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Research Article

A comprehensive framework for selecting building energy modelling tools to support sustainable design

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ABSTRACT

Building energy modeling (BEM) tools are essential for achieving sustainable building design by enabling the simulation and analysis of building energy performance. While Building Energy Modeling (BEM) tools have achieved widespread adoption, a systematic framework for their selection, grounded in project objectives and a comprehensive understanding of tool capabilities and applicability, is still lacking. This research addresses this gap by developing a framework to guide architects and other stakeholders in selecting appropriate BEM tools for sustainable building projects. This study identifies common sustainable design strategies from a comparative analysis of certified sustainable buildings. It evaluates capabilities and applicability of available tools from a comprehensive evaluation of BEM tools listed in the Building Energy Software Tools Directory. The resulting framework provides a structured approach, describing key input/output features and assessing the suitability of different tools for different types of project and analysis objectives. The results of this research can support a more efficient use of BEM tools in sustainable design, enabling professionals and policymakers to make informed decisions and to promote the transition toward a more sustainable built environment.

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INTRODUCTION

Sustainability is a complex notion, crossing disciplinary boundaries. Sustainability challenges require a multidisciplinary approach for complete understanding and tackling [1]. Building Energy Modeling (BEM) tools have become powerful allies in this effort revolutionizing the architectural design process [2–5]. Architects can incorporate BEM in the design process to explore different design alternatives, evaluate their energy performance and make informed decisions to optimize sustainability [4]. The history of building modeling software dates back to the mid-1970s and has undergone significant changes over the years to include energy modeling capabilities [6]. BEM allows architects to understand how design elements affect energy

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consumption so they may reduce the environmental footprint of buildings. Besides uncovering climate opportunities, BEM can also direct the application of essential passive design strategies, even for individuals who are not familiar with specific software tools [7]. The widespread use of BEM in architectural design, together with engineers, has greatly contributed to the aim of sustainable buildings [8]. BEM has been shown to be effective in reducing energy loads with knowledge-based and simulation-based optimization methods achieving energy savings of up to 24% and 33% respectively [9]. Integrating BEM at the early stage of the design process can improve the energy performance of buildings and contribute to a more sustainable future.

BEM tools have become an essential asset in the development of sustainable architecture. These tools provide a powerful platform for prediction and optimization of energy performance of buildings, enabling designers to make informed decisions at early stages of the design process [2–5]. BEM can help in developing more environmentally friendly and sustainable structures by simulating different design options and identifying potential energy-saving strategies. The BEM tools are more accurate and reliable for assessing building energy performance than manual calculations [10]. Such improved accuracy is essential in aiding decisions on building design and operation. There is a wide range of BEM tools, for different needs and levels of expertise. An useful resource to explore these options is the U.S. Department of Energy's Building Energy Software Tools Directory (BESTD) [11]. To effectively use BEM in sustainable design, it is important to select tools that fit the project goals and the designer needs [9]. Careful consideration of the capabilities and limitations of different BEM tools allows designers to make informed decisions that contribute to the achievement of sustainable design objectives.

Physics-based building energy modeling (BEM) has demonstrated its ability to effectively simulate and evaluate various energy conservation measures in different building stocks [12]. However, as shown by the analyzes of BEM tools in terms of the input/output granularity and transparency [13], the choice of appropriate modeling approaches and tools depends on the particular project goals and the complexity of the building under consideration. Comparative studies of BEM software also point out differences in their operation and the level of detail required as input, which in turn affect the ease of use and analytical capabilities [14]. A review of BEM methods, tools and their applicability to various applications showed five key application areas including performance-driven design, model-based optimization of operational performance, integrated data-driven simulation for digital twins, urban energy planning, and building-to-grid interaction for demand response [15]. Research on the influence of design parameters on building energy performance has shown that building shape has a great influence on energy consumption when the boundary conditions are the same, as shown by comparison of different BEM tools [16]. In addition, current trends in BEM tool development highlight an increasing focus on supporting early-stage design decision-making [17].

Numerous studies have been carried out on the use of BEM tools for sustainable design [2, 7, 18]. However, there is still a need to comprehensively evaluate and classify these tools. The simulation community is discussing critical areas for improvement, including user friendliness, knowledge integration, accuracy, interoperability, and integration into the design process [2]. The applicability and simulation capabilities of BEM tools are quite different, especially when applied to sustainable building strategies. However, their comparisons of whole-building energy simulation performance have been limited. Moreover, a systematic classification of BEM tools in terms of their integration with other tools and their functionality for different types of projects, facilities and sustainable strategies is yet to be established. The lack of knowledge stops architects from choosing the right tool for their projects. A well-defined framework would provide a common platform for architects and researchers to effectively utilize and select BEM tools to advance sustainable building practices.

The study is focused on whole-building energy simulation tools, including parametric and optimization techniques to support sustainable building design strategies. This research aims to identify common design strategies and assess the capabilities and applicability of different BEM tools listed in the BESTD by analyzing the sustainable building design strategies based on the most common sustainability indicators of the certified sustainable buildings worldwide. The goal is to propose a holistic framework that can help architects and policy makers to choose and understand suitable BEM tools for sustainable building design and analysis. The framework will offer useful insights into the capability and applicability of BEM tools including strengths and weaknesses of the tools against project objectives and facilities. It will help in making informed choices and optimization of sustainable design approaches by considering common sustainable building strategies. Furthermore, this research also supports the promotion of sustainable building practices by providing effective BEM tools to architects and policymakers for their research and projects. This paper points out the potential of BEM in sustainable design and serves as a basis for further research on the development of innovative BEM tools and practical strategies for sustainable building objectives.

METHODOLOGY

BEM tools are a necessary tool for the design of sustainable and energy efficient buildings, allowing to simulate and predict performance at early stages of design. Many BEM tools have been developed in recent years and the choice of suitable tools for specific research or projects is an important decision for architects and engineers. In this paper a systematic methodology is used to develop a comprehensive framework for the selection of BEM tools

which support sustainable building design. Data collection was performed by an extensive review of peer-reviewed articles published in high-impact journals indexed in databases such as Scopus and Web of Science. We also checked authoritative sources such as the American Institute of Architects (AIA) and the U.S. Department of Energy's Building Energy Software Tools Directory (BESTD) to ensure our information was reliable and comprehensive. To validate the theoretical findings, we also evaluated selected tools in practice in their respective software environments and cross-referenced the results with the literature and official documentation. Figure 1 describes the methodological steps used to develop this framework.

The research approach began with an extensive literature review on BEM tools and existing sustainable design practices. Sustainable building indicators were analyzed systematically and energy efficient strategies were identified. Based on these strategies, a subset of BEM tools listed in BESTD was chosen for further evaluation. The tools chosen for this study include those that support whole building energy simulation, and incorporate advanced features, such as parametric analysis and optimization techniques relevant to sustainable design goals. After the appropriate BEM tools were identified and characterized, their applicability and capabilities were analyzed for input and output features. The advanced functionalities, strengths, weaknesses and limitations were underlined. Therefore, a decision-support framework was designed to help architects, engineers and researchers select the most appropriate BEM tool for sustainable building projects.

