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Occupants' thermal comfort perception on different HVAC system setpoints

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Abstract: ***Research on smart energy saving is becoming famous globally in different sectors. The current research is anticipated to lower energy demand and consumption in the building industry, which has already reached 49% globally and is projected to rise by 2% yearly, incurring significant monthly costs. One prevalent problem nowadays is striking a balance between energy efficiency and thermal comfort. Most research has concentrated on energy efficiency without taking into account occupant thermal comfort, which might pose health risks to both young and old occupants. To build a HVAC controller that ensures the healthy comfort of the occupant, the study conducted an empirical study using 84 participants in the northern part of Nigeria under different settings of HVAC system setpoints. The participants' responses were recorded in terms of their thermal sensation, preference and comfort vote, perceived and preferred control, and overall thermal satisfaction. This information will be used to compute and identify the ideal thermal satisfaction temperature and subsequently assist in modeling rules for smart control, providing insight for future research on modeling HVAC system controllers.***

Keywords: HVAC system setpoints, energy efficiency, thermal comfort, thermal satisfaction

1. Introduction

Today, research on HVAC energy optimization solutions is one of the top famous and trending research in industries and academia. Recent studies show industries, businesses, healthcare, cities, and education sectors are switching from traditional energy control systems to modern approaches to energy saving. The practice can help to reduce the demand for energy in the building sector which has already reached 49% across the globe with an annual increase of 2% costing a lot of dollars monthly (Zaki, Damiati, Rijal, Hagishima, & Abd Razak, 2017). Thermal satisfaction is one of the key factors to consider for healthy living at home and greater productivity at work. However, recent solutions focused on providing a general solution to optimize energy consumption in the HVAC system without considering thermal satisfaction, which varies from region to region, and also ages to age.

Many studies claim the life expectancy of people is over 80 years, and it is estimated to be 25% in 2020 (Codjoe & Nabie, 2014). The expanding population of elderly people presents a significant problem when it comes to providing suitable solutions and circumstances for residential interior spaces that are thermally satisfied. The home atmosphere is crucial in providing a comfortable and healthy place. Despite standards that define general thermal sensation for occupants (P. Wei et al., 2018), our study conducts an experimental analysis of thermal satisfaction across elderly and younger ages with aimed to identify their thermal satisfaction patterns comfort perception, and preference of occupants in an indoor environment.

The most widely used thermal satisfaction balance models, which HVAC engineers use to design thermal satisfaction indoor climates, will be used to compare the results to the available thermal comfort index, such as PMV, SET*, and PET, and use it to establish a range of specific parameters for ideal thermal satisfaction conditions in occupant indoor environments. The indices "Physiological Equivalent Temperature" (PET), "predicted mean vote" (PMV), and "predicted percentage dissatisfaction" (PPD), which were primarily intended to assist air conditioning engineers in creating a thermally comfortable interior atmosphere, can be calculated to do this. With the continuous increase of the population of elderly people around the globe who hope to survive with their thermal comfort lifestyle. This study would help with criterion in developing customized modern HVAC control solutions among different ages.

Furthermore, the research delves into the latest advancements in state-of-the-art, encompassing binary and fuzzy control algorithms, to present a refined idea or methodology that preserves the lifespan of electrical appliances and allows handling of a greater range of values when determining whether to turn them on or off. These parameters include things like interior and exterior temperatures, humidity, and the requirement for system use by occupants, among other things. This gives the ability to manage vague and confusing information so that decisions may be made as though a human is making them.

2. Literature Review

Forecasts of extrinsic factors, like wind, PV, weather, and cost, are usually sourced from outside sources at least one day in advance. The market may provide you with the price for the following day. Regarding the area of smart homes and buildings (F. Salamone, L. Belussi, L. Danza, M. Ghellere, & I. Meroni, 2016; Uribe, Martin, Garcia-Alegre, Santos, & Guinea, 2015) and smart home web applications that utilize cloud computing in (Shakeri et al., 2017; Singh et al., 2017; F. Wei et al., 2018) in conjunction with sensors and actuators, smart systems leverage Zigbee connections to operate smart-home appliances and estimate the local weather. Since all statistical data is stored in the cloud, customers may access it using a laptop or smartphone, and measurement instruments are guaranteed to be compatible. The results of the trial show that the system is a workable one, although it uses a binary method to manage and control the appliances, which frequently causes the power to be regulated up or down. This approach tends to shorten appliance lifespans and increase energy usage in comparison to comparable algorithms like fuzzy, which don't have known or predetermined conditions and need instantaneous responses.

