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Exploring the Role of AR-Integrated BIM Systems in Construction Site Error Management

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ABSTRACT

Managing construction-related errors has become increasingly important as construction projects continue to grow in scale and technical complexity. Digital technologies, particularly the combined use of Building Information Modeling (BIM) and Augmented Reality (AR), offer new opportunities to strengthen inspection procedures and facilitate more effective construction error management. Accordingly, this study evaluates the applicability of BIM–AR integration within the broader framework of smart design and digitally enabled construction management. The research employed a mixed-method design that integrated two complementary components: a bibliometric review of studies on BIM–AR integration and an empirical investigation involving a BIM–AR inspection framework implemented within a residential construction project in Ankara, Türkiye. The empirical stage was further supported through semi-structured interviews conducted with practitioners possessing experience in BIM-enabled construction processes. The bibliometric analysis identified dominant research themes, conceptual relationships, and emerging directions in BIM–AR research, while highlighting the limited empirical investigation of AR-supported inspection workflows from practitioner perspectives. The empirical phase involved BIM model preparation, AR integration, and professional evaluation of the potential contribution of the proposed workflow to construction inspection processes. Findings indicate that BIM–AR-supported approaches may facilitate visualization, improve access to project information, support model-based verification, and contribute to inspection-related decision-making. Due to the exploratory nature of the study and the limited participant group (n = 15), the findings are not intended for statistical generalization. Rather than drawing broadly generalizable conclusions, this research offers an initial understanding of practical implementation issues, professional experiences, and the ways in which AR-enabled BIM workflows may support construction inspection and digital quality assurance. The research contributes by integrating bibliometric mapping, workflow evaluation, and practitioner feedback to examine how BIM–AR technologies may support information management and smart construction practices.

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1. Introduction

1.1 Background and Context

The Architecture, Engineering, and Construction (AEC) industry is characterized by highly dynamic project environments involving multiple stakeholders, complex workflows, and continuously evolving project information. Throughout the construction lifecycle, frequent design revisions, interdisciplinary coordination requirements, and unforeseen site conditions introduce challenges that may adversely affect project quality, cost, and schedule performance (Akbay et al., 2023; Bozkurt et al., 2024). As projects become increasingly sophisticated in terms of scale and technological complexity, maintaining consistency between design intent and construction processes has become increasingly challenging. Ensuring that construction activities remain aligned with approved specifications is therefore recognized as an important issue in contemporary construction management and digital project governance. Construction errors remain among the important factors influencing project performance throughout different phases of construction. Such errors may originate from design inconsistencies, incorrect interpretation of documentation, inaccurate field implementation, material-related deficiencies, dimensional deviations, or inadequate coordination among project participants (Aladağ, 2022; Getuli et al., 2020). Although individual errors may appear relatively limited during construction activities, their cumulative effects can contribute to schedule delays, increased costs, productivity losses, contractual conflicts, and rework requirements. Previous studies indicate that rework associated with undetected construction errors represents a significant source of inefficiency within construction projects (Getuli et al., 2020). Beyond economic consequences, unresolved deviations may influence project quality, client satisfaction, facility operation, and overall confidence in project delivery (Wang et al., 2023). Therefore, improving the ability to identify and manage construction deviations at early stages remains an important objective for both researchers and industry professionals. The increasing complexity of contemporary construction projects has transformed site inspection from a conventional quality-control activity into a broader information-based decision-support process. Effective inspection requires monitoring construction progress, identifying deviations, documenting inconsistencies, and supporting corrective actions through reliable project information. Early identification of potential issues is particularly valuable because the complexity and cost of corrective interventions generally increase as construction progresses. Consequently, improving inspection processes through integrated digital information systems has become an important component of construction quality management. Despite its importance, construction site inspection continues to rely largely on conventional approaches based on manual observations, paper-based documentation, two-dimensional drawings, and visual comparisons between planned and constructed conditions. While these methods remain widely used, they are limited by fragmented information flow, dependence on individual experience, and difficulties in accessing comprehensive project data during inspection activities. Inspectors frequently need to interpret information from different sources, including drawings, digital documents, photographs, and physical construction elements, which may increase cognitive workload and create challenges in identifying inconsistencies. Furthermore, the growing volume and complexity of project information generated throughout the construction lifecycle have increased the demand for more integrated and data-supported inspection approaches (Nawari & Ravindran, 2019). These limitations indicate the need for digital solutions capable of improving information accessibility, visualization, and decision-support capabilities within construction environments. Building Information Modeling (BIM) is widely recognized as a key component of digital transformation in the architecture, engineering, and construction (AEC) sector. Rather than serving solely as a three-dimensional modelling tool, BIM enables the centralized management of multidisciplinary project information, supporting design, construction, and operational activities across the building lifecycle (Gu et al., 2022; Huang, 2020). Unlike conventional two-dimensional documentation, BIM provides a centralized information environment that facilitates interdisciplinary collaboration, improves design coordination, and enhances information consistency among stakeholders. The ability to integrate multiple datasets into a single digital model has supported improvements in planning, clash detection, constructability analysis, and visualization, thereby contributing to more coordinated project management processes (Golparvar-Fard et al., 2011). Consequently, BIM has become an important information management approach within digital construction practices.

Despite these advantages, the effective utilization of BIM during construction inspection processes remains a challenge (Golparvar-Fard et al., 2011). In many projects, BIM models continue to function primarily as information repositories used during design and coordination phases, while field inspection activities frequently depend on conventional drawings, photographs, or document-based systems. This separation between digital project information and physical construction activities creates an information gap that may limit the ability of practitioners to efficiently compare planned design information with constructed conditions. As construction projects generate increasingly complex multidimensional information, there is growing interest in technologies capable of transferring BIM-based information into practical inspection workflows and supporting more intuitive interpretation of construction conditions. Recent developments in digital visualization technologies have accelerated the integration of immersive tools into construction management processes. Among recent digital innovations, Augmented Reality (AR) has become an important tool for construction applications by enabling virtual project information to be displayed directly within the physical environment, allowing users to interact with digital building models alongside actual site conditions (Çıracıoğlu & Yaman, 2022). Instead of requiring users to mentally interpret separate drawings or three-dimensional models, AR enables project information to be visualized in relation to physical surroundings. This capability may support improved spatial understanding, facilitate comparison between design information and construction conditions, and enhance communication among project stakeholders. By merging virtual building information with observations made on site, BIM–AR workflows provide an alternative approach to construction inspection that can strengthen digital decision-making throughout project execution. Through AR-supported BIM workflows, practitioners may visualize model elements, examine potential deviations, and document inspection-related information in a more integrated manner compared with conventional approaches (Huang, 2020). However, despite increasing research interest, empirical evidence regarding the practical applicability of BIM–AR workflows for construction inspection, particularly within specific regional and organizational contexts, remains limited. Therefore, further studies are required to examine how BIM–AR integration can contribute to digital construction governance, smart design policies, and quality-management decision processes. As a result, AR-integrated BIM systems may provide additional support for construction inspection activities and proactive deviation management, although their effectiveness depends on implementation conditions, user adaptation, and organizational readiness (Akın vd., 2018; May et al., 2022).

