Article

Reducing the Operating Energy of Buildings in Arid Climates through an Adaptive Approach

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Abstract: Due to its excessive energy consumption, the building sector contributes significantly to greenhouse gas (GHG) emissions. The type of thermal comfort models used to maintain the comfort of occupants has a direct influence on forecasting heating and cooling demands and plays a critical role in reducing actual energy usage in the buildings. In this research, a typical residential building was simulated to compare the heating and cooling loads in four different Jordanian climates when using an adaptive thermal model versus the constant setting of temperature limits for air-conditioning systems (19–24 °C). The air-conditioning system with constant temperature settings worked to sustain thermal comfort inside the building, resulting in a significantly increased cooling and heating load. By contrast, significant energy savings were achieved using the temperature limits of an adaptive thermal model. These energy savings equated to 1533, 6276, 3951, and 3353 kWh, which represented 29.3%, 80.5%, 48.5%, and 67.5% of the total energy used for heating and cooling for zones one, two, three, and four, respectively.

Keywords: adaptive thermal comfort; low building energy; energy consumption; Mediterranean climate; sustainability

1. Introduction

Due to the tremendous amount of energy consumed, the building sector is responsible for a high level of greenhouse gas (GHG) emissions, which constitute around 33% of global emissions [1]. Therefore, the reduction of energy consumed in buildings is a crucial strategy for mitigating climate change and reducing GHG emissions [2]. Various studies have shown that low-carbon buildings need to decrease energy consumption through the application of passive design strategies [3], as this improves thermal comfort and enables occupants to reduce their dependence on heating and cooling [4–6].

Accurate estimation of cooling and heating demands is necessary to limit energy consumption and simultaneously sustain thermal comfort [7]; this requires an appropriate thermal comfort model and smart monitoring technologies [8]. Due to its cost efficiency and ability to limit the overconsumption of energy, an accurate comfort model provides a convenient and suitable solution [9].

Regarding the thermal comfort models, the level of thermal comfort experienced by occupants in a building varies, as it is a feeling shaped by psychological factors [10]. The thermal sensation felt by the occupants thus determines the thermal comfort level [11].

An experimental study of seven buildings from different sectors in South Korea was conducted to understand the impact of the regulations on the indoor temperature and

the subsequent energy performance. The outputs indicated that the degree of command occupants had upon the conditions of their internal building could diminish heating and cooling demand by around 9–10% while sustaining thermal comfort [12].

The PMV (Predict Mean Votes) model was developed using Fanger's human thermal balance equation [13]. The human body's thermal regulation theory is combined with Fanger's PMV model, and the human body achieves thermal comfort in the building under defined heat and humidity conditions [14]. As a result, the PMV model is widely used to estimate a human body's thermal comfort inside a building [15]. When the human body is close to thermal neutral, there is a linear link between skin temperature, sweat rate, and human activity intensity, according to the PMV model. Based on PMV, the anticipated percentage of discontent (PPD) was established. Many studies challenge the accuracy of PMV prediction, since there is a substantial gap between the PMV value and the real value when PMV is larger than +2 (warm), due to the clear augmentation of evaporative heat loss of sweat. Furthermore, the applicable scope of the PMV model is restricted in the relevant standards [16]. The PMV model is intended for a typical uniform and steady-state air-conditioning environment. It takes into account non-uniform and non-steady-state surroundings, as well as the influence of local hot and cold feelings on the overall thermal experience. As a result, in dynamic circumstances, PMV is not applicable [17].

ASHRAE has developed the "Thermal Environmental Conditions for Human Occupancy" standard, which establishes a range of personal characteristics and indoor environmental conditions needed to attain thermal environments suitable for the inhabitants of buildings. The International Organization for Standardization (ISO), European Committee for Standardization (CEN), and ASHRAE Standards specify the conditions of indoor thermal environments needed to achieve acceptable levels of thermal comfort for a wide range of buildings [18]. ISO and CEN have adopted and implemented two thermal comfort models: PMV and PPD models, and adaptive thermal comfort models.

The researchers identified several limitations in the PMV model, such as the difficulty of precisely measuring the mean vote of metabolic rates and determining clothing insulation [19]. Furthermore, the psychological factors are neglected in the PMV thermal comfort model, despite its vital role in defining the thermal comfort levels [20].