Sustainable Buildings

Since the late 20th century, the demand for energy has increased with the progress of technology and urbanization [19]. With this expansion in energy production and use have come increasing ecological problems. This trend keeps growing without any abatement due to the fast population growth and continuous technological development [20]. Importantly, buildings in many developed nations account for a large percentage (35-40%) of total energy use, with the largest share (65%) used for providing indoor environmental quality via heating, cooling, ventilation and hot water systems [21]. Sustainable building design is a prominent architectural paradigm in response to the growing global awareness on environmental conservation [22, 23]. Sustainable development in an urban and building context involves an extensive range of issues such as natural resources management, environmental protection, energy

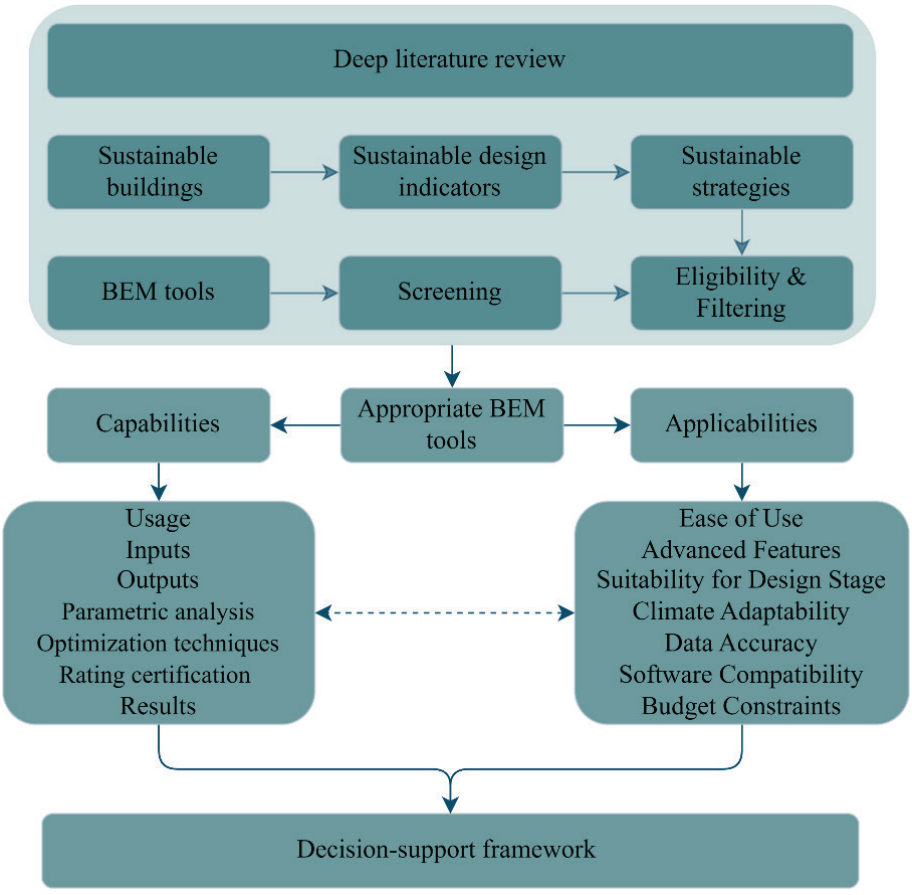


Figure 1. Methodology flowchart of the study.

efficiency, transportation planning, land use optimization, infrastructure development, and social well-being of the population [24]. It takes actions and significant efforts to achieve sustainable building practices. The main elements of sustainable buildings generally consist of site selection, water conservation measures, energy efficiency initiatives, material efficiency, resource optimization, indoor air quality management, effective building operations and maintenance practices [25]. Examples of sustainable buildings can be found in diverse geographical regions worldwide, each adapted to local environmental conditions and cultural preferences. Architects often draw inspiration from existing sustainable building projects to inform their designs. Therefore, this study characterizes the applicability and capability of BEM tools for sustainable building strategies, focusing on the most common sustainability indicators (Site, Energy, Indoor Environmental Quality, Material, and Water) considered in most widely recognized certified sustainable buildings globally.

Interdisciplinary Science and Engineering Complex

The Interdisciplinary Science and Engineering Complex is a LEED Gold-certified, 10,000 square foot research facility designed by Payette and completed in 2017 in Boston, Massachusetts. Detailed information about the sustainable indicators and strategies considered in the design of the Interdisciplinary Science and Engineering Complex is provided in Table 1 [26].

This innovative building has garnered 11 sustainability awards for its exceptional design and performance. The complex is located on a brownfield and serves as a linking element between the various neighborhoods by means of a pedestrian bridge with landscape design. It uses a combination of passive and parametric design strategies to achieve high energy performance. The building's ecological features help plants grow and give wildlife a place to live. Passive design elements include glazed facades, a central atrium with a waterfall and the active systems of radiant panels and a solar wall to maximize energy efficiency. Low-flow fixtures are used to save water, and rainwater is collected for irrigation and toilet flushing. The use of recycled and prefabricated materials allows for both economic efficiency and ecological sustainability. The space is bright and glazed, and the central atrium helps to connect interior and exterior, creating a healthy and inspiring environment for researchers to thrive.

Casa Adelante 2060 Folsom

Casa Adelante is a mixed-use building with 127 permanently affordable homes and a number of community

Table 1. Overview of sustainable strategies implemented in the Interdisciplinary Science and Engineering Complex, adapted from [26]

NO	Sustainable Indicators	Sustainable Strategies
1	Site	The project is in a brownfield area. Provide eco-friendly transportation. Support local vegetation by plantings.
2	Energy	Glazed walls Provide unobstructed views. Reduce the amount of ventilated space. The atrium acts as an air-mixing chamber. A solar wall preheats the air during winter. Heat recovery systems capture heat. Chillers and boilers decrease energy usage.
3	Indoor Environmental Quality	Simulation tools guarantee comfort. CFD confirmed a comfortable interior. Daylighting assesses the atrium skylights. The atrium offers proper views.
4	Material	Recycled aluminum components. Factory prefabrication and recycling. The Proper material selection.
5	Water	Low flow plumbing and fixtures. Rainwater collection tank.
A visual representation of the Interdisciplinary Science and Engineering Complex		

spaces on the ground floor. Its innovative design connects everyday indoor and outdoor areas, promoting well-being and sustainability. The building is arranged around a central courtyard from which spread out the parkland, community facilities and social service offices. Casa Adelante capitalizes on its desirable location with excellent walking and public transit options to promote social equity and reduce carbon emissions on a formerly polluted site. Table 2 [26] provides a detailed view of the sustainable indicators and strategies that were considered in the design of the Casa Adelante 2060 Folsom.

The building's energy-efficient design integrates passive strategies and high-performance electric systems to reduce its environmental impact. The building is oriented for optimal daylighting and views, and has an energy efficient envelope and strategic shading to reduce energy consumption. The project's entry sequence is intended to create a relationship between residents and nature, and also social interaction. We selected materials that were sustainable and long lasting; durable and functional with low carbon footprints. Water-efficient fixtures and a smart irrigation system add to the building's eco-friendly approach.

Albion District Library

The Albion District Library is a prime example of sustainable architecture The building is a Tier 1 Toronto Green Standard certified building designed by Perkins and Will. This is a 29,000 square-foot library in Toronto, Canada, completed in 2017, which has received 10 sustainability awards. The passive design is thought of as an indoor garden with an emphasis on community. Situated on previously developed land, it serves as a vital social resource for a diverse and high-needs population. Detailed information about the sustainable indicators and strategies considered in the design of the Albion District Library is provided in Table 3 [26].

It takes a car-centric public space and converts it into a pedestrian-friendly space, creating habitats for local flora and fauna. The library also features cutting-edge sustainable elements such as photovoltaic arrays, a green roof, daylight harvesting and healthy materials that dramatically reduce energy use. The on-site infiltration system, green roof and rainwater management strategies minimize water usage. The choice of durable, low-maintenance and locally-sourced materials adds to the economic viability of the building and reduces environmental impact. The library is designed to give good natural light, ventilation and access to the outside to make the users feel better. To summarize, the Albion District Library is a model for how sustainability principles can be successfully integrated into a public building.