1.2 Research Gap and Objectives

While Building Information Modeling (BIM) and Augmented Reality (AR) have been widely investigated in construction research, their integrated application for supporting construction inspection, deviation identification, and digital quality-management processes remains relatively underexplored. Although previous studies have demonstrated the technological potential of BIM–AR integration, limited empirical evidence exists regarding how these technologies can be structured within inspection workflows and evaluated from the perspective of construction professionals. In particular, studies conducted in Türkiye remain limited, with only a small number of investigations examining BIM–AR integration within construction management contexts. For example, (Feng & Chen, 2019; Svidt & Gade, 2021; Arowoiya et al., 2023; Kahraman & Bayram, 2025), primarily investigated BIM–AR integration through visualization-oriented prototypes, conceptual approaches, and controlled evaluation environments. Although these studies provided valuable insights into visualization capabilities and system functionality, they offered limited evidence regarding the organization of AR-supported BIM workflows for construction inspection processes and their potential contribution to practical decision-making. Studies by (Eryaman and Akün 2023) and (Aktürk and Irlayıcı Çakmak 2025) further highlighted the increasing importance of integrating emerging digital technologies into construction management and site-related processes. Similarly, (McAuley et al. 2017) and (Karacıgan et al.2023) identified organizational, technical, and operational challenges affecting the successful implementation of BIM within the construction industry. Furthermore, (Tezel and Giritli 2019) identified the continuing expansion of BIM research and recommended extending future investigations to diverse areas of construction practice. Likewise, (Beşiroğlu and Serteşer 2026) reported that digital environments supported by BIM can serve as effective tools for assessing construction processes. Although previous studies have investigated BIM technologies by emphasizing their benefits, implementation challenges, and critical success factors (Azhar, 2011; Özorhon & Karahan, 2017), an important research gap remains regarding how BIM–AR integration can support construction inspection processes within the broader context of digital construction governance and smart design policy. Existing research has generally focused on technological capabilities, visualization performance, or implementation barriers, while limited attention has been given to the relationship between BIM–AR workflows, information-based decision support, and digital quality-management strategies. Furthermore, previous studies have frequently examined bibliometric analyses and technological applications as separate research approaches. Limited research has investigated how the evolution of BIM–AR literature corresponds with practical workflow development and practitioner perspectives. These gaps indicate the need for a research framework that examines both the evolution of BIM–AR scholarship and its practical relevance to construction inspection and digitally enabled construction practices. The research framework presented in Table 1 was developed to overcome the identified research gaps by bringing together bibliometric investigation and a practical assessment of a BIM–AR-assisted inspection process. The contribution of this study is not to provide definitive evidence of performance improvement, but rather to investigate the potential applicability of BIM–AR integration for supporting construction inspection, digital information management, and decision-support processes within the framework of smart design policies.

Table 1: Research gaps identified in the existing literature and the expected contributions of this study.

Focus Area	**Existing Literature**	**Identified Limitation**	**Expected Contribution of This Study**
Application Environment	Laboratory experiments and controlled demonstrations	Limited validation under real construction site conditions	Field implementation in an active construction project in Ankara
Research Focus	Visualization and technical system performance	Limited focus on construction error detection and inspection workflows	Evaluation of BIM–AR integration for construction error detection
Research Scope	Bibliometric reviews or technology implementation studies conducted separately	Limited integration of research trend analysis with field implementation	Combined bibliometric and field-based investigation
Regional Context	Predominantly international case studies	Limited empirical evidence from Türkiye	Field implementation within the Turkish construction industry

To provide a broader understanding of BIM–AR integration in construction, the present research combines bibliometric investigation with an exploratory empirical assessment. The bibliometric component maps the development of the existing literature, identifies major research themes and intellectual relationships, and reveals current directions shaping BIM–AR research within construction-related fields. Subsequently, a BIM–AR-supported inspection workflow is developed and evaluated through professional perspectives to explore its applicability, potential advantages, and implementation challenges. By integrating quantitative literature mapping with practitioner-based evaluations, this study seeks to provide a broader understanding of BIM–

AR technologies and their possible contribution to smart design policy objectives, including improved information management, digital decision support, and more integrated construction governance processes.

Objectives of the Study:

This research investigates the practical use of BIM–AR integration in construction inspection while considering its contribution to construction error management. The study is structured around the following objectives:

1. To examine the evolution, research trends, and intellectual structure of BIM–AR integration in construction-related studies through bibliometric analysis.
2. To investigate the implementation of BIM–AR inspection workflows under real project conditions and explore their role in supporting construction inspection practices.
3. To explore how the combined use of BIM and AR can assist inspectors in visualizing construction components, comparing project information with site conditions, and interpreting inspection findings.
4. To explore practitioner perspectives regarding the potential benefits, implementation challenges, and adoption considerations of AR-integrated BIM technologies in construction quality management.
5. To outline strategic considerations for the wider adoption of BIM–AR technologies in digitally supported construction inspection and future smart design initiatives.

Research Propositions:

Drawing on the gaps identified in the literature and the exploratory scope of this research, the following propositions were formulated to guide the empirical investigation:

P1: AR-integrated BIM systems have the potential to support construction site inspection processes by improving access to digital project information.

P2: AR-integrated BIM workflows may facilitate the identification and verification of construction deviations by enabling comparisons between BIM-based design information and physical construction conditions.

P3: AR-integrated BIM environments may enhance visualization, communication, and information-based decision-support processes among construction stakeholders.

1.3 Contribution and Structure of the Paper

This study contributes to the literature on BIM–AR integration by examining the relationship between digital construction technologies, construction inspection processes, and information-based decision support. Rather than evaluating BIM–AR solely from a technological perspective, this research investigates its potential applicability within construction inspection workflows by combining bibliometric analysis, BIM–AR workflow development, and practitioner perspectives. For the academic community, the study contributes by integrating two commonly examined research perspectives: the analysis of BIM–AR research trends and the exploratory evaluation of BIM–AR-supported inspection processes. Previous research has largely concentrated on technological capabilities, visualization performance, or evaluations conducted under controlled conditions. In contrast, the present study combines bibliometric evidence with an exploratory assessment of BIM–AR implementation to examine construction inspection, digital information management, and quality management from a more practice-oriented perspective. The bibliometric findings further reveal how BIM–AR research has evolved over time, highlight relationships among existing studies, and indicate promising areas for future research. From the perspective of practitioners and policymakers, this study provides exploratory insights into how AR-assisted BIM workflows may support digital construction strategies, quality-management practices, and decision-support processes. The findings may contribute to discussions regarding smart design policy by highlighting the role of integrated digital information environments in improving communication, visualization, and coordination among construction stakeholders. However, the study does not aim to provide definitive evidence of performance improvement or direct reductions in construction errors; rather, it explores the potential contributions and implementation considerations of BIM–AR-supported inspection approaches. Ultimately, this research presents an exploratory framework for understanding the role of BIM–AR integration in construction inspection and digital quality management. By combining bibliometric analysis with workflow evaluation and practitioner feedback, the study provides both theoretical and practical perspectives regarding the adoption of digital inspection technologies within the AEC industry.

