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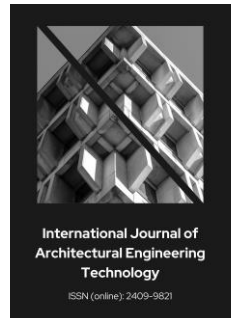

Early-Stage Building Performance Simulation for High-Performance Buildings: A Systematic Review of Methods, Workflows, Uncertainty Handling, and Design Decision Support

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ABSTRACT

This systematic review of the literature examines how early-stage building performance evaluation can assist designers while they are still able to make alterations to their designs. The literature covered in this review comprised all peer-reviewed publications in English from 2013-2025. The review has synthesized the literature into four separate themes: (1) Performance Evaluation and Performance Assessment; (2) Simulation-based Design; (3) Collaborative and Sustainable Workflow Processes; and (4) Early-Stage Simulation Practices. The results show that the evaluation approach now emphasizes performance early in the design process rather than compliance at the final stage. Initial simulations target the building's massing and envelop in relation to climate considerations; later stages will focus on technical enhancements, verification, and ensuring adherence to building codes. The effectiveness of these procedures depends on the ability to establish decision-phase milestones, integrate design tools with performance analysis software, and openly discuss uncertainties throughout the design journey. Effective early-stage performance evaluation is restricted by a number of factors, including inconsistent conversion of Building Information Models (BIMs) to Building Energy Models (BEMs); a lack of verification/validation techniques; and several situations in which the building's actual performance differs from its anticipated energy performance. To improve the integration of performance evaluation into architectural design practice, these obstacles necessitate significant improvements in interoperability, systematic uncertainty reporting, and workflow-oriented methodologies for buildings and building codes.

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1. Introduction

Performance assessment is increasingly regarded as a strategic aspect of delivery rather than a one-time task. Research encourages continuous verification and validation throughout the project cycle, with recommendations for reporting that acknowledge the uncertainties associated with project predictions, as the outcome measures often do not align with them [1]. At the more integrated portfolio scale, the extreme variability in energy consumption observed in so-called high-performance buildings underscores the importance of establishing performance assessment criteria that account not only for regulatory requirements and models, but also for weather, operating, and behavioral attributes [2]. Compared analyses of early- and late-stage evaluations indicate that early-stage evaluations promote climate-responsive design choices in massing, whereas subsequent evaluations focus more on pursuing certificate requirements [3]. Different workshops documented performance evaluations with practice that included short training, a modeling checklist, and an early sensitivity analysis to allow for more concrete changes to orientation, shading, glazing, insulation, and solar sizing while recognizing the need for more clarity to present results at project gates [4]. Technically, in early stages, there is an opportunity to have a streaming, two-way interaction with the authoring tool, which allows the team to evaluate many options in the sketch space, while the project evaluation raises fidelity as inputs become better established; central file exchanges can rarely match this pace [5]. Sustainable, collaborative workflows provide repeatable procedures. Team quality is defined by integration frameworks into measurable benchmarks and indicators that leaders can utilize going forward [6]. In accordance with established requirements for energy, ventilation, and comfort, quality frameworks also assign model accuracy by phase, ranging from basic whole-building models at the schematic stage to hourly and compliance models [7].

Several researchers support engine-neutral data schemas and scenario-aware approaches because measured results vary, even within a clearly defined building type. As a result, targets are set based on ranges and levels of certainty rather than single numbers [1, 8-10]. Early-stage simulation must also account for uncertainty, reviews suggest replacing deterministic runs with statistical workflows that assign distributions to essential inputs, sampled systematically, and rank drivers using global sensitivity methods; eliminating uncertainty in decisions but not uncertainty in the performance thresholds [10, 11].

In this regard, the remainder of the manuscript will examine collaborative processes, simulation strategies, and assessment approaches to evaluate early-stage building performance to support decision-making in high-performance building design. The present article adds value to the field with its proposed decision support typology that links (i) decision support objectives (risk bounding, screening, comparative trade-offs, and optimization), (ii) modeling maturity (massing, zoning, and early systems), and (iii) delivery approaches (in-house, consultant-led, and hybrid). This typology clarifies why building performance evaluation may be viewed as a verification process in some cases and a design driver in others.

In this manner, with the use of a PRISMA-based search methodology, the project will initially examine peer-reviewed English literature within the time frame of 2013 to 2024, being divided into four different thematic areas, specifically including ‘performance evaluation & assessment,’ ‘simulation-based design,’ ‘collaborative & sustainable design environments,’ as well as ‘Early stage simulation practices.’. The review process addressed three research questions: (RQ1) How is “early design” defined and operationalized across the literature, and what input conditions are associated with this design phase? (RQ2) What types of evaluations and simulations are used to support decision objectives during early design, and what types of outputs do they provide? (RQ3) What types of workflows and tool integrations enable performance feedback for design decisions? These research questions will also inform the search strategy, screening, and synthesis process.

2. Methodology

RQ1–RQ3 were addressed by the design of the search technique and screening criteria. Early design words were combined with phrases related to simulation, decision support, workflow, collaboration, and building performance evaluation. Instead of publishing performance results without choice context, studies that directly linked modelling outcomes to design decisions or decision processes were included. This research employed a systematic literature review (SLR) approach, i.e., a method for identifying, evaluating, and synthesizing previously published research on a specific topic that is structured, transparent, and replicable. Pati and Lorusso [12] provided the following definition of SLR, which helps distinguish SLR from standard narrative reviews. SLR follows a clear protocol and objective that helps reduce bias and enhance the reliability of findings. This is achieved by starting with a clear research question, developing a rigorous search strategy, defining inclusion and exclusion criteria, and assessing the validity of the published studies. SLR can systematically organize and analyze evidence, deepen understanding of the existing body of knowledge, and identify gaps in the literature to inform future research directions. This literature review analyses how building performance research has evolved over the past decade and identifies methods that can inform decision-making at the point of engagement (e.g., in building performance projects).

These questions were developed through a structured matrix of potential key terms, crossover terms, and specific terms to ensure a systematic and consistent approach to examining the field. Four themes that organize the paper: (1) Building Performance Evaluation and Assessment; (2) Simulation-Based Building Design; (3) Collaborative and Sustainable Design Workflows; and (4) Early-Stage Design and Building Performance Simulation. The review was developed to specifically track how all the building performance research developed over the last decade, regarding approaches, frameworks, and simulation-based approaches to sustainability and energy efficiency in the built environment.

2.1. Search Strategy

The literature search involved four main academic databases: Google Scholar, ResearchGate, and Scopus. Search terms were derived from the matrix defined in Table **1**, focusing on higher-order concepts: Building Performance Evaluation, Simulation-based Approach, Collaborative Workflows, and Building Energy Modeling, and their related cross terms: *Building Energy Benchmarking, Workflow Comparison, Integrated Building Simulation, and Energy Modeling Tools*. In some cases, specific phrase expressions such as "Accuracy in energy predictions" and "Integrated design process" were used to limit search outputs and create a stronger link with this study's goals (Table **1**). To improve reproducibility, the search strategy was operationalized through database-specific Boolean strings combining the four main thematic concepts with cross terms. Example search strings included: (“building performance evaluation” OR “building performance assessment”) AND (“energy benchmarking” OR “building energy performance”); (“simulation-based design” OR “building performance simulation”) AND (“early design” OR “concept design” OR “schematic design”); (“sustainable design workflow” OR “collaborative workflow”) AND (“building energy performance” OR “integrated design process”); and (“BIM” OR “building information modeling”) AND (“BEM” OR “building energy modeling” OR “energy simulation”). Searches were limited to English-language publications from 2013 to 2024 and were refined through title, abstract, and full-text screening. In this time, terms related to areas outside construction and architecture were removed during the initial screening to improve focus on the built environment.

Table 1: Search terms and Boolean strings used for literature collection.

