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Review

Enhancing Energy Efficiency and Building Performance through BEMS-BIM Integration

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Abstract: This paper presents a comprehensive analysis of the potential benefits and feasibility of integrating Building Energy Management Systems (BEMSs) with Building Information Modeling (BIM) in, but not limited to, the construction and building management sectors. By examining advantages, challenges, and real-world case studies, this study offers valuable insights into the impact of BEMS-BIM integration on building operations. The research methodology includes a literature review and bibliometric analysis to understand the subject domain and identify prevalent keywords. Additionally, case studies demonstrate the effectiveness of BEMS-BIM integration in real-world scenarios. This study investigates the possibilities and challenges of BIM to the BEMS methodology for energy-efficient industrial buildings, emphasizing the importance of addressing uncertainties and enhancing software interoperability. This research highlights the potential of BEMS-BIM integration to revolutionize building performance, enhance sustainability, and contribute to a greener and more efficient future for the construction and building management industries.

Keywords: building energy management systems (BEMSs); building information modeling (BIM); digital twin; integration; energy efficiency; sustainability; building performance

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1. Introduction

Increasing energy expenses and the growing dependency on technology in the management and upkeep of residential, commercial, and service buildings call for the investigation of novel approaches to achieve cost effectiveness [1,2]. In this context, the integration of Building Energy Management Systems (BEMSs) [3,4] with Building Information Modeling (BIM) [5,6] emerges as a promising avenue to optimize energy consumption and enhance the overall efficiency of construction and building operations [7].

BEMS technology represents a synergistic combination of hardware and software systems that enable the monitoring, analysis, and control of a building's energy usage [8]. By optimizing the efficiency of various building services, BEMS plays a pivotal role in helping organizations regulate their environments, ensuring benefits to clients, staff, and product integrity [9].

The evolution of BEMS technology aligns with the progressive integration of measurable parameters, including temperature, humidity, air quality, and other factors, that significantly influence indoor environmental quality. This integration involves a collaborative approach that encompasses the design and construction phases, project implementation, and the ongoing management of building systems and energy resources [10].

One area of significant interest revolves around integrating BEMS with BIM technology [11]. This integration has become feasible due to the innovative progress in hardware and software solutions, particularly in the realm of virtual models, enabling smart technologies to exchange information seamlessly between physical and virtual representations, often referred to as "Digital Twin (DT)" [12].

This integration allows for efficient data collection, processing, and feedback for facilities management through techniques such as data-driven decision making, artificial intelligence (AI), and machine learning (ML) [13]. By leveraging these advanced technologies, superior strategies can be developed to conserve energy and enhance the efficiency of critical building systems like heating, ventilation, and air conditioning [14].

By harnessing the capabilities offered by BEMS technology, organizations can gain comprehensive insights into various facets of energy consumption within a building. Through monitoring and analysis of systems like heating, air conditioning, ventilation, lighting, and more, specific areas for energy savings and operational efficiency improvements can be identified. This leads to the adoption of sustainable practices, cost reductions, and enhanced operational performance [15].

The integration of BEMS into buildings presents numerous advantages, addressing a variety of challenges and unlocking opportunities for enhanced operational efficiency, as discussed in this study. However, the current state of building management indicates significant room for improvement. Research estimates suggest that around 90% of buildings in the heating, ventilation, and air conditioning (HVAC) sector suffer from inadequate management, leading to substantial annual energy cost losses. Inefficient control of heating and cooling sources can result in up to 30% higher energy consumption when compared to buildings equipped with efficient BEMS [4]. Addressing these challenges, BEMS technology offers the capability to analyze energy usage patterns, establish usage limits, and define energy consumption targets for different building systems [7].

However, the integration of BEMS with BIM technology presents its own set of challenges. These include incomplete or limited information in existing buildings, compatibility issues, data integration complexities, and the need for skilled professionals who can effectively operate and maintain the integrated system [16].

Nonetheless, advancements in sensor technologies, data integration methods, and DT solutions provide opportunities for overcoming these challenges. These technologies allow for real-time data collection, seamless integration with BIM models, and the creation of virtual replicas of physical assets. These DTs can be used to simulate and optimize building performance, streamline maintenance activities, and achieve better energy efficiency [17].

To gain more information about the published articles and their connection, the VOSviewer version 1.6.19 was used, developed by Nees Jan van Eck and Ludo Waltman at Leiden University's Centre for Science and Technology Studies, Leiden, Netherlands [18]. It is a sophisticated software tool designed for visualizing and exploring bibliometric and scientometric data. By analyzing relationships between scholarly documents, authors, and keywords, VOSviewer generates informative and visually engaging maps and network visualizations. The tool can be employed to reveal meaningful patterns, trends, and collaborations within extensive datasets of the scientific literature, allowing for the extraction of valuable insights and informed decisions to be made in various research domains.

The aim of this paper is to investigate the integration of BEMS with BIM technology to enhance energy efficiency and sustainability in commercial and service sectors. It covers the advantages and disadvantages of BEMS, the process of creating BEMS models, the role of BIM in building operations, and the challenges and opportunities of integrating BEMS and BIM. This paper also highlights real-world implementations and their benefits, offering practical insights into this integration. Overall, it aims to unveil the potential of BEMS-BIM integration for enhancing building energy management and sustainability.

By examining the advantages and challenges of BEMS, exploring the process of creating BEMS models, and understanding the role of BIM in building operations, this paper delves into the potential benefits of integrating BEMS with BIM for improved energy efficiency and sustainability. This study addresses both the technical aspects and the practical implications of this integration by showcasing real-world implementations. Through comprehensive analysis, this paper aims to offer valuable insights into the feasibility and impact of adopting BEMS-BIM integration in all sectors, as well as mentioning possible future research in this domain.

The integration of BEMS with BIM technology has the potential to revolutionize building operations and maintenance, resulting in significant energy savings, improved environmental conditions, and enhanced overall building performance. This paper aims to contribute to the existing body of knowledge by providing a comprehensive overview of the subject, highlighting its relevance in the current energy landscape, and identifying future research directions.

This paper is divided into six distinct sections, each serving a specific purpose. The introduction section provides contextual information regarding the present situation and offers foundational knowledge essential for comprehending the rationale behind the subsequent review. The subsequent section, dedicated to BEMS, offers a comprehensive examination of BEMS, delving into its intricate details and elucidating its operational mechanisms. This section not only presents an insight into the practical application and potential enhancements in BEMS but also delves into the exploration of synergistic integration with machine learning methodologies. The subsequent section, focusing on BIM, furnishes readers with fundamental theoretical underpinnings relevant to BIM, followed by an exploration of diverse real-world instances that illustrate its practical applications.

In the methodology section, an elaboration of the procedural framework employed for the literature selection and the subsequent construction of bibliometric analyses is meticulously detailed. This is followed by the presentation and discussion of the outcomes derived from the bibliometric analysis, as well as the exploration of feasibility and real use cases stemming from the integration of BEMS and BIM. The conclusion of the review synthesizes the main tenets underscored throughout the paper, accentuating the key points. Additionally, potential avenues for future research are introduced, fostering an awareness of the directions in which the field could evolve.

2. Building Energy Management Systems (BEMSs)

BEMSs play a crucial role in optimizing energy consumption and enhancing building efficiency, particularly in smart and sustainable cities [19].

Based on the analyzed studies concerning the use of BEMS, several advantages and disadvantages of BEMS can be identified [7]:

The advantages of BEMSs [20]:

- Increased energy efficiency;
- Improved environmental conditions;
- More efficient use of personnel;
- Enhanced fire, safety, and emergency procedures;
- Improved building performance standards;
- Streamlined building management;
- Reduced carbon emissions;
- Reduced overall costs through improved energy efficiency and personnel optimization.

The disadvantages of BEMSs:

- Higher initial design and installation costs;
- Potentially higher operation and maintenance costs compared to simpler systems;
- Requires experienced operators;
- Demands commitment at all levels throughout its operational life to sustain maximum efficiency.

Over the past decade, the integration of ML has significantly advanced BEMS applications in various areas, including load/power prediction, fault detection and diagnosis (FDD), and occupancy-related tasks [21].

Load prediction involves forecasting future cooling, heating, and electricity demand, while power prediction focuses on equipment power generation, such as photovoltaic panels and wind turbines. Accurate load/power prediction is essential for improving energy efficiency and flexibility in buildings [22]. These prediction models find practical applications in demand-side management (DSM) and model predictive control (MPC). DSM aims to balance electricity supply and demand, adapting to dynamic building energy consumption and the increased use of renewable energy systems. On the other hand, MPC optimizes building energy systems to meet specific goals under constraints, such as minimizing costs or energy consumption [23].

Various ML algorithms, including autoregressive methods, tree-based methods, artificial neural networks (ANNs), and deep neural networks (DNNs), have been utilized to achieve reliable load/power prediction. ANN, in particular, has proven effective in addressing complex real-world problems, while DNN with long short-term memory (LSTM) layers has demonstrated superior performance compared to tree-based algorithms for building electricity demand prediction [24].

ML has also shown promising results in FDD for building energy systems, enabling the early detection of equipment faults and enhancing energy efficiency [25].

Additionally, ML-based thermal comfort models have been employed to optimize building HVAC systems, resulting in reduced energy consumption and improved occupant satisfaction [26]. The integration of ML with Internet of Things (IoT) devices has facilitated convenient data collection, enabling further enhancements in building energy efficiency. For instance, ANN combined with IoT data has led to significant reductions in HVAC energy consumption [27].

In the realm of advanced energy management, Advanced Energy Management Systems (AEMSs) have emerged as cutting-edge technologies designed to optimize energy consumption and improve building performance. By collecting data from various sources, such as smart meters, sensors, and weather forecasts, AEMS utilizes sophisticated algorithms to monitor and control energy usage within buildings [28].

The key advantages of AEMS include enhanced energy efficiency, improved building performance through real-time analysis, and increased comfort and productivity for building occupants. Statistical evidence supports these benefits, with studies showing reductions in energy usage of up to 35% in commercial buildings and energy savings ranging from 10% to 30% through AEMS implementation [29,30]. Smart energy management systems also have the potential to reduce peak power use by 15% to 20% [31].