Structure of the Paper:

The remainder of this article is organized as follows:

Section 2 describes the overall research design, covering the bibliometric methodology together with the procedures adopted for the empirical investigation.

Section 3 reports the outcomes of the bibliometric assessment alongside the findings obtained from the residential construction case study.

Section 4 interprets the results by comparing them with existing literature and considers their relevance to construction inspection and digital quality management.

Finally, Section 5 summarizes the principal conclusions, acknowledges the study's limitations, and identifies opportunities for future research.

2. Materials and Methods

2.1 Study Design and Setting

To obtain both theoretical and practical evidence, this research combines exploratory mixed-method procedures to examine the use of Building Information Modeling (BIM) and Augmented Reality (AR) in construction inspection and construction error management. The research combines bibliometric analysis with a case-based empirical investigation to establish both a theoretical understanding of current BIM–AR research trends and preliminary practical insights regarding the adoption of AR-supported BIM workflows within construction project contexts (Schoonenboom & Johnson, 2017; Shorten & Smith, 2017). A cross-sectional research strategy was employed, enabling the integration of quantitative and qualitative evidence collected within a defined research period. The overall methodology consisted of four sequential and interconnected phases: (1) literature selection, (2) bibliometric analysis, (3) development and evaluation of a BIM–AR-supported inspection workflow, and (4) integrated interpretation of findings. The initial stage of the research consisted of a bibliometric examination of publications retrieved from the Scopus and Web of Science Core Collection databases covering the period from 2020 to 2025. Bibliometric mapping was performed using VOSviewer and the Bibliometrix R package to explore keyword relationships, citation networks, major thematic clusters, and emerging research directions associated with BIM–AR applications in construction. The outcomes of this analysis provided the conceptual basis for the subsequent empirical investigation. The empirical component was carried out through an exploratory case study involving a residential construction project located in Ankara, Türkiye. This project was considered appropriate because it required multidisciplinary coordination, included comprehensive digital project documentation, and offered suitable conditions for examining the interaction between BIM-generated information and the built environment. A BIM model was developed and prepared for visualization within an AR platform to investigate how digital project information could be incorporated into construction inspection activities. Rather than assessing a fully operational real-time inspection system, the study examined the practical implementation of the proposed BIM–AR workflow under actual project conditions. Evidence was gathered through structured field observations together with semi-structured interviews involving practitioners experienced in BIM implementation, construction inspection, and digitally supported construction management. This approach enabled the investigation of user perspectives, implementation considerations, and potential contributions of BIM–AR integration to inspection and quality-management processes. A convergent mixed-method strategy was adopted by integrating quantitative observations and qualitative findings. Quantitative evidence was obtained through structured evaluation criteria related to visualization capability, model-to-site comparison potential, information accessibility, and inspection workflow support. Qualitative evidence was collected through semi-structured interviews exploring perceived benefits, implementation challenges, and adoption considerations. The integration of these complementary data sources supported methodological triangulation and provided exploratory insights into the applicability of BIM–AR-supported inspection approaches. Participants were selected using purposive sampling based on predefined eligibility criteria. Fifteen professionals with experience in BIM applications and construction inspection processes participated in the study. The participant group included site engineers, architects, BIM coordinators, construction managers, technical supervisors, and other professionals involved in construction coordination and inspection-related activities. The participant group was established through purposive recruitment to ensure the inclusion of professionals with appropriate expertise. A total of fifteen individuals experienced in BIM implementation and construction inspection were included in the empirical investigation. Ethical approval for the study was obtained from the Scientific Research and Publication Ethics Committee of the Faculty of Engineering and Natural Sciences, Çankaya University (Approval No. 2026/18). Informed consent was obtained from all participants prior to their participation in the semi-structured interviews. The objective of the research was not to provide statistical generalization or definitive evidence of performance improvement. Instead, the study aimed to generate exploratory evidence regarding the applicability, implementation challenges, and potential contribution of AR-supported BIM workflows to construction inspection, digital information management, and smart construction practices.

