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Applying Analytical Hierarchy Process (AHP) to BIM-Based Risk Management for Optimal Performance in Construction Projects

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Abstract: This study explores integrating Building Information Modeling (BIM) technology into risk management practices for construction projects, aiming to enhance project performance through improved risk identification, assessment, and mitigation. The research employs the Analytical Hierarchy Process (AHP) to prioritize BIM-based strategies across multiple risk management dimensions, including technical, financial, sustainability, and time management. The findings demonstrate that BIM-based financial strategies rank highest among BIM-driven risk management, followed by sustainability and time. In contrast, technical, operation, and maintenance capabilities have the lowest rank. Given the high priority of BIM financial strategies, they have been applied to conduct sensitivity analysis; the sensitivity analysis results demonstrate the dynamic nature of a BIM sub-criteria strategy in response to changes in the weight of financial considerations. As financial concerns diminish, the shift towards sustainability, health, safety, and time efficiency underscores the importance of a more balanced approach in BIM strategy prioritization. BIM-based risk management improves project outcomes by enabling real-time data-driven decision-making, enhancing stakeholder collaboration and optimizing resource use, cost control, and sustainability. This research contributes to theoretical and practical advancements in construction risk management, suggesting that BIM can be a transformative tool for optimizing project performance while addressing the complexities and uncertainties inherent in the construction industry.

Keywords: risk management (RM); building information modeling (BIM); construction project; Analytical Hierarchy Process (AHP); optimal performance

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1. Introduction

Since the 17th century, "risk" has been used to describe hazardous threats and their repercussions [1–3]. Siegrist and Árvai [4] define risk as the likelihood of financial loss due to unfortunate events affecting an institution's finances. Alaeddini and Dogan [5] and Zou et al. [3] define 'the probability of unwanted risks and the accompanying repercussions' as prospective risks and their effects. Construction projects involve planning, designing, building, operating, and decommissioning, each with risks [6–8]. Structural complexity, new building technologies, and rapid growth increase risks [9]. Logical and methodical risk management requires early identification and risk assessment methods [10]. However, traditional risk management methods are ineffective [11,12]. Zou et al. [3] say risk management occurs throughout building projects. The many common threats that matter are complex to resolve [13]. The risk may increase with an insufficient database, subjective views, and time and cost constraints [14]. Without the advanced data analysis techniques made possible by digital technology, these concerns may be more challenging to manage and research [15–17]. According to Azhar et al. [18] and Liu et al. [19], well-planned and managed risks increase project success. A risk event may affect project success or failure. However, companies can mitigate these risks [20,21]. Given the unpredictable nature of construction and the significant influence risk management has on project completion, this area may considerably benefit from the risk management process [22]. Simultaneously, the construction sector, a significant contributor to GDP in numerous nations, faces challenges that might adversely affect project outcomes [1]. Construction operations involve many stakeholders, resource availability, environmental issues, budgetary constraints, political dynamics, low productivity, and contractual obligations, which might slow project progress [23]. According to Eilers et al. [24] and Aladayleh [25], successful initiatives require time, cost, quality, and performance. Price increases and scheduling delays are the biggest challenges in the construction industry [10].

Azhar [18] believes formal risk management for building projects provides essential data and evaluations. Complexity impacts building projects [26,27]. These risks affect project outcomes [28]. Recent studies link construction to delays [10]. This causes owner–contractor mistrust, lawsuits, and project abandonment [16,17]. Risk increases affect construction time, cost, quality, and safety [25,27,29]. Due to heightened risks, construction projects have cost overruns of between 20.4% and 44.7%, with nine out of ten globally costing more than anticipated [26,29]. Risks include structure damage, injury, mortality, budget overruns, and construction delays [10,28]. These issues stem from design problems, including inadequate load-bearing capacity, material failures such as concrete mix anomalies, unknowledgeable clientele, and poor management [3,30]. Construction in the Middle East, especially Jordan, needs aid with risks and challenges due to 40% execution failures [31]. Corruption, low technical capabilities, limited member knowledge, competition, lack of R&D, a weak real estate market, business delays, bureaucracy, inflation, and land acquisition issues plague the Jordanian construction sector. Politics and the economy limit Jordan's infrastructure investment [23,32,33].

This paper conceptually outlines BIM's risk management and construction performance benefits. This study examines how BIM might reduce risks and losses throughout the construction life cycle while addressing the constraints and tasks of traditional BIM. Construction benefits from better performance. BIM's superior digital technology helps coordinate projects throughout a facility's life cycle [33]. Construction risk management is easier using BIM. BIM helps manage risk [7]. Yang & Mao [34] mention that BIM may collect substantial data on a facility's physical and functional elements throughout its life cycle. Darko et al. [35] claim that data reduce danger and enhance building.

In BIM-based risk management, digital technologies reduce project risks [36,37]. Construction project inefficiencies, losses, and interruptions are reduced via BIM risk management [20,31,38]. BIM offers improved risk management capabilities. Nonetheless, no comprehensive frameworks integrate BIM with traditional risk management [32,33]. Research is required for methodologies that effectively integrate these domains. Current BIM-based risk management technologies predominantly overlook human factors [27]. These instruments must be analyzed for ease of use by construction professionals. BIM-based risk management systems are frequently untested and inadequately assessed in construction projects. These tools must be evaluated practically to ascertain their effectiveness and reliability. Construction risk management encompasses various methodologies owing to its intricacy [4–6]. There is limited research on integrating BIM with other technologies and disciplines to enhance risk management, such as the Internet of Things, artificial intelligence, and machine learning. Data precision and security are crucial for risk management [3].

Research is required on BIM-based data management challenges, such as interoperability, security, and privacy [7]. The absence of established standards and regulations renders BIM-based risk management intricate [14–16]. Research ought to yield industry-wide standards and guidelines for consistent and effective implementation. Addressing these research deficiencies may enhance BIM-based risk management and the productivity of building projects.

Risk management using BIM is a reality in construction. The trip is not over. What remains is to close the conceptual, experimental, and contextual gaps that prevent contractors from maximizing BIM risk management advantages. Only BIM-based best practices may improve conventional risk management from its unacceptably poor productivity to greatly optimized material advantages. This study prioritizes BIM-based risk management research requirements from the literature and technical knowledge to fill this gap. The result is a collection of key study problems that, when addressed by future research, may enable contractors to utilize BIM for risk management not as an assurance but as a dependable way to increase construction risk management productivity.

The construction industry is characterized by high volatility, or uncertainty, often caused by design complexity, market dynamics, innovative technology, and human factors. These uncertainties threaten the success of construction projects, necessitating a diligent and efficient management strategy. Construction risks can take the form of project resources such as time, cost, and quality, or business market, credit, and corporate risks, depending on the nature of the attributes. Regardless of the focus, risk management is a common decision-making practice in various fields of study. However, the choice of risk response is complicated by the interdependence or conflict between responses, context, and project stakeholders. Given these characteristics of construction risks, identifying risks during the project concept phase would facilitate using advanced project management techniques. It would improve decisions regarding setting project objectives. The primary aim of the research is to determine the feasibility of BIM-based risk management for improving performance in the construction industry.

The specific objectives of this research are (1) to assimilate knowledge from the risk management literature to develop a BIM-based risk management framework for identifying, assessing, and managing appropriate risk responses for the construction industry; (2) to investigate the opportunities that present themselves to the construction industry when adopting risk management practices using BIM technologies and methods; and (3) to analyze and evaluate the benefits and limitations.

2. Literature Review

The construction industry is a significant driver of economic activity in the Middle East and Jordan. To support the sector's domestic and international growth, Jordan requires innovative construction management practices. Development plans in Jordan recommend the adoption of Building Information Modeling (BIM) in construction projects. According to Hyarat et al. [33], the Jordanian Society of Engineers provides BIM training, which could help increase BIM adoption in the country. Jordanian design offices already use BIM for 3D visualization to enhance efficiency and cost-effectiveness, support interdisciplinary collaboration, detect clashes, assess energy performance, integrate intelligent objects, and conduct audits [33]. Mohammed and Haron [32] note that contract obligations and interaction, coordination, and interoperability among project stakeholders further promote BIM implementation in Jordan.

Globally, adoption of BIM is also on the rise. A 2010 McGraw Hill study reported that 74% of BIM users in Western Europe experienced a significant return on investment. Numerous studies have examined BIM integration strategies for managing construction risks. Ganbat et al. [20] reviewed 526 studies on BIM-based risk management published between 2007 and 2017, identifying key focus areas such as safety, process simulation, supply chain optimization, and defect prevention. The study also noted financial concerns around BIM implementation, maintenance, and cost overruns, emphasizing the need to mitigate BIM-related risks in construction.

Practical BIM implementation for automated identification and risk assessment is well studied. Zhou et al. [39] detected construction site safety issues using rule-based logic and BIM models. Falls, structural issues, electrical dangers, and bodily damage can be detected autonomously. Researchers built a BIM model expert system to analyze fall, accident, and pothole hazards [19]. Visual and analytical system data enhance risk management. Much research has identified construction hazards using 4D BIM. Hamledari et al. [40] evaluated construction schedule uncertainty using discrete event simulation and 4D BIM.

Risk register-based 4D modeling assessed activity delays and cost overruns [41]. Risk response and mitigation have improved using 4D models and risk data [42]. Researchers created BIM-based building supply chain risk reduction [43].

Darko et al. [35] recommended combining Radio Frequency Identification (RFID) and Global Positioning System (GPS) technologies to track material delivery in real time and increase supply chain visibility. Jalaei and Jrade [44] assessed building supply chain network risks using BIM and social network analysis. Many studies have studied BIM for construction quality and defect management. Pickering and Byrne [45] suggested BIM-enabled seismic risk assessment and mitigation. The researchers also used BIM to improve earthquake and flood resilience in building designs, reducing their effects. BIM-based risk management works, but its implementation needs improvement. Interoperability, data reliability, model accuracy, and organizational integration must be addressed. To maximize BIM-based risk management benefits, frameworks, standards, and best practices must be developed [35].

Construction projects require risk management to regulate cost, time, safety, and quality [10,30]. Researchers employed the Analytic Hierarchy Process (AHP) in Egypt and Saudi Arabia to prioritize risks during the bidding and construction phases. Expert questionnaires indicated that financial risk was the most prevalent, succeeded by design, political, and construction dangers. The Analytic Hierarchy Process (AHP) was streamlined using Expert Choice Software ECS [30]. Musarat et al. [27] used AHP in Malaysia. They found that BIM and integrated systems had the best potential as advanced technologies, with a score of 0.3855, followed by wireless monitoring and sensors at 0.3509. Industrial Revolution 4.0 technology such as robotics, automation, BIM, augmented reality, and wireless monitoring promise to improve worker health and safety in the construction industry. Robin et al. [46] used the Analytical Hierarchy Process to evaluate twenty participants' BIM competencies. Critical performance metrics were policies (37%), procedures (17%), technology (16%), people (15%), and organization (15%). Moshtaghian and Noorzai [21] illuminated the integration landscape in project management and stressed the importance of timely information integration, particularly in risk management. They presented a database to analyze timely risk management influences using 3D, 4D, and 5D models. Alirezaei et al. [47] proposed an online project risk monitoring system using BIM and augmented reality (AR). Overall, 67% of consumers cited better communication, punctuality, and risk awareness.

Dey [11] offered historical background for an Indian oil pipeline project and illustrated AHP and decision tree risk management. This technique separated the project into work packages, assessed hazards, and measured their consequences. Al-Fahad and Burhan [28] linked risk management to BIM using the fuzzy analytical hierarchical process (FAHP) to analyze risks and create pricing estimates for specific categories. Their study found that BIM-integrated systems may lower most risk factors, highlighting the need for procedural solid and training requirements. Hamid and Zainon [48] created a BIM model for a complicated Malaysian airport project that facilitated risk analysis and stakeholder engagement, decreasing change orders by 30% and finishing two months early. A BIM-based 3D model by Fernández-Alvarado et al. [49] identified future disagreements and improved stakeholder communication, lowering safety incidents by 40% in an urban infrastructure upgrade project.