Table 2. Overview of sustainable strategies implemented in the Casa Adelante 2060 Folsom, adapted from [26]

NO	Sustainable Indicators	Sustainable Strategies
1	Site	Located in a brownfield area. Utilizes walkable area social equity. Promote a low-carbon future.
2	Energy	Integrated passive design elements. Building's orientation. High-performance envelope. Optimized window-wall ratio. Fixed exterior shading. Allowing daylighting and views. Operable windows.
3	Indoor Environmental Quality	Connection between residents and nature. Encourage social interaction. Healthy and non-toxic material.
4	Material	Durability and functionality of material. Material resiliency and adaptability. Health and transparency of materials.
5	Water	Low flow fixtures. Irrigation system equipped with a sensor.
A visual representation of the Casa Adelante 2060 Folsom		

Table 3. Overview of sustainable strategies implemented in the Albion District Library, adapted from [26]

NO	Sustainable Indicators	Sustainable Strategies
1	Site	Situated in a post-war suburb. Crucial social resource for immigrants. Engaging to the wellness and environment.
2	Energy	Use high-level sustainable design elements. A rooftop photovoltaic array. Sloping green roof and daylight harvesting. Building's façade to create sunscreens.
3	Indoor Environmental Quality	Considers natural light and views. Courtyards bring nature, light, and color into the plan. Massing, and garden courtyards.
4	Material	Careful selection of healthy materials. Selecting durable materials. A colorful scrim of terracotta ribs wraps around the building.
5	Water	Wetland for stormwater collection. Planting drought-tolerant shrubs. Stormwater management strategies.
A visual representation of the Albion District Library		

One Central Park

One Central Park is a mixed-use development that has received accolades for its state-of-the-art sustainability features and striking architecture. The legendary high-rise residential building is located in a redeveloped urban precinct of Sydney, Australia, and consists of two towers linked by a common base. The two towers rise to 65 and 116 meters and are separated by a shaded space illuminated by innovative daylight technology. A unique feature is the use of heliostats, which reflect sunlight onto a cantilever and nearby park, providing natural illumination. Table 4 [27] provides detailed information on the sustainable indicators and strategies considered in the design of the One Central Park.

The extensive greenery of the building, including balconies and vertical gardens with plantings, provides natural shading and cooling, resulting in considerable savings of energy. One Central Park meets the highest standards of sustainable building with 5-star Green Star ratings for its retail and residential facilities. The project is inviting because of its emphasis on amenity and public space, and a generous amount of greenery. The combination of architectural and biophilic design, with Australia's biggest green façade, has set a new benchmark for sustainable urban development. The vertical gardens, with their 35,000 plants, enhance the beauty of the building and act as natural climate control, resulting in lower energy use and cleaner air. The building's sustainable initiatives are more than just design. It features green infrastructure such as green roofs, living walls, recycled materials, water harvesting and energy efficient systems. These have produced significant environmental benefits such as a good rate of recycling, reduction in greenhouse gas emissions and efficient use of water. One Central Park is a living example of what sustainable design can achieve in developing livable and environmentally friendly cities.

Marco Polo Tower

The Marco Polo Tower is a one-of-a-kind residential building in Hamburg, Germany. The building's design is unique, with a curved structure and rotating floors that provide panoramic views of the harbor and city. The tower is designed in the framework of a waterfront development with an emphasis on sustainability and ecological efficiency. The Marco Polo Tower is designed to use as little energy as possible and features include vacuum collectors for heating and cooling, natural ventilation and balconies for shading. Its sustainable approach has been recognized, including the Mipim Award for Best Residential Project. The overhanging terraces shade the building facades from direct sunlight and obviate the need for additional sunshades, thus improving energy efficiency and esthetic quality. Interior of the tower is unique as the exterior with open living spaces that offer unobstructed views and natural light. Detailed information about the sustainable indicators and strategies considered in the design of the Marco Polo Tower is provided in Table 5 [27].

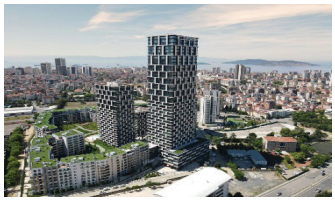
Table 4. Overview of sustainable strategies implemented in the One Central Park, adapted from [27]

NO	Sustainable Indicators	Sustainable Strategies
1	Site	Located in the former industrial area. Amenity and abundance of plant life. Vertical landscape.
2	Energy	Natural sun control device. Using sustainable design strategies Use of a heliostat to produce electricity. Mirror structure to redirect sunrays.
3	Indoor Environmental Quality	Possibility to extend the living space. Green roofs, living façades.
4	Material	Recycling demolished materials. Adaptive re-use of buildings components.
5	Water	Reclaimed and treated blackwater. Irrigation and air conditioning water needs. Reduce the water load. Recycled rainwater.
A visual representation of the One Central Park		

Table 5. Overview of sustainable strategies implemented in the Marco Polo Tower, adapted from [27]

NO	Sustainable Indicators	Sustainable Strategies
1	Site	Located directly on the waterfront area.
2	Energy	Natural ventilation. Shade shielded from sunlight by terraces. Vacuum collectors on the roof. Air louvers, enabling natural ventilation. Balconies arrange shading and wind. Energy-conserving by triple-glazed. Rooftop solar cooling system.
3	Indoor Environmental Quality	High level of flexibility in the internal part. Sound-insulated for noise pollution. Flexible structural for spaces choice.
4	Material	The façade is composed of concrete and glass. Structure material is reinforced concrete.
5	Water	N/A
A visual representation of the Marco Polo Tower		

Table 6. Overview of sustainable strategies implemented in the AND Pastel projects, adapted from, adapted from [27].

NO	Sustainable Indicators	Sustainable Strategies
1	Site	Located on an old industrial estate. Created a lively neighborhood. Encouraging the use of bicycles
2	Energy	Sustainability and advanced technologies. High-efficiency central heating system Decentralized cooling system Energy-efficient mechanical systems Multi-layered facades and appropriate glass Natural ventilation
3	Indoor Environmental Quality	Daylight and natural cross ventilation. Efficient lighting fixtures
4	Material	Recycled Content Materials Local Materials Low Emission Materials
5	Water	Comprehensive water management Gray water and rainwater collection
A visual representation of the AND Pastel projects		

Residents can enjoy spacious balconies and terraces, as well as the option of connecting neighboring apartments for larger living areas. Its modern design and prime waterfront location, coupled with the building's sustainable features, make it a desirable and environmentally friendly residential option.

AND Pastel

AND Pastel is a sustainable residential development on a former industrial site in Istanbul, Turkey. It is surrounded by four towers and three blocks, with 1,200 residential units of various configurations. The complex is a lively community with connected courtyards, a health center, pools, fitness facilities and shops. AND Sustainability is at the heart of Pastel, focusing on energy efficiency, water conservation, resource optimization and indoor comfort. The project is LEED Gold certified with sustainable features including a high efficiency heating system, decentralized cooling and complete water management. The public spaces are compared to an urban park with green spaces and water courses linking the courtyards. AND Pastel promotes cycling and the parking of bicycles as a means of sustainable transportation. Table 6 [27] details the sustainable indicators and strategies used in the AND Pastel projects design.

The building is designed with energy-efficient systems, multi-layered facades and natural ventilation, which cuts energy consumption by 24 %. Apartments are oriented for maximum day lighting and natural cross ventilation, and low energy lighting fixtures are used to increase efficiency. The focus is on the use of sustainable materials such as recycled content, local materials and low emission materials. Paints, adhesives and sealants are selected according to health benefits, so that harmful chemicals are avoided. The building is designed to be flooded with natural light with over 90% of the area receiving direct sunlight. The project also includes water conservation, sustainable landscaping and access to public transportation. To summarize, AND Pastel is an example of a success incorporating sustainability into a residential development. The project demonstrates a commitment to developing a sustainable and desirable urban community by highlighting energy efficiency, water conservation, resource optimization and healthy living environments.

