Towards High-Performance Buildings using IoT and AI technologies: A Comprehensive Review

Lama Alhaj Husein
Department of Industrial Engineering and Engineering Management, College of Engineering
University of Sharjah
Sharjah, UAE.
lhusein@sharjah.ac.ae

Prof. Imad Alsyouf
Sustainable Engineering Asset Management (SEAM) Research Group, Department of Industrial Engineering and Engineering Management, College of Engineering, University of Sharjah
Sharjah, UAE.
ialsyouf@sharjah.ac.ae

Dr. Emad Mushtaha
Department of Architectural Engineering, College of Engineering
University of Sharjah
Sharjah, UAE.
emushtaha@sharjah.ac.ae

Dr. Ahmad Alzghoul
Data Science Department, Princess Sumaya University for Technology
Amman, Jordan
A.Alzghoul@psut.edu.jo

Abstract

Improving buildings' energy efficiency while preserving indoor thermal comfort conditions of hot climate regions has been within the high-interest topics among academics. Researchers have noted that achieving both concepts is essential to improve buildings' sustainability and energy management system. Therefore, it pushes the need to conduct a comprehensive review to maintain a common understanding of the topic and ensure solid foundations for future research. This paper aims to present a review on the state-of-art of Internet of Things (IoT) technology and Artificial Intelligence (AI) techniques to integrate better building energy management systems. This is achieved through a systematic literature review of 30 related papers from the past ten years. The paper argues that very few studies demonstrate the implementation of IoT-AI based methods in the building industry, and its full potential is not realized yet. Therefore, it calls for more attention from academics within the application perspective in the related field.

Keywords
Sustainability, Building Energy Management system (BEMS), Thermal Comfort, Internet of Things (IoT), Artificial Intelligence (AI).

1. Introduction

At the current population growth and urban expansions, the built environment requires more energy and resources to fulfill people's demands. Proportionally, climate change and energy crisis questions have been risen up associated with energy over-consumption and waste over-production, especially in buildings. High-Performance Buildings are buildings that integrate and optimize all major performance building energy attributes, including energy efficiency, durability, life-cycle performance, and occupant comforts (Prowler & Vierra, 2008). In most countries, buildings' operational phase represents a significant energy consumption percentage in the total energy use concerning the growing need to achieve occupants' comfort. Reducing the correlated energy use in buildings while maintaining indoor thermal comfort forms a typical optimization problem and calls for a perceptive system design to be solved.

At the time when building's energy system is undergoing significant change, the digitalization concept arises with the industry 5.0 revolution as the first move toward a data-driven approach. IEA believes that digitalization is modernizing energy efficiency to a more valuable resource than in the past (IEA, 2019). Recent digital innovations offer new ways of looking at the current building energy management issues and finding exceptional ways to address them. Digitalization has a significant potential to enhance energy services and user comfort in buildings by utilizing smart energy management devices and improve the responsiveness to the energy consumed concerning the user behavior and comfort.

Very recently, the technological revolution has deeply modified several facets of daily living. The so-called Internet of Things (IoT) is undoubtedly one technology that has had a significant influence. IoT paradigm has the potential to overcome the barrier between the building's systems by using traditional information and communication technology (ICT) (Rinaldi et al. 2020). While IoT technology promotes device connection and collects intensive data amount related to the desired issue, Artificial Intelligence (AI) techniques analyze the collected data and extract patterns and process behaviors based on those patterns. The integration of IoT devices and AI techniques is a step above the building digitalization concept to smoothly transmit information about the building and the users' demands.

1.1 Research motivation and Objectives

The motivation for this paper comes from the requirements of sustainable development goals (SDGs), especially in buildings. Building energy consumption from HVAC and lighting systems accounts for 40 – 60% of the global energy use in US and European countries just to reach thermal comfort (IEA, 2020). However, the buildings sector has the greatest potential and lowest cost for carbon reductions. Through the years, the awareness about the criteria and the objectives of sustainable buildings have been increased (Mushtaha et al. 2020) with the variety of building's sustainability assessment tools, including BREEAM, LEED, etc. This paper will guide building industry stakeholders' to properly use modern technologies to address specific issues and influence researchers for future advancement. It focuses on looking for a better understanding of the relationship between the occupant's thermal comfort and energy efficiency by implementing new technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) techniques.

To the best of our belief, this paper presents a novel perspective to explore the literature about thermal comfort and energy efficiency concepts, then discusses IoT and AI technologies' role to optimize building's thermal comfort and energy efficiency. Our major objectives through this review are the following:

- Take a look over the potential of IoT and AI methods in developing building performance with respect to human thermal comfort and energy efficiency.
- Providing researchers new insights into the BEMS and integrating a new energy conservation strategy using the 5.0 revolution technologies to assess building energy performance and control for future decision-making.
- Identifying various challenges on the path of how the combination of IoT and AI technologies can be used to achieve energy efficiency and occupant's comfort condition.

The remaining context of this paper is structured as follows: Section 2 covers Thermal comfort and Energy efficiency concepts. It further explains the IoT and AI technologies definition, architecture, and advantages. Section 3 presents the previous research work and applications done using these technologies in buildings. Section 4 discusses the results obtained through this review. Section 5 ends up with potential areas for future research.

2. Literature Review

Occupants are the building's end-users, and a required access to the information about their indoor environment is essential for a better living experience. This paper explores energy efficiency and comfort maximization together by reviewing the state-of-art of IoT and AI technologies. Through this literature review, we will systematically discuss the concepts of thermal comfort and energy efficiency, then investigate the deployment of IoT and AI technologies in building's thermal comfort and energy efficiency improvement. Keywords, such as "Internet of Things", "Artificial Intelligence", "Thermal Comfort", and "Energy Efficiency" were used to collect articles from databases using these search engines: Science Direct, Google Scholar, and Research Gate, covering the period between 2012 and 2022.

2.1 Occupant's Thermal Comfort

In developed countries, many people spent 90% of their life indoors; in working or living mode, and this has a significant effect on human life experience (Robinson & Nelson 1995). Indoor air quality (IAQ) is "the air quality inside an enclosed space where it provides the comfort and health of the occupants" (Jain et al. 2020). The main factor affecting the quality of buildings' indoor environment is thermal comfort. Thermal comfort describes thermal satisfactory degree in an occupied space (Nikol and Roaf 2017). Many studies were conducted about indoor environmental conditions concluded that a higher degree of overall occupants' satisfaction is related to the thermal comfort parameter compared with other indoor environmental conditions. Thermal comfort condition is marked as a feature of sustainable buildings, where human activities consideration is important in buildings' energy management systems to the energy efficiency and environmental effects (Enescu 2017).

