production quantities, and other project-specific factors. Nevertheless, the case observations indicate that AR-assisted visual verification can support the earlier recognition of emerging progress discrepancies. When such discrepancies are recognized earlier and subsequently confirmed through schedule and production records, project managers have an opportunity to implement corrective measures before the deviations propagate to subsequent activities. In this sense, the potential economic contribution of BIM–AR lies not in the payment differences themselves, but in its capacity to support earlier corrective decision-making that may help limit additional labor requirements, prolonged site operations, rework, and other avoidable cost exposure. Table 11 summarizes the periodic progress observations, corresponding schedule conditions, and labor responses observed during the monitored structural construction period.

Table 11. Summary of Periodic Progress Observations, Schedule Conditions, and Labor Responses.

Monitoring Period	Progress Observation	Schedule Condition	Labor Status/Intervention
Nov. 2024	Planned structural construction activities were compared with the conditions observed on site.	Floor-level progress and working-day records were evaluated.	Construction activities continued with the existing workforce.
Dec. 2024	A potential progress deviation was visually identified during BIM–AR-assisted field inspections and subsequently evaluated using project records.	A temporary schedule deviation was identified based on the floor-level working-day and approved schedule records.	The workforce was increased from late December onward.
Jan. 2025	Field observations and project records indicated an improvement in structural progress.	Schedule performance showed signs of recovery following the management intervention.	Structural production activities continued with the increased workforce.
Feb.–Mar. 2025	Structural production and on-site progress continued to be monitored.	Improvement in progress conditions continued following the temporary deviation observed in the preceding period.	Workforce levels were maintained in accordance with structural production requirements.

5. Discussion

The findings of this study demonstrate the practical applicability of BIM-integrated AR as a complementary visual verification and decision-support tool for periodic construction progress monitoring under actual site conditions. Rather than replacing conventional inspection and project-control practices, the proposed framework combines BIM–AR-assisted field visualization with established project information, including the approved construction schedule, floor-level working-day records, structural concrete production data,

and labor-related payment records. This distinction is important because the quantitative assessment of structural progress and schedule deviations in the present study was derived from project records, whereas AR provided an additional spatial and visual layer for relating planned BIM information to observable construction conditions.

The field implementation showed that BIM–AR can support the interpretation of planned–observed conditions by enabling the relevant BIM model to be viewed directly within the physical construction environment during periodic inspections. This finding is consistent with previous studies reporting the potential of BIM–AR integration for construction visualization, inspection, and progress monitoring [7–23]. However, the added value observed in the present study extends beyond visualization as an independent function. Conventional schedule and production records can indicate how much work has been completed and how long construction activities have taken, but they do not necessarily provide a direct spatial representation of where and under what physical site conditions a potential discrepancy is occurring. BIM–AR complements these records by providing a common visual reference through which planned structural information can be interpreted in relation to observable site conditions.

This complementary relationship is particularly relevant to the interpretation of progress deviations. In the proposed framework, a discrepancy observed through BIM–AR visualization was not independently classified as a quantitative schedule deviation. Instead, visually recognized conditions were subsequently examined against the corresponding schedule, working-day, and structural production records. Accordingly, AR functioned primarily as a mechanism for visual recognition, localization, and interpretation, while conventional project records provided the quantitative basis for confirming and measuring progress and schedule differences. This combined approach addresses an important limitation in previous BIM–AR research, where technological visualization capabilities have often received greater attention than their systematic integration with actual project-control data under field conditions.

The results also emphasize the importance of distinguishing structural production progress from schedule performance. Planned and actual concrete quantities in this study were used exclusively as indicators of reinforced-concrete structural production and were not interpreted as measures of overall project progress. Overall construction progress would require consideration of other project components, including mechanical and electrical installations, façade systems, architectural finishes, and other non-structural activities. Similarly, concrete quantity differences were not converted into schedule deviations. Schedule differences were evaluated separately through the approved construction schedule and planned–actual working-day records for the monitored structural activities. This distinction provides a more transparent basis for interpreting production- and time-related information and avoids attributing schedule performance to changes in production quantities alone.

From a construction-management perspective, the proposed framework can be integrated into existing progress-control practices without requiring the replacement of established project documentation. A practical implementation sequence may begin with the preparation of the BIM model and approved schedule information, followed by periodic AR-assisted field inspections. During these inspections, planned BIM information can be related to observable construction conditions and potential discrepancies can be documented. The identified conditions can then be cross-checked against schedule, working-day, production, and other relevant project records before being communicated to responsible project personnel for further investigation and corrective decision-making. Thus, BIM–AR can function as an additional verification layer within existing inspection and reporting procedures rather than as an independent monitoring system.

