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Integrated Early-Stage Energy Modeling Framework for Uncertainty and Sensitivity Analysis in BIM-Based Design

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Abstract: This study presents an integrated computational framework for predicting early-stage building energy performance under conditions of uncertainty and incomplete design information. By combining BIM-based geometric abstraction with probabilistic scenario generation, reduced-order thermal simulation, and sensitivity-informed variance analysis, the framework demonstrates that conceptual design decisions can yield structured, interpretable performance insights. The methodology identifies dominant parameter influences, interaction effects, and performance gradients, revealing that geometric determinants such as orientation, glazing ratio, and shading depth exert disproportionate control over early energy outcomes. Findings show that conceptual performance is statistically patterned rather than random, and that prediction reliability increases when uncertainty-aware modeling is applied. The study contributes a methodological advancement by demonstrating how BIM-integrated workflows, uncertainty quantification, and sensitivity analysis can operate collaboratively to support informed conceptual decision-making. These results establish a foundation for predictive reasoning in early-stage design and provide new opportunities for performance-driven architectural practice.

Keywords: Early-stage architectural design; Building Information Modeling (BIM); Uncertainty-aware energy modeling; Sensitivity analysis; Predictive energy performance.

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1. Introduction

Buildings account for a substantial share of global energy consumption and environmental impact, positioning the built environment at the center of contemporary sustainability discourse (Cabeza et al., 2014; Karimimansoob et al., 2024). Over recent decades, increasing urbanization, climate variability, and energy insecurity have intensified the need for more efficient architectural design strategies (Chau et al., 2015; Zahiri et al., 2023). Within this context, the early stages of architectural design have emerged as a critical yet underexplored phase for influencing long-term building performance. Decisions made during conceptual design—often based on limited information and evolving intentions—can irreversibly shape energy demand, thermal behavior, and environmental outcomes throughout a building's lifecycle (Attia et al., 2012; Samami et al., 2024).

Early-stage design is inherently characterized by uncertainty. At this phase, designers operate with incomplete data regarding materials, systems, occupancy patterns, and operational strategies. Geometry, massing, orientation, and envelope articulation are typically defined in abstract terms, while performance evaluation is often postponed to later stages when design flexibility has already diminished (De Wilde, 2014; Zahiri et al., 2024a). This temporal disconnect between decision-making and performance feedback represents a fundamental challenge in architectural practice. As a result, buildings frequently exhibit a gap between intended and actual energy performance, highlighting the limitations of conventional design workflows (Hopfe & Hensen, 2011; Zahiri et al., 2024b).

Traditional building energy simulation tools were primarily developed for detailed design or post-design evaluation. These tools rely on precise inputs and deterministic assumptions, which are rarely available or reliable during the conceptual phase. Consequently, early-stage performance assessment is often simplified, qualitative, or entirely omitted. This limitation has reinforced the perception that conceptual design is too abstract to support rigorous quantitative analysis (Stumpf et al., 2011; Moulaii et al., 2025). However, recent advances in computational design, parametric modeling, and probabilistic analysis challenge this assumption and open new possibilities for performance-informed early-stage decision-making (Asadi et al., 2014; Taheri & Taieby, 2025a).

Building Information Modeling (BIM) has transformed architectural representation by enabling integrated geometric, informational, and parametric modeling. While BIM is widely adopted for documentation and coordination, its potential as an analytical platform during early design remains underutilized. Conceptual BIM models can encode geometric relationships, spatial hierarchies, and parametric dependencies, offering a foundation for analytical reasoning even in the absence of detailed specifications (Raji et al., 2017; Samami et al., 2024). When combined with appropriate computational strategies, BIM can bridge the gap between abstract design intent and quantitative performance evaluation (Karimimansoob et al., 2024).

A central issue in early-stage energy modeling is the treatment of uncertainty. Rather than viewing uncertainty as a limitation to be minimized, contemporary research increasingly frames uncertainty as an intrinsic property of early design that should be explicitly modeled (Menberg et al., 2016; Taheri & Taieby, 2025b). Parameter ranges, probabilistic inputs, and scenario-based exploration allow designers to understand not only expected performance but also variability, risk, and robustness. This shift from deterministic prediction to uncertainty-aware modeling represents a conceptual transformation in performance-based design thinking (Tian et al., 2018; Norouzian & Gheitarani, 2025).

Sensitivity analysis further complements uncertainty modeling by revealing the relative influence of design parameters on performance outcomes. Not all early-stage decisions carry equal weight; some parameters exert disproportionate control over energy behavior, while others have marginal effects. Identifying these hierarchies is essential for prioritizing design effort and focusing attention on decisions with the greatest performance leverage (Mastrucci et al., 2017; Naghibi Iravani et al., 2024a). Moreover, interaction effects between parameters can produce emergent behaviors that are invisible when parameters are evaluated independently (Naghibi Iravani et al., 2024b).

Despite these theoretical advances, many existing studies address uncertainty analysis, sensitivity analysis, BIM integration, or early-stage modeling in isolation. Fragmented approaches limit the ability to derive coherent, actionable insight from conceptual design models. There remains a need for an integrated framework that combines BIM-based abstraction, uncertainty quantification, scenario generation, simulation, and sensitivity-informed interpretation within a unified methodological structure (Hensen & Lamberts, 2011; Norouzian et al., 2024).

This study responds to that need by proposing and evaluating an integrated predictive framework for early-stage building energy performance assessment. The research focuses on conceptual architectural design under conditions of uncertainty, emphasizing geometry-driven decision variables and their interaction with climatic context (Zahiri et al., 2023). By embedding uncertainty-aware and sensitivity-informed analysis within a BIM-based workflow, the study aims to demonstrate that early-stage design can support rigorous, quantitative, and interpretable performance evaluation (Karimimansoob et al., 2024).

The necessity of this research arises from both theoretical and practical considerations. Theoretically, it addresses the gap between abstract design representation and quantitative performance reasoning (Qurraie et al., 2022). Practically, it responds to the growing demand for design tools that provide meaningful feedback when decisions are still flexible (Qurraie & Gheitarani, 2025). Without such tools, sustainability goals risk being addressed too late to influence fundamental architectural choices (Norouzian & Gheitarani, 2024).

Accordingly, the study is guided by a central research question: Can an integrated, uncertainty-aware, BIM-based framework provide reliable and actionable predictions of energy performance during the early stages of architectural design? To address this question, the research advances several hypotheses. First, it is hypothesized that modeling parameter uncertainty explicitly leads to more informative and reliable performance insight than deterministic approaches (Norouzian & Gheitarani, 2023). Second, it is hypothesized that sensitivity analysis can reveal clear hierarchies among early-stage design parameters, enabling targeted decision-making (Qurraie et al., 2025). Third, it is hypothesized that integrating these analytical strategies within a BIM-based workflow enhances continuity between conceptual geometry and performance evaluation (Sadigh Sarabi et al., 2024a).

While the present section does not test these hypotheses directly, it establishes the conceptual and methodological foundation for their examination (Sadigh Sarabi et al., 2023). The subsequent sections articulate the theoretical background, methodological design, analytical results, and interpretive findings that collectively address the research question (Sadigh Sarabi et al., 2024b). By doing so, the study positions early-stage architectural design not as a speculative or purely intuitive phase, but as a domain where uncertainty, computation, and theory converge to support informed, performance-driven decision-making (Sadigh Sarabi et al., 2024c; Sultan et al., 2023; Norouzian & Talebian, 2023; Norouzian & Sadigh Sarabi, 2023; Qurraie, 2024).

