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Review

Influence of Thermal Comfort on Energy Consumption for Building Occupants: The Current State of the Art

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Abstract: Thermal comfort is a complex issue in the built environment due to the physiological and psychological differences of each individual in a building. There is a growing worry over the environmental implications of energy use as a result of the warming of the global climate and the growth in the number of instances of extreme weather events. Many review articles have been written, but these reviews have focused on a specific aspect of occupant behavior and thermal comfort. To research the trends of thermal comfort and energy, this research adopted mixed reviews, i.e., quantitative and qualitative, to understand the state-of-the-art factors affecting the thermal comfort of occupants concerning energy, different occupant modeling approaches, functions, and limitations. The in-depth qualitative discussion provides deeper insights into the impacts of occupant behaviors, factors affecting thermal comfort, and occupant behavior modeling approaches. This study classified occupant behaviors into five categories: occupant characteristics, perceptions of the occupant, realistic behaviors, heat gain, and occupant interactions with the system. It also went further to classify the factors affecting the thermal comfort of users based on past works of literature. These include structural, environmental, and human factors. It was concluded that factors that have the most significant impact on energy are human, structural, and environmental factors, respectively. In addition, most of the occupant behavior modeling approaches that have been used in past studies have pros and cons and cannot accurately predict human behaviors because they are stochastic. Future research should be conducted on thermal comfort for different building functions by examining the varied activity intensity levels of users, especially in educational or commercial buildings. Additionally, a proper investigation should be carried out on how thermal insulation of structural members influences thermal comfort. These should be compared in two similar buildings to understand occupant behavioral actions and energy consumption.

Keywords: thermal comfort; energy consumption; buildings; occupant behavior; users

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1. Introduction

The building and construction sectors account for a huge part of national and global energy consumption. Advanced countries such as the UK, USA, Japan, Germany, and Australia attribute 30–40% of energy consumption to the building sector [1]. This is due to global climate change and an increase in the frequency of extreme weather, which has environmental repercussions for energy use. Energy consumption in buildings depends largely on several factors, including physical characteristics or geometry of buildings, outdoor environment, building services systems, and different appliances used. Meanwhile, the overall performance of buildings is affected by six major parameters, which are the building envelope, interior design, operations and maintenance, climate, energy, and occupant behavior [2].

Occupant behavior plays a critical role in building energy performance, which has led to discrepancies in predicted and actual energy consumption [3]. This is the user attitude towards building energy-related operations, such as control of HVAC appliances, lighting, adjustment of clothing, windows, blinds, and so on [4]. These actions cannot be predicted for individuals or groups due to the different physiology and psychology of people. However, these differences between predicted and actual performance have been assumed to be a result of occupant behavior. The connection between occupant behavior and energy consumption is due to occupant environmental comfort. Every user desires a pleasant indoor environment for effectiveness and productivity. Occupants' comfort in a building is attributed to four factors, which are thermal, acoustic, indoor air quality, and visual comfort [5].

Thermal comfort is a vital component of indoor environmental quality and depends on environmental and personal parameters [6]. The personal parameters for conventional thermal comfort include clothing insulation and metabolic rate, while environmental parameters are air temperature, relative humidity, air velocity, and mean radiant temperature. Other factors related to personal parameters that also influence comfort are age, size, weight, acclimatization, height, gender, and so on. Nevertheless, studies have used other personal parameters to understand the thermal comfort of occupants using modern comfort models such as machine and deep learning algorithms [7–9]. These factors are important and can determine the sensation and comfort of the individual in a building space [10].

Extensive studies have examined the role of an occupant in building energy performance [3,11]. The connection between occupant behavior and energy consumption stems from occupants' desire for a comfortable indoor environment conducive to productivity and well-being. Thermal comfort, in particular, plays a significant role in determining occupants' satisfaction with their indoor environment, alongside factors such as acoustic quality, indoor air quality, and visual comfort. Understanding the intricate interplay between personal and environmental parameters influencing thermal comfort is essential in designing buildings that promote occupants' well-being while minimizing energy usage.

Moreover, advancements in comfort modeling, including the utilization of machine learning and deep learning algorithms, offer new avenues for exploring and understanding occupant behavior and its impact on building energy performance. By incorporating these modern techniques, researchers can go deeper into the complex relationship between occupant behavior, thermal comfort, and energy consumption, ultimately informing more effective strategies for building design, operation, and management. Occupant behavior modeling has been used to understand patterns in a building, including probabilistic or stochastic, statistical, data mining, and agent-based modeling [4]. Past review studies conducted focus on a particular facet of occupant behavior and thermal comfort. There has been less focus on the limitations of these several models used for understanding behavioral patterns. This review contributes to the body of knowledge in two ways: (1) research topics, trends, and the current state of the art in thermal comfort and energy research are evaluated and identified quantitatively, and (2) research on factors affecting thermal comfort, occupant behavior's effect on energy use, and modeling approaches and limitations are revealed via in-depth qualitative analysis. The following questions will be answered in the study:

1. What is the state of the art on thermal comfort and energy consumption research?
2. What are the effects of occupant behavior on energy consumption for buildings?
3. What are the factors affecting the thermal comfort of users and their relation to energy consumption?
4. What is the occupant modeling approach adopted in understanding energy consumption and its limitations?

This review addresses the above through a systematic review study, as described. The remaining parts of the study present the literature review of key concepts. The methodology was assessed using key concepts and words in a search of the database. Section 2 gives an overview of energy consumption in buildings, thermal comfort, user behavior, and the nexus of occupant behavior, thermal comfort, and energy consumption in buildings.

Section 3 highlights the research method used in the study while Section 4 discusses the critical review of these research questions. The penultimate part consists of the conclusion, limitations, and future directions, while the last section lists references.

2. Literature Review

2.1. Energy Consumption in Buildings

The building sector accounts for one-third of global energy consumption [12]. According to reports from the EU in 2010 and the US in 2015, 40% of global energy consumption comes from buildings. Energy use in a building includes one or more space heating and cooling, water heating, and operation of lights, cooking appliances, and other equipment. Occupants interact with the control systems and building elements to achieve their comfort in different ways, such as opening and closing windows, adjusting blinds, use of lighting, use of HVAC systems through on and off switches and adjusting thermostat temperature, and use of hot water and electrical appliances [13]. These actions affect the energy performance of buildings.

Such operations are important activities in buildings and account for a high rate of consumption of energy. Energy can only be saved when there is proper design, construction, and operation of the building. In recent times, energy consumption has been on the high side, especially for non-residential buildings where energy consumption for heating and cooling is about 50–70% of the entire energy consumption [14]. The energy consumption rate in buildings depends on factors such as thermo-physical properties of building elements, construction technical details, quality and maintenance of HVAC systems, the climatic condition of an area, and occupant behavior. Other factors leading to higher energy demand are increases in population, more time spent indoors, high-demand functions of buildings, global climate change, and indoor environmental quality [15]. Meanwhile, the future goal of sustainable buildings is to enable both energy efficiency and the comfort of users or occupants of buildings.

There are two perspectives from which to consider occupants; the first is the occupant's characteristics (physical) while the second is the occupant's behavior. Occupant characteristics are made up of the number of people, age, household composition, ownership status, education level, sex, race, country of origin, occupation, and income [16–20]. These features determine the mindset of the user to adapt to comfort and the use of energy. Nevertheless, occupant behaviors are active and conscious behaviors which are observable actions that show patterns over a shorter time frame, i.e., hours, days, and seasons.

Occupants are major influencers of energy use regardless of building design: the interaction of occupants with buildings causes variation in energy use even within similar buildings [21]. People have different physio-psychological natures, which makes a set point of comfort for one occupant different from that of others. This makes energy demand in one building different from another depending on the individual inhabiting the building. The impact of occupant behavior has caused a wide gap between the predicted and actual energy consumption in buildings in different countries [22,23]. Although there is now more research focusing on occupant behavior and energy consumption of buildings through the development of models, these models developed are specific to each building and cannot be applied to all buildings.

Building management systems (BMS) play a crucial role in optimizing energy consumption in buildings. Their impact on energy consumption is multifaceted, enabling continuous monitoring and control of various building systems such as HVAC, lighting, and electrical equipment. By collecting real-time data on energy usage and building conditions, a BMS allows facility managers to identify inefficiencies and implement corrective actions promptly. For example, a BMS can adjust HVAC set points based on occupancy schedules or outdoor weather conditions to optimize energy usage without compromising comfort. It can optimize HVAC operation by coordinating equipment schedules, adjusting airflow rates, and implementing strategies such as demand-controlled ventilation and night setbacks [18]. These measures ensure that heating and cooling systems operate efficiently while meeting occupants' comfort requirements. A BMS also facilitates occupancy-based lighting and equipment control to minimize unnecessary energy usage in unoccupied areas. Occupancy sensors detect the presence or absence of occupants and adjust lighting levels, HVAC settings, and equipment operation accordingly. This ensures that energy is only consumed when needed, leading to significant energy savings, especially in commercial buildings with fluctuating occupancy patterns.

2.2. Thermal Comfort

The concept of thermal comfort was introduced in the late 19th century. The American Society of Heating and Cooling Engineers defined thermal comfort as the state or condition of the mind that expresses satisfaction with the thermal environment. Comfort is an important goal in the built environment that influences occupant satisfaction, health, and productivity [24,25]. Thermal comfort is one of the aspects of indoor environmental quality (IEQ) through thermal perception, and it is strongly related to acoustic, visual, and air quality. Thermal comfort in buildings is related to architectural features, which include dimensions, presence of shading systems, building orientation, properties of the building envelope, and window–wall ratio.

Ref. [26] developed two quantitative formulas for measuring thermal comfort: Predicted mean vote (PMV) and predicted percentage dissatisfaction (PPD). PMV integrates the impact of temperature, which is the air temperature and mean radiant temperature, humidity, metabolic heat rate, air velocity, and clothing thermal properties to predict thermal comfort level. Several researchers have studied PMV and PDD models widely for different buildings in various countries [27–29]. These models have been adopted for different groups of people, races, and environments [30]. The PMV index was said to overestimate the perception of users while the adaptive model predicts higher comfort temperatures than actual ones. Fanger's theory was based on experiments but there are discrepancies between the predicted thermal sensation obtained from PMV and real thermal sensation from questionnaires. These issues were attributed to the level of adaptation and adjustments in clothing or control of occupants' environment [31,32]. Thermal comfort studies are mostly conducted through subjective evaluation of people in the buildings [33]. There are three categories of models for conventional thermal comfort in buildings, which are rational, adaptive, and rational–adaptive [10]. The two earlier models seem to have some deficiencies as they predict inaccurately the thermal sensation of people. Recently, the rational–adaptive model has been used because it is more accurate compared to the two others.

Thermal comfort models were classified into two types, i.e., conventional and personal comfort models, as shown in Figure 1. The conventional models are usually based on the predicted mean vote (PMV) and adaptive models. The PMV model uses physical and psychological phenomena and expresses human thermal sensation as an outcome of heat transfer between the human body and the surrounding environment. Few case studies of thermal comfort have been conducted in educational institutions. Ref. [34] conducted research among university students, and indicated that students preferred a warm environment. A study by [35] revealed there are discrepancies between the PMV calculated and people's perceptions. Ref. [36] examined the thermal environment and subjective thermal comfort of students and found that students preferred slightly cooler buildings. In a field study, ref. [37] examined the thermal sensation of students in a university classroom, finding students' subjective thermal sensation was greater than the PMV prediction. Others [38–40] revealed that the thermal comfort level should be kept lower. These mixed results from studies have hindered the development of standards and acceptable thermal conditions for students due to the physio-psychological differences of people who use the universities.

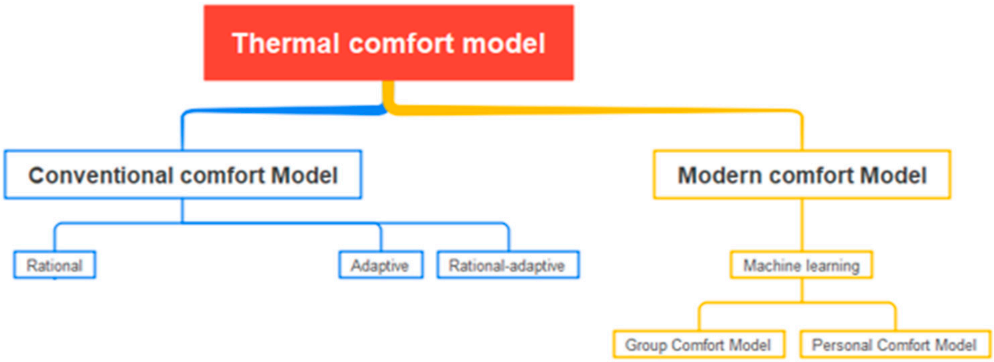

Figure 1. Classification of thermal comfort model.

