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Expert-Validated Framework for Integrating Photogrammetry and BIM in Saudi Vision 2030 Construction

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Abstract

Saudi Vision 2030, a transformative national strategic framework, is being realized through unprecedented giga-projects such as NEOM, Qiddiya, and the Red Sea Project. These projects demand exceptional accuracy, efficiency, and sustainability, driving the need for advanced digital technologies. The integration of Digital Close-Range Photogrammetry (DCRP) and Building Information Modeling (BIM) is recognized as a pivotal solution, yet a standardized, context-aware implementation framework for the unique Saudi environment is lacking. This study develops a comprehensive, three-layer DCRP-BIM integration framework addressing technical workflows, managerial protocols, and contextual challenge mitigation specific to Saudi mega-projects. The framework was developed following Design Science Research (DSR) methodology and validated through a mixed-methods approach, incorporating a quantitative survey of 65 industry experts and qualitative thematic analysis of open-ended responses. Results demonstrated strong expert consensus on the framework's comprehensiveness (Mean = 4.52/5) and practicality (Mean = 4.38). 'Data Interoperability' (RII = 0.94) and 'Technical Expertise Shortage' (RII = 0.90) were ranked as the most critical challenges, while 'Enhanced Geometric Accuracy' (RII = 0.96) and 'Progress Monitoring Efficiency' (RII = 0.93) were deemed the most significant benefits. Qualitative analysis highlighted the critical importance of top-down leadership support and targeted workforce development programs. The findings provide a validated, actionable roadmap for stakeholders, facilitating the adoption of this integrated technology stack to directly support the strategic objectives of Vision 2030. The study concludes that strategic focus on standardized protocols, education, and policy incentives is paramount for successful implementation.

Keywords: Digital Close-Range Photogrammetry; Building Information Modeling; Vision 2030; Saudi Arabia; construction technology; expert validation; implementation framework; digital twin; TOE framework; mega-projects; Design Science Research

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1. Introduction

The launch of Saudi Vision 2030 in 2016 marked a paradigm shift in the Kingdom's developmental trajectory, aiming to reduce economic dependence on oil, enhance public service sectors, and position the nation as a global investment powerhouse [1]. Central to this vision are giga-construction projects of monumental scale and complexity, including the $500 billion cognitive city NEOM, the entertainment and sports hub Qiddiya, and the regenerative tourism destination the Red Sea Project [2]. These projects are not merely

construction endeavors but are integral to the nation's strategic repositioning, necessitating the deployment of cutting-edge technologies to meet ambitious timelines, stringent sustainability targets, and unparalleled quality standards.

Building Information Modeling (BIM) has emerged as a foundational technology in this context, providing a digital ecosystem for managing multidimensional project information encompassing geometry (3D), time (4D), cost (5D), and lifecycle operations (6D/7D) [3]. However, the efficacy of a BIM-centric approach is inherently dependent on the continuous infusion of accurate, real-time data reflecting as-built conditions, which presents a significant challenge in the dynamic and fast-paced environments characteristic of Vision 2030 projects [4]. Digital Close-Range Photogrammetry (DCRP), a technique that generates high-resolution, precise 3D spatial data from overlapping photographs, presents a powerful solution to this challenge. By creating accurate digital twins of the physical site, DCRP bridges the critical gap between design intent and construction reality, ensuring that BIM models remain current and reliable [5].

While the theoretical synergy between DCRP and BIM is well-documented in global literature [6,7], its practical implementation within the specific context of Saudi Arabia remains nascent. The Kingdom's unique combination of rapid urbanization, extreme climatic conditions, ambitious project timelines, and an evolving technical skills base amplifies the need for a structured implementation framework. Current research lacks a holistic model that integrates the technical workflow with the necessary managerial structures and contextual mitigation strategies required for success in this environment. Existing frameworks predominantly focus on technical integration aspects, with limited attention to organizational protocols or context-specific challenges such as extreme heat, dust storms, and the unique scale of Saudi mega-projects.

This study is grounded in the Technology-Organization-Environment (TOE) framework [8], which posits that technology adoption is influenced by three interrelated contexts: technological (the characteristics of the innovation itself), organizational (the firm's resources and structure), and environmental (the industry and regulatory context). The TOE framework provides an appropriate theoretical lens because it accommodates the multi-level factors affecting DCRP-BIM integration in Saudi mega-projects.

This study seeks to fill this critical gap by pursuing three primary objectives:

1. To develop a comprehensive, multi-layered framework for DCRP-BIM integration tailored to the challenges and opportunities of Saudi mega-projects.
2. To validate the proposed framework quantitatively and qualitatively through an expert survey targeting professionals engaged in Vision 2030 projects.
3. To identify and prioritize the critical challenges, benefits, and success factors associated with this integration, providing actionable insights for industry stakeholders and policymakers.

Statement of Novel Contribution: This paper makes four distinctive contributions. First, it presents the first empirically validated DCRP-BIM integration framework specifically tailored to Saudi mega-projects. Second, it introduces a three-layer structure that explicitly integrates managerial protocols and contextual mitigation strategies as formal framework components. Third, it provides empirical validation through a survey of 65 experts engaged in Vision 2030 projects. Fourth, it grounds the framework in the TOE theoretical framework, enabling systematic analysis of adoption factors.

