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The Role of Building Information Modeling (BIM) in Sustainable Development and Optimizing Life Cycle Management of Commercial Buildings

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Abstract

Nowadays, the increasing complexity of construction projects and the need to reduce resource consumption and environmental impacts have heightened interest in the use of advanced technologies in the Architecture, Engineering, and Construction (AEC) industry. Among these technologies, Building Information Modeling (BIM) is an integrated approach for creating, managing, and exchanging project information and has considerable potential to improve the design, construction, operation, and maintenance processes of buildings. The aim of this study is to investigate the role of BIM in achieving sustainable development objectives and improving building performance throughout its life cycle. A review of previous studies indicates that BIM, by integrating information across different disciplines, enhancing coordination among project stakeholders, reducing rework, lowering costs and project duration, and enabling integration with energy, cost, and structural performance analysis tools, can improve decision-making processes in construction projects. Furthermore, the use of BIM during the early design stages enables the evaluation and comparison of different alternatives from both economic and environmental perspectives and can contribute to optimizing energy consumption, resource use, and life-cycle costs. Nevertheless, limitations such as insufficient user training and expertise, information exchange problems among different software platforms, legal and contractual issues, and the concentration of BIM applications on the early stages of projects are considered barriers to fully realizing its potential. Overall, the reviewed studies indicate that integrating BIM with sustainability assessment criteria can serve as an effective approach to supporting decision-making, reducing life-cycle costs, increasing productivity, and improving the environmental performance of buildings. Therefore, extending BIM applications from the design stage to all stages of the building life cycle is one of the key requirements for fully exploiting the potential of this technology in advancing sustainable development in the construction industry.

Keywords: Building information modeling, Sustainable development, Building life cycle, AEC industry, Sustainable design, Energy assessment.

1 | Introduction

The construction industry is one of the most important economic and infrastructure sectors in countries and is responsible for the consumption of substantial amounts of financial, human, material, and natural resources. At the same time, construction activities have significant environmental consequences throughout the life

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cycle of buildings. Increasing project complexity, the involvement of multiple stakeholders, growing requirements for energy efficiency and environmental performance, and the need to control project time, cost, and quality simultaneously have created a growing demand for more integrated approaches to construction management. Consequently, digital technologies and information-based approaches have become increasingly important for improving the efficiency and sustainability of the Architecture, Engineering, Construction, and Operation (AECO) industry [1], [2].

Building Information Modeling (BIM) is one of the most important digital technologies that has contributed to the transformation of the construction industry. The origins of BIM can be traced to early attempts to develop computer-based systems for representing building information. Eastman [3] proposed the Building Description System as an early attempt to establish a structured digital representation of building components and their relationships. Similarly, van Nederveen et al. [4] introduced the concept of modeling multiple views of buildings, contributing to the development of information-based building modeling approaches. With the development of information technologies and specialized software, BIM gradually evolved from a three-dimensional modeling concept into an integrated approach for creating, managing, exchanging, and using building information throughout different stages of the building life cycle [5].

The contemporary understanding of BIM goes beyond the geometric representation of a building. BIM provides an information-rich digital environment in which geometric and non-geometric information can be connected and managed. Information related to design, materials, quantities, scheduling, costs, construction activities, operation, maintenance, and building performance can be associated with the digital model [5]. Consequently, BIM has increasingly been considered not only a design and visualization technology but also an information-management approach capable of supporting collaboration, coordination, decision-making, and life-cycle management.

The development of BIM research during the last two decades demonstrates this transformation. Bibliometric and scientometric studies indicate that BIM research has expanded from early topics such as three-dimensional modeling and design coordination toward broader themes including project management, sustainability, facilities management, safety, life-cycle assessment, digital twins, Internet of Things (IoT), artificial intelligence, and other emerging digital technologies [2], [6]. Recent reviews confirm that BIM and sustainability have become particularly important research areas, with BIM-LCA, BIM-LCC, green buildings, construction waste management, and life-cycle sustainability assessment among the major research themes [7].

One of the major advantages of BIM is its ability to provide an integrated information environment for different project stakeholders. In conventional construction processes, information is frequently generated and managed separately by architects, engineers, contractors, consultants, owners, and facility managers. This fragmentation can result in information loss, duplication, inconsistencies, coordination problems, and rework. BIM can provide a common digital environment in which project information is created, shared, updated, and reused throughout the project life cycle [5], [8]. Therefore, BIM has the potential to improve communication, coordination, design quality, construction planning, cost estimation, and project control.

The importance of BIM is particularly evident in complex construction projects, where numerous stakeholders and technical systems must be coordinated. By providing a digital representation of the building and connecting different categories of information, BIM enables project participants to identify potential conflicts and problems before construction. The use of BIM can therefore contribute to reducing rework, improving planning accuracy, supporting construction sequencing, and improving overall project performance [9], [10].

In addition to technical and managerial benefits, BIM has become increasingly important in the context of sustainable development. Sustainable construction requires the simultaneous consideration of economic, environmental, and functional performance throughout the building life cycle. Decisions made during the early design stages can significantly influence material consumption, energy use, carbon emissions, construction costs, operating costs, maintenance requirements, and end-of-life impacts. Therefore, sustainability assessment should not be limited to the operational stage of a building but should consider the entire life cycle [11], [12].

BIM can contribute to sustainable construction by providing a digital environment in which alternative design solutions can be developed, compared, and evaluated before construction. The integration of BIM with energy analysis, environmental assessment, and optimization tools can enable designers and decision-makers to investigate the potential consequences of different design alternatives. Recent research has emphasized the growing importance of integrating BIM with Life Cycle Assessment (LCA) and Building Energy Modeling (BEM) to support low-carbon and energy-efficient building design [13]. Arenas and Shafique [13], for example, highlighted the potential of BIM, LCA, and BEM integration for sustainable building development while also identifying limitations in current BIM software and interoperability between different analytical tools.

The integration of BIM and LCA has received considerable attention in recent years. LCA provides a systematic approach for evaluating environmental impacts associated with a building throughout its life cycle, while BIM can provide structured information about building elements, materials, quantities, and specifications. Consequently, BIM can reduce the effort required to collect and organize input data for LCA. A systematic review of BIM-integrated LCA studies demonstrated that BIM and LCA integration can support environmental assessment and decision-making, although interoperability between BIM and LCA platforms remains a significant challenge [14].

Recent research has further expanded this discussion toward Life Cycle Sustainability Assessment (LCSA), which considers environmental, economic, and social dimensions of sustainability. A recent critical review of BIM and sustainability research demonstrated that BIM-LCA and BIM-LCC have received substantial research attention, while full integration across all sustainability dimensions remains limited [7]. This indicates that although BIM provides a strong information foundation for sustainable decision-making, further methodological and technological development is required to establish comprehensive life-cycle sustainability assessment frameworks.

Another important aspect of BIM is its contribution to life-cycle cost and project economic performance. BIM can connect building elements with quantities, cost information, and construction activities, thereby supporting more accurate cost estimation and cost control. When BIM is integrated with scheduling and cost data, 4D and 5D BIM environments can be developed, enabling project participants to evaluate the relationships among building components, construction activities, time, and cost [5], [15]. Such integration can improve decision-making and provide a stronger basis for managing the time-cost-quality relationship in construction projects.