A personal comfort model is a new approach to the thermal comfort model, which predicts thermal comfort based on individual preference. This approach does not use the average response of a large population but leverages emerging technologies such as the Internet of Things (IoT) and machine learning to understand individual comfort requirements from data collected every day. Various new data and data techniques are used to predict individual thermal comfort using advanced analytics and cloud-based control. However, researchers adopt different approaches to analyze the personal comfort model. Some of the modeling methods adopted are random forest [41], Gaussian process [42], Bayesian networks [43,44] support vector machines [45], and neural networks [46].

There have been several studies that have examined indoor air quality and thermal comfort. CO_2 has mostly been used as a yardstick or parameter to measure indoor air quality and understand whether it meets the threshold values for air quality [47–50]. A study examined the relationship between CO_2 concentrations, noise, light level, and thermal comfort. Furthermore, Ref. [47] adopted text-based sources for exploring the indoor environmental quality of occupants. Ref. [48] investigated indoor air quality with thermal comfort because both are vital in health, well-being, and productivity. A study noted that CO_2 is highly concentrated when windows are closed [49]; it was obvious that refurbished or renovated buildings have improved thermal comfort but increased CO_2 concentration, which reduces indoor air quality. The impact of various ventilation modes on thermal comfort and CO_2 was also examined [50,51]. Other studies examined the relationship between measured pollutants such as CO, NO_2, and VOCs in outdoor environments.

Ref. [10] reviewed thermal comfort for educational buildings in various countries based on the following parameters: year, educational stage, location, climatic zone, model adopted operation mode, and time of the survey. Investigations of thermal comfort have been mostly based on field data collection, which can be objective and subjective measurements. The PMV–PPD is an objective and adaptive model that has been used to establish acceptable thermal conditions for residential buildings but does not apply to students' thermal comfort [52]. Subjective measurement using questionnaires to measure environmental parameters has been combined with sensing data in most research. Hence, there has not been agreement on how thermal comfort can be assessed globally, leading researchers to use different models and indices, and there is a lack of standards apart from ISO 7730 [53], EN 16798-1 [54], and ASHRAE 55 [55] dealing with thermal comfort, especially in educational buildings.

ISO 7730 guides creating thermal environments that are comfortable for occupants. It specifies methods for assessing thermal comfort based on factors such as air temperature, radiant temperature, air velocity, and clothing insulation [56]. ASHRAE Standard 55 establishes thermal comfort criteria for indoor environments. It provides guidelines for designing HVAC systems and setting temperature and humidity levels to ensure occupant comfort. Standard EN 15251 [57] addresses various aspects of indoor environmental quality, including thermal comfort, indoor air quality, lighting, and acoustics. It outlines requirements and recommendations for designing and maintaining indoor environments that promote occupants' health, comfort, and productivity [58]. LEED certification, standing for leadership in energy and environmental design, while not a standard in the traditional sense, sets criteria for sustainable building design and construction. It includes credits related to indoor environmental quality, thermal comfort, and occupant well-being, encouraging the use of strategies such as natural ventilation, natural lighting, and low-emission materials.

2.3. User Behavior

Occupant behavior in buildings is a dynamic and multifaceted aspect that significantly influences the general efficiency, performance, and sustainability of the built environment [21]. Understanding how occupants interact with and utilize building systems and components is crucial in designing spaces that not only meet their needs but also align with contemporary goals of energy conservation, alleviating environmental damage, and occupant well-being. Similarly, occupant behavior is the interaction with building systems (AC, heater, light control) and components (windows, shading, and doors) in ensuring a good indoor environment for health and productivity [59]. This indoor environment includes visual, acoustic, and indoor air quality, and thermal comfort in the building.

Visual comfort can be defined as adjusting lighting intensity to suit the user, while indoor air quality is the condition of the air in a building or structure affecting health and comfort, while acoustic comfort refers to removing noise and vibrations [56]. People respond to discomfort in buildings to restore their comfort by controlling building systems and components, as shown in Figure 2. Our physical, physiological, and psychological differences and other external drivers such as economic and regulatory issues mean individuals receive, perceive, and respond differently to situations in buildings [58]. These physical differences include age, which can influence the perception of comfort in a building. The metabolic rate of individuals occupying a building varies on the activities performed, age, gender, and weight, which all have an impact on the thermal comfort of users.

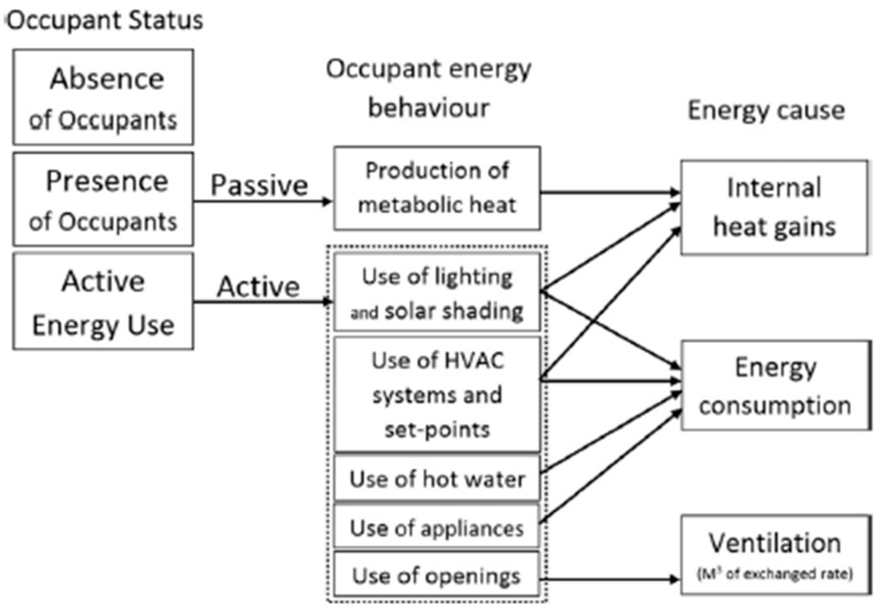

Figure 2. Types of occupant activities affecting building energy consumption, adapted from [60].

Based on these studies, there is still a persistent gap between actual and predicted energy use related to technical workmanship and installations, choice of equipment, materials used, and occupant behavior. Additionally, it is obvious that three-quarters of existing buildings are not efficient, and only a small percentage of buildings are renovated or retrofitted to be energy efficient. Although recently constructed buildings are built using energy-efficient technologies and equipment, priority must be placed on existing buildings and how they can be improved [61].

Extant works of literature have examined the impact of thermal comfort on energy efficiency [52,62]. Research has also been carried out on how occupant behavior affects energy consumption in various countries, such as Singapore and Denmark [3,63]. It was revealed that occupant behavior, such as opening windows, set points, and density of occupants have a considerable influence on and relationship to energy use. Ref. [64] developed a baseline building model for spaces and HVAC systems, in which non-model predictive control (NMPC) was used to integrate the weather forecasting model and occupant behavior patterns for solar decathlon houses. The result revealed that 30.1% of heating was saved and 17.8% was saved using a set-point control strategy.

Ref. [65] demonstrated a significant difference in the total energy consumption of two flats in the same building block. This was due to different occupant behaviors, such as varying times of presence at home, occupancy level, and variation in occupant thermal preferences. Other energy consumption differences in buildings were also reported. According to the study, carried out using energy simulation tools, there was a discrepancy between the predicted and actual energy due to user behavior and occupant preferences of five buildings used as a case study. Ref. [66] examined the quantitative sensitivity analysis for thermal occupant factors (TOF), and it was revealed that occupants' metabolic rate and clothing were relevant factors, in addition to the infiltration rate, in achieving energy-efficient buildings.

2.4. Nexus of Occupant Behavior, Thermal Comfort, and Energy Consumption in Buildings

The link between occupant behavior, thermal comfort, and energy consumption in buildings is a critical and interconnected relationship that profoundly influences the overall performance of the built environment. Understanding and optimizing this connection is essential for designing energy-efficient, comfortable, and sustainable spaces [59]. Occupant behavior varies among different regions, climates, and backgrounds, and the preferences of occupants are diverse. These preferences are influenced by several factors such as clothing, metabolic rate, and physiological state of the users. Consequently, thermal comfort is a complex issue that cannot be easily ensured due to several influencing factors such as activity level, clothing, airflow, and humidity [67,68]. A change in metabolic rate or clothing level will lead to a response of actions such as the use of heaters, fans, and thermostat adjustments to ensure satisfaction. Users must be aware, educated, and sensitized to the implications of anomaly behaviors to ensure sustainable practices and energy conversation [69]. Occupants should learn to adjust to various thermal conditions, allowing for a flexible control approach to temperature.

Understanding occupant comfort through feedback and the use of sensing technologies can enhance proper monitoring and adjustment of the indoor environment to suit occupant comfort [70,71]. Proper comprehension of thermal comfort and preferences can ameliorate excessive mechanical cooling or heating of the building. Integration of smart building technologies can enhance the use of HVAC, lighting systems, and appliances. Sustainable materials and appropriate thermal resistance are necessary components in the design of new and retrofitting of existing buildings using windows, shading, walls, and roofs. The link between occupant behavior, thermal comfort, and energy consumption is a complex and dynamic interplay that requires a holistic and integrated approach. Successful strategies involve the active engagement of occupants, the implementation of smart technologies, and the incorporation of sustainable design principles to create environments that are both energy-efficient and conducive to occupant well-being [72].

Thermal comfort and energy consumption can vary significantly among different types of buildings due to factors such as building use, occupancy patterns, and HVAC system design. Hotels typically prioritize guest comfort to ensure a pleasant stay. Guest rooms are often individually climate-controlled, allowing occupants to adjust temperature settings according to their preferences. Additionally, common areas such as lobbies and restaurants are designed to maintain comfortable temperatures for guests [72]. Hotels have high energy demands due to the continuous operation of HVAC systems, lighting, and other amenities to accommodate varying occupancy levels throughout the day. Energy-efficient HVAC systems, occupancy sensors for lighting, and smart controls can help optimize energy consumption in hotels. Shopping malls aim to provide a comfortable environment for shoppers, with controlled indoor temperatures and adequate ventilation. Large open spaces and high ceilings can present challenges in maintaining uniform thermal conditions throughout the mall. Malls consume significant energy via HVAC systems to maintain comfortable temperatures, especially during peak shopping hours. Energy management strategies such as zoning, setback controls, and efficient lighting can help reduce energy consumption in malls. Hospitals require precise temperature and humidity control to ensure patient comfort and maintain sterile environments in medical areas. Patient rooms, waiting areas, and surgical suites are designed with thermal comfort in mind to promote healing and recovery. Hospitals have complex HVAC systems to meet strict indoor air quality standards and manage infection control.

Energy-efficient HVAC systems, heat recovery systems, and smart controls are essential in minimizing energy consumption while maintaining optimal indoor conditions. Office buildings aim to provide a comfortable working environment for occupants to enhance productivity and well-being [70]. Temperature, humidity, and air quality are carefully controlled to meet occupant preferences and regulatory standards. Office buildings have varying energy consumption depending on factors such as building size, occupancy density, and operational hours. Energy-efficient lighting, HVAC systems, and occupancy sensors are commonly used to optimize energy performance in office buildings. Residential buildings prioritize occupant comfort and satisfaction, with individual control over heating, cooling, and ventilation systems in each dwelling unit. Proper insulation and sealing are crucial in maintaining thermal comfort and energy efficiency in residential buildings [52,62]. Energy consumption in residential buildings depends on factors such as building design, occupancy behavior, and climate conditions. Energy-efficient appliances, insulation, and renewable energy systems can help reduce energy consumption and utility costs in residential buildings.

