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Review

Simulation in the Built Environment: A Bibliometric Analysis

Saman Jamshidi

School of Architecture, University of Nevada, Las Vegas, NV 89154, USA; saman.jamshidi@unlv.edu

Abstract

Simulation has become a pivotal tool in the design, analysis, and optimization of the built environment, and has been widely adopted by professionals in architecture, engineering, and urban planning. These techniques enable stakeholders to test hypotheses, evaluate design alternatives, and predict performance outcomes prior to construction. Applications span energy consumption, airflow, thermal comfort, lighting, structural behavior, and human interactions within buildings and urban contexts. This study maps the scientific landscape of simulation research in the built environment through a bibliometric analysis of 12,220 publications indexed in Scopus. Using VOSviewer 1.6.20, it conducted citation and keyword co-occurrence analyses to identify key research themes, leading countries and journals, and central publications in the field. The analysis revealed seven primary thematic clusters: (1) human-focused simulation, (2) building-scale energy performance simulation, (3) urban-scale energy performance simulation, (4) sustainable design and simulation, (5) indoor environmental quality simulation, (6) building aerodynamics simulation, and (7) computing in building simulation. By synthesizing these trends and domains, this study provides an overview of the field, facilitating greater accessibility to the simulation literature and informing future interdisciplinary research and practice in the built environment.

Keywords: simulation; built environment; architecture; interior design; building; performance

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1. Introduction

Simulation plays a pivotal and increasingly vital role in the design, analysis, and optimization of the built environment. A range of simulation techniques enables professionals in architecture, engineering, and urban planning to test hypotheses, explore design alternatives, and evaluate performance outcomes under various conditions—before any physical construction occurs. Applications span energy consumption [1], airflow [2], thermal comfort [3], lighting [4], structural behavior [5], and human interactions within buildings [6] and urban contexts [7].

The two main categories of simulation methodologies are (1) experimental simulation, which involves physical experimental setups, and (2) numerical simulation, which relies on mathematical models and numerical methods, typically executed via computer software [8]. Examples of experimental simulation include wind tunnel testing and full-scale mock-ups (e.g., [9]). Numerical simulation encompasses techniques such as agent-based modeling, finite element analysis, and computational fluid dynamics (CFD) (e.g., [10]). Numerical simulations are often favored for their flexibility and lower cost per iteration, as they allow for scenario modifications without the physical constraints and resource demands of experimental setups [11]. Nevertheless, experimental simulation remains critical where it serves to validate or calibrate numerical results through empirical testing [12].

The rise in computer-based simulations has been accelerated by advancements in hardware (e.g., GPUs) and software platforms, such as building information modeling (BIM) and digital twins, along with the increasing accessibility of these technologies. These developments have made it possible to simulate complex phenomena. A prime example is building energy performance simulation, which involves modeling a complex interplay of building characteristics, integrated systems (e.g., HVAC and lighting), external weather conditions, and occupant behavior (e.g., [13]).

The benefits of simulation in the built environment are multifaceted. These include the following: (1) supporting more informed decision-making during the design process and reducing costly design errors; (2) optimizing building performance; (3) minimizing risks associated with extreme conditions such as fires, earthquakes, or severe weather; and (4) facilitating scenario testing in dynamic and complex systems. Despite these advantages, simulation methods face several limitations. First, they rely on assumptions that may not fully capture real-world variability, potentially leading to inaccuracies. Second, simulations demand high-quality input data and reliable modeling techniques. Third, detailed simulations can be computationally or physically intensive, posing challenges for iterative design and broad adoption. Finally, ensuring that simulation results correspond to real-world performance—particularly over long-term or system-level studies—remains a persistent challenge.

Considering the breadth and complexity of simulation-related topics in the built environment, mapping the scientific literature can provide valuable insights. A comprehensive overview can support interdisciplinary collaboration by identifying key research themes, uncovering knowledge gaps, and highlighting emerging trends that bridge disciplinary boundaries and foster innovative approaches to complex challenges.

Various literature reviews have previously contributed to understanding simulation's role in specific domains of the built environment, effectively offering partial scientific mappings of their respective areas (e.g., [14–16]). For instance, Harish and Kumar [16] reviewed simulation methods used in modeling building energy systems, while Fumo [17] offered an overview of building energy simulation fundamentals. Although these narrative reviews provide in-depth analysis and critical reflection on specific topics, they often suffer from limitations such as narrow scope and small sample sizes (typically 20 to 200 studies) [18,19].

In contrast, bibliometric analysis offers a quantitative and systematic alternative that addresses many of these limitations. By leveraging computational tools and bibliographic databases, bibliometric methods can analyze large datasets efficiently and objectively. Rather than relying on subjective interpretation, these methods use indicators such as citation counts, h-index values, journal impact factors, and co-authorship networks to assess scholarly influence and connectivity. The increasing application of bibliometric techniques across disciplines (e.g., [19–21]) has been facilitated by access to metadata from databases such as Scopus, along with visualization tools like VOSviewer and Gephi [18].

The two main types of bibliometric analysis are performance analysis and science mapping. Performance analysis assesses the output and impact of research at the levels of individuals, institutions, journals, or countries. Science mapping, on the other hand, visualizes the intellectual structure and development of a research field.