Category	Core Search String	Extended Search String
Building Performance Evaluation and Assessment	(“building performance evaluation” OR “building performance assessment”)	(“building performance evaluation” OR “energy benchmarking”) AND (“building energy performance” OR “EUI”)
Simulation-Based Building Design	(“simulation-based design” OR “building performance simulation”)	(“building performance simulation” OR “energy modeling”) AND (“design process” OR “workflow comparison”)
Collaborative and Sustainable Design Workflows	(“collaborative design” OR “sustainable design workflow”)	(“integrated design process” OR “collaborative workflow”) AND (“building energy performance” OR “sustainability”)
Early-Stage Design and Building Simulation	(“early design” OR “concept design” OR “schematic design”)	(“early-stage simulation” OR “energy modeling tools”) AND (“decision-making” OR “design stage”)

The search process began with a broad, scripted screening of articles, then narrowed the selection based on titles and abstracts, and finally excluded articles that were not focused or relevant to the literature review. The next step was to conduct a full-text review, where only unsuitable articles were removed. This was particularly useful for reviewing other studies based on case studies in countries that deviated from the norm in terms of sustainability draft laws or sustainable resources. To expand the database, a snowball sampling approach was used by reviewing the references of the selected articles to identify additional publications that underwent the same review process. Different databases were searched due to the large number of indexed journals and conference proceedings available, which ultimately made the literature collected more diverse and credible.

2.2. Inclusion and Exclusion Criteria

The inclusion of only research published between 2013 and 2024 assured that the results were indicative of current trends in sustainable design and building practices and performance. This limitation was based on the expectation that substantial change would occur during that period. To be included in our review, studies must focus directly on one or more of the following five areas: evaluation or assessment of building(s) performance, simulation of building(s) performance, early design decisions related to building(s), workflow for simulation-based design, and BIM-to-BEM transfer. Studies that are not buildings, architecture, construction, or building science; only consider non-building infrastructure; do not have full-text access; are not written in English; or do not provide sufficient or relevant methodological and/or conceptual information required by the reviewed themes were excluded.

2.3. Selection and Documentation Process

The entire selection process was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [13]. The PRISMA flow diagram (Fig. **1**) visually summarizes the stages of identification, screening, eligibility assessment, and final inclusion, ensuring transparency and replicability of the review process. The synthesis was carried out thematically. Once all studies had been screened via full texts, they were coded based on their primary contribution, the design/phase of construction applicable to them, the methodology used, focus on performance, and impact on workflows. These codes were grouped into the four thematic categories established for this review: Building Performance Evaluation and Assessment; Simulation-based Building Design; Collaborative/Sustainable Design Workflows; Early-Stage Design & Building Performance Simulation. Through this coding process, it was possible to compare studies based on both decision context and workflow function, not just on the tools used or the recorded metrics.

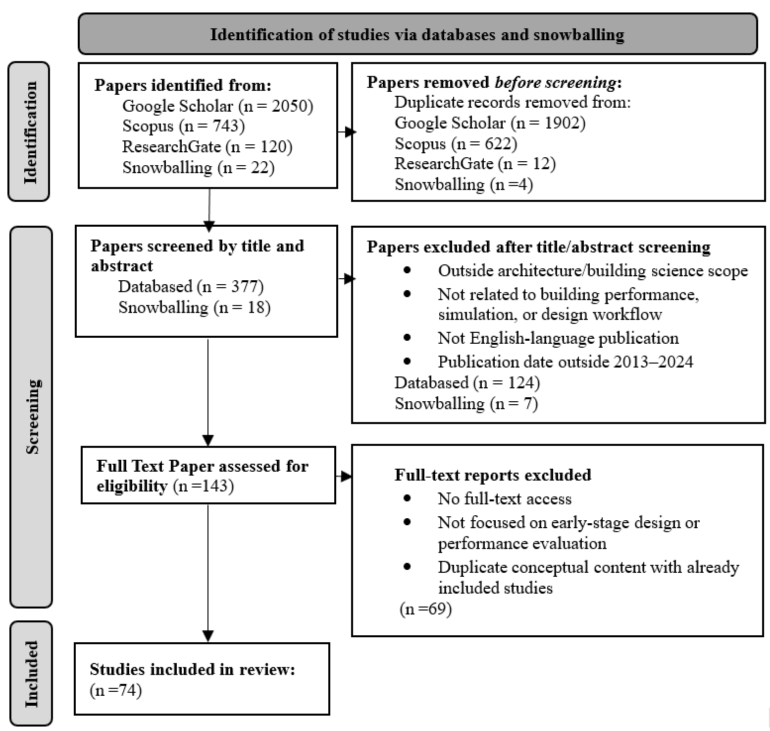

Figure 1: PRISMA flow diagram.

3. Bibliometric Results

The contextual reporting across the included studies is not comparable in all respects, particularly with respect to assumptions and uncertainties. Some studies have emphasized the dependence of performance prediction on weather, operations, and human behavior, although these factors are not consistently represented or validated across studies. Therefore, the magnitudes of performance should be considered context dependent. The synthesis highlights the patterns in the method and workflow, but the claims of improvement and generalization are the main limitations.

Regarding the development of building performance evaluation within the design process and collaboration workflow, Table **2** provides an distributions of the publication on each theme. In-depth discussions of these are given in the following sections. The thematic analysis developed four main themes: Evaluation and Assessment of Building Performance; (2) Simulation-Based Building Design; (3) Sustainable and Collaborative Design Processes; and (4) Early-Stage Design and the Significance of Building Simulation. Furthermore, the articles reviewed are categorized as follows: 33% discussed Building Performance Evaluation and Assessment, 35% discussed Simulation-Based Building Design, and 28% discussed Early-Stage Design (Fig. **2**). The significance of Building Simulation and Sustainable Design Workflows was discussed in 24% of the articles.

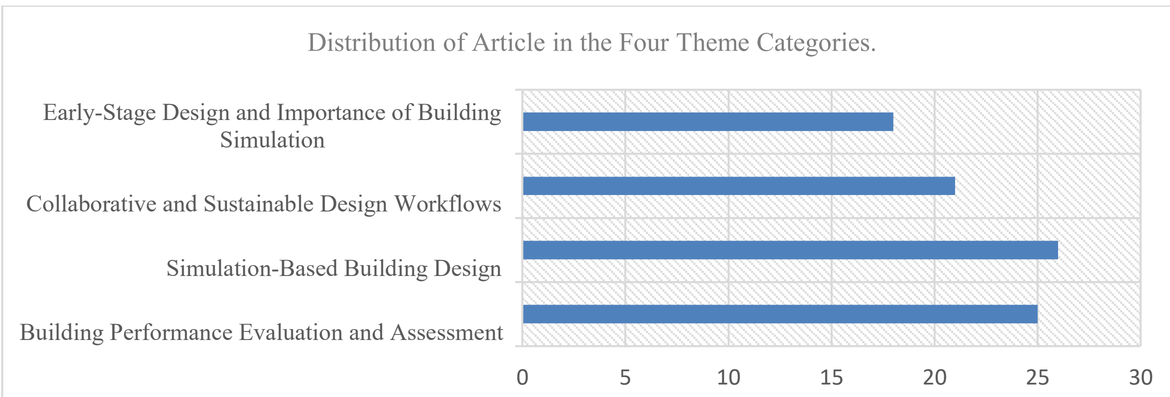

Figure 2: Distribution of articles in the four theme categories.

The creation of Fig. (**3**) was facilitated by applying a co-occurrence mapping method with respect to a set of studies that were part of the systematic review. Keywords came from four sources within the study (title, abstract, keywords provided by authors, and other words that frequently recur during thematic coding). It shows that ‘performance evaluation,’ ‘simulation-based design,’ ‘collaborative workflow,’ and ‘early design decisions’ are interlinked concepts, as opposed to being discrete areas of concern. Overlap terms such as ‘uncertainty,’ ‘benchmarking,’ ‘sensitivity analysis’ and ‘data exchange’ suggest that all four areas of concern are impacted. ‘Early design’ simulation clearly represents the increasing expectation that modeling will provide guidance on massing, envelopes, or other early design considerations. As described in this study "early design" has been operationalized to incorporate activity conducted prior to design (Pre-design) and during both the Concept and Schematic Design stages of a project where major decisions regarding the massing, orientation, zoning of a building, and envelope strategy, lighting/daylighting levels (indirect lighting) through the use of passive design strategies and assumed performances of mechanical systems (HVAC and other building systems) can still being developed. This definition supports recent studies [30, 81-83]. Since the studies reviewed used several different terminologies (massing stage, zoning stage, concept design, schematic design), they were categorized as "early design" if they were describing the types of decisions made prior to issuing a detailed document to make the final system specification or to conduct compliance modeling.