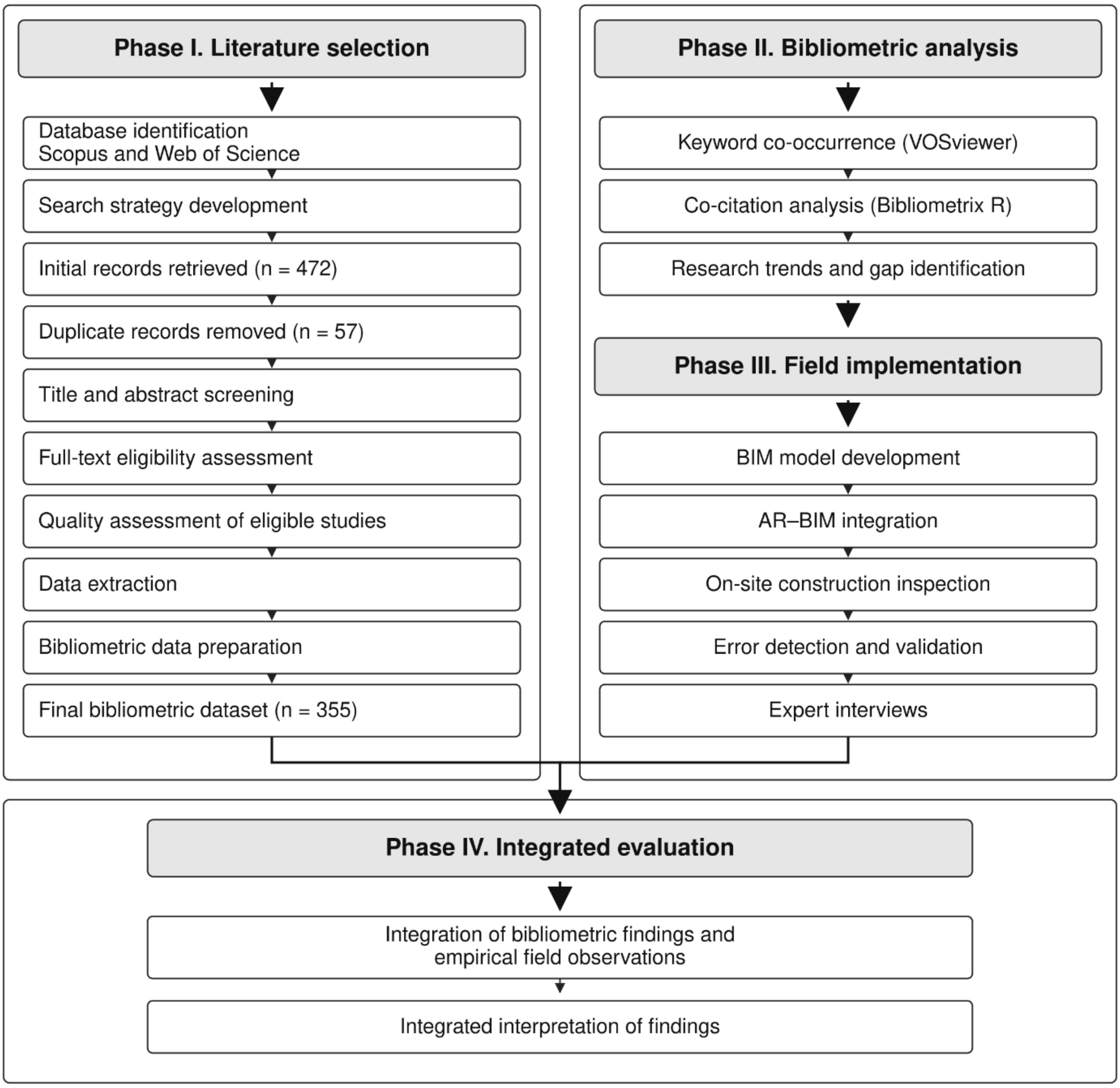

Figure 1. Methodological workflow of the research, illustrating the sequential phases of literature selection, bibliometric analysis, field implementation, and integrated evaluation.

2.2 Bibliometric Analysis

The bibliometric component of the research was undertaken to obtain a comprehensive understanding of how Building Information Modeling (BIM) and Augmented Reality (AR) have been investigated within the fields of construction inspection and construction error management. Instead of providing a conventional review of previous publications, this stage explored the knowledge structure of the field by identifying major research clusters, relationships among keywords and publications, evolving research topics, and areas that continue to require empirical evidence. The results obtained from the bibliometric assessment established the conceptual background for the empirical investigation and supported the identification of research issues associated with the practical implementation of BIM–AR technologies. Relevant publications were collected from the Scopus and Web of Science Core Collection databases because both databases provide extensive coverage of high-quality peer-reviewed research in architecture, engineering, and construction. To reflect recent advances in digital construction technologies, the search was limited to studies published between 2020 and 2025. Search queries incorporated combinations of terms related to Building Information Modeling, Augmented Reality, construction inspection, construction error detection, quality management, and digital construction, with Boolean operators used to improve retrieval accuracy. This search strategy was intended to capture publications addressing not only technological developments but also the practical application of BIM–AR approaches within construction projects. The initial database search resulted in 472 publications. After removing 57 duplicate records, 415 records remained for further screening. A structured selection procedure was subsequently applied, including title screening, abstract evaluation, full-text eligibility assessment, and quality assessment. Only English-language journal articles directly addressing BIM, AR, or their integrated application within construction-related processes were included. Studies that lacked sufficient methodological information, focused solely on unrelated technological applications, or did not contribute to understanding BIM–AR-supported construction inspection processes were excluded. Following the screening and quality assessment stages, bibliographic information including publication year, journal source, authorship information, author keywords, and citation data was extracted from the eligible studies. The extracted records were standardized and prepared for bibliometric analysis using VOSviewer and the Bibliometrix package in R. This process resulted in a final dataset of 355 publications.

The final dataset was analyzed through complementary bibliometric techniques to examine both the conceptual and intellectual characteristics of the research domain. Keyword co-occurrence analysis was conducted using VOSviewer to identify frequently studied concepts, thematic relationships, and emerging research clusters. Co-citation analysis was performed using the Bibliometrix package in R to evaluate influential studies, knowledge structures, and citation relationships shaping the development of BIM–AR research. The combined use of these methods enabled a multidimensional assessment of the research field by integrating conceptual mapping with intellectual structure analysis.

The keyword co-occurrence analysis identified the major research themes and conceptual connections within the BIM–AR domain. As presented in Table 2, Building Information Modeling (BIM) demonstrated the highest occurrence frequency (23) and total link strength (109), indicating its central position within the analyzed research landscape. Augmented Reality was located within the same conceptual cluster, demonstrating its close relationship with BIM-based construction processes and digital visualization approaches. A second thematic cluster consisting of Construction Safety, Safety Management, and Risk Management reflects the increasing interest in applying digital technologies to improve construction monitoring, risk identification, and quality-related decision-making. Additional clusters involving Digital Twin, Visualization, and 4D technologies indicate the expanding integration of BIM with advanced digital environments for construction planning, monitoring, and information management.

Table 2: Top ten keywords identified through keyword co-occurrence analysis, including occurrence frequency, total link strength, and thematic cluster assignment.

Rank	Keyword	Occurrences	Total Link Strength	Cluster
1	Building Information Modeling (BIM) / BIM	23	109	1
2	Building Information Modeling	16	66	1
3	Construction Safety	8	34	2
4	Safety Management	7	31	2
5	Visualization	5	31	4
6	4D	4	26	4
7	Augmented Reality	6	22	1
8	Risk Management	3	18	2
9	Digital Twin	3	12	3
10	Virtual Reality	3	13	1

To improve methodological transparency and support reproducibility, the main analytical parameters used in the bibliometric assessment are summarized in Table 3. These parameters were consistently applied during keyword co-occurrence and co-citation analyses to maintain analytical reliability and ensure consistency throughout the bibliometric process.

Table 3. Bibliometric parameters summarizing dataset characteristics and methodological settings applied during keyword co-occurrence and co-citation analyses.

Parameter	Value
Number of documents analyzed	355
Total keywords identified	121
Minimum keyword occurrence threshold	1
Keywords meeting threshold	84
Number of clusters	4
Largest cluster size	25 keywords
Normalization method	Association Strength
Counting method	Full Counting
Software	VOSviewer Version 1.6.20

As illustrated in Figure 2, Building Information Modeling (BIM) represents the central concept within the keyword network, demonstrating strong relationships with Augmented Reality, Construction, Visualization, Digital Twin, and Virtual Reality. These relationships indicate that BIM continues to serve as a foundational information environment for emerging digital construction applications, including AR-supported inspection workflows. Furthermore, the clustering of Construction Safety, Safety Management, and Risk Management highlights the growing interest in using digital technologies to support construction monitoring, quality assurance, and safety-oriented decision-making. The presence of Digital Twin and Computer Vision-related concepts further demonstrates the broader transition toward interconnected and intelligent construction management systems.

Overall, the bibliometric findings provided an evidence-based understanding of the current BIM–AR research landscape and clarified the limitations of existing studies regarding practical evaluation under construction project conditions. These findings guided the empirical evaluation phase by informing the selection of research focus, assessment criteria, and the development of the AR-supported BIM workflow. Therefore, the bibliometric analysis served not only as a review component but also as an analytical foundation connecting existing knowledge trends with the practical investigation conducted in this study.