Embracing AEMS and incorporating ML-based approaches in BEMS offer significant potential for revolutionizing building performance. These advancements drive efficiency, reduce costs, and contribute to the sustainability of both the environment and building occupants [32].

Creating BEMS models involves several key steps to ensure that the model accurately represents the building's energy performance and behavior. The following is a general process involved in creating them [4,10,33]:

- Data Collection and Building Survey:
  Gather all relevant building data, including architectural drawings, construction plans, specifications, and equipment details, and conduct a comprehensive on-site survey to collect information on building geometry, envelope properties, HVAC systems, lighting systems, occupancy patterns, and any other relevant parameters [34].
- Building Geometry Modeling:
  Use the collected data to create a 3D digital model of the building's geometry. This model represents the physical layout and structure of the building, including floors, walls, windows, doors, and roofs [35].
- Building Energy System Modeling:
  Develop detailed models of the building's energy systems, including HVAC systems, lighting systems, and other energy-consuming equipment, and specify the characteristics and properties of each component, such as the efficiency of chillers, boilers, air handling units, lighting fixtures, etc. [36].
- Energy Simulation Software:

Choose an appropriate energy simulation software that can integrate the building geometry and energy system models. Popular simulation tools include EnergyPlus, eQUEST, and DOE-2, which can analyze the building's energy consumption under different conditions and schedules [37].

- Weather Data and Occupancy Profiles:
  Import local weather data to simulate the building's energy performance under different climate conditions and define occupancy profiles to account for variations in internal heat gains based on the building's usage and occupancy patterns [38].
- Simulation and Calibration:
  Run the energy simulation using the chosen software to analyze the building's energy performance. Compare the simulation results with actual utility bills or historical energy consumption data to calibrate the model and ensure its accuracy.
- BEMS Integration:
  Integrate the calibrated energy model with the BEMS. The BEMS may include sensors, meters, and control algorithms to monitor and manage the building's energy consumption in real-time.
- Sensitivity Analysis and Optimization:
  Perform sensitivity analyses to evaluate the impact of different building parameters and design options on energy consumption. Optimize the BEMS settings and control strategies to achieve energy efficiency and occupant comfort goals.
- Validation and Commissioning:
  Validate the BEMS model by comparing its performance against real-world data after the system is installed and operational. Commission the BEMS to ensure it functions as intended and meets the desired energy efficiency and control objectives.
- Continuous Monitoring and Maintenance:
  After implementation, continuously monitor the BEMS and the building's energy performance to identify any discrepancies or potential improvements. Regularly update the model with new data and changes to the building's systems to maintain its accuracy over time.

There is a lot of research in the field of BEMS, which needs to be highlighted as well. Recent research conducted in South Africa [39] on the state of BEMS research in South Africa identifies several areas of focus and gaps in the existing literature. The findings reveal the following key results:

- Building Typology:
  The research primarily concentrates on BEMS studies related to residential buildings, with commercial, educational, and office buildings also receiving some attention. However, industrial and institutional buildings have been relatively neglected in the literature. The prevalence of energy inefficiencies in domestic households is highlighted as a significant concern.
- Building Services Subsystems:
  The major focus in BEMS studies has been on HVAC systems, underscoring the significant contribution of heating and cooling demands to energy consumption in South Africa. Lighting systems and consumer electronics are other areas of interest, but they have not received as much attention as HVAC systems.
- Applied BEMS Strategies:
  DSM emerged as the most widely adopted strategy, especially in residential buildings, to address energy management challenges. In commercial buildings, MPC was utilized to tackle real-time electricity pricing issues. However, optimization methods and FDD were relatively underrepresented, despite their potential for enhancing energy efficiency.
- Methodological Approaches and Testbeds:
  Classical techniques such as linear programming and linear regression have been commonly used in BEMS studies. To overcome the limitations of these traditional approaches, researchers have applied metaheuristic methods like genetic algorithms

(GAs). Additionally, AI and ML techniques, such as deep learning neural networks, have been employed for energy demand prediction and optimization. The use of simulation testbeds for validation is predominant. Gaps in this section include limited integration of big data analytics, a lack of hybrid methodologies, insufficient consideration of uncertainty and sensitivity analysis, and the need for real-time performance assessment in actual operational conditions.

- Focused Energy Management System Tasks:
  BEMS studies primarily concentrate on control functions, monitoring and evaluation, and analyzing and predicting current and future energy use. Optimizing energy efficiency within the operational stage of buildings has emerged as a key priority. However, the gaps involve the underrepresentation of demand response strategies, limited integration of renewable energy sources (RESs), neglect of occupant behavior modeling, and a lack of multi-objective optimization approaches to balance conflicting objectives.

Similar trends are observed in Europe due to the similarity in weather conditions between South Africa and Europe, with the only difference being the inverted seasons.

In a comprehensive review by [3], energy management strategies for BEMS are explored in both non-residential and residential buildings. The efforts are categorized into a focus on non-residential buildings (71.74%), residential buildings (21.74%), and both types (6.52%). Key strategies include MPC, DSM, optimization, and FDD, with challenges related to model quality and user-oriented optimization.

Another study by [13] presents a taxonomy of ML functionalities in virtual power plants (VPPs) and BEMS. The taxonomy covers three tiers: optimize, forecast, and classify, encompassing various ML applications such as optimization, forecasting (load, price, and renewable generation), and fault detection. This study emphasizes the growing interest in ML for optimizing VPPs and energy forecasting while identifying future research areas and challenges.

3. Building Information Modeling (BIM)

BIM plays a crucial role in building operations. BIM is a digital representation of the physical and functional characteristics of a building or infrastructure [40]. Its primary purpose is to enhance the collaboration, efficiency, and decision-making processes throughout the building's entire lifecycle, including the operational phase. The following are some key ways in which BIM contributes to building operations [5]:

- Facility Management and Maintenance:
  BIM provides a comprehensive database of information about the building, including architectural, structural, and mechanical, electrical, and plumbing (MEP) details. These data can be used by facility managers and maintenance teams to effectively manage the building's assets, plan preventive maintenance, and quickly access information about various systems and components [41].
- Space Management:
  BIM allows for accurate space management, enabling facility managers to visualize and track spaces within the building, assign uses, and manage occupancy. This helps to optimize space utilization, track changes in real-time, and plan for future space requirements [42].
- Energy Efficiency and Sustainability:
  BIM can be utilized to simulate and analyze energy performance, daylighting, and other sustainability factors. By assessing different scenarios and energy-efficient strategies, building operators can make informed decisions to reduce energy consumption and lower operating costs [1,43].
- Asset Tracking and Inventory Management:
  BIM can be integrated with asset tracking systems, allowing facility managers to monitor and maintain equipment and inventory efficiently. This integration streamlines

the process of tracking assets, automating inventory management, and optimizing procurement processes.
- Emergency Planning and Safety Management:
BIM can assist in emergency planning by providing visual and data-rich representations of the building's layout, escape routes, and safety equipment locations. This information aids in developing effective emergency response plans and conducting simulations to assess safety measures [14].
- Upgrades and Retrofits:
During the operational phase, buildings may require upgrades or retrofits. BIM's detailed information and visualization capabilities help architects and engineers plan and execute these projects with greater accuracy and minimal disruption to the building's occupants.
- Collaboration and Communication:
BIM facilitates collaboration among various stakeholders, including architects, engineers, contractors, facility managers, and owners. It serves as a centralized platform for sharing information, making revisions, and documenting changes, ensuring everyone involved has access to the most up-to-date data.
- Data for Decision Making:
BIM generates valuable data and insights throughout a building's lifecycle. By analyzing these data, building operators can identify trends, predict maintenance needs, and make informed decisions to optimize performance and reduce operational costs [6].

BIM's integration into building operations provides numerous benefits, ranging from improved efficiency and cost savings to enhanced safety and sustainability measures. As the technology continues to evolve, its impact on building operations is likely to become even more significant [44].

A digital twin is a big part of BIM. In this context, it refers to a virtual, data-rich representation of a physical building, infrastructure, or facility. It serves as a dynamic digital counterpart, constantly updated throughout the project's lifecycle. The digital twin integrates various data sources, including architectural, structural, and MEP information, along with real-time data from embedded sensors within the physical asset [45–47].

The benefits of a digital twin in BIM are numerous. It fosters enhanced collaboration and communication among project stakeholders, enabling seamless data sharing and informed decision making. Design and construction teams can simulate and analyze different scenarios, identifying clashes and optimizing designs before construction begins, leading to cost and time savings [41].

The real-time monitoring capabilities of the digital twin enable facility managers to assess the asset's performance, predict maintenance needs, and maximize operational efficiency. Moreover, the digital twin provides a holistic view of the project's entire lifecycle, supporting long-term planning, asset management, and eventual decommissioning or renovation [43].

The integration of DT technology within BIM is revolutionizing the design, construction, and management of buildings and infrastructure, harnessing real-time data and advanced modeling for enhanced project outcomes and efficient asset performance [17]. In the context of sustainable energy management, ref. [48] explores the application of DT technology, a key element of Industry 4.0, across domains such as building energy analysis. Enabling real-time monitoring, optimization, and prediction of energy consumption, DT technology contributes to sustainable building energy management and cost reduction. This study reviews the evolution and application of DT technology in building energy, discusses its integration with BIM, and assesses its impact on energy optimization, indoor environmental monitoring, and energy efficiency evaluation [49]. Despite the challenges, including data quality and model complexity, this review underscores the potential of DT technology, especially in conjunction with machine learning, to enhance energy efficiency, reduce carbon emissions, and align with sustainable development objectives [50].

In [51], BIM integration is proposed to enhance energy audit processes, introducing a BIM-based framework and tool for efficient building envelope assessments. Notably reducing assessment effort, this approach envisions wider BIM adoption for building evaluations, aligning with the integration of digital construction practices into energy audits and extending assessments to virtual building representations. The study acknowledges potential issues with calculation accuracy due to incomplete digital building models, emphasizing data verification and standardization for enhanced reliability.

