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A systematic analysis of AI-based methods for thermal control and energy-efficiency in Sustainable Buildings

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Abstract

Construction activities account for a substantial proportion of total energy consumption in many nations, attributable to the widespread adoption of Heating, Ventilation, and Air-Conditioning (HVAC) systems driven by the increasing demand for enhanced thermal convenience. Minimizing energy usage while preserving pleasant environments in structures presents conflicting aims and constitutes a classic optimization challenge for intelligent system design. In the past decade, many strategies utilizing Artificial Intelligence (AI) technologies have been implemented to optimize energy consumption in HVAC devices while ensuring appropriate consumer temperature control. The article conducts a thorough systematic analysis of AI-based models employed in building automation by evaluating their results, the applications in the analyzed studies, and their effectiveness in enhancing energy efficiency while preserving temperature comfort limitations. This provides a comprehensive perspective on (1) the intricacies of achieving comfortable temperatures for occupants within structures in an energy-effective manner and (2) the relevant resources to aid scholars and professionals in addressing this challenge. Amongst the AI tools designed for energy efficiency and comfortable management, functionalities include recognizing patterns and acknowledgment, optimizing, and forecasting. This study indicates that implementing AI technologies in building management is a potential research domain. However, it remains a work in progress, as the efficacy of AI-based management is not yet fully adequate. This is primarily because of the necessity for substantial quantities of high-quality, practical information deficient in the construction and energy industry. The analysis indicates that from 2000 to 2024, the implementation of AI approaches and individualized comfort modeling has facilitated energy reductions averaging 22.5% and 45.5%, alongside comfort ness enhancements averaging between 23.5% and 86.5%. This article examines the problems encountered in utilizing AI to enhance energy usage and reassurance while outlining key future possibilities concerning AI-driven building automation for human convenience and efficient energy administration.

Keywords – Artificial Intelligence, Architecture, Sustainable Buildings, Energy Efficiency

1. Introduction

As energy consumption and the exhaustion of renewable resources have become an ongoing global discourse, inquiries on the magnitude of cost escalation and the apex need for energy have surged significantly. Climate change, characterized by an increased incidence and severity of warmer days annually, has rendered a significant segment of the world population reliant on artificial cooling, exacerbating peak demand during the summer months. The proliferation of Heating, Ventilation, and Air-Conditioning (HVAC) systems will influence peak electricity demand, particularly in countries like Japan, the USA, and South Korea. Conversely, nations with minimal HVAC adoption are projected to have a peak electrical consumption rise of approximately 46% by 2040, as the International Energy Agency (IEA) reported. This substantial consumption prompts apprehensions over these devices' control and energy conservation, considering the temperature well-being of the structure's residents—studies in this domain center on reconciling the two primary objectives: temperature control and conserving electricity.

In affluent nations, buildings across the residential, business, and manufacturing industries account for 20% to 40% of the nation's final energy consumption, with HVAC systems consuming half of that energy [1]. This substantial usage has raised concerns regarding the oversight and energy efficiency of structures from financial, behavioral, and scientific-technical perspectives.

Numerous variables contribute to the rise in energy usage, including the population's quality of life and weather conditions. Indeed, since increasing numbers of individuals allocate substantial portions of their lives to artificially regulated surroundings, temperature comfort directly influences productivity and happiness [2]. If workplace surroundings fail to offer sufficient temperature regulation, employee productivity diminishes. The majority of comfort administration systems are generally not energy-effective. A barrier exists to sustaining residents' temperature comfort while minimizing energy consumption [25]. This challenge presents significant opportunities for study in formulating cost-effective control systems to ensure optimal temperature comfort.

Modeling temperature comfort in architectural settings has proven to be a complex endeavor. In recent decades, numerous indices have been developed to assess climates and HVAC control mechanisms [21]. Evaluating temperature comfort encompasses more than merely assessing temperature. Research has suggested a method for determining temperature convenience that incorporates temperature, relative moisture, average surface temperature, airflow, and individual characteristics, including metabolic rate and apparel temperature insulation.[3]. The research introduced the Anticipated Median Vote (AMV) as a metric derived from these factors [5]. An AMV value approaching zero indicates an enhanced temperature comfort experience for consumers.

