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Enhancing Thermal Comfort and Energy Efficiency in Buildings Using Artificial Intelligence: A Systematic Literature Review

Assia BOUTABBA[1], Wassim ALBALKHY[1], Zoubeir LAFHAJ[1], Johan ROUSSEL[1,2], Pascal YIM,[1] and Thomas DANEL[2]
[1] *Centrale Lille, CNRS, UMR 9013-LaMcube, Lille, France*
[2] *Decima, R&D,* SAINT LAURENT BLANGY*, France*
**Corresponding author's e-mail: zoubeir.lafhaj@centralelille.fr*

ABSTRACT
Improving thermal comfort in buildings is essential for enhancing occupant satisfaction and well-being, but it can often lead to higher energy consumption. Adjusting heating, ventilation, and air conditioning (HVAC) systems, optimizing airflow, or maintaining consistent temperatures can increase energy use.

Recent advancements in Artificial Intelligence (AI) offer the ability to manage both thermal comfort and energy efficiency simultaneously without sacrificing one for the other. This study utilizes a Systematic Literature Review (SLR) of 230 studies to explore AI's potential in improving thermal comfort and energy efficiency. The findings highlight six areas where AI outperforms traditional methods: (1) thermal comfort prediction, (2) personalized thermal comfort models, (3) occupancy detection and behavior prediction, (4) building design for comfort and efficiency, (5) fault detection and system diagnostics, and (6) occupant health and integration with other indoor environmental quality (IEQ) factors. This study highlights several examples of AI's potential and suggests future research directions to fully harness these opportunities.

KEYWORDS
Occupant satisfaction; Thermal comfort; Artificial Intelligence (AI); Energy efficiency; Buildings; Systematic literature review

INTRODUCTION
Occupant comfort directly influences well-being and productivity while also being pivotal in determining energy consumption patterns (Albuainain et al., 2021). Buildings aiming for higher comfort levels often require significant energy for heating, ventilation, and air conditioning (HVAC) systems. With growing concerns about sustainability and rising energy costs, optimizing the balance between occupant comfort and energy efficiency is crucial.

Artificial Intelligence (AI) technologies offer promising solutions for achieving this balance. These technologies have shown potential in transforming energy consumption in buildings and optimizing HVAC, lighting, and energy distribution systems. By using real-time sensor data, AI systems learn from patterns, predict future demands, and adjust building operations accordingly, all while maintaining occupant comfort and reducing energy consumption (Panchalingam & Chan, 2021; Sepasgozar et al., 2020).

The literature has witnessed various endeavors to review AI's potential to improve energy performance (Bilesimo & Ghisi, 2024; Fard et al., 2022; Mehmood et al., 2019; Zhang et al., 2022). Nevertheless, there remain significant research gaps such as the lack of comprehensive reviews that consolidate findings on AI applications in building management. Existing research is often fragmented, with studies focusing on specific areas such as individual building systems, while overlooking the broader impact on occupant comfort (Garlik, 2022).

This study aims to address these gaps by conducting a systematic review of the current literature on AI applications for improving occupant comfort in buildings. In doing so, it will offer a more comprehensive understanding of the current state of AI in building management, identify trends, and highlight the areas where further research is needed. Additionally, this research will provide insights into how AI systems impact occupant satisfaction across various building environments. The findings are expected to contribute to the ongoing efforts to create smarter, more efficient, and more comfortable building environments.

RESEARCH METHODOLOGY

This study follows the Systematic Literature Review (SLR) approach to synthesize existing research on AI applications to improve occupants' thermal comfort in buildings. SLR use ensures comprehensive coverage of the literature while minimizing bias in source selection, promoting transparency, and enabling repeatability (AlBalkhy et al., 2024; Albalkhy & Sweis, 2021; Schuldt et al., 2021).

To ensure rigorous and high-quality reporting, this study adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). The PRISMA framework is a widely accepted methodology for conducting systematic reviews, designed to enhance the clarity and completeness of the review process. Following these guidelines, the review process is structured into three main phases: identification, screening, and eligibility (as shown in Figure 1).

Identification: In this phase, relevant studies were identified by conducting on Web of Science (WoS). The search was performed using the following keyword combination:

(“occupant satisfaction” OR “comfort”) AND (buildings OR building OR construction) AND ("Computer vision" OR "Machine learning" OR "Knowledge-based Systems" OR "Natural Language Processing" OR "Artificial Intelligence" OR "K-Means Clustering" OR "Hierarchical Clustering" OR "Fuzzy Clustering" OR "Model-based Clustering" OR "Linear Discriminant Analysis" OR "Monte Carlo" OR "Deep Belief" OR "Deep Boltzmann" OR "Deep Learning" OR "Convolutional Neural Network" OR "Stacked Autoencoders" OR "Recurrent Neural Network" OR "Deep Neural Network" OR "Speech processing" OR "Evolutionary computing" OR "Evolutionary Algorithms" OR "Swarm Intelligence" OR "Discrete Optimization" OR "Convex Optimization" OR "Automated Planning" OR "Automated Scheduling”).