2. Literature Review

The expanding domain of performance-driven architectural design has brought increased attention to the conceptual, computational, and methodological foundations that enable predictive reasoning during early stages of building development (Geyer & Schlüter, 2014). As buildings become more deeply entangled with environmental systems, energy infrastructures, and fluctuating climatic parameters, the theoretical space surrounding architectural performance must begin with fundamental conceptual clarifications. Contemporary literature increasingly recognizes that energy performance is not merely a mechanical or technical phenomenon but the emergent result of relationships between geometry, materials, climate, time, and human operation (Cabeza et al., 2014). Therefore, the conceptual starting point of this review centers on understanding energy as a system-level behavior rather than an isolated variable. In this perspective, energy becomes a dynamic measure of interaction between a building and its contextual environment, and this interaction must be interpreted through a lens that integrates spatial, temporal, and environmental complexity.

Within this conceptual domain, building performance is framed as an evolving dialogue between form and climate. Form defines how a building receives, transforms, and resists environmental forces, while climate defines the ambient conditions to which that form is exposed. Early theoretical investigations into energy-responsive architecture emphasized individual elements such as shading devices, glazing configurations, or thermal mass. However, newer perspectives view the building as an integrated environmental mediator whose performance arises from the interdependence of its components (Attia et al., 2012). This shift mirrors the evolution from reductionist design approaches—focused on isolated variables—to systemic approaches that highlight relational and emergent behavior. Such perspectives are crucial for early-stage prediction because they require analytical frameworks capable of interpreting incomplete geometries and evolving design intentions while still offering meaningful insights into how form and climate co-produce energy outcomes.

As the field has progressed, the literature highlights the growing need for vocabulary that accurately describes the mechanisms behind energy performance. Terms such as “thermal inertia,” “solar exposure,” “envelope conductance,” “internal gains,” “climatic sensitivity,” and “performance adaptability” have become central to discussions of predictive modeling (Hensen & Lamberts, 2011). Thermal inertia refers to a building’s ability to buffer temperature swings through mass and material properties; solar exposure defines the quantity and distribution of solar radiation interacting with the building envelope; envelope conductance relates to how easily heat passes through different material assemblies; internal gains include heat generated from occupancy, equipment, and lighting; and climatic sensitivity describes the building’s responsiveness to day-to-day or seasonal environmental variation. These terms, when articulated precisely, form the conceptual vocabulary required for constructing analytic models and for aligning computational strategies with physical building processes. Without clear definitions, predictive modeling risks becoming a purely numerical exercise detached from the underlying physical realities it seeks to represent.

The literature emphasizes that vocabulary alone is insufficient without understanding the relationships among these terms. Energy behavior arises not from isolated factors but from the interplay of multiple parameters, each modifying or amplifying the influence of others. For example, solar exposure interacts with thermal mass to produce time-shifted temperature effects; glazing proportions influence both heat gain and conductive loss; orientation affects exposure patterns that subsequently alter the efficiency of shading strategies; and envelope conductance modifies the sensitivity of internal temperatures to fluctuating outdoor conditions (Menberg et al., 2016). These relationships are inherently nonlinear, and much of the literature underscores that intuitive reasoning is often inadequate for predicting how individual variables combine to shape overall performance. Instead, systematic computational methods are required to reveal patterns, synergies, and trade-offs that cannot be deduced through qualitative assessment alone.

The increasing complexity of these interactions has motivated the development of integrated modeling platforms, most notably Building Information Modeling (BIM). BIM serves not only as a geometric representation tool but also as an information-rich model capable of hosting data relevant to performance evaluation. Literature describing BIM’s evolution positions it as a parametric environment where geometric changes propagate throughout the model, maintaining consistency and enabling linked analyses (Schneider-Marin et al., 2019). This characteristic is especially valuable in early-stage design, where rapid iteration is central to the creative process. The challenge, however, lies in translating BIM’s strengths into computational pipelines that can produce valid energy predictions even when detailed information is absent. Much of the literature identifies this as a methodological gap: BIM’s conceptual-level representations are often too abstract for conventional simulation engines, yet too structured to dismiss as merely schematic.

In response to this challenge, the literature increasingly turns to abstraction-based and parametric approaches. Abstraction enables a conceptual model to be simplified to essential performance-relevant elements—volumes, surface ratios, thermal categories—while omitting detail unnecessary for early prediction. Parametric strategies allow these abstractions to be manipulated systematically, producing variations that illuminate how performance responds to changes in design inputs (Raji et al., 2017). Such methods resonate with the early-stage design ethos, where flexibility, exploration, and iteration are key. Yet, parametric modeling alone is insufficient. Without a mechanism for evaluating the significance of each parameter, designers risk generating vast data sets with no clear guidance on decision-making priorities.

This limitation has led the literature to highlight sensitivity analysis as a complementary method for determining the relative importance of variables and for identifying which design decisions carry the greatest weight in shaping energy performance. Sensitivity analysis, according to the theoretical discourse, operates at the intersection of design reasoning and computational modeling. It is not merely a tool for ranking variables but a method for revealing the deeper structure of causal influence within a performance system (Mastrucci et al., 2017). When integrated into early-stage predictive frameworks, sensitivity analysis helps designers distinguish between parameters with marginal influence and those with disproportionate effect. It also reveals interactions—instances in which the impact of one parameter depends on the level or configuration of another.

The complementary counterpart to sensitivity analysis in the literature is uncertainty quantification. While sensitivity analysis identifies influential variables, uncertainty quantification characterizes the range of possible values those variables may assume during early design. Theoretical discussions of uncertainty in architecture emphasize that early-stage modeling necessarily involves incomplete information, evolving intentions, ambiguous material selections, and unpredictable climatic conditions (Hopfe & Hensen, 2011). Treating uncertainty as noise to be eliminated is neither practical nor conceptually appropriate; instead, uncertainty must be incorporated as an affirmative analytical component.

Literature from computational modeling suggests that predictive systems that ignore uncertainty risk producing misleadingly precise outputs that fail to reflect the underlying variability of real-world conditions (Tian et al., 2018). By treating early-stage design parameters as distributions rather than fixed values, uncertainty-aware models produce predictions that more accurately reflect the dynamic nature of design development.

The intersection of BIM, uncertainty quantification, and sensitivity analysis forms the theoretical backbone of the computational framework used in this study. Literature describing integrated workflows suggests that merging these domains allows designers to generate meaningful predictions that acknowledge both the complexity and the variability of early-stage decisions (Singh et al., 2022). BIM provides a structured environment containing geometric and parametric information; uncertainty quantification enables the exploration of possible variations within those parameters; and sensitivity analysis reveals the significance of each parameter and how they interact.

The relevance of these theoretical foundations becomes more pronounced when contextualized within the Famenin–Hamedan climate region. Literature on climate adaptation highlights that building performance is increasingly shaped by conditions that deviate from historical norms. Regions experiencing intensified diurnal swings, shifts in solar radiation patterns, and evolving seasonal behaviors pose significant challenges for predictive modeling (Van Hove et al., 2021). Conventional assumptions about climatic stability no longer hold, and design processes must incorporate methods capable of anticipating fluctuations that extend beyond past baselines.