Building Energy Modeling (BEM)

The development of building energy simulation tools has been strongly influenced by the need for energy efficiency in buildings [14] in the 1970s. Since then, these tools have evolved, taking advantage of advances in computational technology to improve their ability to do mathematical modeling and graphical visualization. This has allowed for more sophisticated analysis of building performance and energy use. Building Energy Modeling (BEM) is an important tool in the sustainable building assessment framework. It aims at helping to achieve and improve sustainable indicators according to site conditions specifically through the

modulation, optimization and analysis of design strategies, in particular for integrated sustainable designs. Building Energy Modeling (BEM) is not a new concept in building design, but it is a subset of Building Information Modeling (BIM) that seamlessly integrates energy analysis throughout the entire lifecycle of buildings from design and construction to operation and maintenance [7, 18]. The integration of BEM tools in the architectural design is creating great changes in the design process, making it more efficient, performance-oriented and flexible, and offering more design alternatives [4]. BEM is a useful tool in building design assessment and energy research to help make informed decisions at the early stages of design and predict the impact of different design solutions on future building performance [28–30]. Thus, BEM tools have become an essential tool for professionals in the architecture, engineering, and construction industry for modeling, analysis, and optimization of building energy performance under different design and operational scenarios [13].

Design of building with BEM tools illustrates how building elements can contribute to energy saving and sustainability to improve energy efficiency and reduce the ecological footprint of the building [7]. The adoption of passive design elements as the basis can open up chances for architects to create energy efficient and cost effective designs, particularly during the early phases of design [31]. The main drivers of building energy consumption are design choices, operational practices and other factors [22]. The BEM principles have become popular in sustainable building design due to their ability to achieve energy efficiency and environmental sustainability [8, 32]. Energy performance simulation programs are powerful tools to analyze energy consumption and thermal comfort in the whole life cycle of a building [3].

BEM is a useful computer tool for analysis and evaluation of architectural designs [31]. It must be noted that the input data and the simulation assumptions can be different for each BEM tool and this can influence greatly the functionalities and capabilities of each BEM tool. The application of BEM in the design of buildings contributes to the following aspects in energy performance: building orientation, massing, form, envelope, daylighting analysis, water harvesting, energy modeling, renewable energy integration, sustainable construction materials, and site and logistics management [33]. Buildings have many parameters, including material properties, occupancy levels, equipment schedules, HVAC and plant operations, and local climate and weather conditions [34].

BEM tools are applied in three major phases of the building life cycle: design, construction and operation/maintenance. The BEM tools are an important part of the design process. They are used to analyze the building site, orientation, massing, envelope design and to compare different design options with different layouts, architectural features and HVAC systems. This large-scale application of BEM tools optimizes the building performance from the very outset. BEM tools can be used during construction to evaluate heating and cooling loads to determine the size of HVAC systems, evaluate lighting levels and evaluate the environmental impacts of construction to ensure that materials and equipment are meeting design specifications. During the operational and maintenance phase, BEM tools monitor the real building performance, detect deviations from the design, and suggest energy-efficient alternatives for renovations or remodels. They also help manage facilities by detecting faults in the HVAC system and predicting potential energy savings from adjustments and retrofits.

Tools for Integrating BEM in Sustainable Building Design and Energy Modeling

Performance analysis of building requires special simulation tools for different aspects like energy, esthetic and cost etc. BEM is especially useful for the design of low-cost and energy efficient solutions to meet and maintain building energy efficiency requirements [5]. The BEM tools are normally automated by computer programming to effectively analyze and solve building energy consumption problems and reduce time and labor requirements [35]. CIBSE proposed two ways of integrating BEM into building design: (1) using simplified tools at the early stages of design and more complex tools at the later stages, and (2) using a single sophisticated simulation tool throughout the design phases [18]. BEM enables the prediction of real building performance in early design stages, allowing proactive actions. The primary goal of using BEM in building design is to reduce industry waste, including wasted energy, increase the value of industry products, and minimize environmental damage by providing accurate and realistic performance predictions [33]. BEM, as an innovative approach, encompasses various useful tools that can significantly evaluate the energy performance of buildings by integrating information about building materials, systems, types, climate zones, and environmental conditions [36]. BEM is continuously evolving, with rapid advancements in techniques and methodologies [37]. BEM is a powerful tool that simulates and optimizes building energy performance, considering various parameters as illustrated in Figure 2.

Over 400 BEM tools have been developed globally to analyze building energy performance. As noted by Gao et al. [31] most BEM tools can be categorized into two groups: those utilizing the calculation engine developed by the US Department of Energy (DOE), such as eQUEST, DesignBuilder, EnergyPlus, and Autodesk Green Building Studio (GBS), and those using their own proprietary calculation engines, such as IES Virtual Environment (IES-VE) and Trace 700. In 2010, the US Department of Energy's Building Energy Software Tools Directory (BESTD) listed over 389 BEM tools, providing a comprehensive overview of available options [2, 3, 38]. As of the last BESTD update in 2018, the directory included 207 software tools, encompassing a wide range of capabilities for simulating various building types, including 111 specifically designed for

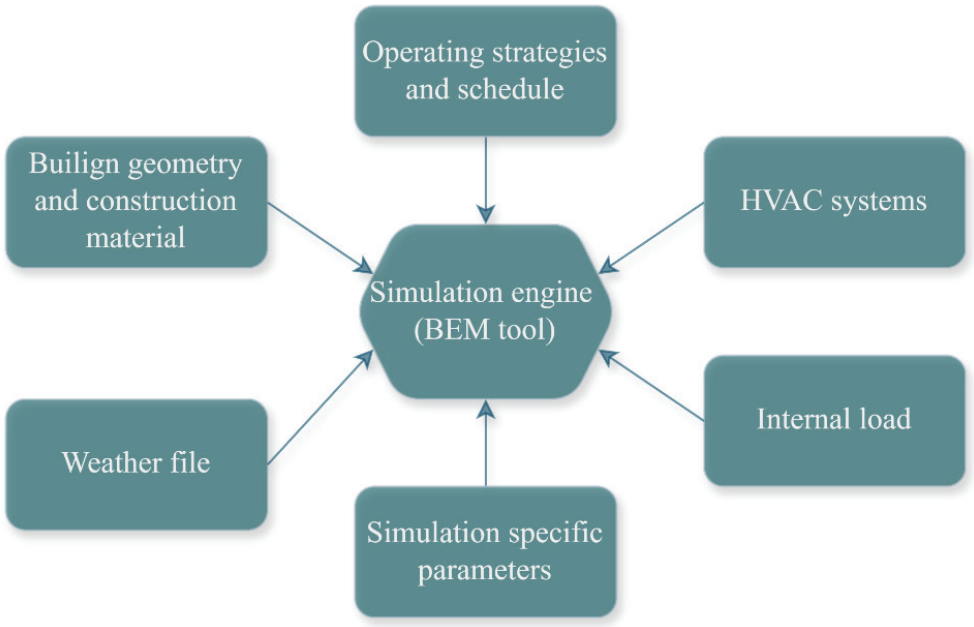


Figure 2. Overview of essential input data for Building Energy Modeling (BEM) tools [3]. Adapted from: Maile T, Fischer M, Bazjanac V. Building energy performance simulation tools - a life-cycle and interoperable perspective. Cent Integr Facil Eng 2007:1–49.

residential buildings [11]. Given the abundance of available BEM tools, it is essential to evaluate their utility in different phases of the building lifecycle [18]. Each program possesses unique features in terms of modeling resolution, solution algorithms, target audience, modeling options, ease of use, flexibility, and more. Attia et al. [2] reviewed 392 energy modeling programs and identified only 40 as suitable for early-stage architectural decision-making [7].