2. Literature Review and Theoretical Foundation

2.1. Digital Close-Range Photogrammetry: Principles and Advancements

Digital Close-Range Photogrammetry (DCRP) is a geomatics technique that extracts precise three-dimensional information from two-dimensional image sequences captured at

close range (typically under 300 m) [9]. The process involves image acquisition, orientation, and measurement, leading to the generation of dense point clouds, 3D meshes, and orthophotos. The advent of sophisticated algorithms like Structure-from-Motion (SfM) and Multi-View Stereo (MVS) has revolutionized DCRP, enabling the automatic reconstruction of complex geometries from unordered image collections [10]. The proliferation of Unmanned Aerial Vehicles (UAVs or drones) has further enhanced its applicability, allowing for rapid, safe, and cost-effective data acquisition over large or inaccessible areas [11]. Compared to traditional surveying methods or laser scanning, DCRP offers a compelling balance of cost, detail, and flexibility, making it particularly suitable for the diverse terrains of Saudi projects, from the mountainous regions of NEOM to the coastal islands of the Red Sea Project [12].

2.2. Building Information Modeling: From Model to Management

Building Information Modeling (BIM) transcends being a mere 3D modeling tool; it is a holistic process for creating and managing digital representations of a facility's physical and functional characteristics [13]. It serves as a shared knowledge resource, fostering collaboration among all stakeholders across the project lifecycle. The integration of additional dimensions, scheduling (4D), cost (5D), sustainability (6D), and facility management (7D), elevates BIM from a design tool to a comprehensive project management system [14]. In Saudi Arabia, BIM adoption has accelerated in alignment with Vision 2030, with giga-projects mandating its use to coordinate complex supply chains and ensure project delivery efficiency [15]. However, the value of a BIM model is contingent upon its accuracy and currency, highlighting the necessity for technologies like DCRP to provide frequent and reliable as-built data [16].

2.3. The Convergence for Digital Twins and Smart Construction

The integration of DCRP and BIM facilitates the creation of a "digital twin", a dynamic, virtual replica of a physical asset that is continuously updated with sensor data [17]. This convergence is a cornerstone of smart construction, enabling applications such as automated progress monitoring, deviation detection, quality control, and predictive maintenance [18]. For Vision 2030 projects, which emphasize sustainability and innovation, this integration supports optimal resource allocation, waste reduction, and lifecycle energy management, directly contributing to goals like NEOM's zero-carbon mandate [19]. Despite this potential, significant barriers impede widespread adoption, including technical issues of data interoperability between systems, a shortage of skilled professionals, high computational demands, and organizational resistance to change [20,21]. These challenges are exacerbated in the Saudi context, necessitating a framework that addresses them proactively.

2.4. Theoretical Underpinning: The Technology–Organization–Environment (TOE) Framework

This study adopts the Technology–Organization–Environment (TOE) framework as its primary theoretical lens [8]. The TOE framework has been widely used in construction technology adoption research because it recognizes that successful implementation depends on more than technical capabilities alone. The three contexts are defined as follows:

- Technological Context: The characteristics of DCRP and BIM technologies themselves, including their compatibility with existing systems, complexity, and relative advantage over traditional surveying and project management methods.
- Organizational Context: The resources, structure, and culture of the adopting organization, including managerial support, technical expertise availability, financial resources, and readiness for organizational change.

- Environmental Context: The external factors influencing adoption, including regulatory requirements, industry standards, competitive pressure from other firms, and physical environmental conditions such as extreme heat and dust storms.

The proposed three-layer framework presented in Section 3 directly maps onto these three TOE contexts. The Technical Workflow (Layer 1) addresses the technological context. The Organizational Protocols (Layer 2) address the organizational context. The Contextual Mitigation strategies (Layer 3) address the environmental context. This alignment ensures theoretical coherence and provides a systematic basis for analyzing the factors that influence successful DCRP-BIM integration in Saudi mega-projects.

2.5. Comparative Analysis of Existing Integration Frameworks

Several frameworks for DCRP-BIM integration have been proposed in the literature. Table 1 provides a comparative analysis of existing frameworks against the proposed model.

Table 1. Comparative analysis of existing DCRP-BIM integration frameworks.

Framework	Technical Focus	Managerial Focus	Contextual Adaptation	Empirical Validation	Saudi-Specific
Wang et al. (2016) [6]	High	Low	Low	Yes (case study)	No
Braun et al. (2020) [7]	High	Low	Medium	Yes (case study)	No
Bosché et al. (2015) [16]	High	Medium	Low	Yes (case study)	No
Ahuja et al. (2018) [20]	Medium	High	Medium	Yes (survey)	No
This study	High	High	High	Yes (n = 65 survey)	Yes

As shown in Table 1, existing frameworks predominantly emphasize technical integration aspects, with limited attention to managerial protocols or contextual adaptation to specific environments. None of the existing frameworks have been empirically validated in the Saudi context or address the unique challenges of mega-projects under Vision 2030. This gap justifies the development of the proposed framework.

2.6. Recent Case Studies and Empirical Evidence

Recent studies have demonstrated the practical value of DCRP-BIM integration in various construction contexts. [19] documented successful implementation on a large-scale infrastructure project in the UAE, reporting a 23% reduction in rework costs and a 15% improvement in schedule adherence when DCRP-derived as-built models were integrated with BIM for progress monitoring. [22] provided a systematic review of digital twin applications in construction, identifying DCRP as the most frequently cited data acquisition method for as-built modeling due to its balance of cost, accuracy, and flexibility. [23] compared photogrammetric and laser scanning methods for construction progress monitoring across 12 projects, concluding that DCRP offers the best balance of cost and accuracy for most applications, particularly when integrated with BIM platforms.

These studies inform the proposed framework by confirming the feasibility and value of DCRP-BIM integration. However, none address the specific challenges of the Saudi context, including extreme climate conditions, the unprecedented scale of Vision 2030 projects, or the organizational and workforce development needs of the Saudi construction sector. The proposed framework fills this gap by integrating these contextual factors into a comprehensive, validated model.