The article examines and categorizes current studies on automated systems of control for energy savings and temperature comfort in structures while identifying suggestions for additional research. It establishes a system of categorization to clarify Artificial Intelligence (AI) [24] or Machine Learning (ML) [7] based models for subsequent studies and assessments. This paper aims to provide a comprehensive understanding of the difficulties associated with delivering temperature control for building occupants in an energy-efficient manner and to generate bibliographical resources to assist researchers and experts in addressing this issue [8].

2. Related Works

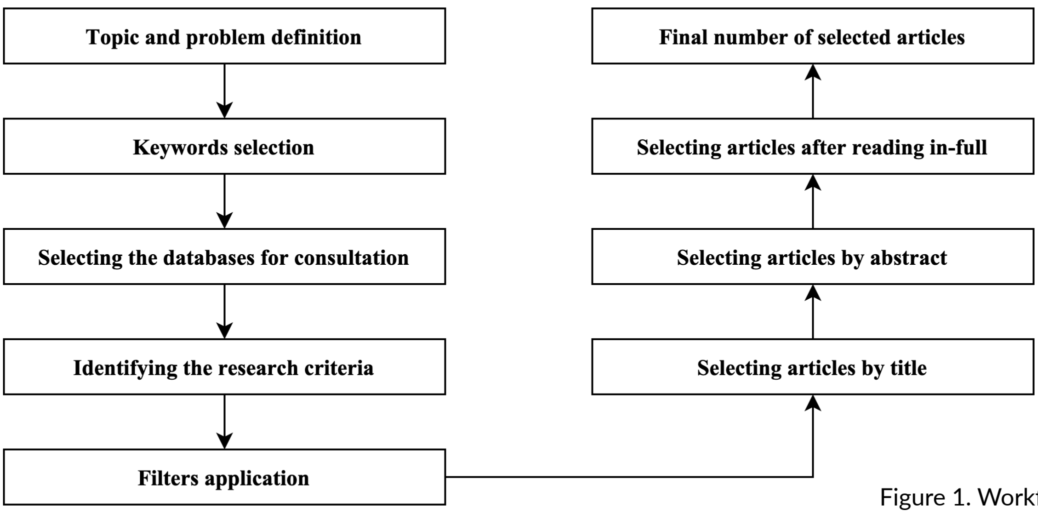

Figure 1. Workflow of the analysis

The literature review approach adhered to the criteria set forth by the rules, intended to direct systematic reviews and meta-analyses [9]. The specified databases are selected as repositories of significant and pertinent scientific papers in the examined field.[6]. The investigation includes exploring the citations of the chosen publications and conducting manual research. Figure 1 illustrates the methodological procedures employed in this review.[12].

For the analysis, the research chose and examined genuine peer-reviewed documents and journal materials from 2000 to 2024, focusing on creating AI-based methods for control mechanisms that minimize energy usage while ensuring heat comfort for building residents [10]. Following the application of filters as per the seeking procedure depicted in Figure 2, an aggregate of 120 articles met the inclusion standards: (1) studies conducted in indoor settings [11]; (2) publications showcasing creative AI-based instruments and their implementation in HVAC and temperature comfort ness management [22]; and (3) analyses detailing system efficiency after the application of the AI control instruments.

3. **Theoretical examination of AI utilized for building management**

The enhancement of energy usage and the preservation of indoor comfort while considering user tastes have prompted scholars to create Building Energies Maintenance Structures, mainly for structures like hotels, offices, and businesses [13]. The items are designed for many applications.[4].These systems monitor and regulate the building's microclimate while minimizing energy consumption and operational expenses. The literature comprises substantial studies on implementing AI methods [14]. The outcomes are more compelling than those of traditional control methods.