The proliferation of BEM tools in the contemporary era, driven by advancements in computer technology, has made selecting the most appropriate tool a complex task. Contemporary BEM tools offer the capacity to evaluate building energy performance during the design phase. However, discrepancies persist among BEM tools, arising from variations in algorithms, computational inaccuracies, implementation errors, inconsistencies in input parameters, and differences in weather data processing methods [14]. There are no clear criteria to classify and evaluate the BEM tools to select the appropriate one, which faced the potential user with the difficulty of choosing a suitable tool among the growing BEM tools pool [2]. According to Toutou et al. [35], parametric and optimization simulation method is the most considerable way to develop the buildings' performance. This study is focused on whole building energy simulation with parametric and optimization for sustainable buildings design. Therefore, according to strategies considered in the evaluated sustainable buildings and BESTD filtration regarding the whole building energy simulation and optimization the following ten BEM tools may considered most appropriate to evaluate and select for building analysis regarding energy efficiency and sustainability.

Despite the abundance of BEM tools, there is a lack of standardized criteria for classifying and evaluating them, making it challenging for users to select the most suitable option [2]. This study focuses on whole-building energy simulation, incorporating parametric and optimization techniques for sustainable building design. Through the analysis of the strategies employed in the evaluated studies [12], sustainable building strategies (Tables 1-6) and the application of BESTD filtration criteria for whole-building energy simulation and optimization, ten BEM tools were identified as the most appropriate candidates for building analysis with respect to energy efficiency and sustainability.

DesignBuilder

DesignBuilder is a comprehensive building performance simulation program that enables users to assess the environmental impact of both new and existing buildings. The intuitive user interface makes it possible to model and analyze energy use, comfort, HVAC, daylighting and sustainability compliance. According to [39], the following are the primary features:

- Provides energy, comfort, HVAC, daylighting and cost analyzes in a single platform.
- Integrated modeling environment and support for BIM imports.
- Full features: BREEAM/LEED credits, CFD and a range of national building regulations.

- Enables energy use calculations, façade design, natural ventilation, lighting control, site layout, equipment sizing, design collaboration and education.
- Advanced capabilities such as automated data generation, EnergyPlus 'Compact HVAC' coupling, natural ventilation simulation, daylighting analysis, shading techniques and flexible data presentation.
- Allows to investigate the effect of variations of design parameters on several performance criteria.
- Generate IDF files for better simulation.

DesignBuilder is a sophisticated building performance simulation software that utilizes the EnergyPlus engine to provide the advanced thermal simulation features to accurately model building energy consumption [14]. It allows to improve the modeling accuracy by providing ready-to-use templates for construction materials, weather data (usually from ASHRAE or EPW files) and HVAC systems. Nevertheless, the accuracy of the simulation is highly dependent on the quality and verification of the input parameters, such as weather data, operating conditions and user defined material properties. For data exchange, DesignBuilder supports file formats like gbXML and IFC, which improve interoperability in BIM workflows. DesignBuilder also adopts the EnergyPlus output format for advanced analysis and collaboration. DesignBuilder is a commercial product and therefore subject to tiered licensing which may be a financial barrier to smaller firms. Furthermore, it requires high computational requirements and powerful hardware configurations, which further increases the overall cost of implementation. DesignBuilder's easy to use interface and extensive functionality provides a powerful solution for architects, engineers and building professionals who want to improve building performance and sustainability.

EnergyPlus

EnergyPlus is a building energy simulation program developed by the U.S. Department of Energy. It is widely used by professionals from many fields to model and analyze the energy performance of buildings [40]. EnergyPlus is a very effective instrument that can:

- It simultaneously models the interactions of building spaces and their heating, ventilation, and air conditioning systems, and produces accurate results for conditioned and unconditioned spaces.
- EnergyPlus utilizes a sophisticated heat balance approach to calculate the surface temperatures accurately and hence, allows accurate thermal comfort and condensation modeling.
- Users can specify custom time steps for high-precision simulation of systems with varying dynamics.
- EnergyPlus contains a detailed heat and mass transfer model for air flow and moisture transfer between zones of the building.
- Provides detailed models for windows, doors and shading devices, enabling accurate simulation of solar energy absorption and heat transfer.
- EnergyPlus can calculate the levels of illuminance and factors of glare so that it can evaluate the visual comfort of building occupants.
- Users can build custom HVAC systems from a library of individual components, allowing the user to model a wide variety of configurations.
- EnergyPlus provides an extensible framework for defining custom control strategies so that users can simulate a variety of operating conditions.
- EnergyPlus can be coupled with other simulation packages using Functional Mockup Interface (FMI) for co-simulation and interoperability.

EnergyPlus is a well-known tool for building energy simulation and highly respected for its thermal and energy performance predictions highly sensitive to the accuracy of input parameters [13]. The software contains a large library of data such as thermophysical properties of materials and meteorology data. The user however has to select data relevant to the context of the project, so as to ensure the validity of the simulation results. EnergyPlus does not include a full native graphical user interface and often relies on third party pre- and post-processing tools such as OpenStudio or DesignBuilder to provide a more user-friendly environment. It is interoperable with other building information modeling (BIM) and analysis software via standard file formats such as gbXML and IDF. EnergyPlus is an open source program, so there is no direct cost to acquire the software, however it requires a highly skilled user to use effectively and may require significant computational resources. You might have to invest in more training and hardware to make the most of these factors. EnergyPlus is a very useful tool for professionals who want to optimize the energy efficiency of buildings, reduce the operational cost and improve the comfort of their occupants [13]. Its versatility and accuracy make it a must-have tool for researchers, designers and engineers in the building industry.

Sefaira Architecture

Sefaira Architecture is a new cloud-based building performance analysis platform that is a breakthrough. Sefaira integrates with the industry standard 3D modeling software allowing architects to quickly evaluate design decisions and make data driven decisions. This iterative process allows architects to keep improving their designs toward the most energy efficient, daylighting and thermal comfort. Sefaira uses state-of-the-art simulation engines like industry-standard EnergyPlus and Radiance to deliver precise, timely results and fast design iterations. Sefaira's main features are [41]:

- Sefaira offers a set of tools to evaluate the energy consumption, carbon emissions, thermal comfort and daylighting performance.
- Architects are given instant feedback on their design decisions, allowing them to make quick adjustments and improvements.

- Sefaira allows team members and external stakeholders to work together, making the design process more efficient.
- The platform features an intuitive user interface that is accessible to architects of any technical skill level.

Sefaira Architecture is a powerful way to analyze building performance with a focus on quick results early in the design process. The simplified modeling methodology provides fast assessment and sound decision making but is based on approximations and standard templates that impose limitations to the extent of precision that can be achieved in detailed design iterations. The software is highly interoperable with popular design platforms like Revit and SketchUp, allowing for real time performance assessment fully embedded in existing workflows. However, the requirement for real-time feedback has come at the expense of better data export capabilities and therefore limits its use for more holistic energy analysis beyond the platform's existing capabilities. The pay-for-use licensing model can also be a financial barrier for smaller companies or individual users. However, the cloud simulation approach reduces the investment in high performance computing infrastructure. Sefaira enables architects to design buildings that are more efficient, more sustainable, more comfortable and that have less impact on the environment.

EcoDesigner Star - ArchiCAD

EcoDesigner STAR is a powerful energy analysis tool fully integrated within the Archicad environment. It allows architects to undertake dynamic building energy calculations which enables them to make informed decisions during the design process. EcoDesigner STAR delivers the same detailed performance reports in the familiar ArchiCAD interface, providing standard-compliant energy analyzes on the Building Energy Model (BEM). The main features of EcoDesigner STAR are [42]:

- Provides international energy standards and combines energy assessment and reporting in the Building Information Modeling (BIM) process.
- Provides export of BIM geometry and thermal property data, thermal bridge simulation, expert building systems settings, integration of on-site renewables, and building energy simulation using a standards-compliant analysis engine.
- Supports climate analysis, building energy model calibration, project specific low-energy building solution sets, low-energy demand architectural design, and whole building energy efficiency optimization.
- Ability to integrate solar photovoltaic and wind energy solutions, and to export directly to a range of analysis tools and translators such as PHPP, iSBEM, VIP-Energy, gbXML and IFC.