At the same time, the fact that ‘collaborative workflow’ terms appear in both simulation design and performance evaluation circles would suggest that technological innovation requires shared sets of data, as well as enhanced collaboration. As used in this review, the term "collaborative workflow" describes the processes

Table 2: Contents identified from publications and papers for four categories.

Publication	Publication Title	Theme of Review			
		BPEA	SBBD	CSDW	EDIBS
Aksamija [14]	A strategy for energy performance analysis at the early design stage: predicted vs. Actual building energy performance”				*
Ali, Jayaraman [15]	A comparative analysis of machine learning and statistical methods for evaluating building performance: A systematic review and future benchmarking framework	*			
An, Li [16]	From building information modeling to building energy modeling: Optimization study for efficient transformation				*
Asl, Stoupine [17]	Optimo: A BIM-based multi-objective optimization tool utilizing visual programming for high performance building design		*		
Ashuri, Wang [18]	A data envelopment analysis (DEA) model for building energy benchmarking	*			
Attia, Gratia [4]	Early decision support for net zero energy buildings design using building performance simulation				*
Augenbroe [19]	The role of simulation in performance-based building		*		
Azari and Kim [6]	Integration evaluation framework for integrated design teams of green buildings: Development and validation	*	*	*	
Beetge, De Canha [20]	Managing the design and development of high-performance buildings through integrated design			*	
Berawi, Kim [21]	Designing a smart integrated workspace to improve building energy efficiency: an Indonesian case study			*	
Bjørnskov, Jradi [22]	Automated model generation and parameter estimation of building energy models using an ontology-based framework		*		
Botchway, Agyekum [23]	Utilization of simulation tools for building performance assessment among design professionals	*			
Brown, Rajkovich [24]	The future of weather files for building performance simulation in New York State		*		
Christine Sotsek, Sanchez Leitner [25]	A systematic review of Building Performance Evaluation criterias (BPE)			*	
De Wilde [26]	The gap between predicted and measured energy performance of buildings: A framework for investigation	*		*	*
Delgarm, Sajadi [27]	Sensitivity analysis of building energy performance: A simulation-based approach using OFAT and variance-based sensitivity analysis methods		*		
Gerber and Lin [28]	Designing in complexity: Simulation, integration, and multidisciplinary design optimization for architecture				*
Han [29]	A New Interoperability Framework for Data-Driven Building Performance Simulation		*		
Han, Huang [30]	Simulation-based decision support tools in the early design stages of a green building—A review				*
Hasan, Palonen [31]	Simulation-based optimization for energy and buildings	*	*		
Heidarinejad, Dahlhausen [32]	Building classification based on simulated annual results: towards realistic building performance expectations		*		
Hemsath [33]	Conceptual energy modeling for architecture, planning and design: Impact of using building performance simulation in early design stages		*		
Hensen and Lamberts [34]	Building performance simulation–challenges and opportunities		*		

Table 2 (contd….)

Publication	Publication Title	Theme of Review			
		BPEA	SBBD	CSDW	EDIBS
Hong, Li [9]	Integrated Design for High Performance Buildings			*	
Hopfe and Hensen [11]	Uncertainty analysis in building performance simulation for design support		*		*
Hu [35]	Optimized Renovation Strategies of Education Building–a novel BIM/BPM/BEM framework		*		
Isley [36]	Examining Integrated Design Workflows that Support Building Performance Integration in Small Architectural Firms				
J Hopfe, Soebarto [37]	Understanding the differences of integrating building performance simulation in the architectural education system			*	
Jaganathan, Mohammed [38]	Descriptive Review of energy performance evaluation approaches	*			
Jia, Srinivasan [39]	Descriptive Review of energy performance evaluation approaches				*
Kamari, Corrao [40]	Sustainable renovation framework: introducing three levels of integrated design process implementation and evaluation			*	
Kono, McNulty [41]	Raising the Bar: Comparing Building Energy Benchmarking Methods	*			
Krstić and Teni [42]	Review of methods for buildings energy performance modelling				*
Lamberts and Hensen [43]	Building performance simulation for design and operation				*
Lee [44]	The integrated design process from the facilitator's perspective			*	
Li, Iulo [45]	A review of the energy performance gap between predicted and actual use in buildings		*		
Li, Hong [46]	System-level key performance indicators for building performance evaluation	*			
Li, Liu [47]	A review of performance-oriented architectural design and optimization in the context of sustainability: Dividends and challenges			*	
Lin and Gerber [48]	Evolutionary energy performance feedback for design: Multidisciplinary design optimization and performance boundaries for design decision support				*
Lin, Chen [49]	MOOSAS–A systematic solution for multiple objective building performance optimization in the early design stage	*			
Lu, Sood [50]	Factors impacting integrated design process of net zero energy buildings: an integrated framework			*	
Mahmoud, Kamara [51]	Opportunities and Limitations of Building Energy Performance Simulation Tools in the Early Stages of Building Design in the UK	*		*	*
Nazeer, Kamardeen [52]	Research needs for enhancing pre-occupancy evaluation of buildings	*			
Nguyen, Reiter [53]	A review on simulation-based optimization methods applied to building performance analysis	*	*		*
O'Brien, Tahmasebi [54]	An international review of occupant-related aspects of building energy codes and standards	*	*		
Østergård, Jensen [10]	Building simulations supporting decision making in early design–A review			*	*
Pan, Zhu [55]	Building energy simulation and its application for building performance optimization: A review of methods, tools, and case studies	*	*		

Table 2 (contd....)

Publication	Publication Title	Theme of Review			
		BPEA	SBBD	CSDW	EDIBS
Purup and Petersen [56]	Research framework for development of building performance simulation tools for early design stages	*			*
Rahman Azari and Kim [57]	Evaluating Integrated Design Process of High-Performance Green Buildings			*	
Raouf and Al-Ghamdi [7]	Framework to evaluate quality performance of green building delivery: project brief and design stage			*	
Rezaee, Brown [58]	Building energy performance estimation in early design decisions: quantification of uncertainty and assessment of confidence			*	
Ribeiro [59]	Developments in local energy efficiency policy: A review of recent progress and research	*			
Roger Chang PE and Crawley [60]	A Metric to Characterize Commercial Building Process Loads, Energy Use	*			
Rosenberg and Eley [61]	A Stable Whole Building Performance Method For Standard 90.1, Part 2		*		
Sayın and Çelebi [62]	A practical approach to performance-based building design in architectural project		*		
Shen, Singhvi [63]	Evaluating the multi-objective optimization methodology for performance-based building design in professional practice		*		
Soebarto, Hopfe [64]	Capturing the views of architects about building performance simulation to be used during design processes		*		*
Sohn and Dunn [65]	Exploratory analysis of energy use across building types and geographic regions in the United States	*			
Stevenson [66]	Embedding building performance evaluation in UK architectural practice and beyond	*			
Stavrakantonaki [67]	A Framework for Input Data Processing During Building Energy Model Calibration	*			
Taylor, Liu [68]	Towards a framework to evaluate the 'total'performance of buildings	*			
Terim Cavka, Cavka [69]	An investigation of the design process's effect on a high-performance building's actual energy system performance			*	
Tian, Heo [70]	A review of uncertainty analysis in building energy assessment		*	*	*
Tian, Zhang [71]	A review of data-driven building performance analysis and design on big on-site building performance data			*	
Utkucu and Sözer [72]	Interoperability and data exchange within BIM platform to evaluate building energy performance and indoor comfort			*	
Van Dronkelaar, Dowson [73]	A review of the energy performance gap and its underlying causes in non-domestic buildings	*			
Vojdani, Rahbar [74]	Comparative study of optimization methods for building energy consumption and daylighting performance		*		
Wang [75]	Workflow for applying optimization-based design exploration to early-stage architectural design–Case study based on EvoMass			*	
Wang, Janssen [76]	Comparing design strategies: a system for optimization-based design exploration		*		
Webb and McConnell [77]	Evaluating the feasibility of achieving building performance standards targets	*			

Table 2 (contd....)

