

Building and Urban-Scale Energy Modeling: A Comparative Literature Review of Building Energy Modeling (BEM) and Urban Building Energy Modeling (UBEM)

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Abstract – Cities consume over two-thirds of the world's energy and account for more than 70% of global CO₂ emissions. Given these negative impacts, cities are major contributors to climate change, one of the most pressing challenges of the 21st century. As dynamic organisms composed of built and natural systems, cities require sustainable design strategies that reduce urban energy consumption. Among these, the building sector plays a key role in overall energy use. In response, Building Energy Modeling (BEM) tools have been developed to estimate and optimize energy consumption during the early design phases of individual buildings. While BEM tools provide accurate simulations of a building's energy performance, they are limited in scope when addressing energy interactions at the neighborhood or urban scale. In dense urban areas, where factors such as shading, wind flow, and microclimates affect energy demand, Urban Building Energy Modeling (UBEM) approaches have gained importance. UBEM enables energy analysis across building clusters, offering a broader perspective on urban energy efficiency. This study presents a comparative evaluation of BEM and UBEM tools, highlighting their application areas, limitations, and potential contributions. The findings provide recommendations for selecting appropriate modeling strategies to improve energy efficiency in both architectural and urban-scale design.

Keywords – Energy Modelling; Building Energy Models (BEM); Urban Building Energy Modeling (UBEM); Energy Simulation Programme; Building Energy Consumption.

I. INTRODUCTION

Urban areas are units where more than half of the world's population resides. By 2050, it is estimated that approximately 68% of the global population will be living in cities. Urbanization rates vary across different regions of the world. In Europe, while the urbanization rate was 74% in 2018, it is projected to reach 87% by 2050 [1]. Considering that urban areas are vibrant mechanisms where all types of consumption needs, particularly housing, are met, it is assumed that they will be among the most affected units. Fragile urban fabrics are expected to be the most impacted places by climate change, which is regarded as one of the most significant problems of our era. However, cities are affected by climate change and responsible for more than two-thirds of global energy consumption and over 70% of CO₂ emissions [2]. This paradoxical situation necessitates positioning cities, their building blocks, residential units, and all related components, at the center of holistic and sustainable design approaches aimed at reducing energy consumption, limiting carbon emissions, and enhancing resilience against climate change in the built environment.

Buildings are responsible for a significant portion of the carbon footprint. It has been determined that approximately 70% of the carbon footprint associated with the energy consumed throughout a building's life cycle occurs during the operational phase [3]. The high energy consumption rate during building operation has necessitated making structures more energy-efficient. In other words, building energy modeling (BEM) methods have been developed to calculate building energy performance during the early design phase and

produce an energy-efficient building stock within the construction sector. Building Energy Modeling (BEM) methods have been introduced to optimize the energy use of buildings to evaluate energy performance at the early design stages [4]. Building Energy Modeling represents the responsive simulation of a building's energy demands, consumption patterns, materials, thermophysical properties, and the impact of varying design parameters on energy performance with high accuracy. In other words, BEMs are used to simulate buildings' energy demands and expenditures [5].

In the design of energy-efficient settlement units and neighborhood clusters, solutions based solely on individual building analyses often prove insufficient. Building positions relative to one another, variations between hard and soft surfaces, and the configurations of building blocks significantly impact energy consumption. However, building energy modeling (BEM) does not address them fully. In other words, broader-scale modeling approaches that account for energy exchanges between building clusters, microclimate effects, and urban heat island phenomena through climatic elements such as sunlight, shading, and wind are needed [6], [7], [8]. Urban Building Energy Modeling (UBEM) has been introduced as a simulation method for assessing the thermal performance of existing cities and neighborhoods to meet this need. With the onset of the climate crisis, UBEMs have increasingly been employed to support the construction of energy-efficient and sustainable urban environments [9].

Simulation studies represent virtual approximations of reality. Therefore, achieving effective and accurate results requires carefully constructing these virtual models and scenarios. However, urban areas are inherently complex and have emerged through self-organization processes [10], [11], making accurate virtual representation challenging. This complexity presents a significant barrier to the effective use of UBEM. Another major challenge in UBEM applications is the uncertainty in model calibration and disruptions in data collection processes. In complex organisms such as cities, the lack of consumption data—or, in other words, the variability in consumption patterns—directly affects the calibration process [12],[13]. Within this framework, the present study comprehensively examines and compares the impacts of UBEM and BEM tools on calculating energy consumption at urban and building scales. Additionally, by analyzing previous studies through qualitative research methods, the study offers recommendations regarding the appropriate and suggested approaches for selecting between UBEM and BEM. Ultimately, the study aims to develop strategic recommendations to enhance sustainable design and energy efficiency, particularly for cities and their subunits severely affected by climate-related disasters such as floods, hurricanes, and droughts. Furthermore, the study highlights the importance of urban planners and architects utilizing Building Energy Modeling (BEM) and Urban Building Energy Modeling (UBEM) approaches in designing resilient, holistic, and energy-efficient cities by considering energy performance across different scales.