The adoption of has been the subject of numerous research a single, standardised technique for smart metering of household appliances, which can manage and reduce energy use by collecting data on energy use. The majority of these methods employ a mobile device's web browser to install an interface that facilitates Zigbee connection and controls energy distribution. The algorithms for energy optimisation, as outlined in (AlFaris, Juaidi, & Manzano-Agugliaro, 2017) utilised sensors to track and display the power consumption rates of houses to occupants using mobile devices and WEB storage applications, with sensors strategically placed throughout the residences. The majority of the controls employed in the suggested research rely on a collection of value feeds procured from the electrical grid by an aggregator.

Many studies report that Lighting is considered to be a leading fraction of global power consumption. For example, in office and home buildings, the power consumed by lighting systems can reach up to 40% of the total power consumption (SAULLES, 2017). For this reason, many studies (AlFaris et al., 2017; Homod, 2018; Salamone, Belussi, et al., 2017; Serra, Pubill, Antonopoulos, & Verikoukis, 2014) attempt to provide solutions to optimize the power consumption concerning lighting system in building with aimed of providing desired illumination comfort condition within with least power consumption. A study by (Yazici, Basurra, & Gaber, 2018) uses a sensor-based luminaire algorithm approach to implement a smart control lighting system and adapt a Q-learning-based approach control system that employs and personalizes users' perceptions to the environment as the feedback signal for optimal control of lighting intensity. Studies in (Akkaya, Guvenc, Aygun, Pala, & Kadri, 2015; Mansur, Carreira, & Arsenio, 2014), provide experimental review analysis of the lighting management approaches by employing the occupancy detection approach and daylight prediction signal processing approach.

According to a study (Naik, Pandit, Naik, & Shah, 2021), air quality, illumination, temperature, and humidity characteristics in contaminated areas may all be monitored remotely. To provide statistical data to LabVIEW, an Android application was utilised. Utilising this data would help limit the potential production of fuels and implement pollution control. In addition, a laboratory experiment was conducted in which the sensor and router nodes were positioned 4.75 metres apart in the same room, and the washbasin node was placed 3.75 metres away from the router node in a different room, creating an environment more like that of a building. Despite the lack of a system comparison, the experimental analysis yields encouraging findings for the proposed system.

According to (Kumar & Lee, 2014), one of the factors that lead to higher energy usage is the inability to remotely control lighting systems in the home when needed. To combat this, an Android application with voice functionality that allows for remote control of such appliances is suggested. The study makes use of an Adrino microcontroller, which houses an application program for energy control based on connected sensors that communicate data from the relevant appliance to a gateway, which then sends data to a mobile application for the tenant to enable remote ON and OFF switching.

2.1 Related Work

The HVAC system is responsible for 40% of power consumption from the majority of buildings in the United States (Part, 2016). This has drawn the attention of researchers from industries to suggest the means to optimize the power consumption of HVAC systems. The summary of the related study is presented in Table 1.

Table 1: Summary of the related study

Class	The focus of the study	Technical approach employed	Reviewed studies
Lighting system	Employ sensor-based to manage the LED output of lighting to perfect the desired condition of illumination to achieve the least power consumption	Customize mobile application, control optimization algorithm, PID control	(Kumar, 2014), (Shah & Mishra, 2016)
HVAC system	Optimize power consumption of the HVAC system in the building sector compromising the occupant privacy and comfort	Kalman filtering, business intelligence control models, gray-box models big data analytic, statistical data, cloud computing service	(Piyare & Lee, 2013), (Kumar, 2014), (Khan, Silva, & Han, 2016), (Sehar, Pipattanasomporn, & Rahman, 2017), (Uribe et al., 2015), (Kumar & Lee, 2014), (Salamone, Belussi, et al., 2017; Salamone, Danza, Meroni, & Pollastro, 2017), (Baig et al., 2013), (Jahn et al., 2010)
Occupancy detection	Observation and detection of intruding occupants in a room to manage and control the power utilization process	Gaussian processes, Background subtraction, sound-based sensor techniques	(Mansur et al., 2014), (Akkaya et al., 2015), (Akkaya et al., 2015)
Fuzzy decision control system	A fuzzy decision system provides the ability to deal with vague and ambiguous data for making certain decisions similar to human decisions.	It uses controllers called 'adaptive controllers' or 'expert systems based in a rule (e.g., if X and Y then Z) to mimic the human fuzzy thinking	(Haider, See, & Elmenreich, 2016), (Tsui & Chan, 2012)
IoT platform	Focuses on the software or hardware infrastructure and offers APIs to enable the execution of the package for power optimisation in the construction industry in real time.	MATLAB with Zigbee transceiver, LABVIEW simulation, ThingSpeak, cloud server	Think Speak (Batista et al., 2018) and Midgar (González García, 2017)