3. Methodology

A mixed review of extant scientific publications in the areas of thematic areas was used as the analytical component in this study, which was conducted utilizing an interpretive philosophical methodology. As indicated by [73] this approach is well adopted in construction education studies and has proven to yield critical research outputs. Furthermore, Ref. [74] adopted a similar approach to examine the role of the Internet of things (IoT) in the assessment and communication of indoor environmental quality (IEQ) in buildings. Ref. [75] combined text mining with bibliometric mapping to evaluate the machine learning techniques adopted in the energy consumption of buildings. Other similar applications in this research area include occupant behavior modeling methods [76], energy consumption [77], and impact of design features [78] among others. Figure 3 presents the scientometric and qualitative analysis approach of the study.

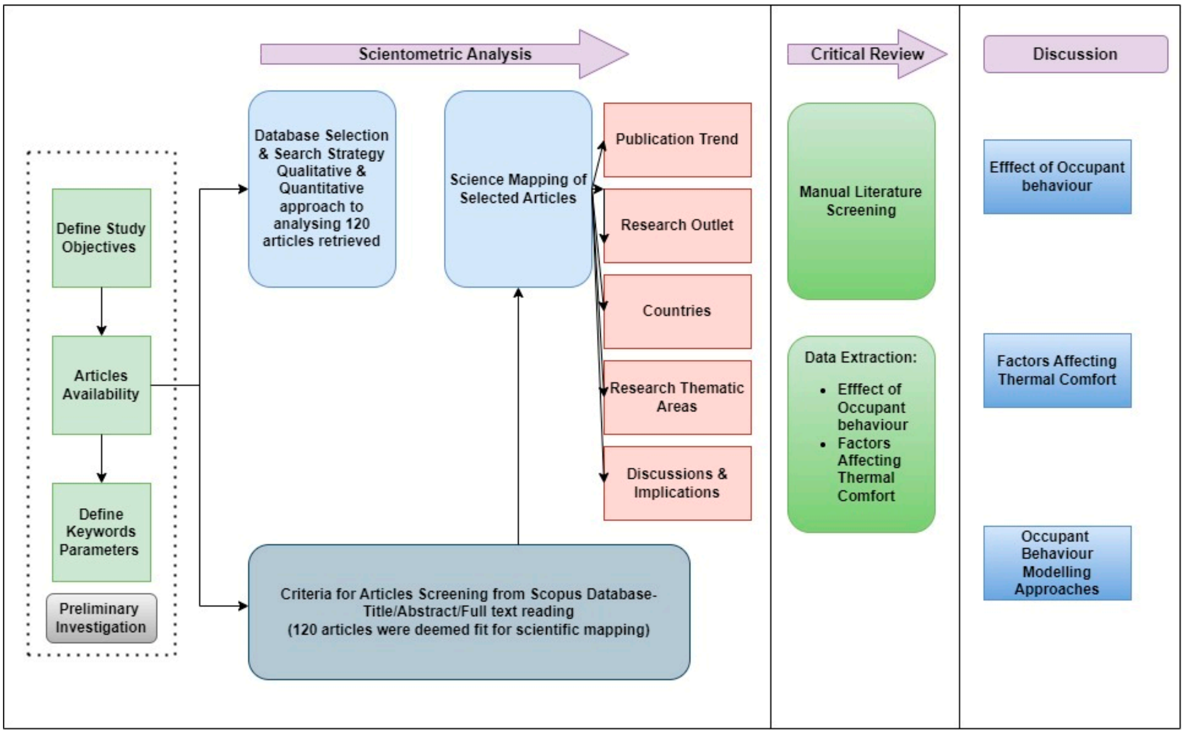

Figure 3. Research method process for the study.

3.1. Scientometric/Quantitative Analysis

To track the advancement of academic research, scientometric reviews analyze and visualize the academic literature [73]. Furthermore, they give insight into the research output on thematic areas as well as that of academics, faculties, and publications. The scientometric analysis has been extensively utilized to show how construction-related research has evolved [79]. Its application has been seen in the areas of building information modeling [80], robotics [81], sustainability, and sustainable development [82], as well as energy use in buildings, and analysis of research areas [74] among others. This approach was adopted in this study to evaluate and illustrate critical findings.

3.2. Preparatory Investigation

To evaluate articles required for this study, a preparatory investigation was required to define the key questions the study would answer, define search areas and subjects, investigate the availability of required scientific papers for the study, and highlight critical keywords to ensure the selection of relevant studies. This ensured the defined criteria and keywords were well-refined to generate significant articles for the study.

3.3. Search Strategy and Database Selection

In scientometric analysis, several digital databases exist. The most popular ones for scientific research are Google Scholar, ISI Web of Science, and Scopus. However, before retrieving articles for a review, it is crucial to choose an effective search technique and the proper database(s). According to [82], there is no discernible difference between the databases Scopus and Web of Science for scientific publications. Regardless, the criteria for choosing Scopus were based on: Scopus houses the vast majority of research publications in the building industry. The largest citation database for all articles that have been peer-reviewed is Scopus; compared to other databases, Scopus performs better in terms of accuracy and consistency. A preliminary search was performed, and it was then honed based on the popular search terms from related publications. The enhancements in the investigation were made through several iterations of improvement, and the generated search string was "occupant behavior" AND "energy consumption" OR "thermal comfort". This query produced 551 results as of November 2022, which were subsequently refined.

3.4. Inclusion and Exclusion Criteria

The requirements for this study's inclusion were (i) research articles in the built environment, (ii) no year limitation, (iii) articles published in English, and (iv) articles with titles and keywords relating to the defined search criteria. However, excluded articles were removed that (i) had related keywords but did not focus on the built environment domain, (ii) were not in English, (iii) were not journal publications, (iv) or had no full text. Finally, the selected articles were further refined based on their abstracts to ensure their relation to the study's objectives. This resulted in a total of 120 journal articles considered fit for qualitative and quantitative analysis.

3.5. Mapping of Selected Articles

For analyzing scientometric research, several software programs are available, including VOSviewer version 1.6.18, BibExcel, CiteSpace, CoPalRed, Sci2, and Vantage-Point [82]. Particularly in graphical and metadata metric studies, construction management researchers have increased their significance and use of VOSviewer software. The flexibility to use many databases for the same study is what sets VOSviewer apart and contributes to its popularity [80]. Through the display of visually comprehensible, esthetically beautiful, and interpretable bibliometric graphs and maps, it is open source, user friendly, and capable of visualizing comparisons, links, interactions, and networks among bibliographic data. Additionally, it excels in recognizably presenting vast networks. VOSviewer was chosen for this study's analysis because of its features, high rate of academic review uptake, and simplicity of use. To visualize networks of documents, VOSviewer provides analysis using both full counting techniques and fractional counting methodology. It was used for (i) visualizing and data mining; (ii) analysis of the co-occurrence of keywords, journals, and countries; and (iii) co-citation analysis.

3.6. Qualitative/Critical Review

To achieve the goal of the qualitative evaluation of the quantitative results, the 120 journal articles used for the scientometric analysis were afterward read in full by the authors in Table 1.

Table 1. Summary of Previous Reviews.

Paper	Title	Research Methods	Database	Analytical Method	No of Articles	Findings	Research Gaps
[74]	The role of the internet of things (IoT) in the assessment and communication of indoor environmental quality (IEQ) in buildings: A review	Qualitative Review	Scopus and WOS	Systematic (PRISMA and content analysis)	N = 91	• The main purpose of applying IoT inside buildings is to reduce energy consumption. • There is an interest in developing low-cost sensing devices with a learning approach. • Machine learning methods are mainly used for energy-saving purposes and to learn about occupants' behavior inside buildings, focusing on thermal comfort. • Sensors in the IoT era are a requirement to help improve people's comfort and well-being	• No consideration • Regarding the difficult task of collecting data inside the built environment • No consideration of bias risk assessment factors
[75]	Machine learning techniques in the energy consumption of buildings: A systematic literature review using text mining and bibliometric analysis	Qualitative Review	IEEE Xplore, Science Direct, Springer, Scopus, and Web of Science	Mixed review (bibliometric and PRISMA-text mining)	N = 106	• Most of the previous studies used four basic intelligent computing models to predict the ECB: neural networks, regression, support vector machines, and deep learning.	• Restricted by the search terms used and the publication interval (last seven years). • Additionally, it utilized a limited number of sources from electronic databases.
[76]	Occupant behavior modeling methods for resilient building design, operation and policy at urban scale: A review	Qualitative review	Google Scholar	Content analysis	N = 206	• Applications for urban-scale buildings still rely on modeling occupant behavior at the level of each building, rather than at the metropolitan scale. • Emerging data sources and approaches in the fields of marketing/promotion, epidemiology, disaster management, and transportation may be able to satisfy the modeling needs of the applications.	• This demands more investigation into neural networks and graphical network analysis to understand behavior towards and interaction with buildings.

Table 1. *Cont.*

Paper	Title	Research Methods	Database	Analytical Method	No of Articles	Findings	Research Gaps
[77]	The impacts of occupant behavior on building energy consumption: A review	Qualitative Review	Scopus	Content analysis	N = 295	• Three main educational approaches have been identified: traditional education (e.g., motivation, social norms, and normative messages), providing feedback and installing smart technologies.	• Key factors to determining considerations from building factors, to avoid unnecessary and redundant data collection is imperative.
[83]	Occupant behavior and building renovation of the social housing stock: Current and future challenges	Qualitative review		Desk review		• Public bodies have to take the lead in renovating their stock of buildings and set an excellent example. • The main motivation for implementing energy-efficient measures is anticipated to come from the energy savings from renovating owner-occupied homes, while the focus on the social housing sector is more difficult given the challenges in addressing energy savings with this vulnerable user group.	• Comprehensive understanding of ways to regenerate cities and face climate change.

Table 1. *Cont.*

Paper	Title	Research Methods	Database	Analytical Method	No of Articles	Findings	Research Gaps
[84]	What drives our behaviors in buildings? A review of occupant interactions with building systems from the lens of behavioral theories	Qualitative review	PsycINFO, Scopus, Web of Science, and Google Scholar	Content analysis	N = 135	• Identify the studies that have applied different behavioral theories to explain occupant interactions with different building systems.	• Few empirical and naturalistic studies use behavioral theories to describe occupant interactions with certain building systems. • Beyond self-reported survey studies, there is a need for more research to gather data in naturalistic situations.
[85]	Past and future trends on the effects of occupant behavior on building energy consumption	Qualitative review	Science Direct	Content analysis	N > 44	• Demonstrates that the hottest research issues in the 2000s are, in order, comfort levels, payback time, and the financial side of energy-saving measures.	• Look into how occupant behavior varies in a close-to-real environment for energy consumption. • Improve and more precisely model the energy use of actual surroundings.

4. Discussion

This aspect discusses the findings from science mapping. The following topics were covered in the scientific mapping discussion for this study: (i) publication trend; (ii) research venues; (iii) mapping of nations; and (iv) mapping of term co-occurrence.

4.1. Annual Publication Trend

Figure 4 below displays the yearly breakdown of the data that were analyzed. The first research, which was published in any of the 120 articles, was authored by [86–89]. This suggests that the topic of the effect of thermal comfort of inhabitants on energy consumption in buildings is a new area of research. Five papers were published in 2015, four papers in 2016, and four papers in 2017. On the other hand, the remaining publications were all published between the years 2018 and 2023. This suggests that there has been a strong interest in the research topic over the past four years. This finding is consistent with the findings of earlier surveys, which have ranked the subject matter in question as one of the most pressing issues in the built environment. The annual publication pattern invariably reveals any changes that have occurred in the commitment to a specific study field. The increasing interest in and attention to thermal comfort and energy consumption is a result of the clamor for more sustainable living. Furthermore, it demonstrates quite clearly that energy consumption and thermal comfort are becoming very necessary in order for the worldwide construction sector to effectively manage energy usage.