II. MATERIALS AND METHOD

The aim of this study is to conduct a comparative evaluation of Urban Building Energy Modeling (UBEM) and Building Energy Modeling (BEM) tools used in analyzing energy consumption at building and urban scales. Within this framework, a qualitative and conceptual methodology has been adopted. A comprehensive literature review has been conducted as part of the study.

During the data collection process, a literature review was conducted using academic databases such as Web of Science, Scopus, and Google Scholar, based on key concepts including energy modeling, urban energy modeling, building energy modeling, UBEM applications, and BEM applications. As a result of the literature review, definitions and theoretical frameworks of BEM and UBEM, their fields of application, advantages, and disadvantages, and their contributions to energy efficiency at both urban and building scales were analyzed. The identified scales were comparatively evaluated within their contexts. Based on the findings, insights were generated regarding the conditions under which UBEM and BEM tools should be preferred. This study will develop strategic recommendations for future design and planning processes, aiming to enhance energy efficiency at both urban and building scales. The methodology and overall framework of the study are illustrated in Figure 1.

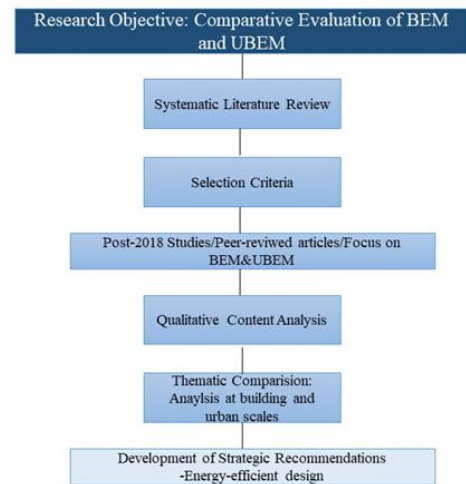


Fig. 1 Methodology of study

III. RESULTS

Achieving energy efficiency and improvements in buildings is a challenging process. Buildings are complex entities containing numerous environmental, mechanical, and electrical variables. Due to the multitude of inputs affecting a building's energy efficiency, the optimization process is complex and time-consuming. In other words, various tools have been developed to consider and optimize many parameters simultaneously [14]. Building Energy Modeling (BEM) is a significant method for evaluating the energy efficiency of buildings with complex structures by assessing different materials and alternative thermophysical properties. Through BEM, it is possible to quickly assess buildings by providing simplified solutions—such as basic spreadsheets—for high-level or general plan types [5].

Numerous studies have been conducted on BEM, and various types of BEM tools are developed by different software companies, varying according to plan types and energy interfaces. BEM tools differ based on user interface, intended use, modeling limitations, simulation time, the accuracy of climate data representation, and overall simulation reliability [15], [16].

BEM tools simulate and optimize the energy performance of buildings using different modeling approaches depending on the complexity of the system, namely physics-based (white-box), data-driven (black-box), and hybrid (grey-box) models [17], [18]. White-box approaches use simplified techniques based on physical parameters such as heat transfer by developing data-intensive alternatives [19], [20]. In black-box approaches, there is no need for a physical system model; instead, predictions are made based directly on available examples and empirical data. In forecasting building energy consumption, methods such as Multiple Linear Regression (MLR), Genetic Algorithms (GA), Artificial Neural Networks (ANN), and Support Vector Machines (SVM) are commonly preferred. When black-box and white-box models are insufficient to solve the problem, grey-box approaches, which combine the strengths of both methods, are employed. As hybrid models use physical and data-driven modeling, they produce the most reliable results [21], [22].

When analyzing building thermal models, it is observed that three different modeling approaches are preferred for different purposes. Computational Fluid Dynamics (CFD) is supported by numerous software platforms based on numerical

analysis methods, such as FLUENT, COMSOL Multiphysics, and MIT-CFD [23]. The zonal method represents the most basic and simplified form of fluid dynamics. In the nodal or multi-zone method, each building is treated as a homogeneous volume, and the solution process is carried out using the finite difference method. Software such as Clim2000, ESP-r, BSim, and BUILDOPT-VIE has been developed based on this approach [24], [25].

Within this context, after reviewing the modeling and analysis methods in BEM, the modeling approaches, advantages, and disadvantages of different and widely used BEM tools identified in the literature have been comparatively evaluated. Figure 2 presents various BEM tools such as DesignBuilder, EnergyPlus, TRNSYS, Modelica, and DeST.