Research (Piyare & Lee, 2013) suggested a level architecture to monitor and regulate the energy consumption of smart home appliances via an embedded micro-web server that uses an IP connection and an intelligent mobile application to schedule which appliances to use depending on preferences and provide remote access control. Appliances were turned on and off using fuzzy logic depending on values entered, which lessens the problem of repeated ON and OFF cycles, which has been shown to shorten the appliances' lifespan. One drawback of this approach is that it breaches tenant privacy because data is shared on the cloud and allows for individual occupant identification.

According to research, an Internet of Things (IoT) based smart home management system that uses ZigBee technology to control energy usage in electric household equipment and reduce the impact of guesswork (Tsai, Lai, & Vasilakos, 2014). The system uses fuzzy modeling to make decisions about turning on or off the HVAC system through the use of WiFi and sensor nodes. Similar to this, the suggested system incorporates a natural light illumination stage in a space to manage light intelligently. When comparing a functioning station's simulation results to a relay and a pure wireless sensor network, considerable energy savings are achieved.

The research conducted by (Walker, Khan, Katic, Maassen, & Zeiler, 2020), uses smart sockets via the Internet of Things devices to get energy usage data from smart metres that regulate and oversee smart home equipment. The suggested solution includes the ability to switch off appliances that are only sometimes used and put routinely used equipment into hibernation mode, which saves energy when turning them on. To help the tenant choose how much energy to buy each month, the system may also calculate the amount of energy consumed each day before making an energy purchase. The design for a smart energy control system was presented (Sehar et al., 2017) to maintain efficient energy consumption in smart home appliances via the use of IoT technologies and attain occupant thermal comfort. The proposed system is divided into two levels. The first layer controls temperature and humidity. For instance, during the winter, the outside air can fall humidity to less than 30%, which can cause uncomfortable symptoms like excessive thirst and skin dryness. Concurrently, a software package in the form of fuzzy evaluated objectives, constrained by a set of rules as an argument and kept in a database, is present in the lower layer to affect the control over how energy should be used in Internet of Things household appliances.

(Uribe et al., 2015) developed three perception layer architectures to regulate energy use, monitor interior temperature and humidity, and maintain occupant comfort. The proposed layers are equipped with three sensors: a fuzzy set of rules at the middle that controls the system's decision-making process based on the temperature and humidity data collected; a nZEB prototype at the bottom that provides data among the nodes that would share updates to the cloud server; and sensors at the top that are responsible for gathering and collecting data about the living conditions of the occupants.

The study by (Batista et al., 2018) emphasizes how the world's increasing reliance on fossil fuels is a direct impact of climate change. The study uses remote monitoring, which places the sensor, router, and sink nodes 4.75 meters apart in one room and 3.75 metres apart from the router node in another, creating a real environment to monitor the temperature, humidity, and air quality parameters in a polluted area. To provide statistical data to LabVIEW, an Android application was utilised. Harnessing this data would help limit the potential production of fuels and implement pollution control. A related study by (Haider et al., 2016) collects temperature and humidity data within the occupancy and shares it with the energy service provider to regulate energy use in smart homes. The suggested Internet of Things platform simulates energy regulation by combining humidity data that is published online with environmental data that has been gathered.

Kumar and Lee (2014), asserted that one of the factors leading to increased energy consumption is the inability to remotely control household electrical appliances when necessary. They also suggested an Android application with a voice feature to facilitate this function. The study makes use of an Adrino microcontroller, which houses an application programme for energy control based on connected sensors that communicate data from the relevant appliance to a gateway, which then sends data to a mobile application for the tenant to enable remote ON and OFF switching.