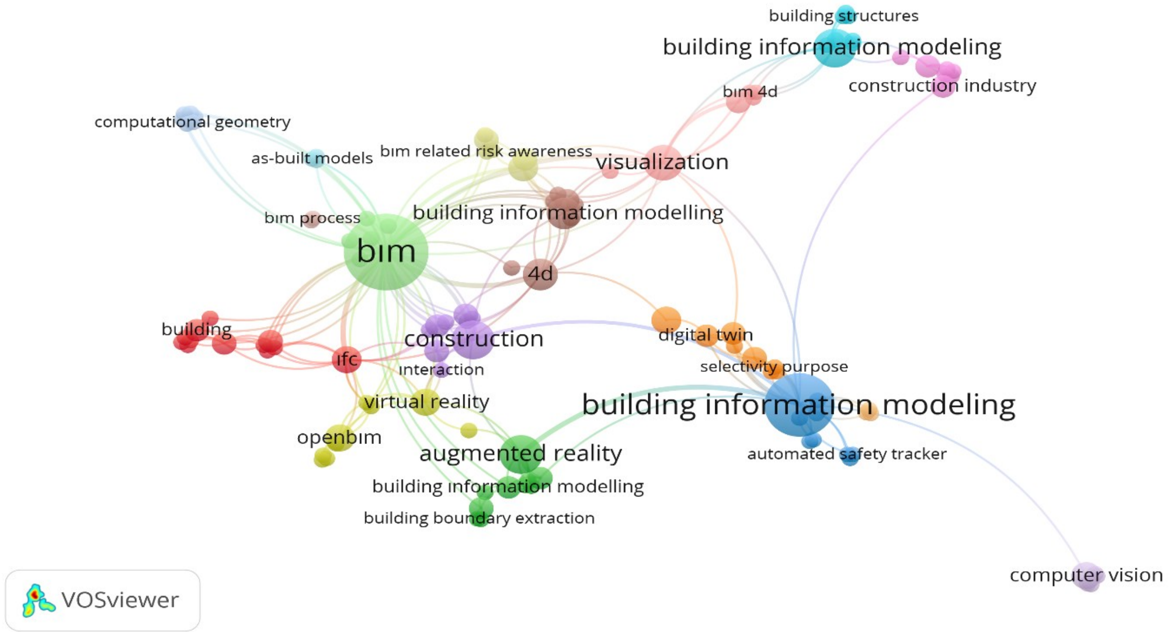

Figure 2. Keyword co-occurrence network generated using VOSviewer illustrating the conceptual relationships among the principal research themes identified in the bibliometric dataset. Node size represents keyword occurrence frequency, link thickness indicates co-occurrence strength, and colors denote thematic clusters.

2.3 Empirical Data Collection

To complement the bibliometric investigation, empirical data were collected through an exploratory BIM–AR workflow evaluation designed to examine the practical applicability of AR-supported BIM technologies for construction inspection and construction error detection. Rather than evaluating the technology as a fully operational inspection system, this phase aimed to investigate the potential contribution of AR–BIM integration to visualization, model-based verification, information accessibility, and decision-support processes within a construction project context.

The empirical evaluation was conducted using a medium-scale reinforced concrete residential development located in Ankara, Türkiye, comprising four residential blocks with a total construction area of approximately 1,871.9 m². The selected project was considered suitable for this research because it involved multidisciplinary coordination requirements and included architectural and mechanical-electrical-plumbing (MEP) components where information consistency and deviation verification represent important challenges during construction processes. A digital BIM model of the selected project was developed in Autodesk Revit at Level of Development (LOD) 300–400 and subsequently prepared for integration into an AR environment to evaluate the feasibility of visualizing digital information in relation to physical construction elements.

The empirical evaluation incorporated multiple sources of evidence to obtain a comprehensive understanding of the applicability of the proposed workflow. The developed BIM–AR workflow was examined according to predefined evaluation criteria, including model visualization capability, accessibility of construction information, potential for identifying deviations between design information and physical conditions, and support for inspection-related decision-making processes. These criteria were evaluated through structured observations and expert-based assessments rather than statistical performance measurement.

Qualitative evidence was collected through semi-structured interviews with professionals experienced in BIM applications and construction inspection processes. The participants included architects, site engineers, BIM specialists, construction managers, and technical supervisors. The interviews explored participants' perceptions regarding visualization quality, information accessibility, potential improvements in inspection workflows, implementation challenges, decision-making support, and the feasibility of integrating AR-supported BIM approaches into construction quality management practices.

The combination of workflow-based observations and expert interviews enabled methodological triangulation by integrating different perspectives regarding the practical applicability of AR-assisted BIM technologies. Due to the exploratory nature of the study and the limited participant group, the collected evidence was interpreted as preliminary insights into implementation potential rather than statistically generalizable performance outcomes.

2.4 Data Interpretation

The interpretation of the collected data followed the exploratory mixed-method strategy adopted in this study, enabling quantitative observations and qualitative findings to be examined together. This analytical approach aimed to provide a comprehensive understanding of AR-supported BIM applications by combining evidence derived from bibliometric analysis with observations obtained during the pilot implementation.

The bibliometric findings were interpreted through keyword co-occurrence and co-citation network analyses. These analyses were used to identify dominant research themes, emerging technological directions, influential publications, and research gaps related to BIM-assisted construction inspection and error detection. As summarized in Table 4, the identified thematic clusters represent the principal conceptual areas within the BIM–AR research domain and provide the theoretical context for interpreting the empirical findings.

Quantitative information obtained during the pilot implementation was examined using descriptive analysis. Observed indicators, including inspection duration, identified construction deviations, visualization capability, and documentation processes, were evaluated to explore the operational potential of the proposed AR-supported BIM workflow. These indicators were not intended to provide statistical generalization but rather to offer preliminary empirical evidence regarding the applicability and potential benefits of AR-assisted BIM technologies for construction inspection.

Qualitative data collected through semi-structured interviews were analyzed using thematic analysis. Interview responses and field observations were systematically reviewed to identify recurring themes related to user experiences, implementation challenges, perceived advantages, and potential areas for improvement. Similar viewpoints were organized into thematic categories to support a structured interpretation of participant perspectives.

Table 4. Main thematic clusters identified through the bibliometric analysis and their representative keywords.

Cluster	Main Theme	Representative Keywords
Cluster 1	BIM and AR Integration	BIM, Augmented Reality, Mixed Reality
Cluster 2	Construction Inspection	Construction Inspection, Error Detection, Quality Control
Cluster 3	Digital Construction	Construction Management, Digital Twin, Information Management
Cluster 4	Visualization Technologies	Visualization, 3D Modeling, Digital Environment

Finally, the bibliometric and empirical findings were interpreted collectively to establish an integrated understanding of BIM–AR research developments and their potential implications for construction inspection practices. The triangulation of literature-based evidence, pilot implementation observations, and expert perspectives supported a more balanced interpretation of the opportunities, limitations, and future application potential of AR-supported BIM workflows.

3. Results

3.1 Respondent profile

The pilot evaluation involved 15 participants representing different professional roles related to construction project management, BIM applications, and site inspection processes. The participant group was purposively selected to include professionals with experience in Building Information Modeling (BIM), construction supervision, quality control, and digital construction practices. The participants represented roles including site managers, BIM coordinators, civil engineers, construction supervisors, safety-related personnel, and technical staff involved in construction coordination and inspection activities.