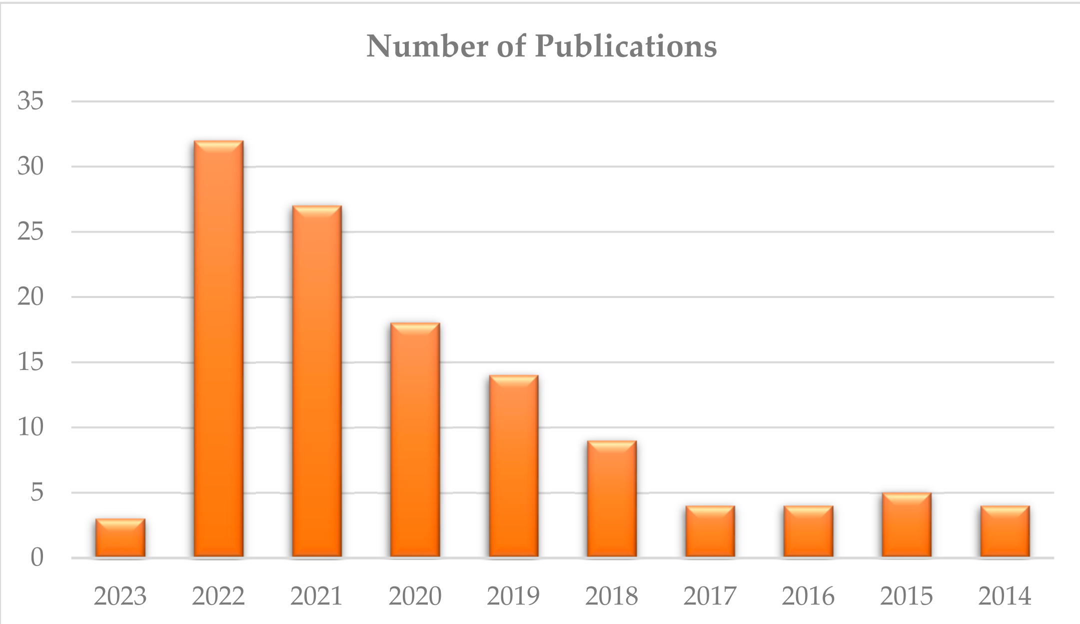

Figure 4. Annual publication chart.

4.2. Journal Publication Analysis

As can be seen in Figure 5, there were 120 publications across 39 different peer-reviewed scientific journals, 23% of the total number in *Energy and Buildings*, followed by 11% in *Buildings and Environment*. The third and fourth-placed journals in the relevant areas were *Energy* and *Sustainability* with 7% each of the total articles. The *Journal of Applied Energy* and *Journal of Energies* made up 5% and 4% of the total publications, respectively. This demonstrates that major articles on thermal comfort and energy consumption themes are published in these journals.

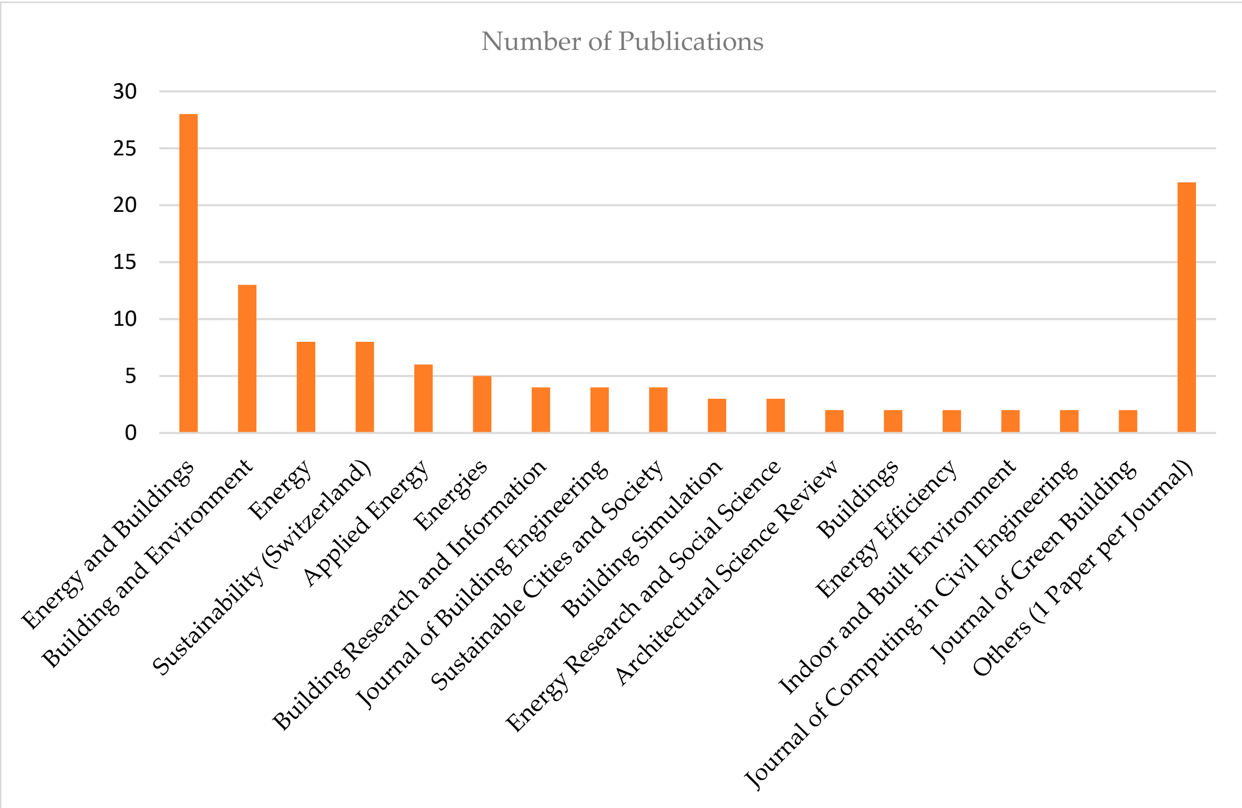

Figure 5. Article distribution per research journal.

4.3. Science Mapping of Countries

The proper mapping of the most productive countries in a specific research subject is frequently improved by the network collaboration of different countries. To successfully promote research funding and collaborations, one must have a crystal clear understanding of the countries that are the most prolific and influential [90]. In this science mapping of countries, the search criteria that were used included analysis type (co-authorship) and analysis unit (country). Additionally, the minimum number of papers from a country was set to 3, and the minimum number of citations from a country was set to 3. According to these search criteria, just 14 of the 46 countries met the minimum requirement. The small number of this representation is in comparison to the number of countries in the world (195). As can be seen in Table 2, this small number shows the area is still emerging.

Table 2. Top countries in thermal comfort and energy consumption research area.

S/N	Country	Documents	Citations	Total Link Strength
1	United States	29	935	10.00
2	China	27	543	8.00
3	Canada	13	240	5.00
4	Australia	7	66	3.00
5	United Kingdom	6	56	3.00
6	Japan	3	68	2.00
7	South Korea	6	147	2.00
8	Spain	6	32	2.00
9	Germany	6	161	2.00
10	Italy	6	127	2.00
11	Austria	3	78	1.00
12	Brazil	4	43	1.00
13	France	8	159	1.00
14	Hong Kong	3	54	0.00

4.4. Major Research Areas of Thermal Comfort and Energy Consumption

The most important aspects of the research were identified through the use of keyword co-occurrence.

Co-occurrence Analysis of Keywords

An academic article's keywords will frequently explain the article's essential ideas. These keywords are typically used as indexation within a database to facilitate efficient search [82]. As a consequence, a network of keywords carries the possibility of describing a knowledge domain [80]. To achieve this goal, scientific mapping of all the keywords contained within the publication set generates a plausible map of the many different study topics and themes present in a certain domain. In this study, the co-occurrence analysis was completed by making use of the authors' keywords. The minimum number of occurrences was set to three occurrences of keywords to guarantee that the cluster results were both thorough and representative. Following a series of tests carried out with the VOSviewer program, this standard was established. It is important to point out that some of the terms in the study were very similar to one another, while others were extremely repetitive.

To choose the threshold, the minimum number of occurrences of a keyword was set to 2. Of the 423 keywords, 47 met the threshold. To eliminate unnecessary keywords and combine keywords with similar meanings, a thesaurus file was utilized during the analysis. Seven clusters were identified from the keywords with distinct colors and are shown in Figure 6. The clusters showing the research areas are indoor environmental quality, energy savings, building performance, occupant behavior, energy consumption, energy performance gap, and thermal comfort. The keywords under these clusters are presented in Figure 7.

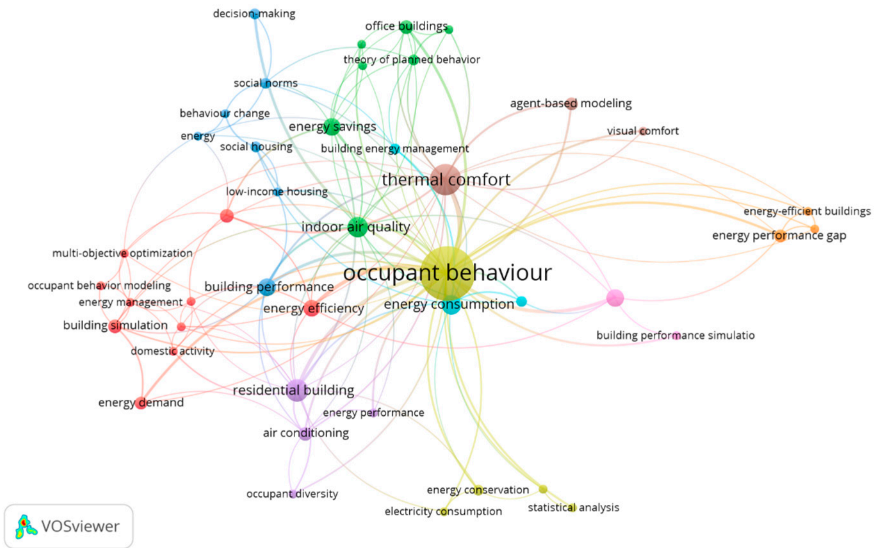

Figure 6. Major research areas.

Thermal comfort factors that are discussed in PMV models (such as indoor temperature, humidity, clothing type, etc.) are considered in building energy assessment tools; however, there is an individual aspect of thermal comfort that is related to personal experiences and expectations that is not reflected in the estimation of energy consumption in buildings. This is because personal experiences and expectations are influenced by a variety of factors, including climate, clothing, and activity level [22].

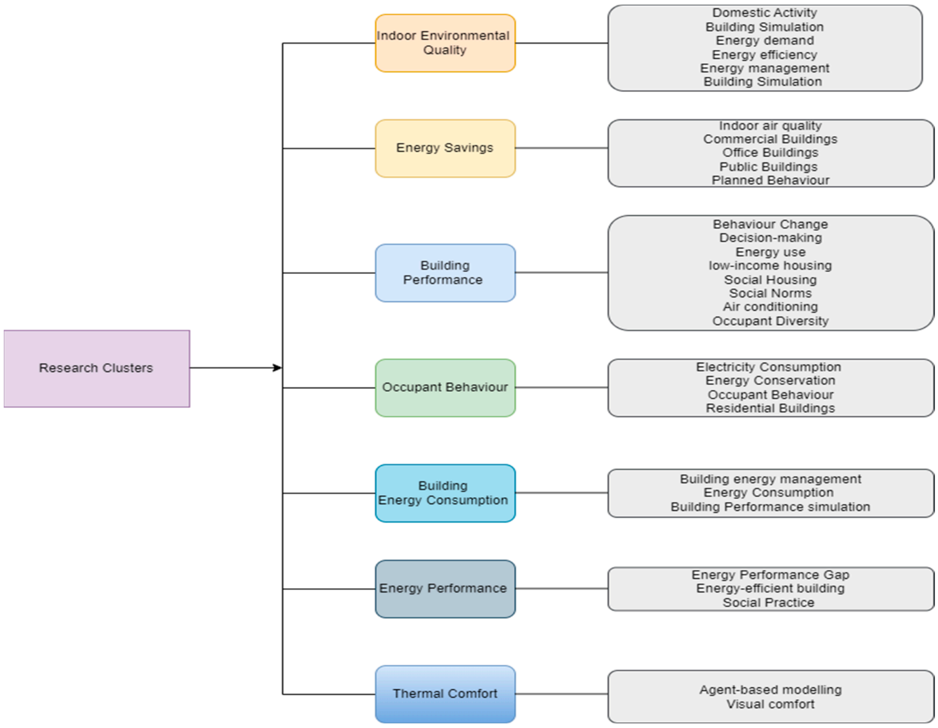

Figure 7. A framework of the major research areas.