The primary limitation of conventional control systems in structures is the necessity for an analytical framework for operational management. Integrating advanced factors that characterize comfort into smart controls makes it possible to manage happiness without regulating heat, moisture, and velocity [15]. The user begins to engage in defining the optimal reassurance inside structures. This section reviews 125 articles in which AI-assisted techniques were utilized and

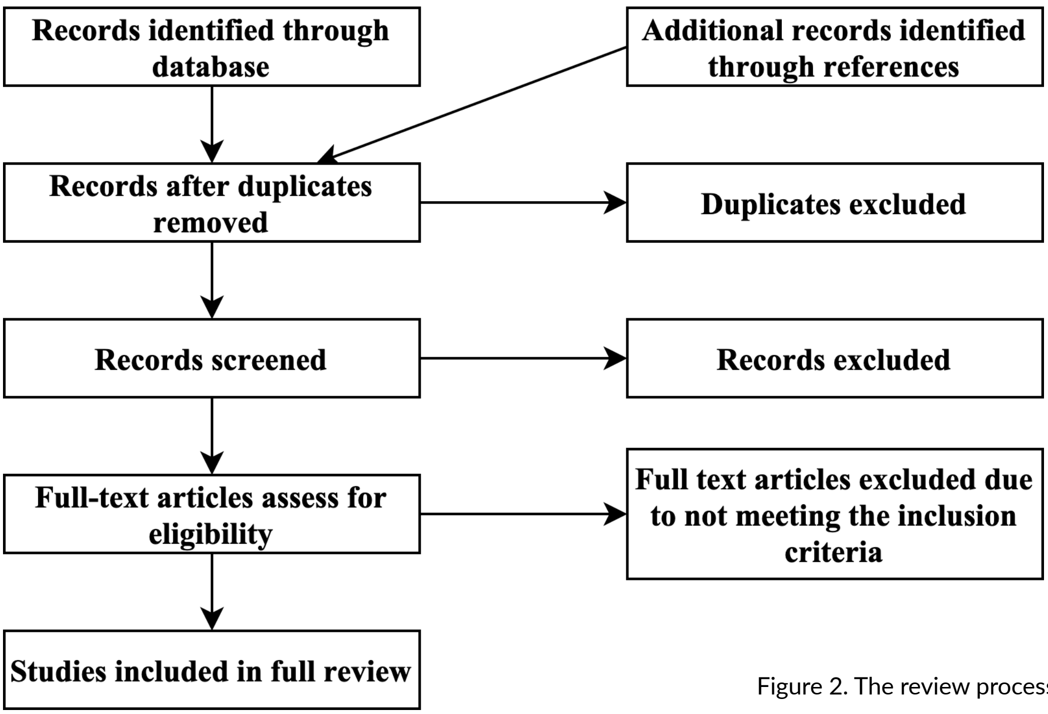

Figure 2. The review process of the research

thoroughly analyzed. The examples are initially analyzed based on the most frequently chosen inputs and their corresponding outputs used by the carried-out designs [16]. The AI methods' controlling effectiveness for energy conservation and temperature is measured. Finally, the approaches for measuring heat comfort are defined and categorized based on the AI tools. Figure 3 illustrates a conventional method for AI-based structural management derived from the analyzed publications.

The essence of AI-based structural management is in Artificial Intelligence (AI) and fuzzy logic, as depicted in Controller 1 [17]. The principal characteristic of this management method is sensor response. The numerous sensors gather diverse factors (e.g., ecological, personal, etc.) stored in a central dataset and utilized by the algorithm to make choices. It is essential to highlight that AI-based equipment is used in the sensor component for enhanced control, as depicted in Controller 2 [18]. Moreover, the most widely used capabilities are the optimum settings and forecasting operations.

4. **Analysis of trends and discourse**

The detailed graphics of the investigations examined in this analysis are presented in Figs. 12-20. Neural networks are the predominant AI method researchers utilize in the study's academic papers (Figure 4). Fuzzy reasoning is extensively employed for energy conservation and enhancement of temperature comfort because it can replicate human actions and facilitate linguistic representations of temperature perception [19]. Hybrid approaches were favored by integrating two distinct methods (e.g., Fuzzy Learning (FL) and Artificial Neural Networking (ANN); ANN and Genetic Approach (GA) or Particle Swarming Optimisation (PSO)). [20]. GA and PSO have been implemented several times to deliver the best options for building and optimizing challenges [26].

Despite the limited number of works utilizing AI and machine learning algorithms, they have been implemented in intricate control structures by integrating several controllers rather than singular controller systems.