Professional experience among participants ranged from approximately two years to more than twenty years, allowing the study to capture perspectives from practitioners with different levels of professional background. Participants also demonstrated varying levels of familiarity with BIM and AR technologies. While some participants reported substantial experience with BIM-based workflows and digital construction applications, others had limited prior exposure to AR-supported inspection processes. This variation provided diverse perspectives regarding the perceived applicability, potential benefits, and implementation challenges associated with BIM-integrated AR workflows.

Given the exploratory nature of the study, the participant selection was not intended to provide statistical representation of the broader construction industry. Instead, the aim was to obtain informed professional perspectives regarding the practical applicability of BIM-supported AR inspection workflows. As presented in Table 5, the participant group includes different professional roles, experience levels, and technology familiarity profiles. Therefore, the findings should be interpreted as exploratory evidence regarding user perceptions and implementation potential within the investigated project context rather than as generalized performance outcomes.

Table 5: Demographic characteristics of the pilot study participants.

Participant Code	Professional Role	Years of Experience	BIM Experience	AR Experience
P1	Site Manager	>20	High	Moderate
P2	BIM Coordinator	11–20	High	High
P3	Civil Engineer	6–10	Moderate	Low
P4	Site Supervisor	11–20	Moderate	Low
P5	Safety Officer	>20	Moderate	Low
P6	BIM Coordinator	2–5	Low	Beginner
P7	BIM Coordinator	2–5	Low	Beginner
P8	BIM Coordinator	2–5	Low	Beginner
P9	BIM Coordinator	5-10	Moderate	Low
P10	BIM Coordinator	10-15	Moderate	Moderate
P11	Site Manager	10-15	Moderate	Moderate
P12	Civil Engineer	11–20	High	Moderate
P13	Site Supervisor	>20	High	High
P14	Technical Staff	6–10	Moderate	High
P15	Technical Staff	2–5	Low	Beginner

3.2 Descriptive analysis

The descriptive findings indicate that the integration of Building Information Modeling (BIM) and Augmented Reality (AR) may support several aspects of construction inspection by providing additional digital information and improving the visualization of project components. Observations obtained during the pilot evaluation suggested that AR-supported BIM workflows facilitated the comparison between digital models and physical construction elements, supported the identification of potential deviations, and assisted the verification of selected installed components.

The bibliometric analysis conducted in the previous phase provided an overview of current research trends and demonstrated that BIM, augmented reality, digital visualization, and construction inspection represent prominent themes within the existing literature. These findings established the conceptual basis for the pilot evaluation and informed the selection of the inspection-related aspects examined within the empirical phase.

Field observations indicated that AR-assisted BIM workflows provided easier access to model-based information during inspection activities and supported improved spatial understanding among participants. Interview feedback further suggested that digital overlays helped participants compare the as-designed BIM model with observed construction conditions more effectively. However, the perceived benefits varied depending on task complexity, user familiarity with digital technologies, and the specific inspection context. Therefore, these findings should be interpreted as exploratory evidence regarding the potential contribution of BIM–AR workflows rather than as statistically validated performance improvements.

Overall, the descriptive analysis demonstrates a conceptual alignment between the research themes identified through the bibliometric investigation and the practical observations obtained during the pilot evaluation. As summarized in Table 6, the identified bibliometric themes informed the design and evaluation criteria of the pilot case study, illustrating how current research directions may be translated into practical construction inspection applications. This relationship highlights the potential role of BIM–AR technologies in supporting digital construction management practices while also emphasizing the need for further empirical validation through larger-scale studies.

Table 6. Relationship between bibliometric themes and the pilot case study design.

Bibliometric Theme	Aspect Evaluated in the Pilot Case Study	Research Objective
BIM Integration	The integration of the BIM model into the on-site inspection process was evaluated.	To examine the applicability of BIM-based digital models for supporting construction inspection activities.
Augmented Reality	The use of AR for comparing virtual BIM models with on-site construction elements was investigated.	To assess the potential of AR visualization for facilitating real-time inspection and verification.
Construction Inspection	A BIM–AR-supported inspection workflow was implemented and observed during the pilot application.	To investigate the applicability of a digital inspection approach under real construction site conditions.
Visualization	The effectiveness of digital model visualization during inspection activities was examined.	To evaluate the potential contribution of enhanced visualization to construction inspection processes.
Digital Workflow	The integration of the proposed digital workflow into routine site inspection activities was assessed.	To explore the feasibility of incorporating BIM–AR technologies into existing construction management practices.

3.3 Pilot Case Study Findings

The pilot case study was conducted to explore the practical applicability of BIM-supported Augmented Reality within a construction project context. The evaluation focused on selected inspection scenarios involving architectural and building service components, where BIM-based information was examined as a digital support mechanism for comparing planned design information with observed construction conditions.

The pilot evaluation indicated that the proposed BIM–AR workflow has potential to support inspection activities by providing additional visual information and improving access to model-based project data. The integration of digital model information with AR visualization enabled participants to examine relationships between BIM elements and physical construction components more intuitively. Participants reported that the BIM–AR workflow could assist in identifying potential geometric inconsistencies, improving spatial understanding, and supporting documentation processes during inspection activities.

The evaluation focused on several qualitative and observational aspects, including information accessibility, visualization capability, model verification processes, documentation procedures, and decision-support potential. The findings represent exploratory observations obtained from the pilot evaluation and should not be interpreted as statistically validated improvements in inspection performance. The technical characteristics and implementation framework of the pilot case study are summarized in Table 7, while the evaluation criteria used for comparing conventional and BIM–AR-supported inspection approaches are presented in Table 8.

Table 7: Overview of the pilot case study implementation.

Component	Description
Project type	Reinforced concrete residential building
Project location	Ankara, Türkiye
BIM software	Autodesk Revit
Coordination software	Navisworks
AR platform	Gamma AR (model visualization) and Dalux (field inspection and issue management)
BIM Level	LOD 300–350
Inspection scope	Architectural and MEP elements
Comparison method	Conventional inspection vs BIM–AR inspection

Table 7 summarizes the technical characteristics and planned implementation framework of the pilot case study. The case context involved a reinforced concrete residential building project located in Ankara, Türkiye. The BIM model was developed using Autodesk Revit at LOD 300–350, while Autodesk Navisworks was used to support interdisciplinary model coordination and model review processes. The prepared BIM model was subsequently integrated into AR-based platforms, including Gamma AR and Dalux, to examine the potential use of model visualization and digital information support during inspection activities.

The pilot workflow consisted of several sequential stages. Initially, the BIM model was prepared and reviewed to ensure model consistency and usability for inspection purposes. This stage was followed by interdisciplinary coordination and preparation of the digital model environment. Subsequently, the BIM data were transferred to AR platforms to examine how digital information could support the interpretation and verification of construction components. Finally, conventional inspection practices and BIM–AR-supported approaches were comparatively examined based on predefined evaluation criteria to explore the potential advantages and limitations of the proposed workflow.

Table 8: Evaluation criteria applied during the pilot case study.