In [52], a Parametric BIM-based Optimality Criteria method is presented, combining parametric BIM with the Optimality Criteria approach to optimize envelope shape and element size in high-rise buildings. This approach aims to improve energy performance and structural efficiency through multi-objective optimization, showcasing potential structural cost variations of up to 60% while enhancing energy efficiency.

Addressing the issue of inadequate organizational BIM capabilities, ref. [53] examines assessment criteria in Malaysia and Iran. The study identifies nineteen criteria for organizational BIM capabilities and highlights the importance of suitable infrastructure and openness to technology as common priorities. Although subsequent criteria vary between countries, the study reveals consistent overarching constructs emphasizing organizational BIM and general capabilities. The research underscores the significance of resource sufficiency and standardized guidelines for effective BIM implementation while also revealing Iran's focus on employee management and rule definition. Future research could explore similar analyses in countries with diverse income levels to further assess criteria variations.

4. Methodology

Through comprehensive analysis, this research aims to offer valuable insights into the feasibility and impact of adopting BEMS-BIM integration in all sectors. By revolutionizing building operations and maintenance, this integration could lead to substantial energy savings, improved environmental conditions, and enhanced overall building performance. This paper seeks to contribute to the existing body of knowledge by providing a comprehensive overview of the subject, highlighting its relevance in the current energy landscape, and identifying potential future research directions. A literature review is crucial for understanding the current state of research, existing gaps, and the foundation upon which this investigation builds.

The research methodology employed in this study involved conducting a literature review. This choice was motivated by its capacity to unite findings from an extensive array of studies concerning the subject matter, thereby furnishing a holistic portrayal of the topic [13]. The primary source of literature was the Web of Science database as well as all databases indexed in WOS, which were complemented by data from Google Scholar to include practical literature.

To dissect the occurrence patterns of keywords within the chosen publications, a bibliometric analysis was executed utilizing VOSviewer software [18]. This analysis allowed for the identification of patterns and trends within the literature, enhancing the understanding of the research landscape.

The process of handpicking studies for the review adhered to a three-fold procedure:

1. Initiation involved conducting a search based on the field of interest, encompassing title, abstract, keywords, and publication year.
2. Subsequently, the outcomes of the initial search were meticulously refined to ensure pertinence and suitability.
3. The final selection of studies transpired through a dual process of visual screening and citation analysis, meticulously guaranteeing the inclusion of pertinent and influential works within the review.

The search step for selecting studies was conducted by using the keyword function on the Web of Science website. The used keywords were "Building Energy Management Systems", and "Building Information Modeling", both abbreviations, as well as "digital twin”. The initial number of papers found was 2186 using the keyword “Building Energy Management Systems” as the must include and all others as should include.

From the found articles, the first one, using both BEMS and BIM as keywords in the abstract, was [54] in 2013, which discussed the increasing interest in improving the energy efficiency of BEMS and HVAC systems in buildings. The study utilizes BIM and Energyplus to analyze energy performance and applies a GA-based optimization technique to obtain an optimized HVAC control schedule for maximizing building energy performance. However, the presence of references to BEMS and BIM can be traced back to as early as 1991 in academic papers. Notably, during this period, BEMS was the predominant term used, whereas BIM gained widespread acceptance only in the early 2000s. The year 2002 was selected as the initial criterion due to its status as the first year in which a minimum of two papers were published in each subsequent year. The revised count of papers meeting this criterion amounted to 2155. The publications were acquired in July of the year 2023, so they contain only approximately 50% of the total publications from that year. A graph illustrating the distribution of these publications over the years starting in the year 2002 is presented in Figure 1.

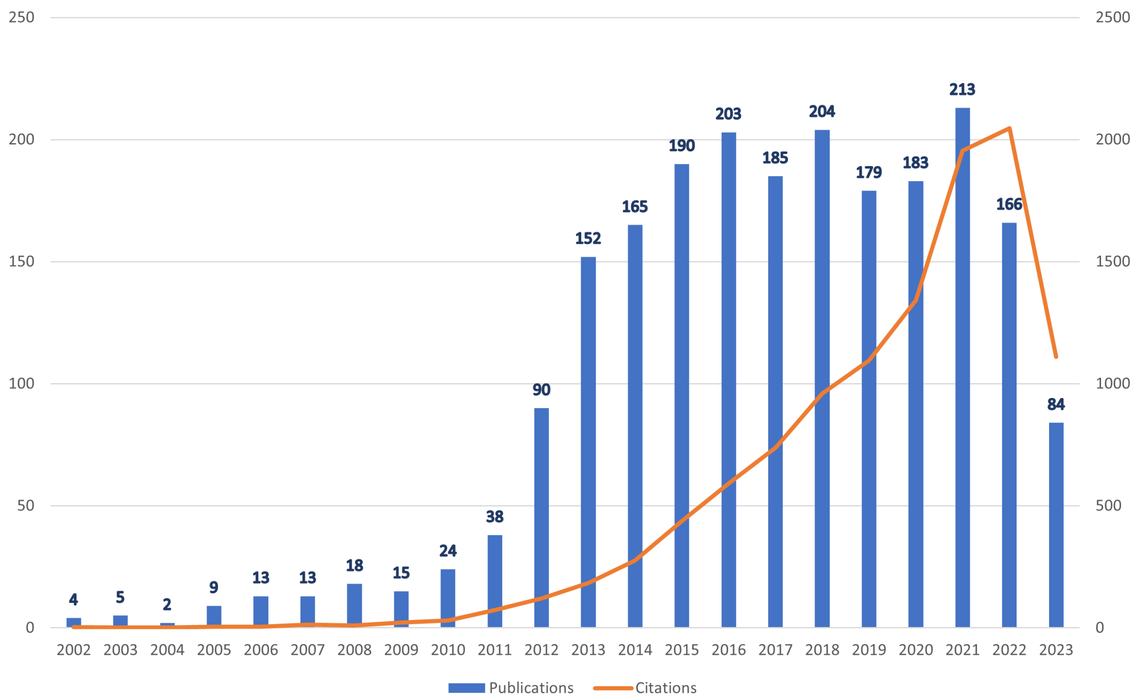

Figure 1. The number of published papers and citations of reviewed articles throughout the years.

The number 2155 underwent additional refinement by exclusively considering articles that did not mention the boundary element method, as this method was frequently identified by the acronym BEMS. Further filtration was performed by changing the keyword “BIM” to must include, resulting in a reduction in the overall article count to 338. Using the integrated Web of Science functionality, a visualization was generated based on the provided papers to determine their country of origin, as depicted in Figure 2. Subsequently, a more detailed analysis was conducted to display the distribution of publications categorized by their respective continents of origin, as represented in Figure 3. The journals to which the publications were submitted were also analyzed, and these results can be seen in Table 1.

In the process of visual screening, the titles, abstracts, findings, conclusions, and citations of various articles were examined. The main criterion for this point was the minimal amount of citations shown in the WOS database. At least five citations were needed to get through this screening process. After the third stage of the search, the final set consisted of 208 unique publications. The whole process can be seen in Figure 4.

Table 1. The top 10 journals where the selected articles were published.

Journal Name	Number of Publications
Energy and Buildings	30
Energies	27
Energy Procedia	12
Journal of the Architectural Institute of Korea Planing Design	12
Sustainability	11
Applied Mechanics AND Materials	9
IEEE Industrial Electronics Society	9
IFAC-PapersOnLine	7
6TH International Building Physics Conference IBPC 2015	6
Applied Energy	6

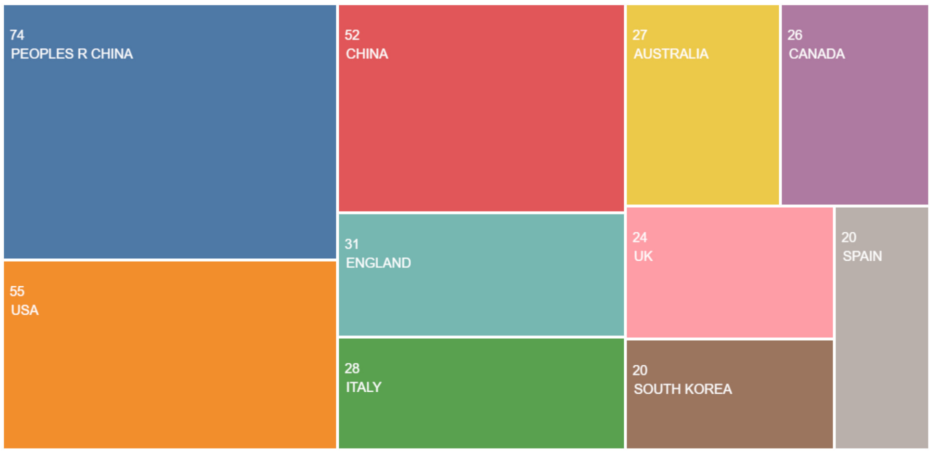

Figure 2. Visualization of the number of reviewed articles by their country of origin (created by the Web of Science database. Only the top 10 countries were taken).

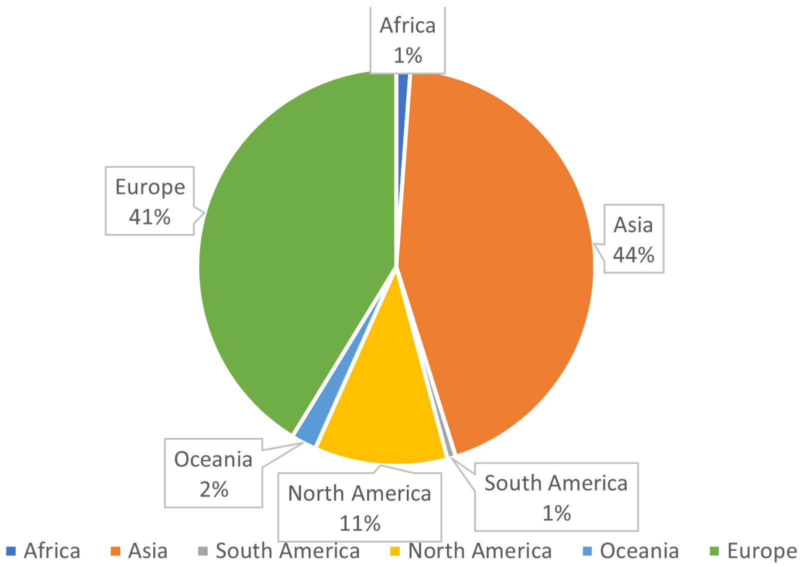

Figure 3. The percentage of publications published in the BEMS domain by their continent of origin.