To obtain a comfortable indoor temperature, the HVAC system has a significant role to provide a comfortable high-quality environment. The supplied air must be within an acceptable range of temperature, humidity, and speed to achieve thermal comfort. To optimize the issue of HVAC energy consumption, the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) established standards to define building indoor environmental conditions which are acceptable by building's occupants with the so called "comfort zone" (Solano et al. 2021).

2.1.1 Predictive mean vote (PMV) index

As a quantitative parameter, Thermal comfort index measure was established by Fanger in the 1970s under the name of "Fanger's comfort equation" (Fanger, 1970). This equation introduces the thermal comfort index, the so-called Predicted Mean Vote (PMV) index. It demonstrates the occupant's degree of satisfaction about the surrounded indoor conditions (Ekici 2013). PMV index combines quantitative parameters related to the environmental and individual variables. It includes four physical variables; which are air temperature, air velocity, mean radiant temperature, and relative humidity, and two personal variables; clothing insulation and activity level, that can be used to calculate the average thermal sensation within an occupied space. According to Fanger's book, the PMV index can be found by the following equation. Where L indicates the thermal load on the body and M presents the metabolic rate (W/m^2).

$$PMV = (0.303e^{-0.036M} + 0.028)\, L$$

Further, the International Standard Organization (ISO) has established a standard called "ISO 7730", where its main goal is to evaluate thermal comfort parameters. ISO 7730 states that the PMV index should be between the ranges of - 0.5 to + 0.5 to ensure adequate thermal comfort (ISO 2005). Table 1. shows the thermal sensation scale.

Table 1. Thermal sensation scale and comments (Fanger, 2005).

	Scale	Comment
-3	Hot	Intolerable warm
-2	Warm	Too warm
-1	Slightly warm	Tolerably uncomfortable, warm
0	Neutral	Comfortable
+1	Slightly cool	Tolerably uncomfortable, cool
+2	Cool	Too cool
+3	Cold	Intolerable cool

2.2 System's Energy Efficiency

Recently, the building sector has been under rapid development that led to an increase in global energy usage. This development initiates the energy crisis with the limited energy resources, where it should be used simultaneously with energy production elements to balance energy supply and demand. Energy efficiency is all needed for controlling energy use. There are many definitions for the energy efficiency concept directing it as a management and restraining tool for energy consumption. Parameshwaran et al. (2012) consider energy efficiency as "a parameter tool that indicates the lowest level of energy used to perform an associated task for a desired end product". Energy efficiency and Building Energy Management System (BEMS) are closely related concerning energy monitoring in buildings. BEMS is explained as "a combination of strategies to improve buildings' energy performance and efficiency" (Mariano-Hernández et al. 2021). With the current increase in energy crisis issue, the main challenge is not just about generating the required energy, but also maximizing energy efficiency. The techniques or indicators used to monitor building's energy performance are a critical element to measure energy efficiency. The most common tool to examine building's energy performance is called Energy Efficiency Index (EEI).

2.2.1 Energy Efficiency Index (EEI)

Assessing buildings' energy performance have begun in 1970 during the energy crisis (Fossati et al. 2016). To reduce the national energy consumption, a benchmark is required to standardize the best practices. Kyoto protocol is an internationally negotiated framework (established in 1997) for limiting the potential negative effects of global warming and related climate change by controlling greenhouse gas emissions of signatory countries (Von Steinm 2008). In consequence, one of the developed energy efficiency indices is known as the Energy Efficiency Index (EEI). The Energy Efficiency Index (EEI) is the most widely used Key Performance Indicator (KPI) for tracking and comparing the energy performance of buildings (Baker et al. 2015). In general, EEI can be viewed in the following equation:

$$\text{EEI} = \frac{\text{Energy Input}}{\text{Factor related to the energy using component}}$$

EEI is determined by the ratio of the amount of energy consumed to any other factors affecting the energy using component. Building's EEI is proportional to its size measured by gross floor area and the savings objectives of this index are always calculated using the building's lowest value of EEI (Goldstein and Eley 2014). Many studies on EEI have been conducted to share knowledge about energy conservation strategies. A study, which was implemented by Ahmad et al. (2012), showed that energy consumed by buildings can be significantly reduced from 5% to 14% of the electricity consumption by using the EEI index in the energy management process. Related to buildings, the index is presented in kWh/m^2, which measures the energy use within the gross floor area. Bakar et al. (2013) deployed the EEI index as an indicator to compare energy performance between buildings. The results showed a reduction in the EEI index and provide opportunities for continuous energy-saving practices throughout 4 years. One more study describes user attitudes towards air conditioning usage patterns and the related energy consumption on building's EEI done by Aziz et al. (2012). Through the results, it has been shown that energy consumption can be reduced by various methods including improving user attitude and awareness towards system's energy efficiency and technical improvement.

2.3 Internet of Things (IoT)

With the industry 4.0 revolution, new technologies and concepts have been improved. However, the Internet of Things (IoT) is the key enabling technology in this data-driven revolution. IoT refers to a number of different physical devices, varying from a few sensors to a complete sensory module, creating a system of a larger network to optimize some aspects of living people routine and realize time and resource efficiencies (Khajenasiri et al. 2017). Despite the fact that researchers have proposed different definitions to explain the IoT technology, Gubbi et al. (2013) defined IoT as "a network of physical things connected through the Internet and are able to generate, transmit, and record real-time data that support the decision-making process in several applications". Further, Sundmaeker et al. (2010) defined IoT as "a technology that cooperates people and things and be connected at anytime, anyplace, with anyone, ideally using any path/network and any service".

The main attribution of this technology is the automation system in smart buildings. Smart buildings use intelligent automation systems to offer an efficient, comfortable, and secured environment. IoT is the prominent advanced technology that enables advanced solutions to improve security and safety, provide remote control of appliances, monitor occupants' behaviors for the sake of enhancing efficiency and improving users' comfort. Correspondingly, researchers have utilized IoT technology to come across its advantages in the buildings sector. Van den Abeele et al. (2015) address through the use of wireless communication technologies the ability to connect heterogeneous devices to manage and exchange data, reduce energy consumption, and maintain security. Moreover, many studies explore the transfer of traditional buildings into smart and efficient buildings by installing these devices within the building infrastructure (Pan et al. 2015) (Al-Ali et al. 2017). It's obvious that the role of IoT has a significant impact on managing both thermal comfort and energy efficiency in buildings.