The potential of BIM, however, is not limited to the design and construction stages. An important development in BIM research has been the extension of its applications to building operation, maintenance, and facilities management. Since a significant proportion of a building's total life-cycle cost occurs during operation and maintenance, the availability of accurate building information during these stages can provide substantial benefits. BIM can support facility managers by providing information about building components, equipment, maintenance requirements, spatial relationships, and operational characteristics [16], [17].

Recent studies have demonstrated that BIM can be used in building operation and maintenance for energy management, maintenance planning, asset management, safety, emergency management, space management, and renovation [17], [18]. However, the transition of BIM information from design and construction to operation and maintenance remains challenging. Problems related to information quality, interoperability, data updating, organizational responsibilities, and the lack of standardized processes can limit the effective use of BIM during the operational stage [16], [17].

The development of Digital Twin technology has created new opportunities to address some of these limitations. While BIM provides a structured digital representation and information environment for a building, a Digital Twin can establish a dynamic connection between a physical asset and its digital representation through real-time or frequently updated data. Recent research suggests that BIM can provide an important information foundation for the development of Digital Twins in the construction industry [19], [20]. Nguyen and Adhikari [19] emphasized that BIM can support the development of accurate and information-rich Digital Twins and that the integration of BIM and Digital Twin technologies can improve building design, construction, and performance management.

The integration of BIM with IoT and Digital Twin technologies is also becoming an important research direction. IoT devices can collect real-time information about building conditions, energy consumption, equipment performance, and environmental conditions. When such data are connected to BIM and Digital Twin platforms, they can support continuous monitoring, predictive maintenance, energy optimization, and performance management. A comprehensive review of BIM, IoT, and Digital Twin research identified these technologies as major components of the emerging digital transformation of the construction industry [20].

Another emerging application of BIM concerns building safety and risk management. BIM can support the identification and visualization of hazards, construction sequencing, safety planning, emergency management, and risk analysis. The integration of BIM with other digital technologies can further improve the ability to identify and respond to construction risks. Recent research on BIM-based risk and disaster management has demonstrated increasing integration between BIM, Digital Twin, artificial intelligence, IoT, and other Industry 4.0 technologies [21].

Despite the considerable potential of BIM, its implementation continues to face several challenges. BIM adoption requires not only appropriate software and hardware but also organizational transformation, skilled personnel, training, new workflows, appropriate standards, and effective collaboration among stakeholders. Previous research has identified barriers including implementation cost, lack of expertise, insufficient training, interoperability problems, legal and contractual issues, organizational resistance, and lack of standardization [22], [23]. Recent research continues to demonstrate that organizational and human factors can significantly influence BIM adoption and that technological capability alone does not guarantee successful implementation.

The issue of interoperability is particularly important because BIM is increasingly expected to interact with LCA, energy simulation, facility management, IoT, Digital Twin, and other information systems. Differences in data structures, terminology, software platforms, and information requirements can make it difficult to transfer information between systems. Recent BIM-LCA research confirms that interoperability remains one of the most important barriers to the effective integration of BIM with sustainability assessment tools [14].

The need for integrated information management becomes even more important in commercial and high-rise buildings. Such buildings generally involve high levels of investment, complex architectural and engineering systems, numerous stakeholders, high energy consumption, and substantial operation and maintenance costs. Consequently, even relatively small errors in design coordination, construction planning, or operational management can have significant financial and environmental consequences. BIM can provide an integrated platform for managing information associated with these complex processes and can therefore contribute to improved decision-making throughout the building life cycle.

Recent research also indicates that BIM is increasingly being connected with circular economy concepts. BIM can provide information about building components, materials, quantities, locations, and relationships that can be used to support material reuse, recycling, deconstruction planning, and circularity assessment. A systematic review of BIM integration with building circularity assessment demonstrated increasing development of BIM-based circularity assessment tools, while also identifying the need for further methodological development and standardization [24].

Therefore, the role of BIM in sustainable construction should be considered within a broader digital transformation of the construction industry. BIM, LCA, LCC, IoT, Digital Twin, artificial intelligence, and circularity assessment can potentially form an integrated information ecosystem capable of supporting decisions from early design through construction, operation, maintenance, renovation, and end-of-life management [7], [19], [20], [24].

Nevertheless, the literature indicates that significant gaps remain. A considerable proportion of BIM research continues to focus on design and construction, while the integration of BIM with operational data, sustainability assessment, life-cycle management, and real-time monitoring remains comparatively fragmented [16], [17]. In addition, although BIM-LCA and BIM-LCC have received significant attention, complete integration of environmental, economic, social, and operational dimensions remains limited [7].

Accordingly, there is a need for a more comprehensive understanding of BIM as an integrated information-management approach capable of supporting sustainable building development throughout the entire life cycle. The present study therefore aims to investigate the capabilities of BIM in supporting sustainable development and building life-cycle management, with particular attention to its potential contribution to reducing costs, improving productivity and quality, reducing resource consumption and environmental impacts, improving coordination, and supporting decision-making during design, construction, operation, and maintenance. By synthesizing the existing literature, the study also seeks to identify the major limitations and research gaps associated with BIM implementation and its integration with sustainability assessment and emerging digital technologies.

2 | Literature Review

BIM has evolved from early computer-based building representation systems into an integrated digital approach for managing building information throughout the project life cycle. Eastman's Building Description System represented one of the early attempts to organize building information within a computer-based environment, while van Nederveen et al. [4] contributed to the development of information-based building representation through the concept of multiple views. Later developments in BIM established a more comprehensive approach in which geometric and non-geometric information could be integrated and shared among project participants [5].

The development of BIM has resulted in the emergence of different dimensions and applications. Three-dimensional BIM primarily supports geometric representation and coordination, while 4D BIM connects the model with construction scheduling and 5D BIM introduces cost information. Further applications have extended BIM toward energy analysis, sustainability, safety, facilities management, and life-cycle assessment [5], [25]. This evolution demonstrates that BIM should not be considered merely as a modeling technology but rather as an information-management framework that can connect different project processes.

Recent bibliometric studies confirm the expansion of BIM research. Babalola et al. identified major developments in BIM research and demonstrated the increasing importance of topics related to sustainability, digital technologies, project management, and information management [2]. Cassandro et al. [6] similarly demonstrated that BIM research has expanded substantially and now includes sustainable construction, emerging digital technologies, project management, facilities management, and other specialized applications.

One of the central areas of BIM research concerns project management. BIM can provide a shared digital environment in which design, construction, schedule, and cost information are connected. Such integration can improve coordination and provide opportunities for detecting design conflicts before construction. The use of BIM in project planning can also support construction sequencing and improve communication among stakeholders [5], [9].

Popov et al. [10] demonstrated the potential of virtual building and construction models for developing 5D environments in which geometric, time, and cost information can be integrated. More recent research has continued to develop this concept by integrating BIM with project scheduling, cost estimation, risk management, and performance assessment. These developments indicate that BIM can contribute to more integrated project decision-making by reducing information fragmentation.

