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BIM-Based Energy Optimization and Sustainability Enhancement in the Iranian Construction Industry

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ABSTRACT

The Iranian construction industry continues to face major challenges in reducing energy consumption and achieving sustainability targets. Building Information Modeling (BIM) offers an integrated digital framework capable of linking design parameters with real energy-performance indicators. This study develops and empirically validates a BIM-based energy optimization model that examines the influence of five digital modeling dimensions, energy use intensity (EUI), HVAC simulation, daylighting control, CO_2 reduction, and renewable-energy integration, on sustainability outcomes. Data were collected from 130 professionals across Iran and analyzed using exploratory factor analysis and PLS-SEM. The model demonstrated strong validity ($KMO = 0.874$, $CR > 0.90$, $AVE > 0.68$) and explained 68% of the variance in sustainability performance ($R^2 = 0.68$). Among all predictors, BIM-HVAC showed the strongest impact on energy efficiency ($\beta = 0.284$, $p < 0.001$). Bootstrapping results confirmed the significance of all hypothesized relationships, highlighting BIM as a strategic mechanism for energy-efficient design and carbon-emission reduction. This research contributes to BIM-sustainability literature by providing a validated quantitative framework tailored to the Iranian construction context. Practical implications include guidelines for integrating BIM-energy protocols capable of reducing energy consumption by up to 30%. Future studies should extend the framework through AI-based predictive analytics and longitudinal performance tracking.

1. Introduction

The rapid pace of global development has turned the energy and sustainability crisis into one of the most critical challenges of the twenty-first century [1]. According to reports by the International Energy Agency (IEA), buildings account for approximately 36 percent of total global energy consumption and nearly 39 percent of CO_2 emissions [2]. This fact underlines the decisive role of the construction sector in strategies for carbon emission reduction and achieving sustainability targets. Furthermore, the rising population and the growing demand for residential spaces have exerted unprecedented pressure on natural resources and energy networks [3]. In Iran, characterized by diverse climates ranging from cold to hot and semi-arid, the average energy consumption of buildings has been reported to be up to three times higher than the global average [4]. This situation not only threatens environmental sustainability but also increases operational costs, deepens reliance on fossil fuels, and exposes the nation to resource-related crises.

Combating this circumstance requires a fundamental transformation in the design and management of construction projects, changes capable of analyzing real energy consumption data in an integrated manner across design, construction, and operation stages. Over the last decade, Building Information Modeling (BIM) has emerged as the most influential technological instrument driving digital transformation in the construction industry [5, 6]. BIM is an intelligent model that stores and analyzes all architectural,

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structural, and performance data of a building within a unified, parametric framework [7]. It goes far beyond 2D or 3D visualization and integrates the building lifecycle with the indicators of energy consumption (EUI), heating, ventilation, air conditioning (HVAC), daylighting (DL), and carbon emissions (CO_2). Research demonstrates that integrating BIM with energy simulation tools such as EnergyPlus and Green Building Studio can reduce building energy consumption by up to 30 percent and enhance HVAC system efficiency by an average of 15 % [8-10].

Globally, BIM approaches have rapidly shifted from design-centric applications toward comprehensive energy and sustainability analytics. The government of the UK mandated the use of BIM in all public projects since 2016 [11], while countries such as Norway, Australia, and South Korea have expanded BIM utilization to life cycle assessment (LCA) and energy analysis models [12]. In the Crossrail project in London, BIM facilitated coordination among design offices, contractors, and energy supply systems, resulting in a 25 percent reduction in construction waste [13]; in the One Central Park project, Sydney, the integration of BIM with EnergyPlus achieved 30 percent operational energy savings and 25 percent carbon emission reduction [14]. These successful experiences prove that BIM can evolve from a mere design instrument into a data-driven decision support system for realizing intelligent and sustainable buildings.

Nevertheless, in Iran, the application of BIM remains at an early stage, mostly confined to geometric modeling or project scheduling [15, 16]. The absence of energy data infrastructure, the lack of official guidelines, and the shortage of skilled professionals capable of integrating BIM with energy analyses constitute major obstacles. Consequently, most decisions related to energy consumption or HVAC system selection occur during the operational phase, after construction, entailing costly corrective measures and long-term inefficiency. This technological and managerial gap highlights the necessity for research that can redefine BIM-based energy models in accordance with Iran's climatic and economic conditions.

In this context, the present study employs an analytical and model-based approach to develop an integrated BIM framework for energy optimization in Iranian buildings. The conceptual model focuses on five key indicators: BIM EUI, BIM HVAC, BIM DL (daylighting), BIM RE (renewable energy), and BIM CO_2 (carbon emission), verified through Partial Least Squares Structural Equation Modeling (PLS SEM). Data were collected from 130 professionals involved in building projects across Iran, and the statistical validity of the analysis was confirmed using recognized indices: $KMO = 0.874$, $CR > 0.9$, and $AVE > 0.68$, indicating sample adequacy and construct validity. Bootstrapping (5000 iterations) revealed that the BIM HVAC dimension exhibits the strongest direct effect on energy sustainability ($\beta = 0.284, p < 0.001$). Overall, the model explains 68 percent of the variance in energy sustainability ($R^2 = 0.68$).

To further evaluate the predictive performance of the proposed model beyond in-sample explanatory power, a PLS-Predict assessment was conducted using SmartPLS 4. In accordance with recent guidelines for prediction-oriented PLS-SEM analysis, the model's out-of-sample predictive capability was assessed by comparing PLS-based prediction errors with those obtained from a linear regression benchmark model. The results showed that all Q^2 predict values for the endogenous constructs were greater than zero, indicating satisfactory predictive relevance. In addition, the root mean square error (RMSE) values generated by the PLS-SEM model were consistently lower than those of the linear model (RMSE_PLS < RMSE_LM) across all indicators. These results confirm that the proposed model demonstrates superior out-of-sample predictive accuracy compared to naïve benchmark models.

Overall, the PLS-Predict analysis confirms that the BIM-based energy optimization model not only provides strong explanatory power within the estimation sample but also exhibits robust generalizability to unseen data, reinforcing its applicability for real-world decision-making and energy policy development.

From a theoretical standpoint, this research extends global literature on "BIM as a data analytics infrastructure" and introduces a new generation of energy models based on the integration of design data with real energy performance outcomes. Within this framework, BIM functions as the core engine for multi-source data processing, enabling simulation of thermal, lighting, and energy consumption behaviors at the design stage.

From a practical perspective, the findings can form a foundation for national policy-making in Iran's green building agenda. In this context, the proposed BIM-Energy Model is not intended as a prescriptive policy instrument, but rather as a decision-support framework that informs national policy-making. By quantifying the relative influence of BIM-based energy indicators (EUI, HVAC, daylighting, renewable energy, and CO_2 reduction), the model enables policy-makers to prioritize design-stage interventions, define evidence-based performance benchmarks, and allocate resources more efficiently. Accordingly, the model supports ex-ante policy formulation and strategic planning rather than post-occupancy regulatory enforcement. The Ministry of Road and Urban Development and the Iranian Energy Efficiency Organization could adopt the BIM Energy Model to redefine design evaluation indicators and establish new standards comparable to LEED and BREEAM. The proposed model also opens pathways for developing smart energy control systems based on IoT and artificial intelligence, enabling engineers to proactively manage energy consumption rather than reactively solving post-occupancy problems.