According to studies (Salamone, Belussi, et al., 2017; Francesco Salamone, Lorenzo Belussi, Ludovico Danza, Matteo Ghellere, & Italo Meroni, 2016), energy usage rose when additional appliances were added. The suggested method makes use of a microcontroller that has temperature and humidity sensors connected to it to sense ambient data and transmit it straight to the DHT22 sensor, which controls the HVAC system. With the use of the acquired energy information, it can also compile energy data from many home servers and plan and regulate household energy use to save energy expenses. Four office buildings were used for the experiment, and the results indicate that each tenant responds differently to thermal comfort and produces amazing energy savings.

In connection with the energy cost of the appliances, (Hampton, Baig, & Zeadally, 2018) suggested a platform to regulate energy consumption that employs a runtime graphical user interface to indicate the duration information and preserve the records for the customer. The system also employs load scheduling, which enables the usage of a single backpack. The EMC findings were demonstrated using LABVIEW, and simulation was performed using MATLAB, the PIC18f4520 microprocessor family, and the MC12311 Zigbee transceiver via Freescale.

According to (Jahn et al., 2010), the retrofitting approach in both rural and urban buildings frequently results in air-tightness, which has the negative effect of creating unfavourable circumstances for the inhabitants that may endanger or even cause illness. The author suggested a set of tools for effective temperature and air quality management indoors to address this issue. Ad hoc sensors are used to monitor total volatile organic compounds (TVOC), CO2, and thermal comfort. A control logic is then used to determine the optimal rules for activating the HVAC system depending on the data gathered... When compared to commercial solutions presented in (Kotopouleas & Nikolopoulou, 2016) an experimental evaluation which was conducted on a laboratory building, demonstrates significant energy savings. It also demonstrates energy savings in the case of the traditional approach (Fan et al., 2017).

3. Material and Methods

Research shows variations in thermal satisfaction among individuals living in rural and urban environments. Similarly, there exist variations of thermal preferences among children, younger adults, and elderly people living in the same environment. Individuals' preferences for different temperatures must be balanced to prevent the residents from becoming fragile and vulnerable, which might have serious ramifications (among many others for the functioning of the home). Besides the issue of thermal preference, many of today's HVAC system uses thermostats that employ binary control algorithm practice in controlling the appliances which is presently not able to reduce the life span appliance and more importantly not suitable for smart control due to its frequent adjustment of temperature. Fortunately, research on thermal comfort makes it feasible to formulate a general criterion that can be applied to make users' satisfaction possible based on ISO7730 (Meinke, Hawighorst, Wagner, Trojan, & Schweiker, 2016) which described acceptable operative temperature for occupant thermal comfort in the building environment. However, due to thermal satisfaction variation among people of different ages in different demographic locations, we attempt to investigate the thermal preference of people living in the northern part of Nigeria. The idea relies upon the range of values (0:5 < PMV < 0:5) as shown in Figure below. The objective is to ascertain their anticipated mean vote (PMV) and predicted proportion of dissatisfaction (PPD). (Meinke, Hawighorst, Wagner, Trojan, & Schweiker, 2017) which can later be simulated in our proposed study to decide which actions to take to balance the comfort level derived from the simulated temperature. Our study considered the thermal variation based on the possibility of adjustment of temperature because attaining optimal thermal satisfaction for entire occupants in all climate situations is very difficult (Meinke et al., 2016)for more clarification.

Sample of our questionnaire responses (see Table 2). Thermal perception, predisposition and comfort vote, Perceived and desirable control, and overall thermal satisfaction based on ASHRAE thermal sensation scale (see Figure 1). The following personal participant's data: age, gender, clothing, weight, and height, were collected. We advertise our questionnaire to 124 participants and categorize them into three groups based on age children (8-14 years), younger adults (15-40 years), and adults/elderly (over 41 years). Each participant was expected to give feedback based on the questionnaire presented to them. However, an assistant was given to those with difficulties comprehending the questions, especially by children to reflect their real thermal perception. Week prior invitations were sent to house participants to accept the invitation before the scheduled interview and we can conclude with 84 respondents. Children were 12, younger adults were 44, and adults/elderly were 28 both male and female in equal ratio.