Several experimental works have found that the PMV is difficult to apply in the operation phase, as it relies on the physiology of respondents and subjective perceptions, which leads to imprecise predictions of comfortable conditions [21].

Multiple empirical and experimental tests have therefore been conducted to develop a new adaptive thermal comfort model that can identify comfortable indoor air temperatures in buildings [19,22].

The adaptive method identifies the comfort zone that exists between 80% and 90% acceptability limits as a range between 2 and 3 °C of an ideal comfort temperature. According to ASHRAE 55-2017, the comfort zone limit can be reached at around 30 °C while remaining within the 80% limit of acceptance [23]. In tropical regions that have a hot summer, decreasing the acceptability limits from 90% to 70% could lead to an approximate 40% reduction in cooling load [24].

Researchers have also used the Australian AccuRate building assessment tool to analyze the influence of several thermal comfort models on the thermal performance of buildings. This performance was evaluated utilizing the comfort of occupants instead of energy usage. The results revealed that an adaptive thermal comfort model yielded the best thermal performance with respect to maintaining the thermal comfort of occupants [25,26].

Thermal comfort has been mentioned in several international and regulatory documents. In 1984, the ISO 7730 standard was originally issued, introducing the Fanger comfort model of standardization. This standard provides the formulae for computing the Fanger thermal comfort indices PMV and PPD. Additionally, ISO 7730 specifies a technique for measuring local thermal discomfort brought on by asymmetric radiation, drafts, and the vertical air temperature difference. In 1994, the standard was updated, and again in 2005 [27,28]. It now includes three separate comfort categories for three different

degrees of PPD (A: PPD < 6% and −0.2 < PMV < 0.2; B: PPD < 10% and −0.5 < PMV < 0.5; C: PPD < 15% and −0.7 < PMV < 0.7). A diagram that demonstrates how to calculate the airspeed required to adjust the thermal comfort range and account for an increase in operating temperature is also included.

Engineers can use ANSI/ASHRAE Standard 55 to define baseline criteria for acceptable interior thermal settings and to determine the overall thermal comfort of a structure. It was first published in 1966 and has since been amended in 1974, 1981, 1992, 2004, 2010, 2013, and 2017. Regarding thermal comfort, the various variations differ in three key ways. The addition of the thermal comfort zone determined using the PMV/PPD technique is the first modification to the 1992 version. Previously, a more straightforward visual comfort zone defined the permitted range of temperatures for occupants [27,28]. Version 2004 introduced the adaptive comfort model, which used the monthly mean outside temperature as the outdoor reference temperature [29]. The most recent revision was issued in 2013, when the outside reference temperature for the adaptive equation was determined using the average outdoor temperature for the seven to thirty consecutive days prior to the day in question [30]. The ANSI/ASHRAE 55:2017 divides the allowable operating temperature ranges into two categories: 80 percent and 90 percent acceptability. This standard, which does not list the kinds of buildings in which it can be utilized, states that the adaptive comfort model can only be employed in occupant-controlled naturally conditioned areas.

The European standard EN 15251 originally published the PMV/PPD model and adaptive comfort approach in 2007 [23]. In 2015, a draft modification of EN 15251 was published, and it was renamed prEN 16798-1 [31]. The adaptive comfort model has undergone two revisions in prEN 16798-1. First, compared to the previous version, the lower limit of ideal operating temperature was reduced by 1 °C. The second was the outdoor running mean temperature range, which covers the lower end of the thermal comfort zone and ranges from 10 to 30 °C to 15 to 30 °C.

In order to offer an adaptive comfort model for assessing the internal thermal environment in free-running buildings during the design and operational phases, the Chinese GB/T 50785 standard was developed in 2012 [32]. China's five-zone climatology provides reference techniques for the severe cold zone and the cold zone, respectively. The second group, which addresses hot and mild climates, consists of the hot and cold winter zone, the hot summer and warm winter zone, and the mild zone. This standard includes two methods for assessing free-running structures: a graphical technique, and a calculation method. It does not specify the types of buildings to which the comfort model can be used.

Regarding the building energy simulation tools, to assess heating and cooling loads, accurate energy simulation analysis and assumptions are required to design low-energy buildings. Such buildings should achieve two primary intents; to maintain occupants' thermal comfort level and encourage reducing energy demand over their lifetime [33].