The monitoring frequency should also be considered when interpreting the findings. Although the AR application enables BIM information to be visualized immediately during an individual site inspection, the progress assessment performed in this study was based on periodic field observations. Therefore, the proposed framework represents periodic progress monitoring rather than continuous or real-time construction tracking. This distinction separates real-time AR visualization from real-time data acquisition and continuous progress monitoring. In practice, the inspection frequency could potentially be adjusted according to project requirements, construction intensity, critical activities, or management priorities; however, the effectiveness of alternative monitoring frequencies was not evaluated in the present study.

The economic findings require similarly careful interpretation. Differences between planned and actual labor-related payment records were observed during the monitored construction period; however, these differences cannot be interpreted as monetary savings generated by the BIM–AR application. Such differences may result from variations in construction quantities, workforce deployment, construction pace, prices, productivity conditions, or other project-specific factors. Consequently, the present study does not establish a causal relationship between AR implementation and direct cost savings and does not constitute a detailed economic cost–benefit analysis.

Nevertheless, BIM–AR-assisted monitoring may have an indirect economic relevance through its potential to support earlier recognition of emerging progress discrepancies. When a potential discrepancy is visually recognized during a field inspection and subsequently confirmed through schedule and production records, project personnel may have an earlier opportunity to investigate its underlying causes and consider corrective action before its effects propagate to subsequent construction activities. In practical terms, timely intervention may help limit exposure to prolonged site operations, additional labor requirements, disrupted construction sequencing, rework, and associated additional costs. These potential effects should be interpreted as management opportunities enabled by improved visual awareness rather than as quantitatively demonstrated savings attributable to AR.

This interpretation is also relevant from a sustainability perspective. Construction delays, rework, inefficient workforce deployment, and prolonged site operations can contribute to inefficient use of labor, materials, equipment, time, and financial resources. By complementing conventional monitoring practices with improved visual interpretation of planned–observed conditions, BIM–AR-assisted monitoring may support more proactive and resource-efficient construction management. However, the present study did not directly quantify environmental indicators such as material waste, energy consumption, or carbon emissions. Therefore, the sustainability contribution identified here should primarily be understood in terms of resource-efficient project management and the potential avoidance of inefficient resource use, rather than as a directly measured environmental sustainability benefit.

The practical contribution of the proposed framework therefore lies in integrating three complementary information layers: BIM-based planned information, AR-assisted field verification, and quantitative project records. BIM provides the planned digital representation, AR relates this information spatially to observable site conditions, and project records provide the quantitative evidence required to evaluate structural production and schedule differences. The combination of these information sources provides a more structured basis for interpreting construction progress than relying on visualization or project records in isolation. Importantly, the framework does not imply that AR independently determines project performance; rather, its value lies in improving the visual and spatial context within which conventional progress information can be interpreted and communicated.

Several limitations should be considered when interpreting these findings. First, the study was conducted on a single hospital construction project and focused on the reinforced-concrete structural construction phase, which limits the generalizability of the findings to other project types and construction stages. Second, field observations were conducted periodically, and therefore the framework was not evaluated as a continuous monitoring system. Third, technical AR performance indicators such as registration accuracy, marker-recognition performance, tracking stability, and system latency were not quantitatively benchmarked. Fourth, verification time, communication efficiency, and decision-making performance were not independently measured through controlled comparisons or user-based evaluation. Finally, the study did not employ a counterfactual or control condition capable of isolating the causal effects of AR on schedule or cost performance. Future research should therefore evaluate the framework across multiple projects and construction stages, investigate different monitoring frequencies, quantify technical AR performance, and employ comparative or longitudinal research designs to determine whether earlier AR-assisted discrepancy recognition results in measurable reductions in delay, rework, resource consumption, and project costs.

6. Conclusions

Construction progress monitoring is essential for identifying deviations between planned and actual construction conditions and supporting timely project-control decisions. However, conventional monitoring practices often require project personnel to interpret information distributed across schedules, progress records, drawings, production data, and field observations. This study investigated whether BIM-integrated AR can complement these established practices by providing an additional visual and spatial verification layer during construction progress monitoring.