EcoDesigner STAR is an ArchiCAD plug-in for building performance analysis. It provides geographically relevant simulations based on the building's geometric model and embedded energy templates, all within the ArchiCAD environment. This method gives moderate accuracy in the temperate and colder climate zones. However, it is based on pre-defined templates which limits its flexibility and predictive ability in the areas with extreme climatic variations. It has excellent integration with ArchiCAD, which enables seamless data exchange within the ArchiCAD ecosystem, but interoperability issues can be observed when exporting data to other building performance simulation platforms. Also a big hurdle is the cost of the software, which requires licenses for both ArchiCAD and the EcoDesigner STAR add-on, especially for smaller firms. EcoDesigner STAR is also desktop-based and requires a workstation with at least mid-range hardware specifications to run efficiently. EcoDesigner STAR is an invaluable tool for architects and engineers seeking to create energy-efficient buildings that meet international standards and support sustainable development.

OpenStudio

OpenStudio is an open source platform that provides flexibility to make building energy simulation easier. It uses EnergyPlus for detailed energy modeling and Radiance for sophisticated daylight analysis [43]. OpenStudio provides an SDK and CLI that together provide a flexible API to interact with the EnergyPlus engine. Most importantly, the API is accessible in scripting languages such as Ruby and Python, allowing users to tailor and improve the capabilities of OpenStudio. OpenStudio also includes graphical tools, such as a Trimble SketchUp plug-in for creating 3D building models and a parametric analysis tool to help users apply energy conservation measures. OpenStudio's broad strategy makes it a useful resource for a variety of professionals, from engineers to policy analysts.

OpenStudio has a technically modular architecture and it can be easily integrated with other applications. The API supports scripting in a variety of languages for customization and automation. OpenStudio also uses the Building Component Library (BCL) as a common platform for building components and data, enabling interoperability and access to the latest standards. OpenStudio is built on the EnergyPlus simulation engine and provides high-fidelity building performance analysis based on accurate input and validation of weather, thermophysical material properties, and HVAC system parameters. The interoperability is supported by the integration with SketchUp for geometry modeling and the compatibility with the larger EnergyPlus ecosystem. In addition, gbXML import/export capabilities allow data to be shared with Building Information Modeling (BIM) systems. OpenStudio is open source and so there are no costs for software licensing but it requires special technical skills to use effectively and there are likely to be training costs to ensure models are developed and simulation results interpreted correctly.

Ladybug and Honeybee

Ladybug and Honeybee are two open source plugins for Grasshopper that augment the ability of architects to

design environmentally sustainable buildings [11]. These tools integrate with Grasshopper, a visual programming environment, and give designers a powerful suite of tools to analyze climate data, simulate building performance and visualize design impacts. _Ladybug_ is about the earliest design decisions. It enables designers to bring climate data and study how it affects a building's exposure to sunlight and radiation. Ladybug's interactive visualizations give instant feedback to design changes, allowing designers to explore different options and make informed decisions in a timely manner.

Honeybee is more suitable for later stage design. It interfaces with four validated simulation engines, EnergyPlus, Radiance, Daysim and OpenStudio. These engines provide detailed analysis of building energy consumption, comfort and daylighting [15]. Honeybee's daylighting and thermodynamic modeling capabilities are especially useful for fine-tuning design decisions. Together, Ladybug and Honeybee provide a comprehensive toolkit for sustainable design. These plugins will allow architects to create more sustainable and energy-efficient buildings by empowering designers to analyze climate data, simulate building performance and visualize the impact of their design.

Ladybug and Honeybee are environmental analysis tools that utilize validated simulation engines (EnergyPlus and Radiance) to provide high-fidelity building performance assessment. The accuracy of their predictions of solar radiation, daylighting and thermal comfort depends on the accuracy of the input parameters as determined by the underlying engines. These tools work in the Rhino/Grasshopper parametric modeling environment, offering great flexibility for design exploration and optimization. However, this combination demands that users are skilled in Rhino/Grasshopper and have access to commercial licenses, which can be a financial barrier for smaller firms, considering that the Ladybug and Honeybee tools themselves are open-source. In addition, the complexity of parametric workflows may require specialized training which adds to the implementation cost.

eQUEST

eQUEST is a powerful building energy performance simulation tool for analysis and design. The user interface is intuitive, with wizards, interactive graphics and parametric analysis making it accessible to a wide range of professionals from architects and engineers to building owners and researchers. The software allows the user to import the geometry of the building from architectural models or to create the geometry in the software. The user is able to run simulations of different complexity. eQUEST provides detailed input options for the design process at schematic design, design development and full DOE-2 based interface [44].

The eQUEST generated output reports provide a brief summary of the simulation results including graphical summaries, comparative analysis, and detailed tabular data. This information is useful to understand the energy performance of buildings and to evaluate the effects of design decisions. One of the primary advantages of eQUEST is the ability to assess whole-building performance during the design process. Wizards allow design teams to explore energy efficiency options early on, while the full-blown interface allows for detailed analysis in later stages. The software operates at a high speed enabling the effective evaluation of large models and the capture of complex interactions between building systems.

eQUEST has built-in components and templates to make energy modeling easy, but this comes at the cost of absolute accuracy. It is good for first energy estimates, but may not be precise enough for complicated analysis. It is based on the DOE-2 format not compatible with modern workflows [14]. And it's not as seamless with other software as newer tools are. However, its main advantage is its accessibility as it is free to use and needs minimal computational resources.

Green Building Studio (GBS)

Green Building Studio (GBS) is a flexible cloud-based platform that is integrated into Autodesk's design suite including Revit and FormIt 360. It is a powerful energy simulation engine, which enables the user to optimize building energy efficiency and carbon footprint at the early design stages [45]. GBS employs the DOE-2.2 simulation engine and delivers accurate energy performance calculations and detailed input files for EnergyPlus. This allows architects, engineers and construction professionals to design high-performance buildings faster and more cost-effectively than traditional methods. It's easy to create geometrically accurate building models with GBS. The program automatically reads data from gbXML-enabled BIM or 3D-CAD programs. In addition, the BIM/CAD program provides the graphical user interface for specifying the additional input parameters.

The software produces a full range of outputs, including customizable heating and cooling load charts, energy consumption, costs, temperature data and wind analysis. Includes valuable features such as parametric studies, annual carbon footprint analysis, renewable energy potential assessment, natural ventilation analysis and preliminary water analysis for LEED compliance. GBS's strength is in enabling energy, carbon and water analysis at the early stages of design, thus lowering design and analysis costs and allowing for greater design exploration within budget constraints. This ultimately speeds up project completion and the process of achieving LEED certification.

Autodesk's cloud-based simulation engine, Green Building Studio (GBS), offers a reasonable level of accuracy for early-stage energy modeling in the design process. However, its output granularity is usually less refined than that of more computationally intensive tools such as EnergyPlus, making it less suitable for detailed analysis in the later stages of the project. While the GBS offers a smooth

interoperability with the Autodesk environment, especially Revit, such tight integration limits its usefulness in workflows involving non-Autodesk Building Information Modeling (BIM) platforms [14]. Another financial hurdle for smaller firms may be GBS's subscription-based licensing model, bundled within the Autodesk suite. GBS is cloud-based, which reduces the costs of investing in hardware, but also means the system depends on consistently strong Internet connections.

Tas Engineering

TAS is an advanced building simulation program, with a particular strength in dynamic thermal simulation of large and complex buildings. Designers can model daylighting and thermal performance for accurate predictions of energy use, CO2 emissions, operation costs and occupant comfort. Tas is a complete thermal simulation solution, including HVAC and system modeling with graphical and component-based analysis. Tas is mainly used by consulting engineers and architects and provides a simple user interface to create or import building geometry from other CAD software. Its extensive database covers thermal properties, climate data, schedules of occupancy, internal heat gains and HVAC characteristics, which facilitates the input processes.