Several bibliometric studies have explored building-related topics, including structural simulation [22], human-building interaction [23], and energy efficiency [24,25]. However, as simulation becomes increasingly embedded across disciplines, the literature remains fragmented. A comprehensive bibliometric analysis is needed to integrate these perspectives and reveal how simulation supports decision-making during the design process across the built environment. This gap motivates the current study.

Accordingly, this research aims to provide a detailed bibliometric map of the scientific landscape surrounding simulation in the built environment. The study is guided by the following research questions:

1. What are the leading countries and journals in the field of simulation in the built environment?
2. What are the central publications in the citation network of this research area?
3. What are the most frequently occurring keywords, and how are they interconnected?
4. What are the major themes in the literature on simulation in the built environment?

This paper offers a unique and comprehensive mapping of simulation research in the built environment that surpasses previous reviews in both scope and analytical depth. While earlier works have addressed specific subdomains, such as energy modeling or occupant behavior, this research is the first to apply a large-scale bibliometric analysis—covering over 12,000 publications—to synthesize trends across the entire interdisciplinary landscape. The originality of this study lies in its data-driven methodology and its ability to reveal the field's intellectual structure, identify emerging themes, and highlight research gaps. In this way, it enhances the state of the art by offering a strategic overview that can guide future research, inform policy, and support practitioners in making more informed decisions about simulation tools and applications. This study is particularly valuable for researchers seeking to position their work within the broader context, for educators designing simulation curricula, and for professionals aiming to integrate simulation into design and planning workflows more effectively.

2. Methods

2.1. Identifying Pertinent Publications

This paper adopts the method of Jamshidi et al. [19], with some modifications. The Scopus database was used to conduct a literature search in order to find publications that were pertinent to simulation in the context of the built environment. The keyword *simulation* was paired with various building-related terms (i.e., *building*, *built environment*, *physical environment*, *interior design*, and *architecture*) to search in the author-provided-keywords field. The search was executed using the following query: AUTHKEY (simulation) AND AUTHKEY (building OR "built environment" OR "physical environment" OR "interior design" OR architecture). No restrictions were applied to this search in terms of publication date, geographic location, language, or document type.

Conducted in April 2025, the search returned a total of 12,220 records dated from 1972 to 2025. Not all of these were directly relevant to simulation in the context of built environments. To enhance the efficiency of the review process, manual screening of records for relevance was not performed. Instead, VOSviewer version 1.6.20 [26], was used to identify relevant publications and exclude outliers. This method allowed for a more streamlined analysis by minimizing the need for time-consuming manual evaluation.

Five analytic techniques are available in VOSviewer version 1.6.20 [26] for assessing an item's relatability, including keywords, countries, and publications. These techniques include: (1) bibliographic coupling, (2) citation analysis, (3) co-citation analysis, (4) co-authorship analysis, and (5) co-occurrence analysis. For a comprehensive explanation and practical examples of these bibliometric methods, refer to Donthu et al. [18]. In this paper, citation analysis and co-occurrence analysis were selected as the primary methods, as detailed in the subsequent section.

2.2. Data Analysis

To identify the most prominent countries and journals in the domain, two primary metrics were utilized: (1) total number of publications (TP), representing research output,

and (2) total citations (TC), reflecting scholarly influence. These metrics served as the basis for generating rankings that highlight both productivity and impact across geographic and publication sources.

To identify key publications in the domain of simulation within built environments, citation analysis was used. This method evaluates the degree of relatedness between documents by examining how frequently they cite one another—a metric referred to as the link count. Higher link counts indicate that publications are more central within the citation network. This approach also facilitated the exclusion of outliers, as irrelevant documents typically lacked citation links to core publications in the field. Based on this analysis, the 40 most influential publications were identified and ranked according to their centrality in the citation network.

The keyword analysis encompassed five components: (1) identifying the most commonly used keywords, (2) creating visual network maps of keyword relationships, (3) detecting clusters of related keywords, and (4) identifying the most frequently occurring keywords in each cluster. Prior to performing these analyses, a thesaurus was developed to standardize variations in terminology, ensuring consistency across different spellings, singular/plural forms, and conceptually similar terms (e.g., "finite element method" and "finite element simulation").

To generate a visual network of keyword relationships, a co-occurrence analysis was conducted using VOSviewer version 1.6.20 [26]. This analysis focused on author-provided keywords from the selected publications. In the resulting network graph, nodes represent individual keywords, with node size corresponding to the frequency of occurrence. Connections (or links) between nodes indicate that the paired keywords appeared together in the same publication. For clarity, the visualization can be filtered to display only the strongest connections, meaning the absence of a visible link does not necessarily imply a lack of association. VOSviewer version 1.6.20 [26] assigns keywords to clusters with different colors to aid in the interpretation of thematic groupings within the network.

Finally, to support the qualitative interpretation of each cluster, the most frequently occurring keywords within each group were identified and ranked. By combining insights from the keyword network visualization with these rankings, thematic labels were assigned to each cluster, enabling a clearer understanding of the dominant topics represented in the literature.