Evaluation Criterion	Conventional Inspection	BIM–AR-Supported Inspection	Evaluation Focus
Inspection workflow	Site-based visual inspection	BIM model supported by AR visualization	Comparison of inspection procedures
Information access	2D drawings and printed documents	Digital BIM model	Accessibility of project information
Model verification	Manual comparison	AR-assisted on-site verification	Verification of construction elements
Visualization	Conventional visual observation	Real-time digital visualization	Spatial understanding

Documentation	Manual recording	Digital documentation	Inspection documentation process
Decision support	Inspector experience	BIM-supported digital information	Decision-making process

3.4 Semi-Structured Interview Findings

Semi-structured interviews were conducted following the pilot evaluation to obtain practitioner perspectives regarding the usability, perceived benefits, and practical applicability of the proposed BIM–AR workflow. The interview findings provided qualitative insights that complemented the observational evidence obtained during the pilot study.

Thematic analysis of the interview data identified several recurring themes related to the potential adoption of BIM-supported AR technologies in construction inspection. Participants frequently referred to improved visualization of construction elements, enhanced interpretation of design information, and potential improvements in communication among project stakeholders. Several participants indicated that digital overlays could reduce ambiguity during inspection activities and provide additional support when comparing planned design information with observed construction conditions.

Participants also identified several practical limitations that may affect the implementation of BIM–AR workflows in routine construction practice. Frequently mentioned challenges included hardware ergonomics, environmental factors affecting AR visualization, calibration accuracy, tracking stability, and the initial learning period required for users unfamiliar with digital construction technologies. Although participants generally expressed positive perceptions regarding the potential value of BIM-integrated AR systems, these findings represent user perspectives obtained within an exploratory pilot context and should not be interpreted as evidence of generalized performance improvement.

The interview findings complemented the observational results by providing additional insights into user experiences, perceived advantages, and implementation challenges associated with BIM–AR-supported inspection workflows. As summarized in Table 9, the identified themes include visualization, model verification, construction error detection, quality control, information accessibility, communication, decision support, user adaptation, and technical limitations.

Table 9: Main Themes Identified from the Semi-Structured Interviews.

Theme	Description	Illustrative Quote
Visualization	Participants generally indicated that the AR-supported BIM model improved the visualization of construction elements and enhanced spatial understanding during inspection activities.	*“Viewing the BIM model directly on-site made it easier to understand the location and installation of building components.”* (P3)
Model Verification	Most participants reported that comparing the BIM model with the physical construction facilitated the verification of installed elements and supported the identification of potential discrepancies.	*“Comparing the digital model with the actual construction was more straightforward than using 2D drawings alone.”* (P7)
Construction Error Detection	Participants indicated that overlaying the BIM model onto the physical construction environment supported the identification of construction deviations and potential execution errors during inspection activities.	*“The AR overlay made it easier to notice differences between the planned model and the constructed elements.”* (P9)
Quality Control	Participants considered that BIM–AR-assisted inspections could contribute to a more systematic quality control process by facilitating	*“The system helped us verify whether completed work corresponded to the BIM model*

	the verification of construction activities against the digital model.	*before proceeding to the next construction stage."* (P14)
Information Accessibility	Participants stated that project information could be accessed more efficiently through the digital BIM model during site inspections.	*"Having the project information available on the tablet reduced the need to consult printed drawings."* (P10)
Communication	Several participants emphasized that the shared visualization environment supported communication and coordination among project stakeholders.	*"Using the same digital model helped everyone discuss issues from the same perspective."* (P5)
Decision Support	Participants suggested that the BIM–AR workflow supported a more structured evaluation of construction conditions during inspection activities.	*"The digital model provided additional confidence when checking the construction work."* (P11)
User Adaptation	Participants reported that adapting to the BIM–AR-supported workflow required an initial learning period. Users with limited experience in digital construction technologies and some site workers accustomed to conventional inspection practices experienced difficulties in integrating the system into their routine inspection activities.	*"The AR-based workflow felt unfamiliar, and I found it difficult to integrate it into my routine inspection practices."* (P12)
Technical and Human-Related Limitations	Participants identified calibration accuracy, lighting conditions, device ergonomics, occasional tracking instability, and challenges associated with introducing BIM–AR-supported inspection workflows to experienced site workers who were more familiar with conventional inspection methods.	*"Some experienced workers preferred to continue using conventional inspection methods rather than incorporating the tablet-based system into their daily routine."* (P8)

3.5 Integrated Findings

The integration of bibliometric analysis, pilot implementation observations, and semi-structured interviews provides an exploratory understanding of the current research landscape and practical applicability of BIM-supported Augmented Reality within construction inspection processes. Rather than relying on a single source of evidence, this study combines findings derived from literature trends, workflow-based implementation observations, and practitioner perspectives to develop a multidimensional evaluation of AR-supported BIM applications. The bibliometric findings indicated that construction inspection, digital visualization, BIM integration, and augmented reality represent prominent research themes within the existing literature. These identified themes informed the design of the pilot implementation and guided the selection of evaluation criteria related to information accessibility, model visualization, construction element verification, and inspection workflow support. The empirical observations obtained during the pilot evaluation suggest that BIM–AR integration may facilitate the comparison between digital models and physical construction elements, while also supporting improved visualization and communication during inspection activities. The qualitative interview findings provided complementary evidence regarding practitioners' perceptions of BIM-supported AR workflows. Participants generally indicated that the integration of digital models with AR visualization could support inspection activities by improving spatial understanding, facilitating model-based verification, and providing additional information for construction-related decision-making. However, participants also emphasized several factors that may influence successful adoption, including hardware limitations, calibration accuracy, environmental conditions, and the need for user adaptation and training.

Overall, the integrated findings suggest that BIM-integrated AR systems may contribute to the development of more information-rich construction inspection workflows by connecting digital project information with physical construction environments. However, considering the exploratory design of the study, the limited participant sample, and the absence of statistical generalization, the findings should be interpreted as preliminary evidence regarding the applicability of AR-supported BIM approaches rather than definitive proof of performance improvement. The combination of bibliometric analysis, pilot implementation observations, and practitioner feedback provides a basis for future studies involving larger samples, comparative evaluations, and more comprehensive performance assessment frameworks.

4. Discussion

The findings of this study should be interpreted by considering the complementary evidence obtained from the bibliometric analysis, the pilot case study, and the semi-structured interviews. Rather than examining Building Information Modeling (BIM) and Augmented Reality (AR) integration solely as technological solutions, this study evaluates their role within the broader context of digital construction management, information-driven inspection processes, and technology-supported decision-making. By combining research trends identified in the literature with observations from a BIM–AR-supported inspection workflow and practitioner perspectives, the study provides insights into both the opportunities and practical limitations associated with the adoption of AR-integrated BIM approaches in construction inspection. However, due to the exploratory nature of the pilot implementation, the single-project context, and the limited participant group, the findings should be considered preliminary and interpreted as evidence regarding applicability rather than as definitive evidence of performance improvement.