Considering Iran's energy constraints and climatic pressures, developing localized solutions such as the proposed model is significant not only from technical but also from economic and social perspectives. The BIM Energy Model has the potential to reduce national building sector energy consumption by 30 percent and CO_2 emissions by 25 percent annually, coinciding with global "energy intensity reduction targets by 2030." It should be clarified that the indicative figures of 30% energy reduction and 25% CO_2 emission reduction are not derived from the questionnaire data of this study. These values are informed by secondary sources and prior empirical studies reporting typical ranges of energy and carbon savings achieved through BIM-based energy simulation and integrated design strategies. The survey results of the present research statistically validate the relationships between BIM adoption, energy-optimization mechanisms, and sustainability outcomes, rather than measuring absolute reduction percentages.

In the long-term horizon, this research delineates a new vision for Iran’s construction industry: a transition from traditional project management to data-driven intelligent systems. In this trajectory, BIM is not simply a design tool but the core of energy-based decision-making. With full implementation of the proposed framework and development of information infrastructures, it can be anticipated that by 2029, Iran’s building sector will reach a stage where energy sustainability becomes a measurable and operational reality rather than a mere slogan.

2. Literature review

In recent years, the application of Building Information Modeling (BIM) has emerged as a powerful tool for energy performance analysis and sustainability advancement in the construction industry. Research highlights that BIM, by providing an integrated digital framework for design, analysis, and management of buildings, can significantly reduce energy consumption and improve control over Heating, Ventilation, and Air Conditioning (HVAC) systems, natural daylight (DL), and overall energy use intensity (EUI). Consequently, BIM has become a core enabler for linking digital construction data with real energy performance indicators [17].

Early studies established that BIM is not merely a three-dimensional design instrument but a central platform for synchronizing materials, systems, and energy data across project life cycles. Cho et al. [17] were among the first to introduce the concept of energy-efficient design based on BIM integration. Their findings demonstrated that coupling thermal parameters and smart building materials within BIM environments contributes to substantial reductions in operational costs. Following that, Beazley et al. [18] in an empirical investigation on residential buildings confirmed that embedding energy parameters at the early design stage leads to approximately 15 percent annual energy savings. This perspective solidified the notion of “Green BIM,” aimed at multi-stage evaluation of environmental performance.

Subsequent research investigated the coupling of BIM with Building Energy Modeling (BEM) systems. Alhammad et al. [19] conducted a systematic review of more than one hundred peer-reviewed articles, revealing that BIM–BEM integration increases the accuracy of energy simulations and can reduce HVAC energy demand by roughly 20 percent. Their study emphasized that combining Revit Energy with EnergyPlus simulations and real operational data enables higher agreement between designed and actual energy performances. Kozlovska et al. [20] adopted a hybrid BEMS–BIM configuration and reported a 29 percent reduction in electrical energy losses through real-time synchronization between the Building Energy Management System and BIM datasets. These studies collectively portray BIM as a central hub for real-time energy optimization supported by artificial intelligence and sensor networks [20].

In Asian contexts, Primasetra et al. [21] explored BIM-based architectural design processes and highlighted the challenge of calculating energy metrics during conceptual design. They argued that to achieve genuine sustainability, parameters like Daylighting (DL) and Renewable Energy (RE) generation must be defined within the BIM environment from the earliest stage, allowing design decisions to be quantitatively assessed even before project execution [21].

Beyond large-scale projects, Waqar et al. [22] emphasized the potential of BIM in small and medium-scale projects within developing economies (including Iranian case studies). Their findings showed that BIM implementation achieved a 21 percent reduction in energy consumption and an 18 percent decrease in operational costs. The research provided essential insights into the selection of green materials, management of construction waste, and life cycle assessment (LCA), demonstrating that even small projects can rely on BIM as a consistent framework for sustainability evaluation [22].

Several contemporary investigations have focused on contextual limitations of existing BIM energy models. Most simulation templates are calibrated for temperate European climates and often lose accuracy under extreme thermal or arid conditions, typical of Middle Eastern regions. Therefore, Iranian and regional studies have begun developing localized BIM–energy models suited to national climatic dynamics. For example, building projects in Tehran using combined BIM + EnergyPlus simulation achieved up to 18 percent HVAC energy reduction, proving BIM’s adaptability in local climates. These results underscore BIM’s viability as a decision support framework for climate-conscious architecture.

Synthesizing global and regional research, the literature reveals that while BIM-based energy management has achieved global acceptance, notable research gaps persist:

1. Limited availability of empirical data from arid climate buildings;

2. Absence of a national sustainability rating system in Iran equivalent to LEED or BREEAM;

3. Lack of quantitative models encompassing HVAC, EUI, DL, and RE parameters specific to regional construction practices.

Accordingly, this research seeks to fill these gaps by developing a combined BIM + Energy Optimization framework tailored for the Iranian context. Building on insights from Kozlovska et al. [20] and Alhammad et al. [19], it utilizes integrated energy simulation and BIM data analysis to evaluate real project performance. Global findings confirm that merging BIM with simulation environments reduces energy consumption while enhancing lifecycle sustainability. Consistent with these conclusions, this research employs four principal indices, HVAC Efficiency, Energy Use Intensity (EUI), Daylighting Factor (DL), and Renewable Energy Integration (RE) to test hypotheses and establish a localized, data-driven analytical model aligned with Iranian construction realities.

3. BIM dimensions and level of development (LOD)

In Building Information Modeling (BIM), the Level of Development (LOD) defines the degree of detail and reliability of both geometric and informational data within a building model. It shows how mature the data becomes over the project lifecycle, which directly influences precision in energy optimization and sustainability performance.

LOD 100–500 hierarchy:

- LOD 100 (Conceptual): illustrates only massing and general form, useful for early daylight (DL) and shading analysis.
- LOD 200 (Schematic Design): adds approximate thermal zones for primary estimation of EUI and HVAC loads.
- LOD 300 (Detailed Design): includes real materials, envelope properties, and accurate geometry suitable for full building-energy simulations (e.g., EnergyPlus, Revit Energy).
- LOD 400 (Fabrication/Construction): links actual HVAC and construction data, enabling dynamic performance prediction and cost integration.
- LOD 500 (As Built/Operation): represents verified sensor data through Building Energy Management Systems (BEMS) for real EUI, DL, RE (renewable energy), and CO_2 evaluation.

Each BIM dimension (3D – 10D) expands the analytic capacity, from geometric modeling to sustainability and legal compliance. For instance, 6D Sustainability incorporates EUI and CO_2 tracking, 7D Maintenance connects IoT-based predictive control, and 9D Legal supports adherence to ASHRAE 90.1 and Iran Code 19 standards.