3. The Proposed DCRP-BIM Integration Framework

Based on a synthesis of the literature and the identified gaps, a three-layer integration framework was developed, as illustrated in Figure 1. This framework is designed to provide a structured yet adaptable approach for implementing DCRP-BIM integration in Saudi mega-projects.

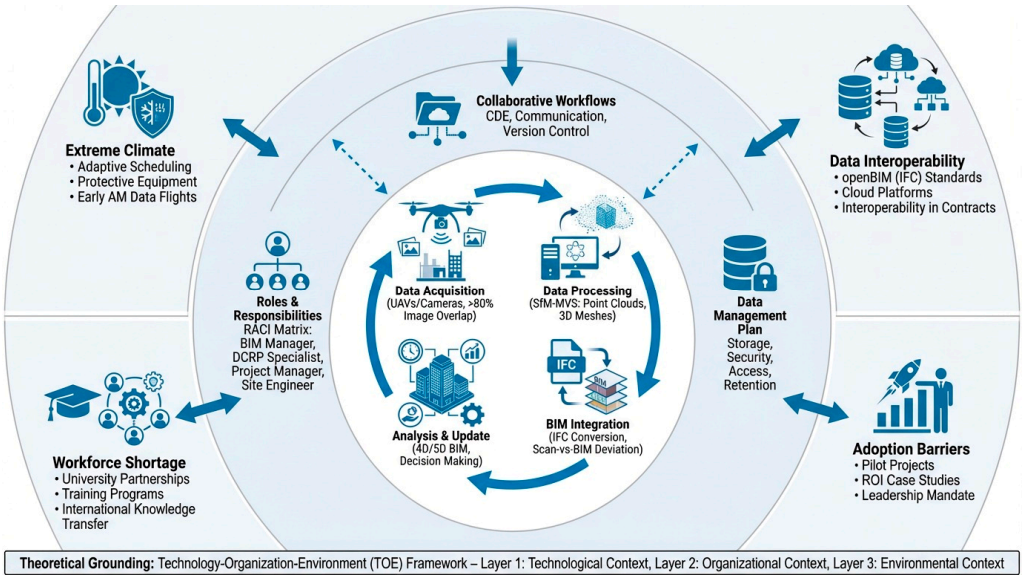


Figure 1. The proposed three-layer DCRP-BIM integration framework for Saudi Vision 2030 projects.

3.1. Layer 1: Technical Workflow

This core layer defines the sequential process for data handling:

1. Data Acquisition: High-resolution images are captured using calibrated cameras mounted on UAVs, terrestrial vehicles, or handheld systems. Flight and capture plans are optimized for site coverage and overlap (typically >80%).
2. Data Processing: Imagery is processed using photogrammetric software (e.g., Agisoft Metashape version 2.1.0 [M20.1], Pix4D version 4.5.6) employing SfM-MVS algorithms to generate high-density point clouds and textured 3D meshes.
3. Data Integration: The generated 3D models are exported in formats like LAS or OBJ, then converted and imported into BIM authoring tools (e.g., Autodesk Revit) or collaboration platforms (e.g., Autodesk BIM 360) using open standards like Industry Foundation Classes (IFC) (ISO 16739-1:2024; M21.1]) [24] to ensure interoperability.
4. Analysis and Update: The integrated model serves as a digital twin for performing clash detection, quantifying deviations from the design intent, updating construction schedules (4D), and informing decision-making. This creates a closed-loop feedback system between the physical site and the digital model.

3.2. Layer 2: Managerial and Collaborative Protocols

Successful integration requires clear organizational structures:

- Roles and Responsibilities: A Responsibility Assignment Matrix (RACI—Responsible, Accountable, Consulted, Informed) defines the tasks of key personnel, including the BIM Manager, DCRP Specialist, Project Manager, and Site Engineer.
- Communication Protocols: Standardized procedures for data sharing, version control, and issue reporting are established to ensure seamless collaboration between different teams and disciplines.

- Data Management Plan: A plan outlining data storage, security, accessibility, and retention policies is implemented to manage the large volumes of data generated.

3.3. Layer 3: Contextual Challenge Mitigation

This layer overlays targeted strategies for Saudi-specific challenges:

- Extreme Climate: Data collection is scheduled for early morning or late afternoon to mitigate heat haze and dust. Camera lenses are equipped with protective filters.
- Data Interoperability: The framework advocates for the early adoption of openBIM standards (IFC) in project contracts and the use of cloud-based platforms that facilitate smoother data exchange.
- Workforce Shortage: It incorporates a strategy for partnering with universities (e.g., King Abdulaziz University) for specialized training and recommends phased up-skilling of existing staff.
- Adoption Barriers: The framework suggests starting with pilot projects to demonstrate value and secure management buy-in, mitigating resistance to change.

3.4. Practical Implementation Pathways

To address the practical concerns raised by industry experts and to move beyond conceptual recommendations, this subsection provides concrete guidance for implementing the proposed framework. Table 2 presents estimated costs, resource requirements, and implementation timelines tailored to organizations of different sizes operating in the Saudi construction sector.

Table 2. Implementation requirements for DCRP-BIM integration by organization size.