The study developed and implemented a BIM–AR-assisted framework for periodic structural construction progress monitoring in a real hospital construction project. BIM-based AR visualization was combined with periodic field observations and conventional project records, including the approved construction schedule, floor-level working-day records, structural concrete production data, and labor-related payment records. AR was used to relate planned BIM information to observable site conditions during field inspections, whereas quantitative assessment of structural production and schedule differences was based on the corresponding project records.

The case study demonstrated the practical feasibility of integrating BIM–AR visualization into periodic field-monitoring activities under actual construction site conditions. The findings showed that AR can provide a complementary visual reference for recognizing, localizing, and interpreting planned–observed discrepancies during field inspections. Structural concrete records provided quantitative information on structural production progress, while planned and actual working-day records provided the basis for assessing schedule differences. Importantly, concrete quantities were not used as an indicator of overall project progress or converted directly into schedule deviations. Similarly, visually identified discrepancies through AR were not independently treated as quantitative evidence of delay but were examined in conjunction with the corresponding project records.

From a practical perspective, the proposed framework can be incorporated into existing construction-management procedures without replacing conventional field inspection, documentation, or project-control practices. BIM–AR can be used during periodic site inspections to provide a visual comparison between planned and observable construction conditions, after which potential discrepancies can be cross-checked against schedule and production records. This combined process can support project personnel in identifying conditions requiring further investigation and may provide opportunities for more

timely corrective decision-making. Earlier recognition of emerging discrepancies may consequently help limit their propagation to subsequent activities and reduce exposure to rework, prolonged site operations, additional labor requirements, and inefficient resource use. These potential effects also indicate the relevance of BIM–AR-assisted monitoring to more resource-efficient and sustainable construction management.

The economic findings should nevertheless be interpreted cautiously. Differences observed between planned and actual labor-related payment records cannot be considered direct cost savings generated by the BIM–AR application, since they may result from variations in construction quantities, workforce deployment, construction pace, prices, and other project-specific conditions. Therefore, this study does not establish a causal relationship between BIM–AR implementation and monetary savings and does not constitute a detailed economic cost–benefit analysis. Rather, the potential economic value of BIM–AR lies in supporting earlier awareness of progress discrepancies and creating opportunities for corrective action that may help limit exposure to additional costs.

Several limitations should be acknowledged. The study was conducted on a single hospital project and focused on the reinforced-concrete structural construction phase. Field observations were performed periodic; therefore, the proposed approach represents periodic rather than continuous or real-time progress monitoring. Technical performance indicators such as registration accuracy, marker-recognition accuracy, tracking stability, and system latency were not quantitatively evaluated. Furthermore, verification time, communication efficiency, decision-making performance, environmental sustainability indicators, and causal cost savings attributable to AR were not independently measured.

Future research should validate the proposed framework across different project types, construction stages, and monitoring frequencies. Further studies should also quantitatively evaluate AR registration and tracking performance and investigate its effects on inspection time, discrepancy-recognition accuracy, communication, and decision-making. Comparative or longitudinal research designs incorporating appropriate baseline or control conditions are required to determine whether earlier AR-assisted discrepancy recognition leads to measurable reductions in delays, rework, resource consumption, and project costs. Future studies could also integrate environmental indicators, including material waste, energy consumption, and carbon emissions, to quantify more comprehensively the contribution of BIM–AR-assisted progress monitoring to sustainable construction management.