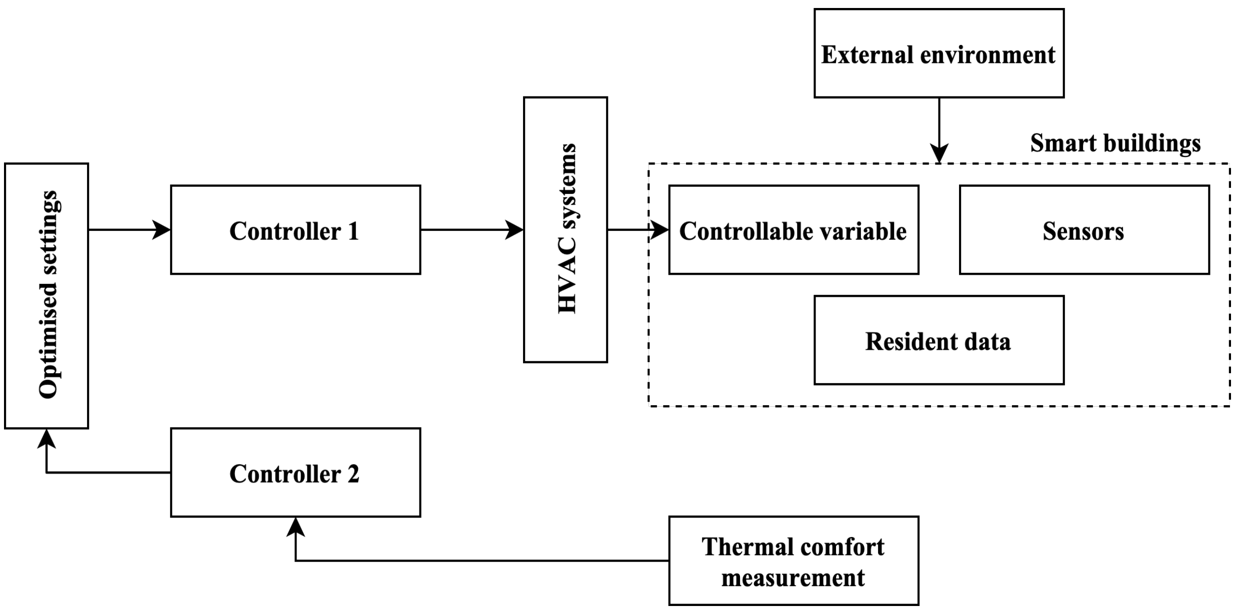

Figure 3. AI-based model for temperature comfort of buildings

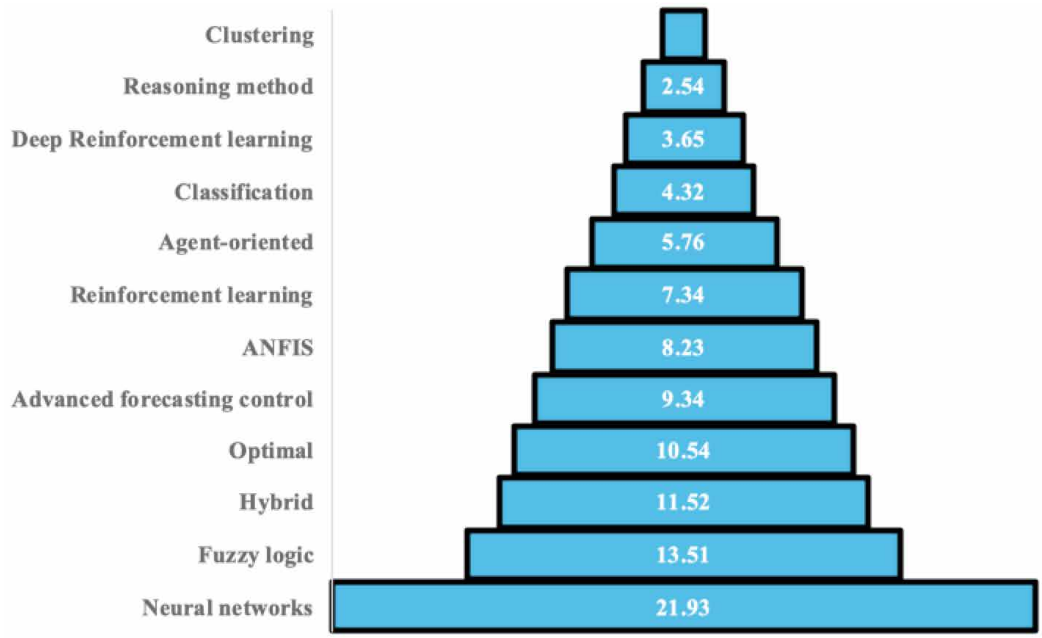

Figure 4. AI-based methods for Sustainable Buildings

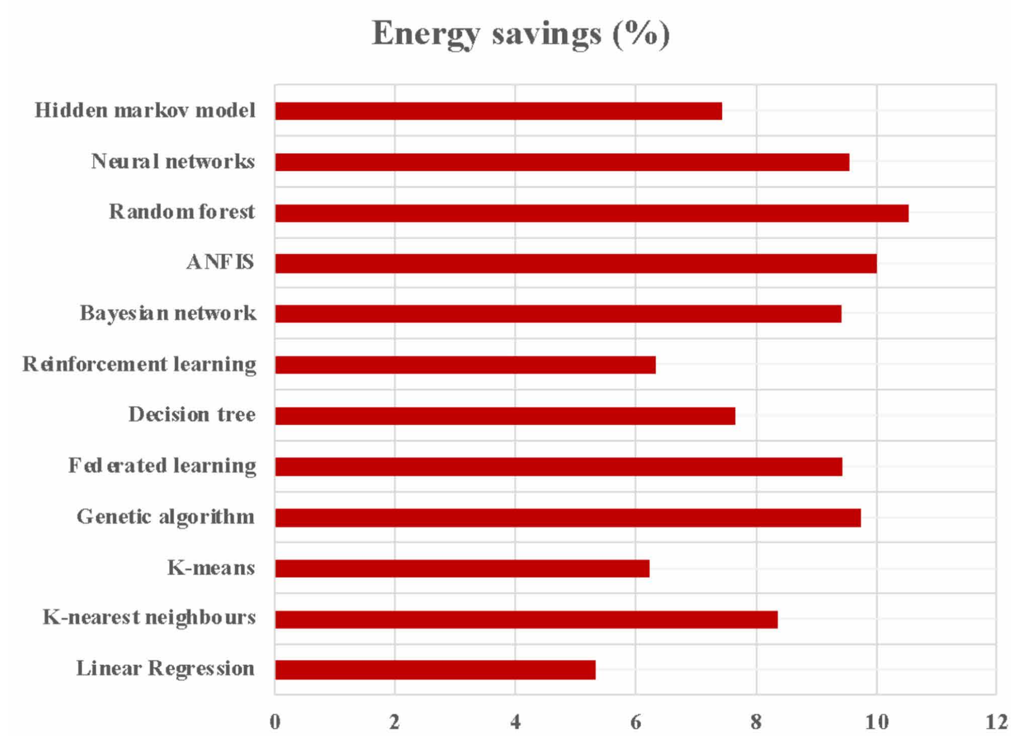

Figure 5. Energy savings analysis of AI models

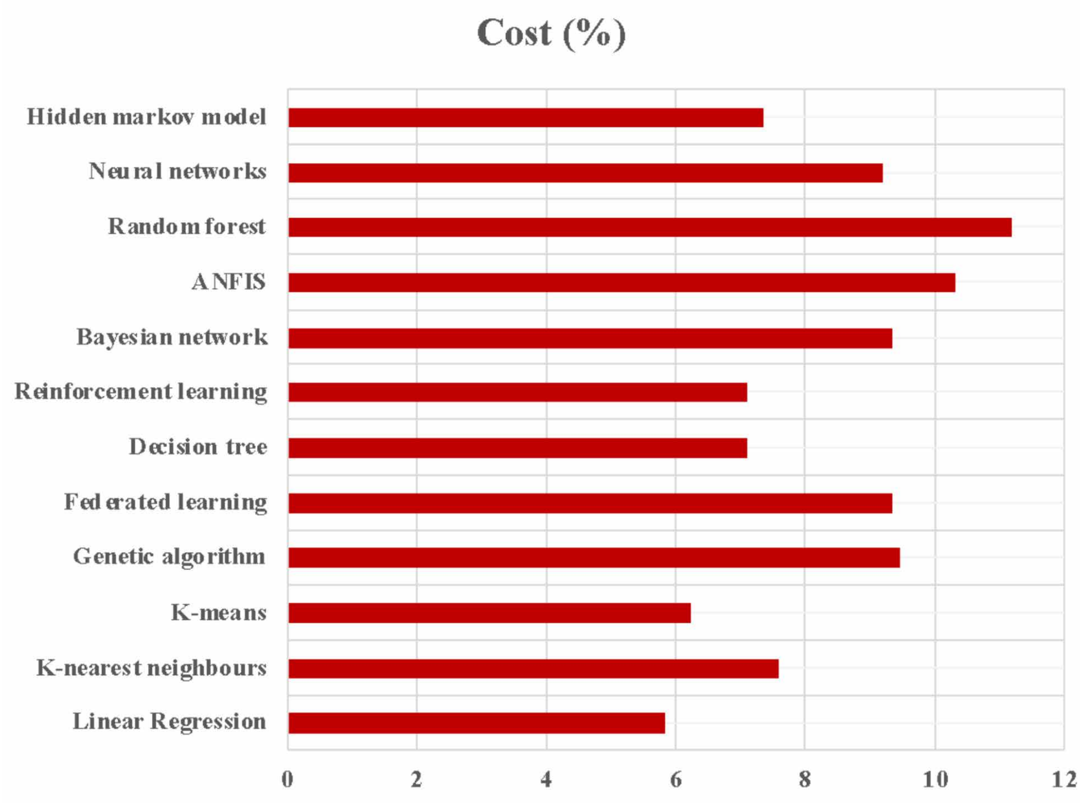

Figure 6. Cost analysis of different AI models

Statistical data indicate that, from 2000 to 2024, the mean reduction in energy usage in buildings achieved by applying AI approaches reached 32.5% (Figure 5). Optimal energy conservation (~88.5%) was attained by implementing a Bayesian network approach to ascertain permissible temperature settings to evaluate employee cognitive abilities across various scenarios. Sophisticated predictive algorithms have demonstrated encouraging outcomes in diminishing energy use, wherein a Training-Based Forecasting Command was utilized to enhance power conservation, achieving approximately a fifty percent decrease in energy usage within an HVAC-Testbed situated in a testing space. A model-oriented forecasting method of Rule-Based Functions (RBF) systems was executed and detected using the technique for management in enormous edifices. The process has demonstrated substantial energy savings, achieving over 50% reduction while covering the temperature feeling scale.

The different cost analyses of AI models are shown in Figure 6. The researchers presented a Smart Customized Office Temperature Management system utilizing the method and k-nearest neighbors (kNN) algorithms to assess room utilization and determine the optimal room temperatures within the office structure. Utilizing the predicted approach, the AI methods established a control plan that achieved approximately 62.5% energy savings while enhancing temperature convenience. Studies have introduced an agent-oriented control utilizing an adaptive Multi-Objective GA to optimize power and pleasure. The designed optimizer has reduced energy usage by up to 65.5%, alongside an enhancement of about 92.5% in comfort levels.

The average enhancement in comfort levels utilizing AI approaches was approximately 50%. In contrast, the peak comfort level was 100% by implementing neural networks, AI, machine learning, and genetic