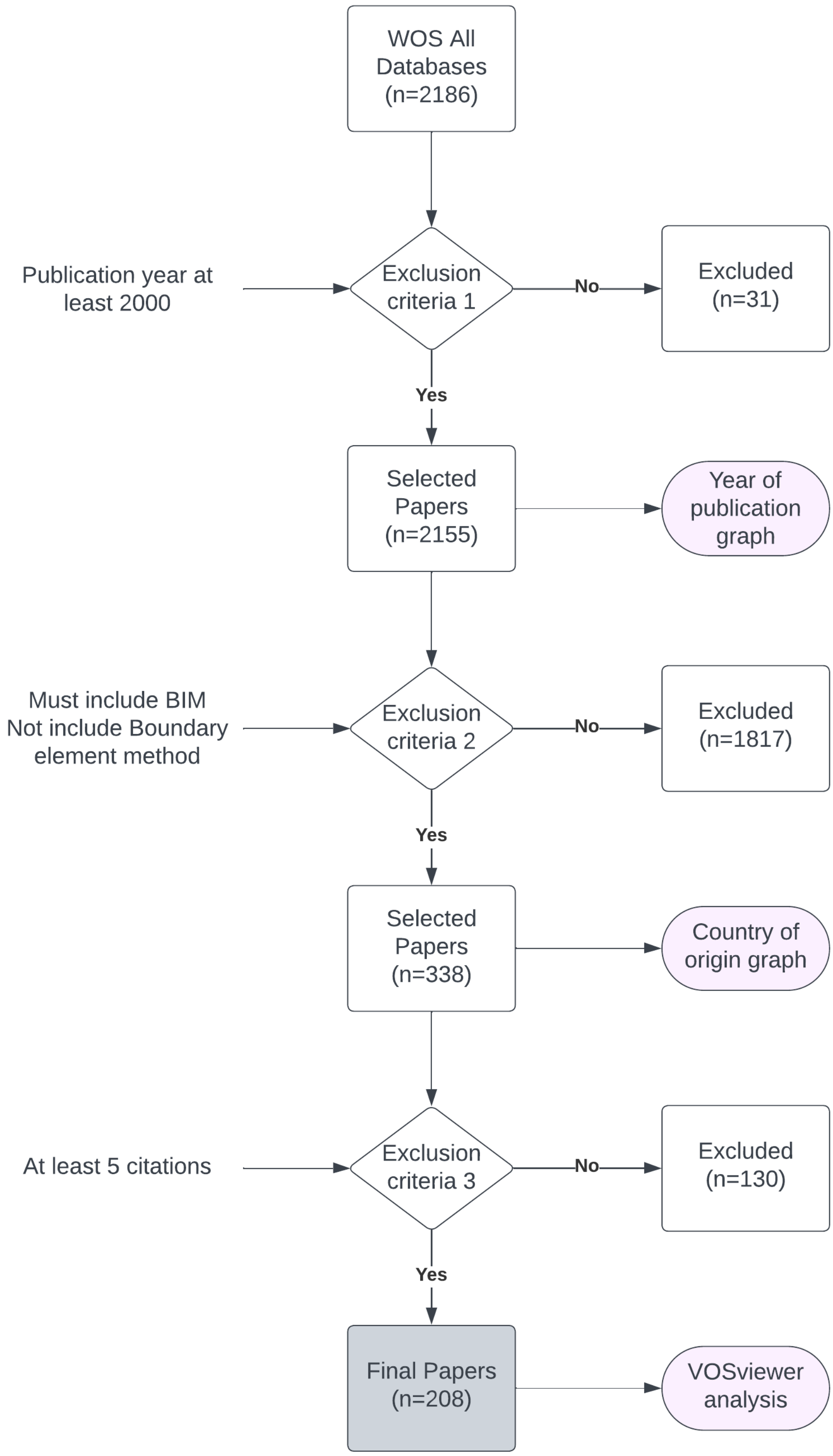

Figure 4. A flowchart depicting the stages of the literature selection process along with the corresponding exclusion criteria for each stage.

5. Results and Discussion

From Figure 1, it can be observed that the trends in the number of publications on BEMS and/or BIM are closely connected with the increasing need for energy optimization and efficiency in buildings. As global concerns about energy consumption, greenhouse gas emissions, and sustainability have grown, the building industry has faced mounting pressure to address these challenges. There was a small slowdown during the economic crisis in 2008, as well as the first year affected by the coronavirus pandemic. A small slowdown in the increasing trend can be seen in the year 2019, when a lot of improvements were made in the cost efficiency of RES, such as solar and wind power and building large off-shore wind plants, as well as the increased use of the natural gas power plants, which were seen as a clean alternative.

The research methodology encompassed the extraction of titles, abstracts, and author information from selected publications in the domain of interest. These publications were obtained from the Web of Science database and exported into a Comma-Separated Values (CSV) report, facilitating meticulous examination. For comprehensive bibliometric analysis and an exploration of the interrelationships between BEMS and BIM concepts, the authors employed VOSviewer—a potent software tool renowned for constructing and visually representing bibliometric networks [18].

Through a meticulous examination of keyword occurrences among the selected publications, the research sought to identify the most prevalent terms shared across the literature. This methodological approach provides valuable insights into the fundamental connections and associations prevailing within the subject domain. To establish a robust analytical foundation, a prudent threshold was set by the authors, requiring at least ten occurrences of keywords within the selected publications. As a result, out of the initial pool of 5999 keywords, which occurred at least once, 131 keywords met the rigorous inclusion criteria of having at least ten occurrences.

Each of the 131 identified keywords underwent an exhaustive evaluation, considering their co-occurrence links with other keywords in the literature. This systematic analysis enabled the identification of the most influential keywords, characterized by their pronounced associations with other terms. Using the default VOSviewer tool setting, only 60% of the most influential keywords were selected to reduce the complexity of the finished visualization. The final amount of keywords visualized was 79.

Among the meticulously curated keywords, "integration", "information modelling", "energy consumption", and "maintenance" emerged as the most prominently employed terms. Remarkably, these keywords played a pivotal role in shaping clusters of significant importance within their respective research contexts. To visually depict these crucial findings, Figure 5 presents the most prevalent single and two-word keyword combinations extracted from the titles, abstracts, or keywords of the analyzed publications.

Notably, an intriguing revelation emerged during the examination of interconnections and citations among the identified keywords. "Integration", "information modelling", and "energy consumption" were found to be the most frequently cited and highly interconnected keywords, exhibiting a remarkable total link strength of approximately 400 each (total link strength is the sum of all individual link strengths based on their co-occurrence frequency in a dataset). Surprisingly, "BIM tool" exhibited a relatively limited presence among the identified keywords, indicating a notable scarcity of research publications concerning the emerging integration between BEMS and BIM. This apparent disparity suggests that the scholarly focus remains predominantly directed toward BEMS, potentially impeding the comprehensive exploration and dissemination of knowledge related to the integration with BIM.

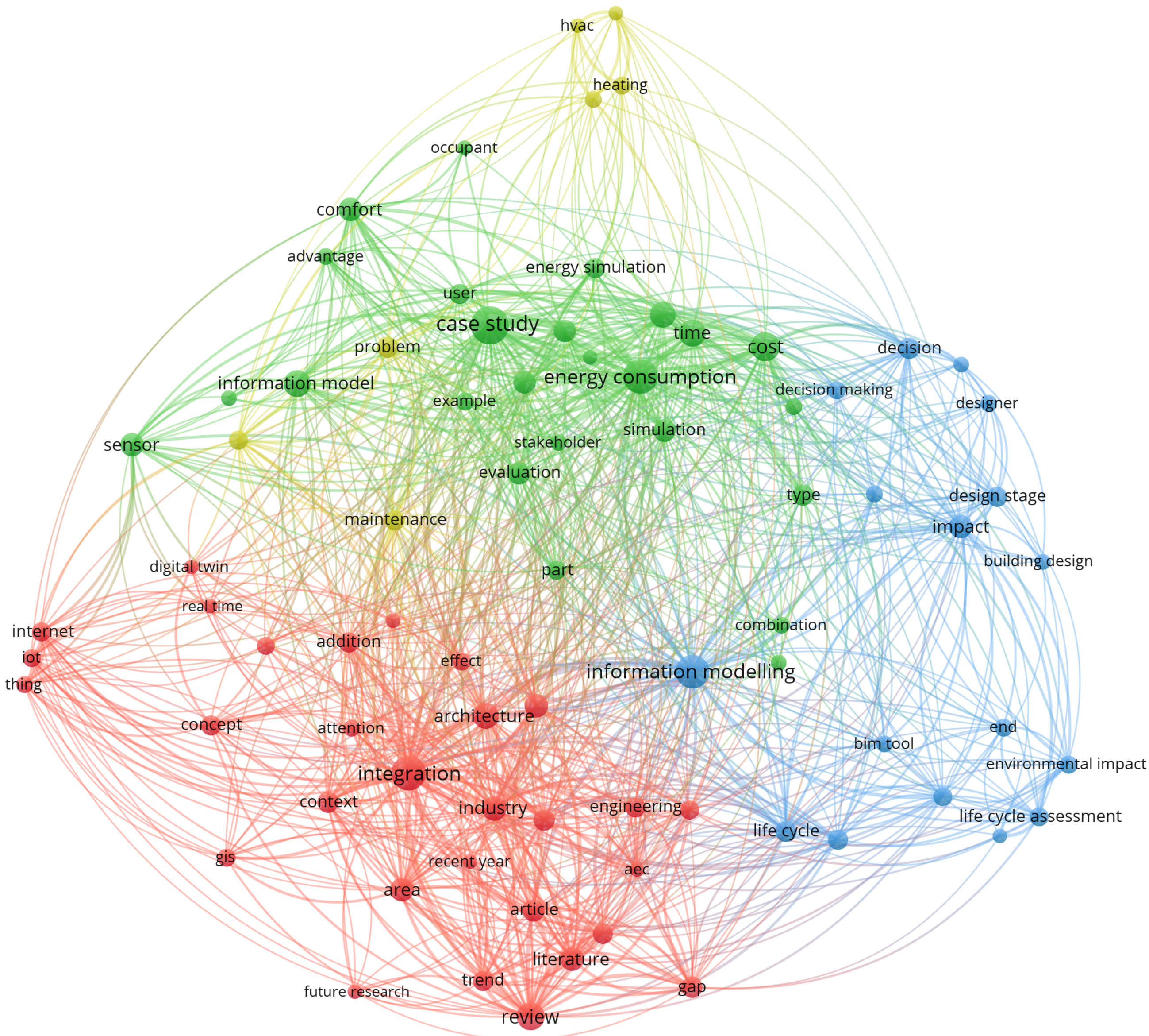

Figure 5. The most common keywords in selected publications related to BEMS and BIM (outputs of VOSviewer).