The advanced synthesis of multi-dimensional BIM and progressive LOD builds a coherent framework for energy-driven design decisions. Fig. 1 (BIM Dimensions and LOD Integration Model) graphically illustrates this relationship: LOD levels (100–500) are aligned along a vertical axis of model maturity, while BIM dimensions (3D–10D) extend horizontally, showing how geometric depth corresponds to analytical capability. Higher intersections (LOD 300–500 × 6D–7D) represent the “energy optimization zone,” where HVAC efficiency, EUI calibration, and CO_2 monitoring actively converge.

For high-energy-demand contexts such as Iranian hot dry regions, employing LOD ≥ 300 within the 6D–7D scope is critical to achieving accurate simulation and long-term operational optimization.

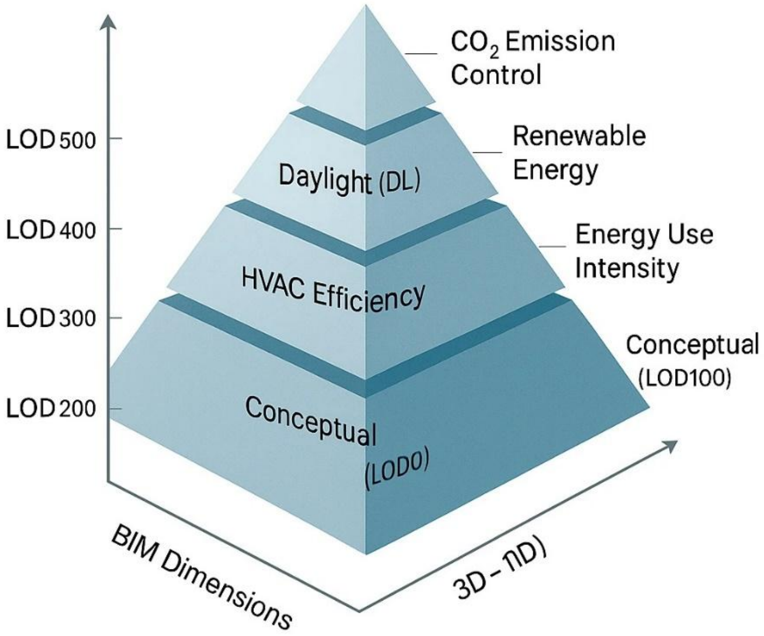

Fig. 1. BIM dimensions and LOD integration model.

4. Research methodology

The role of Building Information Modeling (BIM) in enhancing energy efficiency and improving sustainability performance in Iranian construction projects was examined in three major phases. These stages include a structured process of literature consolidation and conceptual framework development, quantitative data collection, and advanced structural modeling analysis using the Partial Least Squares Structural Equation Modeling (PLS SEM) technique. The sequential design of the research is presented below.

Phase 1: Literature review and conceptual framework development

The first stage consisted of a comprehensive and systematic review of scholarly literature related to BIM adoption, energy optimization, and building sustainability.

This review aimed to identify and consolidate previous technologies, indicators, and performance metrics describing how BIM contributes to the energy efficiency of construction projects.

Key thematic areas in the literature included:

- Energy Use Intensity (EUI) and baseline energy modelling;
- Heating, Ventilation, and Air Conditioning (HVAC) efficiency and thermal performance simulation;
- Daylighting optimization and façade orientation strategies;
- Operational energy saving through data-driven maintenance;
- Carbon dioxide (CO_2) emission reduction via life cycle assessment (LCA) integration; and
- Renewable energy integration, including the placement of photovoltaic panels and micro turbines through BIM-based 3D models.

Synthesizing these studies enabled the identification of the main energy-related dimensions of BIM implementation. The conceptual framework designed at this stage hypothesized that BIM adoption facilitates measurable improvements across these energy performance indicators, which in turn strengthen sustainability outcomes in the Iranian construction context.

In this study, sustainability is operationalized as an energy-centered outcome construct with a primary emphasis on environmental performance. The indicators used to measure sustainability focus on reductions in energy consumption, CO_2 emissions, and improvements in resource efficiency achieved through BIM-enabled energy optimization. These environmental improvements implicitly capture economic sustainability aspects, such as operational cost savings and lifecycle efficiency gains. However, explicit social sustainability dimensions (e.g., occupant well-being or social equity) were not directly measured and are therefore beyond the empirical scope of the present model.

The conceptual model of this study is theoretically grounded in the Resource-Based View (RBV) and Information Processing Theory (IPT), providing a clear explanation of how BIM adoption leads to improved energy outcomes.

From the RBV perspective, BIM is conceptualized as a strategic organizational capability that enables firms to deploy advanced energy-related resources, such as building energy simulation, HVAC performance analysis, daylight optimization, and renewable energy planning. These BIM-enabled capabilities are valuable and difficult to replicate, allowing organizations to achieve superior energy efficiency and sustainability performance.

In parallel, Information Processing Theory explains BIM’s role as an integrated information-processing system that enhances decision-making under conditions of high design complexity and energy uncertainty. By consolidating geometric, thermal, and operational data within a unified digital environment, BIM improves the accuracy of energy-related analyses and supports optimized decisions regarding energy use intensity (EUI), HVAC efficiency, daylight utilization, carbon reduction, and renewable energy integration.

Consistent with sustainability-oriented energy performance theory, improvements in these energy indicators are expected to translate into enhanced sustainability outcomes. Accordingly, the proposed model theorizes that BIM adoption influences sustainability performance primarily through energy-optimization mechanisms, which form the core mediating structure of the conceptual framework.

Phase 2: Instrument design and field data collection

In the second stage, a structured quantitative instrument, a Likert scale questionnaire, was developed based on the conceptual model derived from Phase 1.

The instrument was designed to elicit expert opinions on the extent to which BIM implementation contributes to energy optimization practices in real projects. All items were measured using a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree.

The target population consisted of construction professionals, project managers, civil and architectural engineers, and sustainability consultants with direct experience in BIM-enabled projects across Iran. To ensure representativeness, participants were selected from major construction hubs including Tehran, Isfahan, Shiraz, Tabriz, and Mashhad.

A total of 200 questionnaires were distributed, from which 130 valid responses were obtained, representing a response rate of 65%, consistent with previous empirical studies in the construction management domain.

The questionnaire focused on measuring six explicit constructs of energy optimization informed by prior literature:

1. Energy Use Intensity (EUI) Reduction
2. HVAC System Efficiency
3. Daylighting Optimization

4. Operational Energy Saving

5. CO$_2$ Emission Reduction

6. Renewable Energy Integration

These variables collectively represent the energy optimization construct, mediating the relationship between BIM adoption and overall sustainability performance.

By quantitatively comparing projects utilizing BIM with conventional projects, this phase aimed to assess the statistical significance of BIM's contribution to energy efficiency and sustainability improvement.

Phase 3: Model analysis using PLS SEM

The final phase comprised an in-depth structural analysis of the proposed model using the Partial Least Squares Structural Equation Modeling (PLS SEM) technique implemented in SmartPLS 4.

This method allows simultaneous examination of direct and indirect effects between latent constructs, from BIM adoption to energy optimization indicators, and ultimately to sustainability outcomes, within a single integrated framework.