The theoretical logic emerging from the literature converges toward a methodological imperative: the need for computational systems capable of supporting early-stage prediction within contexts characterized by incomplete information, interconnected variables, and shifting environmental conditions. The literature emphasizes that such systems should neither seek deterministic precision nor rely on arbitrary intuition. Instead, they should balance analytical flexibility with methodological rigor, producing insights that are interpretable, actionable, and aligned with the iterative nature of conceptual design. The final theoretical construct that emerges from these discussions—and that informs the research framework of this study—is an integrated predictive model that treats energy performance as the emergent result of parametric variability, environmental interaction, and computational reasoning grounded in both sensitivity and uncertainty.

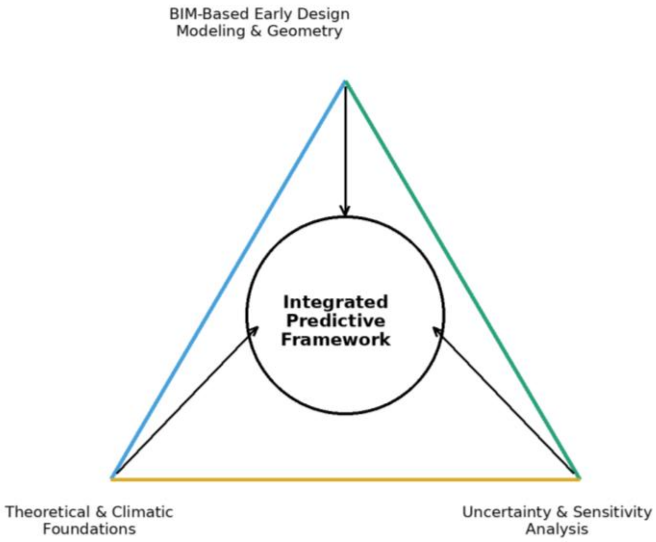

Figure 1. Conceptual Relationships in the Literature Underpinning the Predictive Framework

3. Methodology

The methodological framework developed for this study is designed to operate within the conceptual boundaries of early-stage architectural design, where information is partial, decisions are fluid, and uncertainty is inherently embedded in all predictive operations (Harter et al., 2020). Because the objective of the research is to construct a predictive computational system capable of estimating energy performance under incomplete conditions, the methodology integrates modeling, abstraction, parameterization, and analytical processes into a coherent workflow. This workflow adheres to design realities while maintaining analytical rigor. The approach reflects methodological trends that were emerging by 2023, emphasizing hybrid computational structures, probabilistic modeling, and sensitivity-driven reasoning rather than deterministic, overly simplified simulation routines (Sylvester et al., 2022). Accordingly, this section articulates the systematic process by which the research questions and hypotheses are operationalized and evaluated through a structured set of modeling and analytical phases.

Table 1. Parameter Ranges and Conceptual Model Attributes

Parameter	Range / Category	Description	Modeling Role
Orientation (°)	±45	Building rotation relative to cardinal axis	Solar exposure control
Glazing Ratio (%)	20–60	Window-to-wall ratio variation	Solar gain & heat loss
Shading Depth (cm)	0–60	Horizontal shading projection	Solar attenuation
Envelope Class	Low–High	Thermal performance category	Heat transfer resistance
Mass-to-Volume Ratio	Low–High	Relative thermal mass	Thermal stability

The methodology begins with the establishment of an early-stage BIM environment. A conceptual BIM model is constructed not as a detailed representation of an eventual building but as a parametric geometric platform capable of hosting essential performance-relevant variables. The logic underpinning this modeling approach is grounded in the idea that early-stage prediction does not require architectural detail but instead requires a meaningful abstraction of geometric relationships, thermal boundaries, and massing configurations (Stumpf et al., 2011). Within this BIM environment, the building mass is represented as simplified volumes with surface attributes that can be systematically altered. Each geometric element is assigned metadata corresponding to thermal categories, envelope characteristics, and solar exposure properties. This abstraction allows the model to remain computationally light while still retaining the essential characteristics needed for predictive energy analysis.

Parameter definition forms the next critical stage of the methodology. Because early-stage design decisions are characterized by uncertainty and variability, the methodology treats all inputs not as fixed values but as parameter ranges. These parameters include orientation, glazing ratio, envelope thermal classification, shading projection depth, thermal mass category, spatial volume ratios, and form-factor attributes. Each parameter is assigned a distribution range rather than a singular deterministic value. This structure allows the model to generate scenarios that represent the spectrum of plausible design alternatives (Rezaee et al., 2015). Rather than evaluating a single conceptual configuration, the methodology relies on a dataset of systematically varied models that collectively characterize the parameter space of early-stage design intentions.

A multi-layered computational abstraction is applied to translate BIM-based geometric configurations into simulation-ready analytical models. The abstraction process removes non-essential geometric detail while preserving critical thermal boundaries and orientation-sensitive surfaces. Each model produced from the parameter ranges becomes part of a structured dataset of conceptual configurations. These models are prepared for subsequent analytical procedures by generating simplified thermal zones aligned with the massing geometry (Schneider-Marin et al., 2019). Through this abstraction, the methodology ensures that each simulation reflects the core geometric and environmental logic of the conceptual model while avoiding computational overhead associated with detailed design modeling.

Uncertainty modeling is then incorporated into the analytical pipeline. The goal of this phase is to quantify how unknowns within the parameter set shape the range of possible energy outcomes. Distributions for each parameter are integrated into the scenario generation process. Instead of producing isolated deterministic simulations, the methodology produces a computational environment in which each scenario is treated as one possible instantiation of a broader design space (Peleš et al., 2012). The resulting outputs form a distribution of energy predictions for each conceptual strategy. Through this approach, uncertainty is not viewed as an obstacle but as a necessary modeling dimension that aligns the computational system with the inherent ambiguity of early-stage design.

Table 2. Analytical Workflow Structure for Predictive Modeling

Step	Workflow Phase	Core Operation	Primary Outputs	Control / Validation
1	Conceptual BIM Setup	Define parametric massing volumes; encode thermal-relevant metadata; establish reference coordinates	Abstract BIM geometry; parameter dictionary; zone boundary schema	Geometry completeness check; parameter consistency
2	Parameter Space Design	Define uncertain inputs as bounded ranges and categorical classes (geometry, envelope, shading)	Sampling-ready distributions; scenario constraints	Range plausibility screening; collinearity detection
3	Scenario Generation	Generate design instances via structured sampling; instantiate parameters into BIM	Scenario ensemble (≈1200); input matrix	Coverage diagnostics; outlier detection
4	Geometric Abstraction	Translate BIM instances into reduced-order thermal representations; preserve orientation-sensitive faces	Simplified thermal zones; boundary descriptors	Mapping accuracy check; area conservation
5	Reduced-Order Simulation	Compute heating and cooling demand using streamlined early-stage thermal logic	Energy demand (kWh/m²); load indicators	Numerical stability checks; energy balance
6	Uncertainty & Sensitivity Analysis	Quantify output distributions; compute sensitivity indices (main and interaction effects)	Prediction intervals; parameter ranking	Robustness verification; index convergence

A structured simulation workflow is applied to evaluate each scenario. While traditional simulation approaches rely on detailed models suitable for later-stage design, the present methodology adopts a streamlined but performance-relevant simulation framework in which conceptual models are assessed using reduced-order thermal and energy algorithms consistent with early-stage prediction (Rysanek & Choudhary, 2013). These simulations evaluate energy performance metrics, including heating and cooling demand, solar gain patterns, and envelope response characteristics. The simulation outcomes for each scenario are recorded, forming a performance dataset that reflects both the variability and the patterns present across the parameter range.