Building energy modeling is physics-based software that simulates building energy use. It utilizes input from the building description, including geometry, construction materials, HVAC, illumination, water heating, cooling system, configurations of the renewable production system, control strategies, and element energy efficiencies. Moreover, it applies and runs information of the building, including lighting, occupancy schedules, thermostat settings, and plug loads. This software combines this information with local weather data. It employs physics principles to measure thermal loads, the system response to them, the energy demand to cover those loads, and the relevant metrics such as energy costs and occupant comfort. Calculations are performed on an hourly basis or for shorter periods. In addition, the program explains system interactions, such as the interaction of lighting with heating/cooling [34].

As a response to the deficiency in the thermal performance of buildings, simulations have emerged to evaluate options for change with respect to related matters ranging from human comfort and well-being to a decrease in energy demand and sustainable practices. Due to the growing acceptance of simulation as a means of defining best practices, significant endeavors are now taking place to convert virtual technology to actual practices.

The main reasons behind this are the complexity of the building's system, which includes 'hard' and 'soft' features and the high necessity for prompt feedback regarding building energy usage performance and cost [35].

If real data are not available, a CFD study can be used to model the behavior of the housing modules and establish operative interior air temperatures. Because its simulations include building parts such as floors and walls, for which the engineers may define material thermal characteristics, CFD is a simulation approach that accounts for all of the design variables. During the energy analysis of the modules in this study, custom material-based thermal characteristics for the detailed elements were utilized. A transient solution mode, heat transfer, flow, and radiation were activated and computed in the CFD simulation program by entering the exact position and date of the real modules [36].

Another study examined the capabilities of building energy modeling and simulation software for Mediterranean countries. DesignBuilder is an energy modeling software that utilizes the EnergyPlus simulation engine. A user-friendly interface, a meteorological database, and an intelligent model to analyze internal and solar energy supplies are among its characteristics. It also calculates the average interior and outdoor temperatures throughout the year [37].

Energy-efficient retrofits in commercial buildings are considered from two different standpoints on the market [38]. From a narrow standpoint, retrofits serve the purpose of energy conservation; therefore, funding for the work comes from future savings on energy expenditures. From a broader standpoint, energy efficiency is part of a comprehensive program aimed at improving the suitability of buildings for the activities of occupants. Sometimes, costly retrofits can be funded by the substantial increase in productivity of happier and healthier occupants—an increase of 3% to 25% for office workers and up to 15% or higher in retail sales [39].

Another published study performed retrofits of the building to enhance the energy efficiency, including insulation and using renewable energy sources. The researchers indicate that the use of proper insulation materials and optimum thickness will result in an approximately 15% decline in the annual consumed energy [40].

Another investigation studied the effect of insulation of both the roof and wall as well as the types of windows on energy efficiency in the building. The parameters that were considered in this study are energy usage, cost, and thermal comfort of occupants. The results indicated that the insulation of roofs and walls resulted in less energy use and high-cost savings as well as sustained thermal comfort [41].

In different Jordanian climates, an air conditioner is commonly used, with a consonant operational temperature, which is fixed between 19 °C and 24 °C throughout the year. Through this method, the air-conditioning system remains active for long periods, as the indoor temperature in the building lies outside the operational temperature range most of the time, which substantially increases energy demand.

In Jordan's Mediterranean environment, this study looked at how applying an adaptive thermal comfort operational temperature affected cooling and heating loads; Jordan is characterized by a unique location in the center of the Middle Eastern countries. It is crucial to research the impact of adaptive thermal comfort in this area. The findings of the adaptive thermal comfort testing were contrasted with those of installed air conditioners that operated at fixed operating temperatures.

2. Methodology

To assess the energy performance of two thermal comfort models (constant temperature and adaptive thermal comfort models), a dynamic simulation was conducted in four Jordanian climate zones (these are similar to the climates prevailing in the eastern Mediterranean), although in reality the design characteristics and layout differ from one climate zone to another; this is one of the limitations of this research that will be explained in detail in the limitations section. The DesignBuilder software was implemented

to assess the impact of the operating temperatures of the air conditioner on heating and cooling demands.