Sanchez et al. [50] used BIM to reduce risk during the Sydney Opera House renovation, while Smith [14] used BIM to improve visualization and planning for the Crossrail project in London. BIM was used to manage design coordination throughout the World Trade Center building, enabling efficient planning and safety compliance [51]. These examples demonstrate BIM's ability to improve construction risk management and project outcomes. These studies and implementations show that BIM is a transformative tool for risk management and project success in the construction industry. Numerous research studies have examined BIM and related technologies in construction risk management. However, most evaluations focus on specific aspects of these technologies' applicability, evolution, and limitations [52]. Many academic papers assess traditional risk management methods, while others briefly discuss BIM's pros and cons [46].

A smooth handover process is critical to efficient facility management and customer satisfaction. Effective risk management through BIM contributes to this by ensuring that all necessary documentation—such as operations and maintenance manuals—is accurate and readily available during handover. Using standardized documentation and protocols within a BIM framework ensures that all stakeholders are aligned with project objectives from start to finish.

Integrating BIM into risk management practices dramatically enhances the likelihood of a successful project outcome. By facilitating better communication, early risk detection, and comprehensive documentation throughout the project life cycle, BIM mitigates risk and improves performance, leading to successful delivery. As construction projects become increasingly complex, adopting such innovative technologies will be essential to meeting client expectations and ensuring operational efficiency.

By understanding and effectively implementing these strategies, construction professionals can overcome the challenges inherent in project management while delivering high-quality results on time and within budget.

There is no comprehensive analysis of recent BIM-based risk management research, digital technology, or traditional risk management methodologies. This paper addresses this gap by highlighting the main benefits of BIM in risk management, such as improving construction project efficiency, and encouraging further research.

Risk Mitigation in Construction Projects Using BIM

BIM enables high-efficiency construction management, simplifying and improving industry knowledge [1]. BIM models are created from digital structure simulation models and laser-scanned images from three to n dimensions. Alaeddini and Dogan [5] say completed models communicate process data and operate. BIM is needed to overcome the main limitations of 2D (axonometric and aerial view) and 3D (axonometric and perspective) construction representations [3]. BIM models all building parts over time. BIM positions and shows nD model accessories and structures. Status updates, executive reports, construction progress meetings, and project data are needed [9]. Data assess risk and impact [7]. Data flaws and risks are highlighted. Proactive risk decision-making requires judgment or experience [1]. Risk assessment of data reports requires creativity and expertise. Companies must disclose building project portfolios [10,53]. Data processing, inspection, and proactive risk management are neglected. The firm must prioritize it with senior management approval [16,17,29]. The most progressive people recognize financial challenges or opportunities in the established environment as risk management improves performance preparation [17]. BIM anticipates issues and evaluates building component readiness throughout the project [54]. BIM simulates work area mobility, construction processes, and personnel, helping schedulers optimize logistics [19]. BIM improves risk assessment. The correlation between structural and maintenance data is crucial for risk assessment. Chowdhury et al. [55] say BIM integration aids structural understanding and risk identification.

Risk management is improved by BIM's risk analysis report, which provides specific views of buildings and infrastructure [56]. It can also streamline stakeholders' evaluations and help them eliminate mismatches [19,34]. Finally, reliable design and construction information reduces formalities and access time [20,35]. BIM stores countermeasure and recovery data for building, operating, and maintaining facilities [31,57]. Hazard, risk probability, building damage, and other structured data are integrated into BIM to automatically analyze risk and open chart risk system architectural component information.

Many BIM tools help project managers manage risks [3,54]. Active methods like BIM help digitize plans [58–60]. Parsamehr et al. [36] say BIM's 3D visualization helps stakeholders quickly identify and delete unneeded design elements, reducing risks. BIM centralizes project data, improving drawing flow and management. BIM's precise quantity takeoffs and estimating tool integration eliminate calculation errors [24,61]. BIM integrates with GIS and other data sources to simplify site analysis, reducing the risk of insufficient site investigations during planning and design [3,20,60]. BIM can preserve risk-related information and share project experiences while minimizing risks during design and construction [37,62].

BIM, a digital representation of a construction project, is crucial for reducing risks; improving efficiency, safety, and quality; and meeting deadlines and budgets [36]. It enhances project scope visualization, accuracy, and real-time monitoring, reducing change orders and enabling efficient stakeholder communication [53,58]. BIM also aids inventory management, saves time and money, and improves construction timelines and workflow [58]. It promotes quality, simulates site conditions, and reduces risks while promoting stakeholder openness, discussions, and dispute resolution [30,31]. BIM significantly reduces financial risks in construction projects by providing accurate cost estimates, enabling proactive cost management, and fostering effective stakeholder communication [29–32]. It streamlines approval processes, decreases bureaucratic delays, and offers exact quantity take-offs. BIM helps match project costs and owner funds, reducing finance and cash flow difficulties [31]. It simulates the construction process proactively, detecting quality issues early and reducing quality control and rework [36,41]. BIM also improves insurance prices, allows sensitivity testing for inflation and interest rates, and helps avoid cost overruns by modeling construction techniques and testing design scenarios early in the project life cycle [22,43].

BIM can help address health and safety challenges in construction projects by optimizing design and reducing key building health and safety risks [19,27]. Construction workers face more health and safety risks than others, including falls, automobile accidents, and electrocution [36,46]. BIM can detect dangerous locations, analyze systems, and resolve concerns about workforce safety [40]. It can anticipate, analyze, negate, and mitigate health and safety risks throughout the project life cycle, benefiting from early project risk identification and hazard analysis [31,46,57].

Sustainable phase-based Building Information Modeling (BIM) is crucial for improving building performance and sustainability [6,8]. It aids in risk management, early risk identification, and cost-effective deployment. BIM provides better data for energy simulation and performance evaluation than older methods, aids in life cycle assessment (LCA), and enhances thermal and solar analysis (TSA), which assesses glazing system lighting, cooling, heating, natural vs. artificial lighting, radiation, and cooling loads [6].

BIM technology aids in implementing energy-saving measures at every life cycle phase, allowing designers to implement sustainable practices [25,42]. It also allows for thorough environmental impact evaluations, resource distribution, and increased efficiency [44]. BIM also allows off-site fabrication of standardized components, reducing demand and waste. It also helps track building performance, improve efficiency, and reduce energy and carbon emissions. BIM technology enhances regulatory compliance, sustainability, energy efficiency, environmental impact, resource management, and pollution [49,56].

The construction industry recognizes the importance of managing the entire asset life cycle, from conception to decommissioning. BIM can help address asset management difficulties and possibilities [19]. Environmental sustainability impacts future building operations and maintenance (O&M), accounting for 80–85% of construction costs [19,55]. Own-er-operators can help design and construction teams understand system operation, maintenance, and performance, leading to better O&M outcomes at reduced costs [34]. BIM can provide integrated data for facility management collaboration, ensuring sustainable decision-making and reducing costs and environmental impacts [19,20,54–56].

According to the research model presented in the literature review, after final confirmation of the practical criteria and sub-criteria in enhancing the risk management of construction projects using BIM capabilities and technical, knowledge management, financial management, time potential, sustainability, health and safety, operation, and maintenance and based on the evaluations and validation of experts, the final factors and sub-factors are provided in Appendix A.

3. Methodology

This study aimed to identify and rank BIM-based strategies for enhancing construction project performance through a multi-stage process. Figure 1 presents the research methodology, beginning with defining the research question, identifying keywords, performing a literature review, and categorizing strategies and sub-strategies. Input from industry experts and academics was used to refine the findings, and the Analytical Hierarchy Process (AHP) was applied to prioritize strategies based on likelihood and impact, with sensitivity analysis ensuring the robustness of the results. Expert involvement ensures that the strategies are comprehensive and relevant to industry needs.

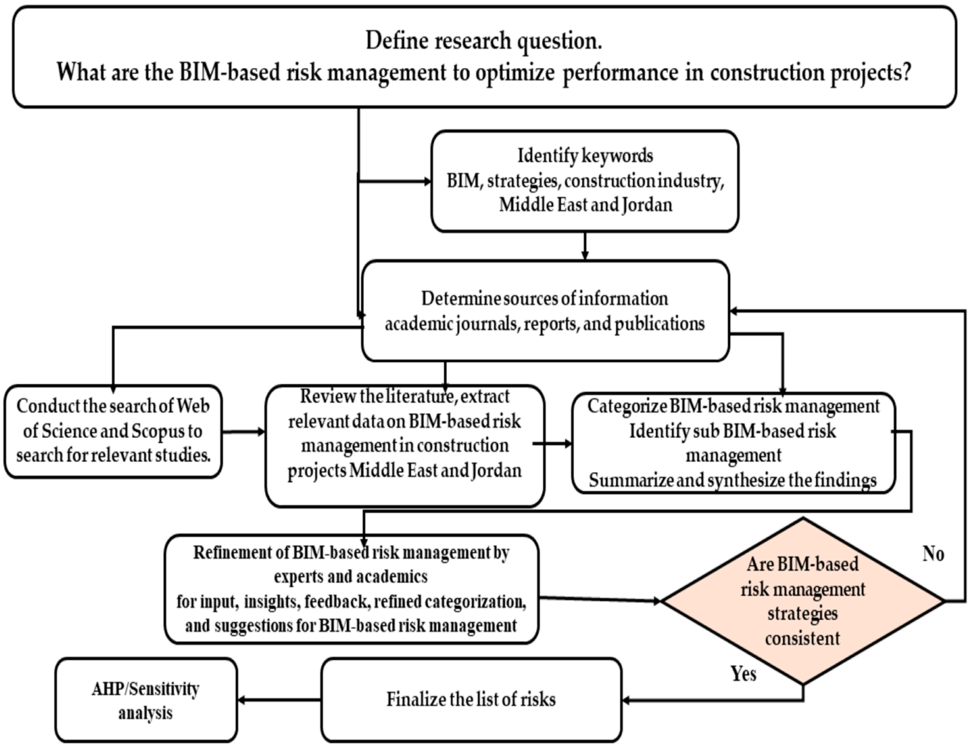

Figure 1. The research methodology's sequencing steps.

The BIM-based risk management assessment framework ranks strategies by calculating their relative importance within construction projects and assigning weights to each strategy to determine its priority. According to Saaty [63], selecting a weighting method is based on flexibility, internal consistency, and applicability. Several methods in the literature support prioritizing decision-making factors or risks, such as multiple regression analysis, factor analysis, and correlation. Other studies also employ interpretive structural modeling (ISM) and similar techniques [64–66].

For example, multiple regression analysis can be challenging to interpret when parameters are nonlinear, often leading to inaccurate structural representations that weaken the model's explanatory power. This model assumes linearity across datasets, presumes normal distribution, and can be sensitive to outliers. It is also limited in handling qualitative factors and can face multicollinearity issues [67]. Correlation analysis helps assign weights but only applies to interrelated variables. Factor analysis and structural equation modeling are more appropriate when variables correlate, but they may require adjustments to fit structural models [64]. Both methods also struggle with limited data and small sample sizes, complicating analyses of nonlinear structures [67]. Similarly, according to Panigrahi and Banerjee [68], ISM effectively illustrates factor relationships, identifying driving forces and dependencies, but it cannot assign precise factor weights or ensure expert consistency.

In contrast, AHP offers a multi-criteria decision-making approach that accommodates qualitative and quantitative criteria [63]. AHP simplifies complex decisions by breaking them down into hierarchical levels, making the process more manageable and enabling systematic evaluation. It is among the few MCDM models that effectively assess decision consistency and handle numerous criteria and sub-criteria [66]. Thus, AHP is particularly suitable for prioritizing BIM technology strategies in construction risk management.

3.1. Analytic Hierarchy Process (AHP)

This study utilized the AHP method for multi-criteria decision-making, organizing BIM strategies and sub-strategies into a hierarchical framework for prioritization. The hierarchy is designed to highlight the most critical BIM strategies at the top, focusing on their outcomes from a managerial viewpoint. This structure assigns considerable weight to the overall strategic outcomes, ensuring that the most critical BIM strategies are identified. The AHP process follows several key steps, as described by Saaty [63]:

Step 1. Problem definition: The first step involves clearly defining the problem or decision by identifying the objectives, criteria, and alternatives relevant to the decision-making process.

Step 2. Construct a hierarchical structure: Next, a hierarchical model is created (see Figure 2), organizing the objectives, criteria, and alternatives in a tree-like structure, with the primary objective at the top and alternatives at the bottom.