BIM adoption and implementation have also become major areas of research. Gu and London [26] examined BIM adoption in the Architecture, Engineering, and Construction (AEC) industry and emphasized the importance of understanding both barriers and facilitating factors. Khosrowshahi and Arayici [27] proposed an implementation roadmap and emphasized the need for structured and gradual BIM implementation. Morlhon et al. [28] further highlighted the importance of organizational maturity and critical success factors in BIM implementation.

More recent studies have demonstrated that many of the barriers identified in early BIM research continue to exist. Sriyolja et al. [22] identified barriers related to cost, legal issues, lack of skilled professionals, interoperability, awareness, organizational culture, management, technology, training, contracts, and standards. Iushkin et al. [23] similarly emphasized that successful BIM implementation requires organizational changes in addition to technological adoption. These findings indicate that BIM implementation should be approached as an organizational transformation rather than simply as the adoption of new software.

Human and organizational factors are particularly important because BIM changes established workflows and responsibilities. Users may resist adopting BIM because of perceived complexity, lack of knowledge, increased initial effort, or preference for existing work practices. Therefore, training, organizational support, leadership, clear implementation strategies, and stakeholder engagement are important for successful BIM adoption [22], [23].

Another major area of BIM research is its application to existing buildings. Volk et al. [29] reviewed BIM applications for existing buildings and identified the importance of developing methods for using BIM in renovation, operation, and maintenance. This issue is particularly relevant because the majority of the existing building stock was not originally developed using BIM. Therefore, technologies such as laser scanning, photogrammetry, Scan-to-BIM, and Digital Twin technologies are increasingly being used to create digital representations of existing buildings.

Drobnyi et al. [30] reviewed approaches for constructing and maintaining building geometric Digital Twins and emphasized the importance of digital representations for construction, operation, and renovation of existing buildings. Their study demonstrates that Digital Twins can serve as information repositories for physical and functional building properties throughout the building life cycle.

BIM and sustainability have become another major research area. Early research demonstrated the potential of BIM for sustainable design, energy analysis, and green building development [31], [32]. Lu et al. [31] conducted a critical review of BIM for green buildings and identified energy analysis, sustainable design, material selection, and performance evaluation as important applications.

Recent studies have expanded this research toward BIM-LCA, BIM-LCC, and LCSA. The integration of BIM and LCA is particularly important because BIM contains detailed information about building components and quantities, while LCA requires information about materials, energy, emissions, and environmental impacts. BIM can therefore facilitate the preparation of data required for life-cycle environmental assessment [14], [33].

Teng et al. [14] conducted a systematic review of BIM-integrated LCA studies and analyzed case studies involving 82 buildings. Their findings identified several approaches for integrating BIM and LCA, including transferring information to third-party applications, importing quantities from BIM into LCA tools, and using BIM plug-ins containing LCA data [14]. However, the study emphasized that interoperability remains a serious challenge because BIM and LCA systems often use different data structures and terminology.

The importance of BIM-LCA integration is also supported by recent sustainability research. Akbari et al. [7] analyzed BIM and sustainability research and identified BIM-based LCSA, BIM for green buildings, BIM-based construction waste management, and emerging technologies as major research categories. Their findings demonstrate that BIM-LCA and BIM-LCC have received significant attention but that complete integration across sustainability dimensions remains limited.

Arenas and Shafique [13] reviewed recent developments in BIM-based sustainable buildings and highlighted the increasing integration of BIM, LCA, and BEM. Their research demonstrated that these technologies can support low-carbon design and sustainable decision-making, while also emphasizing limitations related to BIM software capabilities, interoperability, and the availability of appropriate sustainability indicators.

The use of BIM for sustainability also extends beyond energy and carbon assessment. BIM can support construction waste management by providing accurate information about quantities, materials, construction components, and construction processes. It can also contribute to circular economy practices by supporting material inventories, reuse, recycling, and deconstruction planning. Recent research on BIM and building circularity assessment indicates that this area is developing rapidly, although standardized methodologies and comprehensive assessment frameworks are still required [24].

Building life-cycle management is another important dimension of BIM research. The integration of BIM into facilities management can enable information created during design and construction to be transferred to operation and maintenance. Wang et al. [34] demonstrated the importance of involving facilities management considerations during the design stage and proposed a framework for connecting design information with facilities management.

Matarneh et al. [16] reviewed BIM applications for facilities management and highlighted the potential of BIM to improve information management, maintenance, and operational decision-making. Abideen et al. [17] further reviewed BIM integration into operation and maintenance and concluded that BIM has significant potential in this stage, although technical, organizational, and contractual barriers remain.

Cao et al. [18] examined BIM capabilities during the operation and maintenance stage of green buildings and identified applications including energy management, safety, emergency management, maintenance, renovation, space management, and asset management. These findings demonstrate that BIM can contribute to sustainability beyond the design stage by supporting operational efficiency and long-term building performance.

The development of Digital Twin technologies has created another important research direction. BIM can provide the geometric and semantic foundation required to create a Digital Twin, while IoT and sensing technologies can provide real-time information about the physical building [19], [20]. Nguyen and Adhikari [19] reviewed the relationship between BIM and Digital Twin and concluded that BIM can provide an effective foundation for developing Digital Twins in building construction.

Baghalzadeh Shishehgarkhaneh et al. [20] conducted a large bibliometric and systematic review of BIM, IoT, and Digital Twin research and identified major themes including BIM and Digital Twin, Heritage BIM, smart contracts, ontology, virtual reality, augmented reality, artificial intelligence, and future integration with emerging technologies.

Digital Twin research also emphasizes the importance of standardization and interoperability. Studies have shown that the construction industry still lacks comprehensive standards for Digital Twin implementation, and BIM information-management standards such as ISO 19650 can potentially contribute to developing more interoperable digital environments [35]. This is important because the effectiveness of a Digital Twin depends heavily on the availability, consistency, and continuous updating of information.

Digital Twins can also support the management of existing buildings. Drobnyi et al. [30] demonstrated that geometric Digital Twins can provide information repositories for building assets and can support construction, operation, maintenance, and renovation. This is particularly relevant for commercial buildings, where continuous monitoring and maintenance can have substantial effects on energy consumption, operating costs, and asset value.

BIM has also been increasingly applied to risk and safety management. Zhang et al. [36] demonstrated the potential of BIM for automated safety checking of construction models and schedules. More recent research has expanded these applications toward integrated risk management using BIM, Digital Twin, IoT, and artificial intelligence [21]. Wang et al. [21] reviewed BIM and BIM-related technologies for sustainable risk and disaster management and identified increasing research attention toward the integration of BIM with emerging digital technologies.

The relationship between BIM and building safety is particularly important because construction projects involve numerous hazards and dynamic conditions. BIM can improve safety planning by providing three-dimensional visualization of workspaces, construction sequences, and potential hazards. When combined with scheduling and risk information, BIM can provide a more comprehensive environment for safety management [21], [36].