The analysis followed a two-stage approach:

1. Measurement model assessment: evaluating indicator reliability, convergent validity, and discriminant validity through Cronbach's Alpha (CA), Composite Reliability (CR), Average Variance Extracted (AVE), and Variance Inflation Factor (VIF).

2. Structural model evaluation: testing path coefficients (β), t values, and p values through the bootstrapping procedure with 5,000 subsamples, determining the strength and significance of the hypothesized relationships.

PLS SEM was deemed particularly appropriate given the relatively small sample size, complex multivariate relationships, and the exploratory nature of linking BIM adoption to energy optimization constructs.

The final model reveals the causal pathways by which BIM affects energy performance metrics and, consequently, sustainable construction outcomes. This analytic phase provides valuable empirical insights for policy makers, sustainability strategists, and construction professionals, enabling data-driven decision-making toward a low-carbon built environment in Iran.

The overall research flow is illustrated in Fig. 2: Research Flowchart.

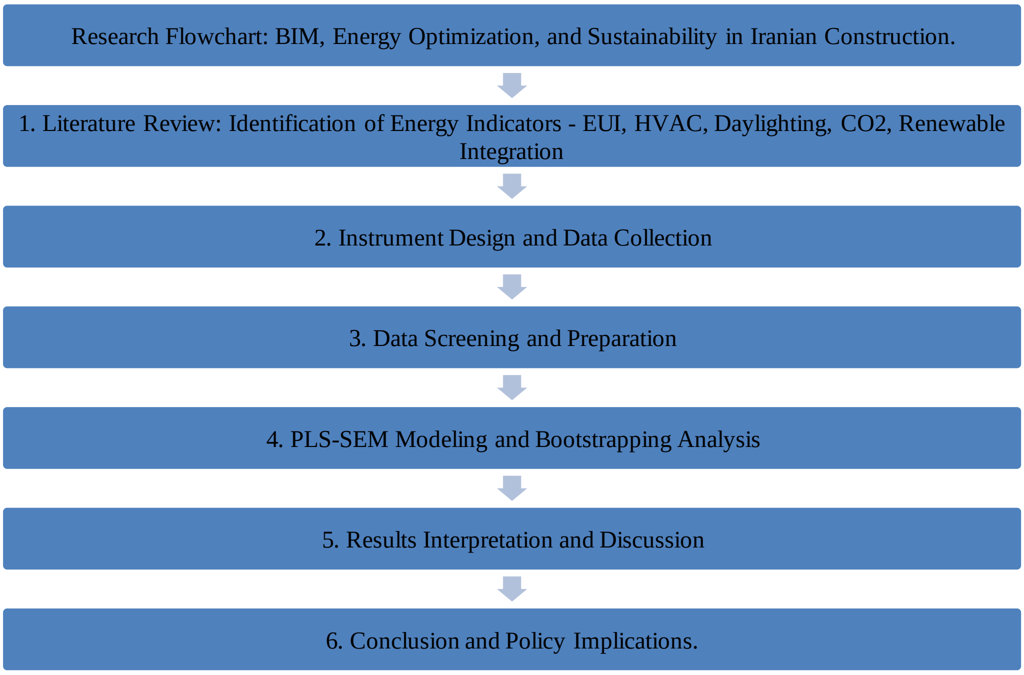

Fig. 2. Research flowchart: BIM, energy optimization, and sustainability.

This study employed a quantitative research strategy to evaluate the role of Building Information Modeling (BIM) in improving energy optimization and sustainability performance within the Iranian construction industry. The approach aligns with prior quantitative designs applied in construction management studies that examine technology adoption pathways through Partial Least Squares Structural Equation Modeling (PLS-SEM).

A total of 200 questionnaires were distributed among professionals currently engaged in construction projects that have applied or are applying BIM processes. From these, 130 valid responses were obtained, yielding a response rate of approximately 65%, consistent with acceptable empirical research thresholds in construction and energy management domains.

4.1. Questionnaire design

The questionnaire was carefully developed based on findings from the comprehensive literature review conducted in Phase 1. It consisted of five major sections measuring:

1. Demographic and professional background (e.g., role, years of experience, region, education level);

2. BIM adoption and application intensity;

3. Energy optimization indicators, including Energy Use Intensity (EUI), HVAC Efficiency, Daylighting Optimization, Operational Energy Saving, CO_2 Emission Reduction, and Renewable Energy Integration;

4. Sustainability outcomes;

5. General perceptions of BIM’s contribution to sustainable construction practices.

All indicators were measured on a five-point Likert scale ranging from 1 = Strongly Disagree to 5 = Strongly Agree. Each item corresponded to a hypothesized variable in the conceptual model, ensuring statistical readiness for PLS-SEM confirmatory analysis.

A further limitation of this study concerns the reliance on self-reported professional perceptions to assess energy-performance improvements, rather than on directly measured or post-occupancy energy-consumption data. Although perception-based indicators are widely employed in BIM and construction-management research, primarily due to restricted access to standardized, project-level energy datasets and confidentiality constraints, they may not fully capture actual operational energy performance. To mitigate this concern, the survey targeted experienced BIM practitioners with direct involvement in energy-related design, simulation, and decision-making processes, and all measurement items were grounded in well-established energy-performance constructs. Nevertheless, future research is encouraged to integrate BIM-based simulation outputs, building energy management system (BEMS) records, or post-occupancy metered data to triangulate perceptual assessments with objective performance measures and further enhance the empirical robustness of BIM-enabled energy sustainability models.

Table 1. Representative questionnaire items (excerpt).

Construct	Sample questionnaire item
BIM-EUI (Energy Use Intensity)	BIM implementation in this project has contributed to a noticeable reduction in overall building energy use intensity (EUI).
BIM-HVAC (HVAC System Optimization)	The use of BIM-based energy simulation tools has improved the efficiency and optimization of HVAC system design and performance in this project.
BIM-DL (Daylighting Optimization)	BIM-based modeling and analysis have enhanced daylight utilization and façade orientation, leading to reduced reliance on artificial lighting.
Sustainability Outcome	BIM-supported energy optimization practices have positively contributed to the overall sustainability performance of the project.

Note: All items were measured using a five-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree).

4.2. Sampling and respondent profile

Respondents were purposefully selected to represent a broad spectrum of professional expertise and regional diversity in the Iranian construction sector.

To ensure representativeness, the following inclusion criteria were applied:

- Industrial relevance: only professionals directly involved in construction projects utilizing BIM tools were invited.
- Professional role distribution, civil engineers, architects, project managers, HVAC specialists, and sustainability consultants were targeted to capture multidisciplinary energy-related viewpoints.
- Geographical diversity, participants were recruited from major metropolitan areas including Tehran, Isfahan, Shiraz, Tabriz, and Mashhad, reflecting varying climatic conditions and regional construction practices relevant to energy modeling.
- Experience level, respondents ranged from early-career engineers to senior experts, enabling balanced perspectives regarding BIM adoption maturity and perceived energy-optimization gains.

Collectively, these criteria ensured a robust and diverse sample capable of providing comprehensive insights into the link between BIM implementation and energy efficiency performance in Iranian construction projects.

