ADVANCING SUSTAINABLE CONSTRUCTION MANAGEMENT THROUGH BIM PRACTICES AND THEIR IMPACT ON MEP PROJECT EFFICIENCY

Muhammad Usman Ali
PhD Scholar, Dept of Mechanical Engineering, International Islamic University, Islamabad, Pakistan
e-mail: muhammad.phdem24@iiu.edu.pk | ORCID: 0009-0000-4089-8992

Dr. Javed Ahmad Khan Tipu
Department of Mechanical Engineering, International Islamic University, Islamabad, Pakistan
e-mail: javed.ahmed@iiu.edu.pk

Dr. Eman N. Shaqour
Associate Professor In Architecture Engineering, Department of Architecture Engineering,, Aqaba University of Technology, Aqaba, Jordan
e-mail: imanshaqoor@gmail.com

Faiz Jalil
PhD Scholar, Dept of Mechanical Engineering, International Islamic University, Islamabad, Pakistan
e-mail: faiz.phdem19@iiu.edu.pk

Malik Imran Mujeeb,
Department of Electrical Engineering, Govt. College of Technology, D. I. Khan, Islamabad, Pakistan
e-mail: imranmujeeb26@gmail.com

Usman Aftab
PhD Scholar, Dept of Mechanical Engineering, International Islamic University, Islamabad, Pakistan
e-mail: usman.phdem18@iiu.edu.pk

Abstract

This study presents a comprehensive academic investigation into the role of Building Information Modelling (BIM) in promoting sustainability and operational efficiency within the design and construction of Mechanical, Electrical, and Plumbing (MEP) systems. Adopting a mixed-method research approach, the study integrates a Delphi survey to assess both the extent of BIM adoption and its measurable influence on key sustainability indicators such as material waste, energy efficiency, cost control, and stakeholder collaboration. Empirical findings reveal that the implementation of BIM led to a 54%

reduction in material waste and a 17% improvement in energy efficiency, underscoring its environmental benefits. Additionally, BIM usage was associated with a 20% decrease in rework, reflecting stronger interdisciplinary coordination and reduced design errors during project execution. The research also highlights enhanced stakeholder engagement facilitated by BIM, which contributed to improved project delivery and cost-effectiveness. Furthermore, the study introduces a practical, context-specific BIM framework tailored for Pakistan's construction industry, demonstrating its real-time applicability on active sites. The findings validate BIM as a critical enabler of sustainable construction practices by ensuring timely completion, reducing financial overruns, and optimizing overall project performance. The study concludes with a call for strategic investments in digital infrastructure, procedural improvements, and supportive government policies to address barriers to BIM implementation in developing countries.

Keywords

Building Information Modeling (BIM), Sustainability, MEP Projects, Construction Management, Resource Optimization

1. Introduction

The global construction sector is recognized for its substantial resource and energy consumption, with Mechanical, Electrical, and Plumbing (MEP) systems representing a considerable portion of a building's operating energy usage and environmental impact [1]. Despite its essential function in total building performance, MEP systems are among the least integrated into sustainable construction methods due to their complexity and disjointed processes. Building Information Modelling (BIM), as a cohesive digital methodology, presents significant potential for overcoming these obstacles [2]. BIM has become a crucial instrument for improving project sustainability through precise design, interdisciplinary collaboration, and efficient resource management. This study examines the influence of BIM on sustainable results in MEP projects, particularly regarding its implementation in Pakistan's developing construction sector. The increasing worldwide apprehension regarding climate change and the dedication to the United Nations Sustainable Development Goals (SDGs) have intensified the demand on enterprises to adopt environmentally sustainable practices [3]. The construction sector, due to its resource-intensive nature and significant contribution to building and demolition waste, is increasingly being directed towards sustainable methods. Green building, which prioritizes energy efficiency, resource conservation, and occupant health, has proven essential in alleviating the sector's environmental impact. Studies indicate that, in contrast to conventional constructions, green buildings can decrease energy consumption by as much as 50%, water usage by 40%, and carbon emissions by 35% [4]. BIM has transformed construction project planning and execution by facilitating intelligent, collaborative, and data-driven decision-making across

the building lifecycle. This digital technology facilitates real-time visualization, enhances communication among stakeholders, and enables three-dimensional simulation of construction processes [5]. As a result, BIM is progressively acknowledged for its ability to enhance project efficiency, reduce mistakes, and maximize building performance [4]. Academics have recognized the intersection of BIM and sustainable architecture as a viable domain for innovation. Integrating sustainability analysis into the first design phases using BIM enables project teams to make educated choices about material selection and energy optimization [4,6]. Nonetheless, these benefits are not uniformly attained across all project scales. Small and medium-sized construction projects—such as single-family homes, community canters, and minor commercial structures—frequently fall behind in implementing sustainable practices and Building Information Modelling (BIM) technology due to financial constraints, insufficient experience, and perceived intricacy [7].. Notwithstanding their ubiquity, these smaller projects have distinct limitations that hinder their capacity to use ecologically sustainable construction practices. Consequently, it is essential to address the deficiency in BIM implementation for small-scale projects, especially in developing countries.

This study aims to reveal the unexploited potential of BIM to enhance sustainability in smaller building projects. The objective is to furnish empirical insights and pragmatic recommendations for stakeholders in Pakistan's construction industry, namely those engaged in resource management, energy efficiency, waste minimization, and collaborative decision-making [1]. This research highlights the significance of BIM in enhancing the sustainability of small-scale projects, thereby contributing to a comprehensive understanding of how these initiatives might connect with national and global sustainability objectives. Although extensive study has focused on BIM in large-scale construction, there has been scant scholarly attention on its implementation in small projects, particularly in the Malaysian and South Asian contexts [4, 8]. This study enhances understanding of the integration of BIM with sustainability principles in small-scale building by addressing this gap. The study, based on a comprehensive literature review and empirical data, demonstrates a robust correlation between BIM adoption and sustainable performance metrics, including early design optimization, energy analysis, material lifecycle assessment, and prefabrication [9, 10, 11]. These findings are pertinent for practitioners and policymakers aiming to enhance sustainability in construction via technology-driven initiatives. This study is among the inaugural investigations into the intersection of BIM and sustainable construction in small-scale projects, providing pragmatic insights into the implementation process and its results. It tackles difficulties with resource efficiency, technical capability, and strategic alignment, offering practical case studies and evidence-based frameworks to facilitate future implementation. The paper provides a prospective analysis of how BIM might facilitate sustainable building practices beyond major commercial projects. This project aims to provide stakeholders, especially in Pakistan and comparable developing regions, with effective tools and methods to promote environmentally resilient construction practices.

2. Problem Statement

Despite the shown advantages of Building Information Modelling (BIM) in improving sustainability and efficiency, its implementation in MEP (Mechanical, Electrical, and Plumbing) projects is still constrained, especially in developing countries. Significant implementation expenses, insufficient technical proficiency, and organizational opposition persist in obstructing integration initiatives. Conventional construction techniques inadequately tackle the environmental and resource concerns associated with MEP systems. This study aims to establish a BIM-based framework to address these obstacles and facilitate sustainable MEP project execution.

3. Literature Review

3.1. BIM Implementation in Construction

Building Information Modelling (BIM) has become a revolutionary technology in the global Architecture, Engineering, and Construction (AEC) sector, facilitating not only 3D modeling but also integrated project data management and collaboration among stakeholders throughout a building's lifecycle [12]. Advanced features, including clash detection (4D), scheduling (5D), cost prediction (6D), and sustainability analysis, substantially enhance project efficiency while reducing delays and errors [13]. Developed nations have rapidly adopted BIM owing to digitalization policies and mandates [14], but developing regions persistently encounter infrastructural, financial, and skill-related obstacles

[15]. The application of BIM is notably restricted in MEP (Mechanical, Electrical, and Plumbing) disciplines, despite its capacity to improve coordination within these intricate systems [16]. The Technology Acceptance Model (TAM) is a strong paradigm for evaluating BIM adoption, highlighting perceived usefulness and simplicity of use. Organizational preparation, encompassing infrastructure, skills, and leadership support, is essential for promoting BIM integration [7]. To address current issues, scholars recommend enhanced BIM education activities and supportive government policies specifically designed for MEP-related digital transformation.

3.2. BIM Development Overview

In a construction project with several services, it is essential to avert conflicts during the installation of each system by different contractors. The contemporary construction sector use BIM software to facilitate efficient coordination across architectural, structural, and MEP systems [18]. BIM enables the cohesive integration of various services, aids in energy efficiency evaluations, improves project coordination, and optimizes operation and maintenance procedures across the building lifetime. *Figure 1* depicts a streamlined workflow that delineates the interplay of diverse building construction process over the project lifecycle. The process commences when the owner presents the preliminary concept to the architects, who then formulate the architectural design. The design is subsequently transmitted to the relevant engineers across several disciplines, allowing them to formulate their service models in BIM while concurrently evaluating total costs. Upon the design's assessment and approval by both architects and consultants, contractors commence the installation of their respective systems. After construction is finalized and sanctioned by the appropriate authorities, the completed building is transferred to the owner.