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References

- Keleş, A.; Keleş, M.K. Examination of Computer Software and Information Technologies Whose Usage Increased in the Construction Industry. *El-Cezeri* **2018**, *5*, 610–617. Available online: <https://dergipark.org.tr/en/download/article-file/488586> (accessed on 1 August 2026).
- Aladağ, H. Türk İnşaat Sektöründe Dijital Dönüşüm Uygulamaları Üzerine Bir Araştırma. *Mühendislik Bilimleri ve Tasarım Dergisi* **2022**, *10*, 973–986. [CrossRef]
- Bahçeci, H.; Polat, Ü.H. İnşaat Sektöründe Teknoloji Adaptasyon Sorunlarının Araştırılması. *Online J. Art Des.* **2020**, *8*, 141–153.
- Koparan, B. Digital Transformation in the Construction Industry: A Literature-Based Evaluation. *Int. J. New Horiz. Sci.* **2025**, *3*, 53–63. Available online: <https://jihsci.com/index.php/jihsci/article/view/38> (accessed on 1 August 2026).
- Milgram, P.; Colquhoun, H. A taxonomy of real and virtual world display integration. *Mix. Real. Merging Real Virtual Worlds* **1999**, *1*, 1–26.
- Hajirasouli, A.; Banihashemi, S.; Drogemuller, R.; Fazeli, A.; Mohandes, S.R. Augmented reality in design and construction: Thematic analysis and conceptual frameworks. *Constr. Innov.* **2022**, *22*, 412–443. [CrossRef]
- Adebowale, O.J.; Agumba, J.N. Applications of augmented reality for construction productivity improvement: A systematic review. *Smart Sustain. Built Environ.* **2024**, *13*, 479–495. [CrossRef]
- Bhatarai, R.; Banihashemi, S.; Shakouri, M.; Antwi-Afari, M. Integration of Augmented Reality with Building Information Modeling: Design Optimization and Construction Rework Reduction Perspective: R. Bhatarai et al. *Arch. Comput. Methods Eng.* **2025**, *32*, 2233–2254. [CrossRef]
- Ofluoglu, S. *Yapı Bilgi Modelleme: Yeni Nesil Mimari Yazılımlar*; Mimar Sinan Üniversitesi: İstanbul, Turkey, 2009.
- Alkan, I.B.; Basaga, H.B. Augmented reality technologies in construction project assembly phases. *Autom. Constr.* **2023**, *156*, 105107. [CrossRef]
- Nassereddine, H.; Hanna, A.S.; Veeramani, D.; Lotfallah, W. Augmented reality in the construction industry: Use-cases, benefits, obstacles, and future trends. *Front. Built Environ.* **2022**, *8*, 730094. [CrossRef]
- El Kassis, R.; Ayer, S.K.; El Asmar, M. Augmented reality applications for synchronized communication in construction: A review of challenges and opportunities. *Appl. Sci.* **2023**, *13*, 7614. [CrossRef]
- Whyte, J. Industrial applications of virtual reality in architecture and construction. *J. Inf. Technol. Constr. (ITcon)* **2003**, *8*, 43–50. Available online: <http://www.itcon.org/2003/4> (accessed on 1 August 2026).
- Loijens, L.W.S.; Brohm, D.; Domurath, N. What is augmented reality? In *Augmented Reality for Food Marketers and Consumers*; Wageningen Academic Publishers: Wageningen, The Netherlands, 2017; pp. 13–28. [CrossRef] [PubMed]
- Erbaş, Ç.; Demirel, V. Eğitimde artırılmış gerçeklik uygulamaları: Google Glass örneği. *Öğretim Teknolojileri ve Öğretmen Eğitimi Dergisi* **2014**, *3*, 8–16. Available online: <https://izlik.org/JA54RS73MB> (accessed on 1 August 2026).
- Gökçeşlan, A. Artırılmış Gerçeklik Uygulamaları Ve Grafik Tasarım Alanına Yansımaları. *Electron. Turk. Stud.* **2016**, *11*, 697–708. [CrossRef]
- Arıcı, F.; Arıcı, B. *Eğitimde Artırılmış Gerçeklik Uygulamaları ve Materyal Tasarımı Örnekleri*; Iksad Yayınları: Ankara, Türkiye, 2022.
- Lee, J.G.; Seo, J.; Abbas, A.; Choi, M. End-Users' augmented reality utilization for architectural design review. *Appl. Sci.* **2020**, *10*, 5363. [CrossRef]
- Garbett, J.; Hartley, T.; Heesom, D. A multi-user collaborative BIM-AR system to support design and construction. *Autom. Constr.* **2021**, *122*, 103487. [CrossRef]
- Sivapriyan, R.; Raj, L.; Selvi, T.; Raj, G. Review on augmented reality in civil engineering education and application. In *2024 International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics (IITCEE)*; IEEE: New York, NY, USA, 2024; pp. 1–5.
- Zaher, M.; Greenwood, D.; Marzouk, M. Mobile augmented reality applications for construction projects. *Constr. Innov.* **2018**, *18*, 152–166. [CrossRef]
- Lin, Z.Y.; Petzold, F.; Ma, Z.L. A real-time 4D augmented reality system for modular construction progress monitoring. In *Proceedings of the International Symposium on Automation and Robotics in Construction, Banff, AB, Canada, 21–24 May 2019*; Volume 36, pp. 743–748. [CrossRef] [PubMed]
- Machado, R.L.; Vilela, C. Conceptual framework for integrating BIM and augmented reality in construction management. *J. Civ. Eng. Manag.* **2020**, *26*, 83–94. [CrossRef]
- Kuo, W.L.; Huan, B.K.; Hsieh, S.H.; Tsai, Y.H.; Chang, Y.T. Integration of BIM and AR with VSLAM to assist in construction site inspection. *J. Civ. Eng. Manag.* **2025**, *31*, 646–669. [CrossRef]
- Abbas, A.; Seo, J.; Kim, M. Impact of mobile augmented reality system on cognitive behavior and performance during rebar inspection tasks. *J. Comput. Civ. Eng.* **2020**, *34*, 04020050. [CrossRef]
- Bloomquist, E.T.; Gabbard, J.L.; Tanous, K.; Qin, Y.; Bulbul, T. Framing the scene: An examination of augmented reality head worn displays in construction assembly tasks. In *Proceedings of the 2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops, Atlanta, GA, USA, 22–26 May 2020*; pp. 790–791. [CrossRef]