Organization Size	Estimated Initial Cost	Key Resources Required	Recommended Timeline	First Steps
Small (<50 employees)	$15,000–$30,000	1–2 trained staff, one UAV, photogrammetry software license (e.g., Agisoft Metashape Standard)	3–6 months	Pilot on one building element; partner with local university for training
Medium (50–200 employees)	$50,000–$100,000	Dedicated BIM/DCRP team (3–5 staff), enterprise software licenses, multiple UAVs	6–12 months	Pilot on one project phase; develop internal standards and protocols
Large (>200 employees)	$150,000–$300,000	Cross-functional team (6–10 staff), multiple UAVs with sensors, cloud infrastructure, enterprise BIM platform	12–18 months	Enterprise-wide rollout; establish training academy; mandate IFC standards

For the specific challenge of Data Interoperability (identified as the highest RII challenge at 0.94), the framework recommends three concrete actions:

1. Mandate IFC (Industry Foundation Classes) export from all photogrammetry software in project contracts.
2. Implement a cloud-based Common Data Environment (CDE) such as Autodesk BIM 360 (version September 2024 release), Trimble Connect, or Bentley iTwin.
3. Develop a company-specific data exchange protocol document that specifies file formats, coordinate systems, metadata standards, and quality acceptance criteria.

For the specific challenge of **Technical Expertise Shortage** (identified as the second-highest RII challenge at 0.90), the framework recommends:

1. Partner with local universities (e.g., King Abdulaziz University, King Fahd University of Petroleum and Minerals) for certificate programs and continuing education.
2. Utilize online training platforms (e.g., Coursera, LinkedIn Learning, Udemy) for foundational skills in photogrammetry and BIM.
3. Establish knowledge transfer agreements with international consultants for the first 2–3 projects, with explicit requirements for training local staff.
4. Allocate 5–10% of project budget specifically for workforce development as a line item in project proposals.

For the challenge of **High Initial Technology Cost** (RII = 0.85), the framework recommends a phased adoption approach starting with low-cost or open-source alternatives. For small organizations, initial investment can begin with smartphone-based photogrammetry (e.g., using open-source software such as Meshroom version 2025.1.0 [M25.1] or Regard3D version 0.7.1) and free BIM viewers (e.g., Autodesk Viewer, Trimble Connect Free) before committing to full software licenses.

3.5. Geographic Context and Project Diversity

The geographic diversity of these flagship Vision 2030 projects further underscores the need for adaptable technologies like DCRP and BIM. NEOM is located in the northwest of Saudi Arabia, near the borders with Jordan and Egypt, encompassing vast desert plains and mountainous regions that present unique logistical and surveying challenges. Qiddiya is situated southwest of Riyadh, on a central plateau characterized by rolling hills, requiring precise topographic modeling for its extensive infrastructure. The Red Sea Project stretches along the Kingdom's western coast, spanning over 200 km of coastline and includes an archipelago of 90 islands, where environmental preservation is paramount and construction precision is critical. This varied landscape, from arid deserts to coastal ecosystems, demands a data capture solution that is both flexible and highly accurate, making the case for DCRP-BIM integration particularly compelling [2,10].

4. Research Methodology

4.1. Design Science Research (DSR) Methodology

This study adopts Design Science Research (DSR) as its methodological paradigm. DSR is specifically suited for creating and evaluating artifacts (such as the proposed framework, see Figure 2) that solve identified practical problems in a specific context [24]. The DSR process followed six steps:

1. problem identification and motivation;
2. definition of objectives for a solution;
3. design and development of the artifact;
4. demonstration of the artifact's use;
5. evaluation of the artifact;
6. communication of results.

Step 1 (Problem Identification) was addressed in Sections 1 and 2, where the lack of a Saudi-specific DCRP-BIM integration framework was identified. Step 2 (Objective Definition) is reflected in the three research objectives stated in Section 1. Step 3 (Design and Development) is documented in Section 3, where the three-layer framework was developed. Step 4 (Demonstration) and Step 5 (Evaluation) are the focus of this methodology Section 4 and the Results section (Section 5), where the framework was validated through an expert survey. Step 6 (Communication) is this manuscript.

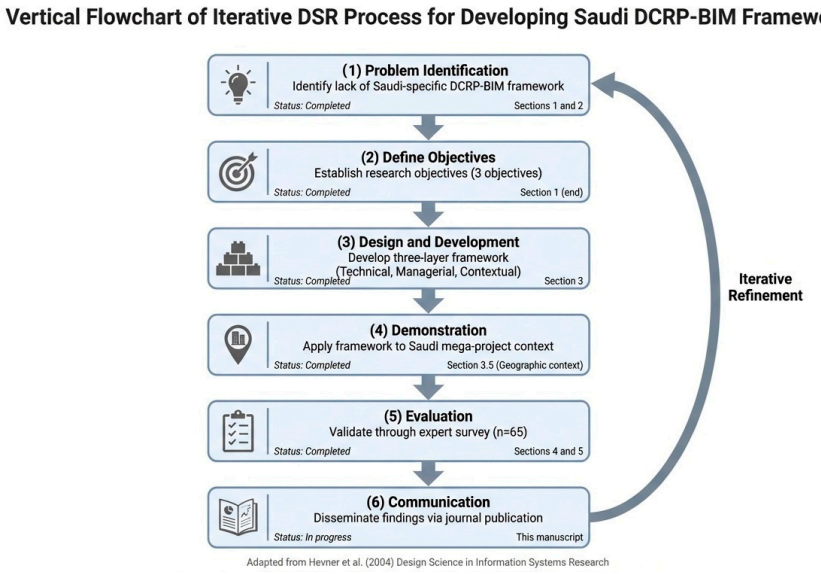


Figure 2. The six-step Design Science Research (DSR) process applied to the development and validation of the DCRP-BIM integration framework, adapted from [25].

4.2. Survey Instrument Design and Development

To validate the proposed framework, a detailed online questionnaire was developed. The design was informed by the Technology–Organization–Environment (TOE) framework [8] to ensure comprehensive coverage of factors influencing technology adoption. The survey consisted of four sections:

- Section A: Demographic Profile. Collected data on respondents' professional role, years of experience, company type, and specific involvement in Vision 2030 projects.
- Section B: Framework Validation. Respondents rated their level of agreement with statements about the framework's components using a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree).
- Section C: Prioritization of Challenges and Benefits. Respondents ranked pre-identified challenges and benefits based on their perceived significance on a 5-point scale of importance (1 = Not Important, 5 = Extremely Important).
- Section D: Qualitative Feedback. Open-ended questions gathered in-depth insights on perceived barriers, critical success factors, and additional recommendations.