3. Results

3.1. Top 20 Countries

Table 1 presents the 20 most active countries in the field, ranked according to two key metrics, total number of publications (TPs) and total citations (TCs), which reflect research productivity and impact, respectively. China leads in terms of publication volume, followed by the United States, Italy, and the United Kingdom. When considering research impact, the United States ranks highest, with China, Italy, and the United Kingdom following in that order.

3.2. Top 10 Journals

Table 2 highlights the top 10 journals contributing to the field of simulation in built environment research, ranked by total publications (TP) and total citations (TC), which reflect output and scholarly influence. The most prolific journals were *Energy and Buildings*, *Building and Environment*, and *Energies*. With respect to research impact, *Energy and Buildings* again ranked first, followed by *Building and Environment* and *Applied Energy*.

3.3. Central Publications

Citation analysis was employed to assess the degree of relatedness between papers by examining the frequency of mutual citations. Following this, the papers were ranked according to their connectivity within the citation network. The 40 most interconnected papers are presented in Table 3.

Table 1. The 20 leading countries ranked by productivity (TP) and research impact (TC).

Rank	Productivity		Impact	
	Country	**TP**	**Country**	**TC**
1	China	2966	USA	62,115
2	USA	1951	China	35,354
3	Italy	1031	Italy	30,178
4	United Kingdom	820	United Kingdom	21,781
5	Germany	708	Canada	16,042
6	France	543	Germany	13,714
7	Canada	532	Hong Kong	11,525
8	Spain	445	France	11,350
9	South Korea	347	Netherlands	11,112
10	Australia	346	Australia	9469
11	Japan	342	Spain	8612
12	India	305	Belgium	8553
13	Hong Kong	297	Switzerland	8322
14	Netherlands	264	Portugal	6178
15	Brazil	253	South Korea	5986
16	Portugal	216	Sweden	5915
17	Belgium	202	Japan	5811
18	Sweden	200	Brazil	5054
19	Switzerland	197	Denmark	3755
20	Iran	181	Iran	3332

Note. TP = total publications; TC = total citations.

Table 2. The 10 leading journals on the topic of simulation in the context of built environments based on productivity (TP) and research impact (TC).

Rank	Productivity		Impact	
	Journal Title	**TP**	**Journal Title**	**TC**
1	Energy and Buildings	875	Energy and Buildings	50,241
2	Building and Environment	385	Building and Environment	21,492
3	Energies	262	Applied Energy	14,864
4	Applied Energy	226	Automation in Construction	5717
5	Journal of Building Engineering	219	Renewable and Sustainable Energy Reviews	5545
6	Buildings	205	Journal of Building Engineering	4561
7	Sustainability	192	Journal of Building Performance Simulation	4405
8	Energy Procedia	190	Energy	4347
9	Building Simulation	155	Energies	4097
10	Journal of Building Performance Simulation	147	Building Simulation	3877

Note. TP = total publications; TC = total citations.

Table 3. The 40 most central publications in the citation network related to simulation research within the context of the built environment.

Rank	Ref.	Publication Main Title	LC	TC
1	[14] *	*Occupant behavior modeling for building performance simulation*	132	743
2	[27]	*User behavior in whole building simulation*	87	522
3	[28]	*Interactions with window openings by office occupants*	85	422
4	[16] *	*A review on modeling and simulation of building energy systems*	80	561
5	[29]	*Co-simulation of building energy and control systems with the building controls virtual test bed*	78	364
6	[30] *	*Advances in research and applications of energy-related occupant behavior in buildings*	73	452
7	[31]	*Building model calibration using energy and environmental data*	67	221
8	[15] *	*Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design*	65	358
9	[32] †	*Building simulation*	65	170
10	[33]	*Results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings*	63	488
11	[34] *	*Methodologies and advancements in the calibration of building energy models*	59	189
12	[35]	*Simulation-based decision support tool for early stages of zero-energy building design*	58	361
13	[13] *	*An ontology to represent energy-related occupant behavior in buildings*	58	271
14	[36]	*Analysis of uncertainty in building design evaluations and its implications*	57	270
15	[37]	*A new methodology for investigating the cost-optimality of energy retrofitting a building category*	56	165
16	[38]	*Calibrating whole building energy models: An evidence-based methodology*	55	237
17	[39]	*Modelica buildings library*	53	529
18	[40] †	*Integrated building performance simulation*	53	150
19	[41]	*A novel approach for building occupancy simulation*	52	256
20	[42]	*On approaches to couple energy simulation and computational fluid dynamics programs*	52	247
21	[43]	*An occupant behavior modeling tool for co-simulation*	52	157
22	[44]	*Window opening behaviour modelled from measurements in Danish dwellings*	51	271
23	[45]	*Impacts of future weather data typology on building energy performance*	51	239
24	[46]	*On the behaviour and adaptation of office occupants*	50	334
25	[47]	*Energy retrofit of historical buildings*	48	180
26	[48] †	*Ten questions concerning occupant behavior in buildings*	47	446
27	[49] *	*The impact of occupants' behaviours on building energy analysis*	47	437
28	[50]	*The influence of building height variability on pollutant dispersion and pedestrian ventilation in idealized high-rise urban areas*	46	368
29	[51]	*Calibrating whole building energy models: Detailed case study using hourly measured data*	46	172
30	[52]	*Simulation of occupancy in buildings*	45	211
31	[53] *	*A review of current and future weather data for building simulation*	45	168
32	[54]	*Verification and validation of EnergyPlus phase change material model for opaque wall assemblies*	44	340
33	[55]	*Numerical evaluation of wind effects on a tall steel building by CFD*	44	252
34	[17] *	*A review on the basics of building energy estimation*	43	356
35	[56] *	*Pedestrian-level wind conditions around buildings*	43	352
36	[57]	*Model calibration for building energy efficiency simulation*	43	165
37	[58]	*Innovative technologies for NZEBs*	43	83
38	[59] *	*Advances in building simulation and computational techniques*	42	144
39	[60] *	*Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency*	40	876
40	[61]	*A green roof model for building energy simulation programs*	40	591