Publication	Publication Title	Theme of Review			
		BPEA	**SBBD**	**CSDW**	**EDIBS**
Wortmann, Cichocka [78]	Simulation-based optimization in architecture and building engineering—Results from an international user survey in practice and research		*		
Xie and Gou [3]	Building performance simulation as an early intervention or late verification in architectural design: same performance outcome but different design solutions				*
Yigit and Ozorhon [79]	A simulation-based optimization method for designing energy efficient buildings		*		
Yin, Liu [80]	Comparing simulated demand flexibility against actual performance in commercial office buildings	*			

BPEA: Building Performance Evaluation and Assessment, **SBD:** Simulation-Based Building Design, **CSDW:** Collaborative and Sustainable Design Workflows, **EDIBS:** Early-Stage Design and Importance of Building Simulation.

associated with coordination among different disciplines involved in architecture, engineering, consulting and sustainability, in terms of exchanging performance data, exchanging models and making design decisions through analysis and feedback through an integration of disciplines over multiple phases during the design process [84-86]. Finally, the broad distribution of terms associated with 'uncertainty' clearly reflects rising interest in scenario-based analyses that statistically account for design variables. Collectively, this figure emphasizes a more integrated approach to 'performance evaluation,' whereby 'collaboration,' 'uncertainty,' and 'early design simulation' must all take place as elements of a seamless, interconnected design process.

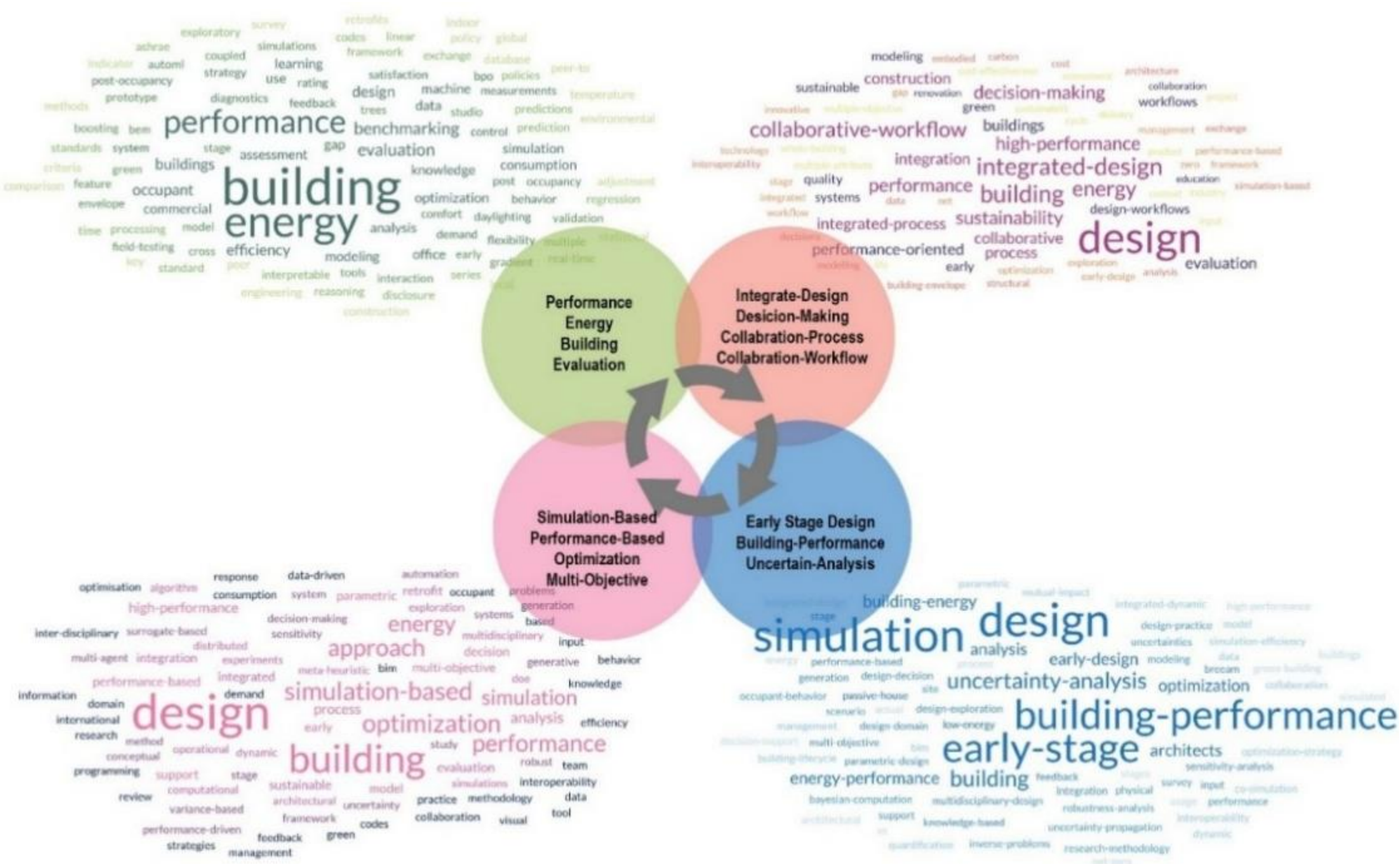

Figure 3: Keywords: co-occurrence network for the four categories and connections.

4. Finding & Discussion

Architects need to develop high-performance buildings or sites in response to the sustainability challenges in the world, such as climate change, building users' needs and comfort, increasing understanding of the link between the indoor environment and the health and well-being of the occupants, and reducing the building's environmental impact [87]. To meet this requirement, architects need models and technologies that enable them to consider interdomain systems, such as transportation and large-scale energy networks. Moreover, to design high-performance buildings, researchers have developed a wide range of tools and technologies for building energy simulation. Research reveals that an early-stage performance evaluation framework is best organized within a typology based on the three relevant areas: the design phase, the purpose of the decision-making process, and the type of performance feedback. The review's primary contribution is a typology of decision support that views early-stage performance evaluation as a series of recurrent decision-making situations rather than a single "early simulation" activity. Based on the analysis operator, available inputs, and conclusions drawn, methods are selected from the dataset. This lens highlights several issues, including sensitivity to presumptions, poor model interchangeability, and ambiguous accountability for outcome interpretation. To understand how the Four Themes relate to decisions made during the Design Phase, Table **3** presents the Four Themes and the major Decisions normally made during each of the Pre-design through Detailed Design Phases. The decision-support typology provides an invaluable resource for developing future research studies by offering a comprehensive representation that links the literature in an organized manner, from early-stage performance methods to decisions made at any design stage, through a systematic framework. This matrix of Phases, based on current research, supports the notion that early-stage simulation is of greatest value when supporting Flexible Decisions such as: Massing, Orientation, Envelope, Glazing, Daylighting, and Uncertainty Management; whereas the use of Simulation or Analysis at later phases is more closely aligned with Technical Refinement, Code Compliance, Verification, and Base Building Performance Feedback [30, 82, 83, 88].

Table 3: Decision matrix linking review themes to design-phase decisions.

Typology Dimension (Theme)	Early-Stage Exploration (Concept / Schematic)	Mid-Stage Comparison (Design Development)	Late-Stage Verification (Detailed / Compliance)
Building Performance Evaluation (BPE)	Goals, benchmarks, comfort criteria	Target checking, assumption refinement	Calibration, verification, POE planning
Simulation-Based Design	Massing, orientation, glazing, shading	Envelope, daylight, system comparisons	Compliance, technical model refinement
Collaborative Workflows	Roles, targets, decision gates	Energy, comfort, cost, carbon trade-offs	Documentation, handoff, commissioning
Early-Stage Building Performance Simulation (BPS)	Uncertainty framing, climate context, model scope	Sensitivity analysis, robust alternatives	Validated or code-based simulation

According to this typology, performance evaluation plays a supportive function throughout different types of design decision-making, including preliminary design exploration (early), mid-stage development comparison/trade-off analysis, and final design verification and compliance (late). These results were discussed in the order of the research questions rather than as isolated themes, thereby enhancing the analytical clarity of the findings. The results for RQ1 describe how performance evaluation and simulation tools have been used at each stage of the design process. This is revealed by comparing late-stage compliance evaluations with tools that support decision-making during the conceptual and schematic phases of design. The results for RQ2 relate to integrating performance tools into the building design process. Barriers that limit the integration of performance tools include input uncertainty, difficulties translating data between BIM and BEM, limited in-house expertise with performance tools, a lack of collaborative design, and misaligned timing of performance assessments with design. RQ3 discusses collaborative workflows related to the use of performance information and describes the conditions surrounding the use of decision gates, coordination of performance analysis among multiple disciplines, and the communication of performance feedback. Overall, while there seems to be consensus in the current literature that early-stage simulations can assist in making decisions about site massing, orientation, envelope design, and daylighting, there is no consensus on how these simulations will be integrated into design practice. Specifically, while tool-based research demonstrates an overwhelming level of technical potential for iterative simulation in integrated design, practice-based research continues to document the late-stage use, outsourcing, lack of expertise, and weak feedback mechanisms associated with performance tools in architectural design workflows [5, 51, 88, 89].