Software	Model Type	Building Thermal Model Type	Application Area	Advantages	Disadvantages
Modelica	Physical Modeling	Nodal (Multi-zone)	System-level HVAC and energy flow modeling	Flexible modeling, extensive libraries	Complex usage, requires expertise
DesignBuilder	EnergyPlus Interface	Nodal (Multi-zone)	Building energy simulation, design optimization	User-friendly interface, rapid modeling	Limited deep control, dependent on EnergyPlus engine
DeST	White-box	Nodal (Multi-zone)	Thermal performance and HVAC system analysis	Optimized for Chinese conditions	Difficult to use, majority of documentation in Chinese
SSEnergyPlus	White-box	Nodal (Multi-zone)	Building energy analysis, detailed HVAC modeling	Advanced algorithms, open-source	High input data requirements, not user-friendly
TRNSYS	White-box	Nodal (Multi-zone)	Thermal system simulation, building energy modeling	Modular structure, system-based simulation	Complex setup, data-intensive
IES-VE	White-box	Nodal (Multi-zone)	Energy performance and environmental analysis	User-friendly interface, LEED compliance	High licensing cost
EnergyPlus + CONTAM + Matlab	Coupled Simulation	Nodal (Multi-zone) + Airflow (CONTAM)	Energy and indoor air quality simulation	Integrated analysis capability	Complex model integration, requires expertise
BEP-TR II	White-box	Nodal (Multi-zone)	Energy Performance Certificate (EPC) issuance in Turkey	Compliance with national regulations, web-based and free	Applicable only in Turkey, limited flexibility
BIM Energy	White-box	Nodal (Multi-zone)	Energy analysis for new and existing buildings	User-friendly interface, quick analysis	Limited customization options
Green Building Studio	White-box	Nodal (Multi-zone)	Cloud-based energy analysis integrated with Revit	Cloud-based, fast analysis	Requires internet connection, limited customization

Fig. 2 Comparison of urban building energy modeling (BEM) tools [5], [18], [22], [26], [27], [28], [29], [30]

Global climate change has led to an increase in extreme weather temperatures, which has caused a deterioration in indoor thermal comfort. In this context, dynamic thermal modeling and simulations at the early design stages play a crucial role in planning buildings in a manner that prioritizes energy savings while significantly contributing to the improvement of indoor thermal comfort and air quality. This approach has become widely adopted and effective in contemporary building design processes. On the other hand, when analyzing the reciprocal interactions between buildings and the urban environment, their role in sustainable resource use, and their dynamic impacts on regional energy systems, it becomes clear that building energy studies are no longer

confined to the individual building scale; instead, they have evolved into multi-scale solution approaches encompassing neighborhood units, settlement patterns, and entire cities [31]. In this regard, considering micro- and macro-scale energy interactions has become indispensable to current urban energy modeling approaches.

Accordingly, Urban Building Energy Modeling (UBEM), which references multiple variables within the urban fabric and delivers results close to real-world conditions, has increasingly been preferred in academic studies and practical applications. UBEM is a physics-based approach developed to simulate the thermal performance of many buildings, employing a bottom-up modeling process with an analytical foundation [32]. To enable more robust urban data streams, UBEM models are increasingly supported by sources such as LiDAR (Light Detection and Ranging) scanning technology and Geographic Information Systems (GIS), leading to more reliable results [33].

The UBEM approach features two different modeling strategies: top-down and bottom-up. The areas of application, data requirements, and level of detail differentiate these approaches [6], [34]. In top-down modeling, macro-scale data is used for modeling energy consumption; however, it cannot reach the individual building level, and integrating technological scenarios becomes highly challenging [31], [35]. Among bottom-up UBEM modeling approaches, it is considered the tool that provides the most realistic results. Energy simulations are performed by comprehensively defining data such as building geometry, building envelope, HVAC systems, occupancy levels, and climate data. Bottom-up models are further divided into three categories: statistical, physical, and hybrid models [36].

When comparing bottom-up and top-down modeling approaches, it is important to recognize that bottom-up methods, which allow for detailed, thermally realistic data input at the building level, yield more accurate and reliable results. Understanding the intended purpose and usage of different UBEM types is crucial in this context. Therefore, it is necessary to classify different UBEM tools and select the optimal option based on the specified objectives. Table 2 presents classifications of UBEM tools according to their different modeling approaches.

According to Figure 3, when comparing UBEM tools, CitySim should be preferred if a detailed and comprehensive modeling process is required. If rapid urban-scale data analysis and the development of carbon footprint strategies are the objectives, LakeSIM or SimStadt would be more appropriate choices. In cases where studies focus on microclimate effects and urban heat islands, ENVI-met is recommended. TEASER is another important tool, particularly valuable for its rapid simulation capabilities and its ability to automatically integrate data into the system. Additionally, for open-source and multi-scale analyses, the use of CEA (City Energy Analyst) is suggested, as it provides a flexible interface for various modeling needs.