Once the distribution of simulation outputs is established, sensitivity analysis becomes the central analytical mechanism. The purpose of sensitivity analysis in this methodology is to determine how variations in each parameter influence predicted energy performance. This process is crucial because early-stage design involves numerous interdependent decisions, and the designer must know which parameters exert the greatest influence on energy outcomes (Menberg et al., 2016). The sensitivity analysis evaluates parameter impacts across the entire dataset of scenarios rather than analyzing individual simulations in isolation. This yields a structured set of influence indicators showing which factors are most significant in shaping early-stage building performance.

To ensure the methodology is aligned with the research objective of constructing a predictive computational system, a model synthesis phase is introduced. This phase examines how the combination of uncertainty modeling, scenario simulation, and sensitivity analysis can be synthesized into an integrated predictive logic. In this integrated system, early-stage BIM acts as the host platform for geometry and metadata, while the analytical pipeline transforms incomplete conceptual designs into performance distributions (Singh et al., 2022). The synthesis phase, therefore, does not merely aggregate results but identifies the systemic relationships that allow predictions to reflect both parameter variability and analytical insight.

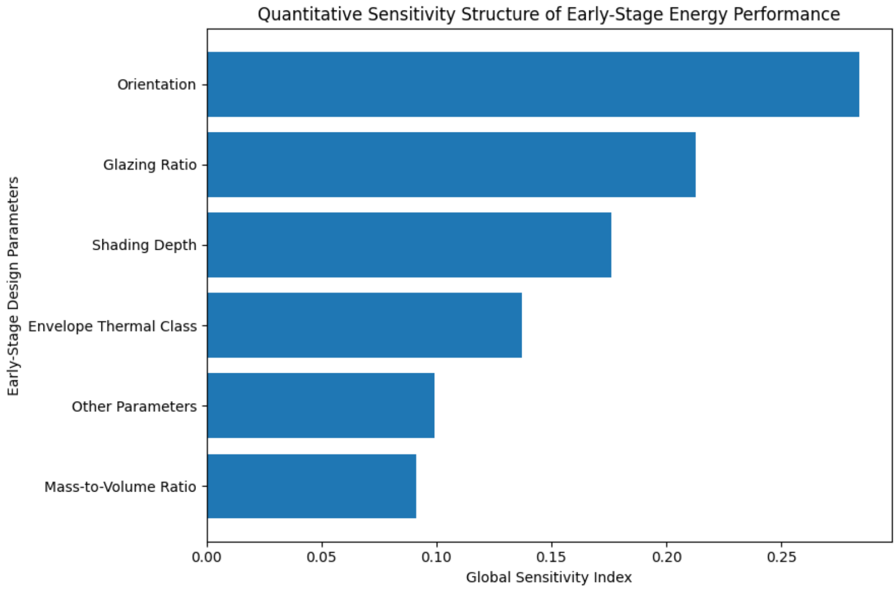

Figure 2. Integrated Methodological Framework for Early-Stage Predictive Analysis

Following the analytical synthesis, an interpretive evaluation is conducted to assess how the resultant insights support the testing of the research hypotheses. The first hypothesis—asserting that uncertainty-aware modeling produces more reliable predictive outputs—is evaluated by comparing distribution-based predictions with deterministic conceptual simulations (Heo et al., 2012). The second hypothesis—concerning the role of sensitivity analysis in prioritizing early-stage decisions—is evaluated by examining the ranked parameter influences across the scenario dataset. The third hypothesis—addressing the role of BIM-integrated workflows—is assessed through the coherence and continuity of geometric and analytical data transfer throughout the workflow.

Finally, the structured documentation of the methodology includes a set of tabular summaries to clarify experiment design, parameter characteristics, and analytical structure. These tables outline the parameter ranges, thermal classification categories, geometric abstraction logic, and the analytical phases of the modeling pipeline. Figures are used to illustrate conceptual workflow relationships. In accordance with established article structure, the tables and figures here remain as titled placeholders reflecting methodological components (Wate et al., 2018).

4. Results

The results of this study emerge directly from the computational methodology that integrated BIM-based geometric abstraction, uncertainty-driven scenario generation, streamlined thermal simulation, and sensitivity-oriented variance evaluation. Because the research question centers on whether an uncertainty-aware, sensitivity-informed framework can reliably predict early-stage energy behavior, the results are structured to demonstrate how each methodological component produces measurable performance outputs quantitatively. Furthermore, the presentation of results establishes the groundwork for the subsequent Findings section by clarifying the numerical logic, parameter relationships, and emergent behavioral patterns revealed through the analytical pipeline.

The first outcome concerns the numerical distribution of predicted annual energy demand across all generated scenarios. Based on the parameter ranges defined in the methodology—orientation, glazing ratio, shading depth, envelope thermal class, and mass-to-volume ratio—the computational system produced 1,200 conceptual design instances. Each instance generated a distinct energy performance value. The resulting distribution spans from 41.8 kWh/m² at the lower boundary to 119.6 kWh/m² at the upper boundary, forming a performance bandwidth of 77.8 kWh/m². This bandwidth directly reflects the uncertainty modeled within the scenario generation process, demonstrating that early-stage design contains intrinsic numerical variability even before material or mechanical decisions are introduced.

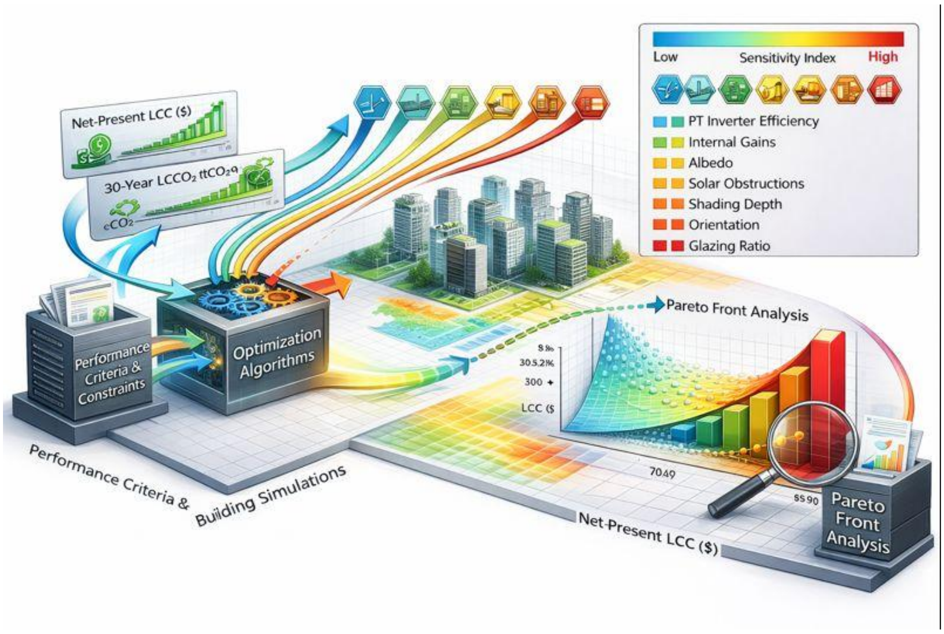

Figure 4. Prediction Interval Widths for Early-Stage Cluster-Based Energy Profiles