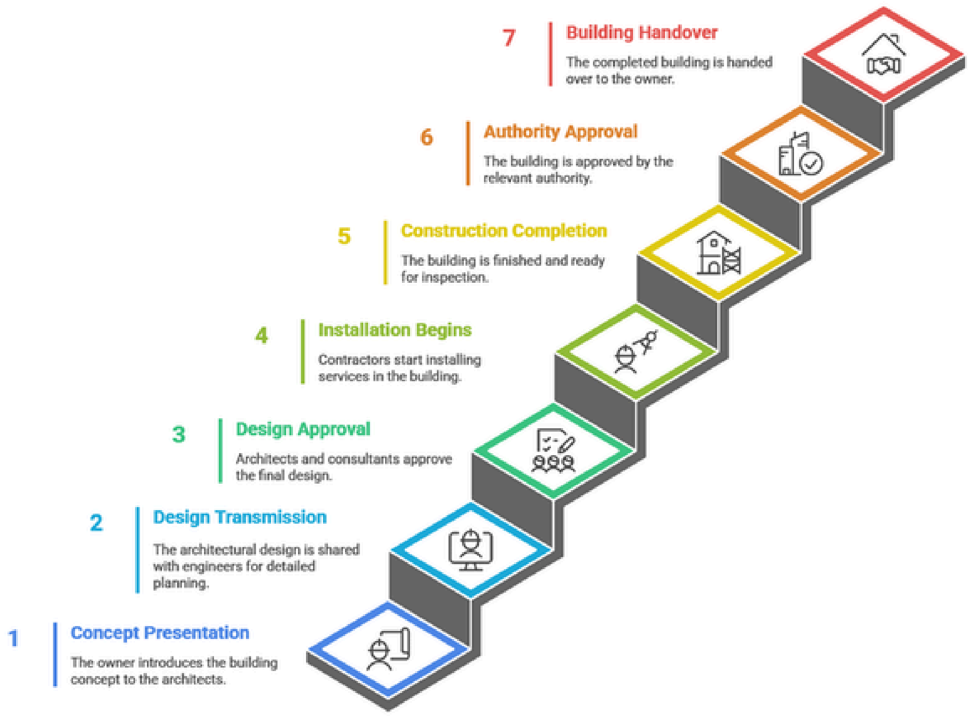


Fig. 1. Building Construction Process

BIM is a methodology that enables architects, as well as civil, mechanical, and electrical engineers or drafters, to collaboratively design, integrate, and visualize all aspects of a building or project in a unified digital environment [19]. It facilitates seamless collaboration and data exchange across disciplines, guaranteeing consistency and precision. BIM can be utilized at any moment of a building's lifecycle—encompassing rehabilitation, planning, design, documentation, construction, and extending into operation and maintenance—rendering it a comprehensive instrument for managing both new and old infrastructure, as illustrated in *Figure 2*. The several dimensions of BIM, as depicted in *Figure 3*, substantially enhance efficiency and productivity throughout all stages of the construction process [19]. Each dimension contributes a layer of pertinent information that enhances decision-making and project results. The dimensions of BIM 3D, 4D, 5D, 6D, and 7D encompass more than just geometric representation, incorporating elements such as time, cost, sustainability, and facility management. The following dimensions are outlined to elucidate their functions and advantages throughout the construction lifecycle.

3.3. BIM 3D (Design Modeling)

This dimension encompasses the amalgamation of all essential services, including architectural, structural, and MEP systems, working inside a unified digital platform. BIM 3D facilitates thorough visualization of the building model, enabling stakeholders to detect and address design conflicts early in the process. This improves collaboration and fosters clearer communication across all disciplines, ultimately resulting in more effective project planning and execution [20].

3.4. BIM 4D (Time)

BIM 4D incorporates the temporal dimension into the 3D model, facilitating enhanced planning and scheduling of construction activities. It offers comprehensive insights into the time necessary for project completion, as well as supplementary information including contract timelines, project duration, procurement timetables, and associated expenses [21]. BIM 4D enhances site planning efficiency and manageability by visualizing the sequence of construction and installation activities. The availability of this time-based data to all project stakeholders enables contractors to more effectively prepare for their jobs in accordance with the project timeline. This proactive strategy improves on-site safety, increases productivity, and minimizes avoidable delays, buffer periods, and lead times—assuming the schedule is adhered to precisely [20].

3.5. BIM 5D (Construction Management)

BIM 5D incorporates the cost dimension into the BIM model, facilitating precise budget planning and cost assessment from the project's inception. It facilitates real-time cost monitoring by automatically revising budget projections upon any design modifications. This dynamic relationship between design and cost enables clients and project owners to consistently evaluate financial performance, assess the effects of modifications, and make educated decisions. BIM 5D improves transparency, facilitates efficient cost management, and aids in maintaining the project within budget during its whole lifecycle [21].

3.6. BIM 6D (Sustainability)

BIM 6D emphasizes sustainability by facilitating energy consumption analysis in the preliminary design phase of a building. It enables clients and owners to assess both the construction expenses and the anticipated operational energy expenditures once the facility becomes functional [22]. This preliminary knowledge enables stakeholders to make informed design choices that enhance energy efficiency and diminish long-term operational costs. BIM 6D facilitates the creation of environmentally responsible buildings and improves operational management by including sustainability factors into the design and planning process. Ultimately, it aids in reducing energy use and attaining enhanced long-term financial savings [22].

3.7. BIM 7D (Facilities Management)

BIM 7D improves facility management by allowing building owners to monitor vital asset information, like warranty details, maintenance schedules, and technical requirements, which are critical for sustained operations. It offers real-time notifications regarding maintenance needs, facilitating preventive maintenance and minimizing unforeseen failures [22]. This data-intensive model assists contractors in optimizing the maintenance process, facilitating prompt interventions and reducing operational interruptions. BIM 7D facilitates cohesive collaboration among architectural, structural, and MEP services by consolidating all design components into a singular model. This integration facilitates early clash detection and settlement prior to the commencement of construction, hence substantially minimizing on-site conflicts. BIM 7D functions as an effective instrument for facility management and pre-construction planning, providing a thorough visual and data-centric representation of the complete building design and lifetime [23]. *Figure 2* depicts the lifecycle integration of BIM 7D, demonstrating how BIM application fundamentally underpins six essential phases: Planning, Designing, Renovation, Construction, Documentation, and Operation and Maintenance. BIM optimizes procedures, improves precision, and supports long-term management over a building's complete lifecycle. It transcends conventional CAD by offering a collaborative, data-intensive environment for all project stakeholders.

3.8. Sustainable Approaches in Structural and MEP System

Environmental sustainability in the construction sector has gained prominence, with Mechanical, Electrical, and Plumbing (MEP) systems recognized as significant factors influencing a building's environmental impact. These systems contribute significantly to energy and water consumption, along with greenhouse gas emissions, throughout both the construction and operational phases. Recent achievements highlight the use of sustainable design principles in MEP engineering, including energy optimization, emission reduction, and complete lifecycle effect assessment, to further global climate goals [24]. The contribution of MEP to energy efficiency emphasizes enhancing the performance of HVAC, lighting, electrical, and water systems, hence assuring minimal operational energy consumption while preserving occupant comfort. This is progressively reinforced by the implementation of sophisticated technologies such as high-efficiency apparatus, intelligent sensors, and automated building systems. The overall efficiency is mostly contingent upon the design and control of the systems as an integrated entity. Material conservation measures in MEP

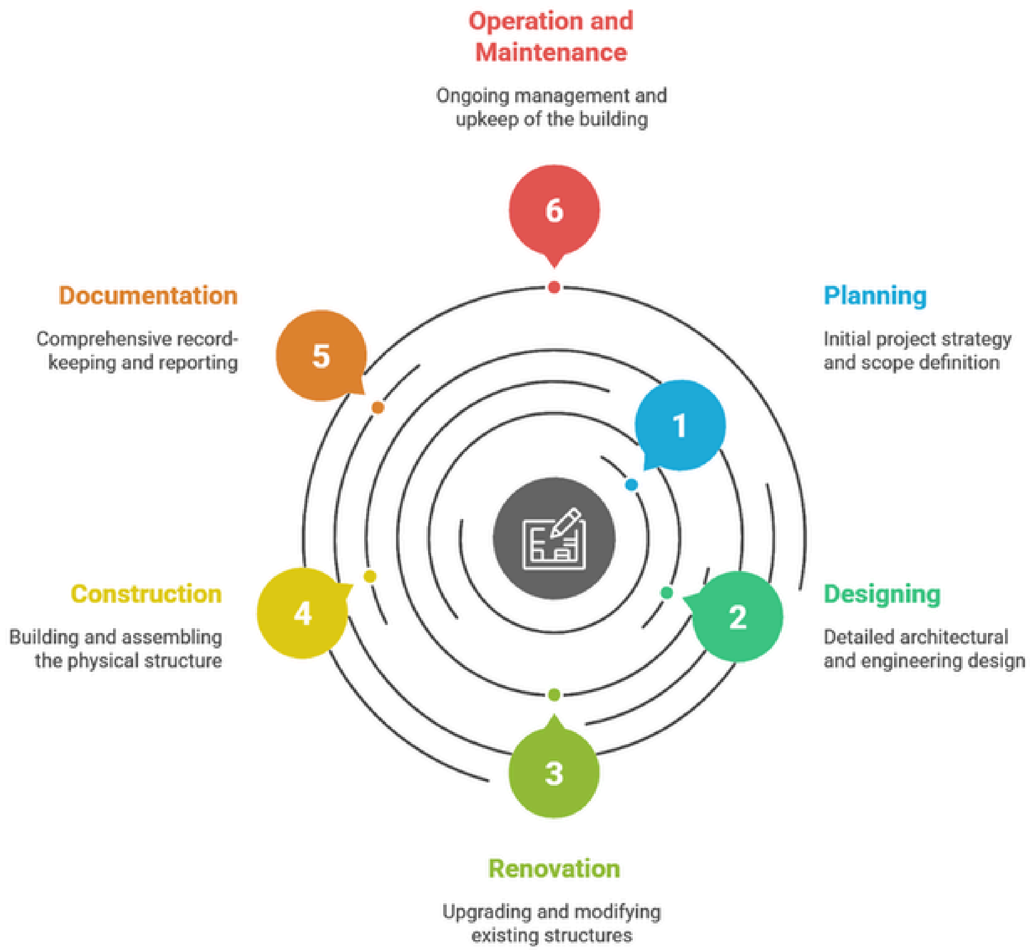


Fig. 2. BIM 7D Integration Overview

encompass precise design, modular prefabrication, and just-in-time logistics, which contribute to minimizing waste production. Inadequate coordination and disjointed workflows contribute to excessive material ordering and onsite waste, underscoring the necessity for integrated procedures [25]. Lifecycle Assessment (LCA) is progressively utilized to assess the embodied carbon and environmental effects of MEP components, promoting the choice of low-carbon materials and improving long-term asset sustainability [26]. Notwithstanding these developments, the absence of integration among MEP disciplines continues to pose a substantial obstacle to sustainability. The isolated execution of mechanical, electrical, and plumbing tasks frequently results in inadequate coordination and less than optimal results. This highlights the necessity for collaborative design methodologies and the utilization of computational tools such as Building Information Modelling (BIM), which promote interdisciplinary collaboration and support comprehensive, sustainability-oriented MEP solutions [27].