4.1. Building Performance Evaluation and Assessment

The issue of building performance evaluation has evolved from an intermittent review to a strategic design process incorporating occupant satisfaction, functionality, environmental issues, and compliance [1]. Among the defining trends in building performance evaluation is the rise in the application of data-driven methods. Though basic transparent methods in statistics like linear regression analyses are applicable and important in instances where the availability of data and time is a concern, studies comparing the two suggest the application of machine learning techniques to improve the predictive capability in more complex and non-linear problems (High-resolution data through sensor networks has enhanced benchmarking and evaluation), and a comparison shows how the two methods can be combined and applied in flexible evaluation strategies in the form of the free benchmarking framework Bahari described in [15].

While benchmarking practices were once solely for ranking buildings or companies, they have evolved into tools for making informed decisions. The development of gradient-boosting trees and multilinear regression models with interaction terms has provided improved predictive ability and interpretability for large office building datasets used for the ENERGY STAR benchmarking program [90]. In addition to the traditional EUI for an entire building, the use of more targeted process-energy indices and system-level KPIs for HVAC, lighting, water heating, and plug loads helps to expose inefficiencies and allows for more effective retrofits [46, 60]. Data Envelopment Analysis (DEA) has also gained popularity as a method to diagnose both technical and scale inefficiencies, to identify peer groups and to help prioritize retrofit strategies [18]. Similarly, recent developments in calibration efforts, such as the use of blackboard-AI systems to reduce the number of simulation runs required to conform to ASHRAE accuracy criteria, illustrate the growing emphasis on streamlining workflows when dealing with common limitations of data [67].

The consistent discrepancy between anticipated and actual energy consumption is one of the most prevalent issues in literature, often exceeding 30%. The research indicates that this discrepancy is attributable to multiple factors rather than a single cause. Because schedules, plug loads, infiltration, internal gains, and operational assumptions are often unclear or oversimplified, the early design phase entails considerable input uncertainty [26, 73]. Behavioral and operational factors also influence building performance; for example, window openings can significantly affect heat loads and comfort levels. Coupled modelling techniques can be used to address such changes [91]. Overall, the research indicates that individual deterministic predictions can be used to generate accurate forecasts when incorporating feedback loops and when calibration-oriented learning and interpreting early-stage results are used within risk-bounded ranges.

Recent research suggests a more adaptive, flexible approach to performance assessment that accounts for the variable demands of operational environments. Specifically, several studies directly compare simulated demand-response behaviors with real-world results and suggest that modelled flexibility is generally ±17% (on average) accurate when comparing with actual flexible results; however, the extent to which a particular model provides an accurate match is dependent upon the type of system being examined [80]. At the same time, the collection of Portfolio-level standards for Building Performance reveals that many buildings currently do not meet the requirements set forth by the latest building performance standards and will require extensive improvements or retrofits in order to keep pace with changing technology and integrate into metrics that will calculate total building emissions, as well as provide accurate calculations on a portfolio-wide basis [77]. Further evidence of this trend toward earlier evaluation includes systems like MOOSAS that automatically link 3D model files to simulation engines and offer simultaneous, multi-objective analysis in real-time during the design phase of projects [49].

A growing body of scholarly work has supported a shift from rule-based retrospective evaluations to continuous and data-driven processes that involve monitoring data, calibrated simulation tools, machine learning algorithms, and occupant feedback. Unfortunately, many gaps remain in performance evaluation practices today. One of the greatest challenges has been to develop standard verification and validation processes. The vulnerability of both the BIM-to-BEM translation and the approach to uncertainty is another example of a gap in the field. Furthermore, the wide gap between predicted and actual building performance indicates that new methods of performance evaluation are needed to assess the behavior of buildings as they are used daily, rather than on idealized assumptions used in building design. In closing, performance evaluation methods have advanced rapidly; however, integrating these assessments into the design process, especially before completion of preliminary design documents, has progressed slowly. Therefore, understanding how simulation is used in the design of high-performance buildings will help identify ways current practices can support or constrain decision-making during the design phase. Also, Several core areas of literature agree that a single factor is not responsible for the performance gap; instead, multiple factors work together, combined with the environmental conditions present within the building, such as uncertainty surrounding interactions amongst the elements of the building (assumptions, behavior of the occupants, operational schedule, weather data, simplifications of models, poor feedback) contribute to making performance gaps [92, 93].

4.2. Simulation-Based Building Design

Simulation-based building design involves treating performance analysis as a proactive participant in design decisions, rather than merely a validation check-off point. The current literature suggests that simulation offers a utility for supporting comparative analysis of design alternatives, understanding evidence in design decisions, and aligning architectural and mechanical designs with functional goals. This common line of thought raises a key question of how simulation can play a practical role in early design decisions, where impact has a proportionally greater role. The subsections below describe the two research paths related to high-performance design simulation workflows.

4.2.1. High-performance Building Design

Design scholarship recommends a structured, performance-driven analysis, rather than a trial-and-error decision-making process. Aided by software such as Optimo, multi-objective optimization techniques are integrated directly into Building Information Modeling (BIM), providing designers with a means to analyze various options comparatively and concurrently [17]. Multi-criteria analysis, including considerations of daylight, acoustics, and energy, extends design options and encourages direct analysis of design objectives. Nevertheless, several studies (Coleman & Robinson, 2018; De Wilde, 2018; Zou *et al*., 2018) suggest that a disconnect between optimization and reality can occur unless nominal inputs, behavioral simulation, and physics-based modeling are accounted for. Without these, optimization runs the risk of overstating benefits and being misled in performance. There appears to be evidence that simulation integrity, with feed-forward simulation enhanced by model behaviour, maintains validity while illustrating design-related decisions focused on energy savings and carbon reduction [45].

Significant gains in multi-objective optimization problems are often reported; however, they are typically dependent on the assumptions made. There is naturally high uncertainty in the early stages of design. The ranking of options and the trade-off between objective values can vary significantly with even small changes in input conditions. Therefore, the best practice for using optimization at these stages is to explore robust regions of the design space and to provide information on assumptions and sensitivity/performance ranges, rather than an “optimal” solution.

Early parametric modeling, in conjunction with design analysis simulation in terms of daylight, energy simulation, and optimization, provides a means of illustrating simulation analysis as developing design, rather than mere minimum compliance with various codes, in support of daylight access, energy performance, and system simulation methodologies combined with simulation, shading, and glare analysis alternatives [63].

4.2.2. Simulation-based Approach in Design

Evidence from educational practice indicates that performance tools are used as individual checks rather than within a continuous cycle when used independently. Students can test and connect massing, daylighting, and ventilation strategies and relate form-making with performance targets in integrated-studio structures that include Sefaira, DIVA, and Coolvent at every stage [37, 94]. In contrast to post-design validation workflow techniques, the early use of daylight-factor studies and solar-insolation mapping in the early stages of schematic design also connects architectural choices with energy targets [33].