4.1 Bibliometric and Practical Implications of BIM–AR Integration

The bibliometric analysis suggests that research on BIM–AR integration has increasingly focused on visualization, model verification, construction inspection, and digital information management. The identified conceptual relationships indicate that BIM–AR technologies are being investigated not only as visualization tools but also as components of broader digital construction strategies that aim to improve information accessibility, coordination, and decision-support processes. Within the context of smart design and digital construction governance, BIM–AR integration represents an emerging approach for connecting digital project information with physical construction activities and supporting more informed management decisions.

The pilot implementation provides an opportunity to examine how these research trends may translate into practical inspection workflows. The integration of BIM models prepared in Autodesk Revit, coordinated through Navisworks, and transferred to tablet-based AR platforms indicated that digital models may support the comparison between planned design information and constructed building elements during inspection activities. Although the evaluation was limited to a single project context, the findings suggest that BIM–AR-supported workflows may complement conventional inspection approaches by providing additional visual information, improving access to project data, and supporting more structured verification procedures.

From a smart design policy perspective, the findings highlight the potential of BIM–AR integration to contribute to more transparent and data-supported construction processes. By enabling a closer relationship between design information and physical implementation, such workflows may support digital quality management strategies and facilitate communication among different project stakeholders. Nevertheless, the effectiveness of these approaches is expected to depend on organizational capabilities, project requirements, technological infrastructure, and user experience rather than technological availability alone.

4.2 User Experience and Implementation Challenges

The semi-structured interviews provide additional insight into the practical considerations associated with BIM–AR adoption from the perspective of construction professionals. Participants generally indicated that digital visualization supported improved spatial understanding and facilitated the interpretation of construction information during inspection activities. These observations suggest that AR-supported BIM environments may provide additional assistance in verifying construction elements and identifying potential inconsistencies between digital models and physical conditions.

However, the findings also demonstrate that technological capability alone does not guarantee successful implementation. Participants identified several challenges related to the integration of BIM–AR workflows into existing construction practices, including calibration accuracy, environmental conditions, device ergonomics, and the learning process required for users with limited experience in digital construction technologies. These factors indicate that implementation strategies should consider not only software and hardware capabilities but also organizational readiness, user training, and workflow adaptation.

The results further suggest that BIM–AR applications may contribute to collaborative decision-making by providing a shared visualization environment where project participants can evaluate construction conditions using common digital information. In this respect, BIM–AR integration may support communication between design, construction, and quality-control teams. However, further research is required to examine how these benefits vary across different project environments and organizational structures.

4.3 Practical Implications and Future Perspectives

The findings of this study suggest that BIM–AR-supported inspection workflows may provide practical value for professionals involved in project supervision, quality management, BIM coordination, and construction decision-making. By connecting digital project information with physical construction environments, these technologies may support more systematic inspection processes, improve information accessibility, and contribute to more effective coordination among project stakeholders.

The study also highlights the potential relevance of BIM–AR integration for digital construction governance and smart design approaches. The ability to visualize design information during construction activities may support more transparent monitoring processes, facilitate early identification of potential deviations, and provide additional information for corrective decision-making. However, these potential contributions should be evaluated through broader empirical studies involving different project types, larger participant groups, and comparative assessment methods.

Several limitations should be acknowledged. The study was conducted as an exploratory pilot investigation within a single reinforced concrete residential project and involved a relatively limited number of participants. Therefore, the findings cannot be generalized to all construction projects or interpreted as evidence of universal performance improvement. Future research may expand the proposed framework by evaluating different project contexts, conducting comparative studies with conventional inspection methods, and developing more comprehensive assessment frameworks. Additionally, future investigations may explore the integration of emerging technologies such as Digital Twins, computer vision, artificial intelligence, and Scan-to-BIM workflows to further advance digital construction inspection and decision-support capabilities.

5. Conclusion

This research examined the use of Building Information Modeling (BIM) in combination with Augmented Reality (AR) for construction inspection and construction error detection through an integrated methodology comprising bibliometric analysis, an exploratory case study, and semi-structured interviews with industry professionals. The overall findings suggest that BIM–AR workflows can improve inspection activities by enhancing digital visualization, facilitating model-to-site comparison, increasing access to project information, and supporting communication among project participants. The study further demonstrates that the effectiveness of BIM–AR implementation is influenced not only by technological functionality but also by organizational preparedness, user acceptance, workflow compatibility, and the specific characteristics of individual construction projects. Consequently, the outcomes should be regarded as preliminary evidence of the practical application of BIM–AR-supported inspection workflows rather than conclusive proof of performance enhancement. This research contributes to the existing body of knowledge by integrating bibliometric analysis with a pilot-based empirical evaluation and practitioner perspectives within a single methodological framework. While previous studies have frequently focused on technological development, visualization capabilities, or controlled experimental environments, this study examines how BIM–AR-supported workflows may be positioned within practical construction inspection processes. In this context, the proposed framework contributes to discussions on smart construction practices by demonstrating how digital models and augmented visualization technologies may support data-informed inspection, digital quality management, and more transparent decision-making processes.

The study also provides implications for digital construction governance by highlighting the role of BIM–AR integration in connecting design information with construction activities. The ability to access and visualize digital project information during inspection activities may support improved coordination among project participants and facilitate the identification of potential deviations. However, these implications should be further validated through broader empirical investigations involving different project contexts and more comprehensive assessment approaches.

The findings of this research should be interpreted in light of several methodological constraints. The empirical investigation was limited to a single reinforced-concrete residential development and relied on a relatively small group of participants because of its exploratory scope. Consequently, the findings reflect the characteristics of a specific project context and cannot be generalized to all construction environments. Furthermore, although the mixed-method design provided complementary quantitative and qualitative perspectives, larger-scale studies with comparative evaluation methods are required to establish stronger evidence regarding the effectiveness of BIM–AR-supported inspection workflows.

Future research may focus on several directions to further develop BIM–AR-supported construction inspection approaches:

1. Conducting larger-scale empirical studies involving different project types, construction sectors, and geographical contexts.
2. Evaluating BIM–AR workflows through longitudinal studies to examine their implementation process, organizational adaptation, and long-term applicability.
3. Investigating user training, adoption strategies, and organizational factors affecting the integration of digital inspection technologies into construction practices.
4. Exploring the integration of BIM–AR with emerging digital technologies, including Digital Twins, Artificial Intelligence, computer vision, and Scan-to-BIM workflows.

Further investigation in these areas could expand current knowledge of BIM–AR implementation and its role in digitally supported construction practices. Beyond the findings presented here, the research framework developed in this study may assist future academic work while also offering practical reference points for researchers, industry professionals, and decision-makers seeking to improve construction inspection and digital quality management.

Overall, this study indicates that AR-integrated BIM should be considered not only as a visualization technology but also as a potential digital support mechanism for connecting project information, construction activities, and inspection processes. Further validation through larger and comparative studies is required to determine its broader applicability and contribution to smart construction and digital quality management strategies.

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The authors declare no conflicts of interest.

Data availability statement
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Institutional Review Board Statement
Ethical approval for this study was obtained from the Scientific Research and Publication Ethics Committee of the Faculty of Engineering and Natural Sciences, Çankaya University (Approval No. 2026/18). Informed consent was obtained from all participants prior to their participation in the semi-structured interviews.

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