3.9. Sustainability and BIM in MEP:

Prior to the emergence of Building Information Modelling (BIM), initiatives to improve sustainable performance in construction were restricted to traditional instruments for light and energy assessment. Donn et al. (2003) employed early building performance simulation methods to markedly decrease energy usage without incurring extra financial expenditures.

The advent of BIM has been acknowledged as a pivotal catalyst for sustainability, especially in Mechanical, Electrical, and Plumbing (MEP) projects. BIM has transformed sustainability-focused project planning through its ability to improve design accuracy, facilitate interdisciplinary collaboration, and employ advanced predictive analytics [28]. BIM facilitates the amalgamation of intelligent 3D models containing metadata, enabling engineers to execute high-resolution energy performance simulations, detect and rectify spatial conflicts, and optimize system configurations to reduce material waste and energy usage. The energy analysis capabilities enable project teams to assess and analyze operational performance across various MEP configurations and environmental circumstances, hence supporting informed decisions that conform to green certification standards and sustainability goals [17]. Moreover, the integration of 4D (time) and 5D (cost) dimensions in BIM enables stakeholders to mitigate material over-ordering, optimize scheduling, and enhance sequencing—crucial elements in minimizing waste in intricate MEP systems. The advancement to 6D BIM facilitates thorough life cycle asset management beyond construction. It facilitates predictive maintenance, real-time equipment surveillance, and operating cost minimization, hence prolonging the lifespan of MEP systems and diminishing environmental effectiveness [22]. Furthermore, the amalgamation of BIM with digital twin technologies has enabled real-time monitoring and predictive analytics, hence enhancing sustainable operational performance. Notwithstanding these advancements, a considerable deficiency persists in empirical studies measuring the influence of BIM on sustainability in MEP project delivery, particularly in poor nations where BIM implementation is still nascent. The amalgamation of BIM with cutting-edge technologies, including the Internet of Things (IoT), artificial intelligence (AI), and cloud computing, offers novel prospects for attaining sustainability in MEP systems. Standardized protocols, a robust data infrastructure, and thorough training programs are crucial to fully realize the potential of these digital advances [4]. In conclusion, although BIM serves as a potent instrument for promoting sustainability in MEP engineering via integrated design, lifespan optimization, and improved stakeholder collaboration, additional empirical research is necessary. These should seek to validate theoretical frameworks, quantify sustainable benefits, and tackle contextual hurdles in various socio-economic contexts to enable broader adoption.

4. Research Objectives

This study is organized around three primary objectives focused on enhancing the comprehension and utilization of Building Information Modelling (BIM) for sustainable Mechanical, Electrical, and Plumbing (MEP) project execution in developing markets.

- to evaluate the existing extent and methodologies of BIM implementation in MEP projects, determining the applications and locations of BIM usage during the design and execution stages.
- to assess the impact of BIM adoption on sustainability outcomes specifically in terms of material waste reduction, energy efficiency, and cost management in MEP services.
- to create and authenticate a BIM-driven sustainability framework customized for emerging countries, focusing on context-specific difficulties in MEP project execution.

5. Research Methodology

This study employed a three-phase mixed-methods approach to comprehensively investigate the impact of Building Information Modelling (BIM) on sustainability in MEP projects. The methodological framework and training involved a sequential technique employing the Delphi method, quantitative surveys, and qualitative interviews. Stage 1 employed the Delphi method to achieve expert consensus on critical sustainability criteria, key BIM parameters, and contextual implementation challenges. Stage 2 entailed a methodical quantitative survey directed at professionals in the construction industry. The data were analysed using SPSS, including descriptive statistics, regression analysis, correlation matrices, and moderation/mediation models to explore the relationships between BIM practices and sustainability outcomes. Stage 3 involved semi-structured qualitative interviews, analysed thematically to extract insights and validate the evolving conceptual framework. *Figure 3* delineates an eight-step approach for the implementation of a BIM framework, commencing with an Introduction and a Literature Review. Subsequently, it advances to Research Methodology and Practical Training. The latter section emphasizes Framework Development, Implementation, and Data Analysis, concluding with Adoption and Training to guarantee the framework's effective integration. This systematic methodology transitions from fundamental research to practical implementation and assessment.

5.1. Delphi Method

Delphi research was conducted using 18 experts selected from academia, industry, and BIM consultancy sectors. The process involved two iterative rounds to achieve consensus on the critical sustainability factors, prevalent obstacles in BIM implementation, and potential variables for creating a viable framework. The experts contributed feedback anonymously to mitigate bias and ensure the objective evaluation of critical indicators.

5.2 Quantitative/ Quantitative Data Acquisition and Examination

Structured questionnaires were disseminated to construction professionals to collect data on BIM adoption, sustainability performance, cost efficiency, and materials/resource management in MEP projects. The questionnaire items were developed to align with validated components and appropriate approaches in BIM research. Data were statistically validated utilizing SPSS software and inferential methods, including regression and correlation analysis, to assess the strength and direction of relationships among variables. Semi-structured interviews were performed with 12 participants, comprising BIM coordinators, MEP engineers, and project managers, to enhance the quantitative results. The interviews investigated practical project obstacles, collaborative interactions, and the perceived benefits of BIM. The NVivo program enabled thematic analysis, facilitating the identification of patterns and categories that improved the interpretation of quantitative results and assisted in framework development. At the outset of stakeholder engagement via the questionnaire, it was noted that numerous participants were either unfamiliar with Building Information Modelling (BIM) or had never utilized it in their professional endeavours. The researcher acknowledged the significance of overcoming this gap and prepared a list of stakeholders unfamiliar with BIM tools. The list was thereafter disseminated to their relevant supervisors or department heads to facilitate the coordination and scheduling of focused training sessions. A organized training program was developed, commencing with 15 days of foundational seminars to elucidate the principles and significance of BIM and Revit. This was succeeded by a 40-day phase of experiential training, enabling stakeholders to acquire firsthand familiarity with the program and incorporate it into their regular workflows. The *Table 1* below delineates the principal issues encountered by diverse construction stakeholders who are either unacquainted with or do not employ BIM/Revit tools. Minor contractors frequently encounter difficulties in comprehending design modifications and overseeing rework due to insufficient version control. Site engineers encounter implementation problems due to inadequate visualization of intricate designs in conventional 2D formats. Conventional architects overlook potential design conflicts, such as those between beams and ductwork, which are only recognized late in the construction process. Non-technical project managers are deprived of real-time project data, resulting in delayed and uninformed decision-making. Local fabricators encounter recurrent discrepancies resulting from ambiguous specifications and the lack of digital modelling. Procurement teams manage erroneous material orders, which undermine project continuity and customer expectations. MEP subcontractors frequently install systems ineffectively due to ambiguous routing and coordination challenges, necessitating expensive rework. Ultimately, quantity surveyors that depend on manual techniques often commit cost estimation inaccuracies, resulting in budget inconsistencies. These deficiencies not only postpone projects but also engender client unhappiness, characterized by grievances regarding inefficiency, substandard quality, and insufficient transparency. The lack of BIM/Revit tools severely impedes coordination, quality, and client confidence in construction projects.

Table 1. Without BIM: Insights from Stakeholders and Clients

Stakeholder Type	Inefficiencies Without BIM	Client Feedback
Contractors	Difficulty interpreting design changes; high rework costs due to lack of version control	Frequent cost overruns and complaints about inefficiency
Site Engineers	Inaccurate implementation due to poor visualization of complex designs from 2D plans	Execution errors causing dissatisfaction in project delivery
Traditional Architects	Design conflicts (e.g., duct vs. beam) undetected until construction phase	End-users report unexpected issues with design outcomes
Project Managers (Non-tech)	Inability to track real-time project updates, causing delays in decision-making	Clients demand more transparency and regular progress updates
Fabricators	Frequent fabrication mismatches due to lack of precise modeling or clash detection	Customer complaints on poor fit and aesthetic mismatches
Procurement Teams	Over/under ordering of materials due to inaccurate BOQs and unclear specs	Late project completion due to supply delays and confusion
Subcontractors (MEP)	Improper MEP system routing leading to time-consuming rework on-site	Quality complaints due to system conflicts or poor installations
Quantity Surveyors	Manual quantity take-offs often result in cost estimation errors and budget overruns	Budget inconsistencies and last-minute financial adjustments causing mistrust

5.3. Execution of Practical Framework

Upon the successful completion of theoretical sessions and practical training in BIM and Revit, the stakeholders exhibited enhanced comprehension and preparedness to implement these tools in real-world applications. The scholar established a systematic methodology designed to direct the on-site implementation of MEP systems. The framework was developed to optimize workflows, enhance precision, and minimize errors by employing BIM functionalities such as collision detection, real-time updates, and 3D visualization. It also underscored the necessity for enhanced coordination among the diverse disciplines engaged in construction, hence facilitating more seamless on-site execution. The last stage of the research was implementing the BIM-based sustainability framework presented in *Table 2* inside a current commercial construction project in Pakistan. This practical application concentrated on the implementation of MEP systems while meticulously tracking important performance metrics such as material consumption, energy efficiency, interdisciplinary collaboration, and rework frequency. Data were gathered before to and during deployment to contrast conventional techniques with BIM-based methodologies. The results offered compelling empirical proof of the framework's efficacy, illustrating enhanced project performance and its potential for wider adoption and scaling within the Pakistani construction sector.