4.5. Effect of Occupant Behavior on Energy Consumption for Buildings

As a direct result of the increasing scientific and political pressure that is being exerted all over the world in response to climate change, the evaluation of energy demand and consumption in buildings has become an increasingly pressing issue [22]. The thermophysical properties of the building elements, construction technical details (i.e., building elements with high energy efficiency might perform poorly if not constructed well), climatic location characteristics, the quality and maintenance of the installed HVAC system, occupants' behavior, and activities towards energy utilization are all related to building energy consumption [83]. The metabolic heat that inhabitants produce passively is one factor that is taken into account within the occupancy portion of energy simulation software; however, this factor is not the only factor that influences the total amount of energy that buildings consume [83].

To achieve some particular degree of comfort, occupants engage with control systems and parts of the building in a variety of ways. Use of building openings (such as opening and closing windows), use of lighting, and controlling solar shading (such as adjusting blinds), use of HVAC systems (such as turning the air conditioning on or off and adjusting the thermostat temperature), and use of hot water and electrical appliances are all examples of things that fall under this category [86]. The term occupant behavior refers to the contact that people have with the building systems to control the indoor environment for the sake of their health, as well as to achieve thermal, visual, and auditory comfort inside of structures [89]. How occupants deal with energy consumption is one of the primary contributors to high rates of energy intensity. This signifies the importance of identifying the effect of occupant behavior on energy consumption. The key functions or roles are identified and described in Table 3. Understanding these functions is vital for designers and building users as it enables decision-making in early design stages as well as making the right energy conservation choices.

Table 3. Summary of roles of occupant behavior in energy consumption for buildings.

S/N	Functions	Description	References
1	Occupants' realistic behavior	Passive, medium, and active energy use by occupants	[11,22,91]
2	Heat gain	Increased internal heat gain	[22,92]
3	Occupant characteristic parameters	The status of the occupants, such as their presence or absence in the space, their arrival or departure, as well as their movement and working routine within the area.	[92,93]
		Occupants' gender, age, employment, family size, household size, socio-cultural background, level of education, awareness of energy issues, and the disparities between male and female thermal preferences are examples of socioeconomic and personal parameters that are taken into consideration.	[91–93]
		A sense of ownership, such as whether the residents are renters or owners of the space, whether they are present or absent.	[93,94]
4	Occupant perception of comfort	The occupants' lifestyle, demographics, economy, interaction with building features and systems, and equipment will all have an effect on their impression of comfort, which will, in turn, affect the amount of energy that is used.	[91,94]
5	Occupant interaction with the systems in a building	Strong correlations exist between occupants' control of their interactions with the systems in buildings and the amount of energy used.	[11,91,94]

4.6. Factors Affecting Thermal Comfort of Users and Its Relation to Energy Consumption

Thermal comfort is a crucial aspect of the indoor environment. Achieving optimal thermal comfort is not only important to human comfort but also has implications for energy consumption within the building. Every occupant controls the building systems and components to suit their thermal comfort level. However, striving for optimal thermal comfort without considering energy efficiency can lead to excessive energy consumption. Numerous parameters influence how occupants use energy in buildings, as explained by works of literature. These include the personal (physiological and psychological), climatic, social, economic, regulation and policies, architecture, and interior design of space and building types. Ref. [95] went further to classify these parameters into five groups: contextual factors, physical environmental factors, physiological factors, psychological factors, and social factors.

Climatic parameters: These include indoor and outdoor temperature, relative humidity, sunlight, wind, and rain as factors that change the interaction of humans with building systems to achieve optimal comfort. Ref. [96] conducted research using cold climatic conditions to understand occupant behavior and window opening in an office block. Other researchers analyzed the responses of occupants to hot summer and cold winter climatic conditions for residential and office buildings [97–99]. Most of these studies used a stochastic model to estimate the user behavior in the building.

Building function: This covers the type of activity taking place, which influences the clothing type, metabolic heat, and occupant-specific needs and expectations in interacting with the building. Research was carried out in residential buildings [100,101] offices [102,103]; and commercial buildings [104,105], although less attention was paid to educational buildings [106,107], which limited the findings. In addition, most of the activities examined in these studies were sedentary activities.

Social and personal parameters: These are psychological and psychological characteristics of an individual and play a major and substantial role in occupant comfort and energy.

Social and personal factors include gender, age, level of awareness of energy issues, family size, and sociocultural background [108]. Some researchers examined the difference in the preference for thermal comfort [109]. Furthermore, Ref. [110] investigated the effect of education and awareness-raising on attitudes to energy. Human behavioral theories use social and personal factors to study electricity consumption in office buildings. Ref. [4] used the DNA framework adopting a behavioral–cognitive theory to suggest four key components governing occupants' energy behavior, which were needs, drivers, actions, and systems. The theory of planned behavior, cognitive complex theory, and cognition as a network of tasks are considered in the changeable human recognition process connecting the human and the environment. This needs to be incorporated into building energy assessment tools to improve the accuracy of energy consumption prediction in buildings [111].

Economic parameters: These include income, socioeconomic factors, and energy prices. Studies revealed that when occupants are directly responsible for paying energy bills, they act more responsibly in the use of energy [99]. Ref. [96] examined the relationship between energy price and occupant thermal tolerance, which influenced the level of energy consumption in buildings. Ref. [112] found that the price of energy made occupants endure dissatisfaction in their buildings by not using mechanical fans. Most low-income occupants expend more electricity on buildings due to low thermal insulation [113]. The economic situation determines the quality and size of housing, which in turn affects energy consumption. A semi-structured interview was conducted with low-income earners, and it was revealed that there was a clear distinction between the energy behaviors of rental-paying occupants and those who were subsidized by the government [97].

Occupant state: This means the time of departure and arrival of occupants. Several types of research have revealed that users usually adjust the building systems more when they arrive and depart. Models have been constructed as regards arrival, presence, and departure in connection with occupants' movements and behaviors [104]. An algorithm was proposed by supposing the present/absent status of occupants in each zone as a miscellaneous Markov chain. Other studies conducted to track indoor occupant movements and presence are vision-based methods, WLAN fingerprinting, ultrasound, and sensor-based methods [114,115].

Architecture and interior design features: These are the integration of sustainable interior design in the construction of buildings, such as the adoption of green materials and energy-efficient systems [116]. They can affect occupant behavior and include visual quality, colors, materials, and compositions of interior spaces that affect the thermal perception of users. The difference between occupant behavior in old and refurbished buildings has been studied [107,117]. Design for sustainable behavior means the designer has a function in directing sustainable user behavior during the design stage.

As discussed above, there are many parameters influencing the state of thermal comfort of users. However, the most popular and widely accepted way to understand thermal comfort is through subjective evaluation of users. Subjective evaluation is the method that is used to determine a person's level of thermal comfort, which is described as the state of mind that conveys contentment with the surrounding temperature conditions [118]. Therefore, the ideal way to describe thermal comfort is as a state in which there are no external factors that could cause a change in the environment through behavior. A deeper understanding of the thermal comfort of temporary structures can lead to the development of solutions that improve the physical and mental health of users as well as the efficiency with which they consume energy [119]. The structural, environmental, and human elements are the primary constituents of parameters that influence the level of thermal comfort. They are highlighted and described in Table 4 below.

Table 4. Summary of factors affecting thermal comfort of users and their relation to energy consumption.

S/N	Factors	Description	References
1	Structural	Performance of the envelope structure (heat storage, water absorption, and thermal conductivity of thermal insulation materials, among others)	[119–122]
		Window design	[119,121,122]
		Shading	[119,123]
		Building orientation	[119,120,122,124]
		Ventilation	[119,121,124]
		Permeability	[119,120,122]
2	Environmental	Temperature	[119,121]
		Humidity	[119,122]
		Solar radiation	[119,121]
3	Human	Gender	[118,124,125]
		Metabolic rate	[118,125]
		Clothing thermal resistance	[118,125]
		User behavior	[118,124]
		Perception of environmental issues	[118,125]
		Spatial perception	[118,123,124]
		Aesthetic perception	[118,123–125]
		Sociodemographic attributes	[121,123]
		Prior thermal history and activity	[118,121,123]

As stated by [119], design and construction are the primary factors that determine the thermal transfer coefficient of walls, which ultimately results in either the transfer of heat from outdoors into the room or the loss of heat from inside the room. Furthermore, indoor temperature regulation is often affected by window opening/shading to control solar radiation. Ventilation and infiltration have an immediate impact on the relative humidity and temperature found inside temporary buildings. The direction and layout of temporary buildings are varied, which may affect the amount of solar radiation that enters the building as well as the ventilation within it, which in turn may affect the thermal comfort of the building and consequently, its energy consumption.

Human factors also play a critical role in thermal comfort as a user's sensitivity to the temperature of their surroundings can be affected by factors such as their gender and metabolic rate. Personal decisions to improve thermal comfort also led to an increase in energy consumption. According to the findings of [118], one's level of comfort is a nuanced perceptual construct that is influenced by a variety of different elements but ultimately affects energy consumption. This would mean ensuring all influencing factors are well accounted for and resolved.

4.7. Occupant Behavior Modeling Approaches

Occupant behavior is stochastic, and it is quite difficult to estimate the randomness of people and predict their behaviors [126]. Various patterns or approaches have been used in understanding occupant behavior in past literature based on the climatic or environmental conditions that users experienced. This is usually done by gathering information about occupant and environmental data of a specific room or building and implemented using building performance simulation tools (BPS). Ref. [127] classified the human behavior model into the gray box model, which is built on statistical and stochastic approach, the white box model built on physical equations, and the black box model, which is based on machine learning algorithms. One study classified the developed model into data-driven and simulation-based approaches [128]. Another study classified the model into implicit and explicit models [129]. The implicit model relates to direct rules and regulations in building systems, which include probability calculations, statistical assessment, occupant-based control models, linear and logistical regression, and Bayesian estimates. They explicitly address the rules and logic directly associated with occupants, including the

Bernoulli process, agent-based modeling, survival assessment, and Markov chains. The methodologies have several drawbacks, the most significant of which are challenges in effectively modeling and predicting human behavior, a dearth of data, an oversimplification of complicated systems, and the need for extensive computer power. There is no one method that is adequate in all circumstances; rather, a thorough understanding of how buildings consume energy may require using several different methods, as shown in Table 5.

Table 5. Occupant behavior modeling approaches, functions, and limitations.

Modeling Approach	Purpose/Functions	Limitations	References
Agent-based modeling	- Most popular modeling, used for single or multiple autonomous actors who interact with each other. - Simulates individual occupants and their behavior.	- Lack of proper agreement or rules for building a theoretical foundation for ABM model development. - Computational requirements and difficulties in accurately modeling human behavior.	[97,128,130,131]
Probabilistic or stochastic model	- Capture and represent the chance of a particular behavior occurring or not. - Comprises three occupant behavior models, Markov chain, Bernoulli process, and survival analysis.	- Best suited to long-term schedule formation or prediction. - Detailed behaviors or occupants' statistics cannot be explored with these statistics.	[132,133]
Data mining modeling approach	- For discovering patterns in large datasets. This improves the weakness of statistical modeling.	- Limited to occupancy and appliances and usage in buildings. - Inadequate information and limited access to behavioral and energy consumption.	[94,134,135]
Statistical modeling	- Create a numerical connection between occupant behavior and indoor/outdoor conditions, e.g., the use of regression.	- The system is confined to one or two fixed categories of behavior analysis. - No matter how higher probability is forecast for occupant behavior patterns, real-life situations of occupant behavior may differ based on mindset and general circumstances limited by lack of data and generalization ability.	[111,136]
Mixed or hybrid modeling approaches	- This approach puts multiple methods together to overcome the limitations of individual approaches but can lead to increased complexity.	- The approach can be complex, resulting in understudying an aspect of the method.	[64,137,138]
Rule-based modeling approach	- This modeling method uses predefined rules, e.g., occupancy during office hours.	- A central limitation is its focus on an aspect of real life, therefore it does not factor in other real-life patterns.	[139,140]
Machine learning/data-driven modeling approach	- This system is based on algorithms to learn patterns in data, e.g., decision trees. - This approach utilizes large amounts of data collected from sensors and other sources.	- This approach lacks interpretability and has the potential for overfitting. - This approach is limited by privacy concerns and the need for data pre-processing and cleaning.	[77,141–143]

5. Conclusions, Recommendations, and Future Directions

5.1. Conclusions and Recommendations

In the modern world, buildings account for a significant portion of the total energy consumed, and there is a need for sustainable development, especially for existing buildings to ameliorate the amount of energy they use. It has been demonstrated that occupant behavior has a major role in the energy performance of buildings. The actions of building occupants need to be carefully considered for a structure to be energy efficient. This is necessary for two reasons: firstly, poor building use can result in a loss of energy, and secondly, an occupant-involved building control system is capable of greatly reducing the energy demand of the building. There is a growing worry over the environmental implications of energy use as a result of the warming of the global climate and the growth in the number of instances of extreme weather events.