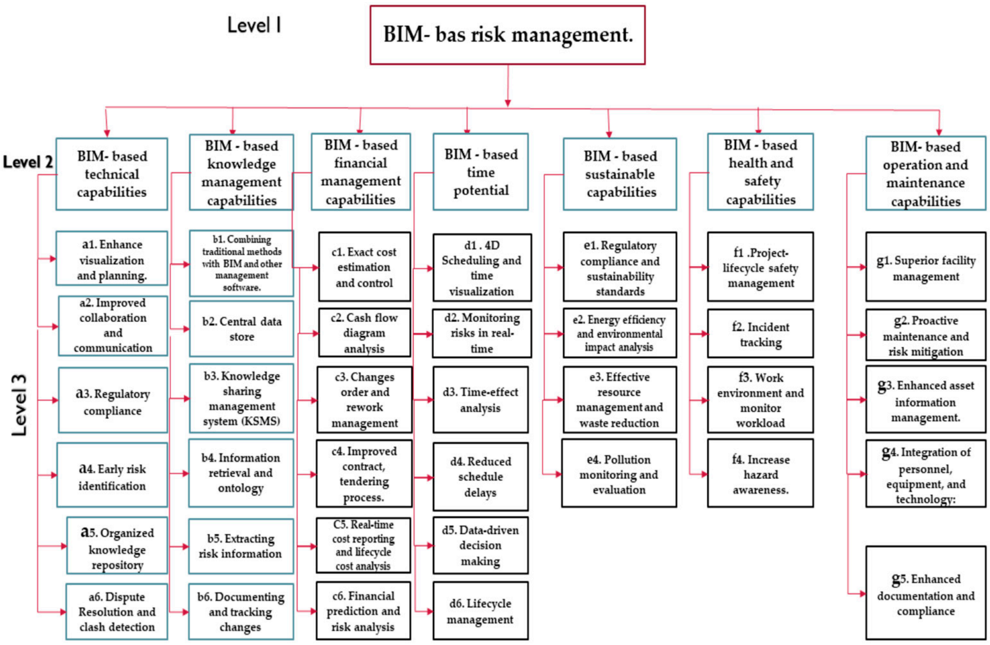

Figure 2. Hierarchal model of BIM strategies.

Step 3. Pairwise comparisons: This step involves comparing strategies and sub-strategies to determine their normalized priority weights. The pairwise comparison includes several sub-steps:

Creates pairwise comparison matrices for BIM-strategies and their sub-strategies.

Pairwise comparison matrices are created for strategies and sub-strategies, with certain elements reflecting reciprocity. This study uses Saaty's [63] nine-point scale (shown in Table 1) to assess the importance of criteria and sub-criteria in a standardized and unbiased way. During pairwise comparisons, these evaluations are converted into integer values. If element (*i*) is deemed superior to element (*j*), the corresponding row and column in the matrix are assigned this integer. In contrast, the reciprocal is placed in the opposite row and column. When two elements are judged equal, both positions receive a value of 1, ensuring the matrix follows the reciprocity principle as shown in Equation (1).

$$c_{ij} = \frac{1}{c_{ji}}\,; i,j = (1,2,\ldots n) \tag{1}$$

Table 1. Saaty's 1–9 scale for pairwise comparison (1987).

Weight Intensity	Definition	Explanation
1	Equally important	Two elements contribute equally to the objective.
3	Moderately important	Experience and judgment slightly favor one over another.
5	Strongly important	Experience and judgment strongly favor one over another.
7	Very strongly important	One element is strongly favored, and its dominance is demonstrated in practice.
9	Extremely important	The importance of one over another is affirmed in the highest possible order.
2, 4, 6, 8	Intermediate weights	Used to express intermediate values between the above-defined weights.

Weight intensity indicates the significance or preference of one element over another in a pairwise comparison. This scale is a crucial aspect of the AHP method, allowing decision-makers to perform consistent and objective comparisons between elements. It provides a numerical basis for assessing various criteria or alternatives' relative importance or preference in decision-making.

Additionally, constructing aggregate comparison matrices involves combining the evaluations of experts who have provided pairwise comparisons for different strategies and sub-strategies. As Vargas [69] described, the geometric mean method is applied to derive the combined judgment for each element within the matrices. This results in an aggregated comparison matrix, A = [aij], corresponding to a specific attribute. Each element (aij) reflects the geometric mean of the judgments from N decision-makers, calculated using Equation (2) as detailed below:

$$\mathrm{a_{ij}} = \left(\prod_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{c_{ij}}\right)^{1/\mathrm{N}} \tag{2}$$

Derive and calculate the relative weights of each strategy and sub-strategy.

Deriving and calculating the relative weights for each strategy and sub-strategy involves generating a normalized matrix (N) corresponding to the comparison matrix (A). The construction of this normalized matrix follows the equations provided in (3) below:

$$\mathrm{N} = [\mathrm{n_i}], \text{where } \mathrm{n_{ij}} = \frac{\mathrm{a_{ij}}}{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{a_{ij}}} \tag{3}$$

Next, all strategies' relative priorities or weights are determined by averaging the elements in each row of the normalized matrix (N), as shown in Equation (4). These priorities form the priority vector W = [wi], a column matrix of dimension n × 1, where each element [wi] represents an eigenvalue and indicates the weight assigned to a particular factor.

$$\mathrm{w_i} = \frac{\sum_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{n_{ij}}}{\mathrm{n}} \tag{4}$$

To ensure the validity of the outcomes, the consistency of each comparison matrix is evaluated using the consistency ratio (CR). A CR of 0.10 or less indicates acceptable consistency within the comparison matrix A, supporting the ranking results [63]. If the CR exceeds 0.10, the rankings cannot be validated, and the decision maker must reassess the evaluation process. A matrix A is deemed consistent if AW = nW. According to Saaty [63], the largest eigenvalue (λmax) should be greater than or equal to (n), with consistency increasing as (λmax) approaches (n). The calculation of (λmax) is performed using Equation (5) as follows:

$$AW = \lambda_{max} W \tag{5}$$

The following formula (Equation (6)) is used to calculate the consistency ratio (CR):

$$CR = \frac{CI}{RI} \tag{6}$$

The CI is the consistency index calculated based on the following formula (Equation (7)):

$$CI = \frac{\lambda_{max} - 1}{n - 1} \tag{7}$$

The random index (RI) is used alongside Saaty's consistency ratio (CR) to evaluate the consistency of a comparison matrix. RI provides a benchmark based on the matrix's order (the number of elements compared) and helps determine if the CR is within an acceptable range. Saaty (1980) outlined recommended CR values in relation to the RI, as shown in Table 2.

Table 2. Random index (RI) and recommended consistency ratio (CR) values (Saaty, 1970).

Random Index	n	3	4	5	6	7	8	9	10
	RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49
Recommended CR value		<0.05	<0.08	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10

The random index assesses the consistency of pairwise comparisons, a key element of the AHP method. A lower consistency ratio (CR) reflects greater consistency and strengthens the reliability of AHP results. As the number of criteria increases, the random index rises, making consistent comparisons more difficult. However, the recommended CR values remain relatively low (<0.10), suggesting consistent comparisons are achievable even with more significant criteria sets. The evaluators' pairwise comparison scores were analyzed using the geometric mean for accuracy.

Calculating global weights

Local weights, obtained from pairwise comparisons, reflect the importance of a sub-strategy relative to others within the same category. On the other hand, global weights represent the overall significance of a sub-strategy within the entire decision hierarchy. The global weight is computed using the following formula:

Global weight of a sub-strategy = Local weight of the sub-strategy × Local weight of the corresponding primary strategy

Step 4. Sensitivity analysis: This process assesses the robustness of the decision by analyzing how variations in weights or input values affect the final outcome.

3.2. Data Collection

The AHP methodology was guided by the insights of ten experts from construction companies. This study examined risk-management-savvy firms with over ten years of experience. The authors asked ten construction professionals and one academic to complete a questionnaire with key strategies and BIM sub-strategies from a literature review. Participants included management, assistant general managers, project managers, quality and development specialists, and a construction industry professor and experts. To avoid inconsistencies, this study only included ten respondents [63,70]. Previous research has successfully used AHP with a few experts [71]. All chosen experts were from Jordanian construction firms. These experts and an academic specialist were interviewed about Jordanian risk management main and sub-BIM strategies.

A hierarchical model was developed to manage risks associated with BIM strategies, featuring a three-level conceptual structure, as shown in Figure 2. The model's goal is to manage BIM strategies (level 1) by utilizing the main BIM strategy categories for decision-making (level 2) and further breaking them down into sub-strategies (level 3). These seven categories were derived from literature reviews and insights from industry experts. Data were collected via a questionnaire in which participants evaluated 8 BIM strategy categories and 37 sub-strategies, making pairwise comparisons at each hierarchical level using Saaty's 1–9 scale. A composite vector with normalized weights was created based on the relationships between the levels. Consistency was verified through the consistency index (CI) and consistency ratio (CR) for BIM strategies and sub-strategies, ensuring reliable expert data.

4. Results

A conceptual hierarchy model for BIM strategies and sub-strategies was developed, as shown in Figure 2, by reviewing existing knowledge and consulting construction industry experts. After aligning with experts, the model was validated against the prior theoretical literature. This framework categorizes BIM strategies at a high level, with each category containing sub-strategies addressing specific concerns. It provides a clear breakdown of key BIM strategies for optimizing performance and mitigating risks in construction, supported by expert input to ensure it reflects the industry's most critical priorities.

4.1. Results of AHP Pairwise Comparison

Table 3 shows BIM strategy criterion-to-criterion pairwise comparisons, while Table 4 shows the normalized matrix at the same level. Table 5 shows the local weights (LW) and local rankings (LR) of the seven BIM strategies from the pairwise comparison matrix and AHP analysis, as shown in Figure 3. Based on its eigenvector values at level 1, the financial criterion (BIM_3) ranks first, with a weight of 0.4099. This suggests that financial factors most influence BIM strategy decisions. Sustainability (BIM_5) ranks second, with 0.1734, followed by time (BIM_4) at 0.1433.

Table 3. Criterion-to-criterion pairwise comparison matrix for BIM strategies.

		BIM_1	BIM_2	BIM_3	BIM_4	BIM_5	BIM_6	BIM_7
Main Strategies (BIM Based)	BIM_1. Technical	1	1/4	1/8	1/3	1/6	1	1
	BIM_2. Knowledge	4	1	1/4	2	1	2	3
	BIM_3. Financial	8	4	1	5	2	9	9
	BIM_4. Time	3	1/2	1/5	1	2	3	5
	BIM_5. Sustainable	6	1	1/2	1/2	1	5	5
	BIM_6. Health and Safety capabilities	1	1/2	1/9	1/3	1/5	1	5
	BIM_7. Operation and maintenance capabilities	1	1/3	1/9	1/5	1/5	1/5	1

Table 4. Matrix normalization for BIM strategies (criterion-to-criterion).

	BIM_1	BIM_2	BIM_3	BIM_4	BIM_5	BIM_6	BIM_7
BIM_1	0.04	0.03	0.05	0.04	0.03	0.05	0.03
BIM_2	0.17	0.13	0.11	0.21	0.15	0.09	0.10
BIM_3	0.33	0.53	0.44	0.53	0.30	0.42	0.31
BIM_4	0.13	0.07	0.09	0.11	0.30	0.14	0.17
BIM_5	0.25	0.13	0.22	0.05	0.15	0.24	0.17
BIM_6	0.04	0.07	0.05	0.04	0.03	0.05	0.17
BIM_7	0.04	0.04	0.05	0.02	0.03	0.01	0.03

Table 5. Eigenvector and largest eigenvector value.