Another important area of research concerns the integration of BIM with Geographic Information Systems (GIS). BIM primarily focuses on building-level information, while GIS provides spatial information at larger scales. The integration of BIM and GIS can therefore support applications involving urban planning, infrastructure, facility management, and regional-scale environmental analysis [37]. This integration is particularly relevant for sustainable urban development because building performance is influenced not only by building-level characteristics but also by location, surrounding infrastructure, climate, and urban context.

Information exchange and interoperability remain fundamental challenges across all these applications. IFC and other open standards have been developed to facilitate information exchange between different BIM platforms and stakeholders. However, differences in software structures, data requirements, and information semantics continue to create difficulties. These challenges become even more significant when BIM is connected to LCA, energy simulation, GIS, facilities management, IoT, and Digital Twin platforms [14], [20], [35].

The literature therefore indicates that BIM has developed from a three-dimensional modeling technology into a broader digital information-management environment. Its applications now cover design, construction, scheduling, cost management, sustainability, life-cycle assessment, facilities management, safety, risk management, Digital Twin development, and circular economy [2], [6], [7].

At the same time, the literature reveals several important research gaps. First, although BIM-LCA and BIM-LCC have been extensively investigated, comprehensive integration of environmental, economic, social, and operational dimensions remains limited [7], [14]. Second, BIM applications remain more mature in design and construction than in operation and maintenance [16–18]. Third, interoperability between BIM and external analytical or management systems remains a major technical challenge [14], [20]. Fourth, the integration of BIM with IoT and Digital Twin technologies is developing rapidly, but many proposed frameworks remain conceptual rather than being validated through long-term real-world applications [19], [20], [30].

Finally, the literature suggests that future BIM development will increasingly depend on the integration of multiple digital technologies rather than the isolated use of BIM. The combination of BIM with LCA, LCC, LCSA, IoT, Digital Twin, AI, GIS, and circular economy assessment can provide a more comprehensive information infrastructure for sustainable building management [7], [19], [20], [24].

Recent studies further confirm the expanding role of BIM in the construction industry. Kaur et al. [38] demonstrated that BIM has evolved into a multidisciplinary digital platform supporting design, construction management, sustainability, safety, and life-cycle management, while interoperability and organizational barriers remain important challenges. Karunaratne et al. [39] further highlighted the growing integration of BIM with Digital Twin technologies, showing their potential to improve asset management, predictive maintenance, productivity, and long-term economic performance. These findings indicate that future BIM development should focus on stronger integration with emerging digital technologies and life-cycle management approaches to achieve greater technical, economic, and environmental benefits.

Overall, the reviewed literature demonstrates that BIM has considerable potential to improve construction efficiency, reduce project risks and rework, support sustainable design, improve cost and time management, and facilitate building operation and maintenance. However, realizing the full potential of BIM requires extending its application across the entire building life cycle and improving interoperability, information quality, organizational readiness, and integration with sustainability and emerging digital technologies.

Therefore, further research is required to establish integrated approaches through which BIM can simultaneously support economic, technical, environmental, and operational objectives throughout the life cycle of commercial and complex buildings.

3 | Research Methodology

In terms of its objective, the present study is applied, while methodologically it is a descriptive-analytical study with a theoretical approach. The research aims to examine the impact of BIM on building life-cycle management and its role in achieving sustainable development objectives. First, through a literature-based approach, the theoretical foundations related to BIM, sustainable development, building life cycle, and factors influencing the sustainability of construction projects are examined. Subsequently, factors and indicators related to BIM implementation and its impact on building sustainability are identified and analyzed.

In the first stage of the study, information is collected using a library-based research method. For this purpose, previous studies and research, books, scientific articles published in reputable journals and conferences, and other relevant sources are examined. The findings obtained from these studies form the basis for identifying factors influencing the application of BIM in support of sustainable development and for developing the initial research framework. Given the theoretical nature of the study, the analysis and organization of information obtained from previous studies are conducted using computer-based tools.

In the next stage, after identifying the factors and indicators influencing construction sustainability and their relationship with BIM, the extracted factors are examined and evaluated. To determine the importance and validity of the identified factors, the opinions of experts and professionals in the construction and BIM fields are utilized. At this stage, the required information is collected through a questionnaire, and the demographic characteristics of the respondents are also examined.

After collecting the questionnaires, the first stage of analysis involves evaluating the identified factors using a Likert scale and conducting an initial screening of the factors. The purpose of this stage is to identify the more important factors and eliminate or reduce the influence of factors that are considered less important by the respondents. As a result of this process, a set of major factors and sub-factors with the strongest relationship to BIM implementation and sustainable development in construction projects will be determined.

In the main stage of the research, the Fuzzy Analytic Hierarchy Process (FAHP) is used to determine the relative importance of the identified factors and sub-factors. This method enables the comparison and prioritization of different factors while taking into account the uncertainty and ambiguity inherent in expert judgments. Accordingly, the factors influencing BIM implementation in support of sustainable development are organized into a hierarchical structure, and the relative importance of each factor and sub-factor is determined.

Finally, based on the results obtained from the fuzzy analytic hierarchy analysis, the effective factors and strategies for applying BIM to achieve sustainable development objectives are prioritized. In this way, the research model can determine the relative importance of each factor influencing BIM utilization and its role in making construction projects more sustainable. The results can provide a basis for identifying the most important strategies for using BIM in building life-cycle management and moving construction projects toward increased productivity, reduced costs, reduced resource waste, and achievement of sustainable development objectives.

Overall, the research process can be summarized in four main stages: 1) Reviewing theoretical foundations and previous studies and identifying influencing factors, 2) Developing and distributing the questionnaire and conducting an initial evaluation of the factors, 3) Screening and determining the main factors and sub-factors based on experts' perspectives, and 4) Prioritizing the factors and strategies using the FAHP.

4 | Demographic Characteristics of the Research Questionnaire

The following section presents the results related to the demographic characteristics of the respondents, including age, work experience, and professional responsibilities.

4.1 | Age Distribution of Respondents

Based on the collected data, out of 38 respondents, 4 respondents are between 20 and 30 years old, 25 respondents are between 30 and 40 years old, 8 respondents are between 40 and 50 years old, and 1 respondent is over 50 years old. The percentage frequencies of respondents in these groups are 10.52%, 65.79%, 21.05%, and 2.6%, respectively. Therefore, the highest frequency is observed in the 30–40 age group. As can be observed, the distribution is approximately normal.

Table 1. Frequency distribution of respondents by age.

Age	Frequency	Percent
20-30	4	10.52
30-40	25	65.8
40-50	8	21
+50	1	2.6
Total	38	100

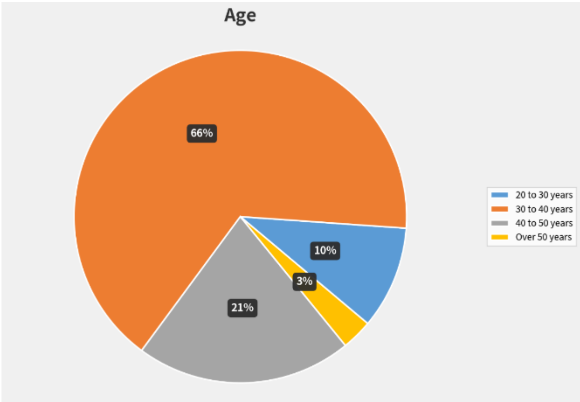

Fig. 1. Percentage distribution of respondents by age.