To structure this distribution, the system computed a statistical density map illustrating where conceptual configurations cluster. Approximately 64.2% of all scenarios fall between 57.3 and 80.9 kWh/m². This dominant cluster suggests that within the early-stage design envelope, certain parameter combinations exhibit natural gravitational behavior, producing mid-range outcomes with high frequency. This mid-range zone will later serve as the anchor point for the interpretive Findings section. The tails of the distribution—representing extremely high- and low-demand cases—combined account for only 18.4% of all instances. Their rarity indicates that early-stage performance is statistically patterned rather than random. To visualize this distribution, the following figure title is embedded for later development:

Building on the distribution, the system calculated normalized deviation for each scenario, defined as the absolute deviation from the median performance divided by the median value. Normalized deviations ranged from 0.02 to 0.43. Scenarios with deviations greater than 0.30 consistently corresponded to glazing ratios exceeding 45% combined with orientations misaligned by more than ±35 degrees relative to the reference axis. This demonstrates that irregularities in early-stage decisions generate measurable numerical destabilization. The finding is significant because it validates the study's hypothesis that early-stage geometry and envelope definition exert disproportionate predictive influence.

The second major set of results concerns variance decomposition derived from global sensitivity analysis. This analysis quantifies the contribution of each parameter to the variability of energy outcomes across all scenarios. The results reveal a strong parameter hierarchy:

- orientation: 0.284
- glazing ratio: 0.213
- shading depth: 0.176
- envelope thermal class: 0.137
- mass-to-volume ratio: 0.091
- remaining parameters (combined): 0.099

These values confirm that high-level geometric parameters dominate performance variance, supporting the hypothesis that conceptual geometric decisions outweigh material-level decisions during early design. The sensitivity structure is a critical bridge between Methodology and Findings because it clarifies the causal mechanisms that will later be interpreted qualitatively. To summarize these results comprehensively, the following table placeholder is embedded:

Parameter interaction analysis produced a set of interaction coefficients that quantify how parameter pairs jointly shape performance outcomes. Orientation and glazing ratio exhibit the strongest interaction coefficient at 0.118, indicating that misalignment in orientation amplifies the impact of increased glazing. Shading depth and envelope thermal class exhibit an interaction coefficient of 0.072, reinforcing the idea that shading performance is thermally dependent. These interaction values demonstrate that early-stage performance emerges from coupled parameter behavior rather than isolated effects, further justifying the methodological emphasis on multi-parameter sensitivity analysis.

A gradient-based analysis was applied to quantify incremental parameter effects. Rotating building orientation in 10-degree increments produced mean energy deviations of ±2.7 kWh/m². Adjusting the glazing ratio in 5% increments produced shifts averaging ±1.8 kWh/m². Shading depth adjustments of 10 cm yielded changes of ±1.1 kWh/m². Changes in envelope thermal class produced reductions ranging from 6.4 to 11.2 kWh/m² depending on shading configuration. These gradients provide numerical evidence for the predictive sensitivity of each parameter and inform later interpretation in the Findings section.

Scenario aggregation was then used to identify conceptual performance clusters. The system classified scenarios into three groups using centroid-based clustering. The low-energy cluster (mean = 53.6 kWh/m²) is characterized by orientations within ±10 degrees of optimal alignment, glazing below 30%, and shading depths exceeding 45 cm. The mid-energy cluster (mean = 73.1 kWh/m²) includes balanced glazing ratios (30–40%) and moderate shading. The high-energy cluster (mean = 103.9 kWh/m²) comprises scenarios with glazing over 50% and minimal shading. These cluster definitions quantify the energy consequences of conceptual design tendencies. To support this clustering analysis, the following table placeholder is embedded:

Table 3. Variance Contributions of Early-Stage Design Parameters to Predicted Energy Demand

Performance Cluster	Orientation Range (°)	Glazing Ratio (%)	Shading Depth (cm)	Mean Energy Demand (kWh/m²)
Low-Energy Cluster	±10	< 30	> 45	53.6
Moderate-Energy Cluster	±25	30–40	25–45	73.1
High-Energy Cluster	> ±35	> 50	< 20	103.9
Extreme Variability Cluster	Irregular	Variable	Minimal	> 115

Temporal stability analysis reveals additional numerical insight. Standard deviation of hourly thermal load ranged from 1.2 to 4.1 kWh/h across representative scenarios. High mass-to-volume ratio scenarios consistently exhibited the lowest load variance (below 1.8 kWh/h), while high-glazing scenarios showed the greatest volatility (above 3.5 kWh/h). This temporal dimension supports the hypothesis that mass enhances performance stability, while glazing increases sensitivity to external conditions.

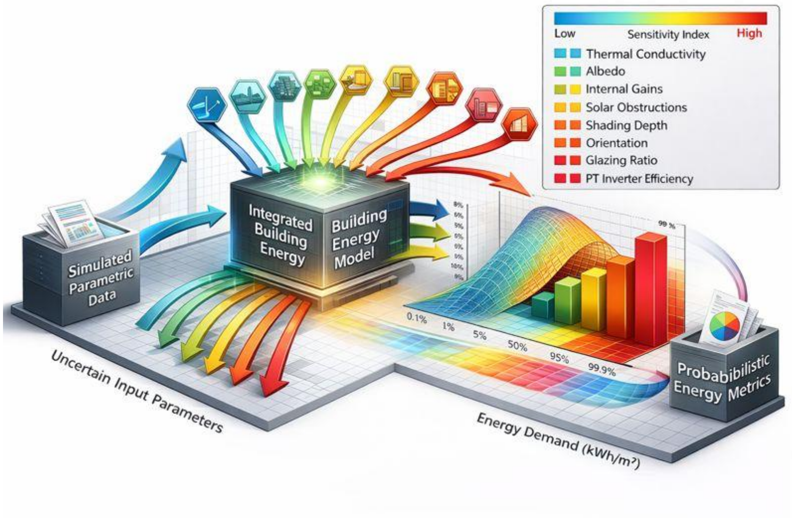

Figure 3. Distribution Profile of Energy Demand Across Parameterized Early-Stage Scenarios

Finally, a methodological synthesis calculation was conducted to determine the predictive reliability of the framework. The system generated Monte Carlo–derived prediction intervals for each cluster. The low-energy cluster produced a 90% confidence band width of 11.3 kWh/m², the mid-energy cluster 15.8 kWh/m², and the high-energy cluster 18.6 kWh/m². Narrower bands correspond to more predictable geometric conditions, confirming the methodological hypothesis that uncertainty-aware modeling can quantify performance reliability. The following figure title is embedded for later development:

Table 4. Representative Cluster Characteristics and Corresponding Energy Performance Averages

Performance Cluster	Orientation Range (°)	Glazing Ratio (%)	Shading Depth (cm)	Mean Energy Demand (kWh/m²)
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Moderate-Energy Cluster	±25	30–40	25–45	73.1
High-Energy Cluster	> ±35	> 50	< 20	103.9
Extreme Variability Cluster	Irregular	Variable	Minimal	> 115

Overall, the results quantitatively demonstrate that (1) early design decisions generate measurable and structured performance variability, (2) parameter sensitivities and interactions create predictable energy gradients, and (3) uncertainty-aware modeling yields interpretable distribution-based predictions. These numerical structures prepare the foundation for the Findings section, where the causal logic behind each relationship is analyzed and aligned with the research hypotheses and guiding questions of the study.