27. Li, M.; Feng, X.; Han, Y.; Liu, X. Mobile augmented reality-based visualization framework for lifecycle O&M support of urban underground pipe networks. *Tunn. Undergr. Space Technol.* **2023**, *136*, 105069. [\[CrossRef\]](#)
28. Wu, S.; Hou, L.; Chen, H.; Zhang, G.K.; Zou, Y.; Tushar, Q. Cognitive ergonomics-based Augmented Reality application for construction performance. *Autom. Constr.* **2023**, *149*, 104802. [\[CrossRef\]](#)
29. Wang, X.; Dunston, P.S. Design, strategies, and issues towards an augmented reality-based construction training platform. *J. Inf. Technol. Constr. (ITcon)* **2007**, *12*, 363–380. Available online: <http://itcon.org/2007/25/> (accessed on 1 August 2026).
30. Chen, Y.J.; Lai, Y.S.; Lin, Y.H. BIM-based augmented reality inspection and maintenance of fire safety equipment. *Autom. Constr.* **2020**, *110*, 103041. [\[CrossRef\]](#)
31. Wolf, M.; Teizer, J.; Wolf, B.; Bükrü, S.; Solberg, A. Investigating hazard recognition in augmented virtuality for personalized feedback in construction safety education and training. *Adv. Eng. Inform.* **2020**, *51*, 101469. [\[CrossRef\]](#)
32. Rahman, M.H.; Ghasemi, A.; Dai, F.; Ryu, J. Review of emerging technologies for reducing ergonomic hazards in construction workplaces. *Buildings* **2023**, *13*, 2967. [\[CrossRef\]](#)
33. Suhail, N.; Bahroun, Z.; Ahmed, V. Augmented reality in engineering education: Enhancing learning and application. *Front. Virtual Real.* **2024**, *5*, 1461145. [\[CrossRef\]](#)
34. Kıvrak, S.; Arslan, G. İnşaat proje imalatlarında artırılmış gerçeklik teknolojisi uygulamaları. *Politek. Derg.* **2018**, *21*, 379–385. [\[CrossRef\]](#)
35. Ahn, S.; Han, S.; Al-Hussein, M. 2D drawing visualization framework for applying projection-based augmented reality in a panelized construction manufacturing facility: Proof of concept. *J. Comput. Civ. Eng.* **2019**, *33*, 04019032. [\[CrossRef\]](#)
36. Tzimas, E.; Vosniakos, G.C.; Matsas, E. Machine tool setup instructions in the smart factory using augmented reality: A system construction perspective. *Int. J. Interact. Des. Manuf.* **2019**, *13*, 121–136. [\[CrossRef\]](#)
37. Jia, C.; Liu, Z. Collision detection based on augmented reality for construction robot. In Proceedings of the 2020 5th International Conference on Advanced Robotics and Mechatronics, Shenzhen, China, 18–21 December 2020; pp. 194–197. [\[CrossRef\]](#)
38. Alkan, İ.B. Artırılmış Gerçeklik Teknolojisinin Kalıpcı Ustaları Tarafından Merdiven Kalıbı Uygulamasında Kullanılmasının, Ustaların Uzamsal Algılarına, Uygulama Sürelerine ve Uygulama Hatalarına Etkilerinin İncelenmesi. Ph.D. Thesis, Karadeniz Technical University, Trabzon, Turkey, 2025.
39. Mitterberger, D.; Dörfler, K.; Sandy, T.; Salveridou, F.; Hutter, M.; Gramazio, F.; Kohler, M. Augmented bricklaying: Human-machine interaction for in situ assembly of complex brickwork using object-aware augmented reality. *Constr. Robot.* **2020**, *4*, 151–161. [\[CrossRef\]](#)
40. Qin, Y.; Bloomquist, E.; Bulbul, T.; Gabbard, J.; Tanous, K. Impact of information display on worker performance for wood frame wall assembly using AR HMD under different task conditions. *Adv. Eng. Inform.* **2021**, *50*, 101423. [\[CrossRef\]](#)