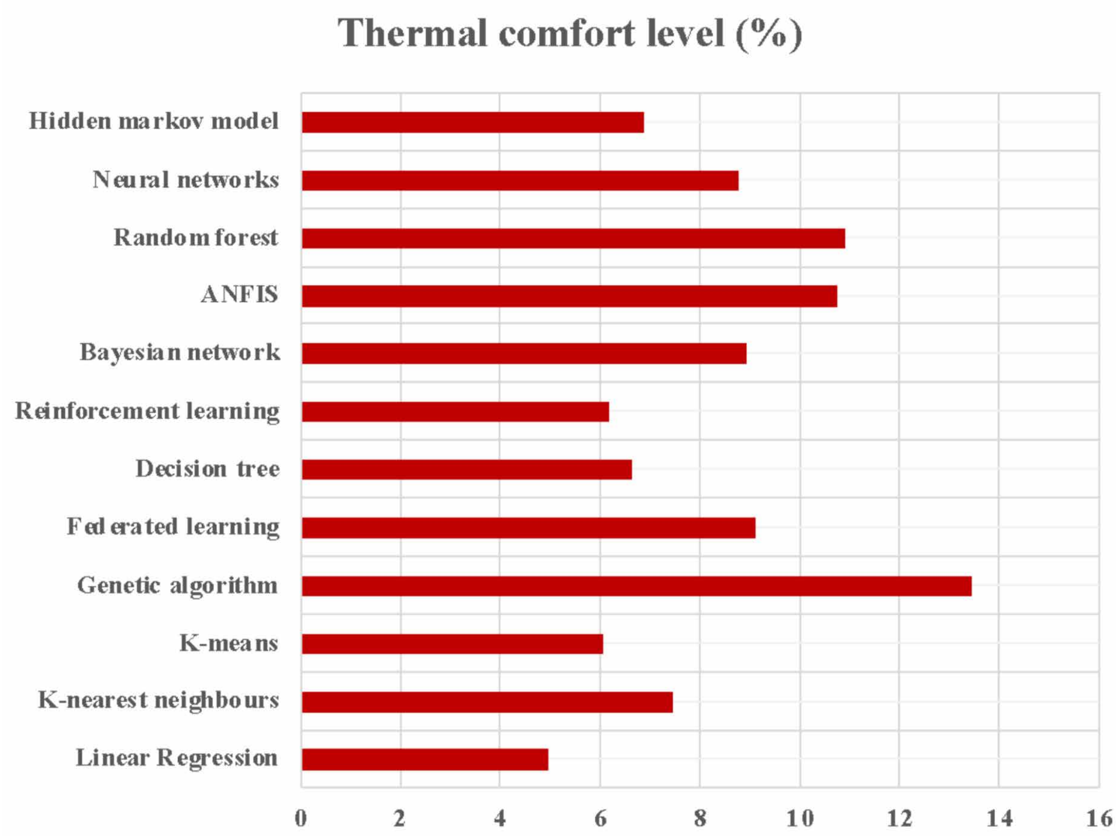

Figure 7. Temperature reassurance level analysis of different AI models

algorithms (Figure 7). Reassurance enhancement was evidenced by the creation of Integrated Reassurance Control Software, which integrates human intelligence with methods for minimizing energy consumption in HVAC systems. The technology achieved optimal reassurance by maintaining a comfortable region while conserving energy. The approach has demonstrated its efficacy by attaining optimal power effectiveness and comfort ness standards for cooling and heating systems, reducing initial and operational expenses by up to 35%, and diminishing comfort ness expenditures by 45%. Only 6.7% of the analyzed works addressed another purpose: temperature convenience and energy savings enhancements. These are cost-effective, factoring in operational expenses, decreased power prices, and comfort-related expenditures. The mean price decrease achieved by AI/ML methodologies reached 34%, with a peak of 58% in energy savings.

Intelligent control does not necessitate a mathematical framework for controller setting and relies exclusively on human assessment of temperature convenience. Moreover, in temperature comfort regulation, which relies on predetermined temperature principles, it is unnecessary to maintain the temperature inside at a constant level; instead, a range of those values suffices to establish a comfortable environment.[23]. Achieving a reduction in energy consumption and associated expenditures while ensuring that temperature indices remain within acceptable limits is a key objective in selecting a suitable control strategy. Fuzzy controls have demonstrated substantial efficacy in temperature building management by accurately replicating user actions and generating linguistic representations of temperature sensations, which calculate AI model computations to enhance the management of systems (Figure 8).