However, the use of simulation in practice varies widely, and many firms still struggle to apply it consistently throughout the design process. Many firms still rely on external assistance for modeling, or resort to it only when certifying, due to time constraints, skill gaps, and contracts that do not fully account for analysis. When they resort to simulation, it typically occurs during the concept phase to refine the design, verify daylight availability, and evaluate energy consumption. Optimization in practice often invokes general genetic algorithms, despite more specific techniques potentially providing greater accuracy and efficacy [64, 78]. Rules mandated by regulations are making the guidelines less ambiguous: the ASHRAE 90.1 Appendix G fixed baseline facilitates fair comparisons across various phases and schemes, such as LEED. Nevertheless, code assumptions of occupancy, schedule, and load differences can still lead to different predictions, which indicates that inputs ought to be normalized if resorting to simulation in demonstrating compliance [54, 61, 95].

One of the most emphasized themes in literature is the need to improve the connection between assumptions used in simulation and reality. By linking simulations to monitoring data, designers can create envelopes and systems that are adaptive to observed occupant usage rather than based on assumed usage [96]. Co-simulation methods, which combine energy engines and behavioral components, provide a means to incorporate occupancy- and comfort-related behavioral effects into actual performance simulations [91]. The latest ontology systems in simulation development further reduce manual effort in updating simulations by dynamically generating content based on the evolving nature of design changes, which may help mitigate sensitivities associated with simple BIM/BEM transfer methods [22]. Sensitivity analysis can further improve simulation outcomes by identifying the parameters that most affect the output, thereby enabling a systematic approach to designing simulation inputs with clearer objectives [27, 32].

Recent technological developments have expanded opportunities for how simulation integrates into continuous design feedback loops. Hybrid parametric/optimization strategies, based on cloud technology and evolutionary algorithms, enable simultaneous assessment of massing and system designs, allowing designers to make informed decisions early in the design stage [76]. Integrated simulation/optimization environments reduce the cost of coupling and speed up investigations of envelope and system designs [79]. Simulation/optimization research using physics engines in combination with metaheuristic algorithms extends design exploration to other model parameters and combinations of geometric and/or envelope designs, with machine learning models shortening computation time and improving forecast accuracy [53, 55, 71]. Such simulation/optimization workflows demonstrate how simulation can resolve performance trade-offs, such as visual comfort and overheating in highly glazed buildings, by investigating color schemes, façade proportions, and space-planning solutions for these design tasks [62]. Retrofits are also aided by the interoperability of simulation models with BIM, aligning environmental, economic, and energy parameters to support evidence-based decision-making [35]. One area where caution is generally advised in the literature is the impact of climate assumptions. Research shows that simulation outcomes are highly sensitive to the assumptions used to select the simulation weather files; thus, caution is necessary in this area [19, 24, 34].

A pattern consistently observed across these studies is the effectiveness of simulation when it is continuous, integrated, and grounded in actual building behavior. Most current workflows use simulations only at very late stages, which may lead to a lack of feedback on a design's real-world performance and to the use of inappropriate assumptions that diminish a simulation's predictive ability. There is a lack of integration between modelling systems, which creates inconsistencies between simulations and designs; moreover, the absence of systems to incorporate simulations into the design process introduces additional uncertainty and fragmentation. The above points provide direct support for the subsequent exploration of collaborative, sustainable workflows, with a focus on organizational factors, communication patterns, and collective work processes that determine whether simulation is a strategic tool for design or merely a separate technical activity.

4.3. Collaborative and Sustainable Design Workflows

The collaborative and sustainable design processes are multispecialty, early-stage, performance-informative co-design processes based on shared BIM/BPS models, simultaneous option testing, and explicit decision gates. Within this family, sustainable design processes use parametric studies, sensitivity/uncertainty analysis, and benchmarking to compare with code or prototype baselines to achieve energy, carbon, and comfort outcomes [37, 53, 62, 71, 94, 97]. This workflow is best understood not as a compilation of individual practices, but as a repetitive process of steps designed to reduce information density. In such an understanding, a team might develop a set of assumptions, a clear intent for performance, multiple options developed in parallel, analyses performed at a speed consistent with the maturity of the information, an evaluation of the outcome relative to a standard or target, and finally, the implementation of design changes before continuing to the next step. The literature suggests that errors occur at specific points: data loss arises from transferring models between Building Information Modeling (BIM) software and analysis tools, assumptions change over time, and authority is unclear when consultants or other disciplinary groups generate outcome data (Fig. **4**).

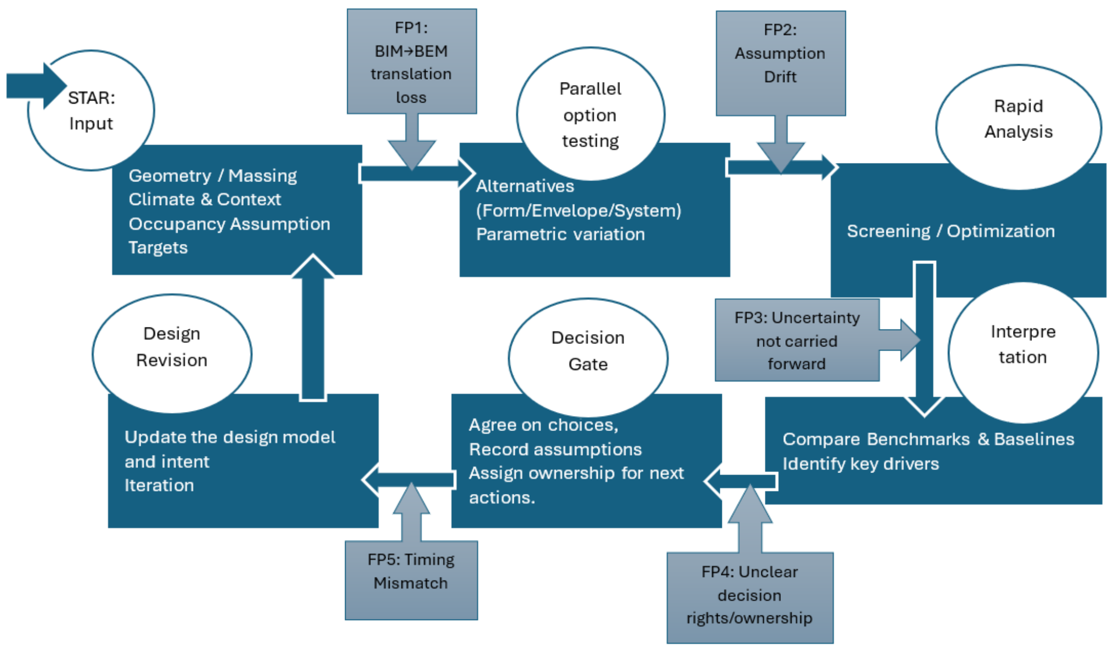

Figure 4: Collaborative performance workflow with failure points.

Fig. (**4**) portrays an example of a collaborative performance workflow along with five repeatable failure points. Failure Point 1 (FP1) indicates data loss when translating Building Information Models (BIM) to Building Energy Models (BEM), such as geometric and zoning inconsistencies that must be corrected manually after translation. Failure Point 2 (FP2) represents the concept of "assumption drift", where input items such as construction schedules and system parameter values change between iterations of the model without being tracked in a consistent manner. Failure Point 3 (FP3) considers the inability to carry forward uncertainty into subsequent iterations of the model, resulting in an overreliance on deterministic output. Failure Point 4 (FP4) relates to unclear decision rights across numerous discipline teams, resulting in an inability to interpret and act on received information. Failure Point 5 (FP5) relates to discrepancies in the timing of when simulation output is received, creating an inability to influence design decisions due to the time lag. Failure Points 1, 2, 3, 4, and 5 demonstrate common challenges documented in the literature, such as interoperability issues, fragmented communication, and misalignment between analysis and design workflows. For these reasons, a performance-oriented process might remain a technical exercise in parallel with the development of tools for benchmarking, sensitivity analysis, and parametric analysis [37, 53, 62, 71, 94, 97]. In addition to the previous information, IFC and gbXML, which are examples of neutral built environment data exchange schemas, represent two of the primary forms of transferring

BIM models into energy simulation software, however there are often Geometry related errors, missing envelope components, zoning inconsistencies, and material transfer problems that can cause additional work and therefore are not addressed in this review, which will focus on decision making, not technical benchmarking. These errors will be addressed as workflow limitations affecting the reliability and timeliness of early-stage performance feedback [98-100].