4.2 | Educational Attainment of the Questionnaire Respondents

Among the 38 respondents, 0 respondents hold an associate degree, 22 hold a bachelor's degree, 15 hold a master's degree, and 1 holds a doctoral degree.

Table 2. Frequency distribution of respondents by educational level.

Degree	Frequency	Percent
Associate degree	0	0
Bachelor's degree	22	57.9
Master's degree	15	39.47
Doctoral degree	1	2.6
Total	38	100

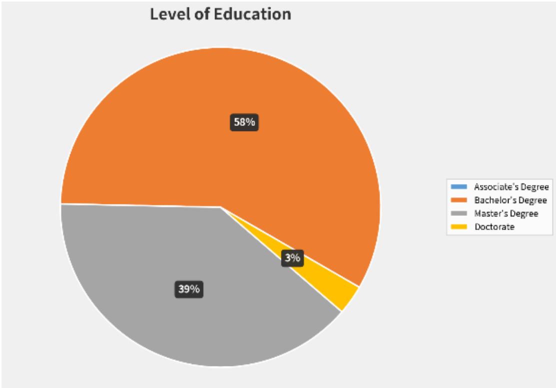

Fig. 2. Distribution of respondents by educational level.

4.3 | Job Position in Construction Projects

Among the 38 respondents, 24 are civil or architectural engineers, 7 are project managers, 1 is a client/owner, and 6 are contractors. *Table 3* presents the corresponding frequency and percentage distributions.

Table 3. Frequency distribution of respondents by job position in construction projects.

Valid	Frequency	Percent
Civil and architectural engineer	24	63.15
Project manager	7	18.42
Client/Owner	1	2
Contractor	6	15.8

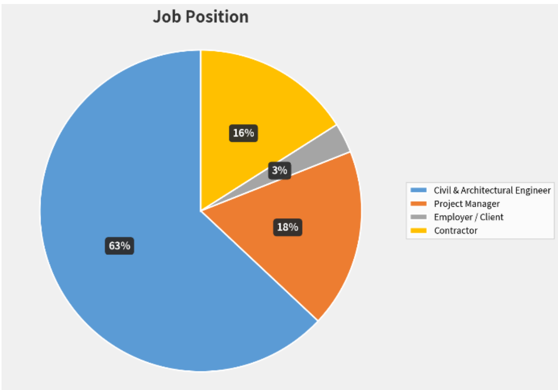

Fig. 3. Percentage distribution of respondents by job position in construction projects.

4.4 | Distribution of Respondents' Work Experience in Construction Projects

Based on the collected data, out of the 38 respondents, 7 have less than 5 years of work experience, 18 have between 5 and 15 years of work experience, 8 have between 15 and 25 years of work experience, and 5 have more than 25 years of work experience. The highest frequency corresponds to the group with 5–15 years of work experience, while the lowest frequency corresponds to the group with more than 25 years of work experience.

Table 4. Frequency distribution of respondents by work experience.

Work Experience	Frequency	Percent
-5	7	18.42
5-15	18	47.37
15-25	8	21.05
+25	5	13.16
Total	38	100

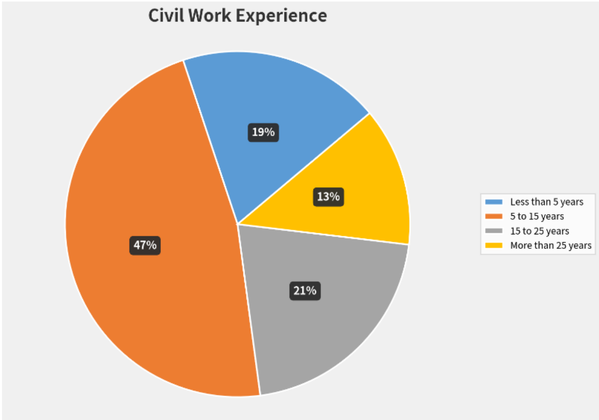

Fig. 4. Percentage distribution of respondents based on work experience with BIM in construction projects.

Out of the 38 respondents, 5 have no work experience with BIM in construction projects, 15 have less than 5 years of experience, 14 have more than 5 years of experience, and 2 have experience with BIM in a limited number of projects.

Table 5. Frequency distribution of respondents by work experience with BIM.

Valid	Frequency	Percent
No experience	5	13.16
Less than 5 years of experience	15	39.47
More than 5 years of experience	14	36.84
A limited number of construction projects	4	10.52

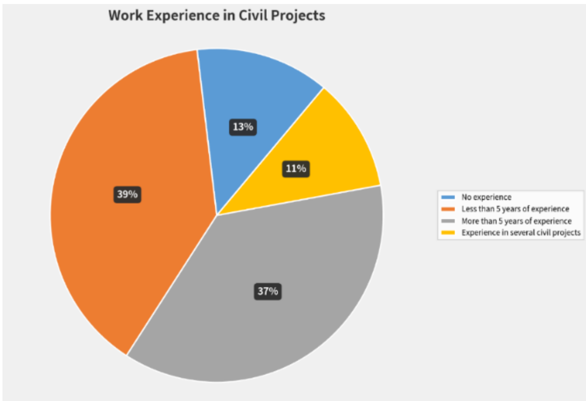

Fig. 5. Percentage distribution of respondents based on experience in construction projects.

5 | Assessment of the Importance of the Identified Factors

After identifying and determining the evaluation factors affecting the achievement of sustainable development objectives through BIM, three groups comprising a total of 15 factors and 46 effective evaluation indicators were identified through a literature review and the opinions of experts and specialists. An initial assessment of the importance of the identified factors was then conducted using statistical techniques and SPSS software in order to identify the most fundamental factors. One of the advantages of reducing the number of factors to the most fundamental ones is the development of a more accurate model with a lower margin of error. For this purpose, a questionnaire was developed and distributed among the statistical population. After collecting the responses, statistical tests were conducted using SPSS software to analyze the data.

A five-point Likert scale was used to interpret the questions and determine their degree of importance [1]. Respondents were asked to indicate the degree to which each criterion affected the research objectives by selecting the appropriate option. The general structure and scoring of this scale are presented in the following table, ranging from 5 to 1, where 5 represents "Very High" and 1 represents "Very Low."

Table 6. Five-point Likert scale.

Response Option	Score
Very low	1
Low	2
Moderate	3
High	4
Very high	5

Based on the above considerations, the research hypothesis associated with each questionnaire item is defined similarly as follows:

The factor under consideration is highly important.

Since a five-point Likert scale was used in the questionnaire based on the opinions of experts and professors, the following hypotheses were formulated.

5.1 | Hypothesis Testing of the Factors (Main Research Factors)

The hypotheses related to the main factors identified in the study were subsequently tested. As stated previously, the most important factors affecting the application of BIM in construction projects for sustainable development and life-cycle management of commercial buildings can be examined through 15 main factors. Accordingly, the following hypotheses were defined:

Hypothesis 1. Collective efficiency factors significantly affect the increased application of BIM in construction projects and contribute to the sustainability of the building life cycle.