Even though IoT can take different forms, its core components stay consistent beyond the various kind of applications it's used for (Marques 2019). IoT architecture first refers to two or more physical devices connection integrated with the Internet that sense and exchange information as the hardware layer of the system. These devices can range between meters, sensors, microcontrollers, or even smart mobiles that are used to measure required conditions. After this system of devices is built, a software layer is needed to monitor and control the transmitted information from devices and perform a platform to utilize the system for which it's implemented. Moreover, IoT architecture involves people, as an essential part of the system, who will use the system and cooperate with it effectively (Khajenasiri et al. 2017). Figure 1 shows the Fundamentals of IoT architecture.

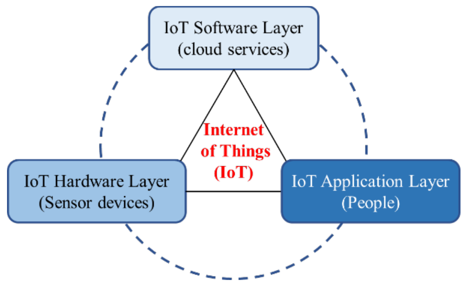

Figure 1. Fundamental IoT architecture.

2.4 Artificial Intelligence (AI) Technology

In the context of the industry 4.0 revolution with the exponential improvement of digital technologies in data transmittance and analytics, Artificial Intelligence (AI) evolution has gained significant attention in many applications. In contrast to conventional computational methods, AI assures a superior attitude towards dealing with complicated and dynamic issues carried with great uncertainty and intensive data (Pan and Zhang 2021). AI has capabilities that should be leveraged to find ways to temper worldwide problems. First, AI allows for the automation of time-consuming and repetitive tasks, letting people focus on other priorities. Further, by utilizing AI technology, data generated from photos, videos, social media posts, and e-mail messages can be analyzed in a manner that previously required manual management and analysis by humans. In addition, AI can integrate human-computer interaction with other resources to mitigate complex problems. Therefore, a thorough investigation is required to determine how AI solutions might be integrated with the human brain to handle complicated problems (Nishant et al. 2020). Most AI methods are placed under the Machine Learning (ML) category (shown in Figure 2).

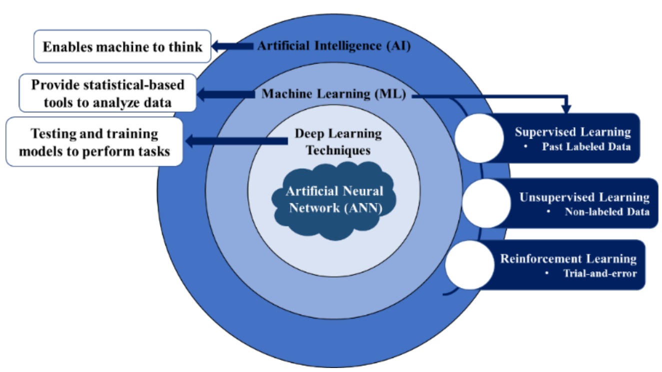

Figure 2. Artificial Intelligence and Machine Learning Techniques.

As shown in Figure 3, IoT and AI technologies have a very strong relationship in finding solutions for real-world problems; IoT enables the use of device connection to collect a large amount of data about a certain process, while AI analyzes collected data and extracts patterns and process behaviors. Based on those patterns, AI subset techniques will learn sufficiently from the robust data and then act to make smart decisions adaptively. These technologies together can create real smart devices with the ability of learning, self-improvement, and decision making.

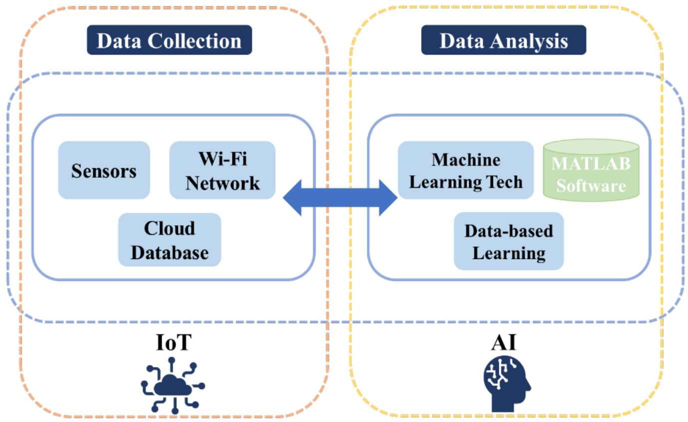

Figure 3. The relationship between IoT and AI Technologies.

ML techniques have been dramatically developed over the past two decades. As a subset of the AI revolution, ML has emerged as the method that applies advanced algorithms to analyze patterns from previously collected data and pursue better future analysis (Makridakis et al. 2018). Rapid growth has been seen in the ability to capture and mine the massive amount of data to improve services, or the so-called "Big Data". With this phenomenon, scientists and engineers have relied on ML techniques to customize their services to fulfill people's needs. This review will focus on describing the following ML Techniques: Artificial Neural Networks (ANN), Support Vector Machine (SVM), and Fuzzy Logic (FL).

2.4.1 Artificial Neural Networks (ANN)

The ANN is the paradigm that mimics human brain biological structure (Orosa et al. 2019). It was developed in 1950 by McCulloch and Pitts (Wang 2019). This algorithm has a set of inputs that produce outputs using hidden layers (shown in Figure 4). Hidden layers set between the input and output layers, where the computational processes took place (Manic et al. 2016). ANN is a black-box model that learns from the relationships between input parameters to generate the output(s). The main advantage of the ANN method is its ability to implicitly recognize the complicated nonlinear relationship between the inputs and outputs. Chen et al. (2014) figured out that ANN is excellent in solving data-intensive and multi-variable issues. ANN has a highly interconnected layering system, where it performs several tasks including pattern classification and clustering, problem optimization, and prediction (Abiodun et al. 2018).