5	Extremely hot
4	Very hot
3	Hot
2	Warm
1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold
-4	Very cold
-5	Extreme cold

Figure 3.1: ASHRAE thermal sensation scale

Table 3.2. Sample of our proposed questionnaire

	Thermal sensation, preference, and comfort vote		
*	'How do you feel now?' The feedback was based on a seven-point classification ASHRAE thermal sensation scale from 'cold' (–3) to 'hot' (+3) (see Fig.)		
*	'How would you prefer to feel now?' Feedback based on the five-point classification thermal preference scale from 'much cooler' (–2) to 'much warmer' (+2) (see Fig.)		
*	'How do you evaluate the temperature now?' Feedback was based on the four-point thermal satisfaction scale from 'not comfortable' (–2) to 'comfortable' (+2) (see Fig.)		
	Perceived and preferred control		
*	'To what extent you can control thermal conditions right now?' Feedback was based on a seven-point classification scale from 'none' (1) to 'very much' (7). Individual thermal preference evaluation		
*	'To what extent do you want to control thermal conditions right now?' feedbacks were based on a seven-point classification scale from 'none' (1) to 'very much' (7). individual thermal preference evaluation		
	Overall thermal satisfaction		
*	Do you feel comfortable at the moment?	Yes	No

4. Experimental Analysis

We computed PET, PMV, and PPD using the RayMan programme, which is accessible at https://www.urbanclimate.net/rayman/, based on participant comments to determine the thermal satisfaction index. As a sample shown in Table 3, each PET index, the distribution of the participant's thermal sensation frequency (ASV), and their thermal satisfaction were created at specific times (morning, afternoon, and evening).

Table 4.3: Example of Distribution PET Index, ASV of a particular participant.

Time	Humidity	Indoor temperature (⁰C)	Outdoor temperature (⁰C)	PET	Thermal perception	Grade of physiological stress
9:20 am-12:00 pm	55	29	22	4	Very cold	Strong cold stress
12:30 pm-1:00 pm	44	32	29	0.6	Neutral	Comfortable
6:00 pm-8:00 pm	45	32	29	-2.6	Cold	Moderate cold stress
1200:am-5:30 am	60	25	19	-3	Cold	Moderate cold stress

Table 3 displays the ranges of the physiological equivalent temperature (PET) and predicted mean vote (PMV) for various grades of thermal sensitivity based on individual physiological stress. The participant profiles were also categorised according to their state of membership. Kebbi State accounted for 39%, Sokoto for 30%, and Kano State for 31%.

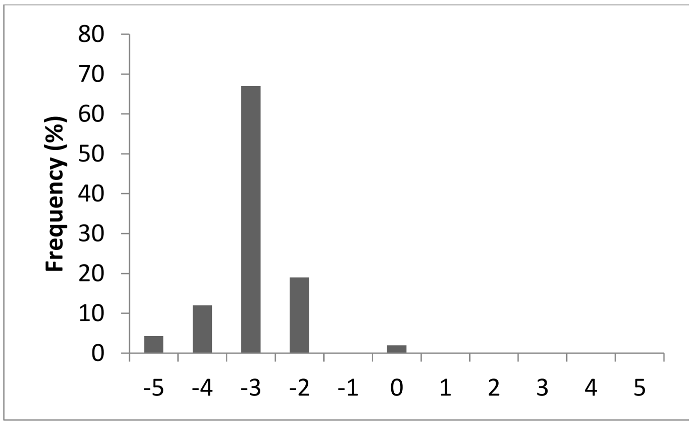

Figure 4.2: ASV Frequency of participant

Many of the participants showed tolerant to high temperatures as 93% of participants revealed to be feeling cold after 10 minutes of operation of air-conditioning at 22⁰C and 20 minutes at 27- 30⁰C this is because people living in this region are exposed and accustomed to high temperatures (thermal sensation) and 7% report thermal sensation to be "little cold" or "cold." (See Figure 2 and 3) This satisfaction and thermal sensation is mainly due to the individual influence of psychological perspective. We obtained comparable results when repeating the experiment at the same temperature; On the other hand, direct sunshine causes air conditioners to take a lot longer than usual to stabilize the room, giving the feeling that it is "little warm". Particularly in the afternoon when the outdoor temperature was about 34°C, participants tended to request a lot of time in such settings. This led to variances in defining the proper thermal pleasure and suggested thermal sensations of "warm," which we attempted to avoid.