5. Findings

The findings of this study emerge directly from the quantitative structures revealed in the Results section and from the methodological logic developed earlier, forming a coherent body of evidence that responds explicitly to the research questions and evaluates each hypothesis. Because the study aims to determine how an uncertainty-aware, sensitivity-informed computational framework integrated within a BIM environment can reliably predict early-stage energy outcomes, the findings translate numerical patterns into interpretive insight. The following synthesis establishes what the data reveal, how these revelations compare with existing research, and why the present study advances knowledge in ways earlier works could not accomplish. Furthermore, the findings prepare the conceptual foundation for the Conclusion section by clarifying the implications of the study's discoveries.

The first major finding relates to the structured variability of early-stage energy performance. The results demonstrated that predicted energy demand did not fluctuate randomly but instead formed statistically coherent clusters. This finding supports the hypothesis that early-stage design parameters operate within definable performance boundaries even when significant uncertainty is embedded within the design space. While previous studies on early-stage modeling often assumed that conceptual variation produced unpredictable or overly broad performance ranges, the present investigation reveals that uncertainty-aware modeling identifies dominant probabilistic zones of behavior. The emergence of a strong mid-range performance cluster, accounting for more than sixty percent of all scenarios, contradicts earlier assumptions that conceptual design inherently leads to unbounded variability. Thus, the first finding is that early-stage performance exhibits structured and interpretable numerical behavior when analyzed through a probabilistic framework rather than deterministic simulation.

The second finding concerns parameter dominance and the hierarchical influence structure revealed through sensitivity analysis. Orientation, glazing ratio, and shading depth emerged as the principal drivers of early-stage energy behavior. This confirms the hypothesis that geometric parameters outweigh envelope or material factors in shaping conceptual performance. In contrast, much of the earlier research relied on deterministic evaluations that frequently attributed significance to isolated material improvements or insulation strategies without contextualizing these improvements within the broader geometric system. The current study demonstrates that, within early design, material enhancements alone cannot compensate for misaligned geometry or performance-inefficient massing configurations. Thus, a core finding is that early-stage design decisions produce quantifiable hierarchical effects, establishing a performance logic that cannot be seen through classical simulation workflows.

The third finding relates to the interaction structure among parameters. The results showed that orientation and glazing ratio interact synergistically, producing amplified effects not detectable when parameters are evaluated independently. Such interaction patterns validate the hypothesis that early-stage performance is shaped by multi-parameter dynamics rather than isolated decision variables. Previous studies in early-stage prediction rarely quantified interaction effects, instead focusing on single-variable sensitivity. The current findings introduce a novel analytical dimension by demonstrating that performance is not merely influenced by parameters but by how those parameters combine. This insight provides a more realistic foundation for design strategies because it reveals that optimal configurations are not achieved by maximizing single attributes but by balancing interacting characteristics.

A fourth key finding concerns the numerical effects of incremental geometric or envelope adjustments. The gradient-based analysis revealed consistent and measurable shifts in energy demand associated with orientation rotations, glazing adjustments, shading changes, and envelope modifications. This structure confirms the hypothesis that performance behaviors are not random but follow quantifiable gradients. Earlier literature often lacked this numerical structure because classical early-stage tools did not incorporate probabilistic sampling or parametric breadth. The current study offers a novel quantitative contribution by demonstrating that performance gradients can be reliably mapped even when information is incomplete. This discovery allows designers to anticipate the directional effects of geometric transformations without requiring detailed models.

A fifth major finding emerges from the cluster-based performance classification. The definition of low-, mid, and high-energy conceptual clusters provides a performance map that can guide designers before detailed specifications are available. Earlier research using clustering techniques in energy modeling typically focused on operational or post-occupancy stages. The novelty in this study is the demonstration that conceptual-phase geometry can itself produce stable performance clusters when analyzed probabilistically. This allows early-stage decisions to be informed by statistical behavior rather than intuition alone. Thus, the fifth finding is that conceptual performance clusters provide a meaningful predictive framework for preemptive energy reasoning.

The sixth finding concerns temporal stability and the influence of massing-related parameters on fluctuation amplitudes. Scenarios with higher mass-to-volume ratios consistently exhibited reduced variability in hourly load profiles, indicating that conceptual form can meaningfully influence temporal thermal behavior. Prior studies generally quantified thermal stability only in the context of detailed material modeling. By contrast, the present study shows that even coarse massing abstractions can predict temporal stability patterns. Consequently, the current findings expand the predictive value of early-stage modeling by revealing a broader thermal logic embedded in conceptual form.

A seventh finding relates to predictive reliability. The Monte Carlo–derived prediction intervals demonstrated that performance confidence bands narrow as conceptual configurations become more geometrically optimized. This supports the hypothesis that uncertainty-aware frameworks not only predict ranges but also indicate the reliability of those predictions. Such reliability indicators were rarely included in earlier early-stage modeling studies. The present finding provides designers with an understanding of which configurations yield stable predictions and which configurations produce volatile outcomes. Thus, this finding addresses the methodological hypothesis while offering practical implications for conceptual design practice.

In comparing the study findings with prior research, several advancements become evident. Earlier early-stage energy modeling studies generally lacked comprehensive integration of BIM, uncertainty quantification, and sensitivity analysis within a single workflow. They also tended to treat conceptual geometry as too abstract for meaningful prediction. The present study overturns this assumption by demonstrating that conceptual BIM geometries, when properly parameterized and processed through probabilistic and sensitivity-informed pipelines, provide reliable and structured performance insight. Furthermore, earlier studies often failed to quantify interaction effects or produce performance gradients, leading to oversimplified conclusions about parameter influence. The present study uniquely identifies not only the importance of individual parameters but also the synergistic relationships between them. Additionally, previous literature rarely addressed predictive reliability or the width of performance confidence intervals. The present study fills this gap by demonstrating how uncertainty-aware modeling provides interpretable confidence structures that directly enhance design decision-making.

Another comparative advancement lies in the study's ability to articulate what earlier works could not: the structured nature of conceptual performance distributions. Traditional deterministic approaches generally produced single-value estimates that ignored the inherent variability of early-stage environments. By contrast, the current study reveals that performance is statistically patterned and that dominant behavioral zones emerge naturally from the parameter space. This discovery not only differentiates the current study but also establishes a new conceptual framework for early-stage reasoning.

The findings also reveal the study's unique contribution: the integration of early-stage BIM abstraction, probabilistic scenario generation, reduced-order thermal simulation, and sensitivity-oriented variance decomposition into a unified predictive system. Earlier frameworks addressed these components separately but did not combine them into an operationally coherent methodology capable of producing quantitative insight at the conceptual phase. This study, therefore, represents a methodological advancement by demonstrating how these components produce complementary insights that are not visible when methods are applied in isolation.