An insightful analysis can be derived from examining the continental origins of the selected papers, as illustrated in Figure 3. The notable presence of Asia, accounting for 44% of the chosen publications, can be attributed to several compelling factors. Asia's rapid economic growth and urban expansion have led to an escalating demand for sustainable and energy-efficient building solutions. Consequently, researchers and professionals in Asian countries have actively pursued investigations and implementations of BEMS and BIM integration to tackle energy consumption challenges within the built environment. Moreover, governmental policies and initiatives prioritizing energy efficiency and eco-friendly building practices, particularly in nations like China, Japan, South Korea, and India, have likely stimulated vigorous research and development in this domain.

The 41% contribution from Europe underscores the region's longstanding commitment to environmental sustainability and energy conservation. European nations have been pioneering the adoption of RES and advocating for sustainable building methods for an extended period. The convergence of BEMS with BIM aligns seamlessly with Europe's emphasis on intelligent and energy-efficient structures, rendering it an area of paramount interest for researchers, policymakers, and industry stakeholders across the continent.

The 11% share attributed to North America among the chosen publications can be linked to the region's persistent endeavors to curtail carbon emissions and address the exigencies of climate change. Countries such as the United States and Canada have made significant investments in research and innovation pertaining to energy management and building sustainability. The integration of BEMS and BIM offers promising avenues to optimize energy usage and amplify building performance, garnering substantial attention from researchers and practitioners in North America.

The representation of Africa, South America, and Oceania in the chosen publications is equally noteworthy. Africa's 1% presence reflects a nascent yet growing interest in sustainable building practices and energy-efficient solutions. The continent's burgeoning urbanization and evolving development landscape are likely to drive increased research and application of BEMS and BIM integration in the future.

Similarly, South America's 1% share reflects a developing trend toward addressing energy consumption challenges in the built environment. The region's diverse climate zones and socio-economic contexts provide fertile ground for exploring innovative strategies such as BEMS and BIM integration.

The 2% representation from Oceania may be correlated with the region's emphasis on sustainable development and ecologically sound building practices. Oceania's distinctive environmental challenges, encompassing extreme weather conditions and water scarcity, have catalyzed interest in energy-efficient edifices and advanced technologies like BEMS and BIM. It is likely that researchers and industry experts in Oceania are actively exploring these integrative methodologies to mitigate environmental impacts and ensure the prudent utilization of resources.

The distribution of selected publications across these diverse continents serves as a reflection of the global resonance surrounding sustainable building practices and the quest for energy efficiency. The variations in percentage distribution among continents can be ascribed to region-specific priorities, governmental policies, and the extent of research and development endeavors in the realm of BEMS and BIM integration. As the urgency to address climate change and energy consumption intensifies, collaborative endeavors spanning continents are poised to play a pivotal role in shaping a more sustainable future for the built environment.

The integration of BEMS and BIM has emerged as a powerful approach to optimize building performance, enhance energy efficiency, and create smarter, more sustainable built environments. This synergistic coupling of BEMS and BIM technology holds great promise for the construction and building management industries. The integration of these two technologies allows for the real-time exchange of data, creating a powerful platform for effective building management [47,55].

This integration yields a range of substantial benefits, mainly directed at reducing energy consumption in buildings, improving energy performance prediction accuracy, and generating potential cost savings. This integration brings together real-time operational data from BEMS and the comprehensive architectural insights of BIM, forming a symbiotic relationship that optimizes energy efficiency across the building's lifecycle [56]. The main benefits are the following:

- Energy consumption reduction by empowering stakeholders to make well-informed decisions from the outset. Architects and engineers can utilize real-time BEMS data during the design phase to tailor building orientation, system sizing, and layout to maximize energy efficiency. This data-driven design approach ensures alignment with actual operational parameters, creating a solid foundation for buildings that inherently prioritize energy conservation.
- Real-time performance monitoring and management, which contributes to prompt energy-saving interventions. By integrating BEMS data into BIM models, facility managers gain continuous insights into energy consumption patterns and system effi-

ciencies. This real-time feedback loop enables the early identification of inefficiencies or deviations, facilitating proactive measures to prevent energy wastage and ensuring optimal system performance.

- An enhancement in the accuracy of energy performance predictions through dynamic simulations, a hallmark of the BEMS-BIM integration. By incorporating real-time operational data and occupant behavior, these simulations provide a realistic representation of how building systems will function. The result is a more reliable estimation of energy usage during the design phase, ensuring that energy-efficient strategies are grounded in empirical data and better poised to translate into operational efficiency.
- Cost savings as a significant financial advantage of BEMS-BIM integration. Reduced energy consumption translates directly into lower operational costs over the building's lifespan. The integration assists in optimal system sizing, mitigating the oversizing that often leads to capital and operational inefficiencies. Timely fault detection and maintenance practices, guided by real-time data, minimize downtime, yielding not only operational cost savings but also improved occupant satisfaction.
- Retrofitting and upgrades by using the integration's insights to guide well-informed decisions on energy-saving measures, ensuring that resources are allocated efficiently to generate maximum impact. Furthermore, streamlined collaboration among stakeholders, fostered by BEMS-BIM integration, minimizes errors, reworks, and associated costs throughout the project's lifecycle.

However, the integration of BEMS and BIM also comes with technical aspects and practical implications. Data standardization is a crucial challenge, as harmonizing data formats between BEMS and BIM systems is essential for smooth data transfer and interoperability. Establishing a robust communication protocol is vital to ensure real-time data synchronization between the two systems. Moreover, integrating two critical systems demands robust security measures to safeguard against potential cyber threats and data breaches [57]. The successful implementation of BEMS-BIM integration also requires a skilled workforce capable of operating and managing both technologies effectively [12].

There are some effective strategies, which can be used for overcoming these technical challenges:

- Clear Project Goals and Requirements:
  Define clear project goals and requirements for the integration of BEMS and BIM. Understand the specific objectives, data exchange needs, and desired outcomes. This will provide a strong foundation for the integration process and help guide decisions throughout the project.
- Standardized Data Formats and Protocols:
  Ensure that both BEMS and BIM systems use standardized data formats and protocols for data exchange. Common standards such as Industry Foundation Classes (IFCs), Building Controls Virtual Test Bed, and Building Automation and Control Networks can facilitate seamless communication between systems. Implementing these standards reduces compatibility issues.
- Open Application Programming Interfaces (APIs):
  Utilize open APIs to enable data sharing and communication between BEMS and BIM systems. Open APIs allow developers to create custom integrations that suit specific project needs. This approach promotes flexibility and scalability, making it easier to adapt to changes in technology and system requirements.
- Interdisciplinary Collaboration:
  Foster collaboration between various project stakeholders, including architects, engineers, facility managers, and IT professionals. Interdisciplinary teamwork ensures that different perspectives are considered, leading to a more holistic integration approach. Regular communication and coordination can address technical challenges and enhance the overall integration process.
- Data Mapping and Transformation:

Develop a clear data mapping and transformation strategy to align data structures between BEMS and BIM systems. This involves identifying equivalent data fields, units, and semantics to enable accurate data exchange. Data transformation tools or middleware can be employed to facilitate this process and ensure consistency across systems.

- Pilot Testing and Validation:
  Before full-scale implementation, conduct pilot testing to validate the integration approach. Use a smaller-scale project or a subset of data to identify and address any technical issues or bottlenecks. Pilot testing helps refine the integration process and minimizes risks associated with large-scale deployment.

Despite its potential benefits, there are several problems and challenges to consider. Integrating BEMS and BIM may require initial capital investment and upgrades to existing systems, which could be a barrier for some stakeholders. The complexity of integrating two complex systems demands careful planning and skilled implementation to avoid complications. Additionally, some stakeholders may be hesitant to embrace new technologies and workflows, necessitating change management strategies [1].

Nevertheless, the feasibility of BEMS-BIM integration is evident as many BEMS and BIM systems already have API capabilities, making integration technically viable. Moreover, various industry organizations are actively working to develop standards and best practices for BEMS-BIM integration, further promoting its feasibility.

The process of creating a BEMS model integrated with BIM involves three main steps [11]:

1. The creation of a BIM model:
   A BIM model is created by the BIM designer based on the building's structure using a BIM authoring system. This model includes information and geometric object data, as well as spatial relationships between objects. To ensure compatibility and ease of use, the model is exported using the IFC format, which is supported by various BIM software manufacturers.
2. The creation of the BEMS model:
   Simultaneously with the creation of the BIM model, the BEMS designer processes information related to the BEMS. A comprehensive list of all data points is generated, with automatic generation possible for most systems. However, manual enrichment of data with additional information may be required. Each data point is then mapped to a specific device in the BIM model.
3. The optimization and updating of the BEMS model:
   Once the BEMS model is created, it is essential to ensure the correct functioning of the energy data used. Regular updates and adjustments become necessary during renovations, layout changes, or sensor replacements. Such updates are typically localized and do not significantly affect the overall model structure. The model maintenance workflow involves fewer but similar tasks compared to the model creation workflow. Multiple actors, including BIM and BEMS modelers, may be involved in these updates. Before integrating the BEMS, data quality from individual measurement points must be verified and then updated in the BEMS model.