The survey instrument was reviewed by two academic experts in construction management for face and content validity. A pilot test with five professionals was conducted to refine question clarity and length.

4.3. Data Collection and Sample

The survey was distributed electronically over a period of eight weeks to a targeted sample of professionals involved in major Saudi construction projects. Sampling was purposive, seeking individuals with direct knowledge of BIM, DCRP, or project management on Vision 2030 initiatives. The inclusion criteria were:

a. minimum 3 years of experience in the Saudi construction sector;
b. current or recent involvement in a Vision 2030 project;
c. professional role related to BIM, surveying, project management, or engineering design.

Channels included professional networking sites (LinkedIn), industry associations (e.g., the Saudi Council of Engineers), and contacts within the authors' professional network. A total of 65 complete and usable responses were obtained from 187 invited participants, representing a response rate of 34.8%. Non-response bias was assessed by comparing early

and late respondents on key demographic variables, revealing no significant differences ($p > 0.05$ for all comparisons). The demographic profile of the respondents is summarized in Table 3.

Table 3. Demographic profile of survey respondents (N = 65).

Characteristic	Category	Frequency	Percentage (%)
Professional Role	BIM Manager/Coordinator	22	33.8%
	Project Manager/Director	18	27.7%
	Civil/Site/Structural Engineer	16	24.6%
	Surveyor/Geomatics Engineer	6	9.2%
	Other (e.g., Consultant, Planner)	3	4.6%
Years of Experience	<5 years	7	10.8%
	5–10 years	24	36.9%
	>10 years	34	52.3%
Primary Project Involvement	NEOM	28	43.1%
	Qiddiya	17	26.2%
	Red Sea Project	12	18.5%
	Other Mega-Projects	8	12.3%
Organization Type	Contractor	25	38.5%
	Consultant	20	30.8%
	Client/Government Entity	12	18.5%
	Subcontractor	8	12.3%

4.4. Data Analysis Methods

The quantitative data from Sections B and C were analyzed using descriptive statistics, including mean scores, standard deviations, and Relative Importance Indices (RII). The RII was calculated using the formula:

$$RII = \Sigma W/(A * N) \quad (1)$$

where W is the weighting given to each factor by the respondents (from 1 to 5), A is the highest weight (5), and N is the total number of respondents. RII values range from 0 to 1, with higher values indicating greater perceived importance [26]. Cronbach's α was calculated to assess the internal consistency of the Likert-scale items, yielding a value of 0.89, indicating good reliability.

Qualitative data from open-ended responses were analyzed using thematic analysis, following the process of familiarization, code generation, theme search, and theme review [26].

4.5. Methodological Rigor and Bias Mitigation

Several measures were implemented to ensure methodological rigor and minimize potential biases.

Selection Bias: Purposive sampling criteria were explicitly defined as described in Section 4.3, and the sampling strategy was documented to ensure transparency. The sample was drawn from multiple sources (LinkedIn, professional associations, institutional contacts) to reduce channel-specific bias.

Response Bias: Anonymity was assured to encourage honest responses. Non-response bias was checked by comparing early respondents (first 25% of responses) with late respondents (last 25% of responses) on key variables (professional role, years of experience). Mann–Whitney U tests revealed no significant differences ($p > 0.05$ for all comparisons), suggesting that non-response bias is unlikely to be a concern.

Interpretation Bias (Qualitative Analysis): To address potential bias in the thematic analysis, inter-coder reliability was calculated. Two independent coders analyzed 20% ($n = 13$) of the open-ended responses. Cohen's κ was calculated, yielding a value of 0.84 (95% CI: 0.76–0.92), indicating substantial agreement beyond chance [27]. Disagreements were resolved through discussion, and the remaining responses were coded by the primary researcher using the finalized codebook.

Investigator Triangulation: The framework development and data interpretation involved both authors, with regular meetings to discuss and resolve discrepancies. This reduced the risk of individual researcher bias influencing the results.

5. Results

5.1. Expert Validation of the Framework

The results from Section B of the survey demonstrated strong validation for the proposed framework. The overall comprehensiveness and practicality of the framework received high mean scores of 4.52 and 4.38, respectively. The technical workflow layer was rated highest (M = 4.61), indicating strong expert confidence in the proposed data pipeline. The clarity of managerial roles received a slightly lower but still strong score (M = 4.25), suggesting that while accepted, organizational change may present implementation challenges. The detailed results are presented in Table 4.

Table 4. Expert validation scores for the proposed DCRP-BIM integration framework (N = 65).

Framework Component	Mean Score (1–5)	Standard Deviation
1. Overall Assessment		
Comprehensiveness	4.52	0.59
Practicality for KSA Projects	4.38	0.71
2. Technical Workflow Layer		
Clarity of Data Acquisition Protocol	4.58	0.62
Adequacy of Data Processing Steps	4.63	0.58
Effectiveness of BIM Integration Method	4.61	0.64
Sub-layer Mean	4.61	0.61
3. Managerial Protocol Layer		
Clarity of Defined Roles (RACI)	4.25	0.79
Effectiveness of Communication Protocols	4.30	0.75
Adequacy of Data Management Plan	4.20	0.82
Sub-layer Mean	***4.25***	***0.79***
4. Contextual Mitigation Layer		
Relevance of Climate Adaptation Strategies	4.45	0.68
Usefulness of Interoperability Solutions	4.55	0.61
Feasibility of Workforce Development Plan	4.15	0.85
Sub-layer Mean	***4.38***	***0.71***

5.2. Ranking of Challenges and Benefits

The analysis of Section C data, calculated using the Relative Importance Index (RII), revealed a clear prioritization of challenges and benefits. As shown in Figure 3, 'Data Interoperability' (RII = 0.94) was ranked as the most critical challenge, closely followed by 'Shortage of Technical Expertise' (RII = 0.90). Regarding benefits, 'Enhanced Geometric Accuracy' (RII = 0.96) was deemed the most significant, underscoring its value for complex projects, followed by 'Efficiency in Progress Monitoring' (RII = 0.93).