Hypothesis 2. Organizational innovation factors significantly affect the increased application of BIM in construction projects and contribute to the sustainability of the building life cycle.

Hypothesis 3. Senior management support factors significantly affect the increased application of BIM in construction projects and contribute to the sustainability of the building life cycle.

Hypothesis 4. Technology compatibility and quality factors significantly affect the increased application of BIM in construction projects and contribute to the sustainability of the building life cycle.

Hypothesis 5. Output quality factors significantly affect the increased application of BIM in construction projects and contribute to the sustainability of the building life cycle.

Hypothesis 6. Self-efficacy and personal competency factors significantly affect the increased application of BIM in construction projects and contribute to the sustainability of the building life cycle.

Hypothesis 7. Personal innovation factors significantly affect the increased application of BIM in construction projects and contribute to the sustainability of the building life cycle.

Hypothesis 8. Internal pressure factors significantly affect the increased application of BIM in construction projects and contribute to the sustainability of the building life cycle.

Hypothesis 9. External pressure factors significantly affect the increased application of BIM in construction projects and contribute to the sustainability of the building life cycle.

Hypothesis 10. Perceived usefulness factors significantly affect the increased application of BIM in construction projects and contribute to the sustainability of the building life cycle.

Hypothesis 11. Perceived ease-of-use factors significantly affect the increased application of BIM in construction projects and contribute to the sustainability of the building life cycle.

Hypothesis 12. Consensus on allocation factors significantly affect the increased application of BIM in construction projects and contribute to the sustainability of the building life cycle.

Hypothesis 13. Individual intention to adopt BIM significantly affects the increased application of BIM in construction projects and contributes to the sustainability of the building life cycle.

Hypothesis 14. Organizational intention to adopt BIM significantly affects the increased application of BIM in construction projects and contributes to the sustainability of the building life cycle.

Hypothesis 15. Agreement on allocation significantly affects the increased application of BIM in construction projects and contributes to the sustainability of the building life cycle.

The testing procedure used to compare the mean with a specific value (a mean of 2.5 in this study) is presented in *Table 7*.

Table 7. Statistical test used for comparing the mean with a specific value.

No.	Significance Level	Variable Distribution	Test
1	Greater than 0.05	Normal	One-Sample T-Test
2	Equal to or less than 0.05	Non-normal	Wilcoxon Test

As shown in the above table, when the variables are normally distributed, the parametric one-sample T-test is recommended; otherwise, the equivalent non-parametric Wilcoxon test is used. The hypotheses were defined as follows:

- *The variable under consideration has a normal distribution.*
- *The variable under consideration does not have a normal distribution.*

If the significance level of the test is greater than 0.05, the variable under consideration can be considered normally distributed; otherwise, the variable is considered non-normal. The results of examining the distribution of the factors (main variables) are presented in *Table 8*.

Table 8. Selected options based on the Likert scale for the factors (main variables).

No.	Factor	Mean	T-Test	Significance Level	Decision
1	Collective efficiency	2.991223	0.808	0.053567	Hypothesis supported
2	Organizational innovation	3.359643	0.8187	0.0539	Hypothesis supported
3	Senior management support	2.973680	0.8035	0.0529	Hypothesis supported
4	Technology compatibility and quality	3.342100	0.781	0.0539	Hypothesis supported
5	Output quality	3.335525	0.735	0.051365	Hypothesis supported
6	Self-efficacy and personal competency	3.280697	0.812	0.052163	Hypothesis supported
7	Personal innovation	3.201750	0.807	0.05796	Hypothesis supported
8	Internal pressures	3.210520	0.8215	0.05145	Hypothesis supported
9	External pressures	3.175437	0.7941	0.051223	Hypothesis supported
10	Perceived usefulness	3.173678	0.7495	0.054266	Hypothesis supported
11	Perceived ease of use	2.859643	0.8134	0.05261	Hypothesis supported
12	Consensus on allocation	3.236840	0.8341	0.0516	Hypothesis supported
13	Individual intention to adopt BIM	3.254380	0.8194	0.053797	Hypothesis supported
14	Organizational intention to adopt BIM	2.877187	0.8309	0.054627	Hypothesis supported
15	Agreement on allocation	3.149117	0.795	0.0547	Hypothesis supported

As shown in the above table, the significance level of all the main research variables (main factors) is greater than 0.05. Therefore, the null hypothesis is not rejected for any of the variables, and all the main research variables are considered normally distributed. Consequently, the hypotheses are supported, and the results indicate that the identified main factors are effective in increasing the application of BIM and promoting the sustainability of the building life cycle. In the next stage of the research, the FAHP is used to prioritize the factors within the three main groups.

5.2|Data Analysis Using the Fuzzy Analytic Hierarchy Process

In the previous sections, after identifying the independent and dependent variables of the study, the most important and fundamental variables were determined. Accordingly, three main groups comprising a total of 15 factors (opportunities and challenges) were identified as the decision-making and prioritization variables of the study. These parameters are presented in *Table 9* and are designated by corresponding indices.

Table 9. The most important factors affecting the application of BIM and the sustainability of the building life cycle.

Main Factor	Criterion	Index
Factors related to the external variable (A)	Collective efficiency	A1
	Organizational innovation	A2
	Senior management support	A3
	Technology compatibility and quality	A4
	Output quality	A5
	Self-efficacy and personal competency	A6
	Personal innovation	A7
	Internal pressures	A8
	External pressures	A9
Factors related to the internal variable (B)	Perceived usefulness	B1
	Perceived ease of use	B2
	Consensus on allocation	B3
Factors related to individual and organizational variables (C)	Individual intention to adopt BIM	C1
	Organizational intention to adopt BIM	C2
	Agreement on allocation	C3

The hierarchical structure consists of three main levels: The goal, criteria (factors), and alternatives (sub-factors). The criteria level can be further divided into multiple sub-criteria. The goal constitutes the highest level of the hierarchical structure and includes only one parameter, the selection of which is the responsibility of the highest level of project decision-making. The criteria that encompass and contribute to achieving the goal are referred to as criteria. In fact, criteria serve as benchmarks or measurement instruments for the goal. The more comprehensively the criteria cover the components of the goal and the more accurately they represent the goal, the greater the likelihood of obtaining more accurate results.

Following the collection of the experts' initial opinions, pairwise comparison matrices for the factors and sub-factors were developed. It should be noted that, in conducting the pairwise comparisons based on the experts' opinions, the experts were asked to evaluate the pairwise comparisons of the factors and sub-factors using linguistic terms within the FAHP method.

The tables presented in the following sections show the arithmetic mean of the opinions provided by the experts in response to the pairwise comparison matrices.

5.3| Comparison of the Factors in Main Group A (External Factors)

Table 10 presents the pairwise comparison matrix of the factors for the first group, namely the external variables, based on the experts' opinions. *Fig. 6* presents the ranking of the sub-criteria for the first main factor. The horizontal axis of the chart represents the sub-factors, while the vertical axis represents their relative importance and weight.

Table 10. Mean pairwise comparisons of the factors related to the main external-variable group.