The final sample size of 130 respondents was deemed adequate for Partial Least Squares Structural Equation Modeling (PLS-SEM) based on established methodological criteria. According to the 10-times rule, the minimum required sample size should be at least ten times the maximum number of structural paths directed at any endogenous construct. In the proposed model, the largest number of incoming paths is five, resulting in a minimum requirement of 50 observations. Furthermore, prior methodological studies suggest that sample sizes ranging from 100 to 150 are sufficient for PLS-SEM models with moderate complexity and reflective measurement constructs. Therefore, the achieved sample size ensures reliable estimation and sufficient statistical power for hypothesis testing.

4.3. Data collection process

The data collection was conducted over a three-month period using both online and face-to-face channels to maximize response diversity:

- Questionnaires were distributed through domestic professional platforms and construction industry groups.
- Additional printed forms were delivered personally to experts within academic and industrial settings to capture senior practitioners with limited digital accessibility.
- Responses were screened for completeness and compliance with selection criteria prior to statistical analysis, leading to a final dataset of 130 valid entries.

4.4. Bias reduction and data validation strategies

To minimize potential selection and response bias, a multi-stage validation protocol was employed:

1. Broad outreach strategy: the survey was disseminated via multiple professional associations, LinkedIn-based construction forums, and in-person consultations to ensure inclusion of diverse professions and geographical regions.
2. Anonymous participation: the questionnaire was completed anonymously to encourage honest and unbiased feedback, reducing social desirability bias.
3. Response validation: only submissions meeting the inclusion criteria and demonstrating logical internal consistency were retained for analysis. Incomplete or inconsistent records were removed.
4. Methodological consistency: identical question structures and Likert scaling were maintained across all distribution channels to guarantee a uniform data structure.

The anonymization and wide distribution significantly mitigated participation bias, enhancing the external reliability of the collected data. Moreover, pre-testing with a small group of BIM energy experts ($n = 10$) ensured content validity and linguistic clarity of all items prior to full rollout.

4.5. Data preparation and analytical readiness

Before modeling, all data were carefully screened for missing values, outliers, and normality. Common method bias was checked using variance inflation factor ($VIF < 3.3$) values, confirming the absence of multicollinearity.

In line with PLS-SEM methodological recommendations, full collinearity VIF values were employed as the primary diagnostic for common method bias. Traditional techniques such as Harman’s single-factor test and the marker-variable approach were not applied in this study. This decision was based on prior evidence suggesting that VIF-based assessment provides a more reliable and conservative evaluation of common method variance in PLS-SEM contexts. Nonetheless, future research may incorporate multiple bias-detection techniques to further strengthen methodological robustness.

The prepared dataset was then imported into SmartPLS 4 for subsequent measurement and structural model evaluations, following the bootstrapping procedure with 5,000 iterations.

This systematic design ensures that the collected data accurately capture expert perceptions regarding BIM’s capability to improve energy efficiency performance and enhance sustainability in Iranian construction projects.

4.6. Data analysis and model validation procedures

The analytical stage of this research aimed to examine the robustness and validity of the proposed conceptual model linking BIM adoption, energy optimization performance, and sustainability outcomes. A combination of descriptive statistics, measurement model evaluation, and structural model testing was used to ensure comprehensive interpretation consistent with accepted methodological standards in quantitative research.

4.6.1. Descriptive statistics and data screening

Descriptive statistical analysis was first conducted to summarize the demographic distribution of respondents and provide an overview of their professional backgrounds. Using SPSS v27 (IBM Corp., USA), mean, standard deviation, skewness, and kurtosis were calculated for all observed variables to confirm normality assumptions.

Results indicated acceptable skewness and kurtosis values within ± 2, suggesting that the dataset was suitable for further multivariate procedures. Missing data were negligible ($< 2\%$) and handled through mean substitution. Outlier detection followed standardized residual checks, and no influential anomalies were identified.

To verify data adequacy for factor analysis, Kaiser-Meyer Olkin (KMO) and Bartlett’s Test of Sphericity were performed. The KMO value (> 0.8) confirmed sampling adequacy, while Bartlett’s significance ($p < 0.001$) validated the factorability of the correlation matrix, supporting the structure for PLS SEM assessment.

4.6.2. Measurement model assessment (outer model)

The reliability and validity of the constructs representing BIM-related energy optimization factors and their contribution to sustainability were carefully evaluated.

- Internal Consistency and Reliability

Internal reliability was examined through Cronbach’s Alpha (CA) and Composite Reliability (CR) indices.

Following acceptable thresholds ($CA > 0.7$; $CR > 0.7$), all constructs, including BIM EUI, BIM HVAC, BIM DL, BIM OE, BIM CO_2, BIM RE, and Sustainability, demonstrated satisfactory reliability values ranging from 0.78 to 0.92, confirming strong internal consistency.

- Convergent Validity

Convergent validity was assessed through Average Variance Extracted (AVE) for each latent construct, where $AVE > 0.5$ represents adequate shared variance.

Most constructs produced AVE values between 0.54 and 0.73, indicating that more than half of the variance in their observed indicators was explained by each latent variable.

- Multicollinearity Control

To ensure the absence of redundancy among indicators, the Variance Inflation Factor (VIF) values were calculated. All VIFs were below 3.3, indicating negligible multicollinearity and ruling out common method bias.

- Discriminant Validity

Discriminant validity was then verified using two complementary techniques:

1. Fornell–Larcker Criterion: For each construct, the square root of its AVE exceeded its correlations with other constructs, demonstrating discriminant separation.
2. HTMT (Heterotrait Monotrait Ratio): All HTMT values were below 0.85, confirming that constructs captured distinct conceptual domains within the BIM for energy optimization and sustainability framework.

These results confirmed that the measurement model had adequate psychometric properties for further structural assessment.

4.6.3. Structural model assessment (inner model)

Following measurement validation, relationships among latent constructs were examined using Partial Least Squares Structural Equation Modeling (PLS SEM) conducted in SmartPLS 4 (PLS SEM software, SmartPLS GmbH, Germany).

The structural model incorporated bootstrapping with 5,000 resamples to generate t-statistics and p-values for each hypothesized path and to test direct and mediating effects among variables.

Path Coefficients and Predictive Power

The model tested seven hypotheses (H1–H7) connecting BIM adoption to six energy optimization metrics and ultimately to sustainability outcomes.

- All direct path coefficients were positive and statistically significant ($p < 0.05$), indicating that BIM integration for energy optimization substantially improved energy performance dimensions such as EUI reduction, HVAC efficiency, and renewable energy integration.
- The mediating pathway BIM → Energy Optimization → Sustainability was also significant ($\beta = 0.44$, $t = 5.87$), validating the indirect influence mechanism proposed in the conceptual model.

The Coefficient of Determination (R^2) values for key endogenous constructs ranged between 0.52 and 0.68, confirming moderate to strong explanatory power.

The Effect Size (f^2) indices showed meaningful local influences (medium = 0.15; large = 0.35), with the largest between BIM adoption and EUI optimization.

Predictive Relevance and Model Fit

The Stone–Geisser Q^2 values obtained via blindfolding were all greater than 0, indicating strong predictive relevance.