Criterion	W	Rank	AW	λ	CI	RI	CR
BIM_1	0.0388	6	0.2972925	7.6602688	0.0990636	1.32	0.0750481
BIM_2	0.1387	4	1.0810368	7.7936061			
BIM_3	0.4099	1	3.2016413	7.810613			
BIM_4	0.1433	3	1.1111247	7.7526839			
BIM_5	0.1734	2	1.3010401	7.5052778			
BIM_6	0.0631	5	0.4633211	7.3443781			
BIM_7	0.0328	7	0.2393591	7.2938417			
				7.5943813			

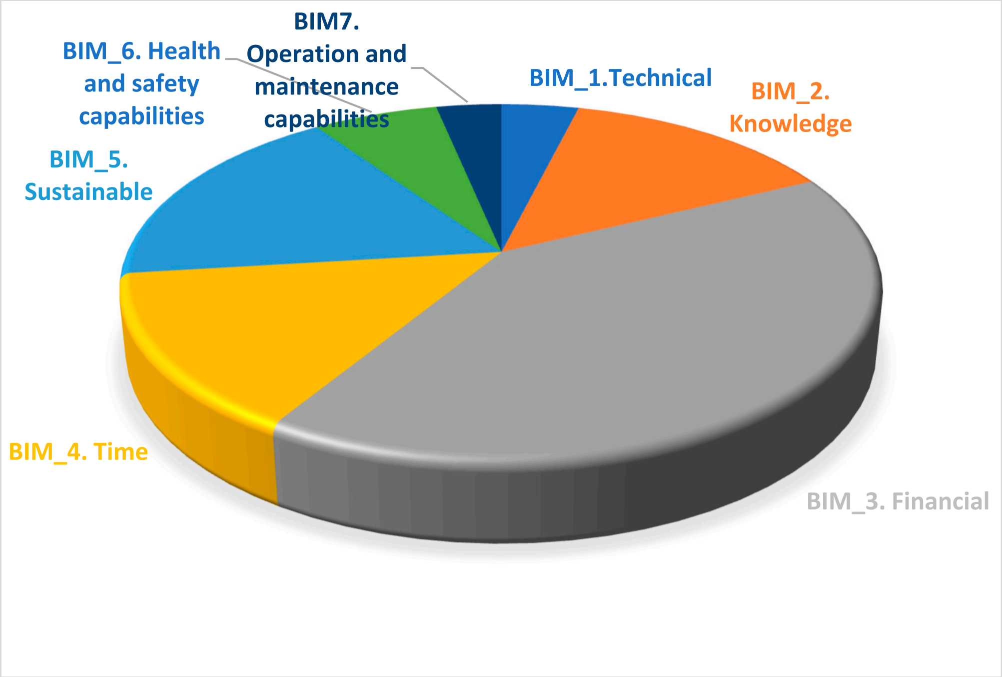

Figure 3. Eigenvector Values of BIM strategies.

Knowledge (BIM_2) ranks fourth, with 0.1387 weight, indicating moderate importance. Health and safety capabilities (BIM_6) rank fifth, with 0.0631, less critical than financial, sustainability, and time factors. Technology (BIM_1) strategies rank sixth, with 0.0388, while operation and maintenance capabilities (BIM_7) rank last, with 0.0328.

The weights and ranks indicate that financial, sustainability, and time factors dominate the formulation of a BIM strategy, as supported by Siegrist and Árvai [4]. At the same time, technical capabilities, health and safety, and operational maintenance are less critical. In the BIM decision-making process, this hierarchy prioritizes cost, environmental sustainability, and project schedules over technical and operational factors. Finally, Table 6 shows the randomness index (RI) and the recommended consistency ratio (CR), checked against the value of the most important eigenvector in Table 2.

A pairwise comparison matrix was used to determine the local weights (LW) and local rankings (LR) of the BIM sub-strategies using the same AHP methodology. Table 6 shows the sub-strategies' local weights and rankings from the AHP analysis.

The local weights of each BIM sub-strategy were multiplied by their primary strategy's local weights to calculate global weights (GW) and rankings. Table 6 shows these results. Figure 4 ranks the BIM sub-strategies with the highest global weights and cumulative impact to show the model's most important.

Table 6. Final ranking of BIM strategies and sub-strategies.

Local Weight (LW) and Global Weight (GL)						Consistency Checks		
Main Criteria	**Index Sub Criteria**	**LW**	**Rank (LW)**	**GW**	**Rank (GW)**	**CI**	**RI**	**CR**
BIM-based technical	a1	0.0407	6	0.0016	36	0.08	1.24	0.06
	a2	0.1499	3	0.0058	29			
	a3	0.4453	1	0.0173	18			
	a4	0.1417	4	0.0055	31			
	a5	0.1764	2	0.0068	24			
	a6	0.0461	5	0.0018	35			
BIM-based knowledge management capabilities	b1	0.0409	6	0.0057	30	0.08	1.24	0.06
	b2	0.1482	3	0.0206	14			
	b3	0.4436	1	0.0615	6			
	b4	0.1427	4	0.0198	16			
	b5	0.1779	2	0.0247	10			
	b6	0.0466	5	0.0065	26			
BIM-based financial management capabilities	c1	0.0407	6	0.0167	19	0.08	1.24	0.06
	c2	0.1570	3	0.0644	5			
	c3	0.4396	1	0.1802	1			
	c4	0.1412	4	0.0579	7			
	c5	0.1757	2	0.0720	3			
	c6	0.0458	5	0.0188	17			
BIM-based time potential	d1	0.0409	6	0.0059	27	0.07	1.24	0.06
	d2	0.1496	3	0.0214	13			
	d3	0.4514	1	0.0647	4			
	d4	0.1401	4	0.0201	15			
	d5	0.1715	2	0.0246	11			
	d6	0.0465	5	0.0067	25			
BIM-based sustainable capabilities	e1	0.0563	4	0.0098	22	0.03	0.90	0.03
	e2	0.2077	2	0.0360	9			
	e3	0.6068	1	0.1052	2			
	e4	0.1293	3	0.0224	12			
BIM-based health and safety capabilities	f1	0.0564	4	0.0036	34	0.02	0.90	0.03
	f2	0.2023	2	0.0128	21			
	f3	0.6090	1	0.0384	8			
	f4	0.1323	3	0.0083	23			
BIM-based operation and maintenance capabilities	g1	0.0417	5	0.0014	37	0.08	1.12	0.07
	g2	0.1658	3	0.0054	32			
	g3	0.4678	1	0.0154	20			
	g4	0.1471	4	0.0048	33			
	g5	0.1776	2	0.0058	28			

The BIM strategies and sub-strategies analysis shows local weights (LW) and global weights (GW) for different criteria, highlighting construction industry risk management and performance optimization priorities. Regulatory compliance (a3) has the highest local weight (LW = 0.4453, ranked 1st) and global weight (GW = 0.0173, ranked 18th) among BIM-based technical capabilities, indicating its importance. Enhance visualization and planning (a1) and dispute resolution and clash detection (a6), ranked 36th and 35th, respectively, have lower global impacts, with GW values of 0.0016 and 0.0018, making them less critical to BIM technical strategy.

In BIM-based knowledge management capabilities, knowledge sharing management system (KSMS) (b3) is highly significant, with the highest LW (0.4436, ranked 1st) and GW (0.0615, ranked 6th). This sub-strategy emphasizes the importance of information dissemination in enhancing BIM performance [11,12,24]. Other sub-strategies, such as extracting risk information (b5) (LW = 0.1779, ranked 2nd; GW = 0.0247, ranked 10th) and central data store (b2) (LW = 0.1482, ranked 3rd; GW = 0.0206, ranked 14th), further underscore the importance of managing knowledge and information within construction projects.

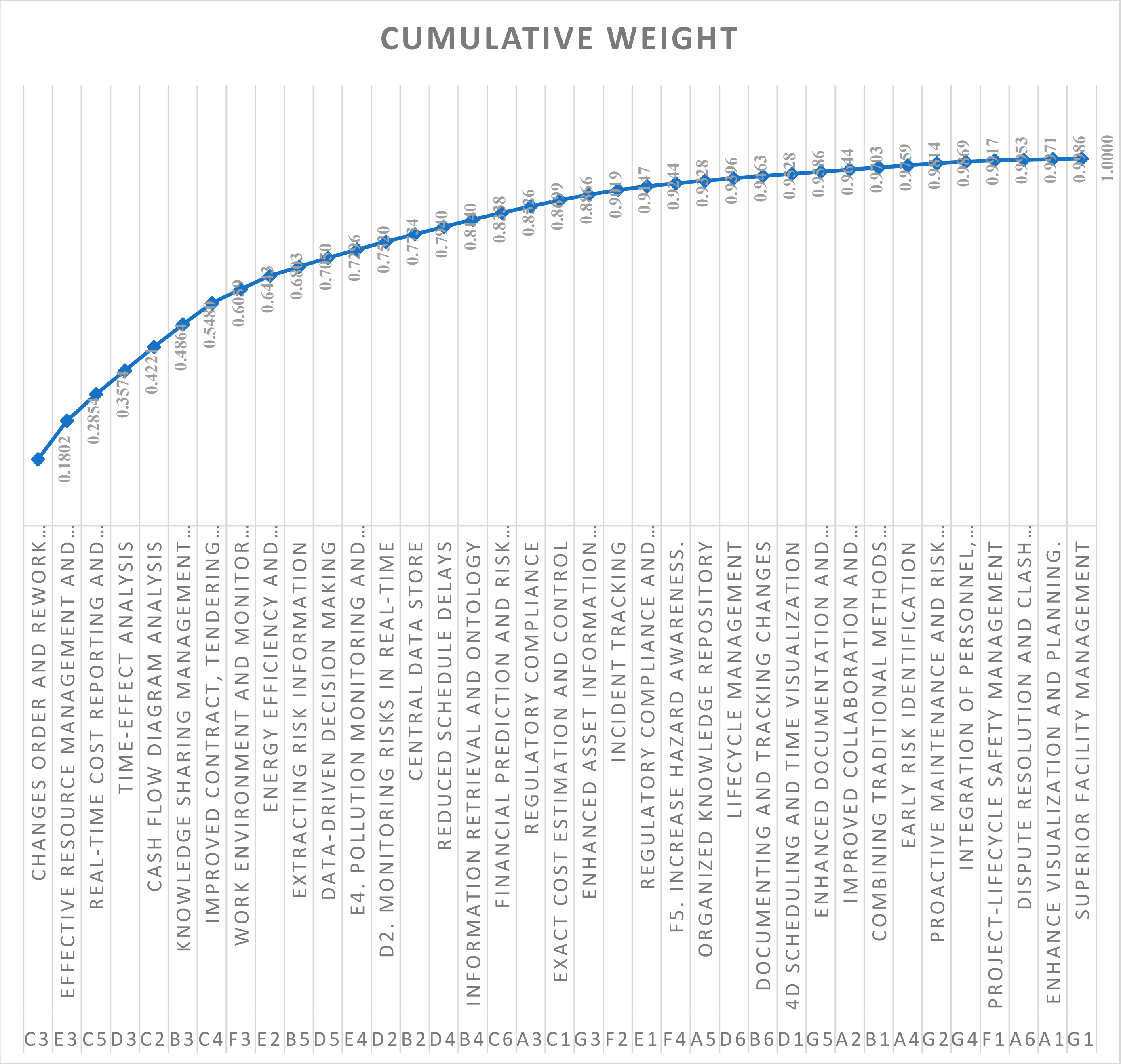

Figure 4. BIM sub-strategies' global weight (GW) and cumulative weight in increasing order.

For BIM-based financial management capabilities, changes order and rework management (c3) dominates, holding the top local weight (LW = 0.4396, ranked 1st) and global weight (GW = 0.1802, ranked 1st overall), signifying its paramount importance in minimizing financial risks and ensuring project stability. Real-time cost reporting and life-cycle cost analysis (c5) follows, with a significant GW (0.0720, ranked 3rd overall), underscoring the importance of real-time financial monitoring in BIM [20,39,40].

In the BIM-based time potential category, time-effect analysis (d3) takes the lead, with a LW of 0.4514 (ranked 1st) and a global weight of 0.0647 (ranked 4th), highlighting the criticality of time management and its effect on project outcomes [3,35]. Similarly, monitoring risks in real-time (d2) (GW = 0.0214, ranked 13th) and data-driven decision-making (d5) (GW = 0.0246, ranked 11th) play key roles in optimizing project timelines.

When focusing on BIM-based sustainable capabilities, effective resource management and waste reduction (e3) emerges as the most influential sub-strategy, with the highest LW (0.6068, ranked 1st) and GW (0.1052, ranked 2nd overall), reflecting the industry's increasing prioritization of sustainability and resource efficiency. Energy efficiency and environmental impact analysis (e2) follows closely (GW = 0.0360, ranked 9th), showing its critical contribution to sustainable construction practices, which is supported by Refs. [9,27,59].

The BIM-based health and safety capabilities category highlights work environment and monitor workload (f3) as the leading sub-strategy, with the highest LW (0.6090, ranked 1st) and GW (0.0384, ranked 8th). Musarat et al. [27] emphasize the importance of maintaining safety standards and ensuring an optimal working environment. Incident tracking (f2) and increased hazard awareness (f4) also contribute to this category, although they rank lower globally (21st and 23rd, respectively).