Criteria Comparison	A1	A2	A3	A4	A5	A6	A7	A8	A9
A1	(1,1,1)	(2.33,4.54,5.35)	(0.2,0.333333,1)	(0.25,0.5,1)	(0.166667,0.25,0.5)	(1.4,2.33,4.5)	(0.2,0.333333,1)	(0.25,0.5,1)	(0.2,0.333333,1)
A2	(0.16667,0.25,0.5)	(1,1,1)	(0.2,0.333333,1)	(0.2,0.333333,1)	(0.2,0.333333,1)	(1,2(1.6,2.8,3.44)4)	(0.2,0.333333,1)	(0.166667,0.25,0.5)	(1.6,2.8,3.44)
A3	(1.61,2.33,4.7)	(1,3,5)	(1,1,1)	(1.4,2.33,4.5)	(0.2,0.333333,1)	(1,3,5)	(1,2, (1.25,1.6,3.4))	(1,3,5)	(1,2.5,4.5)
A4	(1,2,4)	(1,3,5)	(0.25,0.5,1)	(1,1,1)	(0.25,0.5,1)	(1,2.5,4.5)	(1.61,2.33,4.7)	(1.4,2.33,4.5)	(1,2.5,4.5)
A5	(2,4,6)	(1.61,2.33,4.7)	(1,3,5)	(1,2.5,4.5)	(1,1,1)	(2,4,6)	(1,3,5)	(1,3,5)	(1,2.5,4.5)
A6	(0.25,0.5,1)	(0.25,0.5,1)	(0.2,0.33333,1)	(0.25,0.5,1)	(0.16667,0.25,0.5)	(1,1,1)	(0.2,0.333333,1)	(0.25,0.5,1)	(0.2,0.333333,1)
A7	(1,3,5)	(1,3,5)	(0.25,0.5,1)	(0.2,0.33333,1)	(0.2,0.33333,1)	(1,3,5)	(1,1,1)	(0.2,0.333333,1)	(0.166667,0.25,0.5)
A8	(1.6,2.8,3.44)	(2.33,4.54,5.35)	(0.2,0.33333,1)	(0.2,0.33333,1)	(0.2,0.33333,1)	(1.4,2.33,4.5)	(1,3,5)	(1,1,1)	(0.166667,0.25,0.5)
A9	(1,3,5)	(0.25,0.5,1)	(0.25,0.5,1)	(0.25,0.5,1)	(0.25,0.5,1)	(1.61,2.33,4.7)	(2.33,4.54,5.35)	(2.33,4.54,5.35)	(1,1,1)

Table 11. Calculation of the degree of preference of the factors in the main external-variable group for determining the preferred sub-factor.

Determination of the More Important Factor	Normalized Weights
A1	0.09544
A2	0.08313
A3	0.13642
A4	0.12998
A5	0.14825
A6	0.05314
A7	0.10908
A8	0.11656
A9	0.12801

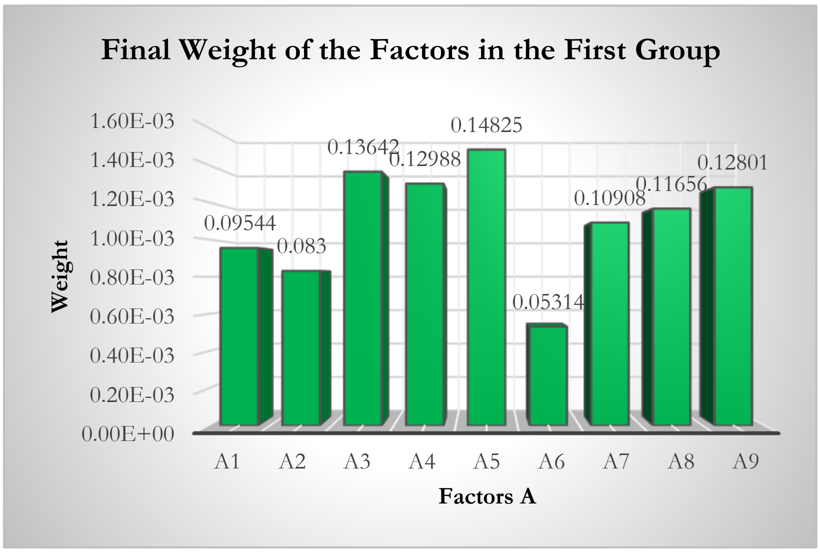

Figure 6. Final weight of the factors in the main external-variable group.

Based on the results obtained from the above tables and charts, the prioritization of the main factors affecting the application of BIM for sustainable building life-cycle development in the first main group, namely the external variables, is as follows:

I. Senior management support (A5)

II. Output quality (A3)

III. Technology compatibility and quality (A4)

IV. External pressures (A9)

V. Internal pressures (A8)

VI. Personal innovation (A7)

VII. Collective efficiency (A1)

VIII. Organizational innovation (A2)

IX. Self-efficacy and personal competency (A6)

According to the results, the prioritization of the factors in the external-variable group indicates that, from the experts' perspective, senior management support ranked first, output quality ranked second, and technology compatibility and quality ranked third. Therefore, from the experts' perspective, the company's provision of sufficient resources for BIM implementation, the availability of training facilities, and the accuracy and stability of BIM are important factors in increasing the adoption of this technology.

5.4 | Comparison of the Factors in Main Group B (Internal Factors)

Table 12 presents the pairwise comparisons of the factors in the second group, namely the factors related to internal variables, based on the experts' opinions. *Fig. 7* presents the ranking of the factors in the second group. The horizontal axis of the chart represents the sub-factors, while the vertical axis represents their relative importance and weight.

Table 12. Mean pairwise comparisons of the factors related to the main internal-variable group.

Criteria Comparison	B1	B2	B3
B1	(1, 1, 1)	(1.8, 3.7, 5.4)	(1.6, 3.7, 5.4)
B2	(0.16667, 0.25, 0.5)	(1, 1, 1)	(0.25, 0.5, 1)
B3	(0.2, 0.33333, 1)	(1.11, 2.941, 3.704)	(1, 1, 1)

Table 13. Calculation of the degree of preference of the factors in main group B for determining the preferred sub-factor.

Determination of the More Important Factor	Normalized Weight
B1	0.54283
B2	0.11829
B3	0.33887

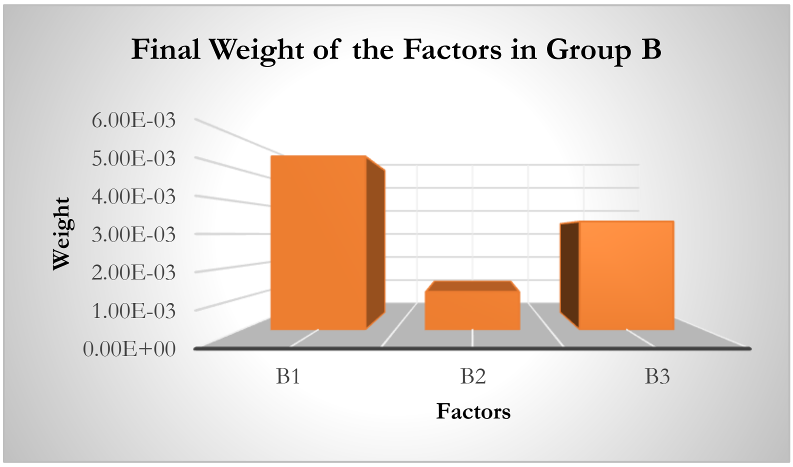

Fig. 7. Final weight of the factors in the main internal-variable group.