Note. * Literature review; † position paper; Ref. = reference; LC = links count; TC = total citations.

Twelve of the publications listed in Table 3 are literature reviews that explore a variety of themes within the domain of building simulation. These themes include simulation tools and methodologies for assessing building performance [15,59], patterns of occupant behavior in indoor environments [13,14,30,49,52], energy modeling and validation techniques [16,17,34,53], applications of phase change materials [60], and building aerodynamics [56]. These reviews offer valuable entry points for readers seeking deeper insights into specific subfields.

Some of these literature reviews address multiple topics, reflecting the interconnected nature of the subjects. For example, the top-ranked review by Yan et al. [14], published in *Energy and Buildings*—a journal that leads in both publication volume and citation impact on the topic of simulation in the context of built environments (see Table 2)—focused on the significance of modeling occupant behavior in building performance simulations. It provided a comprehensive overview of the current research landscape, addressing key challenges such as data acquisition, model formulation, validation, and integration with existing simulation platforms.

3.4. Keyword Analysis

This section offers two complementary keyword analyses: (1) an examination of the most commonly used author-provided keywords, and (2) a network-based analysis that reveals clusters of related terms based on their co-occurrence patterns.

3.4.1. Most Frequently Occurring Author-Provided Keywords

Using VOSviewer 1.6.20 [26], a co-occurrence analysis was conducted to evaluate the relatedness of author-provided keywords, based on how often they appeared together across documents. Through several iterations, a minimum occurrence threshold of 20 was chosen, yielding a clear set of keyword clusters and a manageable dataset. This analysis identified the 50 most frequently co-occurring keywords, as shown in Table 4.

A qualitative analysis of these 50 keywords reveals that they generally fall into five overarching roles in building simulation: (1) simulation objectives (e.g., risk assessment, wind load, and energy analysis), (2) simulation techniques (e.g., CFD, large-eddy simulation, and agent-based modeling), (3) enabling technologies (e.g., BIM, virtual reality, and digital twin), (4) climatic and environmental context (e.g., weather information), and (5) simulated features (e.g., building envelope, passive design strategies, and phase change materials). Table 5 provides a detailed breakdown of these keyword categories based on these five roles.

3.4.2. Keyword Networks and Thematic Clustering

Figure 1 displays the keyword network, where each thematic cluster is visually represented using a distinct color. To enhance visual interpretability, the network highlights only the 300 most significant connections. For further qualitative exploration, the 10 most frequently used keywords in each cluster were extracted (Table 6), and an additional classification based on their roles in building simulation was conducted (Table 7). The following subsections provide detailed insights into the nature and implications of each identified cluster.