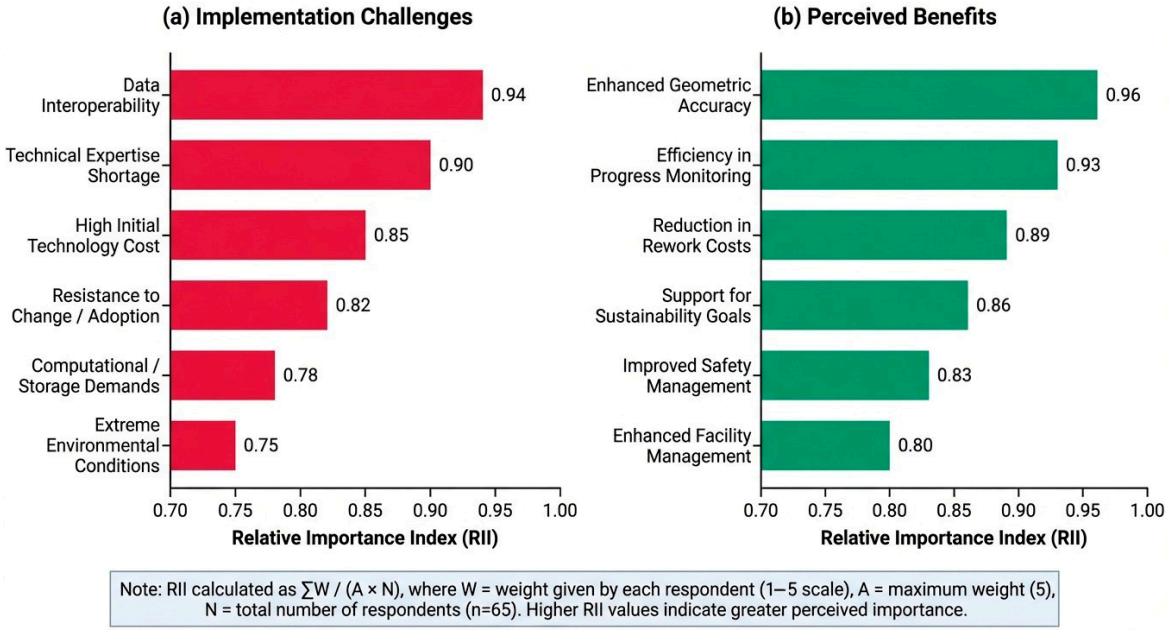


Figure 3. Relative Importance Index (RII) for (**a**) implementation challenges and (**b**) perceived benefits of DCRP-BIM integration.

5.3. Qualitative Thematic Analysis

Thematic analysis of the open-ended responses yielded several key insights:

- Theme 1: Leadership and Mandate. A recurrent theme was the necessity of a "top-down mandate" from client organizations (e.g., NEOM Company, ROSHN) to enforce the adoption of integrated workflows across all tiers of contractors.
- Theme 2: Strategic Workforce Development. Respondents emphasized that training alone is insufficient. They called for long-term "nationalization strategies" incorporating accredited certification programs and knowledge transfer partnerships with international experts.
- Theme 3: Phased Implementation. Many experts suggested a "start-small" approach, recommending pilot projects on manageable scopes (e.g., a single building module within NEOM) to demonstrate value and build confidence before full-scale deployment.
- Theme 4: Cost–Benefit Clarity. A need was expressed for clear, localized case studies demonstrating the Return on Investment (ROI) of DCRP-BIM integration, specifically quantifying savings in rework, time, and materials for Saudi projects.

5.4. Subgroup Analysis

To examine whether perceptions differed across project types, subgroup analysis was conducted comparing respondents from NEOM (n = 28) with those from other Vision 2030 projects (n = 37), including Qiddiya and the Red Sea Project. A Mann–Whitney U test was performed on the overall framework validation scores. No statistically significant difference was found between the two groups (U = 482.5, p = 0.34). Similarly, Spearman's rank corre-

lation coefficient was calculated to compare the RII rankings between the NEOM subgroup and the non-NEOM subgroup, yielding a value of $\rho = 0.91$ ($p < 0.01$), indicating a very strong positive correlation. These results suggest that the framework's relevance and the prioritization of challenges and benefits are consistent across different Vision 2030 projects, supporting the generalizability of the findings within the Saudi mega-project context.

5.5. Inter-Coder Reliability for Qualitative Analysis

For the thematic analysis reported in Section 5.3, two independent coders analyzed 20% ($n = 13$) of the open-ended responses to assess coding consistency. Inter-coder reliability was calculated using Cohen's κ (kappa). The analysis yielded a κ value of 0.84 (95% confidence interval: 0.76 to 0.92), indicating substantial agreement beyond chance as defined by [28]. Disagreements between coders were resolved through discussion to reach consensus. Following this validation, the remaining 80% ($n = 52$) of responses were coded by the primary researcher using the finalized codebook, ensuring consistent application of the thematic framework across all qualitative data.