Finally, in BIM-based operation and maintenance capabilities, enhanced asset information management (g3) leads, with a LW of 0.4678 (ranked 1st) and a GW of 0.0154 (ranked 20th), indicating its critical role in operational efficiency and maintenance management, which is supported by [19,55].

The consistency check, conducted using the consistency index (CI), random index (RI), and consistency ratio (CR), reveals reliable and valid pairwise comparison results. The CR values across all categories are well within the acceptable threshold of CR < 0.10, with values ranging from 0.02 to 0.07, ensuring consistency in the expert judgments. This consistency indicates that the hierarchical model's comparisons and weight assignments are coherent and logically aligned [71]. For instance, the BIM-based sustainable capabilities category shows a CR of 0.03, affirming that the judgments related to sustainability criteria are robust and consistent. Similarly, other categories such as health and safety capabilities and knowledge management capabilities also demonstrate low CR values of 0.03 and 0.06, respectively, further strengthening the model's reliability.

Table 7 outlines the global weights (GW) and rankings of various BIM sub-strategies and their cumulative weights. The top-ranked sub-strategy, "changes order and rework management" (c3), has the highest global weight (GW) of 0.1802, which significantly contributes to the overall strategy, with a cumulative weight of 0.1802. This is followed by "effective resource management and waste reduction" (e3), ranked second, with a GW of 0.1052 and a cumulative weight of 0.2854, showing its considerable impact on BIM strategies. "Real-time cost reporting and life-cycle cost analysis" (c5) ranks third, with a GW of 0.0720 and a cumulative weight of 0.3574.

The next group of sub-strategies includes "time-effect analysis" (d3) and "cash flow diagram analysis" (c2), with global weights of 0.0647 and 0.0644, respectively, both contributing notably to the cumulative weight, reaching 0.4864 by the fifth sub-strategy. These top five sub-strategies collectively account for almost half (48.64%) of the overall BIM strategy, highlighting their importance in the prioritization process.

As the ranking continues, sub-strategies such as "knowledge sharing management system" (b3), "improved contract, tendering process" (c4), and "work environment and monitor workload" (f3) play key roles, with global weights ranging from 0.0615 to 0.0384. By the time these sub-strategies are considered, the cumulative weight reaches 0.6443, indicating that more than two-thirds of the overall BIM strategies are covered by the top eight sub-strategies.

The subsequent sub-strategies, including "energy efficiency and environmental impact analysis" (e2), "extracting risk information" (b5), and "data-driven decision making" (d5), continue to build up the cumulative weight, which reaches 0.7734 by the 13th sub-strategy, "monitoring risks in real-time" (d2).

Lower-ranked sub-strategies, such as "incident tracking" (f2), "regulatory compliance and sustainability standards" (e1), and "increase hazard awareness" (f4), contribute less individually to the overall strategy, with global weights below 0.0130. However, their collective impact still pushes the cumulative weight close to full coverage, reaching 0.9528 after 26 sub-strategies.

Table 7. BIM sub-strategies' global weights (GW), rankings, and their cumulative weights.

Index-Sub Criteria	GW	Rank (GW)	Cumulative Weight
c3	0.1802	1	0.1802
e3	0.1052	2	0.2854
c5	0.0720	3	0.3574
d3	0.0647	4	0.4221
c2	0.0644	5	0.4864
b3	0.0615	6	0.5480
c4	0.0579	7	0.6059
f3	0.0384	8	0.6443
e2	0.0360	9	0.6803
b5	0.0247	10	0.7050
d5	0.0246	11	0.7296
e4	0.0224	12	0.7520
d2	0.0214	13	0.7734
b2	0.0206	14	0.7940
d4	0.0201	15	0.8140
b4	0.0198	16	0.8338
c6	0.0188	17	0.8526
a3	0.0173	18	0.8699
c1	0.0167	19	0.8866
g3	0.0154	20	0.9019
f2	0.0128	21	0.9147
e1	0.0098	22	0.9244
f4	0.0083	23	0.9328
a5	0.0068	24	0.9396
d6	0.0067	25	0.9463
b6	0.0065	26	0.9528
d1	0.0059	27	0.9586
g5	0.0058	28	0.9644
a2	0.0058	29	0.9703
b1	0.0057	30	0.9759
a4	0.0055	31	0.9814
g2	0.0054	32	0.9869
g4	0.0048	33	0.9917
f1	0.0036	34	0.9953
a6	0.0018	35	0.9971
a1	0.0016	36	0.9986
g1	0.0014	37	1.0000

Finally, the lowest-ranked sub-strategies, including "dispute resolution and clash detection" (a6) and "superior facility management" (g1), have minimal individual global weights, contributing marginally to the overall strategy. Figure 4 highlights the BIM sub-strategies' global weight (GW) and cumulative weight in increasing order.

The organized ranking and aggregate weights of BIM sub-strategies establish a definitive framework for prioritizing initiatives in BIM implementation. Organizations can significantly refine their BIM strategies by concentrating on critical domains such as order management and resource optimization, resulting in enhanced project outcomes and efficiencies within the construction sector [22].

4.2. Sensitivity Analysis

This study's sensitivity analysis checks the stability of the rankings and examines how changes in the importance (or "weights") of crucial BIM strategies affect the rankings of related sub-strategies. This analysis is essential to confirm the proposed framework's reliability by observing how weight shifts impact rankings—a method also used in previous research, such as that conducted by Munny et al. [72] and Kumar et al. [73].

This study focuses on seven main BIM strategies. Among them, the financial strategy (BIM_3) is the top priority due to its strong influence on optimizing construction performance. Small changes in the weight of this financial strategy can significantly impact other BIM strategies.

In this analysis, the weight of the financial strategy was adjusted in steps—from 90% down to 10% of its original value (0.4099)—to see how these changes affect the importance and ranking of other BIM strategies. For instance, reducing the financial strategy's weight by 10% at each step produced values like 0.3689 (90%), 0.3279 (80%), and so on, until it reached 0.041 at 10%. Table 8 in this study shows how each change influences the overall weights and rankings of the BIM criteria, helping to understand how the importance of each criterion shifts when the financial strategy's influence is reduced incrementally.

As the financial weight is progressively reduced, the analysis reveals shifting importance among the other criteria; the incremental changes in the other criteria indicated that BIM_1 (technical) consistently maintains a low rank (6th place) throughout most weight reductions but moves up to 5th position when the financial weight is reduced to 10% of its original value, reaching a local weight of 0.1003. This indicates that while the technical criterion has less influence under normal circumstances, it becomes relatively more significant when financial considerations are diminished.

BIM_2 (knowledge) shows steady performance, retaining its 4th place ranking in most scenarios. However, when the financial weight is drastically reduced (to 30% or lower), it advances to 3rd place, highlighting its increasing relevance when the financial factor becomes less dominant.

BIM_3 (financial), the most dominant criterion in the base case, experiences a significant drop in importance as its weight is reduced. By the time the financial weight is cut to 50%, it still holds the first position but loses this ranking as the weight is further reduced to 40%, where sustainable (BIM_5) takes over. Once the financial weight reaches 20%, the financial criterion plummets to 7th place, with a weight of just 0.0410, indicating that its dominance heavily depends on its original weight allocation.

BIM_4 (time) displays consistency, maintaining its 3rd position under most weight scenarios. When the financial weight is reduced to 30% or less, time rises to 2nd place, illustrating that the criterion becomes more influential when financial concerns are minimized.

BIM_5 (sustainable) shows a steady increase in importance as the financial weight is reduced. It climbs to 1st place when the financial weight drops to 40% or lower, indicating the growing priority of sustainability considerations when financial constraints are relaxed. Its final weight at 10% of the financial criterion is 0.2348, the highest among all criteria at that point.

BIM_6 (health and safety) remains relatively stable in 5th position but eventually rises to 4th place when the financial weight drops to 20%. This reflects that health and safety concerns become more prominent in lower financial weight scenarios, though they remain moderately influential overall.

Finally, BIM_7 (operation and maintenance) consistently holds the lowest rank (7th place) throughout most sensitivity analyses. However, it rises to 6th place when the financial weight is reduced to 10%, suggesting that while it generally has a lower impact, its importance increases slightly in less financially-driven scenarios.

The key observation from sensitivity analysis offers a clear view of how various BIM criteria shift in relevance as financial considerations are adjusted. For instance, the financial criteria of construction projects are dominant, as the financial criterion (BIM_3) clearly dominates under normal conditions but rapidly loses its influence as its weight is decreased. This underscores the critical role financial considerations play in BIM decision-making, though this influence can shift significantly when financial factors are deprioritized. Furthermore, sustainability emerges as the sustainable criterion (BIM_5) shows notable growth in importance, eventually surpassing.

Table 8. BIM criteria change with the varying weight of the financial criterion (BIM_3).

Criteria	**Normal Weights**	**Normal Ranks**	**Incremental Changes**																	
			BIM_3.*0.9	**Rank**	**BIM_3.*0.8**	**Rank**	**BIM_3.*0.7**	**Rank**	**BIM_3.*0.6**	**Rank**	**BIM_3.*0.5**	**Rank**	**BIM_3.*0.4**	**Rank**	**BIM_3.*0.3**	**Rank**	**BIM_3.*0.2**	**Rank**	**BIM_3.*0.1**	**Rank**
BIM_1.Technical	0.0388	6	0.0456	6	0.0525	6	0.0593	6	0.0661	6	0.0730	6	0.0798	6	0.0866	6	0.0935	5	0.1003	5
BIM_2. Knowledge	0.1387	4	0.1455	4	0.1524	4	0.1592	4	0.1660	4	0.1729	4	0.1797	3	0.1865	3	0.1934	3	0.2002	3
BIM_3. Financial	0.4099	1	0.3689	1	0.3279	1	0.2869	1	0.2459	1	0.2050	2	0.1640	4	0.1230	4	0.0820	7	0.0410	7
BIM_4. Time	0.1433	3	0.1502	3	0.1570	3	0.1638	3	0.1706	3	0.1775	3	0.1843	2	0.1911	2	0.1980	2	0.2048	2
BIM_5. Sustainable	0.1734	2	0.1802	2	0.1870	2	0.1938	2	0.2007	2	0.2075	1	0.2143	1	0.2212	1	0.2280	1	0.2348	1
BIM_6. Health and safety capabilities	0.0631	5	0.0699	5	0.0767	5	0.0836	5	0.0904	5	0.0972	5	0.1041	5	0.1109	5	0.1177	4	0.1246	4
BIM7. Operation and maintenance capabilities	0.0328	7	0.0396	7	0.0465	7	0.0533	7	0.0601	7	0.0670	7	0.0738	7	0.0806	7	0.0875	6	0.0943	6
	1.00		1		1		1		1		1		1		1		1		1	

Financial when the latter is weight decreases to 40% or less. This shift highlights the increasing relevance of sustainability in situations where financial concerns are less central. Moreover, consistency of time and knowledge as both time (BIM_4) and knowledge (BIM_2) show stability throughout the analysis, maintaining similar rankings across different financial weight scenarios. This indicates that these criteria maintain their importance regardless of financial shifts, reflecting their intrinsic value in BIM strategies. Finally, technical and health and safety (BIM_1 and BIM_6) show modest but noticeable improvements in their rankings as the financial weight decreases, reflecting their growing importance in less financially driven decision-making contexts. Figure 5 illustrates the BIM criteria changes with the varying weight of the financial criterion (BIM_3).