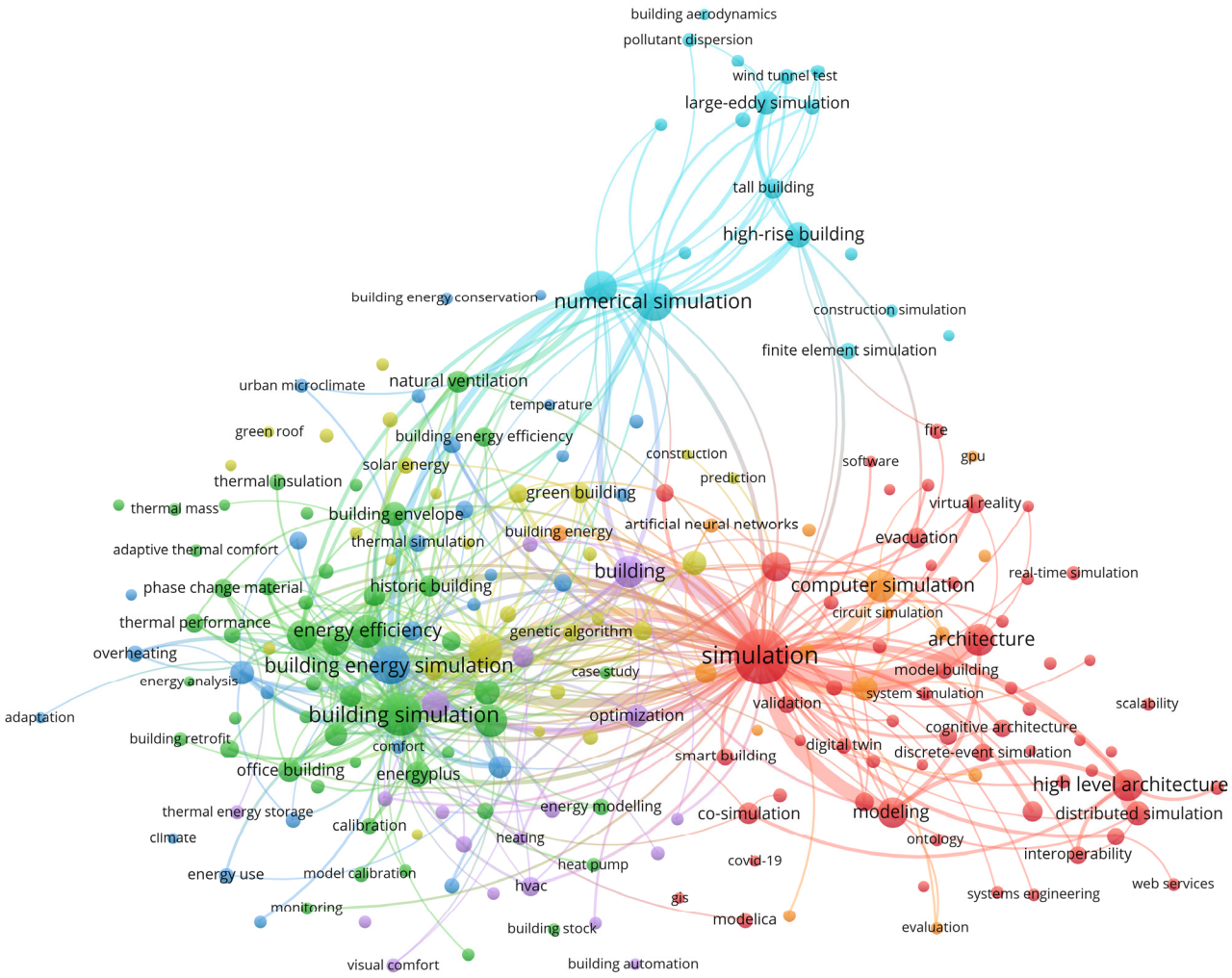


Figure 1. A keyword co-occurrence network was created using VOSviewer version 1.6.20, showing seven color-coded clusters. Each node represents a keyword, with its size indicating how often the keyword appears. Lines connecting the nodes represent instances where the keywords appear together in the same document; thicker lines indicate more frequent co-occurrences.

Cluster 1: Human-Focused Simulation. The first cluster (shown in red in Figure 1) focused on simulations within built environments that involve direct human engagement. It included keywords focused on behavior-related scenarios—such as *evacuation* and *crowd simulation*—as well as cognitive-oriented applications like *education* and *visualization*. This cluster also highlighted terms related to emergencies and public safety, including *fire*, *COVID-19*, and *risk assessment*. Among the keywords related to the enabling technologies role in building simulation were *BIM*, *virtual reality*, *digital twins*, and *GIS*.

Cluster 2: Building-Scale Energy Performance Simulation. The second cluster (shown in green in Figure 1) focused on energy performance primarily at the building scale. The key terms in this cluster included *NZEB*, *passive design*, *natural ventilation*, *energy storage*, *thermal mass*, *thermal insulation*, *phase change material (PCM)*, and *heat pump*.

Cluster 3: Urban-Scale Energy Performance Simulation. The third cluster (shown in blue in Figure 1) was closely related to Cluster 2, as both addressed issues of energy performance. This connection was visually represented in Figure 1, where the two clusters appeared adjacent. However, Cluster 3 distinguished itself by incorporating a broader climatic and environmental perspective. The key terms in this cluster included *climate change*, *global warming*, *urban heat island*, *urban microclimate*, *weather data*, *solar radiation*, and *climate*.

Table 4. The 50 most frequently occurring author-provided keywords.

Rank	Keyword	Occurrences	Total Link Strength
1	Simulation	2447	3168
2	Building simulation	1103	1583
3	Numerical simulation	860	673
4	Building energy simulation	840	1030
5	Energy	548	1013
6	Building performance simulation	502	730
7	Computational Fluid Dynamics (CFD)	484	757
8	Energy efficiency	482	1052
9	High level architecture	462	462
10	Building	431	901
11	Computer simulation	415	457
12	Architecture	414	560
13	Thermal comfort	412	961
14	Modeling	372	570
15	Building Information Modeling (BIM)	364	510
16	Residential building	301	590
17	Dynamic simulation	257	416
18	Energy consumption	231	453
19	High-rise building	228	279
20	Performance	213	296
21	EnergyPlus	211	482
22	Monte Carlo simulation	205	168
23	Distributed simulation	200	272
24	Large-eddy simulation	191	214
25	Building envelope	186	360
26	Climate change	184	379
27	Office building	171	356
28	Energy saving	165	331
29	Natural ventilation	154	336
30	Optimization	151	350
31	Occupant behavior	151	340
32	Historic building	142	271
33	Energy performance	140	294
34	Co-simulation	139	191
35	Daylight	133	236
36	Sensitivity analysis	129	286
37	Machine learning	126	247
38	Evacuation	112	129
39	Green building	109	224
40	Software architecture	108	106
41	Tall building	103	135
42	TRNSYS simulation	102	199
43	Thermal performance	100	217
44	Sustainability	96	260
45	Agent-based simulation	96	113
46	Virtual reality	93	130
47	Building performance	90	200
48	Multi-objective optimization	89	192
49	Uncertainty analysis	89	184
50	Phase change material	89	179

Table 5. Categorization of keywords by role in building simulation.