In real-world scenarios, the integration enables optimized designs, real-time performance monitoring, predictive maintenance, and collaborative efforts. BEMS data inform energy-efficient designs, while integration allows continuous energy tracking during construction and occupancy. Predictive maintenance minimizes downtime, and collaboration is enhanced among stakeholders [58].

One of the uses of the fusion of BEMS and BIM is to facilitate a 3D visualization of sensor readings, including temperature and CO_2 data, localized to specific building levels [59]. Additionally, historical sensor data from selected rooms can be graphically represented, allowing for the analysis of trends over defined time spans. This synergy between BEMS and BIM not only empowers instantaneous comprehension but also furnishes an analytical framework for deciphering patterns within architectural spaces. An example of this can be seen in Figure 6.

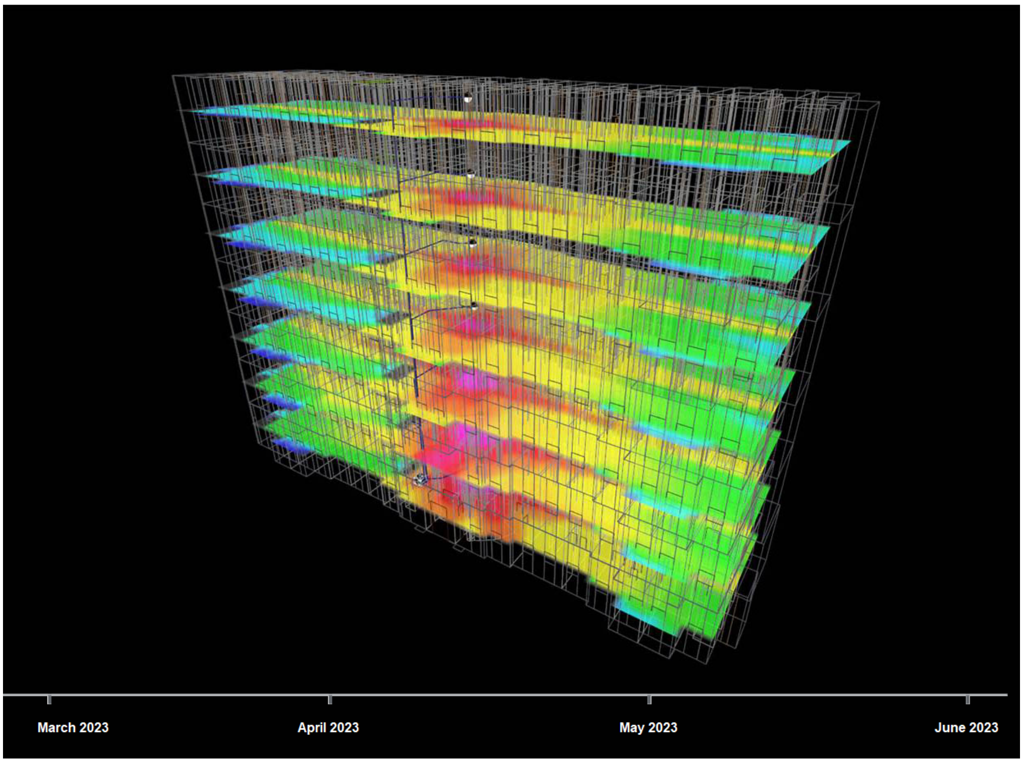

Figure 6. Heat map created in BIM model using BEMS historical sensor data [59].

Challenges include harmonizing diverse data sources and addressing complexity, necessitating training and robust security measures. Nonetheless, opportunities are significant. The integration empowers comprehensive decision making, extends sustainability efforts, simplifies compliance, and drives innovation. Ultimately, research into BEMS-BIM integration reshapes sustainable building design and construction [60].

Several case studies were already created, where this integration was used. Ref. [47] conducted a case study of this integration. Ports, being essential hubs for human activities and trade, are closely linked to environmental concerns. Anzio, a fishing port in Italy's Lazio region, is one such example with a rich history of local development. To address the challenges of sustainability, a new approach utilizing BEMS and BIM has been adopted.

The integration of BEMS and BIM allows for better decision making and energy performance evaluation in the port area. Digital models created using BIM technology provide detailed information on various building systems, while BEMS monitors and controls energy usage. The combination of these technologies has resulted in remarkable improvements.

The optimization of lighting terminals through the use of LED structures has led to a substantial reduction of about 65% in energy consumption for lighting compared to the previous state. Additionally, the installation of charging devices for boats in the port area has further enhanced energy efficiency.

Wind energy potential assessment revealed suitable locations for micro wind turbines, and with the installation of fifteen turbines, the port can produce around 36,300 kWh of energy annually.

Moreover, a solar energy assessment demonstrated the feasibility of installing photovoltaic panels in the port area. The placement of solar canopies over parking areas generated approximately 186,254.63 kWh per year. In conjunction with wind energy, the port can achieve zero-energy demand status, producing more energy than it consumes.

The adoption of these RESs significantly contributes to reducing CO_2 emissions. The port's transformation into a sustainable zone has been successful, benefiting both the environment and the community.

Considering the investment costs, the overall expense for installing wind and solar systems amounted to EUR 512,400. However, state incentives, such as feed-in tariffs and tax deductions, make the return on investment feasible and financially attractive.

In conclusion, the integration of BEMS and BIM in Anzio's port area has yielded impressive results, showcasing the potential of sustainable energy solutions in transforming ports into environmentally friendly and self-sufficient zones.

The study in [14] introduces a novel framework designed to achieve continuous Bayesian calibration of whole building energy simulation (BES) models. This framework harnesses data from BIM and BEMS. By leveraging information from both BIM and BEMS, this approach optimizes the calibration process, resulting in notable time and effort savings.

To ensure the fidelity of the translation from BIM to BES models, the study employed five geometric test cases. These cases effectively demonstrated a strong concordance between the original BIM and the BES model based on the Green Building XML format.

Furthermore, the study showcases a practical calibration case study involving a real building. This case study utilized BIM alongside three years of monthly electrical energy consumption data. The effectiveness of the continuous Bayesian calibration method was assessed and the findings indicated reduced prediction uncertainty and heightened accuracy when compared to non-continuous approaches. The research also delves into the incorporation of probabilistic BES predictions, underlining the significance of analyzing the distributions of the coefficient of variance of the root mean square error and the normalized mean biased error for more robust evaluations.

In summary, this research offers a promising approach for enhancing the calibration of BES models by integrating BIM and BEMS data, paving the way for more accurate and efficient building energy simulations and predictions.

The study conducted in [15] investigates the possibilities and challenges of using BIM to BEM methodology for modeling, analyzing, and optimizing energy-efficient industrial buildings. Two industrial facilities were analyzed as case studies. The research identified varying needs in the level of development and semantic differences among disciplines (architecture, structural engineering, analysis) as problems. Time pressure was also identified as a significant factor leading to building model defects. These deficits represent different types of uncertainties related to integrated energy modeling using BIM to BEM.

The study emphasizes the importance of conducting an uncertainty analysis as the initial step in integrated modeling and developing strategies to address these uncertainties. To minimize BIM to BEM uncertainties, improvements in software interoperability (modeling uncertainty) are necessary, but equally important is the reshaping of the design process and the augmentation of individual competencies to tackle process-related uncertainties.

Another paper [61] addresses the issue of constrained operational flexibility resulting from conventional CHP unit modes, which, in turn, limits the efficient use of renewable energy. This problem is akin to challenges faced in the integration of BEMS and BIM, where optimizing building systems' performance requires overcoming operational rigidity. To tackle this, a novel scheduling model based on chance-constrained programming is proposed. This model aims to minimize costs in a small integrated energy system, accounting for renewable uncertainties and thermal comfort requirements in buildings. The solution approach, employing sequence operation theory and the CPLEX solver, transforms chance constraints into solvable formats.

Key findings from simulations include: The proposed model optimizes thermal inertia and auxiliary equipment, bolstering operational flexibility and encouraging renewable energy consumption. The solution approach efficiently resolves the model, converting chance constraints into solvable formats via the CPLEX solver. Different auxiliary equipment choices influence flexibility, and their coordinated operation enhances both flexibility and energy supply reliability.

In summary, the text presents a solution to enhance operational flexibility in energy systems, which resonates with the challenge of optimizing building performance through the integration of BEMS and BIM. This solution encourages better integration of renewable energy while ensuring system efficiency and reliability are maintained.

Looking to the future, there are exciting research directions to explore. Developing interoperability standards and formats that facilitate seamless integration across different BEMS and BIM platforms is crucial. Additionally, researchers can explore the potential of AI to analyze and optimize data from both BEMS and BIM, unlocking new avenues for sustainable building management. Furthermore, conducting a lifecycle analysis to understand the long-term impact of BEMS-BIM integration on building performance, energy efficiency, and occupant comfort is essential. Some of these future perspectives and challenges mentioned in [62] can be seen here:

- Performance-Driven Design:
  Challenges in performance-driven design encompass generation, simulation, and optimization. Architects must develop algorithms for design parameter adjustment, enhancing generative design. Performance-driven methods emphasize conceptual logic over outcomes, yet current algorithms lack geometric diversity. Integrating inner space topology with energy/ventilation performance remains underexplored.
- Model-Based Operational Performance Optimization:
  Operational optimization relies on efficient simulations for energy savings. Ensuring computation speed aligns with real-time control constraints is essential. Balancing computation speed and model accuracy is a key challenge, warranting investigation.
- Integrated Simulation for Digital Twins:
  Digital twins demand data integrity and real-time simulations. Data quality, cost-effective sensor use, and real-time simulations are priorities. Scaling simulations for urban use requires diverse data integration.
- Building Simulation for Urban Energy Planning:
  Urban energy modeling's accuracy can improve through uncertainty analysis and model calibration. Integrating UBEM with urban energy systems enhances energy infrastructure modeling.
- Building-to-Grid Interaction Modeling:
  Enhancing building–grid interaction modeling entails leveraging flexibility and adapting to rapid grid changes. Addressing occupancy impact on energy consumption and exploring larger-scale simulations and control are critical.