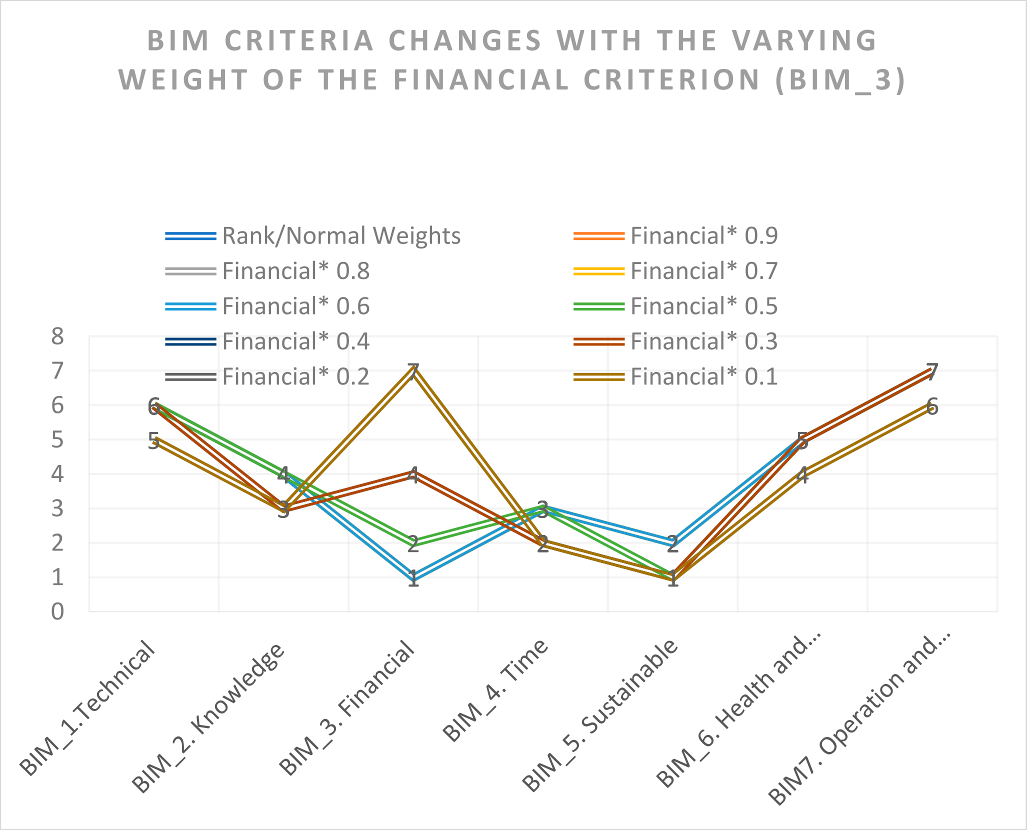

Figure 5. BIM criteria change with the varying weight of the financial criterion (BIM_3).

The analysis of the results from Table 9 reveals several significant shifts in rankings among the BIM sub-criteria as the weight of the financial criterion (BIM_3) is reduced incrementally. The following focuses on the sub-criteria that demonstrate the most pronounced changes:

1. Financial Management Sub-Criteria

- Changes order and rework management (c3): Initially ranked 1st in the normal weight scenario, this sub-criterion remains highly prioritized when the financial weight is 0.9 or 0.8. However, as the financial weight continues to decrease, its rank gradually drops, particularly after financial*0.5, where it moves to 4th and then to 16th when financial is 0.1. This indicates that the importance of this sub-criterion is highly sensitive to financial considerations, and as financial factors become less dominant, the importance of managing change orders and rework declines substantially.
- Real-time cost reporting and life-cycle cost analysis (c5): Ranked 3rd under normal conditions, this sub-criterion remains in the top ranks until the financial weight reaches 0.4, where it starts to drop significantly, eventually falling to 29th when the financial

weight is 0.1. This demonstrates that while cost reporting is crucial in financially-driven contexts, its relevance diminishes when financial concerns are deprioritized.

- Improved contract, tendering process (c4): Ranked 7th in the normal scenario, this sub-criterion sees a steady decline in rank as the financial weight decreases, reaching 32nd place when financial*0.1. Like the others, it indicates a strong dependence on the financial criterion for its importance.

2. Sustainable Capabilities Sub-Criteria

- Energy efficiency and environmental impact analysis (e2): Starting at 9th place in the normal weight scenario, this sub-criterion improves its rank as the financial weight decreases, moving up to 5th place at financial*0.1. This suggests that sustainability-related concerns, such as energy efficiency, become increasingly important in scenarios where financial priorities are reduced.
- Effective resource management and waste reduction (e3): This sub-criterion consistently ranks at the top, remaining in 1st position throughout the weight reductions. It highlights the critical and stable importance of effective resource management, even when financial concerns are diminished.

3. Time Potential Sub-Criteria

- Time-effect analysis (d3): Initially ranked 4th, this sub-criterion remains consistently in the top 3 across the different scenarios, ultimately rising to 2nd place when the financial weight reaches 0.1. This suggests that time-related efficiency is a critical factor, even when financial constraints are reduced.
- Monitoring risks in real-time (d2): Ranked 13th initially, this sub-criterion sees its importance rise as the financial weight decreases, moving up to 10th place when financial*0.1. Real-time monitoring of risks gains prominence when financial pressures lessen.

4. Health and Safety Sub-Criteria

- Incident tracking (f2): This sub-criterion starts at 21st place in the normal scenario but gradually improves its rank as the financial weight decreases, moving up to 15th at financial*0.1. The importance of health and safety management, particularly tracking incidents, becomes more relevant in lower financial weight scenarios.
- Work environment and monitor workload (f3): Ranked 8th in the normal scenario, this sub-criterion climbs to 4th place when financial*0.1, indicating that as financial concerns become less dominant, the management of work environments and monitoring workloads become more critical.

5. Operation and Maintenance Sub-Criteria

- Enhanced asset information management (g3): Initially ranked 20th, this sub-criterion sees significant improvement in its ranking as the financial weight decreases, eventually moving up to 7th at financial*0.1. This suggests that asset information management becomes increasingly important as financial priorities are scaled back.
- Proactive maintenance and risk mitigation (g2): Initially ranked 32nd, this sub-criterion improves its rank significantly as financial weight decreases, ultimately reaching 20th place when financial*0.1, highlighting the growing relevance of proactive maintenance strategies in less financially constrained contexts.

The general observations from the sensitivity analysis highlights the following:

- Highly financial-dependent criteria: Sub-criteria like c3 (changes order and rework management) and c5 (real-time cost reporting and life-cycle cost analysis) are highly dependent on the financial criterion. As the financial weight decreases, their relevance diminishes dramatically, which is indicative of their strong connection to financial management capabilities.
- Rising sustainability and time-effectiveness: As the financial criterion is deprioritized, sustainability-related sub-criteria such as e2 (energy efficiency) and time-related sub-

criteria such as d3 (time-effect analysis) gain importance. This shift suggests that when financial concerns are not the primary focus, there is a greater emphasis on sustainable practices and time optimization.

Table 9. BIM sub-criteria changes with the varying weight of the financial criterion (BIM_3).

Main Criteria	**Index- Sub-Criteria**	**Normal W and Ranks**			**Incremental Changes in Global Ranks When Financial Criterion Change**								
		Local W	**Global W**	**Global Rank**	**Financial* 0.9**	**Financial* 0.8**	**Financial* 0.7**	**Financial* 0.6**	**Financial* 0.5**	**Financial* 0.4**	**Financial* 0.3**	**Financial* 0.2**	**Financial* 0.1**
BIM-based technical	a1	0.0409	0.0016	36	36	36	36	36	36	36	36	34	34
	a2	0.1494	0.0058	28	27	26	26	27	25	25	24	22	21
	a3	0.4409	0.0171	18	17	14	12	11	8	7	7	6	6
	a4	0.1428	0.0055	31	30	28	28	28	26	26	26	23	22
	a5	0.1795	0.0070	24	24	24	24	21	20	20	20	17	17
	a6	0.0464	0.0018	35	35	35	35	35	35	35	35	33	33
BIM-based knowledge management capabilities	b1	0.0409	0.0057	30	32	33	33	33	33	32	31	31	28
	b2	0.1494	0.0207	14	14	15	16	16	16	14	13	13	12
	b3	0.4409	0.0612	6	5	4	4	4	4	3	3	3	3
	b4	0.1428	0.0198	16	16	18	18	18	18	17	15	15	14
	b5	0.1795	0.0249	11	10	10	10	10	11	9	9	9	8
	b6	0.0464	0.0064	26	28	30	31	31	31	29	29	29	26
BIM-based financial management capabilities	c1	0.0409	0.0168	19	20	21	21	25	29	33	34	37	37
	c2	0.1494	0.0613	5	6	6	7	8	9	16	18	24	31
	c3	0.4409	0.1807	1	1	1	1	2	2	4	5	8	16
	c4	0.1428	0.0585	7	7	8	8	9	13	18	19	27	32
	c5	0.1795	0.0736	3	4	5	6	6	7	11	17	21	29
	c6	0.0464	0.0190	17	19	20	20	23	28	31	33	35	36
BIM-based time potential	d1	0.0409	0.0059	27	31	32	32	32	32	30	30	30	27
	d2	0.1494	0.0214	13	13	13	15	15	15	13	11	11	10
	d3	0.4409	0.0632	4	3	3	3	3	3	2	2	2	2
	d4	0.1428	0.0205	15	15	16	17	17	17	15	14	14	13
	d5	0.1795	0.0257	10	11	11	11	12	12	10	10	10	9
	d6	0.0464	0.0067	25	26	29	30	30	30	28	28	28	25
BIM-based sustainable capabilities	e1	0.0563	0.0098	22	22	22	23	22	23	24	25	26	24
	e2	0.2057	0.0357	9	9	9	9	7	6	6	6	5	5
	e3	0.6076	0.1053	2	2	2	2	1	1	1	1	1	1
	e4	0.1304	0.0226	12	12	12	13	14	14	12	12	12	11
BIM-based health and safety capabilities	f1	0.0563	0.0036	34	34	34	34	34	34	34	32	32	30
	f2	0.2057	0.0130	21	21	19	19	19	19	19	16	16	15
	f3	0.6076	0.0383	8	8	7	5	5	5	5	4	4	4
	f4	0.1304	0.0082	23	23	23	22	20	21	21	21	18	19
BIM-based operation and maintenance capabilities	g1	0.0415	0.0014	37	37	37	37	37	37	37	37	36	35
	g2	0.1678	0.0055	32	29	27	27	26	24	23	23	20	20
	g3	0.4657	0.0153	20	18	17	14	13	10	8	8	7	7
	g4	0.1489	0.0049	33	33	31	29	29	27	27	27	25	23
	g5	0.1761	0.0058	29	25	25	25	24	22	22	22	19	18

The sensitivity analysis demonstrates the dynamic nature of BIM sub-criteria rankings in response to changes in the weight of financial considerations. The shift towards sustainability, health and safety, and time efficiency as financial concerns diminish underscores the importance of a more balanced approach in BIM strategy prioritization.

The analysis for BIM-based financial management capabilities (BIM_3; financial) shows a dynamic shift in financial sub-criteria prioritization as financial criterion weighting changes. In particular, the exact cost estimation and control (c1) sub-criterion declines in importance. This sub-criterion drops from 19th to 37th as financial weight decreases. This suggests that cost estimation and control are essential when financial constraints are prioritized but less so when they are not. Cash flow diagram analysis (c2) follows a similar pattern. Starting at 5th under normal financial conditions, it steadily falls to 31st. Cash flow management depends heavily on financial factors but becomes less important when sustainability or operational efficiency takes precedence.

Under normal financial conditions, changes in order and rework management (c3) is the most essential financial prioritization sub-criterion. It falls to 16th place as its financial weight decreases. According to this result, managing changes and rework can significantly reduce costs in financially driven environments. However, as financial concerns fade, other factors take precedence, reducing the focus on this sub-criterion. Improved contract, tendering process (c4) starts at 7th and drops to 32nd as financial weight decreases. This shows that contract and tendering process improvements are more important when financial management is critical but less so when not.

Also falling in rank are real-time cost reporting and life-cycle cost analysis (c5). This sub-criterion drops from 3rd to 29th as financial weight decreases. According to the findings, financial criteria require real-time cost monitoring and life-cycle cost analysis. When financial concerns become less important, other project management tasks take precedence, reducing the importance of real-time cost management. Financial prediction and risk analysis (c6) starts at 17th and drops to 36th as financial weight decreases. This supports the idea that financial prediction and risk analysis are closely related to financial management and become less relevant as financial constraints are deprioritized.

The analysis shows that financial management sub-criteria depend heavily on the financial criterion. As the financial criterion decreases, sub-criteria like exact cost estimation and control (c1), changes order and rework management (c3), and real-time cost reporting and life-cycle cost analysis (c5) become less important. This suggests that financial management activities are most crucial in financially driven decision-making contexts but less critical when sustainability or operational efficiency are more important. The consistent decline across all financial sub-criteria shows that BIM decision-making is multidimensional and requires balancing financial priorities with other critical issues. The findings suggest that BIM implementation should be flexible, prioritizing financial management capabilities according to project priorities.