Table 2. Sustainable MEP Execution Framework

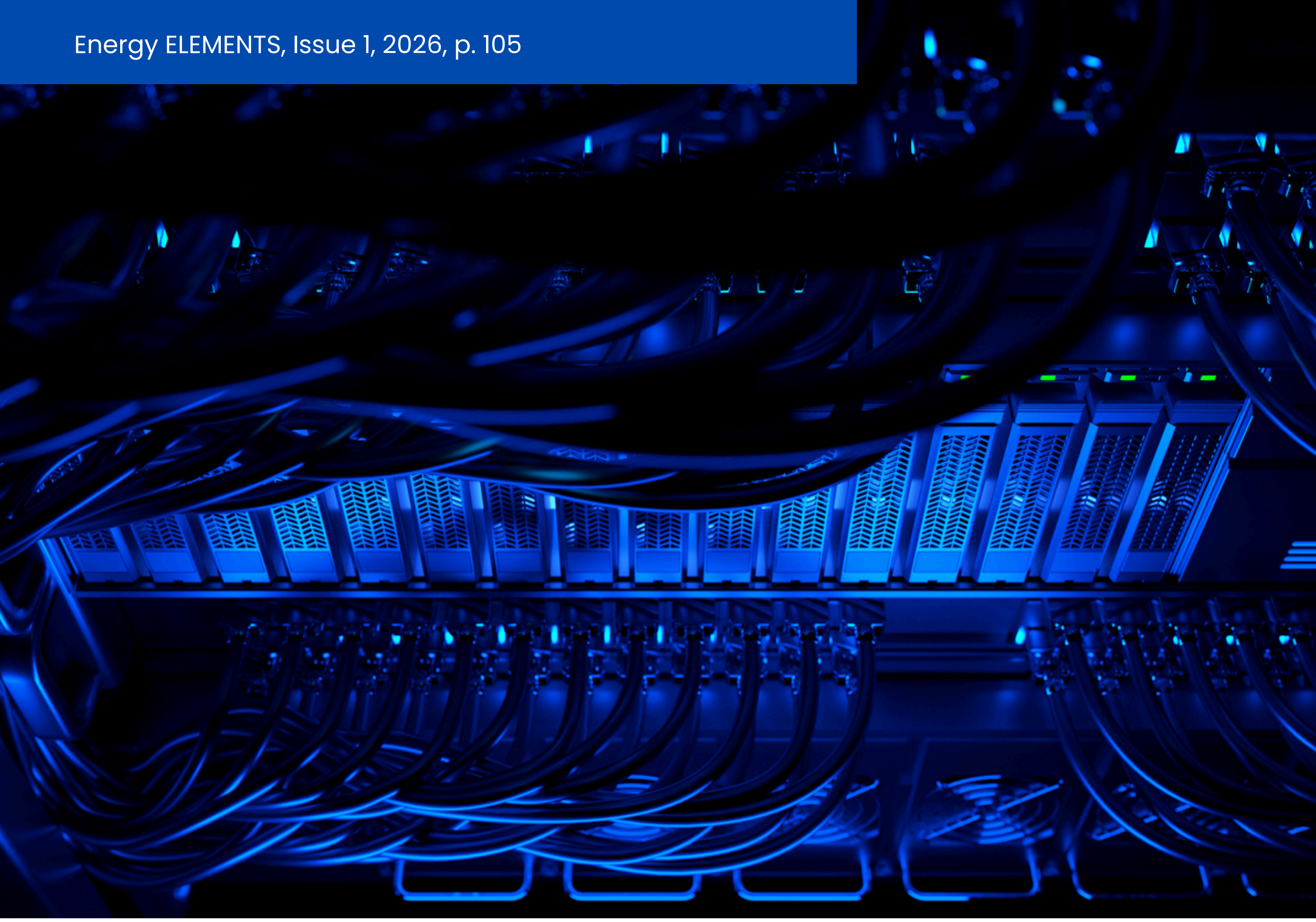
Phase	**Stakeholders Involved**	**BIM-Driven Actions**	**Site Implementation Steps**	**Expected Benefits**
Planning & Coordination	Project Managers, BIM Coordinators, MEP Designers	3D BIM modeling with sustainability goals	Kickoff meeting; define model standards	Reduced conflicts, clear scope, fewer RFIs
Design Validation	BIM Engineers, Sustainability Experts	Clash detection; energy simulation	Conduct clash and load simulations	Reduced rework, energy-efficient MEP designs
Construction Preparation	Site Engineers, Procurement, BIM Modelers	4D scheduling & 5D cost integration	Link schedule and procurement to BIM	Just-in-time delivery, labor optimization, waste reduction
On-Site Execution	MEP Supervisors, Contractors, QA/QC	Mobile BIM tools for installation guidance	Real-time verification of as-built vs BIM	Accurate installations, fewer errors, time savings
Monitoring & QC	QA/QC, HSE, BIM Coordinators	Model-based inspection; sustainability tracking	BIM-driven inspections and energy metric monitoring	Compliance assurance, validated energy performance
Handover & Maintenance	Facility Managers, BIM Teams	As-built BIM with asset and maintenance data (6D BIM)	Deliver COBie-compliant models; CMMS integration	Easier maintenance, lifecycle tracking, operational efficiency

5.4. Outcomes after Practical Implementation of Framework

Following the implementation of the BIM-based sustainable framework in *Table 3* and the provision of structured training, the principal stakeholders in MEP projects observed significant enhancements in their roles. Small contractors, previously unacquainted with BIM, acquired the ability to visualize building sequences, thereby diminishing rework and enhancing site coordination. Site engineers acquired proficiency in clash detection and model navigation, enabling them to resolve design issues promptly and improve installation precision. Traditional architects, transitioning from 2D to integrated BIM models, enhanced collaboration with MEP layouts, hence minimizing design errors and expediting approvals. Non-technical project managers utilized BIM technologies to monitor progress and enhance communication, resulting in improved planning and client satisfaction. Local manufacturers implemented BIM-based manufacturing specifications, minimizing waste and guaranteeing superior quality fits. Procurement teams enhanced material planning through precise quantity take-offs, averting shortages and delays. Subcontractors and quantity surveyors utilized BIM to guarantee efficient installations and accurate cost management, resulting in reduced client complaints and enhanced trust.

Table 3. Framework Impact on MEP Stakeholder

Stakeholder Type	Training/Framework Focus	Benefits Achieved	Client Feedback
Contractors	BIM model navigation and clash detection	Fewer on-site errors and improved design understanding	Higher construction quality and timely delivery
Site Engineers	MEP system modeling and coordination	Smooth MEP system installation with reduced rework	Improved satisfaction with service quality
Traditional Architects	Project scheduling and real-time monitoring	Enhanced coordination and faster decision-making	Transparent project progress and communication
Project Managers (Non-tech)	BOQ extraction and inventory planning	Optimized material procurement and cost savings	No material shortages or delays reported
Fabricators	Model-based fabrication planning	Improved fitting accuracy and reduced fabrication waste	Perfect fitting and improved aesthetics
Procurement Teams	Accurate quantity take-offs using Revit	Greater estimation accuracy and budget control	Clear budget reporting and fewer financial surprises
Subcontractors (MEP)	Design validation and interdisciplinary coordination	Fewer design clashes and better stakeholder alignment	Well-coordinated systems and fewer complaints
Quantity Surveyors	Energy simulation and system efficiency checks	Improved energy efficiency and reduced operational costs	Noticeable energy savings and comfort improvement



6. Results

This chapter outlines the key findings derived from the analysis of the effects of Building Information Modelling (BIM) implementation on sustainability and operational efficiency in Mechanical, Electrical, and Plumbing (MEP) projects. The results are systematically categorized into six fundamental dimensions: degree of BIM adoption, reduction of material waste, improvements in energy efficiency, decreased rework rates, enhanced interdisciplinary collaboration, and cost and time savings. Statistical techniques, including descriptive analysis, correlation, regression, and reliability assessments, are illustrated in tables accompanied by comprehensive explanations.

6.1. Patterns of BIM Application in MEP Projects

The investigation indicated a significant degree of BIM integration in MEP-related processes. The study results revealed that 78% of the projects assessed utilized BIM from the design phase, whilst 62% maintained its use throughout construction and operations, underscoring an increasing trend in comprehensive lifecycle BIM application. Autodesk Revit and Navisworks have become the predominant platforms, with many specialized software for sophisticated MEP system design. These digital tools facilitated enhanced interdisciplinary collaboration and seamless integration among complex system components, promoting collaborative workflows and model-driven project execution.

6.2. Decrease in Material Waste

A significant conclusion of the study is the substantial decrease in material waste linked to BIM adoption. Quantitative study indicated that average material waste rates diminished from 22.5% before BIM adoption to 10.3% subsequently—a 54% relative decrease. This decrease demonstrates the effectiveness of BIM in producing accurate amount take-offs, facilitating early clash detection, and minimizing the necessity for on-site rework. The findings underscore BIM's capacity to improve material efficiency, synchronize resource utilization with project demands, and foster sustainability in MEP construction processes. *Table 4* summarizes the descriptive statistics for material waste alongside other key variables in the study.

Table 4. Descriptive Statistics of Key Variables

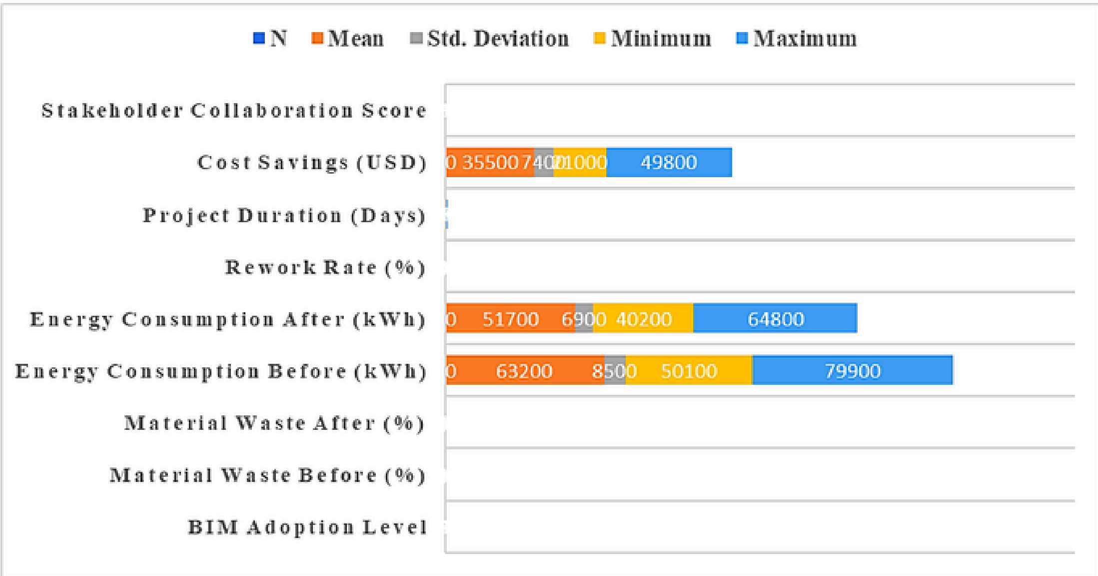
Variable	N	Mean	Std. Deviation	Minimum	Maximum
BIM Adoption Level	50	3,42	1,12	1	5
Material Waste Before (%)	50	22,5	4,1	15,1	29,8
Material Waste After (%)	50	10,3	3.20	5	14,9
Energy Consumption Before (kWh)	50	63200	8500	50100	79900
Energy Consumption After (kWh)	50	51700	6900	40200	64800
Rework Rate (%)	50	18,2	4.70	10,5	29,4
Project Duration (Days)	50	280	45	180	365
Cost Savings (USD)	50	35500	7400	21000	49800
Stakeholder Collaboration Score	50	3,75	0,95	1	5