WoS was chosen as it stands out as a primary resource for accessing research materials due to its robust capabilities in facilitating scholarly reviews and detailed citation analysis. Its reliability, advanced search features, extensive coverage, and citation analysis capabilities make it a preferred choice for conducting systematic reviews.

In addition to the keywords, the study identified a set of inclusion and exclusion criteria. All studies that were written in another language than English, not related to buildings, and did not directly focus on the topics of AI and comfort were excluded. The inclusion was specifically for journal articles, conference papers, and reviews. Additionally, due to the increased focus on the topic and the exponential evolution in the field of AI in the last decade, all studies that were more than 10 years old were excluded.

Screening: After the initial identification of studies, a thorough screening process was applied to exclude irrelevant or duplicate records. The titles and abstracts of the identified articles were reviewed to ensure that they met the inclusion criteria.
Eligibility: In the final phase, the full texts of the remaining studies were assessed for eligibility. This process involved evaluating the methodological rigor, the relevance of the findings, and the clarity of reporting in each article. Only studies that provided insights into the use of AI to improve energy consumption and occupant comfort in buildings were included in the final review. As a result, the final number of eligible studies was 230 studies.

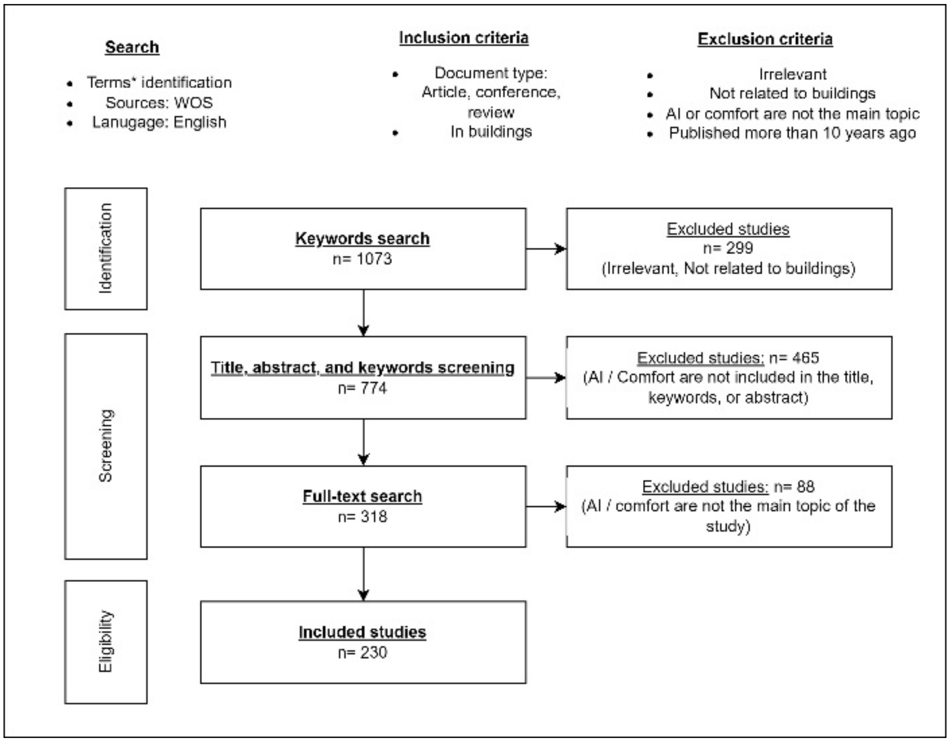

Figure 1. The methodology of the study.

RESULTS

Literature Characterization

The literature on AI applications for enhancing thermal comfort in buildings has grown substantially over the past decade, rising from just 2 studies in 2015 to 55 in 2023. This increase highlights growing interest in AI-driven optimization of building systems. Geographically, most studies were conducted in China, the U.S., and Singapore, with research reflecting local climatic and architectural challenges. In China, studies focused on diverse climates and urban settings, while U.S.-based research addressed varied conditions across regions. Southwest Asian research tackled humid tropical environments, and European studies emphasized adaptability across mixed climates. In the Middle East, cooling system efficiency was a primary focus, whereas Indian studies explored urban energy challenges and retrofitting. Globally, simulation-based studies utilized international datasets to assess scalability and general trends. Regarding building types, AI was most frequently applied in office and commercial buildings (48 studies), followed by residential (27), educational (24), and healthcare facilities (5). Commercial studies often focused on HVAC and lighting for workplace comfort, while residential applications targeted energy efficiency and personalized comfort. Educational buildings used AI to optimize classroom environments, and healthcare studies emphasized indoor air quality and thermal control for safety and comfort.