2.1. Jordanian Climate Zones and Their Characteristics

Figure 1 shows the location of Jordan, which is between the eastern Mediterranean from the north and west sides and the Arabian Desert from the south and east sides. This location can help in explaining its climatic conditions. It typically experiences long, hot, and dry summers that extend from June to September, with an average temperature between 20 °C and 35 °C. The lowest and highest monthly outdoor temperatures are highly variable in this climate throughout the year. Jordan has short and cold winters, from December until February, with a mean temperature of 4 °C to 11 °C. The temperature increases during the summer daytime to reach around 42 °C, especially when there is a dry, hot south-eastern wind. The precipitation mainly occurs in the winter and ranges between 250 and 450 mm, while in summer, it decreases or stops totally.

Figure 1. Jordan Location from map data. © 2021 Google.

Jordan has several climate zones. Some of those zones have a desert climate, while others are akin to the Mediterranean climate. There are four different seasons in Jordan, of which autumn and spring lie in the optimal human comfort zone. Figure 2 shows the central climate zone in Jordan.

Zone 1: This is characterized by hot to mild summers with a maximum temperature between 32 °C and 34 °C, and there is a high sun glare during the summer daytime. There are cold winters with a minimum temperature range between 3 and 5 °C, with a notable temperature lag between day and night. The average rainfall per year ranges from 75 and 150 mm.

Zone 2: Hot Saharan climates experience high pressure and stable air. They are characterized by year-round sunshine, which results in dry and warm weather over the year in general. During the summer season, the maximum temperatures reach 40–43 °C, with an average temperature of 35 °C. The winter has cold nights, where the temperatures reach below zero.

Zone 3: This zone has hot to extremely hot daytime summers, with a mean temperature of around 31–34 °C. It is characterized by high sun glare, where the sunshine is around 12 h per day during July and August. During the winter season, there is a meaningful temperature variation between the warm daytime and cold night-time. The coldest temper-

ature of 13 °C occurs mainly in December and January. The average annual rainfall reaches 10 mm.

Zone 4: The major cities in Jordan are characterized by warm summers and cold winters. During the summer, the average temperature is about 30 °C, and the daytime is dry, with cool evenings. During the winter, the average temperature is around 9 °C, with wet nights. The average annual rainfall is 350 mm, and there are occasional snowfalls.
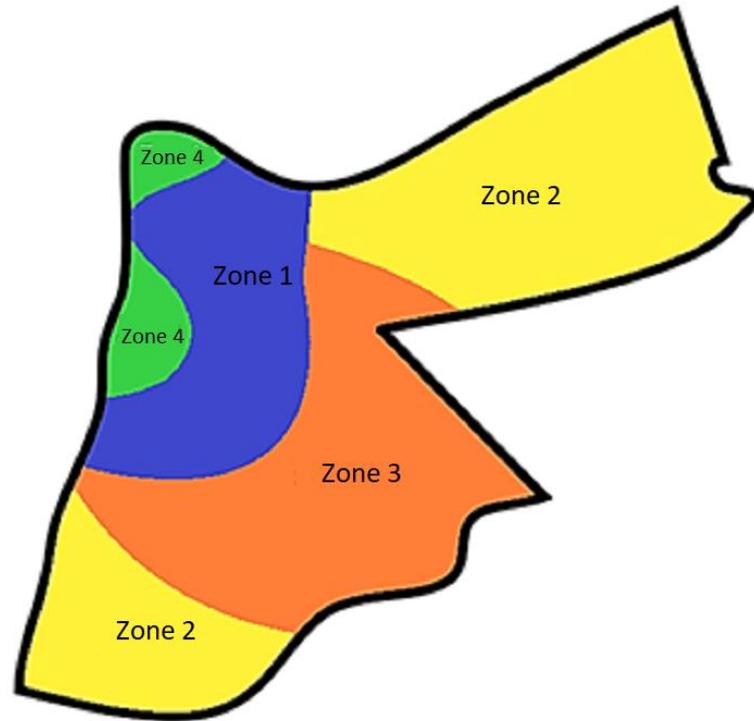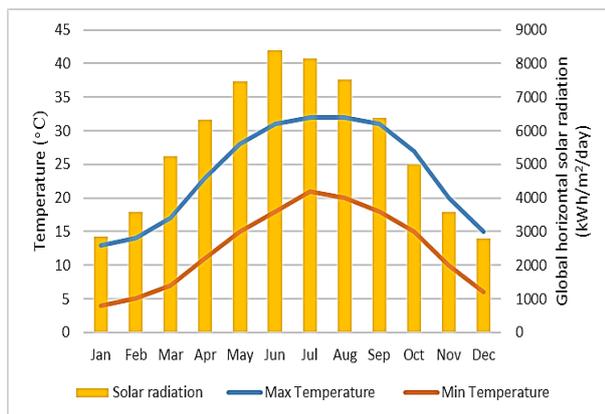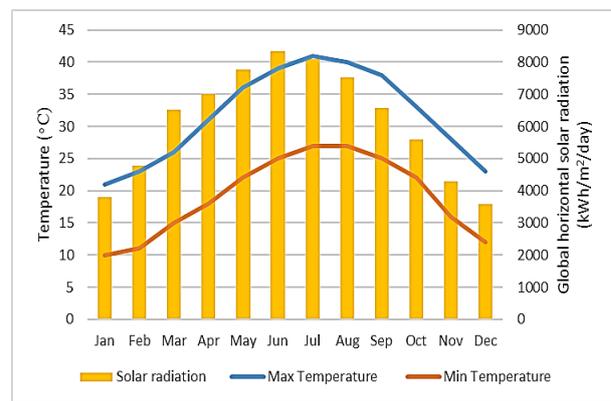