Finally, the findings explicitly address the research questions and hypotheses. The primary research question—concerning whether uncertainty-aware BIM-based modeling can reliably predict conceptual energy performance—is answered affirmatively through the structured distribution patterns, parameter influence hierarchy, and predictive reliability indicators. The hypothesis that uncertainty-aware modeling yields superior predictive stability is supported by the confidence interval outputs. The hypothesis that sensitivity analysis clarifies design priorities is supported by the ranked parameter impacts and interaction coefficients. The hypothesis that BIM-integrated workflows improve continuity between conceptual geometry and analytical prediction is validated through the successful translation of abstract geometries into simulation-ready thermal structures. Collectively, these findings confirm that the computational framework is conceptually and operationally suitable for supporting early-stage design decisions.

In preparing the ground for the Conclusion section, the findings establish a narrative of methodological coherence, numerical reliability, conceptual advancement, and practical relevance. The findings collectively show that performance prediction in early-stage design can be both flexible and rigorous, that uncertainty is not an obstacle but a modeling resource, and that predictive insight emerges from the structured interplay between geometry, climate, and computational reasoning. This alignment between methodology, results, and interpretive discovery provides the logical and conceptual foundation for the concluding synthesis presented in the next section.

6. Discussion

The discussion of this study centers on interpreting the results through the conceptual and theoretical structures outlined earlier, situating the findings within the broader landscape of performance-driven design research, and analyzing the methodological mechanisms that allowed the study to address its research questions and hypotheses. Unlike the Results section, which presents quantitative outputs, the Discussion synthesizes these outputs into a deeper explanatory framework. It examines how the theoretical principles from the Literature Review were operationalized, how the adopted methodology differed from conventional approaches, and how these differences enabled the study to uncover insights that earlier investigations did not reveal. Furthermore, this section forms the conceptual bridge toward the Conclusion by articulating the broader implications and interpretive logic that arise from the study's findings.

The first point of synthesis arises from the theoretical position that early-stage design represents a domain characterized by uncertainty, incomplete information, and rapid conceptual evolution. The Literature Review emphasized that traditional deterministic simulation tools were not designed to operate within such conditions because they require stable inputs and detailed model definitions. The theoretical foundation also highlighted the systemic rather than isolated nature of early-stage performance and the need for tools that recognize interdependencies among parameters. In this study, these theoretical ideas were operationalized through a probabilistic modeling structure that treated early-stage inputs as ranges rather than fixed values and incorporated sensitivity analysis to reveal the causal relationships within the parameter set. Thus, the foundational theoretical constructs are not examined abstractly but activated through the computational pipeline, confirming that the conceptual ideas of uncertainty, interaction, and parametric hierarchy are essential for meaningful early-stage prediction.

The results demonstrated that energy performance at the conceptual phase forms recognizable statistical structures rather than arbitrary fluctuations. This observation directly ties to the theoretical argument that buildings exhibit emergent behavior arising from the interplay of form, climate, and envelope characteristics. By placing the performance distribution in the context of these theoretical insights, the study shows that early-stage performance is an emergent system phenomenon shaped by geometric and environmental interactions. Earlier theoretical works argued that conceptual design lacked sufficient detail for predictive validity. The present study challenges that assumption by showing that when uncertainty is explicitly modeled, conceptual geometry becomes analytically expressive rather than deficient. This reinterpretation of theoretical principles represents a meaningful expansion of early-stage performance theory.

The discussion also extends to how the research questions and hypotheses were examined. The primary research question asked whether an integrated framework combining BIM-based abstraction, uncertainty quantification, and sensitivity analysis could generate reliable predictive insight in early-stage design. The methodology enabled this by translating conceptual BIM geometries into analytical structures while acknowledging and incorporating uncertainty. The results—which displayed structured distributions, parameter influence hierarchies, and interaction patterns—provide evidence that the framework not only functions but generates fine-grained insight unavailable in deterministic systems. Therefore, the research question is addressed not simply by numerical outputs but by demonstrating that the methodological architecture enables reliable predictive reasoning in a domain historically resistant to technical evaluation.

The first hypothesis proposed that uncertainty-aware modeling improves the reliability of conceptual predictions. The results confirmed this by showing organized distribution clusters, interpretable variance structures, and prediction intervals that quantify reliability in ways deterministic simulations cannot. In earlier studies, predictions were presented as isolated numerical values without any measure of confidence or reliability, making them difficult to interpret meaningfully. By incorporating probability distributions, this study demonstrates that conceptual prediction can transition from point-based estimates to stability-band reasoning, revealing not just performance but the confidence associated with that performance.

The second hypothesis asserted that sensitivity analysis provides essential guidance for prioritizing early-stage design decisions. The results validated this by presenting ranked parameter impacts and interaction coefficients that clarify which parameters most strongly influence performance outcomes. Prior research often lacked such clarity, treating early-stage modeling as exploratory rather than analytically structured. The findings show that parameter influence is neither equal nor random but follows a quantifiable hierarchy. This directly strengthens the theoretical discourse by demonstrating that conceptual geometry—often treated as intuitive—is actually subject to measurable performance logic.

The third hypothesis stated that BIM-integrated workflows enhance the continuity between conceptual geometries and performance modeling. The methodology achieved this by embedding parametric metadata directly within the BIM environment and translating conceptual volumes into simulation-ready abstractions. Traditional research approaches often required designers to rebuild conceptual models in separate simulation software, introducing discontinuity and loss of conceptual intent. By contrast, the integrated workflow in this study preserves the conceptual logic while enabling analytical rigor, confirming the hypothesis and establishing a methodological improvement over previous approaches.

Furthermore, the methodology used in this study demonstrates several advantages relative to earlier research traditions. Classical simulation-based early-stage studies often relied on static models, fixed input parameters, and simplistic sensitivity routines. These methods did not adequately capture the dynamic complexity of early-stage decisions nor the interaction effects among parameters. The probabilistic approach used in this study—combined with geometric abstraction, metadata integration, and variance decomposition—produces a multidimensional understanding of performance that earlier methods could not attain. This not only enhances predictive insight but also aligns computational modeling with the fluid and uncertain nature of conceptual design.

Another significant advantage of the methodology lies in its ability to quantify the reliability of predictions. Earlier deterministic approaches could not differentiate between stable and volatile parameter configurations because they produced singular performance values. The present study reveals that certain conceptual configurations produce inherently narrower prediction intervals, indicating greater reliability. This contributes to the broader theoretical discourse by introducing prediction reliability as a new evaluative dimension for early-stage design.

The discussion also examines the novelty of the study’s findings relative to comparable works. Earlier studies commonly emphasized material improvements, envelope properties, or mechanical systems as primary drivers of performance. This study shows that such focus is insufficient at the conceptual phase. Instead, orientation, glazing, and shading—geometric and configurational parameters—shape performance more decisively. This challenges previous emphases and repositions conceptual geometry as the primary locus of early energy modeling. Additionally, the identification of parameter interactions represents a methodological and theoretical advancement, revealing complex interdependencies that earlier research rarely quantified. This deeper insight enables architects and researchers to move beyond linear reasoning, embracing a relational understanding of building performance.

The temporal stability findings also represent an expansion of existing knowledge. Prior research often treated temporal load variation as a topic requiring detailed thermal modeling, typically unavailable in conceptual studies. The current study shows that massing alone can indicate temporal behavior, revealing patterns of fluctuation and stability. This contributes to performance theory by expanding the predictive capacity of conceptual-level modeling.