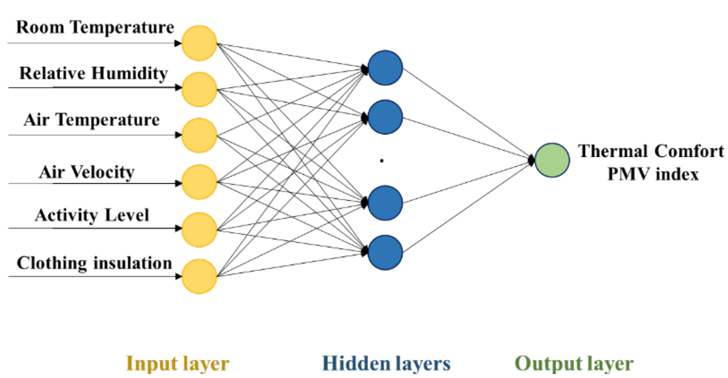

Figure 4. Artificial Neural Network (ANN) layers for thermal comfort index.

2.4.2 Support Vector Machine (SVM)

SVM is a supervised learning tool that utilizes kernel functions to modify data to a high dimensional feature space, then a linear model is employed to overcome any complicated non-linear models (Goodfellow et al. 2016). SVM method was proposed by Cortes and Vapnik in 1995 (Jiménez-Cordero et al. 2021). This technique is usually used to solve classification and regression problems. The main aim of SVM models is to find a function that has the least deviation from the actual obtained targets. Basically, SVM uses small size data to establish a continuous functional relationship between the input and output with the least error possible (Son et al. 2015). The advantage of this algorithm is its high efficiency. It classifies data with more safety margin and less error. In this technique, vectors are chosen as a selection criterion to act as the boundaries to categories the data (Fan et al. 2013). One of its disadvantages is that it works with fewer training data and variables because it is more sensitive to variations in variables.

2.4.3 Fuzzy Logic (FL)

Another algorithmic technique that is applied to mimic human intelligence is Fuzzy Logic (FL). It was first introduced in 1965 by Zadeh to model and describe complex issues that are difficult to solve using classical mathematics (Manic et al. 2016). FL modeling is developed from the classical Boolean set of rules to make decisions, where possible outputs are constrained to be 0 or 1; or true or false (Ngarambe et al. 2020). This algorithm has been studied to be useful in many applications that required control, classification, and prediction of non-linear and time-varying data systems. One of the great benefits of this technique is the model accuracy in control strategies (Hernández et al. 2018). FL control technique doesn't require data to work, which avoids the use of mathematical models. Moreover, it is based on rules formulated by a system's expertise or designer.

The general components FL system is shown in Figure 5. The fuzzification process transformed data to fuzzy terms using the membership function. Fuzzy rules are established to generate the output. These rules are simple IF-THEN rules. The inference engine incorporates both membership functions and control rules. The defuzzification process produces a quantitative outcome based on the membership functions and then turns the output to non-fuzzy values (Bai and Wang 2006).

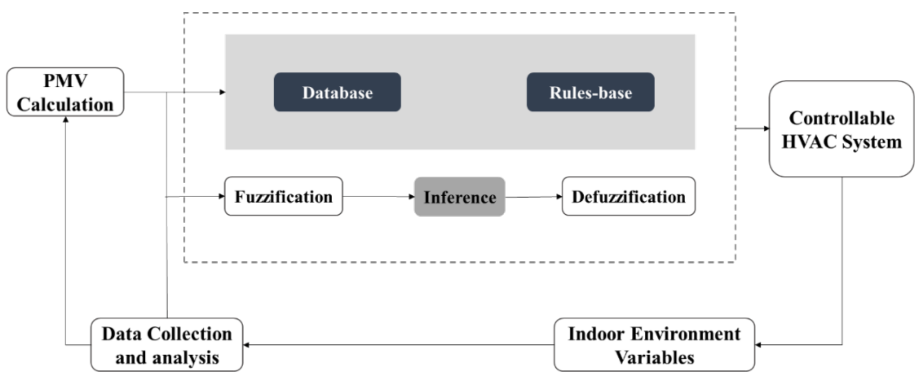

Figure 5. Fuzzy Logic System for HVAC control system.

3. Overview of IoT and AI Applications

In order to conduct the review article, we identified existing thermal comfort and energy efficiency optimization papers and set different attributes to assess IoT and AI applications. We performed a literature review of both technologies' applications to identify the different elements and tools used, this helped us in determining the different applications and use cases. 1) IoT applications, which cover the use of sensors, meters, microcontrollers, Wi-fi transmittance devices, and visualization software. 2) AI techniques, which include Artificial Neural Network (ANN), Support Vector Machine (SVM), and Fuzzy Logic (FL) techniques figure 6.

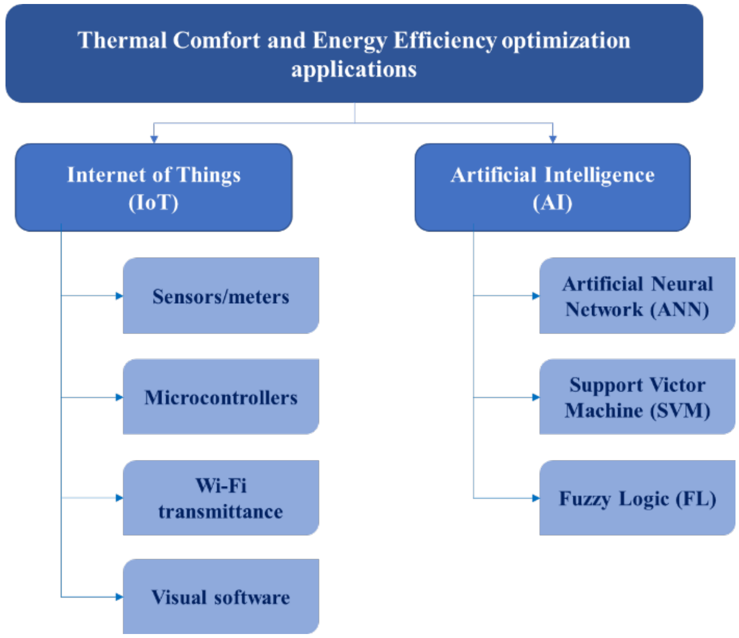

Figure 6. Thermal comfort and Energy efficiency optimization using IoT and AI technologies.