AI Applications to Improve Comfort in Buildings

The analysis of the 230 studies revealed that AI can be used for various applications to improve occupant comfort. These applications can be classified into the following main groups as follows:

Thermal Comfort Prediction

The application of AI to predict thermal comfort in buildings has shown significant advancements over traditional models like Fanger's Predicted Mean Vote (PMV). Several studies illustrate how machine learning (ML) and deep learning (DL) models offer more accurate and adaptable predictions across diverse building types and climates.

In naturally ventilated residential buildings, ML algorithms such as artificial neural networks (ANNs) were used to predict occupants' thermal comfort votes (TCV) and thermal sensation votes (TSV) based on various environmental and personal parameters (Chai et al., 2020). This model outperformed PMV-based predictions by accounting for local climate variability and personal factors such as clothing insulation and metabolic rates. The results suggested that thermal comfort ranges in these buildings could be much broader than previously assumed by ASHRAE standards.

A Bayesian deep neural network approach further demonstrated enhanced accuracy (78%) in predicting thermal sensation across different building types and climates, using data from the ASHRAE Global Thermal Comfort Database (Cakir & Akbulut, 2022).

In addition, ML was applied to phase change materials (PCMs) in building envelopes to predict thermoregulation performance using a backpropagation neural network. The model predicted thermal comfort duration with minimal deviation, offering practical guidance for the application of PCMs in walls (Xiao et al., 2023).

Studies on naturally ventilated indoor environments also employed deep belief neural networks to enhance thermal comfort prediction accuracy by incorporating outdoor environmental factors and personal parameters such as clothing resistance and activity level (Lei & Shao, 2024). The study's DL approach outperformed traditional models, offering flexibility in rapidly changing outdoor conditions.

For individuals with disabilities, an Internet of Things (IoT)-based deep learning model was developed to predict thermal comfort in real-time. This system integrated wearable sensors and cloud-based data analysis, achieving 94% accuracy, thus addressing a previously overlooked aspect of thermal comfort monitoring (Brik et al., 2021).

Personalized Thermal Comfort Models

Personalized thermal comfort models using AI and ML offer a major improvement over traditional static models such as PMV by using personal data such as physiological signals, environmental factors, and behavioral inputs. These models provide real-time, adaptive predictions tailored to individual needs, enhancing occupant comfort and energy efficiency in buildings.

Youssef et al. (2019) used wearable sensors to monitor physiological parameters, and a Support vector machine (SVM)-based model predicted individual thermal sensation with 86% accuracy.

Similarly, Cosoli et al (2023) used physiological and environmental data, achieving up to 90% accuracy in predicting thermal sensation. Nafiz et al (2024) integrated psychological factors into ML models, showing that Random Forest (RF) performed best in predicting comfort in office environments.

In Singapore, Cosoli et al (2023) utilized ML models to predict thermal comfort in hot, humid conditions, outperforming traditional PMV models (achieving 86% accuracy with RF). Personal comfort models developed by Chaudhuri et al (2017), based on occupants' heating and cooling behaviors, also surpassed conventional models, showing that behavioral data can significantly enhance predictive accuracy.

Katic and Zeiler (2020) combined skin temperature and personal comfort system (PCS) control behavior data to create personalized comfort models, achieving a high median accuracy of 84% with RUSBoosted trees. In turn, Uddin et al (2024) applied ML models to predict thermal and visual comfort in naturally ventilated educational buildings, with RF achieving 96% accuracy.

Occupancy Detection and Behavior Prediction

AI has played a significant role in optimizing energy efficiency and thermal comfort by detecting occupancy, monitoring occupant behavior, and responding in real-time to improve building management systems (BMS). DL networks have been developed to accurately detect the presence and number of occupants in a space using non-intrusive methods like thermal imaging and wearable sensor data (Fan et al., 2023). These models provide real-time feedback to HVAC systems, enabling automated control that reduces energy consumption by conditioning only occupied spaces.

ML models such as SVMs have been used to predict occupant behavior related to cooling and heating preferences (Amasyali & El-Gohary, 2018), enhancing energy efficiency by optimizing HVAC settings based on real-time data. These models consider complex occupant interactions with the building environment, such as window-opening behavior in naturally ventilated settings (Furuhashi et al., 2022) and help reduce unnecessary energy use.

AI has also been used to detect and optimize thermal discomfort cues by analyzing visual cues from video recordings such as facial expressions and physical cues (Bucarelli & El-Gohary, 2023).