6. Conclusions

The integration of Building Energy Management Systems with Building Information Modeling creates a big shift within the domain of sustainable building design and construction. This integration empowers stakeholders to optimize energy efficiency and ensure occupant well-being from design to operation and maintenance. By merging real-time BEMS data with BIM's holistic insights, decisions are driven by comprehensive information.

This integration facilitates a data-centric approach to sustainable design. The combination of real-time BEMS data and BIM's visualization capabilities allows architects and engineers to meticulously analyze energy consumption patterns and system performance. This leads to designs that not only meet sustainability standards but also prioritize occupant comfort while minimizing energy use.

Predictive maintenance is a key advantage of the BEMS-BIM synergy. Real-time BEMS insights seamlessly interfaced with BIM enable stakeholders to anticipate maintenance needs and prevent energy inefficiencies. Collaboration is enhanced as architects, engineers, energy analysts, and facility managers work together, fostering effective communication and shared problem solving. Moreover, on a larger scale, this integration contributes to urban sustainability by optimizing energy allocation and load management. Overall, the integration of BEMS and BIM propels energy-efficient and eco-conscious building practices, aligning with global efforts to combat climate change and establish sustainable built environments.

The feasibility of BEMS-BIM integration is evident, as many systems already have API capabilities, and industry organizations are actively developing standards and best practices for integration. However, technical aspects and practical implications, such as data standardization, communication protocols, and cybersecurity, need to be carefully addressed for successful implementation.

Moreover, case studies have showcased the effectiveness of BEMS-BIM integration in real-world scenarios. From continuous Bayesian calibration of BES models to utilizing BIM for modeling energy-efficient industrial buildings, these studies have demonstrated significant improvements in accuracy, efficiency, and sustainability.

While this review article highlights the transformative potential of integrating BEMS with BIM for sustainable building design and operation, it is important to acknowledge certain limitations inherent in such review-based analyses. Firstly, the comprehensiveness and accuracy of the conclusions heavily rely on the quality and scope of the selected literature. Despite the efforts to include a diverse range of sources, there might still be gaps in coverage or biases in the literature selection process that could impact the overall validity of the conclusions drawn. Additionally, as the field of BEMS-BIM integration is continually evolving, the review's findings might be subject to a degree of temporal relevance, where new advancements or changes in practices emerge after the review's publication. Furthermore, while the review provides valuable insights and highlights key trends, it might not capture every nuanced detail or specific context that individual studies could offer. Finally, as with any review, the interpretations and synthesis of information are subject to the author's perspective and potential biases, which could influence the overall assessment of the integration's benefits and challenges. Despite these limitations, this review serves as a valuable resource for understanding the current state and future potential of BEMS-BIM integration within the domain of sustainable building practices.

Looking ahead, exciting research directions await. Developing interoperability standards and formats for seamless integration across different BEMS and BIM platforms will facilitate widespread adoption. Furthermore, exploring the potential of AI for data analysis and optimization will unlock new possibilities for sustainable building management. Conducting lifecycle analyses will provide a comprehensive understanding of the long-term impact of BEMS-BIM integration on building performance, energy efficiency, and occupant comfort.

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Abbreviations

The following abbreviations are used in this manuscript:

AEMS	Advanced Energy Management System
AI	Artificial Intelligence
ANN	Artificial Neural Network
API	Application Programming Interface
BEMS	Building Energy Management System
BES	Building Energy Simulation
BIM	Building Information Modeling
CSV	Comma-Separated Values
DNN	Deep Neural Network
DSM	Demand-Side Management
DT	Digital Twin
FDD	Fault Detection and Diagnosis
GA	Genetic Algorithm
HVAC	Heating, Ventilation, and Air Conditioning
IFC	Industry Foundation Class
IoT	Internet of Things
LSTM	Long Short-Term Memory
MEP	Mechanical, Electrical, Plumbing
ML	Machine Learning
MPC	Model Predictive Control
RES	Renewable Energy Source
VPP	Virtual Power Plant

References

1. Kaewunruen, S.; Rungskunroch, P.; Welsh, J. A digital-twin evaluation of net zero energy building for existing buildings. *Sustainability* **2018**, *11*, 159. [CrossRef]
2. Yu, Z. Green building energy efficiency and landscape design based on remote sensing technology. *Soft Comput.* **2023**, 1–10. [CrossRef]
3. Mariano-Hernández, D.; Hernández-Callejo, L.; Zorita-Lamadrid, A.; Duque-Pérez, O.; García, F.S. A review of strategies for building energy management system: Model predictive control, demand side management, optimization, and fault detect & diagnosis. *J. Build. Eng.* **2021**, *33*, 101692.
4. Control, E. What Is BEMS Technology? 2017. Available online: https://www.essentialcontrol.co.uk/what-is-bems-technology (accessed on 20 November 2022).
5. Borrmann, A.; König, M.; Koch, C.; Beetz, J. *Building Information Modeling: Why? What? How?* Springer: Berlin/Heidelberg, Germany, 2018.
6. Azhar, S.; Khalfan, M.; Maqsood, T. Building information modeling (BIM): Now and beyond. *Australas. J. Constr. Econ. Build.* **2012**, *12*, 15–28.
7. Petrushevski, F.; Montazer, M.; Seifried, S.; Schiefer, C.; Zucker, G.; Preindl, T.; Suter, G.; Kastner, W. Use cases for improved analysis of energy and comfort related parameters based on BIM and BEMS data. In *Advanced Computing Strategies for Engineering, Proceedings of the 25th EG-ICE International Workshop 2018, Lausanne, Switzerland, 10–13 June 2018*; Proceedings, Part II 25; Springer: Berlin/Heidelberg, Germany, 2018; pp. 391–413.
8. Al-Ghaili, A.M.; Kasim, H.; Al-Hada, N.M.; Jørgensen, B.N.; Othman, M.; Wang, J. Energy management systems and strategies in buildings sector: A scoping review. *IEEE Access* **2021**, *9*, 63790–63813. [CrossRef]
9. Missaoui, R.; Joumaa, H.; Ploix, S.; Bacha, S. Managing energy smart homes according to energy prices: Analysis of a building energy management system. *Energy Build.* **2014**, *71*, 155–167. [CrossRef]
10. Ahmad, M.W.; Mourshed, M.; Mundow, D.; Sisinni, M.; Rezgui, Y. Building energy metering and environmental monitoring–A state-of-the-art review and directions for future research. *Energy Build.* **2016**, *120*, 85–102. [CrossRef]
11. Gaida, S.; Kastner, W.; Montazer, M.; Preindl, T.; Suter, G.; Blöchle, M.; Shadrina, A.; Sipetic, M.; Schiefer, C. Building Information Modeling for Building Energy Management Systems. 2020. Available online: https://nachhaltigwirtschaften.at/de/sdz/projekte/bim4bems-building-information-modeling-for-building-energy-management-systems.php (accessed on 9 October 2022).
12. Peng, Y.; Zhang, M.; Yu, F.; Xu, J.; Gao, S. Digital twin hospital buildings: An exemplary case study through continuous lifecycle integration. *Adv. Civ. Eng.* **2020**, *2020*, 8846667. [CrossRef]
13. Sierla, S.; Pourakbari-Kasmaei, M.; Vyatkin, V. A taxonomy of machine learning applications for virtual power plants and home/building energy management systems. *Autom. Constr.* **2022**, *136*, 104174. [CrossRef]