3.1 IoT-related applications

The studied applications of the IoT systems related to this review are associated with building energy management and smart buildings approach. Smart building's automated processes, such as heating, cooling, and lighting system control method is the prime goal of utilizing IoT devices within the power system. This is done to promote building's energy efficiency, minimize wasted power, and make sure that energy is almost spent to serve occupant's needs. Fotopoulou et al. (2017) present an innovative energy-aware information technology (IT) ecosystem that aims to support the design and development of energy management and awareness services that can lead to occupants' behavioral shift towards positive actions to enhance energy efficiency. The study was implemented on a university building using the ENTROPY IT ecosystem and a reduction of energy consumption was achieved. In addition, Ramprasad et al. (2018) conduct a study showing the replacement of existing BEMS into IoT-enabled network capable to integrate control strategies. Their research contributes an efficient and dynamic framework to support and facilitate building management to reduce energy costs.

From this application point, several recent research works have been conducted related to this technology. Casini (2014) investigated the use of IoT devices to provide smart control for HVAC, lighting system, high load devices, and domestic hot water system. His research shows that each system can be activated remotely, and therefore can be applied to improve building's energy performance. The work of Agarwal et al. (2016) addresses the installation of the IoT architecture within a Lab building infrastructure. It explores the strategic selection and placement of sensors with respect to building energy management to provide a good observability and control solution. This study showed a reduction of at least 48% of energy consumption by implementing the proposed strategy. Similarly, Lork et al. (2019) and Wicaksono et al. (2012) approved the capability of these smart devices to be integrated within the home energy management strategy.

Referring to Appendix 1, Marinakis and Doukas (2018) develop an Intelligent energy management for buildings system in laboratory building using IoT devices to monitor and contribute to the system energy consumption. The results show a significant potential for energy savings up to 8-12%. Moreover, Rafsanjani and Ghahramani (2019) demonstrated how IoT could display occupants' energy-use patterns for appliances in an office building. Using a Wi-fi network, these patterns could be interpreted for better understanding and prediction of energy consumption. Another study conducted by Mataloto et al. (2019) applied automated saving actions for lighting and HVAC systems. The IoT system consists of a developed sensory board to measure temperature, humidity, CO2, motion, and light sensors. these devices are integrated with Raspberry PI microcontroller and ESP32 Wi-fi transmittance. The proposed platform results for 20 - 25% of energy savings. Moreover, Moreno et al. (2014) utilizes a home automation system to first analyze the main parameters affecting the energy efficiency and then control it with different control strategies. After applying the proposed method on three different smart buildings with different contexts, 23% of energy saving has been achieved in the real-time scenario.

As mentioned before, the HVAC system represents a significant energy consumption within any power system. Accordingly, Png et al. (2019) and Terroso-Saenz et al. (2019) develop an Intelligent IoT-based energy management approach to monitor and control AC system. IoT-based sensor module, which consists of Arduino unit, analog, and digital sensors, was constructed to Improve energy management in buildings and achieve energy savings. Further, the work of King and Perry (2017) and Tang et al. (2017) address the installation of the IoT architecture within building's lighting system. It explores the control strategy to enhance the system's energy efficiency. Both experiments show adequate energy saving in utilizing the proposed IoT-based control strategy.

For the sake of environmental and energy system monitoring, Tanasiev et al. (2021) investigate the use of IoT devices to monitor and control HVAC system within a research laboratory building. This integration, as expected, shows an efficient approach to minimize energy consumption and maximize comfort. Furthermore, Sung and Hsiao (2020) develop a thermal comfort control system on an IoT-based smart house, where it focuses on controlling devices load in the indoor environments efficiently to let people perceive good thermal conditions. PMV thermal index is determined to assess human thermal satisfaction.

3.2 AI-related applications

As a consequence of the outstanding growth of AI applications in achieving both thermal comfort and energy efficiency through buildings' power systems, there are many proposed applications with great potential to redesign our future energy system. Von Grabe (2016) built an ANN model for predicting indoor thermal comfort. An example showed that the accuracy of this model performs excellently the traditional PMV model under different conditions. Moreover, Chaudhuri et al. (2018) utilize the SVM technique to evaluate indoor thermal comfort. Using human skin temperature and its gradient feature as input variables of the model. Results showed that 87% is the prediction accuracy of the developed thermal state model.

Related to Appendix 2, Ahn and Cho (2017) utilize ANN to assess building energy performance. The study works to develop an intelligent energy model to balance both thermal comfort and energy efficiency on different kinds of buildings. It shows that in offices 2.5% of thermal comfort enhancement can be achieved and 10.2% in residential buildings. In consequence, it shows 17.4% and 25.7% of energy-saving respectively. To the same extent, Zhong and Choi (2017) provide an intelligent HVAC control technique using ANN. The experiment shows 45% of energy-saving with achieving 44.3% of better thermal comfort conditions. Furthermore, Liu et al. (2007) utilize the ANN model to first evaluate the indoor thermal comfort and then control the HVAC system to achieve this comfort. Using experimental data and occupant surveys to detect average radiation temperature, air temperature, wind speed, and relative humidity, the study concludes with the important role of ANN to connect individual thermal comfort with the control on the air conditioner.

Mares (2012) proposes an intelligent system to minimize energy use by optimizing several systems' operations (especially HVAC system) without affecting customers' comfort. It was concluded that ANN-FL proposed approach demonstrates 25.2% of energy-saving prediction can be achieved by maintaining customer comfort. Moreover, Moon and Ahn (2020) and Sung and Ahn (2020) provide control strategies using the ANN-FL technique. This control approach has improved the thermal attributes with a significant energy saving percentage.

Building's energy use is gaining an important on-going time. According to IEA (2018) report, it was proven that Building's HVAC system creates a sizable portion of the overall building energy consumption (around 70%) (IEA 2018). Towards that end, several studies were conducted about the use of the FL technique to control this system to be as efficient as possible while achieving user comfort. Homod et al. (2020) investigate the use of FL in HVAC control as means of enhancing building's thermal comfort and energy efficiency. The results show that the FL HVAC controller managed to increase the energy saving percentage by 37% as well as provide the required thermal comfort condition. In the same direction, Teixeira et al. (2019) present the use of FL controller to manage the issue of thermal comfort and energy consumption balance in an office. It demonstrates that using this technique could save up to 27% of the energy consumption with an adequate thermal comfort condition.

3.3 IoT-AI related applications

Various traditional BEMS relied on pre-fixed environment parameters that have very little interaction with occupants. That causes challenges to solve the related problem of achieving occupant's thermal comfort and energy efficiency (Yao and Zheng 2010). Further, very few studies follow the trend of integrating the use of IoT devices and AI techniques to optimize this problem. Relating to Appendix 3, Jiang et al. (2017) develop an SVM thermal sensation model based on real-time IoT-based data collection to evaluate occupants' thermal comfort. Based on this model, it was shown that energy consumed by the HVAC system could be reduced by 10% whilst fulfilling occupants' thermal comfort requirements. Moreover, Zhao et al. (2020) provide an intelligent IoT and AI-based control system. Using IoT sensors and FL control techniques, results show superior performance to bring thermal comfort and energy saving.