Category	Keywords
Simulation Objectives	Climate change, cooling, education, energy conservation, energy performance, evacuation, global warming, indoor air quality, life cycle assessment, monitoring, natural ventilation, NZEB, performance, pollutant dispersion, risk assessment, sustainability, thermal comfort, turbulence, urban heat island, urban microclimate, ventilation, visual comfort, visualization, wind load
Simulation Techniques	Agent-based sim., artificial intelligence, building thermal sim., CFD, circuit sim., computational modeling, computational sim., construction sim., co-simulation, deep learning, discrete-event sim., distributed interactive sim., distributed sim., dynamic building, sim., dynamic energy sim., dynamic sim., dynamic thermal sim., economic analysis, finite element sim., genetic algorithm, hybrid sim., hygrothermal sim., large-eddy sim., machine learning, model predictive control, Monte Carlo sim., multi-agent sim., multi-objective optimization, network sim., neural networks, numerical sim., parametric analysis, real-time sim., sensitivity analysis, thermal sim., uncertainty analysis, virtual sim., wind tunnel test
Enabling Technologies	BIM, virtual reality, digital twin, Modelica, GIS, EnergyPlus, TRNSYS, high performance computing, GPU, building automation
Climatic and Environmental Context	Weather data, temperature, solar radiation, typical meteorological year
Simulated Features	Building aerodynamics, building energy, building energy consumption, building envelope, building materials, building renovation, built environment, COVID-19, crowd simulation, daylight, demand response, energy storage, energy use, fire, green building, green roof, heat pump, high-rise building, HVAC, interior design, lighting, low-rise building, passive design, phase change material, photovoltaic, renewable energy, retrofitting, solar energy, super high-rise building, thermal energy storage, thermal insulation, thermal mass

Note. Sim. = simulation; NZEB = nearly zero-energy buildings; HVAC = heating, ventilation, and air conditioning; CFD = computational fluid dynamics.

Cluster 4: Sustainable Design and Simulation. The fourth cluster (shown in yellow in Figure 1) was closely related to Clusters 2 and 3, a relationship also visually reflected by their adjacency in Figure 1. However, Cluster 4 specifically emphasized strategies aimed at enhancing building sustainability. Its associated keywords included *life cycle assessment*, *green building*, *renewable energy*, *solar energy*, *green roof*, and *photovoltaic*, indicating a strong focus on sustainable design practices and technologies.

Cluster 5: Indoor Environmental Quality Simulation. The fifth cluster (shown in purple in Figure 1) included keywords related to factors influencing indoor environmental quality. The key terms in this cluster included *indoor air quality*, *cooling*, *ventilation, HVAC*, *visual comfort*, *daylight*, and *lighting*, indicating a focus on the physical and perceptual conditions that affect occupant comfort within buildings.

Cluster 6: Building Aerodynamics Simulation. The sixth cluster (shown in cyan in Figure 1) focused on the simulation of building aerodynamics using computational methods and wind tunnel testing. Two major themes emerged from this cluster: (1) wind loads on high-rise buildings and (2) pollutant dispersion in the environment. The key terms in this cluster included *CFD*, *high-rise building*, *building aerodynamics*, *turbulence*, and *wind tunnel test*, highlighting its emphasis on airflow analysis and environmental impact at the building scale.

Cluster 7: Computing in Building Simulation. The seventh cluster (shown in orange in Figure 1) focused primarily on the computational tools and infrastructures supporting building simulation. The key terms in this cluster included *machine learning*, *artificial intelligence*, *deep learning*, *computational modeling*, *neural networks, high performance comput-*

ing, and *GPU*, reflecting the growing integration of advanced computing technologies in simulation workflows.

Table 6. The 10 most frequently occurring author-provided keywords in each cluster.

Rank	Keywords		
	Cluster 1	**Cluster 2**	**Cluster 3**
1	Sim.	Building sim.	Building energy sim.
2	High level architecture	Building performance sim.	Climate change
3	Architecture	Energy efficiency	Occupant behavior
4	Modeling	Thermal comfort	Building performance
5	BIM	Dynamic sim.	Building design
6	Distributed sim.	Energy consumption	Building energy consumption
7	Co-sim.	EnergyPlus	Thermal sim.
8	Evacuation	Building envelope	Heat transfer
9	Software architecture	Office building	Urban heat island
10	Agent-based sim.	Energy saving	Overheating
	Cluster 4	**Cluster 5**	**Cluster 6**
1	Energy	Building	Numerical sim.
2	Monte Carlo sim.	Residential building	CFD
3	Green building	Optimization	High-rise building
4	Sustainability	Daylight	Large-eddy sim.
5	Multi-objective optimization	HVAC	Tall building
6	Uncertainty analysis	Energy conservation	Finite element sim.
7	Genetic algorithm	Indoor air quality	Wind pressure
8	Renewable energy	Ventilation	Low-rise building
9	Solar energy	Cooling	Wind tunnel test
10	Life cycle assessment	Air conditioning	Wind load
	Cluster 7		
1	Computer sim.		
2	Performance		
3	Machine learning		
4	Building energy		
5	Artificial neural networks		
6	Artificial intelligence		
7	Deep learning		
8	Computational modeling		
9	Parallel architectures		
10	Evaluation		

Note. Sim. = simulation; CFD = computational fluid dynamics; BIM = building information modeling; HVAC = heating, ventilation, and air conditioning.