Green-building targets are pushing toward a hybrid-driven process in which architects and engineers pass analysis and design back and forth, employ interoperable tools connecting BIM and parametric modeling and simulation, and iterate targets in parallel option testing; bracketing and mockup at the design stage close the loop on forecasted vs. actual energy use [47].

4.3.1. Integrated Design Building Performance Framework

Functional and durable design workflows are within reach when teams participate in early, interdisciplinary co-design, using specific checkpoints and a shared decision-making vernacular. Two evaluation matrices validate the approach. The first uses the Context, Input, Process, and Product model to describe how teams plan, collaborate, and measure results during the implementation stage; it recommends a weighted set of criteria for an Integration Maturity Index, thereby facilitating incremental evaluation and improvement of projects [57]. The second converts the quality of collaboration into measurable terms. It details twenty integration factors and sixty-five indicators, rates them on a five-point scale, and places them into indices that predict project success, providing leaders with clear thresholds for decisions to proceed or hold back [6].

Evidence from practice demonstrates the importance of governance levels. For instance, "building performance" remains amorphously defined in small firms, so targets set early on remain tenuous; a three-firm case study presented thirty-three daily complications and abstracted eight integrated design themes that assist teams in acting on early-design performance [36]. Collaboration guarantees accountability only if there is a specific structure to the facilitation. A facilitator model provides preparatory phases for the establishment of a common purpose and structured reviews for decision gates; the standard criteria for assessment made the gates auditable and provided feedback across disciplines [44].

The net-zero energy building framework by Lu, Sood [50] systematically classifies different factors and their critical interconnections under the banners of Context, Input, Process, and Product. It then verifies these aspects in a live university project. The research team undertook eight design workshops that considered different alternatives through an "energy story" eye on the overall building energy budget, gathered occupant-use data on a room-by-room basis to support load specifications, and utilized mock-ups with user trials to ratify an innovative hybrid heat, ventilation, and air-conditioning system—converting checkpoints into decisions supported by measurable energy and comfort results [50]. Across the brief and design stages, a quality framework outlines the participants, scheduling, and deliverables at each stage: including cross-disciplinary charrettes, early decisions on risks and delivery, and a first-in first-out commissioning brief; followed by a simplified whole-building energy model in the scheme design, hourly energy modeling alongside initial indoor-environmental evaluations in the preliminary design, and a compliance energy model with integrated reviews of durability and building management in the final design stage, all tied into established standards in the field of energy, ventilation, and comfort [7]. Data and uncertainty management form the foundation of performance-informed gates. An engine-neutral protocol guides choices across scenarios for maintenance and operational quality, weather data selection, and user activity, so targets are established as distributions and confidence levels rather than a point. An engine-independent performance-data schema is paired with it and connects results and inputs, remaining up to date with code changes to reduce rework during handoffs. Measurement portfolio evidence of results (e.g., broad distributions in energy use intensity among "high-performance" offices) points out why these checks need to reside on the inside of early design and not after the fact [9].

In conclusion, two lenses are used to complement this section. According to a management study, comprehensive building optimization requires goal setting during the pre-design stage, cross-disciplinary co-design from the outset, life-cycle economic considerations, and deliberate commissioning. It also identifies practical barriers, like current contracts and procurement models that do not currently support integrated teamwork [20]. Additionally, a three-stage development framework for renovation links multi-stakeholder workshops with a foundation in Building Information Modeling, allowing for staged assessments that let teams modify integrated design to suit particular situations while keeping an eye on energy and comfort goals at every turn [40].

4.4. Building Performance Simulation at Early-Stage Design

Early use of Building Performance Simulation encourages climate-responsive massing and envelope decisions, whereas late use is associated with "point chasing" (optimizing for certification points rather than real performance). As a result, projects that use it to guide design perform better than those that only use it for end-stage verification [3]. Therefore, Building Performance Simulation is appropriate for concept and schematic stages. Groups in workshops used this configuration to orient adjustment, external shading, glazing, insulation, and solar sizing; however, a more precise presentation of results was still needed. Informative early procedures include brief training and a checklist for modeling with DesignBuilder or ZEBO, followed by sensitivity runs and a climate study [4]. Architects typically avoid complex, expert-only software that impedes sketching or compromises form.

Furthermore, early analysis is frequently limited by costs and time restrictions. Many offices outsource modeling, resulting in static reports. This might hinder two-way communication and budgetary analysis throughout the conceptual and planning stages [56, 64]. According to Negendahl [5], a live link between the design tool and the solver allows for quick, in-context parametric tests. It also prefers runtime connections over slow file exchanges, requires careful scripting and validation when using distributed setups, and starts light and gets more precise as inputs mature. According to Østergård, Jensen [10] the method selection should account for early uncertainty, proactive parametric runs, sensitivity and uncertainty analyses with knowledge-based defaults, and allow teams to explore a wide range of options before deciding with a declared level of confidence. Simple behavior scenarios or a light co-simulation loop can capture how window, door, and blind actions affect total energy and the end-use mix. People's effects should be included from the beginning [39]. Since engine differences and typical 10–30 percent gaps to observed data are common in idea investigations, phase-appropriate methods and specific error limitations are necessary [14]. Effective transfers from Building Information Modeling to Building Energy Modeling allow for the use of early studies. For example, an Industry Foundation Classes-based repair and zoning pipeline reduces export losses from Green Building eXtensible Markup Language, producing reliable energy models for confident gates and speedy option testing [16].

4.4.1. Challenges and Developments of Building Performance Simulation

In the early stages, small inputs, rapidly changing geometry, and large option spaces make single deterministic runs unreliable guides. Instead of focusing on one variable at a time, Østergård, Jensen [10] suggests exploring the design space globally and considering key inputs as uncertain from the beginning. At the same time, the field is moving toward evaluating simulations based on their performance throughout the entire building life cycle. However, quality control remains uneven, as validation and verification should commence at the problem formulation stage, and confidence intervals must be reported; however, this is frequently not the case [1]. Recent research in the UK indicates that most users apply simulation for validation late, rather than at the concept stage. Non-users report insufficient knowledge, time, or money to use software. Interest is growing in plug-ins, cloud runs, and parametric add-ons that fit sketch-speed workflows [51].

Three advancements treat these early design issues. The first action employs uncertainty and sensitivity analyses, including ranking drivers using global sensitivity analysis, conducting multiple runs, using distributions for uncertain inputs, and employing sampling. Second, decisions are made that communicate certainty rather than merely relying on numerical and scenario factors, such as weather or occupancy, which are treated directly [10, 11]. Third, live coupling and automation: the Evolutionary Energy Performance Feedback for Design framework takes Excel, Green Building Studio, and Revit, and automatically translates, evaluates many options, and shows side-by-side energy, cost, and program views; using this, users made better Pareto solutions in the same session, and after running just a few generations of genetic algorithms, helpful "performance boundaries" emerged that were amazing for fast gates [48]. Lastly, experts prioritize simple data processing and clear graphics over maximal concept precision; cloud-based systems and plug-ins reduce latency, so that feedback can keep pace with design. Ultimately, the latest advances in software engineering are facilitating the exchange of BIM data with simulations [51].

Despite these developments, important gaps remain. Many methods are validated in controlled or tool-specific environments, across different design settings, and on various software platforms. The incorporation of methods for handling uncertainty is uncommon in practical applications, whereas live coupling is always a technical challenge or a tool-specific solution. Again, few studies in this area analyze adoption in practical applications, design decision-making, or the role of workflow design in effectiveness. The current literature provides robust technical solutions. However, there is a gap in understanding their practical applications in simulation-based performance evaluation tools, techniques, or workflows for addressing design-related uncertainties or challenges across various applications and design fields. Table **4** summarizes recurring evidence patterns from the literature review by listing matching key or main claims and their associated consistent findings. This synthesis demonstrates a correlation between the primary claims of the reviewed studies and the consistent findings in the literature, and illustrates where there is consensus and inconsistency among the reviewed studies with regard to the claims made.

Table 4: Structured evidence supporting key review claims.