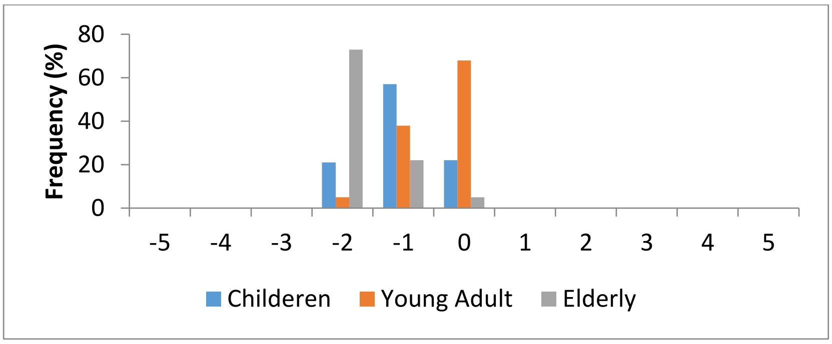

Figure 4.3. Thermal Preference frequency of participants based on age group

Figure 3 shows the frequency of Actual Sensation Votes (ASV) over the period. It analyses ASV according to age group, finding that 21%, 5%, and 73%, respectively, do not feel comfortable at 220C in the morning and prefer it to be warm; in the afternoon, however, 57%, 68%, and 5% felt comfortable at that temperature; in the same vein, 22%, 38%, and 22% want it to be slightly warm during the night, so they want to regularly control the temperature. In general, the result analysis showed majority of participants fined it comfortable of leaving in the daytime when the indoor temperature is 22^0C and don't want to be controlling temperature frequently. For thermal preference in Figure 3, children and younger adults showed more interest in cooler temperatures or "wet" weather, than elderly people same temperatures.

Drawing from the aforementioned data, it is imperative to ascertain and delineate the temperature comfort value range for each vote sensation examined in Figure 4, which illustrates the PET data categorized according to ASV, taking into account the total number of participants and the age group variation that optimally falls between 21 and 280°C, with a median value of 24°C. This suggests that optimal PET levels are higher than those previously established by Fontes et al. (2012). However, the result of analysis on age category shows, a median PET neutrality temperature of 26.5°C and neutrality values ranging from 25.1 to 30°C, the younger people show a stronger tolerance to heat. Other users' comfort range readings are comparable; that is, they display PET values between 23.2 and 26.5°C for kids and between 22.1 and 26.7°C for teens, with median values of 24.3 and 24.1°C, respectively.

5. Conclusion

The global energy issue has been a concern that has been addressed in recent years, and computer systems have worked extremely hard to meet this challenge. Current research on HVAC systems has concentrated on offering ways to lower energy usage without compromising occupant comfort, which is one of the key components of a smart home. We conducted a thermal satisfaction survey of individuals departing from Northern Nigeria (Kebbi, Sokoto, Zamfara, Kastina, and Kano) based on their age group (Children, younger adults, and elderly) at an indoor temperature of 220C. Individuals' thermal satisfaction varies depending on their demographic location and age. This would enable us to ascertain the residents' preferred temperature for optimal thermal enjoyment. This enables us to model and create a customised control that provides a comfortable and healthy interior temperature.

The reason for this is that if an intelligent HVAC management system is designed without taking age and thermal satisfaction into account, it may result in major health issues. It is common knowledge that younger adults can withstand temperatures lower than those experienced by the elderly because their bodies are less able to control how much heat they lose (due to decreased vasoconstriction and less useful body fat) and are generally less capable of producing heat on their own (due to slowed metabolisms). The stress brought on by the increased need to cool down by pumping blood to the extremities makes elderly people less able to handle it, and the higher chance of pre-existing pulmonary and cardiovascular diseases that develop as they age can make vasodilation more problematic. Similarly, a resident experiencing dementia, a mental disorder associated with aging, would be unable to operate the HVAC system and hence communicate their preferred temperature to others.

As part of our survey, we also examined the way that temperature management is now handled, which is mostly based on the conventional binary technique (turning the HVAC system on or off). Few providers provide fuzzy approaches when the values are greater or lower than the desired value that is manually specified. An air conditioner thermostat, for instance, is programmed to activate when the outside temperature rises over 18◦C. The problem is that the control has to turn on and off frequently when the temperature fluctuates near 18°C (for example, between 17°C and 19°C), which shortens the life of electric appliances. Those with a fuzzy approach do not adapt both occupancy detection and machine learning to their decision. Hence, we proposed an approach that combines occupancy detection and machine learning approach with the help of fuzzy sets and linguistic variables control that uses ranges of values in which the temperature is suitable. With this, our control would enable us to decide the best moment to turn ON/OFF HVAC systems by considering the outdoor and indoor ambient conditions.

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