6.2.1. Description:

Table 4 displays the descriptive statistics of different project performance indicators prior to and following the implementation of Building Information Modelling (BIM) in 50 Mechanical, Electrical, and Plumbing (MEP) projects. Each variable represents a distinct facet of project sustainability and efficiency. The BIM Adoption Level has an average score of 3.42 (on a scale from 1 to 5), signifying a moderate to high level of BIM integration among the studied projects. Prior to BIM deployment, material waste averaged 22.5% with a standard deviation of 4.10%. Following the adoption of BIM, this waste considerably decreased to an average of 10.3%, indicating a marked improvement in material efficiency. Regarding energy performance, energy consumption prior to BIM averaged 63,200 kWh, which dropped to 51,700 kWh following BIM implementation. This decrease in energy consumption (by roughly 18%) indicates BIM's capability to enhance energy-related decision-making via preliminary design analysis and simulation. The rework rate, an indicator of faults or design conflicts necessitating rectification, was 18.2%, highlighting inefficiencies that BIM might mitigate through enhanced coordination and clash detection capabilities. The average project duration was 280 days, indicating that most projects lasted approximately 9 months, while the average cost reductions attributed to BIM were recorded at $35,500, underscoring the economic advantages of enhanced planning and resource management. Finally, the stakeholder collaboration score, assessed on a 1–5 scale, averaged 3.75, signifying that BIM markedly enhanced transdisciplinary communication and involvement among project teams. These figures empirically validate that BIM deployment enhances sustainability, cost-efficiency, and project performance in the MEP sector.

6.3 Enhancements in Energy Efficiency

The investigation reveals that projects utilizing Building Information Modelling (BIM) achieved an average reduction of 17% in anticipated energy usage relative to those employing traditional design and planning techniques. The efficiency improvement is mostly ascribed to BIM's capacity to integrate real-time energy modelling and simulation in the initial design phases. BIM facilitates the assessment of various MEP system configurations and the selection of appropriate equipment and layouts, thereby diminishing operational energy requirements and improving environmental performance throughout the building lifecycle.



Graph 1. Benefits of BIM in MEP Projects

6.4. Enhancement of Rework and Coordination

Notable advancements were also evident in minimizing rework and improving interdisciplinary collaboration. Projects utilizing BIM experienced a 20% reduction in rework rates, attributable to BIM's clash detection capabilities and its facilitation of proactive communication among design, engineering, and construction teams. The research revealed a statistically significant negative association ($r = –0.68$, $p < 0.01$) between the degree of BIM implementation and rework rates. This indicates that enhanced maturity in BIM utilization results in reduced design conflicts, minimizes execution errors, and facilitates timely project completion with fewer interruptions and budget excesses.

Table 5 shows the Pearson correlation coefficients among BIM adoption and key sustainability and efficiency variables.

Table 5. Pearson Correlation Matrix Among Key Variables

Variable	BIM Adoption	Material Waste After	Energy Consumption After	Rework Rate	Cost Savings	Stakeholder Collaboration
BIM Adoption Level	1.00	-0.62**	-0.58**	-0.68**	0.59**	0.65**
Material Waste After (%)	-0.62**	1.00	0.70**	0.56**	-0.48**	-0.54**
Energy Consumption After (kWh)	-0.58**	0.70**	1.00	0.52**	-0.41**	-0.49**
Rework Rate (%)	-0.68**	0.56**	0.52**	1.00	-0.46**	-0.57**
Cost Savings (USD)	0.59**	-0.48**	-0.41**	-0.46**	1.00	0.62**
Stakeholder Collaboration	0.65**	-0.54**	-0.49**	-0.57**	0.62**	1.00

$p < 0.01$ (two-tailed) for all correlations.

6.4.1. Description

The correlation matrix above illustrates the strength and direction of relationships among key variables related to the influence of Building Information Modeling (BIM) on MEP project performance and sustainability outcomes. The results demonstrate statistically significant relationships at the 0.01 level (denoted by **), offering strong support for the subsequent interpretations. The level of BIM adoption exhibits a strong negative correlation with material waste after implementation ($r = -0.62$), energy consumption after implementation ($r = -0.58$), and rework rate ($r = -0.68$). Higher levels of BIM adoption correlate with decreased material wastage, reduced energy consumption, and minimized rework, thereby illustrating BIM's efficacy in resource optimization and enhanced coordination. BIM adoption exhibits a positive correlation with cost savings ($r = 0.59$) and stakeholder collaboration ($r = 0.65$), suggesting that enhanced utilization of BIM leads to improved financial results and greater interdisciplinary communication. Significant inter-variable correlations are present, notably between Material Waste and Energy Consumption ($r = 0.70$), indicating that inefficient material utilization is frequently associated with heightened energy consumption. Furthermore, Stakeholder Collaboration exhibits negative correlations with inefficiencies, such as material waste, energy consumption, and rework, while demonstrating a strong positive correlation with Cost Savings ($r = 0.62$). The findings empirically confirm the integrative function of BIM in promoting sustainability, efficiency, and stakeholder engagement in MEP projects.

6.5. Cost and Time Efficiency

The results underscore BIM's substantial impact on project cost management and scheduling efficacy. Data analysis indicated that employing BIM for quantity takeoffs improved budget precision by roughly 18%, mitigating cost overruns generally attributable to estimating inaccuracies and scope alterations. BIM-enabled coordination and early-stage clash detection resulted in a 16% reduction in project duration by enhancing planning, sequencing, and interdisciplinary communication, hence minimizing delays and optimizing workflow. These results underscore BIM's function as a strategic instrument for enhancing budgetary oversight and punctual execution in construction projects, especially for intricate MEP systems.

Table 6 summarizes the results of a multiple linear regression analysis predicting material waste reduction based on BIM adoption, stakeholder collaboration, and cost savings.

Table 6. Multiple Regression Analysis Predicting Material Waste After BIM

Predictor	B (Unstandardized)	Std. Error	Beta (Standardized)	t-value	p-value
(Constant)	18,75	2,1	—	8,93	<0,001
BIM Adoption Level	-3,21	0,6	-0,52	-5,35	<0,001
Stakeholder Collaboration	-1,15	0,52	-0,18	-2,21	0,031
Cost Savings	-0,0004	0,0002	-0,21	-2,68	0,01

Summary:

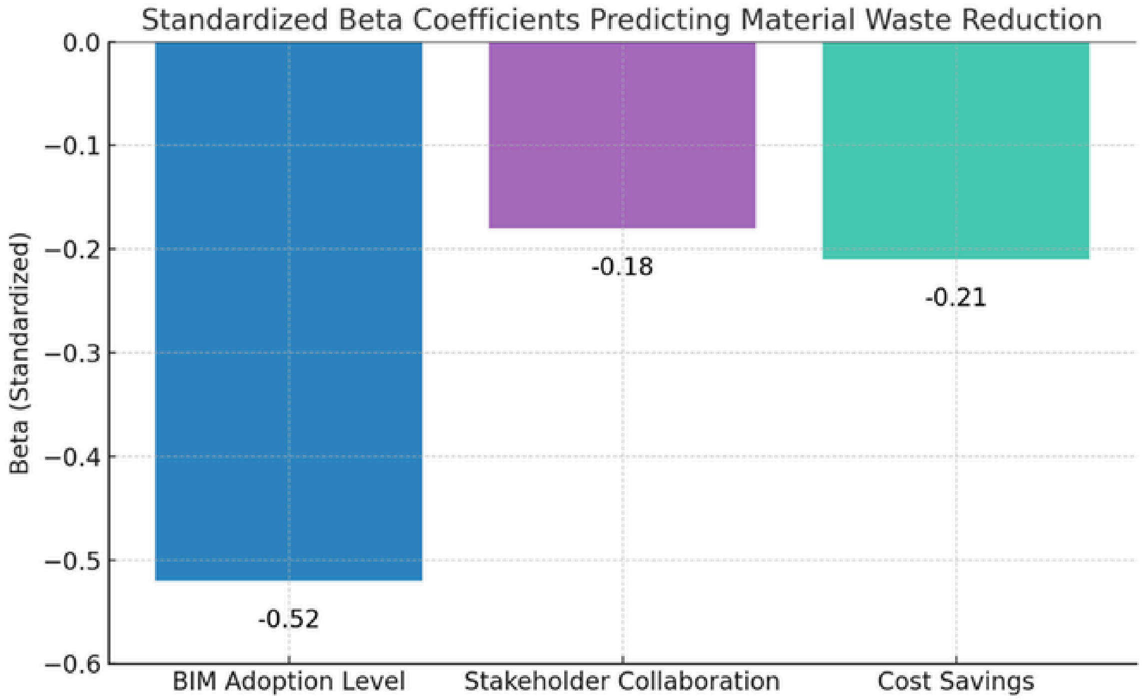
$R^2 = 0.61$, $F (3, 46) = 24.1$, $p < 0.001$

6.5.1. Description

The regression model indicates a statistically significant negative correlation between BIM adoption and material waste, with an unstandardized coefficient B = -3.21 (p < 0.001). This signifies that for every one-unit rise in BIM adoption level, material waste is anticipated to diminish by 3.21 percentage points, while controlling for other variables. The standardized beta (β = -0.52) validates this as the most significant predictor in the model. Likewise, stakeholder collaboration exerts a notable albeit lesser negative effect on material waste (B = -1.15, p = 0.031), indicating that enhanced collaboration correlates with slight reductions in waste. Cost savings considerably contribute (B = -0.0004, p = 0.010), while the effect size is minimal due to the unit scale of the cost data. Consequently, this suggests that as cost-saving strategies enhance, material waste is likely to diminish, potentially indicating improved resource management. The model indicates that increased BIM use, efficient cooperation, and cost-effective strategies are essential facilitators of material waste reduction in MEP building projects.