Regarding serving occupants, few recent studies have deployed the combination of IoT and AI-based approaches for assessing occupants' thermal comfort with the related energy use. Meana-Llorián et al. (2017) develop a strategy to efficiently monitor indoor temperature based on external temperature and humidity using IoT devices to improve thermal comfort. By utilizing the FL control technique, around 40% of energy saving is achieved. Another study that's done by Laftchiev and Nikovski (2016) proposed a new IoT-based system to create a personalized system of thermal comfort by using low-cost sensory devices and users' inputs, where the inputs of this system will be used for machine learning data analysis (SVM). The experimental findings demonstrate that this approach has a high enough degree of resolution to increase thermal comfort prediction accuracy by roughly 50%.

4. Results and Discussion

High-performance and smart buildings are the outcome-based integration of advanced technologies. Although it has been proposed for several years, there is no limit for upgrading energy efficiency and thermal comfort need. More generations and ideas will be integrated within smart buildings as the technology improves. Based on the findings of the literature research, smart building future trends will focus on the use of IoT and AI technology. IoT control application for energy efficiency accounts for 54% of the collected papers. AI applications were about 33% (for thermal comfort and energy efficiency, 23% and 10% respectively as shown in Figure 7). However, only 13% of the collected papers integrate the use of IoT-AI based strategies to achieve both occupants' comfort and energy efficiency.

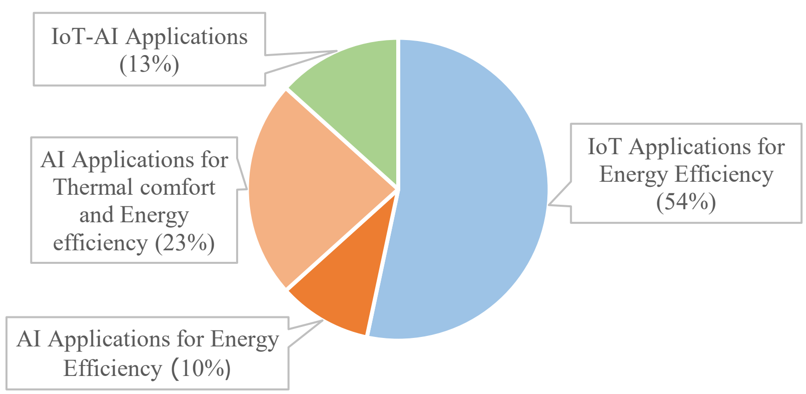

Figure 7. Publications covered of IoT and AI applications in Thermal Comfort and Energy Efficiency.

Although many studies prove the potential and benefits brought by IoT to the system's efficient energy use in the buildings field, a few demanding challenges and issues need to be resolved for the excellent implementation of IoT in this industry. For example, anticipating the energy use data of the occupants can be easily reached by monthly/yearly invoices in most systems. However, it's important to let users know more about their energy use patterns and behaviors to check if their usage is efficient or not. This can be also proceeded by using IoT monitoring devices. Another thing that is really important to be served by IoT technology is controlling the HVAC system. If the current indoor environmental information becomes available, it could automatically control the operation schedules of this system to serve the occupant's thermal comfort. Research is still going to explore the interrelationship between occupant thermal comfort levels, energy savings, and environmental parameters. From the collected research works, it's shown that IoT-based sensory module architecture consists of an interface, sensor devices, and Wi-Fi or Bluetooth transmittance device.

Based on the reviewed literature, different AI-based methodologies have been employed to detect the balance between energy usage and occupant's comfort levels satisfaction. However, most AI-based studies rely on simulation data to verify its application. While using PC simulation software to study such complex parameters saves time (e.g., DesignBuilder and TRNSYS software), this procedure may be subjected to many errors. Investigations that examine the potential of AI-based control systems relying on real-time data collection are necessary for accurate study.

This overview clarified that several AI-based techniques have been utilized within building systems that affect energy efficiency and indoor thermal comfort. Artificial Neural Networks (ANN) has been commonly utilized to solve recognition and optimization problems. In building energy management system (BEMS), ANNs were used to estimate the thermal comfort (PMV) index. In addition, the other frequent technique that was used to model human decision-making is the Fuzzy Logic (FL). Several works utilize FL to control building systems that affect the thermal comfort and energy efficiency as a fuzzy variable. Models were designed to monitor indoor conditions to achieve the best level of thermal comfort and optimal energy savings. Almost all FL-based studies were also used depending on the PMV index.

Many previous works have conducted a study about evaluating the thermal comfort or the energy efficiency independently within building energy management systems. However, very few studies have introduced the conflict of the relationship between maximizing occupant's thermal comfort while minimizing the energy use to achieve it. This requires investigating the application of IoT devices and AI techniques to assess and control both thermal comfort and energy efficiency in buildings. Moreover, IoT technology enables more effective energy management by offering a streamline data collection of associated occupant-focused data. Control modeling is the best solution to enhance building energy performance while continually maintaining occupant thermal comfort, thanks to the precision provided by AI algorithms paired with the simplicity of data collecting from IoT-based sensors. In addition, adjustments and technical advancements that are offered by IoT-AI methods are contributing to raise the quantity of data enabling to build an effective data-driven experiments and results. Figure 8 shows the architecture of the proposed IoT-AI system (Figure 8).