4. Discussion

This paper provides a comprehensive bibliometric overview of the scholarly landscape concerning simulation within the context of the built environment. It highlights the most influential countries, journals, and publications, and uncovers key thematic areas within the field.

Through network analysis, seven distinct thematic clusters emerged, each defined by frequently associated keywords and their interrelations. These clusters were categorized as follows: (1) human-focused simulation, (2) building-scale energy performance simulation, (3) urban-scale energy performance simulation, (4) sustainable design and simulation, (5) indoor environmental quality simulation, (6) building aerodynamics simulation, and

(7) computing in building simulation. Examples of studies representing each cluster are discussed in the following paragraphs.

Table 7. Categorization of keywords in each cluster by role in building simulation.

Cluster #	Simulation Objectives	Simulation Techniques	Simulated Features
1	Evacuation Visualization Education Risk assessment	Distributed sim. Agent-based sim. Co-simulation Discrete-event sim. Distributed interactive sim. Network sim. Hybrid sim. Multi-agent sim. Real-time sim. Virtual sim.	Built environment Fire COVID-19 Crowd simulation
2	Thermal comfort Natural ventilation Energy performance Monitoring NZEB	Dynamic sim. Sensitivity analysis Parametric analysis Building thermal sim. Dynamic building sim. Dynamic thermal sim. Economic analysis	Building envelope Passive design Phase change material Retrofitting Thermal insulation Heat pump Thermal mass Energy storage
3	Climate change Urban heat island Urban microclimate Global warming	Thermal sim. Hygrothermal sim. Computational sim.	Building energy consumption Energy use Building materials
4	Sustainability Life cycle assessment	Multi-objective optimization Uncertainty analysis Monte Carlo sim. Genetic algorithm Dynamic energy sim.	Green building Renewable energy Solar energy Green roof Photovoltaic Building renovation
5	Energy conservation Indoor air quality Visual comfort Cooling Ventilation	Model predictive control	Daylight HVAC Demand response Thermal energy storage Lighting
6	Wind load Turbulence Pollutant dispersion	CFD Numerical sim. Large-eddy sim. Wind tunnel test Finite element sim. Construction sim.	High-rise building Low-rise building Super high-rise building Building aerodynamics Interior design
7	Performance	Machine learning Artificial intelligence Deep learning Computational modeling Neural networks Circuit sim.	Building energy

Note. TSL = total link strength; sim. = simulation; NZEB = nearly zero-energy buildings; HVAC = heating, ventilation, and air conditioning; CFD = computational fluid dynamics.

Cluster 1 focused on simulations within built environments that involve direct human engagement. For example, Wang et al. [62] simulated fire smoke diffusion and personnel evacuation (i.e., human behavior) in a high-rise medical building with the aim of improving the fire safety performance of the building in emergency situations. Another example is the work of Possik et al. [63], who used agent-based modeling and discrete event simulation methods to simulate the operations (i.e., behaviors) within an intensive care unit (ICU), and used virtual reality to visualize the ICU's physical environment to run various scenarios for training purposes (i.e., cognitive). Their aim was to enhance hospital operations, management, and training, particularly in response to the challenges posed by the COVID-19 pandemic. Another example of simulation for training purposes is the work of Gunasagaran et al. [64], who used virtual reality to simulate various conditions of daylighting and examined how architecture students perceive the usefulness of this visualization method in their architectural education.

Cluster 2 focused on energy performance primarily at the building scale. For example, Tang et al. [65] simulated heating and cooling loads in multiple buildings to assess the impact of wall insulation thickness and window glazing layers on thermal performance. Zuo et al. [66] investigated the use of phase change materials by comparing the thermal performance of building envelopes constructed with these materials to those built using conventional methods, using EnergyPlus for simulation.

Cluster 3 focused on energy performance on an urban scale. For example, Shi et al. [67] developed a framework to evaluate building thermal resilience at the urban scale during compound events such as heat waves and power outages. Their approach addresses the limitations of prior studies that focused only on individual buildings or overlooked urban microclimates. Their analysis revealed that excluding microclimate factors can result in a 13% overestimation of a building's thermal resilience. Similarly, Kim and Kim [68] used solar radiation simulations to assess the solar accessibility of individual blocks within urban development plans.

Cluster 4 focused on strategies to improve building sustainability. For instance, Fan et al. [69] performed a life cycle assessment of several university buildings in China to quantify their carbon emissions and identify reduction strategies. Similarly, Gao et al. [70] combined Building Information Modeling (BIM) with life cycle assessment to compare the carbon emissions of prefabricated buildings with those of traditional cast-in situ structures. In another study, Jung et al. [71] used energy simulations to determine the most cost-effective type and installation timing of building-integrated photovoltaic window systems, aiming to maximize their economic viability.