Key Claim	Evidence Pattern in Literature	Implication for Practice
Early-stage simulation supports design decisions	Studies consistently show use in massing, orientation, envelope, and daylight analysis	Simulation is most valuable before design decisions are fixed
Performance gap remains significant	Reported differences between predicted and actual performance linked to assumptions, behavior, and operations	Results should be communicated with uncertainty, not single values
Simulation adoption is inconsistent	Practice-based studies report late-stage use, outsourcing, and limited expertise	Integration depends on workflow and organizational capacity
Collaborative workflows improve outcomes	Studies highlight decision gates, shared models, and interdisciplinary coordination	Workflow structure determines impact of simulation on design
BIM–BEM interoperability is a barrier	Studies report geometry, zoning, and data-transfer issues	Model exchange affects reliability and timing of feedback

Beyond the emphasis on uncertainty analysis, the literature offers limited guidance on method selection under time constraints and with limited information about the model in the early stages of development. Therefore, in practice, method selection is generally determined by available computational resources, time constraints, and model maturity. As a result, it is often more practical to use screening methods during rapid early-stage exploration (i.e. Morris) and to depend on variance-based methods (i.e. Sobol) as the model becomes more stable and detailed [101, 102]. The implication of a staged approach is that low-cost, early-stage sensitivity screening supports early-stage decision-making, while subsequent analyses are conducted with greater detail as the design nears resolution.

5. Conclusion

There is broad consensus on the need for performance work to move into concept and schematic design, on reporting uncertainty rather than a single number, and on the need for decision gates to guide decision-making. What is not evident in the literature is how architecture firms accomplish this during the brief periods when early decisions occur. There is little practical evidence of how teams conduct verification, validation, and confidence reporting with real deadlines and fee constraints. The significant variations in measured energy use for buildings of the same type also indicate a need for protocols and benchmarking related to weather, operations, and occupants, which are integral to daily delivery rather than merely compliance models.

Comparative accounts of who performs which analyses, how the analysis connects to design gates, how feedback is conveyed to the design team while geometry remains variable, and how client goals and ownership models affect decision-making remain crucial practice topics. Many places encourage early investigation of close ties, which are two-way or more frequently one-way links from design tools to solutions. However, there is little proof of adoption or practical effects. Some frameworks outline gate policies and define the required model accuracy for each phase. Still, examples of how they are used across project types and company sizes have not been consistently shown. Existing interoperability challenges compound the difficulty of the early evaluation process. Although the existing literature addresses the translation between BIM and BEM, information on the representation of the number of failures in terms of the approach used under time constraints is scarce. Adoption studies often view simulation as a late or outsourced process, acknowledging the limited in-house skills for this purpose (Fig. **4**). However, few studies examine how realized performance or specific in-house gate policies influence this process. Fig. (**5**) synthesizes the consensus in the literature, documented practice gaps, and the resulting motivation for this study.

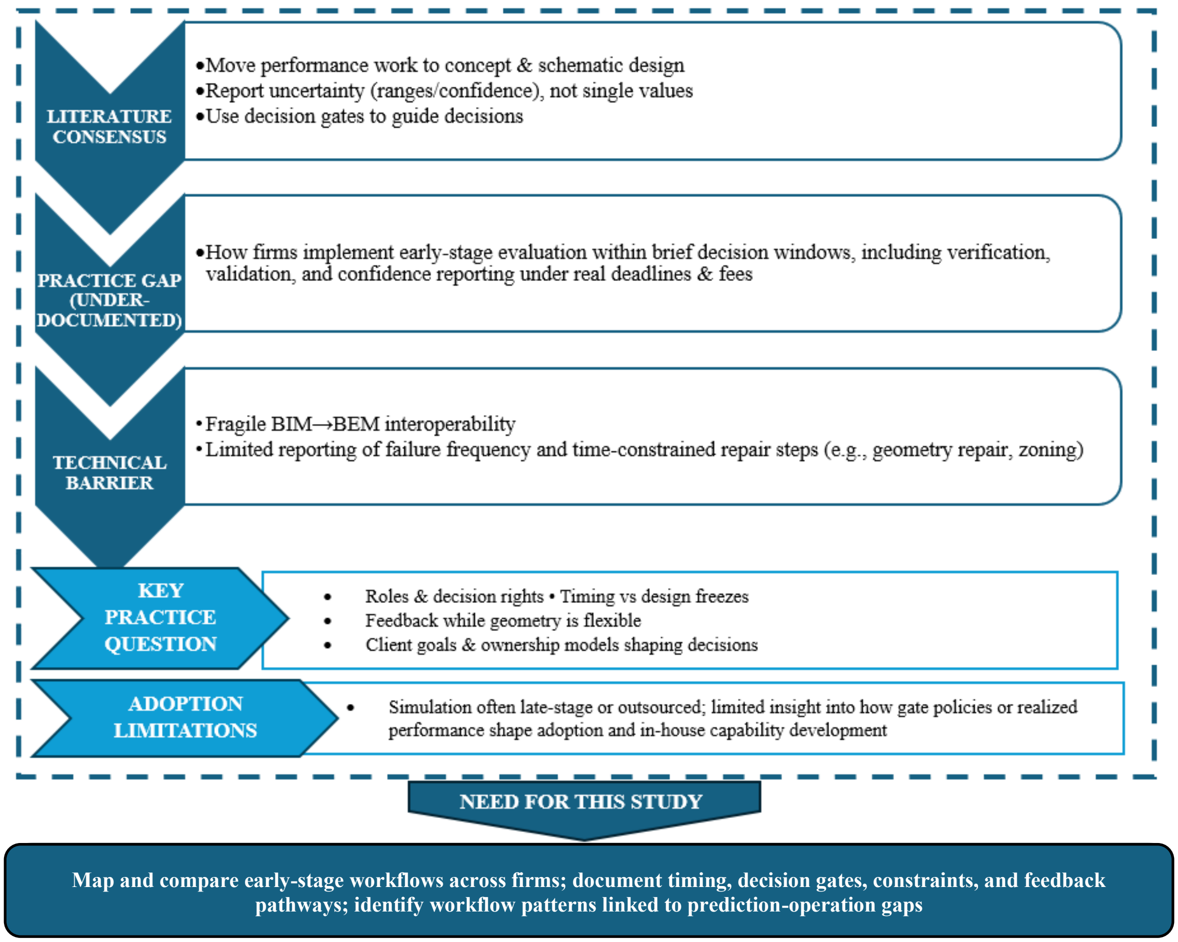

Figure 5: Conceptual synthesis of literature consensus, gaps, and study motivation.

This review identified a gap in the literature and proposed a clear direction for future research: investigating and charting performance evaluation in the early stages of the workflow in architectural practices. The aim is not to define an optimal approach, but to clarify how simulation is integrated in the project workflow, how performance information is propagated in the design process, and how this influences the decision-making process. Taking a workflow-centered approach can help to generate practice-based evidence and to reveal patterns that explain the discrepancies between predicted and actual performance.

Future Research

To clarify, this section of paper outlines future research directions and identifies additional testing areas and relevant questions related to the use of simulation to support decision-making in construction projects. In particular, in order to begin to explore the questions raised above about how simulation is being used, researchers will need to answer the following questions: (1) How do the procurement model or contract structure affect the integration of simulation into different firms size?; (2) How does the timing of events or the establishment of design freeze points diminish the usefulness of simulation as a source of feedback for early design stages?; (3) How does the existence of in-house skills and the characteristics of the firm's organizational structure affect the use of simulation as a design tool versus a means of compliance?; and (4) How do various decision gate systems affect the transfer of performance information and/or uncertainty from one design stage to another?

Limitation

The conditions and assumptions governing modeling practices are not clearly specified in the literature reviewed with respect to uncertainty, verification, and validation. Consistent with the literature, there is evidence that discrepancies between predicted and measured results can be substantial due to differences in weather patterns, operating conditions, and human behavior. Based on these considerations, this review emphasizes patterns in methods and workflows rather than actual improvements and generalization limitations.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of Generative AI Use

The author acknowledges the use of ChatGPT (OpenAI, *https://chat.openai.com*) and Grammarly to assist with manuscript preparation. AI was used to help refine grammar, enhance clarity, and rephrase certain technical explanations for improved readability. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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