The analysis of regulatory compliance (a3) shows that it gains importance as financial weight decreases. Financial considerations start at 18th and rise to 6th when prioritized. This shows how vital regulatory compliance is in non-financial environments.

Due to compliance requirements' non-negotiability, organizations appear to prioritize regulatory standards over financial criteria as the latter lose weight. Unlike financial management, regulatory compliance is often required and directly affects project legal and operational feasibility. Its steady rise from 18th to 6th place shows its growing importance as other financial factors fade.

This suggests that financial management drives project planning in the early stages, but regulatory compliance takes over as finances fade. This criterion becomes more critical as economic concerns are deprioritized because organizations must comply with regulations to avoid legal penalties, project delays, and other risks.

Regulatory compliance (a3) is becoming more critical as financial priorities change. In BIM decision-making, regulatory compliance becomes increasingly essential to project success and viability, especially when financial constraints are less important. The steady rise in ranking reflects a shift from financial management to operational and legal considerations.

Finally, documenting and tracking changes (b6) performs consistently across financial weights. It starts at 26th and drops to 31st before returning to 26th as finances ease. This stability suggests that BIM processes must document and track changes regardless of financial priorities. A temporary focus on financially oriented criteria may explain its slight ranking drop. Still, its overall position indicates its foundational importance despite being a secondary priority to cost control and compliance.

Life-cycle management (d6) starts at rank 25 and fluctuates to 26–30 before returning to 25 across financial weightings. This consistency shows its long-term role in BIM, which is essential but not a priority when economic factors are emphasized. Even without financial considerations, life-cycle management remains critical, but minor changes suggest periodic shifts in focus to other criteria.

5. Discussion

This study investigates incorporating (BIM) technology into construction project risk management to improve risk detection, assessment, and mitigation. Technical, financial, sustainability, and time management concerns prioritize BIM-based plans using the Analytical Hierarchy Process (AHP). Economic strategy, sustainability, and temporal variables are crucial to BIM-driven risk management. The research shows how BIM improves project results by enabling real-time decision-making, collaboration, cost management, and resource utilization efficiency. The findings of this study are consistent with the current body of literature because they emphasize the significance of financial strategies, particularly those centered on cost reporting and life-cycle analysis, during the first phases of Building Information Modeling (BIM) deployment [74].

Integrating BIM in construction risk management has shown significant potential for enhancing project performance. This study's findings validate the significance of BIM-based techniques, especially in addressing financial risks, sustainability issues, and time efficiency in building projects. Financial management has emerged as the paramount aspect, corroborating prior research that underscores the importance of financial methods for project stability and cost control [10,53,74].

This study's sensitivity analysis reveals how altering the weights of fundamental BIM strategies, notably financial criteria, impacts sub-strategies' ranking and relevance. This approach verifies ranking framework robustness [72]. It also shows how criteria and sub-criteria change when financial considerations change, demonstrating the dynamic nature of a BIM strategy prioritizing decision-making [74]. Under normal conditions, the financial strategy (BIM_3) is prioritized most. Therefore, any change in its weight considerably influences the total ranking of BIM strategies. Once the financial weight falls below 40%, BIM_5 (sustainable) becomes the most significant criterion. This trend shows sustainability is becoming more critical in non-financial circumstances [8,9]. BIM_4 (time) and BIM_2 (knowledge) perform similarly across financial weight scenarios, demonstrating their value independent of financial priority, which is supported by [24,35]. The sensitivity analysis shows that financial weight affects specific tactics more than others. BIM_1 (technical) and BIM_6 (health and safety) gain somewhat when financial weight declines. These factors are crucial when financial concerns are decreased, demonstrating that technical and safety issues become more significant in decision-making when cost limitations are lowest.

The sub-strategy analysis shows that financial weight strongly influences change order and rework management, real-time cost reporting, and life-cycle cost analysis. These sub-criteria drop sharply when the economic criterion is weighted down, showing diminished relevance in non-financial circumstances. As financial concerns decrease, sustainability-related sub-criteria rise in rank, including energy efficiency, environmental impact assessments, efficient resource management, and waste reduction. Aladaileh et al. [8] assert that reduced financial priorities may make sustainable practices and resource management more important in decision-making.

The ability of BIM to facilitate better collaboration between stakeholders can enhance sustainability efforts by improving resource utilization and reducing waste. Furthermore, effective time management through BIM can reduce delays, a common source of conflict in construction projects.

Interestingly, the research identifies technical, operational, and maintenance capabilities as the lowest ranked in the context of BIM-driven risk management strategies. This points to a potential gap in how these aspects are integrated into BIM frameworks. The complexity of construction projects often leads to challenges in maintaining operational efficiency and addressing technical issues. Future research should focus on developing methodologies that more effectively integrate these elements into BIM systems to enhance overall project performance.

The sensitivity analysis conducted in this study reveals the dynamic nature of BIM sub-criteria strategies in response to changes in financial considerations. This adaptability is critical in an industry characterized by volatility and uncertainty. As market conditions evolve, the ability to adjust risk management strategies accordingly can significantly impact project outcomes. This dynamic capability underscores the need for ongoing training and development for construction professionals to harness BIM's potential for risk management fully. In addition, the sensitivity analysis shows that BIM plan prioritizing should be more balanced, especially when budgetary restrictions are less critical. Financial factors frequently dominate decision-making, but sustainability, time efficiency, and health and safety gain prominence when financial concerns wane. These data imply that flexible and dynamic BIM deployment improves project performance in varied circumstances.

BIM also improves environmental and health and safety procedures, which are more important in less financially motivated situations. This study advances BIM as a transformational tool by providing a systematic way to balance building project goals.

Proposing Building Information Modeling (BIM) as a powerful solution for risk management and project optimization can benefit the construction industry in Jordan and the Middle East. This study can provide greater insight, making it directly relevant to readers interested in the construction industry in Jordan and the Middle East. BIM improves risk management in volatile environments. Construction projects in Jordan and the Middle East face uncertainty due to economic fluctuations, political instability, and market dynamics. This study demonstrates how BIM can manage these complexities by providing real-time data, predictive insights, and improved stakeholder collaboration, helping to mitigate risks such as project delays, cost overruns, and safety incidents. This study also focuses on financial management as a top priority for BIM, which is particularly useful in a region where cost control is critical to project success. Sustainability is a growing concern in the Middle East due to environmental regulations and the push towards greener construction practices. This study identifies the potential of BIM to enhance resource management, reduce waste, and enhance energy efficiency, which aligns with regional initiatives for sustainable construction and reduced environmental impact. As the construction sector is a vital part of Jordan's economy, contributing to GDP and employment, this study suggests that adopting BIM can address Jordan's specific challenges, such as limited technical capabilities and recurring project implementation issues. Implementing BIM-based risk management can improve project success rates, attract foreign investment, and contribute to the country's economic development.

Thus, future research should improve BIM-based risk management frameworks for broader use. This study shows that BIM plans are dynamic and require a balanced strategy that adjusts to shifting objectives for long-term project success.

6. Conclusions

Experienced Jordanian construction specialists find BIM helpful in minimizing and analyzing risks across the project life cycle. The results are specific to the Jordanian building sector and cannot be generalized. Experts from various populations may potentially have different results. This study should be seen as an experimental study that gives first insights into using BIM to manage construction project risks, which may inform future studies on BIM in diverse contexts.

The conceptual hierarchical model of BIM strategies and sub-strategies put forward in this study advances our understanding of construction performance and risk. The model organizes BIM strategies by interviewing experts and comparing their replies to earlier studies. This technique emphasizes the responsibilities of different methods and shows how cost, long-term goals, and time management affect decision-making.

This study shows that financial criteria (BIM_3) are the most important, with a weight of 0.4099, meaning they significantly impact how the BIM strategy is made. As we can see, the second and third most important factors are sustainability (BIM_5) and time management (BIM_4). This order of importance shows that the industry focuses on being cost-effective and positively affecting the environment.

AHP helped the researchers to appreciate the importance of tactics and strategies more thoroughly. Regulatory compliance has become a technological talent, indicating its importance as financial priorities shift. Documenting and monitoring modifications and other sub-strategies perform consistently across financial weights, proving they are crucial to BIM operations even if they are not always prioritized. The link between project elements and economic priorities is complicated in BIM-based financial management. As financial weight reduces, cost predictions, tight management, cash flow analysis, and real-time cost reporting become less critical. This shows they are more relevant in cost-sensitive circumstances. Following regulations becomes increasingly vital when economic concerns decrease, proving its importance to legal and operational success. This shows why firms must be adaptable when utilizing BIM to modify project goals. Financial management is crucial while planning, but compliance and operations become increasingly vital as projects advance. This research shows how difficult BIM decision-making is and how essential financial management, operational, and regulatory demands are for project success. The research enhances construction management, digital technologies, and risk management theory. It shows how digital techniques like BIM may improve risk management theories by employing dynamic data instead of static or fragmented information to identify, analyze, and mitigate risks. The findings show that BIM integrates environmental effect assessment and real-time monitoring, promoting sustainability theory in construction and green building practices. Finally, this complete BIM strategy framework emphasizes the importance of cost, environment, and time considerations for building organizations. According to the research, BIM initiatives should balance regulatory compliance and operational efficiency. Thus, organizations may manage current construction complexity while monitoring crucial performance parameters.

6.1. Theoretical Implication

For the theoretical implication, this study supports the idea that data-driven risk mitigation is better in complex environments like construction. Knowledge management using BIM promotes stakeholder knowledge sharing and aligns with knowledge-centric project management philosophies. The results show that BIM can combine environmental effect assessment and real-time monitoring, promoting sustainability theory in construction and green building practices. This study uses the Analytical Hierarchy Process (AHP) in a BIM framework to help project managers prioritize risks and decisions, improving risk prioritization models. It shows BIM's complicated function in enhancing risk management, wise financial decision-making, and construction sustainability, addressing current theories' flaws.

This study provides practical tools and processes that construction companies can implement immediately. It also advances theoretical research in BIM-based risk management, providing a framework for exploring the diverse capabilities of BIM in construction management in the future.

BIM-based risk management model advancement.

This study contributes to a growing body of literature on BIM in risk management, particularly by emphasizing the Analytical Hierarchy Process (AHP) as a prioritization tool within BIM strategies. Future research can use this approach to explore the scalability of BIM in managing diverse project risks across various regions.

BIM research integrates financial, environmental, and safety factors

This study shows that BIM sub-criteria are dynamic, primarily consisting of financial, environmental, and safety connections. This multi-dimensional approach to BIM study can stimulate further research into how these factors interact under diverse project settings, enhancing our understanding of BIM's building adaptability.

Sensitivity analysis as a methodological contribution

By applying sensitivity analysis to BIM-based strategies, this study presents a robust methodological approach that can be used to test the stability of risk management frameworks. This approach provides a path for future studies to evaluate how different project priorities (e.g., cost versus sustainability) affect the effectiveness of BIM.

Focus on Regional construction management issues

BIM research is generally broad and not adapted to regional concerns, so focusing on Jordan's building industry fills a void. This case study of Jordan can inform theoretical frameworks for the construction sector's needs in other developing nations.

Basis for policy suggestions driven by BIM

The paper provides a theoretical foundation for policy advocacy by highlighting BIM's role in resolving safety and environmental issues as well as operational inefficiencies. This theoretical underpinning can facilitate additional research into BIM as a tool for standardization and regulatory compliance in the building sector by fostering theoretical models that connect industry practice and policy.

6.2. Practical Implications

Practical implications are significant for industry professionals, particularly in improving the management, execution, and outcomes of construction projects. Project managers may also guarantee that designs fulfill regulatory standards, eliminating delays and penalties. These practical consequences show that BIM-based risk management may improve cooperation, reduce risk, and make building projects more efficient, cost-effective, and sustainable. Construction businesses that use BIM to improve project results and reduce operational inefficiencies may gain a competitive edge.

Enhanced project risk management

To help construction enterprises in Jordan and the Middle East better identify, assess, and mitigate risks, this study offers a framework for incorporating BIM into risk management processes. This paradigm can help practitioners improve project reliability by proactively managing uncertainties, including budget overruns and schedule delays.

Improved project cost and time efficiency

BIM prioritizes financial and time management, allowing businesses to control project budgets and timetables better. Construction organizations can use BIM's real-time data capabilities to avoid cost overruns and ensure timely project completion, satisfying customer expectations and enhancing profitability.