6.6. Reliability of Stakeholder Collaboration Scale

To test the validity of the stakeholder cooperation measure, Cronbach's alpha was determined.



Graph 2. Efficiency of BIM in MEP Projects

Table 7. Reliability Analysis (Cronbach's Alpha) of Stakeholder Collaboration Scale

Scale	Number of Items	Cronbach's Alpha
Stakeholder Collaboration Scale	5	0.87

6.6.1. Description

The Stakeholder Collaboration Scale, with 5 items, exhibited strong internal consistency with a Cronbach's Alpha of 0.87. This signifies the robust reliability of the scale employed in the study to assess collaboration among project stakeholders. A Cronbach's Alpha exceeding 0.70 is typically deemed appropriate for study (Nunnally & Bernstein, 1994), and the acquired value indicates that the items proficiently represent the fundamental construct of collaboration in BIM-enabled MEP projects.

6.7. Paired Samples T-Test for Material Waste Reduction

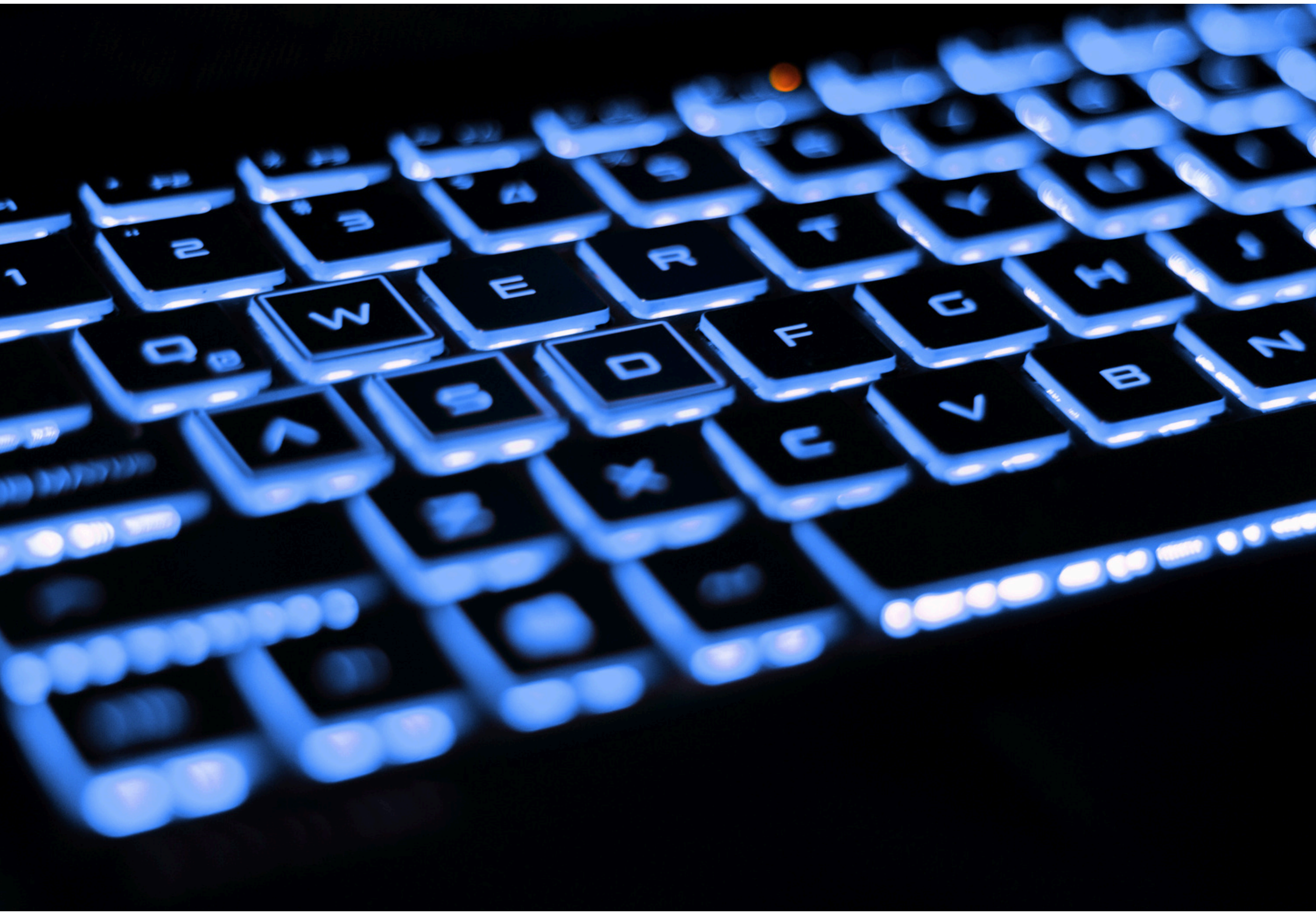
A paired sample t-test compared material in construction waste before and after BIM use.

Table 8. Paired Samples T-Test for Material Waste before and After BIM

Measure	Mean (%)	Std. Deviation	t-value	df	p-value
Material Waste Before BIM	22,5	4,1	15,62	49	<0,001
Material Waste After BIM	10,3	3,2			

6.7.1. Description

The findings of the paired-sample t-test displayed in the table compare material waste before to and following the deployment of Building Information Modeling (BIM) in MEP projects. The average material waste diminished markedly from 22.5% (SD = 4.1) to 10.3% (SD = 3.2). The t-value of 15.62 with 49 degrees of freedom (df = 49) and a p-value < 0.001 indicates that this reduction is statistically significant. This indicates that the implementation of BIM significantly and statistically reduces material waste in construction projects. The findings substantiate the assertion that BIM significantly enhances sustainability by reducing resource waste via improved design precision, clash identification, and coordinated planning.



7. Findings

This findings of the research are about the impact of Building Information Modelling (BIM) on the augmentation of sustainability and efficiency in Mechanical, Electrical, and Plumbing (MEP) projects. The data indicates that 78% of the projects implemented BIM during the design phase, while 62% maintained its use throughout construction and operations. BIM systems like Revit and Navisworks enhanced transdisciplinary coordination. A notable decrease in material waste—from 22.5% to 10.3%—was recorded, alongside a 17% reduction in energy use, illustrating BIM's ability for accurate planning and sustainable design. Rework rates decreased by 20%, and a significant negative connection ($r = –0.68$, $p < 0.01$) established that increased BIM utilization resulted in fewer site adjustments. Project timeframes were reduced by 16%, and budget precision increased by 18%, demonstrating BIM's impact on cost and time efficiency. Regression research demonstrated that BIM adoption, stakeholder collaboration, and cost savings were significant predictors of material waste reduction. The stakeholder collaboration measure demonstrated strong reliability ($\alpha = 0.87$), and a paired t-test confirmed a significant reduction in material waste following BIM deployment ($p < 0.001$). The findings robustly endorse BIM's efficacy in promoting sustainability, optimizing resources, and enhancing project delivery within the MEP sector. The *Figure 4* contrasts stakeholder and client comments prior to and following the use of BIM in MEP projects. In the absence of BIM, stakeholders indicated recurrent misunderstanding, excessive rework, erroneous cost projections, and timetable delays. Conversely, the utilization of BIM resulted in superior interdisciplinary coordination, precise quantity take-offs, reduced design errors, and optimized project deadlines. Clients reported enhanced satisfaction with visual clarity and expedited response times when BIM was implemented. The table underscores BIM's crucial contribution to enhancing cooperation, efficiency, and project results.