Tool Name	Modeling Type	Target Users	Temporal Resolution	License Type	Developer Institution
CitySim	Physics-based energy balance	Researchers, urban planners	Hourly	Commercial / Licensed	LESO-PB, EPFL
SimStadt	ISO-CEN-based reduced-order model	Urban planners, policymakers	Monthly	Licensed	Hochschule für Technik Stuttgart
LakeSIM	ISO-CEN-based reduced-order model	Urban planners, policymakers	Sub-hourly	Open access	Argonne National Laboratory (ANL)
UMI	Energy, daylight, walkability simulation	Researchers, urban designers	Hourly	Partially open	MIT Sustainable Design Lab
ENVI-met	CFD-based microclimate modeling	Urban climate researchers	Minute-hourly	Commercial / Licensed	ENVI-met GmbH
CityBES	EnergyPlus + OpenStudio-based	Urban energy planners	Hourly	Web-based, free	Lawrence Berkeley National Laboratory (LBNL)
OpenIDEAS	Modelica-based reduced-order model	District energy managers	Hourly	Free, open-source	KU Leuven
TEASER	Modelica-based reduced-order model	District energy managers	Hourly	Free, open-source	RWTH Aachen University
EnergyAtlas	ISO-CEN-based reduced-order model	Urban planners, policymakers	--	-	Technische Universität München
CEA (City Energy Analyst)	Tool-specific calculation modules	Urban planners, energy analysts	Hourly	Free, open-source	ETH Zurich

Fig. 3 Comparison of urban building energy modeling (UBEM) tools

[6], [7], [12], [33], [31], [36], [37], [38], [39], [40], [41]

IV. DISCUSSION

The construction sector is among the major contributors to the climate crisis, as the carbon footprint left throughout the building life cycle is significantly high. Projections related to climate change indicate that, in the future, many cities will be increasingly affected by disasters such as floods, extreme heat events, droughts, and wildfires. Accordingly, reducing energy consumption in urban areas has become a critical process. Before the construction phase begins, all components—from material selection to building functions—must be considered in the design phase to ensure energy-efficient choices are made.

In this context, simulations have started to be conducted through Building Energy Modeling (BEM) tools before construction, allowing for the estimation of a building's future energy loads and consumption, thus enabling the construction of structures that minimize energy loss and reduce carbon footprint. However, it has been observed that improving energy efficiency solely at the single-building scale is insufficient to achieve the sustainability of cities in the face of the climate crisis. In other words, when cities and their subcomponents are considered clusters, it becomes evident that factors such as mutual shading and wind effects between buildings and microclimatic properties significantly influence energy efficiency beyond the individual building scale.

In line with this understanding, UBEM (Urban Building Energy Modeling) has been increasingly employed for studies focusing on urban heat islands, microclimate impacts, and strategies to reduce the carbon footprint at the scale of building blocks or neighborhood units. Accordingly, this study presents a comparative analysis of UBEM and BEM tools, discussing their general characteristics and types.

V. CONCLUSION

Based on the comparative evaluations made throughout this study regarding the capabilities, application areas, and limitations of both BEM and UBEM tools, several key

conclusions have been reached. As a result of the study, the following conclusions were drawn:

- In individual building energy simulation studies, BEM should be preferred because it realistically models detailed material properties and HVAC system operations. However, BEM is insufficient at the urban fabric scale to address factors such as shading, wind, and urban heat island effects.
- UBEM provides an integrated design opportunity by simulating the relative positioning of buildings, heat exchanges between structures, and their responses to climatic conditions.
- Using diverse data inputs such as LiDAR and GIS in UBEM enhances the accuracy and realism of the simulation results.
- When comparing different UBEM modeling approaches, bottom-up models should be prioritized, as they realistically construct the full physical characteristics of buildings.
- In the future, the importance of UBEM tools will further increase in the construction of climate-resilient cities. Climate change is not merely the result of individual responsibilities but the collective outcome of all components related to the urban environment.

Within the scope of this study, data collection methods, data requirements, advantages, disadvantages, and different types of software associated with UBEM and BEM tools have been examined and comparatively evaluated in detail. Based on the study's findings, hybrid modeling strategies should be developed in the future, combining the strengths of both UBEM and BEM approaches. Such an integrated approach would allow energy efficiency to be considered at the level of individual structures or aggregated building masses that do not fully reflect real-world conditions and as dynamic, living spatial systems. Thus, the design and construction of sustainable and climate-resilient cities could be carried out more holistically and effectively.

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