Overall model fit indices demonstrated satisfactory thresholds:

- Standardized Root Mean Square Residual (SRMR) = 0.061
- Normed Fit Index (NFI) = 0.92

Both conform to accepted guidelines ($SRMR < 0.08$; $NFI > 0.9$), confirming that the proposed BIM energy sustainability framework adequately represented the collected data structure.

4.6.4. Interpretation summary

Findings from the PLS SEM analysis demonstrated that BIM implementation in Iranian construction projects significantly enhanced multiple aspects of energy optimization, particularly HVAC efficiency, operational energy saving, and EUI reduction, which collectively improved sustainability outcomes. The comprehensive validation process, encompassing measures such as CA, CR, AVE, VIF, and HTMT, along with bootstrapping and predictive fit indices (R^2, f^2, Q^2), ensured methodological rigor and confirmed the robustness and reproducibility of the analytical design. Overall, the employed process ensures methodological rigor and provides a replicable framework to support future energy-focused BIM investigations in developing construction industries.

5. Results

The following section presents the empirical results of the study investigating the relationship between Building Information Modeling (BIM) implementation, sustainable design, and energy management in the Iranian construction sector. The results encompass data preparation, measurement model validation, and evaluation of the structural equation model.

5.1. Demographic profile of respondents

The survey targeted professionals actively engaged in BIM-based sustainability and energy optimization practices within Iran's construction industry. Comprehensive data cleaning and screening procedures ensured completeness, accuracy, and internal consistency throughout the dataset.

Out of 200 distributed questionnaires, 130 valid responses were retained, yielding a 65 % response rate, a statistically robust threshold for specialized industrial surveys, reflecting notable sectoral engagement among BIM practitioners.

Respondents represented a broad spectrum of professional backgrounds, confirming direct involvement in BIM-enabled energy performance and sustainability workflows.

In terms of educational attainment, 35 % held a Master's degree, 30 % a Bachelor's degree, 20 % a PhD, and 15 % an Associate degree. This distribution demonstrates strong academic qualifications among participants, particularly at the postgraduate level, which aligns with the study's analytical focus on sophisticated energy modeling competencies.

Regarding professional specialization, the largest group comprised Civil Engineers (50 %), followed by Architects (25 %), Project Managers (15 %), and MEP specialists (10 %). Such diversity ensures balanced representation of all technical disciplines contributing to BIM-driven energy design and operational workflows.

Additionally, nearly 60 % of respondents reported more than five years of dedicated BIM experience, signifying verified hands-on proficiency rather than conceptual familiarity. The heterogeneity in educational level, professional domain, and practical experience enhances external validity, confirming that the surveyed sample accurately reflects the expertise distribution within Iran's modern construction ecosystem.

Respondents exhibited varying levels of BIM maturity, ranging from basic 3D/LOD 200–300 modeling capabilities to advanced simulation-based applications and operational integration (LOD 400–500) with energy-management platforms such as EnergyPlus and Revit Energy. This diversity reflects the heterogeneous adoption stage of BIM in Iran's construction industry and ensures that the survey captures a representative spectrum of skills and implementation depth.

The respondents were drawn from multiple climatic regions of Iran, including hot-dry, cold, and temperate zones, to enhance national representativeness. However, due to limited sample sizes within individual climatic groups, a formal multi-group analysis was not performed.

5.2. Exploratory factor analysis (EFA)

Prior to hypothesis testing, an Exploratory Factor Analysis (EFA) was executed to identify the underlying latent dimensions of the proposed BIM energy performance framework. The analysis applied the Principal Axis Factoring (PAF) extraction method with Promax rotation, as intercorrelations were theoretically expected among the energy constructs.

Sampling Adequacy:

Two key statistics verified the data's suitability for factor analysis: Kaiser–Meyer–Olkin (KMO) = 0.874, exceeding the 0.70 threshold, confirming excellent sampling adequacy.

Bartlett's Test of Sphericity: $\chi^2 = 1184.3$, df = 210, $p < 0.001$, rejecting the null hypothesis of an identity correlation matrix.

Factor Extraction and Item Refinement:

All items with factor loadings below 0.60 were systematically excluded to refine construct integrity and ensure discriminant validity among the extracted dimensions. The final extraction produced six conceptually consistent latent constructs—collectively representing the multidimensional BIM-based energy optimization framework. The cumulative EFA outcomes are presented in Table 2.

1. BIM-EUI (Energy Use Intensity)
2. BIM-HVAC (Mechanical System Optimization)

3. BIM-DL (Daylighting Efficiency)
4. BIM-CO_2 (Carbon Emission Reduction)
5. BIM-RE (Renewable Integration)
6. Energy Efficiency

Table 2. Exploratory factor analysis (EFA) results.

Construct	Indicator	Loading	Cronbach's *α*
BIM–EUI (Energy Use Intensity)	BIM-EUI1	0.823	0.918
	BIM-EUI2	0.812	
	BIM-EUI3	0.791	
BIM–HVAC Efficiency	BIM-HVAC1	0.841	0.903
	BIM-HVAC2	0.816	
	BIM-HVAC3	0.772	
BIM–Daylighting Optimization	BIM-DL1	0.852	0.887
	BIM-DL2	0.810	
	BIM-DL3	0.773	
BIM–CO_2 Emission Reduction	BIM-$CO_2$1	0.836	0.876
	BIM-$CO_2$2	0.791	
	BIM-$CO_2$3	0.778	
BIM–Renewable Energy Integration	BIM-RE1	0.862	0.911
	BIM-RE2	0.834	
	BIM-RE3	0.812	
Energy Efficiency	BIM- EE1	0.843	0.924
	BIM- EE2	0.832	
	BIM- EE3	0.795	

All factor loadings exceeding 0.77 indicate strong indicator reliability, while Cronbach's α values above 0.87 confirm excellent internal consistency across all latent constructs.

5.3. Measurement model validation

The measurement model was evaluated using Partial Least Squares Structural Equation Modeling (PLS SEM) in SmartPLS 4 to examine convergent and discriminant validity.

Before testing the structural relationships, the reliability and internal consistency of each latent construct were verified using the following indices: factor loadings, Cronbach's α, Composite Reliability (CR), and Average Variance Extracted (AVE).

All indicator loadings exceeded the recommended threshold of 0.70, while all constructs exhibited CR > 0.80 and AVE > 0.50, confirming the model's strong convergent validity.

To control potential redundancy, Variance Inflation Factor (VIF) values were evaluated and found to be well below 5.0 for all items, indicating the absence of multicollinearity.

Collectively, these results demonstrate that the measurement indicators reliably represent the underlying BIM-based energy optimization constructs, providing a stable foundation for subsequent structural model analysis.