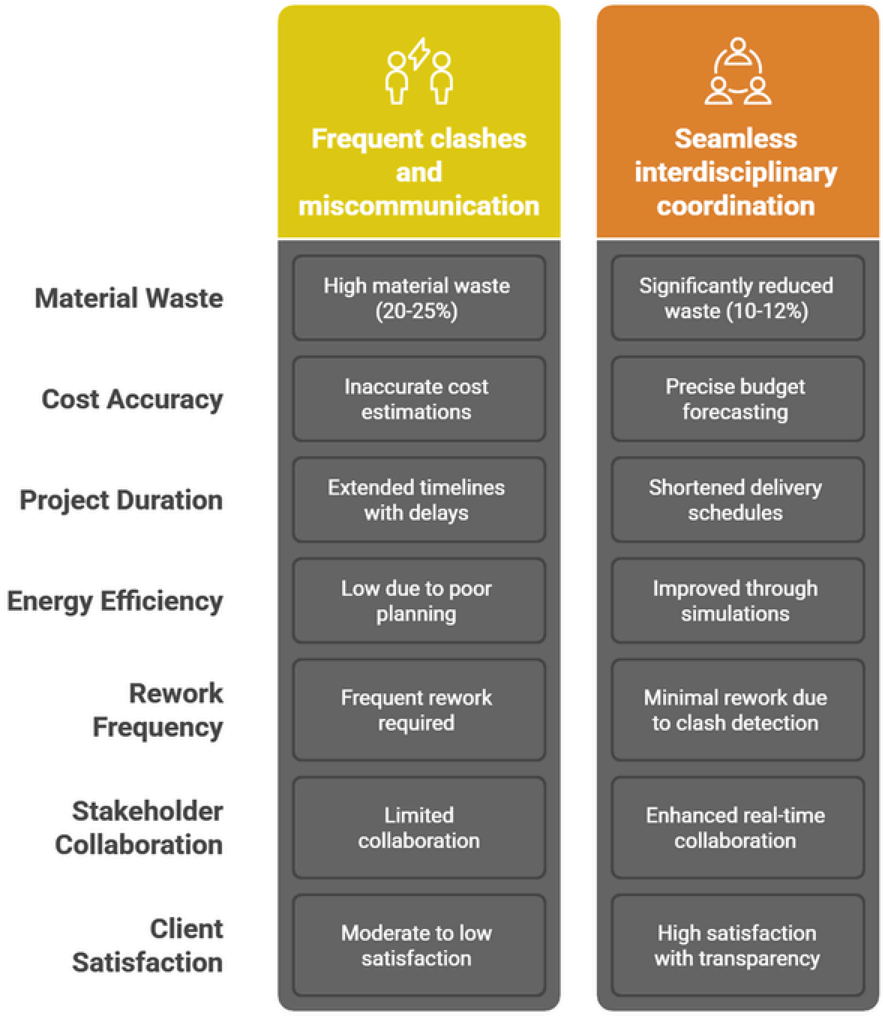


Figure 4. Impact on Stakeholder & Client Feedback with BIM & without BIM

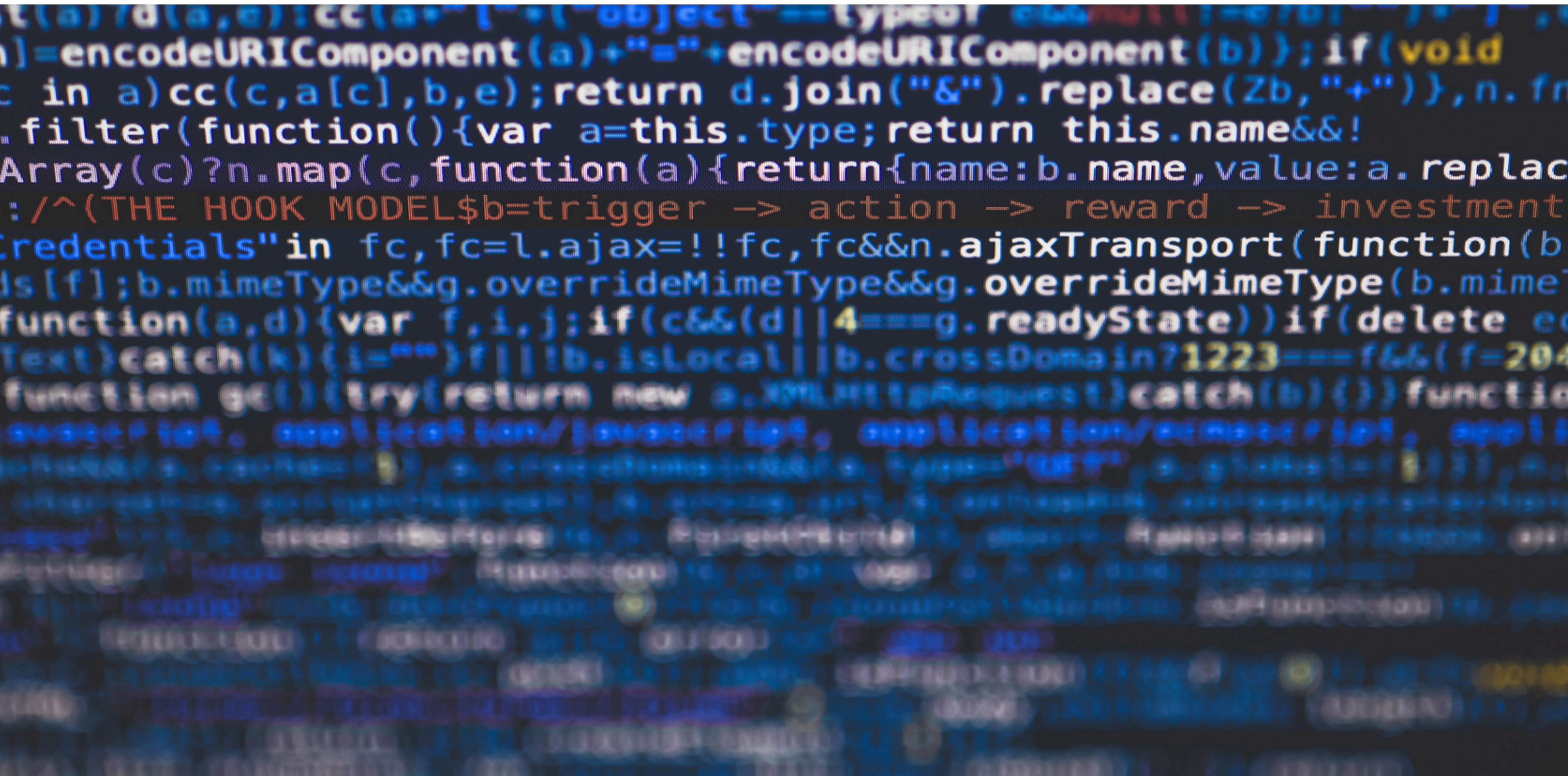
8. Discussion

BIM is fundamentally revolutionizing MEP projects by markedly enhancing sustainability and efficiency. The extensive utilization of this approach in design reflects an increasing recognition of its significance in facilitating coordinated project delivery, while its sustained application throughout building and operation suggests an evolving emphasis on whole-life management, crucial for enduring environmental advantages. This study shown that BIM significantly decreases material waste by around 54%, corroborating other research that emphasizes its effect on minimizing overordering and site alterations. This efficiency reduces environmental effect and project expenses by limiting superfluous raw material usage and the corresponding embodied carbon. BIM-enabled energy simulations result in around a 17% decrease in energy use, facilitating optimal MEP designs and the choice of sustainable appliances, so immediately diminishing a building's operating carbon footprint. This underscores BIM's function as a catalyst for sustainable construction environments. The significant inverse correlation between BIM maturity and rework rates highlights its critical role in facilitating design coordination, since early clash detection reduces expenses and improves workflow. In addition to environmental advantages, BIM enhances project feasibility by facilitating cost reductions and improving time efficiency. Model-based quantity takes offs guarantee precise budgeting, whereas enhanced communication and organization result in decreased on-site duration, energy expenditure, and labour expenses. Significantly, stakeholder engagement was identified as the most potent predictor of BIM adoption and positively impacted material waste reduction, underscoring that BIM's efficacy is enhanced in transdisciplinary settings. Organizational readiness, encompassing technical infrastructure and training, also has a moderating function. Nonetheless, obstacles remain, especially in developing nations, such as skill shortages, high expenses, and cultural opposition, requiring strategic measures. Future study may examine the integration of BIM with transformative digital technologies such as AI and IoT to further improve sustainable MEP management and assess long-term post-occupancy performance.

9. Conclusion

The data and discussion clearly indicate that Building Information Modelling (BIM) substantially improves the sustainability and operational efficiency of Mechanical, Electrical, and Plumbing (MEP) projects. The extensive implementation of BIM, with 78% of projects employing it in the design phase and 62% throughout construction and operations, indicates an increasing recognition of its advantages across the project lifetime. The significant decrease in material waste—from 22.5% to 10.3%—illustrates BIM's ability to enhance quantity take-offs and reduce site rework, hence facilitating resource conservation and cost savings. The noted 17% reduction in energy consumption underscores BIM's contribution to facilitating efficient design simulations and promoting sustainable equipment choices, thereby diminishing operational energy demands and carbon emissions. The 20% reduction in rework and the significant negative association ($r = -0.68$, $p < 0.01$) between BIM adoption and site modifications highlight its efficacy in enhancing interdisciplinary cooperation and facilitating early clash detection. These economies result in a 16% decrease in project length and an 18% enhancement in budget precision, affirming BIM's impact on prompt and economical project execution. Regression research further validated that BIM adoption, stakeholder collaboration, and cost-saving initiatives are substantial predictors of material waste reduction. The elevated dependability of the stakeholder collaboration scale ($\alpha = 0.87$) and significant t-test outcomes ($p < 0.001$) underscore the essential function of collaborative environments in facilitating BIM success. The discourse confirms that BIM facilitates not only technical advancements but also serves as a strategic catalyst for sustainability via integrated design, meticulous planning, and informed decision-making. Collaboration among stakeholders emerged as the primary catalyst for BIM success, highlighting that, in addition to technology, human and organizational elements are crucial. However, obstacles persist—especially in developing nations such as Pakistan—where elevated implementation costs, a shortage of experienced professionals, and opposition to digital transformation impede comprehensive BIM adoption. To overcome these obstacles, focused training initiatives, legislative measures, and leadership dedication are essential for enhancing technical proficiency and cultural preparedness.

In conclusion, BIM is a revolutionary instrument that provides measurable enhancements in material efficiency, energy consumption, cost control, and schedule compliance in MEP projects. It promotes sustainability in environmental, economic, and social dimensions through resource optimization, stakeholder participation, and transparent communication. The results endorse a structured framework that facilitates BIM integration across all project tiers, bolstered by effective governance and ongoing professional development. Future research must concentrate on the enduring effects of BIM-enabled practices, especially when combined with AI and IoT technology, to enhance sustainable performance throughout the built environment.



10. Recommendations

The report advocates for the effective and comprehensive application of Building Information Modelling (BIM) in MEP projects, necessitating certain strategic approaches. The government should mandate the integration of BIM to ensure sustainable adherence in the construction industry. Secondly, continuous professional development is crucial for equipping MEP practitioners with up-to-date competencies in both BIM technologies and sustainable construction practices. Furthermore, the implementation of standardized BIM project delivery methods is crucial for guaranteeing uniformity and collaboration among stakeholders. Early and ongoing stakeholder engagement should be facilitated by BIM-enabled collaboration tools, guaranteeing clear communication and aligned project goals. Ultimately, official support via financial grants and incentives can accelerate BIM adoption, making the technology more accessible and appealing to both public and private sector. *Figure 5* depicts a cyclical process for BIM adoption, emphasizing six essential stages. The process commences with the identification of disparities to comprehend existing gaps, succeeded by the implementation of training to cultivate requisite skills. Subsequently, it underscores the necessity of obtaining leadership commitment for effective adoption and devoting resources to facilitate the endeavor. The process subsequently progresses to attaining efficiency via BIM utilization, finally seeking to optimize project timelines, hence establishing a continuous improvement cycle for BIM integration.