To reveal the state of the art of thermal comfort and energy research, critical reviews must include the impact of occupant behavior on energy consumption and factors affecting the thermal comfort of users. To research the trends of thermal comfort and energy, this research adopted mixed reviews, i.e., quantitative and qualitative, to understand the state of the art. VOSviewer was used to understand top journals, publication year, countries, the most trending keywords, and so on. Additionally, the cluster for keywords identified in the scientometric analysis was synthesized to form a structure for the classification of major research areas, which are indoor environmental quality, energy savings, building performance, occupant behavior, building energy consumption, energy performance, and thermal comfort. Similarly, the study classified different occupant behaviors, which are occupant realistic behaviors, occupant characteristics parameters, heat gain, occupant perception of comfort, and occupant interaction with systems. The factors influencing the thermal comfort of users were grouped into three areas, which are structural, human, and environmental factors. The study went further to discuss the functions and limitations of different occupant modeling approaches that have been deployed in past studies. The review contributes to the body of knowledge in two ways: 1) by synthesizing research topics and trends in thermal comfort and energy research; and 2) by revealing research needs through critical in-depth discussion of research questions two, three, and four.

5.2. Future Directions

The physical and emotional health of building users is intimately connected to the thermal comfort of their interior environment. The mental and physical well-being of residents of homes is impacted by the level of thermal comfort they experience. Users will automatically adjust behavior (using adaptive behavior, environmental adjustment behavior, and psychological behavior) to increase their thermal comfort when experiencing cold and hot situations that are uncomfortable for them. These behavioral actions are intended to improve their thermal comfort and include the use of fans, thermostat adjustment, wear/removal of clothes, opening and closing of windows/doors, light control, and so on. This review study has some limitations: (1) the search for string was limited to the Scopus database. Future work can be carried out to obtain more comprehensive data by including multiple databases such as Google Scholar, Web of Science, and ScienceDirect. Further research can be conducted on thermal comfort for different building functions by examining the varied activity intensity levels of users, especially in educational or commercial buildings. A proper investigation can also be carried out on how thermal insulation of structural members such as windows, walls, and roofs influences thermal comfort. This can also be compared between two similar buildings in understanding occupant behavioral responses/actions and energy consumption.

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References

1. Santamouris, M. Chapter 2—Energy Consumption and Environmental Quality of the Building Sector. In *Minimizing Energy Consumption, Energy Poverty and Global and Local Climate Change in the Built Environment: Innovating to Zero*; Santamouris, M., Ed.; Elsevier: Amsterdam, The Netherlands, 2019.
2. Latha, H.; Patil, S.; Kini, P.G. Influence of architectural space layout and building perimeter on the energy performance of buildings: A systematic literature review. *Int. J. Energy Environ. Eng.* **2023**, *14*, 431–474. [CrossRef]
3. Mahdavi, A.; Berger, C.; Amin, H.; Ampatzi, E.; Andersen, R.K.; Azar, E.; Barthelmes, V.M.; Favero, M.; Hahn, J.; Khovalyg, D.; et al. The role of occupants in buildings' energy performance gap: Myth or reality? *Sustainability* **2021**, *13*, 3146. [CrossRef]
4. Hong, T.; D'oca, S.; Turner, W.J.N.; Taylor-Lange, S.C. An ontology to represent energy-related occupant behavior in buildings. Part i: Introduction to the dnas framework. *Build. Environ.* **2015**, *92*, 764–777. [CrossRef]
5. Horr, Y.A.; Arif, M.; Kaushik, A.K.; Mazroei, A.; Katafygiotou, M.; Elsarrag, E. Occupant productivity and office indoor environment quality: A review of the literature. *Build. Environ.* **2016**, *105*, 369–389. [CrossRef]
6. Kim, J.; Schiavon, S.; Brager, G. Personal comfort models—A new paradigm in thermal comfort for occupant-centric environmental control. *Build. Environ.* **2018**, *132*, 114–124. [CrossRef]
7. Rehman, S.U.; Javed, A.R.; Khan, M.U.; Nazar Awan, M.; Farukh, A.; Hussien, A. Personalised Comfort: A personalised thermal comfort model to predict thermal sensation votes for smart building residents. *Enterp. Inf. Syst.* **2022**, *16*, 1852316. [CrossRef]
8. Morresi, N.; Casaccia, S.; Sorcinelli, M.; Arnesano, M.; Uriarte, A.; Torrens Galdiz, J.I.; Revel, G. Sensing Physiological and Environmental Quantities to Measure Human Thermal Comfort Through Machine Learning Techniques. *IEEE Sens. J.* **2021**, *21*, 12322–12337. [CrossRef]
9. Čulić, A.; Nižetić, S.; Šolić, P.; Perković, T.; Čongradac, V. Smart monitoring technologies for personal thermal comfort: A review. *J. Clean. Prod.* **2021**, *312*, 127685. [CrossRef]
10. Lamberti, G.; Salvadori, G.; Leccese, F.; Fantozzi, F.; Bluyssen, P.M. Advancement on thermal comfort in educational buildings: Current issues and way forward. *Sustainability* **2021**, *13*, 10315. [CrossRef]
11. Paone, A.; Bacher, J.P. The impact of building occupant behavior on energy efficiency and methods to influence it: A review of the state of the art. *Energies* **2018**, *11*, 953. [CrossRef]
12. Kaewunruen, S.; Rungskunroch, P.; Welsh, J. A digital-twin evaluation of net zero energy building for existing buildings. *Sustainability* **2019**, *11*, 159. [CrossRef]
13. Cibinskiene, A.; Dumciuviene, D.; Andrijauskiene, M. Energy Consumption in Public Buildings: The Determinants of Occupants' Behavior. *Energies* **2020**, *13*, 3586. [CrossRef]
14. Anand, P.; Deb, C.; Yan, K.; Yang, J.; Cheong, D.; Sekhar, C. Occupancy-based energy consumption modelling using machine learning algorithms for institutional buildings. *Energy Build.* **2021**, *252*, 111478. [CrossRef]
15. Cao, X.; Dai, X.; Liu, J. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy Build.* **2016**, *128*, 198–213. [CrossRef]
16. Rouleau, J.; Gosselin, L.; Blanchet, P. Understanding energy consumption in high-performance social housing buildings: A case study from Canada. *Energy* **2018**, *145*, 677–690. [CrossRef]
17. Loukou, E.; Heiselberg, P.; Jensen, R.; Johra, H. Energy performance evaluation of a nearly Zero Energy Building and the reasons for the performance gap between expected and actual building operation. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *352*, 012017. [CrossRef]
18. Sangalli, A.; Pagliano, L.; Causone, F.; Salvia, G.; Morello, E.; Erba, S. Behavioural Change Effects on Energy Use in Public Housing: A Case Study. In *Sustainability in Energy and Buildings*; Littlewood, J., Howlett, R.J., Capozzoli, A., Jain, L.C., Eds.; Springer: Singapore, 2020; pp. 759–768.
19. Cuerda, E.; Guerra-Santin, O.; Sendra, J.J.; Neila González, F.J. Comparing the impact of presence patterns on energy demand in residential buildings using measured data and simulation models. *Build. Simul.* **2019**, *12*, 985–998. [CrossRef]
20. Hahn, J.; Schumacher, P.; Lang, W.; Jensch, W. Performance Gap and Occupant Behavior—Review and Analysis of High-Efficiency Residential Buildings in Germany. In Proceedings of the 33rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS, Osaka, Japan, 29 June–3 July 2020.
21. D'oca, S.; Hong, T.; Langevin, J. The human dimensions of energy use in buildings: A review. *Renew. Sustain. Energy Rev.* **2018**, *81*, 731–742. [CrossRef]
22. Delzendeh, E.; Wu, S.; Lee, A.; Zhou, Y. The impact of occupants' behaviours on building energy analysis: A research review. *Renew. Sustain. Energy Rev.* **2017**, *80*, 1061–1071. [CrossRef]

23. Pellegrino, M.; Simonetti, M.; Chiesa, G. Reducing thermal discomfort and energy consumption of indian residential buildings: Model validation by in-field measurements and simulation of low-cost interventions. *Energy Build.* **2016**, *113*, 145–158. [CrossRef]
24. Frontczak, M.; Goins, J.; Arens, E.; Zhang, H.; Wargocki, P. Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. *Indoor Air* **2011**, *22*, 119–131. [CrossRef] [PubMed]
25. Tham, K.W.; Willem, H.C. Room air temperature affects occupants' physiology, perceptions, and mental alertness. *Build. Environ.* **2010**, *45*, 40–44. [CrossRef]
26. Shaw, E.W. Thermal comfort: Analysis and applications in environmental engineering, by p. O. Fanger. 244 pp. Danish technical press. Copenhagen, denmark, 1970. Danish kr. 76, 50. *R. Soc. Health J.* **1972**, *92*, 164. [CrossRef]
27. Liu, C.-C.; Kuo, W.-L.; Shiu, R.-S.; Wu, I.C. *Estimating and Visualizing Thermal Comfort Level via a Predicted Mean Vote in a Bim System*; Osaka University: Osaka, Japan, 2016.
28. Lan, L.; Zhai, Z.; Lian, Z. A two-part model for evaluation of thermal neutrality for sleeping people. *Build. Environ.* **2018**, *132*, 319–326. [CrossRef]
29. Song, C.; Liu, Y.; Liu, J. The sleeping thermal comfort model is based on local thermal requirements in winter. *Energy Build.* **2018**, *173*, 163–175. [CrossRef]
30. Zhao, Q.; Lian, Z.; Lai, d. Thermal comfort models and their developments: A review. *Energy Built Environ.* **2021**, *2*, 21–33. [CrossRef]
31. Kumar, S.; Singh, M.K.; Mathur, A.; Mathur, J.; Mathur, S. Evaluation of comfort preferences and insights into behavioural adaptation of students in naturally ventilated classrooms in a tropical country, india. *Build. Environ.* **2018**, *143*, 532–547. [CrossRef]
32. Singh, M.K.; Kumar, S.; Ooka, R.; Rijal, H.B.; Gupta, G.; Kumar, A. Status of thermal comfort in naturally ventilated classrooms during the summer season in the composite climate of india. *Build. Environ.* **2018**, *128*, 287–304. [CrossRef]
33. Zomorodian, Z.S.; Tahsildoost, M.; Hafezi, M. Thermal comfort in educational buildings: A review article. *Renew. Sustain. Energy Rev.* **2016**, *59*, 895–906. [CrossRef]
34. Corgnati, S.; Filippi, M.; Viazzo, S. Perception of the thermal environment in high school and university classrooms: Subjective preferences and thermal comfort. *Build. Environ.* **2007**, *42*, 951–959. [CrossRef]
35. Buratti, C.; Ricciardi, P. Adaptive analysis of thermal comfort in university classrooms: Correlation between experimental data and mathematical models. *Build. Environ.* **2009**, *44*, 674–687. [CrossRef]
36. Jung, G.J.; Song, S.; Ahn, Y.; Oh, G.; Im, Y. Experimental research on thermal comfort in the university classroom of regular semesters in korea. *J. Mech. Sci. Technol.* **2011**, *25*, 503–512. [CrossRef]
37. Cao, B.; Zhu, Y.; Ouyang, Q.; Zhou, X.; Huang, L. Field study of human thermal comfort and thermal adaptability during the summer and winter in beijing. *Energy Build.* **2011**, *43*, 1051–1056. [CrossRef]
38. Wang, Z.; Li, A.; Ren, J.; He, Y. Thermal adaptation and thermal environment in university classrooms and offices in Harbin. *Energy Build.* **2014**, *77*, 192–196. [CrossRef]
39. Wang, Z.; Ning, H.; Zhang, X.; Ji, Y. Human thermal adaptation based on university students in China's severe cold area. *Sci. Technol. Built Environ.* **2017**, *23*, 413–420. [CrossRef]
40. Serghides, D.K.; Chatzinikola, C.K.; Katafygiotou, M.C. Comparative studies of the occupants' behaviour in a university building during winter and summer time. *Int. J. Sustain. Energy* **2015**, *34*, 528–551. [CrossRef]
41. Li, D.; Menassa, C.C.; Kamat, V.R. Personalized human comfort in indoor building environments under diverse conditioning modes. *Build. Environ.* **2017**, *126*, 304–317. [CrossRef]
42. Cheung, T.C.T.; Schiavon, S.; Gall, E.T.; Jin, M.; Nazaroff, W.W. Longitudinal assessment of thermal and perceived air quality acceptability in relation to temperature, humidity, and co2 exposure in singapore. *Build. Environ.* **2017**, *115*, 80–90. [CrossRef]
43. Auffenberg, F.; Stein, S.; Rogers, A. A personalised thermal comfort model using a Bayesian network. In Proceedings of the International Joint Conference on Artificial Intelligence, Buenos Aires, Argentina, 25–31 July 2015.
44. Ghahramani, A.; Tang, C.; Becerik-Gerber, B. An online learning approach for quantifying personalized thermal comfort via adaptive stochastic modeling. *Build. Environ.* **2015**, *92*, 86–96. [CrossRef]
45. Rana, R.; Kusy, B.; Jurdak, R.; Wall, J.; Hu, W. Feasibility analysis of using humidex as an indoor thermal comfort predictor. *Energy Build.* **2013**, *64*, 17–25. [CrossRef]
46. Liu, W.; Lian, Z.; Zhao, B. A neural network evaluation model for individual thermal comfort. *Energy Build.* **2007**, *39*, 1115–1122. [CrossRef]
47. Chinazzo, G. Investigating the indoor environmental quality of different workplaces through web-scraping and text-mining of glassdoor reviews. *Build. Res. Inf.* **2021**, *49*, 695–713. [CrossRef]
48. Bluyssen, P.M.; Zhang, D.; Kurvers, S.; Overtoom, M.; Ortiz-Sanchez, M. Self-reported health and comfort of school children in 54 classrooms of 21 dutch school buildings. *Build. Environ.* **2018**, *138*, 106–123. [CrossRef]
49. Chitaru, G.-M.; Istrate, A.; Catalina, T. Numerical analysis of the impact of natural ventilation on the indoor air quality and thermal comfort in a classroom. *E3s Web Conf.* **2019**, *111*, 01023. [CrossRef]
50. Ranjbar, A. Analysing the effects of thermal comfort and indoor air quality in design studios and classrooms on student performance. *Iop Conf. Ser. Mater. Sci. Eng.* **2019**, *609*, 042086. [CrossRef]
51. Almeida, R.; Freitas, V. IEQ assessment of classrooms with an optimized demand controlled ventilation system. *Energy Procedia* **2015**, *78*, 3132–3137. [CrossRef]