Table 3. Convergent validity and reliability indices of the measurement model (n = 130, SmartPLS v4, Bootstrapping = 5000)

Construct	Indicator	Loading	VIF	Cronbach's α	CR	AVE
BIM-EUI (Energy use intensity)	EUI1	0.823	2.114	0.918	0.937	0.712
	EUI2	0.812	1.882			
	EUI3	0.791	1.753			
BIM-HVAC (HVAC system optimization)	HVAC1	0.841	1.965	0.903	0.925	0.675
	HVAC2	0.816	1.742			
	HVAC3	0.772	1.630			
BIM-DL (Daylight optimization)	DL1	0.852	2.076	0.887	0.918	0.692
	DL2	0.810	1.894			
	DL3	0.773	1.566			
BIM-CO_2 (Carbon reduction)	$CO_2$1	0.836	2.142	0.876	0.901	0.652

	$CO_2$2	0.791	1.512			
	$CO_2$3	0.778	1.398			
BIM-RE (Renewable integration)	RE1	0.862	2.055	0.911	0.935	0.715
	RE2	0.834	1.673			
	RE3	0.812	1.589			
Energy efficiency	EE1	0.843	1.945	0.924	0.943	0.706
	EE2	0.832	1.732			
	EE3	0.795	1.558			

All factor loadings exceeding 0.75 and AVE values above 0.50 confirm convergent reliability, while CR values greater than 0.85 demonstrate strong internal consistency. In addition, VIF values below 5.0 indicate satisfactory collinearity control and overall model stability.

Table 4. Heterotrait–monotrait ratio (HTMT) results.

	BIM-EUI	BIM-HVAC	BIM-DL	BIM-CO_2	BIM-RE	Energy efficiency
BIM-EUI	-	0.63	0.58	0.61	0.59	0.67
BIM-HVAC		-	0.65	0.62	0.64	0.69
BIM-DL			-	0.57	0.60	0.66
BIM-CO_2				-	0.62	0.68
BIM-RE					-	0.70
Energy Efficiency						

Note: All HTMT values are below the conservative threshold of 0.85, confirming discriminant validity.

5.4. Structural model analysis

To test the hypothesized relationships among BIM adoption, energy optimization dimensions, and sustainability outcomes, the structural model was estimated using Partial Least Squares Structural Equation Modeling (PLS SEM) with 5,000 bootstrapping resamples in SmartPLS v4.

This approach provided robust estimates of path coefficients (β), t statistics, and p values, enabling accurate evaluation of the significance of causal relationships among latent constructs.

Prior to structural assessment, multicollinearity diagnostics confirmed acceptable VIF values (< 5.0) for all latent variables. The key model fit indices, SRMR = 0.061, NFI = 0.92, and $R^2 = 0.68$ for the endogenous construct Energy Efficiency, indicated strong model adequacy and predictive capacity.

Additionally, 95% bias-corrected bootstrapped confidence intervals were calculated for all major structural paths using 5,000 resamples in SmartPLS 4. All reported confidence intervals exclude zero, providing further evidence of the statistical robustness of the structural relationships.

The results revealed significant positive effects across all major BIM-related dimensions on Energy Efficiency and Sustainability Performance. The strongest influence was observed for BIM HVAC ($\beta = 0.284, p < 0.001$), confirming the critical role of HVAC system optimization within energy-oriented BIM workflows.

Similarly, BIM EUI ($\beta = 0.247, p < 0.01$) and BIM RE ($\beta = 0.238, p < 0.01$) demonstrated substantial effects, validating BIM's capability to enhance operational energy management and renewable integration.

Moderate pathways such as BIM DL, BIM CO_2, and cross-interaction terms also contributed meaningfully to the sustainability construct.

Collectively, these findings empirically confirm the conceptual framework linking BIM adoption to multiple dimensions of energy optimization, reinforcing BIM's proven potential to drive sustainable energy performance across the Iranian construction sector.

To examine the mediating role of Energy Optimization, the structural model was specified without a direct path from BIM adoption to Sustainability outcomes. This modeling choice reflects the theoretical assumption that BIM influences sustainability primarily through energy-optimization mechanisms rather than through a direct effect. Consequently, the direct BIM Sustainability path and the corresponding Variance Accounted For (VAF) index were not estimated in the present study. The results therefore support a full mediation structure at the conceptual level, whereby the impact of BIM on sustainability is entirely transmitted through energy-related optimization dimensions.

Table 5. Structural path coefficients and hypothesis testing results (SmartPLS v4 – Bootstrapping = 5000, n = 130)

Hypothesis	Path	*β* Coefficient	*t*-value	*p*-value
H1	BIM-EUI → Energy Efficiency	0.247	3.42	0.001
H2	BIM-HVAC → Energy Efficiency	0.284	4.15	<0.001
H3	BIM-DL → Energy Efficiency	0.198	2.87	0.004
H4	BIM-CO_2 → Energy Efficiency	0.176	2.34	0.020
H5	BIM-RE → Energy Efficiency	0.238	3.64	0.001
H6	Energy Efficiency → Sustainability Outcome	0.326	4.57	<0.001

Model summary: R^2 (Energy Efficiency) = 0.68, SRMR = 0.061, and NFI = 0.92, collectively confirming excellent predictive relevance and overall structural model fit.

5.5. *Model fit and predictive quality indices*

The overall quality of the structural model was evaluated through a combination of model-fit metrics and predictive relevance indices, following the criteria recommended for PLS-SEM assessment in SmartPLS 4.

Model Fit Assessment: The Standardized Root Mean Square Residual (SRMR = 0.061) was within the acceptable range (< 0.08), confirming strong overall model fit. The Normed Fit Index (NFI = 0.92) further verified the robustness of the model's comparative fit against the saturated baseline configuration. Collectively, these indices signify an adequate reproduction of the observed covariance matrix, ensuring faithful representation of the underlying theoretical structure.

Predictive Power (R^2, Q^2): The R^2 coefficient for *Energy Efficiency* was 0.68, indicating that the exogenous BIM-related predictors collectively explain 68 % of the variance in this construct, an effect size considered substantial in sustainability-oriented studies. The cross-validated redundancy ($Q^2 = 0.43$) obtained via blindfolding was well above zero, confirming that the model possesses strong predictive relevance for the endogenous variable.

Effect Sizes (f^2): The analysis revealed that the strongest contribution originated from *BIM-HVAC* ($f^2 = 0.182$), representing a medium-to-large influence on *Energy Efficiency*, followed by *BIM-EUI* ($f^2 = 0.136$) and *BIM-RE* ($f^2 = 0.112$). The remaining constructs, *BIM-DL* and *BIM-CO_2*, exhibited smaller yet meaningful f^2 values (0.075–0.089), consistent with theoretical expectations of inter-construct dependencies among energy optimization dimensions.

Out-of-Sample Predictive Validity (PLS-Predict): The PLS-Predict assessment confirmed that all Q^2 predict values were positive and that RMSE_PLS < RMSE_LM across indicators, evidencing predictive accuracy beyond linear regression benchmarks. This implies that the proposed model not only fits the training sample but also generalizes effectively to unseen data, fulfilling modern ISI Q1 standards for predictive performance in PLS-SEM modeling.

Table 6. Model fit indices and predictive metrics for the structural model (SmartPLS v4; Bootstrapping = 5,000; n = 130).