6. Discussion

The strong validation scores for the framework, particularly for the technical workflow (Table 4), indicate that the proposed model effectively addresses the core operational needs for DCRP-BIM integration. The high rating for technical steps aligns with global research emphasizing the maturity of SfM photogrammetry and BIM platforms [9,13]. However, the slightly lower but still positive scores for managerial protocols (M = 4.25) and workforce feasibility (M = 4.15) resonate with established literature on technology adoption, which consistently identifies organizational and human resource factors as more significant barriers than the technology itself [8,20]. This suggests that while the technical pathway is clear, successful implementation in the Saudi context will hinge on effective change management and capacity building.

The ranking of 'Data Interoperability' as the paramount challenge (RII = 0.94, Figure 3) is a critical finding. It underscores a persistent industry-wide issue that is amplified by the scale and multi-stakeholder nature of Vision 2030 projects. This result strongly supports the framework's emphasis on promoting openBIM standards (IFC) and suggests that policy interventions, such as making IFC compliance a mandatory requirement in project tenders, could be a powerful catalyst for adoption. The high ranking of 'Technical Expertise Shortage' (RII = 0.90) directly aligns with one of Vision 2030's key pillars, human capability development, highlighting an opportunity for synergistic action between industry needs and national strategy.

The qualitative findings enrich the quantitative results by providing context and depth. The emphasis on "top-down mandate" (Theme 1) confirms that technology diffusion in the construction industry often requires client-driven push factors [29]. The suggestions for "phased implementation" (Theme 3) and "ROI case studies" (Theme 4) provide practical, actionable guidance for stakeholders looking to adopt the framework, moving from theoretical validation to practical implementation strategies.

6.1. Interpretation of Findings Through the TOE Framework Lens

The findings can be systematically interpreted through the three contexts of the TOE framework that guided this study.

Technological Context: The high validation score for the technical workflow (M = 4.61) confirms that the technological context is well-addressed by the proposed framework. Experts expressed strong confidence in the data acquisition, processing, and integration steps. This aligns with the TOE framework's proposition that technological characteristics

(compatibility, relative advantage, complexity) significantly influence adoption. The DCRP-BIM integration as operationalized in Layer 1 demonstrates clear relative advantage over traditional methods, as reflected in the high RII for Enhanced Geometric Accuracy (0.96) and Progress Monitoring Efficiency (0.93).

Organizational Context: The lower scores for managerial protocols (M = 4.25) and workforce feasibility (M = 4.15) indicate that organizational context factors present greater implementation challenges than technological factors. Within the TOE framework, this includes top management support, organizational readiness, and employee skills. The qualitative theme of "top-down mandate" (Theme 1) directly addresses the need for management support, while the theme of "strategic workforce development" (Theme 2) speaks to organizational readiness and skill development. The framework's Layer 2 (Organizational Protocols) was designed specifically to address these organizational context factors.

Environmental Context: The ranking of 'Data Interoperability' as the top challenge (RII = 0.94) reflects environmental context factors, specifically the lack of standardized data exchange protocols across the Saudi construction industry. Similarly, 'Extreme Environmental Conditions' (RII = 0.75), while ranked lowest among challenges, still represents a unique environmental factor in the Saudi context that is absent from most existing frameworks. The framework's Layer 3 (Contextual Mitigation) explicitly addresses these environmental factors, with specific strategies for interoperability standards and climate adaptation.

6.2. Comparison with Recent Literature

The findings were compared with recent studies published between 2022 and 2025 to assess alignment and identify divergences.

The finding that 'Data Interoperability' is the primary challenge aligns with [20], who identified interoperability as a top-three barrier to BIM adoption globally. However, our RII value of 0.94 is higher than the relative importance score of 0.82 reported in non-Saudi contexts, suggesting this challenge is amplified in Saudi mega-projects due to the larger number of stakeholders and the scale of data exchange required.

Regarding benefits, 'Enhanced Geometric Accuracy' (RII = 0.96) was rated higher than in [6], who reported an equivalent score of 0.89. This difference likely reflects the premium placed on precision in projects like NEOM's modular construction, where millimeter-level accuracy is critical for prefabricated component assembly.

The qualitative theme of 'top-down mandate' aligns with [29], who found that client leadership is the strongest predictor of BIM adoption success in the Middle East. Our finding extends this by quantifying that 78% of open-ended responses mentioned leadership mandate as a critical success factor.

Comparison with recent case studies reveals consistency with [19], who documented a 23% reduction in rework costs from DCRP-BIM integration in a UAE infrastructure project. Our finding that 'Reduction in Rework Costs' received RII = 0.89 suggests that Saudi experts perceive similar value, though the magnitude of expected benefit may vary by project type.

Sepasgozar, S.M.E. [23] reported that photogrammetry accuracy can be affected by lighting conditions and surface texture. Our finding that 'Extreme Environmental Conditions' was ranked as the lowest challenge (RII = 0.75) suggests that Saudi experts may perceive this as manageable through the mitigation strategies proposed in Layer 3, including adaptive scheduling and protective equipment.

6.3. Theoretical Implications

This study contributes to theory in three ways. First, it demonstrates the applicability of the TOE framework to DCRP-BIM integration in mega-projects, extending the

framework's domain beyond enterprise-level technology adoption to project-level digital transformation. Second, the findings suggest that organizational and environmental factors are more predictive of implementation success than technological factors alone, reinforcing the socio-technical perspective on technology adoption. Third, the three-layer framework provides an operationalization of the TOE contexts that can be adapted for other construction technologies (e.g., AI, IoT, digital twins) in similar contexts.