Tas can produce outputs such as building loads, HVAC sizing, energy use, comfort conditions and natural ventilation. Pre-formatted reports and data export capability to various software packages facilitates customized report preparation. Tas has strengths in whole building energy simulation, load calculations, HVAC system selection, parametric optimization, energy conservation measure analysis and code compliance [11]. It also supports utility bill analysis, weather data analysis, lighting simulation, air flow simulation, detailed component simulation, solar and photovoltaic analysis, wind turbine analysis, and building simulation data-driven CFD analysis for thermal comfort assessment.

TAS Engineering software is known for its robust HVAC simulations and high-fidelity thermal modeling, but it has some limitations. Its accuracy is largely dependent on the user's expertise in data entry and can be a source of error if not done carefully. In addition, the lack of interoperability with current Building Information Modeling (BIM) platforms requires the user to enter data manually or to use proprietary, often outdated, import formats which may impede efficient workflows. The software represents a large financial investment and may be too costly for smaller firms or projects with limited budgets. Lastly, its desktop-based architecture, which demands only moderate hardware specifications, restricts access and collaboration in comparison to cloud-based alternatives.

Home Energy Efficient Design (HEED)

HEED is a simple software that allows homeowners, builders and professionals to design energy efficient residential buildings. The tool supports the design process by creating a reference house and by providing possibilities to improve the energy performance of the reference house by applying different design changes [11]. You can easily enter basic information about the home you are looking for, such as its size, number of stories, type and location. HEED uses the data to create an initial design, which can then be customized to personal preferences. The tool comes with a suite of visualization tools such as 3D models, animated shadows, and complex graphs to help users understand how different design choices impact energy consumption, cost, and carbon emissions.

HEED includes many features to support energy efficient design, including passive heating and cooling techniques, solar energy integration and the ability to add high-mass materials for thermal regulation. The tool also allows users to access climate data from thousands of locations around the world so that they can adapt their designs to the local conditions. The main advantage of the HEED is the possibility to compare various options of design and analyze their energy efficiency. Users can experiment with different layouts, materials and systems to identify best solutions to reduce energy consumption and environmental impact.

This tool is for Residential building energy efficiency design. It is a simple tool and is fairly accurate in the early stages of design. Limited customization so not good for large scale or non-standard projects. It is a standalone program with limited integration capabilities and is therefore not suitable for advanced workflows that require data exchange with other tools. It is also cheap and needs little hardware, so it is affordable for small users or designers at home.

DISCUSSION

Recent advances in computer science and the increasing demand for sustainable buildings have prompted the application and study of simulation-based optimization techniques in the building industry. Rapid urbanization and construction activities have caused a huge energy consumption and environmental degradation. This has resulted in the greater focus on energy efficiency and sustainable building design. The most frequently certified sustainable buildings in the world show a pattern of strategies used to create sustainable and eco-friendly design. One of the main strategies for improving sustainable building practices and promoting energy efficiency is the application of BEM tools in the early phases of building design. BEM has been playing an increasingly important role in building design in the last decades, driven by the growing population, economic growth and the demand for better quality of life [31]. But not all the BEM tools are useful for architects. Accurate modeling and prediction is one of the great challenges in building energy simulation [34]. Users should carefully check the accuracy and reliability of the

tool with the information available on the building which will be entered as input [3]. The choice of the right tool is a multi-faceted assessment – well-thought-out strategies, abilities, convenience and availability. The right choice of BEM tools at the start of the design process could bring great advantages [18]. The successful architectural projects are usually characterized by the effective use of BEM in the design process [7]. Therefore, Attia et al. [2] proposed four selection criteria for BEM tools: usability, computing capability, data exchange capability and database support. More importantly, the choice of the most appropriate BEM tool from the variety of alternative design options and strategies calls for careful evaluation of a number of design parameters, building performance, software-specific capabilities and the needs of the researchers [36, 46]. As such, the evaluation and selection of an appropriate BEM tool should be made of the following steps:

1. Building lifecycle phases: Specify the particular phases of the building lifecycle where the BEM tool will be used.
2. Define input needs Define input data needs of selected building life cycle stages. Use this as a checklist to help evaluate potential BEM tools.
3. What are the key outputs to be generated from the BEM tool. Use this as a checklist to help you evaluate potential tools.
4. Weight other criteria: Look at other criteria like interoperability, usability and speed and weigh them for their importance.
5. Score: Appropriately weight the criteria to find the scores for BEM tools satisfying prerequisites in steps 1-3.

The selection criteria for building energy modeling (BEM) tools are affected by a number of variables, including input and output specifications, building or district scale analysis, and project-specific requirements [13]. By considering these criteria, users can make informed decisions in selecting a BEM tool that best meets their individual needs and design goals. The design of sustainable buildings analyzed using global case studies presented in Tables 1 to 6, shows key indicators such as Site, Energy, Indoor Environmental Quality, Materials and Water. The following tables indicate the exact strategies that have been put in place for each of these indicators to promote sustainability. Therefore, BEM tools are very important in the design process especially in the conceptual stage as they have their own capabilities and applications to provide simulations and analyzes to ensure the accuracy of meeting sustainability goals. In this regard, the study proposes a detailed framework (Table 7) for the selection of the most suitable BEM tools based on their input/output characteristics and software functionalities.

The framework is based on an in-depth assessment of sustainable building indicators, strategies applied and the applicability and capabilities of different BEM tools. This assessment considers all the relevant tools included in the BESTD directory and the sustainable strategies used in the assessed buildings as shown in Tables 1-6. This comprehensive study has resulted in the identification of the ten most relevant and compatible BEM tools for sustainable building design and analysis. This framework provides useful insights into the inputs and outputs of these tools, emphasizing their capabilities and advanced functionalities, which can greatly improve the accuracy and efficiency of sustainable building design.

However, the input and output capabilities of the BEM tools, which are demonstrating their functionality and capabilities, are not enough for the selection of the most suitable tool for a specific project or study. Equally critical is the utility and strengths and weaknesses of these tools vis-à-vis the study or project requirements. Therefore, the study provides a comparison framework (Table 8) to guide users in selecting suitable BEM tools through a comprehensive assessment of their strengths, weaknesses and limitations. This framework offers useful guidance on important selection criteria such as integration capabilities with other software, adaptability to regional and climatic conditions, usability for less experienced users and small firms with limited resources, comparative evaluation of various BEM tools, and economic aspects of their implementation. In view of these factors, users can make a more informed decision about which BEM tools are accessible and appropriate for their project needs and context.

The analytical approaches used in this work were specifically designed to allow for a comprehensive and robust comparative assessment of BEM tools. The evaluation criteria were carefully developed to focus on key parameters important to sustainable building design, including inputs and outputs, applicability, usability, compatibility with local climate data, accuracy of energy performance simulations and integration with design workflow. These criteria were developed through extensive literature review and aligned with industry best practices for relevance and comprehensiveness. For further validation of the findings, cross-checking with case studies and previous research was done for each of the BEM tools tested, to ensure the assessment results are in line with the prevailing trends of tool performance.

The comprehensive evaluation presented in Tables 7 and 8 offers useful insights into the operational capacities and applicability of each BEM tool for particular project or research situations. This conclusion is based on a systematic review of the pertinent literature and authoritative resources such as the American Institute of Architects (AIA), U.S. Department of Energy's Building Energy Software Tools Directory (BESTD) to ensure completeness and reliability. The selected tools were practically validated in their respective software environments for the theoretical findings and compared to the literature and official documentation. Moreover, the data shown in the tables are also verified by the results presented in references [13, 15, 17].