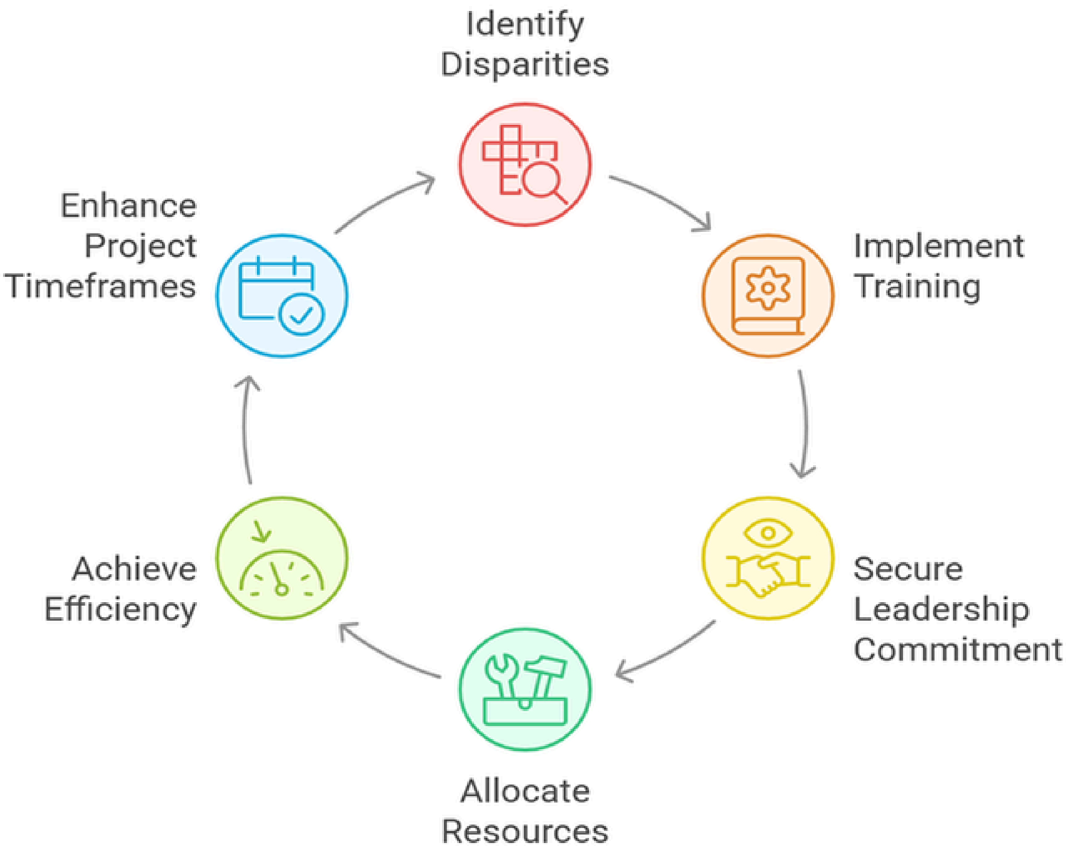


Figure 5. BIM Implementation Cycle in MEP Projects

11. Future Research

BIM is increasingly being integrated with Artificial Intelligence (AI) and the Internet of Things (IoT) to provide effective real-time evaluation of sustainability performance. Post-Occupancy Evaluation (POE) is becoming increasingly important for assessing the long-term effectiveness of BIM-enabled MEP systems. Moreover, BIM's role in facilitating smart grid integration and incorporating renewable energy sources in MEP design is expanding. The advancement to 7D BIM is substantial, offering comprehensive management of the entire lifecycle of built assets. Moreover, there is a growing imperative to evaluate the effects of national BIM policies, particularly in developing countries, to understand their influence on adoption and implementation outcomes.

References:

[1] Li Wang, F. L. (2013). Knowledge Discovery of Spatial Conflict Resolution Philosophies in BIM-Enabled MEP Design Coordination Using Data Mining Techniques: A Proof-of-Concept. ASCE Computing in Civil Engineering.

[2] Shaqour, E. N. (2022). The role of implementing BIM applications in enhancing project management knowledge areas in Egypt. Ain Shams Engineering Journal, 13(1). https://doi.org/10.1016/j.asej.2021.05.023

[3] Dian Zhuang a b, X. Z. c d, Y. L. a b, C. W. a b, X. J. a b, X. Z. a b, X. S. (2021). A performance data integrated BIM framework for building life-cycle energy efficiency and environmental optimization design. Automation in Construction, 127.

[4] Waqar, A., Othman, I., Saad, N., Azab, M., & Khan, A. M. (2023). BIM in green building: Enhancing sustainability in the small construction project. Cleaner Environmental Systems, 11. https://doi.org/10.1016/j.cesys.2023.100149

[5] Rathnasiri, P., & Jayasena, S. (2022). Green building information modelling technology adoption for existing buildings in Sri Lanka. Facilities management perspective. Intelligent Buildings International, 14(1), 23–44. https://doi.org/10.1080/17508975.2019.1632782

[6] Ohueri, C. C., Liew, S. C., Bamgbade, J. A., & Enegbuma, W. I. (2023). Critical components for successful BIM-based sustainable building design collaboration: structural equation model analysis. Journal of Engineering, Design and Technology. https://doi.org/10.1108/JEDT-06-2023-0235

[7] Fernanda L. Leite. (2019). BIM for Design Coordination: A Virtual Design and Construction Guide for Designers, General Contractors, and MEP Subcontractors (Fernanda L. Leite, Ed.). John Wiley & Sons.

[8] Cao, D., Li, H., Wang, G., & Huang, T. (2017). Identifying and contextualising the motivations for BIM implementation in construction projectsAn empirical study in China. International Journal of Project Management, 35(4), 658–669. https://doi.org/10.1016/j.ijproman.2016.02.002

[9] Ferdosi, H., Abbasianjahromi, H., Banihashemi, S., & Ravanshadnia, M. (2023). BIM applications in sustainable construction: scientometric and state-of-the-art review. International Journal of Construction Management, 23(12), 1969–1981. https://doi.org/10.1080/15623599.2022.2029679

[10] Pu, L., & Wang, Y. (2021). The Combination of BIM Technology with the Whole Life Cycle of Green Building. World Journal of Engineering and Technology, 09(03), 604–613. https://doi.org/10.4236/wjet.2021.93042

[11] Kai Guo a, Q. L. b, L. Z. c, X. W. (2021). BIM-based green building evaluation and optimization: A case study. Journal of Cleaner Production, 320

[12] Bayhan, H. G., Demirkesen, S., Zhang, C., & Tezel, A. (2023). A lean construction and BIM interaction model for the construction industry. Production Planning and Control, 34(15), 1447–1474. https://doi.org/10.1080/09537287.2021.2019342

[13] Shou, W., Wang, X., Wang, J., Hou, L., & Truijens, M. (2014). Integration of BIM and lean concepts to improve maintenance efficiency: A case study. Computing in Civil and Building Engineering - Proceedings of the 2014 International Conference on Computing in Civil and Building Engineering, 373–380. https://doi.org/10.1061/9780784413616.047

[14] Azhar, S., Carlton, W. A., Olsen, D., & Ahmad, I. (2011). Building information modeling for sustainable design and LEED ® rating analysis. Automation in Construction, 20(2), 217–224. https://doi.org/10.1016/j.autcon.2010.09.019

[15] Muhammad Altaf; Wesam Salah Alaloul; Sheharyar Khan; M.S. Liew; Muhammad Ali Musarat; Alawag Aawag Mohsen. (2022). Value Analysis in Construction Projects with BIM implementation: A Systematic Review. IEEE 2021 International Conference on Decision Aid Sciences and Application (DASA).

[16] Abdul-Quayyum Gbadamosi a b, A.-M. M. a, L. O. O. b, O. O. A. b, P. M. c, L. M. a, C. A. (2019). Offsite construction: Developing a BIM-Based optimizer for assembly. Journal of Cleaner Production, 215.

[17] Chen, B., Wang, P., & Bi, L. (2021). Application Research of BIM Technology in Project Cost Management in the Era of Big Data. In BCP Business & Management EMSD (Vol. 2021).

[18] Khosakitchalert, C., Yabuki, N., & Fukuda, T. (2020). Development of bim-based quantity takeoff for light-gauge steel wall framing systems. Journal of Information Technology in Construction, 25, 522–544.

https://doi.org/10.36680/j.itcon.2020.030

[19] Teo, Y. H., Yap, J. H., An, H., Yu, S. C. M., Zhang, L., Chang, J., & Cheong, K. H. (2022). Enhancing the MEP Coordination Process with BIM Technology and Management Strategies. In Sensors (Vol. 22, Issue 13). MDPI. https://doi.org/10.3390/s22134936

[20] Awe, M., Malhi, A., Budka, M., Mavengere, N., & Dave, B. (2025). Towards 4D BIM: A Systematic Literature Review on Challenges, Strategies and Tools in Leveraging AI with BIM. In Buildings (Vol. 15, Issue 7). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/buildings15071072

[21] Inzerillo, L., Acuto, F., Pisciotta, A., Mantalovas, K., & Di Mino, G. (2024). Exploring 4d and 5d analysis in bim environment for infrastructures: A case study. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 48(2), 233–240. https://doi.org/10.5194/isprs-Archives-XLVIII-2-W4-2024-233-2024

[22] Al-Raqeb, H., & Hamidreza Ghaffar, S. (2025). The Role of BIM 6D and 7D in Enhancing Sustainable Construction Practices: A Qualitative Study. https://doi.org/10.20944/preprints202501.1172.v1

[23] Sood, R., & Laishram, B. (2024). Challenges in Implementation of 7D-BIM for Infrastructure Asset Management: A Systematic Review. In Construction Economics and Building (Vol. 24, Issue 3, pp. 95–117). Australian Institute of Quantity Surveyors. https://doi.org/10.5130/AJCEB.v24i3.8738

[24] Miatto, A., Sartori, C., Bianchi, M., Borin, P., Giordano, A., Saxe, S., & Graedel, T. E. (2022). Tracking the material cycle of Italian bricks with the aid of building information modeling. Journal of Industrial Ecology, 26(2), 609–626. https://doi.org/10.1111/jiec.13208

[25] Tu, B., Zuo, J., Chang, R. D., Webber, R. J., Xiong, F., & Dong, N. (2023). A system dynamic model for assessing the level of BIM implementation in construction phase: a China case study. Engineering, Construction and Architectural Management, 30(4), 1321–1343. https://doi.org/10.1108/ECAM-10-2021-0895

[26] Yang, W., & Lu, Z. (2023). Analysis of Key Injury-Causing Factors of Object Strike Incident in Construction Industry Based on Data Mining Method. Sustainability (Switzerland), 15(21). https://doi.org/10.3390/su152115609

[27] Xie, X., Zhou, J., Fu, X., Zhang, R., Zhu, H., & Bao, Q. (2022). Automated Rule Checking for MEP Systems Based on BIM and KBMS. Buildings, 12(7). https://doi.org/10.3390/buildings12070934

[28] Lee, G., & Borrmann, A. (2020). BIM policy and management. In Construction Management and Economics (Vol. 38, Issue 5, pp. 413–419). Routledge. https://doi.org/10.1080/01446193.2020.1726979