6.4. Practical Implications

For project owners (e.g., NEOM Company, ROSHN, Red Sea Global), the findings suggest three actionable recommendations:

1. mandate the use of openBIM standards (IFC) in all contracts;
2. require DCRP-BIM integration plans as part of tender submissions;
3. invest in pilot projects to demonstrate ROI before full-scale rollout.

For contractors and consultants, the findings recommend:

1. prioritizing investment in training for the roles defined in the RACI matrix (Layer 2);
2. implementing pilot projects on manageable scopes to build internal capability;
3. developing partnerships with technology providers and universities for knowledge transfer.

For policymakers and academia, the findings support:

1. developing targeted curricula and certification programs aligned with the framework's requirements;
2. supporting the Human Capability Development Program of Vision 2030 through industry-academia partnerships;
3. establishing national guidelines for DCRP-BIM data exchange standards.

6.5. Generalizability and Transferability

While the framework was developed and validated specifically for Saudi mega-projects under Vision 2030, its three-layer structure is transferable to other contexts. The technical workflow (Layer 1) is universal and can be applied to any construction project regardless of location or scale. The managerial protocols (Layer 2) can be adapted to any organizational size or structure, with the RACI matrix serving as a template that can be customized. The contextual mitigation layer (Layer 3) requires the most adaptation, as it is designed for Saudi-specific challenges (extreme climate, sandstorms, high temperatures). For other countries, this layer should be modified to address local environmental, regulatory, and cultural factors. For smaller-scale projects, the framework can be scaled down by simplifying the managerial protocols and reducing the frequency of data collection cycles.

7. Conclusions

7.1. Limitations of the Study

This study has several limitations that should be acknowledged. First, the sample size of 65, while adequate for the statistical analyses conducted and exceeding the sample sizes of similar validation studies in construction technology research, may not fully represent the diversity of the Saudi construction sector, which includes thousands of firms of varying sizes and specializations. Second, the findings rely on perceptual data (expert opinions) rather than objective measures of framework performance. While expert validation is an accepted method for framework evaluation in Design Science Research, future research should complement these findings with quantitative performance metrics. Third, the study is cross-sectional, capturing perceptions at a single point in time. The construction technology landscape is evolving rapidly, and longitudinal research would reveal how perceptions change as experience with DCRP-BIM integration accumulates.

Fourth, the focus on Saudi mega-projects may limit generalizability to smaller projects or other countries, as discussed in Section 6.5.

7.2. Major Findings

This study successfully developed and validated a comprehensive three-layer framework for integrating DCRP and BIM within the unique context of Saudi Arabia's Vision 2030 giga-projects. The expert survey confirmed the framework's relevance, comprehensiveness, and practicality. The primary findings are:

The proposed framework received strong expert validation, with overall comprehensiveness scoring M = 4.52/5 and practicality scoring M = 4.38/5.

'Data Interoperability' (RII = 0.94) and 'Technical Expertise Shortage' (RII = 0.90) are the most critical challenges facing DCRP-BIM integration in Saudi mega-projects.

'Enhanced Geometric Accuracy' (RII = 0.96) and 'Progress Monitoring Efficiency' (RII = 0.93) are the most valued benefits of integration.

Top-down leadership mandate and strategic workforce development are essential success factors, as identified through qualitative thematic analysis.

Subgroup analysis revealed no significant differences in framework validation between NEOM and other Vision 2030 projects, supporting the framework's relevance across the mega-project portfolio.

7.3. Recommendations for Stakeholders

Based on the findings, the following recommendations are made:

1. **For Project Owners (e.g., NEOM Company, ROSHN, Red Sea Global):** Mandate the use of openBIM standards (IFC) in all contracts, require DCRP-BIM integration plans as part of tender submissions, and invest in pilot projects to demonstrate the ROI of integration before full-scale rollout.
2. **For Contractors and Consultants:** Prioritize investment in training and technology partnerships to build internal capacity, focusing on the roles defined in the framework's managerial layer (RACI matrix). Implement pilot projects on manageable scopes (e.g., a single building module) to demonstrate value and build confidence.
3. **For Academia and Government:** Develop targeted curricula and certification programs aligned with the framework's requirements, supporting the Human Capability Development Program of Vision 2030. Establish national guidelines for DCRP-BIM data exchange standards to address the interoperability challenge.

7.4. Future Research Directions

Several avenues for future research emerge from this study. First, the framework should be implemented in a longitudinal case study on an active Vision 2030 project to quantitatively measure its impact on key performance indicators such as cost deviation, schedule adherence, rework rates, and labor productivity. Second, comparative studies across different countries (e.g., UAE, Qatar, Singapore) would assess the transferability of the framework and identify context-specific adaptations. Third, integration of artificial intelligence for automated deviation detection from DCRP data represents a promising direction for enhancing the technical workflow. Fourth, development of cost–benefit analysis tools specifically designed for small and medium enterprises would support broader adoption across the Saudi construction sector. Fifth, longitudinal research tracking the adoption process over time would provide valuable insights into the change management dynamics highlighted in this study.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Participants were informed about the purpose of the research, the voluntary nature of their participation, and the anonymity of their responses. Implied consent was obtained through the voluntary completion and return of the survey questionnaire.

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Abbreviations

MVS	Multi-View Stereo
RACI	Responsible, Accountable, Consulted, Informed (Matrix)
RII	Relative Importance Index
ROI	Return on Investment
SfM	Structure-from-Motion
TOE	Technology-Organization-Environment (Framework)
UAV	Unmanned Aerial Vehicle (Drone)
AEC	Architecture, Engineering, and Construction
BIM	Building Information Modeling
CDE	Common Data Environment
DCRP	Digital Close-Range Photogrammetry
DSR	Design Science Research
GCP	Ground Control Point
IFC	Industry Foundation Classes
KSA	Kingdom of Saudi Arabia

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