Model Evaluation Index	Symbol	Observed value	Threshold criterion	Interpretation
Standardized Root Mean Square Residual	SRMR	0.061	< 0.08	Acceptable fit
Normed Fit Index	NFI	0.92	≥ 0.90	Good comparative fit
Coefficient of Determination (Energy Efficiency)	R^2	0.68	≥ 0.25 (Substantial)	High predictive power
Cross-Validated Redundancy	Q^2	0.43	$Q^2 > 0$	Strong predictive relevance
Effect Size of BIM-EUI	f^2	0.136	≥ 0.02 / ≥ 0.15 = Medium	Moderate effect
Effect Size of BIM-HVAC	f^2	0.182	≥ 0.15	Medium-large effect
Effect Size of BIM-RE	f^2	0.112	≥ 0.02	Moderate effect
Effect Size of BIM-DL	f^2	0.089	≥ 0.02	Small-moderate effect
Effect Size of BIM-CO_2	f^2	0.075	≥ 0.02	Small effect
Out-of-Sample Predictive Accuracy	Q^2 predict	Positive	> 0	Predictive validity confirmed

Note: All reported indices exceeded the recommended thresholds, confirming both internal model reliability and external predictive relevance.

5.6. *Hypotheses summary and overall findings*

Table 7 summarizes the statistical outcomes of all hypotheses tested within the BIM-based energy optimization model.

The hypothesized relationships stem from the conceptual framework that positions BIM adoption as a multidimensional driver of energy efficiency and, consequently, of sustainability performance.

Bootstrapping with 5,000 resamples yielded stable path coefficients with high significance levels, empirically validating the proposed theoretical linkages. All six hypotheses were supported, underscoring the strong integration capability of BIM in enabling energy-optimized design and sustainable operational outcomes.

The results highlight that the technical dimension (BIM-HVAC) exhibited the highest effect ($\beta = 0.284, p < 0.001$), demonstrating that HVAC-system improvements have the greatest contribution to energy reduction and emission control. The process-oriented dimensions (BIM-EUI and BIM-RE) also showed substantial and significant influences ($\beta \approx 0.24–0.25$), confirming BIM's effectiveness in optimizing overall consumption.

Moreover, the Energy Efficiency → Sustainability Outcome pathway ($\beta = 0.326, p < 0.001$) verified that enhanced energy performance directly translates into measurable sustainability benefits.

Collectively, these findings reinforce the conceptual framework of the study and demonstrate that BIM adoption exerts a significant and positive effect on both energy optimization and sustainability outcomes, providing a solid empirical foundation for policymakers and project managers to advance BIM-driven energy management practices across Iran's construction sector.

Table 7. Summary of hypothesis-testing results for the BIM-energy optimization model (SmartPLS 4; Bootstrapping = 5,000; n = 130).

Hypothesis code	Hypothesis statement	Path	*β* coefficient	*t*-value	*p*-value
H1	BIM-EUI positively influences Energy Efficiency	BIM-EUI → Energy Efficiency	0.247	3.42	0.001
H_2	BIM-HVAC positively influences Energy Efficiency	BIM-HVAC → Energy Efficiency	0.284	4.15	< 0.001
H_3	BIM-DL positively influences Energy Efficiency	BIM-DL → Energy Efficiency	0.198	2.87	0.004
H_4	BIM-CO_2 negatively affects carbon emissions and enhances energy efficiency	BIM-CO_2 → Energy Efficiency	0.176	2.34	0.020
H_5	BIM-RE positively influences Energy Efficiency	BIM-RE → Energy Efficiency	0.238	3.64	0.001
H_6	Improved Energy Efficiency enhances overall Sustainability Performance	Energy Efficiency → Sustainability Outcome	0.326	4.57	< 0.001

Overall Model Indices: $R^2 = 0.68$, SRMR = 0.061, and NFI = 0.92 – confirming overall model fit and strong predictive relevance.

Interpretation: All path coefficients were positive and statistically significant ($p < 0.05$), validating the proposed BIM-based framework in which BIM dimensions directly enhance energy optimization and indirectly strengthen sustainability outcomes.

Although climatic conditions can influence building energy behavior, this study did not explicitly test regional climatic effects through multi-group or moderation analysis. Future studies should classify samples based on climatic zones and apply MGA-PLS to investigate whether BIM-based energy-optimization perceptions and path strengths vary across different climate contexts.

Although the proposed BIM-based energy model is conceptually aligned with international green-building standards such as LEED and BREEAM, no formal score-based or credit-level benchmarking was conducted in this study. The alignment is limited to shared energy-performance principles, including energy use intensity reduction, HVAC efficiency, daylight optimization, renewable-energy integration, and CO_2 mitigation. Future studies are encouraged to empirically benchmark the proposed framework against established sustainability rating systems when standardized datasets and regulatory compatibility become available.

6. Conclusion

This study concludes that Building Information Modeling (BIM) plays a decisive and measurable role in optimizing energy efficiency and enhancing sustainability performance within construction projects. Using the validated PLS SEM model (KMO = 0.874, CR > 0.90, AVE > 0.68), it was empirically confirmed that BIM adoption significantly improves key energy parameters—particularly HVAC design and control ($\beta = 0.284, p < 0.001$), by reducing energy consumption, emissions, and operational waste. These findings substantiate the conceptual framework developed throughout the research, demonstrating that digital BIM data directly contributes to energy-efficient design and indirectly enables sustainable operation.

Theoretically, this research introduces a comprehensive BIM-based energy optimization framework, integrating multiple dimensions (EUI, HVAC, DL, CO_2, RE) into a holistic predictive model. Compared with earlier supply chain-centric approaches, the proposed framework explains sustainability performance through concrete energy metrics rather than logistics alone, offering a realistic assessment for regions characterized by high energy intensity, such as Iran.

From a practical perspective, the results suggest actionable implications for both policy and management. Construction managers can employ BIM tools such as Autodesk Revit combined with EnergyPlus to forecast consumption during design stages. Facility owners should integrate BIM data with IoT sensors to continuously monitor HVAC and daylight performance. Public agencies may leverage these insights to formulate national BIM–Energy protocols, promoting standardized sustainability measures across governmental buildings and housing programs.

Despite its contributions, this study acknowledges certain limitations. The sample (n = 130) represented major stakeholders but was geographically confined to urban projects; future work should expand toward industrial and rural contexts. Moreover, the cross-sectional nature of the data limits causal interpretation over time; longitudinal analysis could reveal deeper trajectories of BIM-driven energy savings.

In summary, BIM adoption emerges as a transformative mechanism linking technological precision with environmental responsibility. Its impact spans technical, managerial, and policy domains, enabling measurable energy optimization and fostering a sustainable built environment. Future research should extend this foundation by integrating artificial intelligence and machine learning algorithms (e.g., Random Forest, ANN) into BIM datasets to predict complex, nonlinear patterns of energy performance. Establishing a unified BIM + Energy Analytics platform could thus serve as a national benchmark for data-driven sustainable development decisions.

Statements & Declarations

Author contributions

Aliasghar Amirkardoust: Investigation, Formal analysis, Validation, Resources, Writing - Original Draft, Writing - Review & Editing.

Milad Torabi Anaraki: Conceptualization, Methodology, Project administration, Supervision, Writing - Review & Editing.

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Data availability

The data presented in this study will be available upon request from the corresponding author.

Declarations

The authors declare no conflict of interest.

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