Cluster 5 focused on factors influencing indoor environmental quality. For example, Herrera et al. [53] employed multiple simulation tools alongside a CFD model to evaluate the air quality of an apartment under different ventilation strategies. Similarly, Conceição et al. [72] applied simulation methods to analyze indoor air quality and thermal comfort across various building scenarios, incorporating passive design strategies like shading and geothermal systems. In another study, Uriarte et al. [73] simulated daylighting conditions in a virtual restaurant using three different shading systems to determine the optimal daylight glare index.

Cluster 6 focused on building aerodynamics. For instance, Zhang et al. [74] used large-eddy simulations to study how vertical strips on tall buildings influence aerodynamic forces acting on the structure. In another study, Liu et al. [75] analyzed the impact of two different building layouts along streets on pollutant dispersion, using CFD simulations validated through wind tunnel experiments.

Lastly, Cluster 7 centered on the computational tools and infrastructures that support building simulation. The studies in this cluster explored various simulation methods and

enabling technologies, including machine learning [76], artificial intelligence (AI) [77], and neural networks [78]. For instance, Sarfarazi et al. [79], in a review paper, discussed how AI and machine learning are being integrated with simulation models for structural assessment, aiming to enhance predictive accuracy and optimize performance.

The landscape of built-environment simulation has rapidly shifted towards data-driven, AI-enabled paradigms [80]. AI-powered generative design tools generate optimal building configurations by iteratively testing alternatives against defined criteria, delivering more efficient and sustainable solutions than conventional methods [81]. Digital twins (i.e., virtual replicas of buildings, infrastructure or entire cities) have become central to this shift [82]. These twins continuously ingest real-time data from on-site sensors, satellite imagery, layering inputs from vehicles, building systems and external environment with artificial intelligence to simulate and monitor performance [83,84].

The evolving field of built-environment simulation is inherently interdisciplinary, integrating knowledge from architecture, engineering, data science, urban planning, and environmental studies. This interdisciplinary nature is exemplified by emerging tools that combine BIM with the Internet of Things and AI, enabling the transformation of static design models into dynamic digital twins that span design, construction, and operational phases.

Looking forward, simulation is expected to become a strategic tool for decision-making. Beyond traditional applications focused on predicting engineering performance, future simulators will facilitate multi-criteria policy analysis and support comprehensive long-term planning.

5. Limitations

This study faces four primary limitations. First, it draws exclusively from the Scopus database. Although Scopus is extensive, it may not capture every pertinent publication, meaning some relevant works might have been excluded. Nonetheless, given the inclusion of 12,220 records—and considering that most high-quality publications from other sources are also indexed in Scopus—the study likely offers a representative overview of the key topics.

Second, there is a chance that some non-relevant publications were inadvertently included. This issue is partially addressed through the use of co-occurrence analysis, which gauges study relevance based on the frequency with which keywords appear together in a single document. Since keywords unrelated to the built environment simulation field are unlikely to co-occur with relevant ones, this method helps limit the inclusion of outliers.

Third, bibliometric techniques cannot establish the directionality of relationships or infer causality between nodes. As such, this approach should be regarded as a supplement to more traditional forms of literature review [18].

Finally, although keyword clustering is based on quantitative methods, interpreting these clusters is a qualitative process and thus open to some subjectivity. To help address this, the 10 most frequent keywords in each cluster are provided, allowing readers to form their own interpretations.

6. Conclusions

This study presents a comprehensive bibliometric analysis of simulation research in the built environment, encompassing 12,220 publications indexed in Scopus from 1972 to 2025. The seven identified clusters highlight the field's multidimensional nature, which spans technical, environmental, and human-centric concerns. Notably, the increasing integration of digital technologies—such as BIM, digital twins, and machine learning—demonstrates a clear shift toward more data-driven and intelligent simulation environments.

Despite recent advances, several critical research gaps persist. First, even with the growing use of computational tools and data-driven methods, there remains a consistent discrepancy between simulated and actual building performance. This gap often stems from overly simplified models [34] that fail to capture complex, real-world factors—such as human behavior within built environments [49,85].

Second, there is a shortage of high-quality field data needed to accurately represent occupant behavior, material properties, and unpredictable environmental influences (e.g., [59]). Variability in occupancy patterns, construction quality, and weather conditions introduces significant uncertainty into model predictions (e.g., [85,86]), posing a major challenge for AI models that rely on robust, high-quality datasets for effective training [79].

Third, a disconnect remains between research and real-world application. This is largely due to factors such as the need for specialized expertise, long computation times, and the lack of integration between simulation and optimization workflows [15].

Fourth, the absence of standardized practices for data collection, modeling, and simulation continues to limit the broader adoption and effective implementation of building simulations [13].

Finally, as AI becomes increasingly embedded in engineering workflows, there is a growing need to prepare future professionals to critically interpret AI-generated results within the framework of fundamental engineering principles [79].

Overall, this study offers a strategic, data-driven map of the simulation research landscape in the built environment. It provides a valuable resource for scholars seeking to position their work within the broader intellectual structure of the field, for educators developing curricula on simulation tools and methods, and for practitioners and policymakers aiming to harness simulation for performance-based design, sustainability, and urban resilience.

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