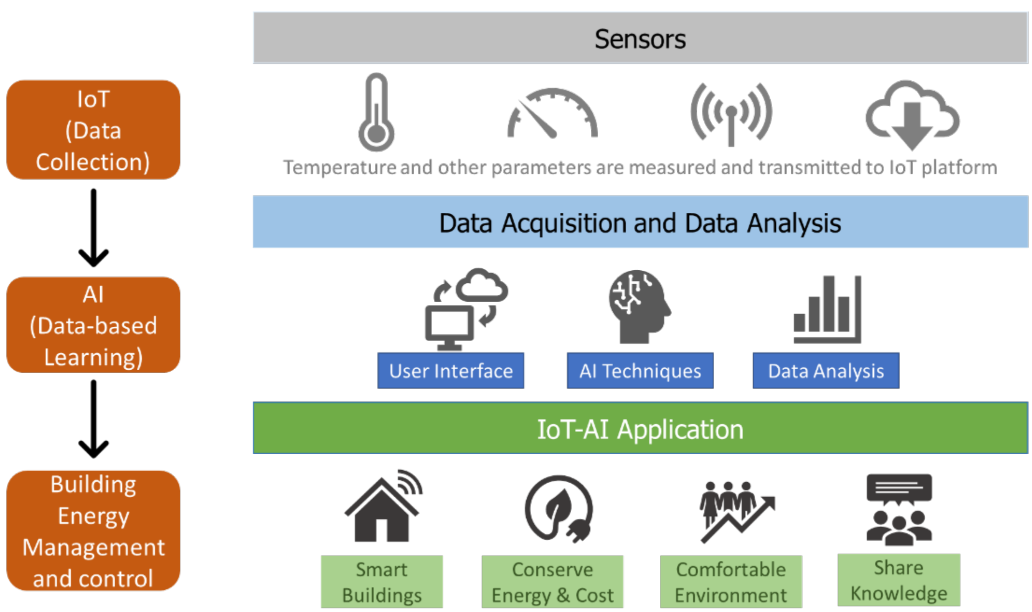

Figure 8. The general architecture of IoT-AI framework for optimizing building's Thermal Comfort and Energy Efficiency.

Although the concept is still promising, there is number of crucial challenges that may postpone the implementation of this approach in buildings systems:

- ***Empirical results:*** while there is excellent theoretical evidence discussing the potential use of IoT-AI methods serving both occupant's thermal comfort and building energy savings, a need for empirical research to verify the advantages of integrated technologies on traditional buildings rather than smart buildings.
- ***Financial cost:*** the cost of the application of IoT-AI based control model in buildings' systems is another major debate that has been disregarded in the literature. This problem is exacerbated for personal comfort models, which likely need a customized data collection during model creation and training. Consequently, comparing the installation costs of IoT system and deploying cost of AI techniques in developing the energy conservation model in the long-term of energy savings, providing occupant thermal comfort, and reducing CO_2 emissions will highly encourage engineers to implement the system as its high return of investment.
- ***Dynamic control:*** another line of research also includes the human being in dynamic comfort modeling and temperature adjustments. This kind of research needs an intelligent and integrated method. IoT and AI techniques will extend the opportunities to increase energy saving percentage while keeping the building thermally comfortable. For example, automated temperature modification in office buildings is connected to the occupant's activity. Tracking human activities introduce the concept of context-awareness and increasing staffs' productivity level is another research field that will add more value to efficient energy management with thermal comfort satisfaction. Surely, High-performance buildings bring many interesting active research lines with many opportunities with the application of IoT and AI technologies.

5. Conclusion

The growth of the newly developed technologies and their integration in several industrial fields have opened up new opportunities to optimize buildings' energy performance, which can be extended to communities and cities. This paper reviewed the current state-of-art of IoT and AI technologies and their research contributions towards high-performance buildings. A paper survey was conducted in web databases using relevant research keywords. To determine the research trends in this topic, an up-to-date literature scan (from the last 10 years) was performed.

Research direction of intelligent thermal comfort and energy efficiency control systems for buildings will gradually increase with the development of IoT and AI technologies. Moreover, the fundamental aim of the reviewed research gap is to predict or control building energy consumption efficient methods while maintaining occupants' thermal comfort. In future research, the proposed framework of utilizing IoT-AI based methods for detecting the indoor environmental variables will introduce us to more parameters depending on the various types of AI algorithms. Further, extended investigations of real-time investigations are required to discover the potential of the system.

Since the aim of IoT-AI technology is to emerge occupants entirely with the indoor environment, the application of this methodology will become popular to participate in the improvement of smart buildings or renovating traditional buildings initiatives. With the state-of-the-art review of the proposed technologies and their applications, this work expects to provide an overall motivation to the academic researchers and engineers who would like to seek for the potential of IoT and AI in the building industry for more fascinating innovations.

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Biographies

Eng. Lama Alhaj Husein graduated from University of Sharjah with a bachelor's degree in architectural engineering in 2020 and currently a master's Student in Engineering Management Program at University of Sharjah. She is working as a Research assistant within the Research Institute of Sciences and Engineering (RISE). Her research interest includes Sustainability, Building energy management system, and green building design.

Prof. Imad Alsyouf is a professor of Industrial Engineering, currently employed by University of Sharjah, UAE, and previously worked at Linnaeus University in Sweden. He has produced more than 25 journal and conference publications. He has about 24 years of industrial and academic experience in various positions in Jordan, Sweden, and UAE. His research interests include productivity improvement, performance measurement, life cycle cost analysis, reliability and maintenance engineering, and optimization of decisions at various phases of system life cycle. He has developed and taught more than 25 courses covering a wide range of Industrial Engineering and Management fields.

Dr. Emad Mushtaha works at the Department of Architectural Engineering, University of Sharjah (UOS), UAE as an Associate Professor of Architecture and Urban Design. He Holds Ph.D. in Urban and Environmental Engineering from Hokkaido University, Japan. His main interest is to conduct research that deals with environmental urban/architectural design and planning management.

Dr. Ahmad Alzghoul My educational background is in the field of computer science and engineering. My experience is in the fields of data analysis, machine learning, statistics, and their diverse applications in industry, business, and medicine sectors. I received my Ph.D. in 2013 at Luleå University of Technology, Department of Engineering Sciences and Mathematics, Sweden. I received a M.Sc. degree in Computer Engineering (Intelligent

Systems) in 2007 from Halmstad University, Sweden, and another M.Sc. degree in Software Engineering from Linnaeus University, Sweden in 2009. My scientific work is associated to the topics of managing and analyzing data from various applications.

Appendix A - Table of covered papers in the literature.