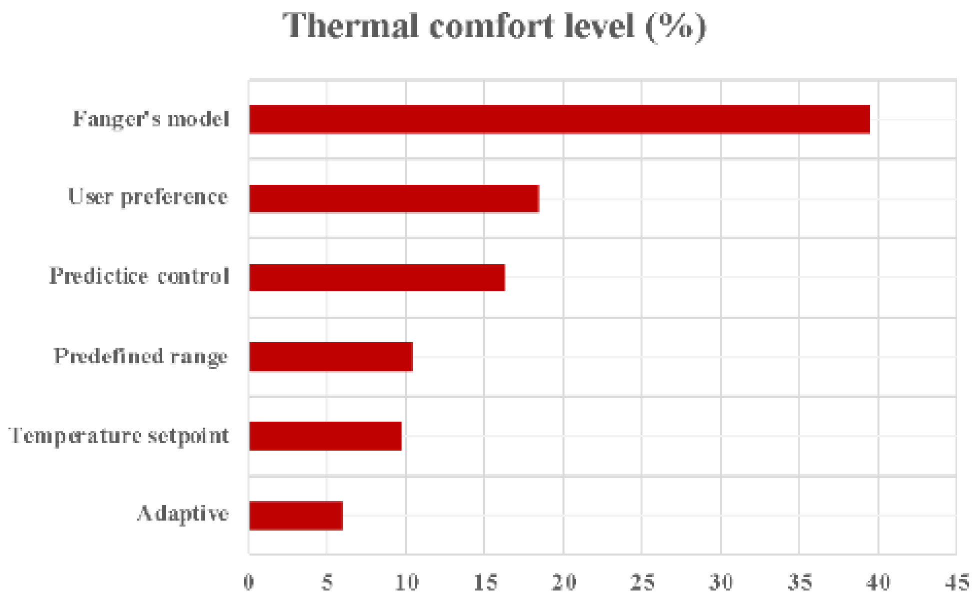

Figure 8. Temperature comfort level analysis

5. Conclusion

This study thoroughly evaluates machine learning methodologies for Building Energy Maintenance Solutions that facilitate energy conservation while considering temperature convenience. To assess the effectiveness of AI-oriented approaches in power conservation and temperature improvement, a review and compilation of the applications of these approaches from published literature have been undertaken based on established eligibility requirements. The study methodology employed in the peer-reviewed articles was predominantly scientific investigation, with information regarding temperature regulation and energy consumption gathered mainly through practical research (such as surveys and interviews with residents and data evaluations) or by utilizing existing publicly available datasets. The study results indicated that several AI-based strategies were employed in different components of building management systems. Artificial Neural Networks (ANNs) are being used to address challenges associated with recognition and verification, utilizing learning methods that enable data retention and classification.

The assessment indicates that integrating machine learning technologies in construction remains an important study topic. This is due to these algorithms' requirement for actual-world information. In contrast, the energy sector, particularly buildings, has thus far lacked sufficient data. Modifications and technological innovations are enhancing the volume and complexity of data (Intelligent Meter delivery, cloud-based space, etc.), facilitating the development of significantly more effective studies based on data. The report continues by outlining some problems confronting the academic group, the requirement for additional data for AI-oriented modeling in structures, and IoT-enabled intelligent and linked structures to enhance effective administration and information gathering for subsequent investigations. Intelligent structures will provide challenges related to security, privacy, information sensibility, and significant data streams. Situational awareness techniques that enhance the ability of buildings to adjust to human activity for dynamic comfort adjustment and improved energy efficiency are of considerable relevance to the neighborhood.

Another study area involves including people in the loop for reassurance models to facilitate flexible heat set-point modifications. The study will require a mixed-methods approach, wherein AI technologies can facilitate enhanced energy usage while maintaining occupant comfort in buildings. Specifically, modifying dynamic set-points in corporate edifices will rely on the correlation between reassurance modeling and people's behavior within the structure. Monitoring people's behavior shows contextual awareness, representing a study avenue to enhance effective building administration while ensuring sufficient comfort for inhabitants. As these simulations exchange data regarding the building and its residents, safety, and confidentiality are critical concerns to examine in innovative structures. Intelligent structures present numerous intriguing research difficulties that remain active areas of investigation, offering ample prospects for using AI methods.

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