52. Jing, S.; Lei, Y.; Wang, H.; Song, C.; Yan, X. Thermal comfort and energy-saving potential in university classrooms during the heating season. *Energy Build.* **2019**, *202*, 109390. [CrossRef]
53. *ISO 7730*; Ergonomics of the Thermal Environment-Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. ISO: Geneve, Switzerland, 2006.
54. *EN 16798-1*; Energy Performance of Buildings-Ventilation for Buildings-Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting, and Acoustics. CEN: Brusselles, Belgium, 2019.
55. ASHRAE. *ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy*; ASHRAE: Peachtree Corners, GA, USA, 2004.
56. Asadi, I.; Mahyuddin, N.; Shafigh, P. A review on indoor environmental quality (IEQ) and energy consumption in building based on occupant behavior. *Facilities* **2017**, *35*, 684–695. [CrossRef]
57. *Standard EN 15251*; Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics. German Version EN: Brusselles, Belgium, 2007; p. 15251.
58. Bluyssen, P. *The Indoor Environment Handbook: How to Make Buildings Healthy and Comfortable*, 1st ed.; Routledge: London, UK, 2009. [CrossRef]
59. Ebuy, H.T.; Bril El Haouzi, H.; Benelmir, R.; Pannequin, R. Occupant Behavior Impact on Building Sustainability Performance: A Literature Review. *Sustainability* **2023**, *15*, 2440. [CrossRef]
60. Page, J.; Robinson, D.; Morel, N.; Scartezzini, J.L. A generalised stochastic model for the simulation of occupant presence. *Energy Build.* **2008**, *40*, 83–98. [CrossRef]
61. Tan, B. Design of balanced energy savings performance contracts. *Int. J. Prod. Res.* **2020**, *58*, 1401–1424. [CrossRef]
62. Ali, H.H.; Al-Hashlamun, R. Assessment of indoor thermal environment in different prototypical school buildings in jordan. *Alex. Eng. J.* **2019**, *58*, 699–711. [CrossRef]
63. Zhan, S.; Chong, A. Building occupancy and energy consumption: Case studies across building types. *Energy Built Environ.* **2021**, *2*, 167–174. [CrossRef]
64. Dong, B.; Lam, K.P. A real-time model predictive control for building heating and cooling systems based on the occupancy behavior pattern detection and local weather forecasting. *Build. Simul.* **2014**, *7*, 89–106. [CrossRef]
65. HUb, Z.C. *Post-Occupancy Evaluation, Rowner Research Project Phase Two*; Zero Carbon HUB: Milton Keynes, UK, 2015.
66. Alsharif, R.; Arashpour, M.; Golafshani, E.M.; Hosseini, M.R.; Chang, V.; Zhou, J. Machine learning-based analysis of occupant-centric aspects: Critical elements in the energy consumption of residential buildings. *J. Build. Eng.* **2022**, *46*, 103846. [CrossRef]
67. Lee, J.; Ham, Y. Physiological sensing-driven personal thermal comfort modelling in consideration of human activity variations. *Build. Res. Inf.* **2021**, *49*, 512–524. [CrossRef]
68. Talarosha, B.; Satwiko, P.; Aulia, D. Air temperature and CO_2 concentration in naturally ventilated classrooms in hot and humid tropical climate. *Iop Conf. Ser. Earth Environ. Sci.* **2020**, *402*, 012008. [CrossRef]
69. Oltra-Badenes, R.; Guerola-Navarro, V.; Gil-Gómez, J.-A.; Botella-Carrubi, D. Design and Implementation of Teaching–Learning Activities Focused on Improving the Knowledge, the Awareness and the Perception of the Relationship between the SDGs and the Future Profession of University Students. *Sustainability* **2023**, *15*, 5324. [CrossRef]
70. Xu, X.; Yu, H.; Sun, Q.; Tam, V.W.Y. A critical review of occupant energy consumption behavior in buildings: How we got here, where we are, and where we are headed. *Renew. Sustain. Energy Rev.* **2023**, *182*, 113396. [CrossRef]
71. Arowoiya, V.A.; Moehler, R.C.; Fang, Y. Digital twin technology for thermal comfort and energy efficiency in buildings: A state-of-the-art and future directions. *Energy Built Environ.* **2024**, *5*, 641–656. [CrossRef]
72. Ahmed, O.; Sezer, N.; Ouf, M.; Wang, L.; Hassan, I.G. State-of-the-art review of occupant behavior modeling and implementation in building performance simulation. *Renew. Sustain. Energy Rev.* **2023**, *185*, 113558. [CrossRef]
73. Onososen, A.O.; Musonda, I. Research focus for construction robotics and human-robot teams towards resilience in construction: Scientometric review. *J. Eng. Des. Technol.* **2022**, *21*, 502–526. [CrossRef]
74. Broday, E.E.; Gameiro da Silva, M.C. The role of internet of things (IoT) in the assessment and communication of indoor environmental quality (IEQ) in buildings: A review. *Smart Sustain. Built Environ.* **2022**, *12*, 584–606. [CrossRef]
75. Abdelaziz, A.; Santos, V.; Dias, M.S. Machine learning techniques in the energy consumption of buildings: A systematic literature review using text mining and bibliometric analysis. *Energies* **2021**, *14*, 7810. [CrossRef]
76. Dong, B.; Liu, Y.; Fontenot, H.; Ouf, M.; Osman, M.; Chong, A.; Qin, S.; Salim, F.; Xue, H.; Yan, D.; et al. Occupant behavior modeling methods for resilient building design, operation, and policy at urban scale: A review. *Appl. Energy* **2021**, *293*, 116856. [CrossRef]
77. Chen, S.; Zhang, G.; Xia, X.; Chen, Y.; Setunge, S.; Shi, L. The impacts of occupant behavior on building energy consumption: A review. *Sustain. Energy Technol. Assess.* **2021**, *45*, 101212. [CrossRef]
78. Heydarian, A.; Carneiro, J.P.; Gerber, D.; Becerik-Gerber, B. Immersive virtual environments, understanding the impact of design features and occupant choice upon lighting for building performance. *Build. Environ.* **2015**, *89*, 217–228. [CrossRef]
79. Shukla, A.K.; Janmaijaya, M.; Abraham, A.; Muhuri, P.K. Engineering applications of artificial intelligence: A bibliometric analysis of 30 years (1988–2018). *Eng. Appl. Artif. Intell.* **2019**, *85*, 517–532. [CrossRef]