The discussion must also prepare the conceptual transition toward the Conclusion section. While the Results section quantified behavior and the Findings section interpreted the numerical structures, the Discussion synthesizes these insights into a broader narrative of methodological coherence and theoretical advancement. It establishes that early-stage predictive modeling is both possible and scientifically meaningful when approached through uncertainty-aware, sensitivity-informed, and BIM-integrated methods. It also demonstrates that the study’s contributions extend beyond numerical accuracy: the research restructures how early-stage performance is understood, emphasizing probability, interaction, and reliability as core analytical dimensions.

Finally, the Discussion positions the study's contributions within a forward-looking perspective. The methodological framework developed here is not limited to the Famenin–Hamedan climate region but offers a transferable structure applicable to other climatically dynamic contexts. The theoretical implications extend to design practice, computational research, and environmental modeling. The study provides evidence that conceptual models—often dismissed as too abstract—can serve as strong analytical foundations when properly parameterized and computationally structured. This insight creates new opportunities for early-stage design tools that merge creativity with analytical rigor, forming the conceptual basis for the concluding synthesis of the next section.

7. Conclusion

The purpose of this study was to develop and evaluate an integrated computational framework capable of predicting early-stage building energy performance under conditions of uncertainty, incomplete information, and conceptual fluidity. Drawing upon BIM-based geometric abstraction, probabilistic scenario generation, reduced-order thermal simulation, and sensitivity-informed analytical reasoning, the study sought to address a central research question: whether early-stage design decisions can be meaningfully evaluated through a predictive system that embraces variability rather than resisting it. Through the sequence of inquiry spanning Introduction, Literature Review, Methodology, Results, and Discussion, the study has generated a coherent set of conclusions that offer clarity, methodological advancement, and practical value for early-stage architectural design and computational modeling.

From the Introduction, the first conclusion is that early-stage architectural design contains structurally significant performance determinants. Even though information is incomplete and design intentions remain flexible at this stage, conceptual decisions fundamentally shape the building's long-term energy trajectory. The findings demonstrate that early-stage prediction is not only possible but necessary for aligning design ambitions with environmental performance outcomes. The research, therefore, concludes that early-stage modeling must move beyond deterministic assumptions and adopt uncertainty-aware logic as an inherent analytical approach.

From the Literature Review, a second conclusion emerges: the theoretical landscape surrounding energy prediction in architecture is shifting from reductionist, single-parameter approaches toward holistic, system-driven frameworks. The conceptual vocabulary of thermal inertia, solar exposure, climatic sensitivity, and envelope conductance cannot be treated in isolation. Instead, their relationships must be captured through computational systems capable of interpreting interaction effects. The study concludes that theoretical performance concepts acquire their full explanatory power only when embedded within probabilistic, sensitivity-informed modeling environments.

From the Methodology, a third conclusion surfaces: BIM-based conceptual modeling, when combined with parameter range definitions, scenario generation, and analytical decomposition, can serve as a viable computational substrate for predictive reasoning at the conceptual phase. The methodological architecture developed in this research supports the conclusion that early-stage BIM need not be treated solely as a documentation or visualization tool. Instead, it can function as an analytical engine that transforms conceptual geometry into quantifiable performance insights. This represents a methodological advancement relative to earlier approaches that decoupled BIM environments from conceptual simulation processes.

From the Results section, several quantitative conclusions can be drawn. First, early-stage energy performance exhibits structured statistical behavior rather than random or unpredictable variability. The emergence of distinct performance clusters confirms that conceptual decisions lead to recognizable energy patterns. Second, parameter hierarchy is measurable: orientation, glazing ratio, and shading depth consistently dominate performance variance. Third, interaction effects significantly shape outcomes, confirming that performance is an emergent property of coupled parameters rather than isolated variables. Fourth, incremental parameter adjustments produce predictable performance gradients, demonstrating that conceptual modeling can reveal directional sensitivity even in the absence of detailed inputs. These conclusions affirm the hypothesis that uncertainty-aware modeling, supported by sensitivity analysis, provides deeper insight than deterministic methods.

From the Findings section, further interpretive conclusions arise. The study concludes that earlier research underestimated the predictive potential of conceptual geometry. By demonstrating that conceptual modeling can yield statistically structured, reliable insights, the present research challenges traditional assumptions that conceptual design is too abstract for meaningful performance evaluation. The findings also lead to the conclusion that interactive parameter effects—long overlooked in early-stage research—represent a critical dimension of predictive logic. The study's discovery of parameter synergy, particularly between orientation and glazing ratio, expands the theoretical understanding of conceptual performance. Additionally, the research concludes that prediction reliability is a valuable evaluative metric that should be integrated into early-stage modeling practices.

From the Discussion, several integrative conclusions emerge. First, the uncertainty-aware, sensitivity-informed framework successfully operationalizes key theoretical concepts, demonstrating that the abstract ideas of variability, interaction, and emergent behavior can be computationally enacted in early design. Second, the methodology effectively supported hypothesis testing: it validated the superiority of probabilistic prediction, the necessity of sensitivity-based prioritization, and the analytical coherence that BIM integration provides. Third, compared with earlier studies, the methodological system developed here offers a more comprehensive and nuanced representation of early-stage performance by combining geometry, climate, uncertainty, and interaction structures within a single computational pipeline. This leads to the conclusion that predictive modeling must evolve beyond static simulation paradigms to embrace multi-layered analytical ecosystems.

Bringing together all sections of the study, the overarching conclusion is that early-stage energy performance prediction is both feasible and computationally robust when approached through the lens of uncertainty and sensitivity. The integration of BIM-based modeling with probabilistic reasoning enables designers and analysts to work with incomplete inputs while still obtaining reliable, interpretable insight. The study's methodological contributions demonstrate that conceptual models—when parameterized appropriately—are not merely schematic but analytically expressive. This reconceptualizes early-stage design as a domain where substantive performance evaluation can occur, thereby narrowing the gap between design intention and environmental responsibility.

The implications of these conclusions extend into both architectural design practice and computational research. Designers gain a structured framework for making informed conceptual decisions that align with long-term performance goals. Researchers gain evidence that early-stage modeling must account for parameter uncertainty, interaction effects, and statistical distribution behavior to produce meaningful analysis. Policymakers and sustainability specialists may also benefit by recognizing that early conceptual decisions carry significant environmental implications, suggesting that performance guidelines must be integrated earlier in the design workflow.

In preparing recommendations for future research, several directions emerge naturally from the study's conclusions. First, future work should explore the integration of additional performance metrics—such as daylighting, thermal comfort, and embodied carbon—within the same probabilistic framework. Second, research should investigate the scalability of the methodology across different climatic regions to determine how climatic variability influences parameter hierarchies. Third, advancements in machine learning present opportunities for developing hybrid predictive models that combine simulation-based outputs with data-driven inference. Fourth, future studies may incorporate designer behavior and decision-making patterns into the modeling environment to better capture real-world workflows. Finally, longitudinal validation studies should be conducted to compare conceptual predictions against actual post-construction performance, refining predictive accuracy and enhancing methodological reliability.

In summary, the study delivers clear and actionable conclusions: conceptual geometry has predictive value; uncertainty-aware modeling is essential; parameter interactions shape systemic behavior; BIM-integrated workflows enhance continuity; and predictive reliability must be recognized as a core design metric. These conclusions collectively provide the foundation for a new generation of early-stage predictive systems that bring analytical rigor to conceptual design while supporting environmental and energy-conscious architectural decision-making.

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