Sustainable and eco-friendly practices

BIM's sustainability capabilities match the region's green construction push. Companies may satisfy environmental goals and legal standards and improve their image using BIM for resource management and waste reduction.

Increased safety on construction sites

BIM's health and safety features make it easier to keep track of incidents and be aware of hazards, making workplaces safer. Using these BIM-based safety practices can reduce accidents at work, lower insurance costs, and boost morale among workers, which is very important for Jordan's building industry, which relies on a lot of manual labor.

Regional policy and standardization framework

The findings can help governments create BIM adoption and risk management standards. These rules can improve regional construction project outcomes and accord with international best practices by encouraging industry-wide consistency.

Capacity and knowledge management

This study emphasizes training and education by emphasizing BIM knowledge management. This focus on BIM information-sharing helps firms create institutional memory, decreasing knowledge gaps and improving future project decision-making.

The research provides construction companies with actionable tools and procedures to instantly put into their operations. This contributes to the advancement of theoretical research in BIM-based risk management and provides a framework for the future exploration of BIM's numerous capabilities in construction management.

6.3. Limitations

This study focuses on BIM-based risk management within the construction industry, particularly in Jordan, which may limit the generalizability of the findings to other contexts. The unique challenges and dynamics of the Jordanian construction industry, including its regulatory, economic, and political environments, may differ from different regions. While this study uses expert input to validate its framework and strategies, the sample size of experts is relatively small (10 participants). This small sample size may not capture the diversity of opinions and experiences within the broader construction sector, limiting the robustness of the findings. The sensitivity analysis also revolves primarily around financial criteria (BIM_3), which, while important, may overshadow other BIM strategies such as sustainability, time, and health and safety. A more comprehensive analysis that includes all BIM strategies equally may reveal different insights. This study does not fully explore integrating emerging technologies such as artificial intelligence, machine learning, or the Internet of Things with BIM to enhance risk management practices. This omission may lead to missing potential avenues for innovation and efficiency in construction management.

Future research should look beyond Jordan to evaluate BIM-based risk management solutions in other cultural, economic, and regulatory contexts. More considerable research with additional building industry professionals from different sectors would give a broader viewpoint and improve dependability. Including specialists from other locations or industries would make the framework more relevant.

Longitudinal studies are needed to assess BIM-based risk management systems' long-term efficacy. Researchers may follow projects over time to discover how BIM adoption affects construction project success across the project life cycle.

A more balanced BIM strategy investigation is needed. Instead of concentrating on finances, future studies should analyze sensitivity assessments on BIM strategies, including sustainability, time management, and health and safety. This would clarify how tactics interact in different project situations.

6.4. Recommendations

This study finding target critical stakeholders in the construction industry. These recommendations will enable a more structured, efficient, and sustainable construction industry that benefits all stakeholders while promoting BIM-based risk management practices across Jordan and the Middle East. The authors note the importance of developing and implementing BIM adoption policies and standards to ensure consistency and quality in construction projects, including BIM-based risk management guidelines, safety protocols, and sustainability standards that align with national development goals. Regulatory bodies can use this study's insights to create a unified framework for BIM, improving project compliance, safety, and sustainability in public and private construction projects. Clear standards can attract foreign investment by demonstrating Jordan's commitment to efficient and safe construction practices. By integrating BIM technology and risk management into construction and engineering curricula and creating certification programs focusing on BIM applications, including financial management, sustainability, and safety protocols, educational institutions can better prepare students with the practical and theoretical skills needed in an industry focused on BIM. This policy also supports a knowledgeable workforce prepared to implement advanced risk management practices, which benefits the industry and addresses the talent gap in BIM expertise. This study recommends creating BIM-based training, certification, and continuing education programs for industry professionals. This study also urges and recommends educating clients and investors about BIM-based project management's financial and long-term sustainability benefits. For example, investors should be encouraged to request the use of BIM on projects, which ensures greater transparency and reduced exposure to risk. Clients and investors benefit from improved project costs, schedules, and quality control transparency. This study's focus on financial management and sustainability through BIM can help these stakeholders reduce the risks associated with cost overruns, delays, and substandard construction quality. Technology providers also benefit from aligning their products with industry demand and regulations, improving market penetration. Supporting BIM adoption among SMEs can help the industry achieve greater standardization, leading to more effective risk management across all project types.

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Appendix A

Table A1. Main criteria and sub-criteria of BIM-based risk management.

Index	Main Criteria	Index	Sub Criteria	Descriptions	References
A	BIM-based technical capabilities	a1	Enhance visualization and planning	BIM's 3D visualization of building projects helps discover design and logistical concerns early on. This visualization prevents expensive mid-construction adjustments and delays.	[3,4,54]
		a2	Improved collaboration and communication	BIM improves stakeholder cooperation by allowing real-time updates and communicating changes to all team members. Live collaboration reduces errors and misunderstandings.	[47,49]
		a3	Regulatory compliance	Automatically checking if project designs comply with standards. This feature reduces the risk of compliance-related issues, potential fines, or rework.	[60]
		a4	Early risk identification	Fast 3D project information modeling. Accurate forecasting and visualization of project development, management, and maintenance improves risk communication and mitigation.	[55,56]
		a5	Organized knowledge repository	BIM organizes, stores, and shares risk information from project participants, capturing and using fragmented data to address risk concerns quickly.	[1,4,6]

Table A1. *Cont.*

Index	Main Criteria	Index	Sub Criteria	Descriptions	References
		a6	Dispute resolution and clash detection	Early clash detection allows for solving problems in the virtual environment (e.g., structural, mechanical, electrical), reducing the risk of rework and delays.	[32,33]
B	BIM-based knowledge management capabilities	b1	Combining traditional methods with BIM and other management software.	Utilizing databases, risk management tools, and project management software enhances project development risk detection, analysis, and information management, facilitating end-to-end risk management through data transit across systems.	[11,12]
		b2	Central data store	BIM helps all stakeholders have access to the latest information by consolidating data. Effective risk management requires centralized risk detection, analysis, and mitigation throughout a project.	[24,61]
		b3	Knowledge Sharing Management System (KSMS)	Project managers and engineers may exchange BIM expertise on KSMSs. This technology may record project information for future risk mitigation.	[54,55]
		b4	Information retrieval and ontology	BIM technology utilizes ontology and semantic web technologies to describe construction risk information semantically. This improves safety management risk knowledge and communication.	{16,17}
		b5	Extracting risk information	BIM manages 3D/4D information models in a virtual environment before construction to improve risk information extraction. It simplifies risk identification and communication, improving risk management.	[15–17]
		b6	Documenting and tracking changes	BIM excels in recording and tracking project changes. For risk management, this ability helps project teams track changes, understand their implications, and manage their risks.	[18]
C	BIM-based financial management capabilities	c1	Exact cost estimation and control	3D/D5 BIM models improve cost predictions, reduce budget overruns, and enhance project control through detailed visualizations and accurate calculations, enhancing financial understanding of design and construction decisions. BIM's improved project cost and budgeting risk control	[20]
		c2	Cash flow diagram analysis	allows comprehensive cash flow analysis by integrating schedule and cost data (4D BIM). This function estimates project funding needs to ensure sufficient funds are available. It helps anticipate cash flow gaps and reduce risk via proactive financial planning.	[39]
		c3	Changes order and rework management	BIM's financial impact assessment tools and effective change order management are made more accessible, reducing the risk of cost escalations.	[20,40]

Table A1. *Cont.*

Index	Main Criteria	Index	Sub Criteria	Descriptions	References
		c4	Improved contract, tendering process.	BIM incorporates contract terms and conditions into the project model to improve contract management. This interface controls milestones, payments, and penalties for contract financials, avoiding disputes and ensuring compliance. BIM gives potential contractors comprehensive and accurate project information, lowering financial risks and improving tendering transparency.	[43]
		c5	Real-time cost reporting and life-cycle cost analysis	BIM offers real-time project cost and financial performance updates, detecting economic risks and managing data throughout a building's life cycle, enabling informed decisions to balance early investments with long-term savings.	[41,42]
		c6	Financial prediction and risk analysis	Advanced analytical techniques in BIM enable financial risk analysis and prediction. These tools assist in controlling project risk by simulating financial situations and their effects.	[43]
D	BIM-based time potential	d1	4D scheduling and time visualization	This helps spot scheduling issues and understand how delays affect the project. BIM's 4D scheduling mixes 3D models with the project schedule to see construction progress.	[40,43]
		d2	Monitoring risks in real-time	BIM links virtual models to construction progress and real-time early warning system data to monitor risk. This enables the immediate detection and resolution of any issues.	[3]
		d3	Time-effect analysis	BIM provides accurate time impact analysis by examining project schedule changes and delays. This identifies key routes and activities that might delay the project.	[24,35]
		d4	Reduced schedule delays	BIM reduces unexpected project delays by enabling proactive planning, conflict detection, and risk reduction.	[13,14]
		d5	Data-driven decision making	Data (e.g., geospatial, structural, environmental) analytics and real-time access improve risk assessments and decision-making.	[24]
		d6	Life-cycle management	A long-term perspective helps identify and mitigate risks associated with building performance, maintenance, and future renovations.	[14]
E	BIM-based sustainable capabilities	e1	Regulatory compliance and sustainability standards	Automatically verify building code, legal, and sustainability designs. Including sustainability criteria in BIM models helps project teams make informed decisions that fulfill safety, budget, and operational requirements while promoting environmental, economic, and social sustainability. This reduces the risk of non-compliance, fines, and rework.	[8,9]

Table A1. *Cont.*

Index	Main Criteria	Index	Sub Criteria	Descriptions	References
		e2	Energy efficiency and environmental impact analysis	Detailing energy use and environmental effect using BIM aids sustainability. Designers can maximize building performance for LEED and BREEAM.	[27]
		e3	Effective resource management and waste reduction	BIM enhances sustainable management by improving time, labor, and material estimates, preventing overestimating or underestimating resource demands and promoting project sustainability by reducing waste and optimizing material and energy use.	[59]
		e4	Pollution monitoring and evaluation	BIM's real-time sustainability monitoring and evaluation is a big benefit. This permits continual risk assessment and management throughout the project. BIM can integrate with environmental monitoring tools to track pollution levels in real-time during construction.	[9]
F	BIM-based health and safety capabilities	f1	Project life-cycle safety management	BIM assists safety management from design to construction and operation, assuring health and safety priority.	[27]
		f2	Incident tracking	BIM facilitates the monitoring and documentation of near-misses and incidents, enabling in-depth analysis and the formulation of preventative measures against future occurrences.	[46]
		f3	Work environment and monitor workload	BIM technology can enhance workplace well-being by optimizing natural light, ventilation, and noise, reducing overtime and preventing burnout and stress by promoting a healthy work environment.	[40]
		f4	Increase hazard awareness	3D BIM models provide early hazard detection by visualizing the building site. Simulations may show where equipment and personnel are placed, revealing possible conflicts or Risks.	[31,57]
G	BIM-based operation and maintenance capabilities	g1	Superior facility management	Improved O&M efficiency. Facility management is enhanced by space and comprehensive asset information from BIM. Controlling unexpected behaviors like energy-hungry activities or facilities management problems improves operational efficiency. This proactive building performance management reduces operational inefficiencies and risks.	[20,34]
		g2	Proactive maintenance and risk mitigation	Predictive maintenance. This preventative strategy aims to prevent equipment failure and the resulting expensive repairs, downtime, and safety risks. The real-time performance of equipment may be monitored by integrating BIM data with Building Management Systems (BMS).	[19,55]

Table A1. *Cont.*

Index	Main Criteria	Index	Sub Criteria	Descriptions	References
		g3	Enhanced asset information management.	Improved asset monitoring and visualization, consolidated data repository. BIM models can store component warranties, maintenance instructions, and historical data. This reduces errors from outdated or missing data, allowing facility managers to make smart maintenance and repair decisions.	[34]
		g4	Integration of personnel, equipment, and technology	Personnel, equipment, technology, and management processes are integrated via BIM. Effective planning, maintenance, repair, and emergency management, addressing workers' fundamental requirements and improving construction project efficiency.	[19,20]
		g5	Enhanced documentation and compliance	Including compliance criteria in the model assures regulatory compliance with standards and legislation. BIM tracks all building alterations and upkeep. Inspections by regulatory organizations need this documentation to ensure that all maintenance actions are code-compliant and limit the risk of non-compliance.	[55,56]

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