Table 7. A holistic framework for assessing and selecting building energy modeling (BEM) tools based on their capability

Criteria for BEM tools selection		DesignBuilder	Sefaira Architecture	EcoDesigner Star	EnergyPlus	OpenStudio	Ladybug & Honeybee	eQUEST	Autodesk GBS	Tas Engineering	HEED
Usage	Software	✓			✓	✓		✓		✓	✓
	Plugin / Cloud base		✓	✓			✓		✓		
	Text coding				✓						
Inputs	Building geometry	✓				✓	✓	✓		✓	✓
	Import models	✓	✓	✓	✓	✓		✓	✓	✓	
	Weather file	✓	✓	✓	✓	✓	✓	✓		✓	✓
	Construction material	✓			✓	✓		✓			✓
	HVAC	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Lighting	✓		✓	✓			✓			
Outputs	Climate analysis	✓					✓		✓	✓	
	Building performance	✓	✓	✓	✓			✓			✓
	Energy analysis	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Daylighting	✓	✓		✓		✓	✓		✓	✓
	Electric lighting	✓		✓		✓			✓	✓	
	Natural ventilation	✓	✓	✓	✓			✓	✓	✓	✓
	Passive design	✓	✓	✓	✓			✓	✓		✓
	Carbon emission	✓	✓	✓	✓			✓	✓	✓	✓
	Façade elements	✓	✓		✓						
	Thermal analysis	✓		✓	✓			✓		✓	✓
	Heat transfer	✓		✓	✓						
	Heating and Cooling	✓		✓	✓	✓		✓	✓	✓	✓
	Solar analysis	✓			✓		✓	✓			✓
	Renewable systems	✓	✓	✓					✓	✓	✓
	Comfort analysis	✓	✓		✓		✓			✓	
	CFD analysis	✓									
	Cost analysis	✓			✓			✓	✓	✓	✓
Advanced functionalities	Parametric	✓				✓		✓		✓	
	Optimization	✓		✓	✓					✓	
	Life cycle assessment	✓			✓			✓	✓		
	Rating certification	✓							✓	✓	
Results	Graphic	✓	✓	✓	✓		✓	✓	✓	✓	✓
	Report / Text	✓		✓	✓	✓		✓	✓	✓	

As building performance simulation is a large and complex field it is not feasible to provide a comprehensive introduction to all aspects of building performance simulation within the limits of a single review paper [15]. The proposed frameworks can greatly contribute to the progress of sustainable building design by addressing important gaps in the current knowledge base. A key problem in this area is the lack of a systematic approach to the selection of BEM tools that are explicitly intended to support sustainable design goals. This study contributes to filling this gap by offering a comprehensive assessment framework that uses holistic and comparative criteria. The framework helps architects, engineers and researchers to make informed and evidence-based decisions when choosing energy

Table 8. A holistic framework for assessing and selecting building energy modeling (BEM) tools based on their applicability

Tool	Ease of Use	Advanced Features	Suitability for Design Stage	Climate Adaptability	Data Accuracy	Software Compatibility	Budget Constraints
DesignBuilder	Moderate	High	Detailed design	High	High	BIM-compatible (gbXML, IFC)	Paid, high-end hardware needed
Sefaira Architecture	High	Moderate	Early-stage design	Moderate	Moderate (early-stage focus)	Revit/SketchUp integration	Subscription-based, cloud-based
EcoDesigner Star	High	Moderate	Conceptual & early stages	Cold climates	Moderate (cold-climate focus)	Integrated with ArchiCAD	Expensive, desktop-based
EnergyPlus	Low	High (detailed modeling)	Detailed design	High (all climates)	High	Limited GUI, integrates with OpenStudio	Free, training & hardware costs
OpenStudio	Moderate	High	Detailed design	High	High	SketchUp/BIM integration	Free, training costs
Ladybug & Honeybee	Moderate	High	Early to detailed design	High	High	Rhino/Grasshopper platform-dependent	Free, Rhino licenses required
eQUEST	Moderate	Moderate	Early to detailed design	Moderate	Moderate (basic analysis)	DOE-2 format, limited BIM compatibility	Free, lightweight hardware
Autodesk GBS	High	Moderate	Early-stage design	High	Moderate	Autodesk-only integration	Subscription-based, cloud-reliant
Tas Engineering	Moderate	High	HVAC & detailed analysis	Moderate	High	Limited modern BIM integration	Paid, moderate hardware
HEED	High	Low	Residential projects	Low	Moderate (residential focus)	Standalone, minimal integration	Affordable, low hardware costs

modeling tools, which in turn facilitates a better integration of sustainability principles in building design practices. The study also suggests new directions for future research on the development of BEM tools, in particular the improvement of user interfaces, the integration of local climate issues and the expansion of tools to support sustainable design approaches. The research not only contributes to the advancement of architectural and engineering curricula but also informs the development of policy guidelines for sustainable building standards by emphasizing the significance of tool selection for sustainability.

A major limitation of this study is the breadth and rapid growth of BEM tools developed in recent years, many of which require specialized expertise for effective application and analysis. Besides, a full practical implementation of all tools on real case studies with a comparative evaluation of the performance would have greatly extended the scope and length of the manuscript and was therefore out of the aims of this study. However, this study benefits from overcoming this limitation by systematically reducing the list of BEM tools through authoritative sources such as the official BESTD and systematically evaluating their functionalities. A detailed analysis of the selected tools was carried out to identify those with a broad application and strong capabilities for supporting sustainable building design. Future research should include a wider range of BEM tools with a particular focus on dedicated comparative studies evaluating the practical use of these tools in real projects and analyzing the results. Moreover, it is proposed that the use of Multi-Criteria Decision-Making (MCDM) methods may improve the selection process and increase the reliability of the results in the future studies.

CONCLUSION

This work provides a detailed framework for the selection of BEM tools which can represent a valuable resource for informing decisions in the early stages of sustainable design. This study gives architects, engineers and policy makers the necessary knowledge to improve their design processes by benchmarking and comparing ten popular BEM tools. The framework takes into account a variety of technical and contextual factors that affect the complexity of choosing the right tool and thus provides a structured

methodology that can be applied to different types of projects and needs.

The significant contribution of this research is the systematic approach to identify the best BEM tools based on the input-output characteristics, and their specific application in various design scenarios. These factors are important in selecting a tool as they have immediate effects on the effectiveness and efficiency of the energy modeling process. The input-output capabilities of each tool are a good measure of the technical competence of the tool in modeling energy performance, whereas the applicability criteria are a good measure of the usability of the tool in real-world projects considering the local climate, building type and sustainability goals. This double classification enables the decision-makers to understand the trade-offs between different tools by emphasizing their strengths and weaknesses.

The research emphasizes the need for BEM tools in sustainable building design to optimize the key performance indicators such as site, energy, indoor environmental quality, materials and water use. These are the basic elements of a sustainable design and BEM tools play an essential role to avoid the creation of energy efficient, environmentally responsible and comfortable for their users' buildings. These tools combine passive strategies and local environmental considerations to improve the accuracy of energy simulations and to improve the design decisions in accordance with sustainability goals.

Moreover, the study gives a detailed comparative analysis of each BEM tool, which is very useful for professionals in the field. Table 7 and Table 8 summarize the performance of each tool according to the defined criteria, providing a clear and easily accessible guide to select the appropriate tool for the specific needs of a project. This comparative analysis can help architects to not only choose the right tool for a particular project, but also to determine which tools are better suited for a particular stage of the design process, for example, early-stage conceptual design or post-occupancy analysis.

More broadly, the study proposes a new and reliable framework for selecting BEM tools, applicable to a wide range of projects and offering significant support to architects, engineers and decision makers in achieving optimal design results. This study guides the selection of the most appropriate tool by systematic evaluation of capabilities and applicability, assisting with the streamlining of the design process and ensuring energy efficiency and sustainability goals are met effectively. This approach can improve overall performance of building designs and can help in developing more sustainable, energy efficient and environmentally responsible built environments.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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