IoT applications				
Reference	**Application**	**Scope**	**Platform**	**Benefits**
King and Perry (2017)	Control Home energy system (Lighting system).	Enhance energy efficiency of a house.	IoT sensors.	5-15 % energy savings is achieved from upgrading the system.
Tang et al. (2017)	Control Home energy system (Lighting system).	Allowing the control of individual or multiple luminaires.	IoT sensors (Arduino, light sensors, and mobile app).	Achieve power saving of up to 50%.
Fotopoulou et al. (2017)	Develop an innovative energy-aware information technology system.	Support the design novel energy management services that have a positive impact on energy efficiency.	IoT sensors and ENTROPY IT ecosystem program.	Reduction of energy consumption was achieved.
Agarwal et al. (2016)	Observe optimal number and location of sensors to maximize energy efficiency.	Developing Sensor driven building energy management	IoT sensors (Smart energy meter, PIR, Temp sensors).	Accomplish more than 48% energy saving.
Casini (2014)	Intelligent system controls (HVAC, lighting, high-energy devices, and domestic hot water).	Improving buildings energy performance.	IoT sensors.	IoT can remote each sub-system and be used in energy management.
Lork et al. (2019)	Energy Optimization in households.	Establish a framework for energy management in buildings.	IoT sensors.	achieve 5-12% of energy savings.
Wicaksono et al. (2012)	Energy management in households.	Suggest an intelligent framework for energy management in buildings.	IoT sensors.	Helps to enhance system's energy efficiency in households.
Png et al. (2019)	Minimize energy use for HVAC system in commercial buildings.	control strategies used for savings energy.	IoT sensors (Arduino, DHT-11, and MH-Z19 sensors).	Achieve energy saving up to 20%.
Marinakis and Doukas (2018)	Intelligent energy management for buildings system in laboratory building.	Monitor and contribute on system's energy consumption.	IoT sensors (Energy meters, environmental sensors).	Significant potential for energy savings from 8-12%.
Terroso-Saenz et al. (2019)	Intelligent IoT-based energy management in buildings.	Monitor energy consumption of HVAC system through IoT platform.	IoT sensors and IoT data platform.	Improve the energy management system in buildings.
Rafsanjani and Ghahramani (2020)	Intelligent energy management in office building.	Deliver comprehensive energy-use behaviors of occupants.	IoT energy meters.	better understanding and prediction of occupant-energy behavior.
Tanasiev et al. (2021)	Minimize energy consumption and maximize comfort in a research laboratory.	Control and monitor HVAC system in a real building.	IoT sensors (a custom-built Printed Circuit Board, CO_2, and temperature sensors).	IoT integration-based approach is efficient in monitoring building's HVAC system.
Mataloto et al. (2019)	Provide data management to increase overall efficiency.	Control HVAC and lighting systems in kindergarten school.	IoT devices (Raspberry PI, DHT-11, photoresistor, PIR, and MQ-135 sensors, ESP32 Wi-fi device)	The proposed platform results a 20 - 25% of energy saving.
Sung and Hsiao (2020)	Efficiently control devices load to provide good thermal comfort.	Control and monitor load devices in the research laboratory.	IoT sensors (Arduino, DHT-11, Rev. C4, and CO_2 sensor).	IoT sensing devices achieve a good controlling system.
Moreno et al. (2014)	Control energy consumption in smart buildings using different management strategies.	Analyze and control the main buildings parameters that affect the building energy management	Home automation module and IoT platform.	Energy saving up to 23%.
Ramprasad et al. (2018)	Replace the existing BEMS to IoT-enabled network.	Develop new architecture to support BEMS data streaming.	IoT platform.	Provide significant opportunity for energy saving.

AI applications				
Reference	**Application**	**Scope**	**Platform**	**Benefits**
Von Grabe (2016)	Intelligent individual thermal comfort prediction.	Predicting thermal comfort index.	ANN technique.	Outperformed the traditional PMV index under different conditions.
Chaudhuri et al. (2018)	Evaluate indoor occupant's thermal state.	Thermal comfort evaluation.	SVM technique.	Establishing intelligent model for thermal comfort stating.
Ahn and Cho (2017)	Intelligent cooling and heating energy model.	Achieve both thermal comfort and energy savings for different kind of buildings.	ANN technique.	Enhance thermal comfort in offices by 2.5% and 10.2% for residential building, while 17.4% and 25.7% of energy savings respectively.
Zhong and Choi (2017)	Intelligent HVAC control method.	Enhance building energy performance, while keeping an acceptable thermal comfort range.	ANN technique.	Achieve energy saving up to 45% and 44.3% better thermal comfort.
Mares (2012)	optimizing power consumption of HVAC system without effecting occupants' comfort.	Design an energy-efficient management model.	ANN and FL techniques.	Prediction of 25.2% of energy saving that is achieved while maintaining customer´s comfort.
Moon and Ahn (2020)	Intelligent network control model.	Improves thermal attributes and energy savings.	ANN and FL techniques.	Improve 4.3% thermal comfort and up to 44.1% of energy saving.
Sung and Ahn (2020)	Predictive control strategies with abnormal conditions.	Enhance buildings energy performance.	ANN and FL techniques.	Improve energy efficiency from 13.1 to 44.4% and reduce thermal dissatisfaction by 20 to 33.6%.
Teixeira et al. (2019)	Manage the conflict of thermal comfort and energy consumption of an office.	Maintaining thermal comfort with energy efficiency.	FL technique.	achieve thermal comfort conditions with 27% of energy saving.
Homod et al. (2020)	HVAC System control in buildings.	Achieve both thermal comfort and system's energy efficiency.	FL technique.	Provide required thermal comfort with 37% of energy saving.
Liu et al. (2007)	Building's thermal comfort evaluation.	Control HVAC system.	Surveys, ANN technique.	Connecting thermal comfort assessment with the AC control.
IoT-AI applications				
Reference	**Application**	**Scope**	**Platform**	**Benefits**
Meana-Llorián et al. (2017)	Improve indoor environment with efficient temperature control.	Maintain thermal comfort and control the indoor temperature.	IoT sensors + AI techniques (FL).	Thermal comfort is achieved with 40% of energy saving.
Zhao et al. (2020)	Intelligent IoT and AI-based control system.	Energy consumption prediction with thermal comfort control factors.	IoT sensors + AI techniques (FL).	Superior performance of energy saving and thermal comfort control.
Jiang et al. (2017)	develop a novel BEMS in an office building.	Reduce the energy consumed by the HVAC system while maintaining occupant' thermal comfort.	IoT sensors (EL-GFX-2, Tinytag ULTRA2, HT30, and Testo 405 V1) + AI techniques (SVM).	Reduction of 10% the energy consumption while meeting occupants' thermal comfort requirements (-0.5 to +0.5).
Laftchiev and Nikovski (2016)	Thermal comfort prediction in an office room.	IoT-based system that uses ML techniques to model the thermal comfort parameter.	IoT sensors (Arduino Mega 2560, DHT-11, Rev.C, PIR sensors) + Machine Learning techniques (SVM).	Improves the thermal prediction by about 50%.