80. Saka, A.B.; Chan, D.W.M. A scientometric review and meta-synthesis of building information modeling (BIM) research in Africa. *Buildings* **2019**, *9*, 85. [CrossRef]
81. Onososen, A.O.; Musonda, I.; Ramabodu, M. Construction Robotics and Human—Robot Teams Research Methods. *Buildings* **2022**, *12*, 1192. [CrossRef]
82. Olawumi, T.O.; Chan, D.W.M. A scientometric review of global research on sustainability and sustainable development. *J. Clean. Prod.* **2018**, *183*, 231–250. [CrossRef]
83. Santangelo, A.; Tondelli, S. Occupant behavior and building renovation of the social housing stock: Current and future challenges. *Energy Build.* **2017**, *145*, 276–283. [CrossRef]
84. Heydarian, A.; McIlvennie, C.; Arpan, L.; Yousefi, S.; Syndicus, M.; Schweiker, M.; Jazizadeh, F.; Rissetto, R.; Pisello, A.L.; Piselli, C.; et al. What drives our behaviors in buildings? A review on occupant interactions with building systems from the lens of behavioral theories. *Build. Environ.* **2020**, *179*, 106928. [CrossRef]
85. Torabi, M.; Mahdavinejad, M. Past and future trends on the effects of occupant behaviour on building energy consumption. *J. Sustain. Archit. Civ. Eng.* **2021**, *29*, 83–101. [CrossRef]
86. Marique, A.F.; De Meester, T.; De Herde, A.; Reiter, S. An online interactive tool to assess energy consumption in residential buildings and for daily mobility. *Energy Build.* **2014**, *78*, 50–58. [CrossRef]
87. Bonte, M.; Thellier, F.; Lartigue, B. Impact of occupant's actions on energy building performance and thermal sensation. *Energy Build.* **2014**, *76*, 219–227. [CrossRef]
88. Anderson, K.; Lee, S.; Menassa, C. Impact of Social Network Type and Structure on Modeling Normative Energy Use Behavior Interventions. *J. Comput. Civ. Eng.* **2014**, *28*, 30–39. [CrossRef]
89. Clevenger, C.M.; Haymaker, J.R.; Jalili, M. Demonstrating the Impact of the Occupant on Building Performance. *J. Comput. Civ. Eng.* **2014**, *28*, 99–102. [CrossRef]
90. Oluleye, B.I.; Chan, D.W.M.; Saka, A.B.; Olawumi, T.O. Circular economy research on building construction and demolition waste: A review of current trends and future research directions. *J. Clean. Prod.* **2022**, *357*, 131927. [CrossRef]
91. Tam, V.W.Y.; Almeida, L.; Le, K. Energy-related occupant behaviour and its implications in energy use: A chronological review. *Sustainability* **2018**, *10*, 2635. [CrossRef]
92. Barthelmes, V.M.; Becchio, C.; Fabi, V.; Corgnati, S.P. Occupant behaviour lifestyles and effects on building energy use: Investigation on high and low performing building features. *Energy Procedia* **2017**, *140*, 93–101. [CrossRef]
93. Grover, A.C. Understanding the role of Occupants in green building energy performance. In Proceedings of the 53rd International Conference of Architectural Science Association, Roorkee, India, 28–30November 2019; pp. 547–556.
94. Uddin, M.N.; Wei, H.H.; Chi, H.L.; Ni, M. Influence of occupant behavior for building energy conservation: A systematic review study of diverse modeling and simulation approach. *Buildings* **2021**, *11*, 41. [CrossRef]
95. Fabi, V.; Andersen, R.V.; Corgnati, S.; Olesen, B.W. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Build. Environ.* **2012**, *58*, 188–198. [CrossRef]
96. Rijal, H.B.; Tuohy, P.; Humphreys, M.A.; Nicol, J.F.; Samuel, A. An algorithm to represent occupant use of windows and fans including situation-specific motivations and constraints. *Build. Simul.* **2011**, *4*, 117–134. [CrossRef]
97. Langevin, J.; Wen, J.; Gurian, P.L. Simulating the human-building interaction: Development and validation of an agent-based model of office occupant behaviors. *Build. Environ.* **2015**, *88*, 27–45. [CrossRef]
98. Schakib-ekbatan, K.; Çakici, F.Z.; Schweiker, M.; Wagner, A. Does the occupant behavior match the energy concept of the building?–Analysis of a german naturally ventilated office building. *Build. Environ.* **2015**, *84*, 142–150. [CrossRef]
99. Wang, Z.; Zhao, Z.; Lin, B.; Zhu, Y.; Ouyang, Q. Residential heating energy consumption modeling through a bottom-up approach for China's hot summer–cold winter climatic region. *Energy Build.* **2015**, *109*, 65–74. [CrossRef]
100. Yang, J.; Santamouris, M.; Lee, S.E. Review of occupancy sensing systems and occupancy modeling methodologies for the application in institutional buildings. *Energy Build.* **2016**, *121*, 344–349. [CrossRef]
101. Chen, S.; Yang, W.; Yoshino, H.; Levine, M.D.; Newhouse, K.; Hinge, A. Definition of occupant behavior in residential buildings and its application to behavior analysis in case studies. *Energy Build.* **2015**, *104*, 1–13. [CrossRef]
102. Gandhi, P.; Brager, G.S. Commercial office plug load energy consumption trends and the role of occupant behavior. *Energy Build.* **2016**, *125*, 1–8. [CrossRef]
103. Karjalainen, S. Should we design buildings that are less sensitive to occupant behaviour? A simulation study of effects of behaviour and design on office energy consumption. *Energy Effic.* **2016**, *9*, 1257–1270. [CrossRef]
104. Rafsanjani, H.N.; Ahn, C. Linking building energy-load variations with occupants' energy-use behaviors in commercial buildings: Non-intrusive occupant load monitoring (niolm). *Procedia Eng.* **2016**, *145*, 532–539. [CrossRef]
105. Karatas, A.; Stoiko, A.; Menassa, C.C. Framework for selecting occupancy-focused energy interventions in buildings. *Build. Res. Inf.* **2016**, *44*, 535–551. [CrossRef]
106. Pisello, A.L.; Castaldo, V.L.; Piselli, C.; Fabiani, C.; Cotana, F. How peers' personal attitudes affect indoor microclimate and energy need in an institutional building: Results from a continuous monitoring campaign in summer and winter conditions. *Energy Build.* **2016**, *126*, 485–497. [CrossRef]
107. Ouf, M.; Issa, M.; Merkel, P. Analysis of real-time electricity consumption in canadian school buildings. *Energy Build.* **2016**, *128*, 530–539. [CrossRef]

108. Martinaitis, V.; Zavadskas, E.K.; Motuzienė, V.; Vilutienė, T. Importance of occupancy information when simulating energy demand of energy efficient house: A case study. *Energy Build.* **2015**, *101*, 64–75. [CrossRef]
109. Indraganti, M.; Ooka, R.; Rijal, H.B. Thermal comfort in offices in india: Behavioral adaptation and the effect of age and gender. *Energy Build.* **2015**, *103*, 284–295. [CrossRef]
110. Janda, K.B. Buildings don't use energy: People do. *Archit. Sci. Rev.* **2011**, *54*, 15–22. [CrossRef]
111. Yan, D.; Hong, T.; Dong, B.; Mahdavi, A.; D'oca, S.; Gaetani, I.; Feng, X. Iea ebc annex 66: Definition and simulation of occupant behavior in buildings. *Energy Build.* **2017**, *156*, 258–270. [CrossRef]
112. Park, J.S.; Kim, H.J. A field study of occupant behavior and energy consumption in apartments with mechanical ventilation. *Energy Build.* **2012**, *50*, 19–25. [CrossRef]
113. Romero, R.A.; Bojórquez, G.; Corral, M.; Gallegos, R. Energy and the occupant's thermal perception of low-income dwellings in hot-dry climate: Mexicali, méxico. *Renew. Energy* **2013**, *49*, 267–270. [CrossRef]
114. Milan, A.; Schindler, K.; Roth, S. Detection- and trajectory-level exclusion in multiple object tracking. In Proceedings of the 2013 IEEE Conference on Computer Vision and Pattern Recognition, Portland, OR, USA, 23–28 June 2013; pp. 3682–3689.
115. Fet, N.; Handte, M.; Wagner, S.; Marrón, P.J. Locomotion: An acceleration-assisted person tracking system based on wireless lan. In *Evaluating aal Systems through Competitive Benchmarking*; Chessa, S., Knauth, S., Eds.; Springer: Berlin/Heidelberg, Germany, 2013; pp. 17–31.
116. Lee, E.; Allen, A.; Kim, B. Interior design practitioner motivations for specifying sustainable materials: Applying the theory of planned behavior to residential design. *J. Inter. Des.* **2013**, *38*, 1–16. [CrossRef]
117. Agha-Hossein, M.M.; El-Jouzi, S.; Elmualim, A.A.; Ellis, J.; Williams, M. Post-occupancy studies of an office environment: Energy performance and occupants' satisfaction. *Build. Environ.* **2013**, *69*, 121–130. [CrossRef]
118. Manavvi, S.; Rajasekar, E. Assessing thermal comfort in urban squares in humid subtropical climate: A structural equation modelling approach. *Build. Environ.* **2023**, *229*, 109931. [CrossRef]
119. Zheng, P.; Wu, H.; Liu, Y.; Ding, Y.; Yang, L. Thermal comfort in temporary buildings: A review. *Build. Environ.* **2022**, *221*, 109262. [CrossRef]
120. Alwetaishi, M.S. Impact of building function on thermal comfort: A review paper. *Am. J. Eng. Appl. Sci.* **2016**, *9*, 928–945. [CrossRef]
121. Volkov, A.A.; Sedov, A.V.; Chelyshkov, P.D. Modeling the thermal comfort of internal building spaces in social buildings. *Procedia Eng.* **2014**, *91*, 362–367. [CrossRef]
122. Heracleous, C.; Michael, A. Thermal comfort models and perception of users in free-running school buildings of East-Mediterranean region. *Energy Build.* **2020**, *215*, 109912. [CrossRef]
123. Mamani, T.; Herrera, R.F.; Rivera, F.M.; Atencio, E. Variables That Affect Thermal Comfort and Its Measuring Instruments: A Systematic Review. *Sustainability* **2022**, *14*, 1773. [CrossRef]
124. Hang-Yat, L.A.; Wang, D. Carrying my environment with me: A participatory-sensing approach to enhance thermal comfort. In Proceedings of the BuildSys 2013—Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings, Roma, Italy, 13–14 November 2013. [CrossRef]
125. Rupp, R.F.; Vásquez, N.G.; Lamberts, R. A review of human thermal comfort in the built environment. *Energy Build.* **2015**, *105*, 178–205. [CrossRef]
126. Zou, P.; Xu, X.; Sanjayan, J.; Wang, J. A mixed methods design for building occupants' energy behaviour research. *Energy Build.* **2018**, *166*, 239. [CrossRef]
127. Papadopoulos, S.; Azar, E. Integrating building performance simulation in agent-based modelling using regression surrogate models: A novel human-in-the-loop energy modelling approach. *Energy Build.* **2016**, *128*, 214–223. [CrossRef]
128. Jia, M.; Srinivasan, R.S.; Raheem, A.A. From occupancy to occupant behaviour: An analytical survey of data acquisition technologies, modelling methodologies and simulation coupling mechanisms for building energy efficiency. *Renew. Sustain. Energy Rev.* 2017; 68, 525–540. [CrossRef]
129. Hong, T.; Sun, H.; Chen, Y.; Taylor-Lange, S.C.; Yan, D. An occupant behaviour modelling tool for co-simulation. *Energy Build.* **2016**, *117*, 272–281. [CrossRef]
130. Malik, J.; Mahdavi, A.; Azar, E.; Chandra Putra, H.; Berger, C.; Andrews, C.; Hong, T. Ten questions concerning agent-based modeling of occupant behavior for energy and environmental performance of buildings. *Build. Environ.* **2022**, *217*, 109016. [CrossRef]
131. Malik, J.; Azar, E.; Mahdavi, A.; Hong, T. A level-of-details framework for representing occupant behavior in agent-based models. *Autom. Constr.* **2022**, *139*, 104290. [CrossRef]
132. Parys, W.; Saelens, D.; Hens, H. Coupling of dynamic building simulation with stochastic modelling of occupant behaviour in offices—A review-based integrated methodology. *J. Build. Perform. Simul.* **2011**, *4*, 339–358. [CrossRef]
133. Jang, H.; Kang, J. A stochastic model of integrating occupant behaviour into energy simulation with respect to actual energy consumption in high-rise apartment buildings. *Energy Build.* **2016**, *121*, 205–216. [CrossRef]
134. Zhao, J.; Lasternas, B.; Lam, K.P.; Yun, R.; Loftness, V. Occupant behavior and schedule modeling for building energy simulation through office appliance power consumption data mining. *Energy Build.* **2014**, *82*, 341–355. [CrossRef]
135. D'Oca, S.; Hong, T. A data-mining approach to discover patterns of window opening and closing behavior in offices. *Build. Environ.* **2014**, *82*, 726–739. [CrossRef]

136. Gunay, B.; Corgnati, S.P.; Di Torino, P. On Modelling And Simulation of Occupant Models. In Proceedings of the 14th Conference of IBPSA, Hyderabad, India, 7–9 December 2015. [CrossRef]
137. Haldi, F.; Robinson, D. The impact of occupants' behaviour on building energy demand. *J. Build. Perform. Simul.* **2011**, *4*, 323–338. [CrossRef]
138. Peng, Y.; Lei, Y.; Tekler, Z.D.; Antanuri, N.; Lau, S.K.; Chong, A. Hybrid system controls of natural ventilation and HVAC in mixed-mode buildings: A comprehensive review. *Energy Build.* **2022**, *276*, 112509. [CrossRef]
139. Dorokhova, M.; Ballif, C.; Wyrsch, N. Rule-based scheduling of air conditioning using occupancy forecasting. *Energy AI* **2020**, *2*, 100022. [CrossRef]
140. Luo, Y.; He, J.; He, Y. A rule-based city modeling method for supporting district protective planning. *Sustain. Cities Soc.* **2017**, *28*, 277–286. [CrossRef]
141. Li, X.; Yao, R. A machine-learning-based approach to predict residential annual space heating and cooling loads considering occupant behaviour. *Energy* **2020**, *212*, 118676. [CrossRef]
142. Sun, D.; Baek, I.; Hwang, S.; Lee, S.; Lee, S.-K. Sensor-based straight-line control of the end-point of a typical retrofitted hydraulic excavator. *Autom. Constr.* **2020**, *120*, 103385. [CrossRef]
143. Amasyali, K.; El-Gohary, N.M. Real data-driven occupant-behavior optimization for reduced energy consumption and improved comfort. *Appl. Energy* **2021**, *302*, 117276. [CrossRef]