Based on the results obtained from the above tables and charts, the prioritization of the main factors affecting the application of BIM for sustainable building life-cycle development in the second main group, namely the internal-variable factors, is as follows:

I. Perceived usefulness (B1)

II. Consensus on allocation (B3)

III. Perceived ease of use (B2)

Among the factors in the internal-variable group, perceived usefulness of BIM ranked first in terms of importance. This factor includes the ability of BIM to improve coordination and compatibility among stakeholders, facilitate comprehensive BIM management throughout the project life cycle, and reduce decision-making time in projects through the implementation of BIM.

5.5 | Comparison of the Factors in Main Group C (Individual and Organizational Factors)

Table 14 presents the pairwise comparisons of the factors in the third group, namely the factors related to individual and organizational variables, based on the experts' opinions. Table 15 also presents the degree of preference of the factors relative to one another in order to determine the more preferred factor. Figure 8 presents the ranking of the factors in the third main group. The horizontal axis of the chart represents the sub-factors, while the vertical axis represents their relative importance and weight.

Table 14. Mean pairwise comparisons of the factors related to the individual and organizational main group.

Criteria Comparison	C1	C2	C3
C1	(1,1,1)	(0.2,0.333333,1)	(0.166667,0.25,0.5)
C2	(1,3,5)	(1,1,1)	(0.166667,0.25,0.5)
C3	(2,4,6)	(2,4,6)	(1,1,1)

Table 15. Calculation of the degree of preference of the factors in the third main group relative to one another for determining the preferred sub-factor.

Determination of the More Important Factor	Normalized Weights
C1	0.06669
C2	0.35908
C3	0.57423

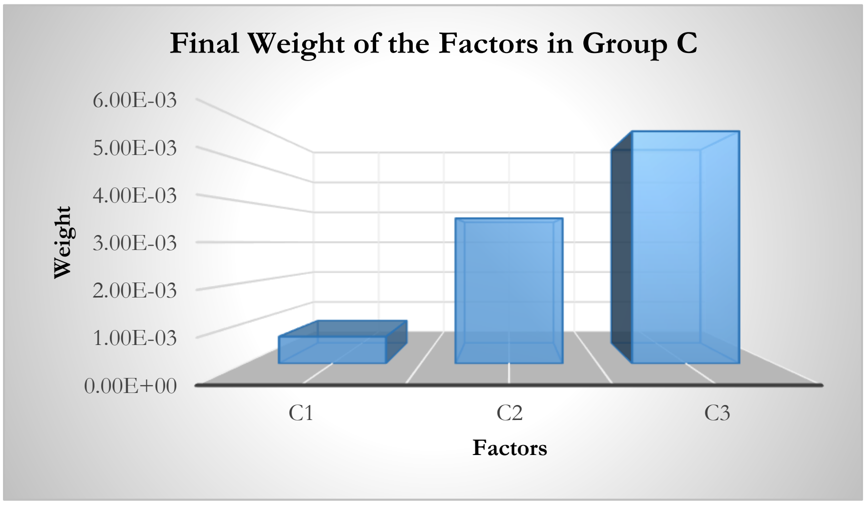

Fig. 8. Ranking of the sub-factors related to the individual and organizational main group.

Based on the results obtained from the above tables and charts, the prioritization of the main factors affecting the application of BIM for sustainable building life-cycle development in the third main group, namely individual and organizational factors, is as follows:

I. Consensus on allocation (C3)

II. Organizational goal (C2)

III. Individual goal (C1)

Among the individual and organizational factors, consensus on allocation, which encompasses the adoption and development of BIM applications, coordination among project members in the use of BIM, and the relevant guidelines, was identified as the most important factor. This result is not unexpected, given the importance of coordination and agreement among project stakeholders in the successful implementation of BIM.

6 | Conclusion

Today's society requires new construction projects to comply with the principles of sustainable development while adhering to fundamental engineering principles such as design quality, economic feasibility, safety, and constructability. Achieving these objectives requires the application of systems such as BIM. Evaluating performance and the measures undertaken in this broad field requires multiple indicators capable of effectively assessing sustainability and supporting its implementation in the construction industry.

Although the BIM revolution is still developing and evolving, many companies have invested in this field and have incorporated at least some aspects of BIM into their business practices. This represents positive prospects for the younger generation entering the construction industry. On the other hand, some contractors and architects have not yet demonstrated full willingness to embrace these significant changes. Continued training and the passage of time will demonstrate the advantages of this approach to construction management compared with traditional methods. All construction management activities can be improved and optimized through BIM, and this approach can be applied to projects of all sizes, whether large or small.

Following the survey analysis, the use of the Likert scale, and the necessary statistical calculations, statistical results were obtained for 46 evaluation factors. Based on these results, statistics were calculated for the main factors, and 15 factors were examined in relation to their impact on the research objective. The significance levels and statistical tests conducted on the main factors demonstrated that all 15 selected factors have an influence on sustainable building life-cycle development through the application of BIM.

In the next stage, the 15 main factors were prioritized to determine which factors should receive greater attention and be considered as higher-priority strategies in decision-making, planning, and implementation. This was achieved using the FAHP and pairwise comparisons to determine the final weights of the main factors. The resulting prioritization is presented below.

Main Group 1: External Variables

The prioritization of the factors in the first main group, namely the external variables, is as follows:

I. Senior management support (A5)

II. Output quality (A3)

III. Technology compatibility and quality (A4)

IV. External pressures (A9)

V. Internal pressures (A8)

VI. Personal innovation (A7)

VII. Collective efficiency (A1)

VIII. Organizational innovation (A2)

IX. Self-efficacy and personal competency (A6)

Main Group 2: Internal Variables

The prioritization of the factors in the second main group, namely the internal variables, is as follows:

I. Perceived usefulness (B1)

II. Consensus on allocation (B3)

III. Perceived ease of use (B2)

Main Group 3: Individual and Organizational Variables

The prioritization of the factors in the third main group, namely the individual and organizational variables, is as follows:

I. Consensus on allocation (C3)
II. Organizational goal (C2)
III. Individual goal (C1)

As the results indicate, achieving sustainability objectives in building construction can be facilitated by considering the capabilities of BIM. By utilizing BIM, the complexities of construction projects can be analyzed more effectively, while design and construction problems can be identified and managed more efficiently.

Furthermore, BIM provides a platform for incorporating emerging technologies into the design and construction process, many of which have recently been developed to support sustainable construction. The effective use of these capabilities, however, depends heavily on the knowledge, expertise, and experience of employees and project stakeholders. Therefore, specialized training and the development of professional competencies are essential prerequisites for the successful implementation of BIM and for achieving sustainable construction objectives.

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