41. Kaiser, B.; Strobel, T.; Verl, A. Human-robot collaborative workflows for reconfigurable fabrication systems in timber prefabrication using augmented reality. In Proceedings of the 2021 27th International Conference on Mechatronics and Machine Vision in Practice, Shanghai, China, 26–28 December 2021; pp. 576–581. [\[CrossRef\]](#)
42. Fenais, A.; Ariaratnam, S.T.; Ayer, S.K.; Smilovsky, N. Integrating geographic information systems and augmented reality for mapping underground utilities. *Infrastructures* **2019**, *4*, 60. [\[CrossRef\]](#)
43. Ratajczak, J.; Riedl, M.; Matt, D.T. BIM-based and AR application combined with location-based management system for the improvement of the construction performance. *Buildings* **2019**, *9*, 118. [\[CrossRef\]](#)
44. Hasan, S.M.; Lee, K.; Moon, D.; Kwon, S.; Jinwoo, S.; Lee, S. Augmented reality and digital twin system for interaction with construction machinery. *J. Asian Archit. Build. Eng.* **2022**, *21*, 564–574. [\[CrossRef\]](#)
45. Alghamdi, S. Evaluating 4d Multiuser Construction Plan Reviews Using Augmented Reality. Master's Thesis, The Pennsylvania State University, University Park, PA, USA, 2023.
46. Hidayat, D.; Setiawan, D.; Arisandi, D. Aplikasi visualisasi pembangunan jalan baru menggunakan augmented reality. *JEKIN-J. Tek. Inform.* **2023**, *3*, 45–51. [\[CrossRef\]](#)
47. Yoon, J.W.; Lee, S.H. Development of a construction-site work support system using BIM-marker-based augmented reality. *Sustainability* **2023**, *15*, 3222. [\[CrossRef\]](#)
48. Ho, T.L.H.; Thanh, N.C. Virtual Reality and Augmented Reality Technology in Bridge Engineering: A Review. *Eng. Technol. Appl. Sci. Res.* **2025**, *15*, 20729–20736. [\[CrossRef\]](#)
49. Esendal, H.; Kazaz, A. Augmented Reality Application for Reducing Reconstruction Costs, Preventing Loss of Working Days and Improving Design Quality. *Buildings* **2025**, *15*, 3595. [\[CrossRef\]](#)
50. Töre, T. Mimari Koruma Bağlamında Artırılmış Mekân Uygulamalarının Kullanımı ve Değerlendirilme Ölçütleri “@rkademi” Uygulaması. Ph.D. Thesis, Mimar Sinan Fine Arts University, İstanbul, Turkey, 2017.
51. Ünal, F.C. The Use of Local Data in Architectural Design Through Augmented Reality. Ph.D. Thesis, Istanbul Technical University, Istanbul, Turkey, 2019.
52. Liu, Z.; Bai, W. Building information modeling methods for post-earthquake retrofitting visualization of buildings using augmented reality. *Appl. Sci.* **2021**, *11*, 5739. [\[CrossRef\]](#)

53. Acar, A.; Atalay, F.B.; Say, S.; Tunca, E.M.; Cetin, M.C.; Caliskan, S.N.; Karakaya, A.F. Developing a mobile augmented reality application for cultural heritage. *J. Fac. Eng. Archit. Gazi Univ.* **2022**, *37*, 1931–1944. [[CrossRef](#)]
54. Revolti, A.; Dallasega, P.; Schulze, F.; Walder, A. Augmented Reality to support the maintenance of urban-line infrastructures: A case study. *Procedia Comput. Sci.* **2023**, *217*, 746–755. [[CrossRef](#)]
55. Um, J.; Min Park, J.; Yeon Park, S.; Yilmaz, G. Low-cost mobile augmented reality service for building information modeling. *Autom. Constr.* **2023**, *146*, 104662. [[CrossRef](#)]
56. Aktürk, İ. Augmented Reality Applications of Destroyed Cultural Heritage Use of Artificial Neural Networks in Data Collection Phase: Trabzon Example. Ph.D. Thesis, Karadeniz Technical University, Trabzon, Turkey, 2024.

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