14. Chong, A.; Xu, W.; Chao, S.; Ngo, N.T. Continuous-time Bayesian calibration of energy models using BIM and energy data. *Energy Build.* **2019**, *194*, 177–190. [CrossRef]
15. Gourlis, G.; Kovacic, I. A holistic digital twin simulation framework for industrial facilities: BIM-based data acquisition for building energy modeling. *Front. Built Environ.* **2022**, *8*, 918821. [CrossRef]
16. Nástroje pre Simulácie Energetických Požiadaviek Pomocou BIM. 2020. Available online: https://www.bimas.sk/single-post/2017/08/09/n%C3%A1stroje-pre-simul%C3%A1cie-energetick%C3%BDch-po%C5%BEiadaviek-pomocou-bim (accessed on 9 October 2022).
17. Shen, K.; Ding, L.; Wang, C.C. Development of a Framework to Support Whole-Life-Cycle Net-Zero-Carbon Buildings through Integration of Building Information Modelling and Digital Twins. *Buildings* **2022**, *12*, 1747. [CrossRef]
18. Van Eck, N.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef]
19. Gökçe, H.U.; Gökçe, K.U. Intelligent energy optimization system development and validation for German building types. *Int. J. -Low-Carbon Technol.* **2021**, *16*, 1299–1316. [CrossRef]
20. Salerno, I.; Anjos, M.F.; McKinnon, K.; Gomez-Herrera, J.A. Adaptable energy management system for smart buildings. *J. Build. Eng.* **2021**, *44*, 102748. [CrossRef]
21. Chen, Z.; Xiao, F.; Guo, F.; Yan, J. Interpretable machine learning for building energy management: A state-of-the-art review. *Adv. Appl. Energy* **2023**, *9* , 100123. [CrossRef]
22. Zhang, L.; Wen, J.; Li, Y.; Chen, J.; Ye, Y.; Fu, Y.; Livingood, W. A review of machine learning in building load prediction. *Appl. Energy* **2021**, *285*, 116452. [CrossRef]
23. Chen, Y.; Guo, M.; Chen, Z.; Chen, Z.; Ji, Y. Physical energy and data-driven models in building energy prediction: A review. *Energy Rep.* **2022**, *8*, 2656–2671. [CrossRef]
24. Li, G.; Li, F.; Xu, C.; Fang, X. A spatial-temporal layer-wise relevance propagation method for improving interpretability and prediction accuracy of LSTM building energy prediction. *Energy Build.* **2022**, *271*, 112317. [CrossRef]
25. Gaur, M.; Makonin, S.; Bajić, I.V.; Majumdar, A. Performance evaluation of techniques for identifying abnormal energy consumption in buildings. *IEEE Access* **2019**, *7*, 62721–62733. [CrossRef]
26. Chaouch, H.; Çeken, C.; Arı, S. Energy management of HVAC systems in smart buildings by using fuzzy logic and M2M communication. *J. Build. Eng.* **2021**, *44*, 102606. [CrossRef]
27. Javed, A.; Larijani, H.; Wixted, A. Improving energy consumption of a commercial building with IoT and machine learning. *IT Prof.* **2018**, *20*, 30–38. [CrossRef]
28. Bhattacharjee, S.; Nandi, C. Advanced Energy Management System (A-EMS) Design of a Grid-Integrated Hybrid System. *Iran. J. Sci. Technol. Trans. Electr. Eng.* **2023**, *47*, 1021–1044. [CrossRef]
29. Energy5. Elevate Building Sustainability with State-of-the-Art Energy Management Systems. 2023. Available online: https://energy5.com/elevate-building-sustainability-with-state-of-the-art-energy-management-systems (accessed on 20 July 2023).
30. Muqeet, H.A.; Javed, H.; Akhter, M.N.; Shahzad, M.; Munir, H.M.; Nadeem, M.U.; Bukhari, S.S.H.; Huba, M. Sustainable solutions for advanced energy management system of campus microgrids: Model opportunities and future challenges. *Sensors* **2022**, *22*, 2345. [CrossRef] [PubMed]
31. Dive, R. Energy Management System Market Report. 2020. Available online: https://www.researchdive.com/134/energy-management-system-markets (accessed on 20 July 2023).
32. Azeroual, M.; Boujoudar, Y.; Aljarbouh, A.; Fayaz, M.; Qureshi, M.S.; El Moussaoui, H.; El Markhi, H. Advanced energy management and frequency control of distributed Microgrid using multi-agent systems. *Int. J. Emerg. Electr. Power Syst.* **2021**, *23*, 755–766. [CrossRef]
33. Collaborations, U.; Hub, P.S. Building Energy Management Systems (BEMS). 2016. Available online: https://www.ctc-n.org/technologies/building-energy-management-systems-bems (accessed on 20 July 2023).
34. Park, K.; Kim, Y.; Kim, S.; Kim, K.; Lee, W.; Park, H. Building energy management system based on smart grid. In Proceedings of the 2011 IEEE 33rd international telecommunications energy conference (INTELEC), Amsterdam, The Netherlands, 9–13 October 2011; pp. 1–4.
35. Ma, Y.; Deng, W.; Xie, J.; Heath, T.; Xiang, Y.; Hong, Y. Generating prototypical residential building geometry models using a new hybrid approach. *Build. Simul.* **2022**, *15*, 17–28. [CrossRef]
36. Doukas, H.; Patlitzianas, K.D.; Iatropoulos, K.; Psarras, J. Intelligent building energy management system using rule sets. *Build. Environ.* **2007**, *42*, 3562–3569. [CrossRef]
37. Mathews Roy, A.; Prasanna Venkatesan, R.; Shanmugapriya, T. Simulation and Analysis of a Factory Building's Energy Consumption Using eQuest Software. *Chem. Eng. Technol.* **2021**, *44*, 928–933. [CrossRef]
38. Thorve, S.; Baek, Y.Y.; Swarup, S.; Mortveit, H.; Marathe, A.; Vullikanti, A.; Marathe, M. High resolution synthetic residential energy use profiles for the United States. *Sci. Data* **2023**, *10*, 76. [CrossRef]
39. Agbajor, F.D.; Mewomo, M.C.; Umoh, V.B.; Makanjuola, S.A. Building energy management system research in South Africa—A decade overview. *Energy Rep.* **2023**, *9*, 33–39. [CrossRef]
40. Dong, B.; O'Neill, Z.; Li, Z. A BIM-enabled information infrastructure for building energy Fault Detection and Diagnostics. *Autom. Constr.* **2014**, *44*, 197–211. [CrossRef]

41. Opoku, D.G.J.; Perera, S.; Osei-Kyei, R.; Rashidi, M. Digital twin application in the construction industry: A literature review. *J. Build. Eng.* **2021**, *40*, 102726. [CrossRef]
42. Duivenvoorden, E.; Hartmann, T.; Brinkhuijsen, M.; Hesselmans, T. Managing public space–A blind spot of urban planning and design. *Cities* **2021**, *109*, 103032. [CrossRef]
43. Daniotti, B.; Masera, G.; Bolognesi, C.M.; Lupica Spagnolo, S.; Pavan, A.; Iannaccone, G.; Signorini, M.; Ciuffreda, S.; Mirarchi, C.; Lucky, M.; et al. The development of a BIM-based interoperable toolkit for efficient renovation in buildings: From BIM to digital twin. *Buildings* **2022**, *12*, 231. [CrossRef]
44. Zhou, X.; Sun, K.; Wang, J.; Zhao, J.; Feng, C.; Yang, Y.; Zhou, W. Computer vision enabled building digital twin using building information model. *IEEE Trans. Ind. Inform.* **2022**, *19*, 2684–2692. [CrossRef]
45. Hosamo, H.; Hosamo, M.H.; Nielsen, H.K.; Svennevig, P.R.; Svidt, K. Digital Twin of HVAC system (HVACDT) for multiobjective optimization of energy consumption and thermal comfort based on BIM framework with ANN-MOGA. *Adv. Build. Energy Res.* **2023**, *17*, 125–171. [CrossRef]
46. Zhou, Y.; Wei, X.; Peng, Y. The modelling of digital twins technology in the construction process of prefabricated buildings. *Adv. Civ. Eng.* **2021**, *2021*, 2801557 . [CrossRef]
47. Agostinelli, S.; Cumo, F.; Nezhad, M.M.; Orsini, G.; Piras, G. Renewable Energy System Controlled by Open-Source Tools and Digital Twin Model: Zero Energy Port Area in Italy. *Energies* **2022**, *15*, 1817. [CrossRef]
48. Tahmasebinia, F.; Lin, L.; Wu, S.; Kang, Y.; Sepasgozar, S. Exploring the Benefits and Limitations of Digital Twin Technology in Building Energy. *Appl. Sci.* **2023**, *13*, 8814. [CrossRef]
49. Shen, Y.; Pan, Y. BIM-supported automatic energy performance analysis for green building design using explainable machine learning and multi-objective optimization. *Appl. Energy* **2023**, *333*, 120575. [CrossRef]
50. Mulero-Palencia, S.; Álvarez-Díaz, S.; Andrés-Chicote, M. Machine learning for the improvement of deep renovation building projects using as-built BIM models. *Sustainability* **2021**, *13*, 6576. [CrossRef]
51. Spudys, P.; Jurelionis, A.; Fokaides, P. Conducting smart energy audits of buildings with the use of building information modelling. *Energy Build.* **2023**, *285*, 112884. [CrossRef]
52. Wong, B.C.; Wu, Z.; Gan, V.J.; Chan, C.; Cheng, J.C. Parametric building information modelling and optimality criteria methods for automated multi-objective optimisation of structural and energy efficiency. *J. Build. Eng.* **2023**, *75*, 107068. [CrossRef]
53. Rajabi, M.S.; Radzi, A.R.; Rezaeiashtiani, M.; Famili, A.; Rashidi, M.E.; Rahman, R.A. Key assessment criteria for organizational BIM capabilities: A cross-regional study. *Buildings* **2022**, *12*, 1013. [CrossRef]
54. Jung, D.K.; Lee, D.H.; Shin, J.H.; Song, B.H.; Park, S.H. Optimization of energy consumption using BIM-based building energy performance analysis. *Appl. Mech. Mater.* **2013**, *281*, 649–652. [CrossRef]
55. Becerik-Gerber, B.; Kensek, K. Building information modeling in architecture, engineering, and construction: Emerging research directions and trends. *J. Prof. Issues Eng. Educ. Pract.* **2010**, *136*, 139–147. [CrossRef]
56. Yuan, S.; Hu, Z.Z.; Lin, J.R.; Zhang, Y.Y. A framework for the automatic integration and diagnosis of building energy consumption data. *Sensors* **2021**, *21*, 1395. [CrossRef]
57. Teisserenc, B.; Sepasgozar, S. Adoption of blockchain technology through digital twins in the construction industry 4.0: A PESTELS approach. *Buildings* **2021**, *11*, 670. [CrossRef]
58. Xu, X.; Xiao, B.; Li, C.Z. Stakeholders' power over the impact issues of building energy performance gap: A two-mode social network analysis. *J. Clean. Prod.* **2021**, *289*, 125623. [CrossRef]
59. Rohit, J. BMS Integration with BIM (Building Information Model). 2023. Available online: https://www.linkedin.com/pulse/bms-integration-bim-building-information-model-rohit-jain (accessed on 18 August 2023).
60. Ohlsson, K.A.; Olofsson, T. Benchmarking the practice of validation and uncertainty analysis of building energy models. *Renew. Sustain. Energy Rev.* **2021**, *142*, 110842. [CrossRef]
61. Li, Y.; Wang, C.; Li, G.; Wang, J.; Zhao, D.; Chen, C. Improving operational flexibility of integrated energy system with uncertain renewable generations considering thermal inertia of buildings. *Energy Convers. Manag.* **2020**, *207*, 112526. [CrossRef]
62. Pan, Y.; Zhu, M.; Lv, Y.; Yang, Y.; Liang, Y.; Yin, R.; Yang, Y.; Jia, X.; Wang, X.; Zeng, F.; et al. Building energy simulation and its application for building performance optimization: A review of methods, tools, and case studies. *Adv. Appl. Energy* **2023**, *10*, 100135. [CrossRef]

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