Building Design for Comfort and Efficiency

AI has been used to optimize the design and selection of building materials and structures for better thermal regulation and energy efficiency. For instance, Guo et al (Guo et al., 2022) utilized neural networks to predict indoor temperatures based on outdoor conditions, allowing architects to design buildings that naturally maintain comfortable climates. Vettorazzi et al (2023) applied DL models to detect window openings, informing heating system optimization and improving insulation for better energy efficiency. Additionally, Lin et al. (2021) developed machine learning-based predictive models for thermal comfort, which guide the design of energy-efficient building envelopes. Zhang et al. (2023) explored how personal comfort can be predicted using ML to design spaces that improve ventilation and thermal comfort based on occupant behavior. Additionally, various studies showcase how AI optimizes insulation materials, window placement, and facade design for enhanced energy efficiency and comfort (Forouzandeh et al., 2023; Liu et al., 2023; Takhmasib et al., 2023).

Fault Detection and System Diagnostics

AI has significantly advanced Fault Detection and Diagnostics (FDD) in building systems, particularly for HVAC systems. AI-driven methods help identify faults early, ensuring energy efficiency, system reliability, and optimal thermal comfort for occupants. For instance, Haruehansapong et al. (2023) developed a DL model for automated FDD in HVAC systems, achieving over 97% accuracy and enabling real-time fault detection without physical modifications. Albayati et al. (2023) applied semi-supervised learning to rooftop HVAC units, reaching 95.7% accuracy, allowing for proactive maintenance and preventing system failures. Nelson and Culp (2022) explored various ML algorithms such as neural networks and SVMs to minimize energy waste by detecting faults that cause system inefficiencies, ensuring stable thermal comfort. Additionally, Gharsellaoui et al. (2020) used feature extraction techniques combined with ML classifiers to diagnose faults in heating systems, providing high accuracy in identifying and preventing issues.

Occupant Health and Integration with Other Indoor Environmental Quality (IEQ) Factors

AI has been instrumental in improving occupants' health by enhancing thermal comfort in buildings. By utilizing advanced ML and DL techniques, researchers have developed models that monitor and control the indoor environment more efficiently, leading to better health outcomes.

For instance, Chaudhuri et al. (2018) explored the use of AI-driven computer vision to optimize building ventilation based on real-time occupancy and CO^2 levels. This ensures that indoor air quality remains at optimal levels, reducing the risk of issues such as Sick Building Syndrome (SBS), which can be exacerbated by poor ventilation. Similarly, Takhmasib and Lee (2023) employed ML to predict and mitigate SBS using environmental data to develop risk prediction models. This proactive approach helps in adjusting indoor thermal conditions to prevent SBS symptoms

In Wang et al. (2022), DL models were applied to an adaptive facade system, which dynamically adjusts based on occupants' posture and spatial position. The system responds in real-time to thermal and visual discomfort, ensuring that environmental conditions are personalized to the occupant's needs. This approach not only improves thermal comfort but also supports long-term health by minimizing discomfort from glare or suboptimal temperatures.

CONCLUSIONS

This systematic review of 230 studies highlights the potential of AI in enhancing occupant thermal comfort while improving energy efficiency in buildings. The results showed that AI-driven models have consistently outperformed traditional methods offering more accurate and adaptable predictions for thermal comfort by incorporating real-time data and personal factors such as physiological signals and behavioral inputs. In some cases, AI-based HVAC optimization led to energy savings of up to 58.5%, while thermal comfort improvements reached 60% through personalized, dynamic adjustments (Fard et al, 2022; Vettorazzi, 2023).

In addition to energy efficiency, AI's role in fault detection and diagnostics has proven highly effective, with some studies achieving over 97% accuracy in identifying HVAC faults early, reducing maintenance costs, and preventing energy losses (Haruehansapong et al., 2023) . The integration of AI with the IoT further allowed real-time monitoring and system adjustments in smart buildings.

Despite these advancements, several limitations and complexities remain. Computational complexity is a significant challenge, as many AI models require substantial resources, limiting their real-time application in smaller buildings or regions with less infrastructure. Data

availability is another obstacle, as AI models depend heavily on high-quality, real-time data, which may not always be accessible or feasible in all environments. Furthermore, occupant behavior variability complicates AI applications, as human preferences for comfort are subjective and can vary widely, making it difficult to develop universally applicable solutions.
Future research should focus on addressing these challenges by developing more efficient AI algorithms that require fewer computational resources and can adapt to a wider range of building types and occupant preferences. Additionally, expanding AI's role in sustainable building design, including lifecycle cost analysis and environmental impacts, will further support long-term energy and comfort optimization.

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