Figure 2. Main climate zones in Jordan.

The average maximum and minimum temperatures and the solar radiation are shown in Figure 3.

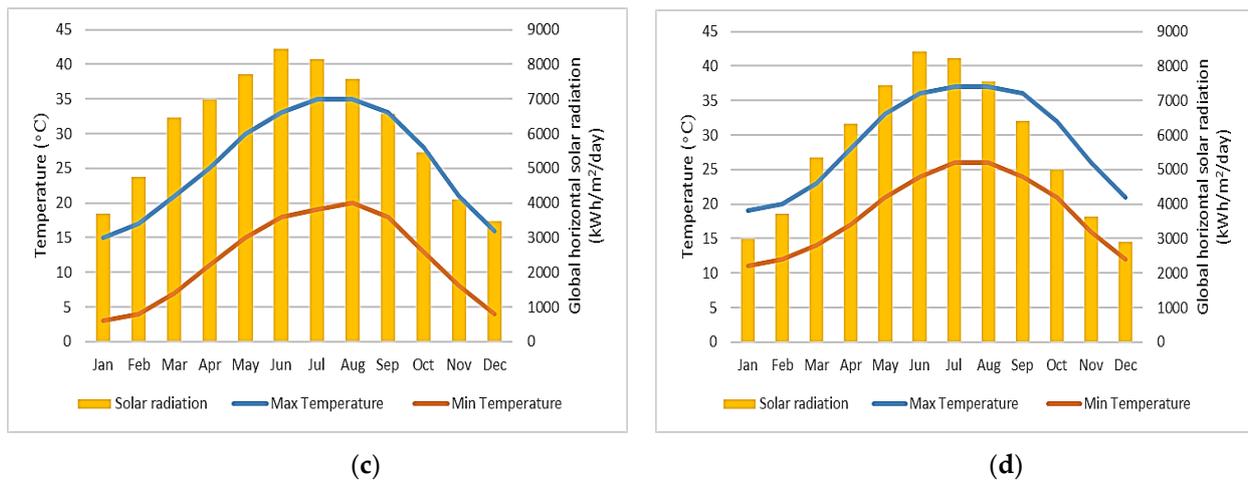(a)   (b)

Figure 3. *Cont.*

(**c**)

(**d**)

Figure 3. Average maximum and minimum temperatures and solar radiation profile for each climate zone. (**a**) Climate Zone 1; (**b**) Climate Zone 2; (**c**) Climate Zone 3; (**d**) Climate Zone 4.

2.2. Description of Baseline Building Characteristics and Shape

A typical Jordanian residential building [25], in accordance with different Jordanian building codes, was developed and simulated using DesignBuilder software. This baseline building is one floor, comprising the main bedroom and two other bedrooms, two bathrooms, a living room, a guest room, a kitchen, and a storage room, with a total area of around 186 m^2. After collecting the fundamental information from the Jordanian building codes, which includes the thermal permeability of the various building elements (external and internal walls, roof, ground, windows, etc.), the building was designed as illustrated in Figure 4.

(**a**)

(**b**)
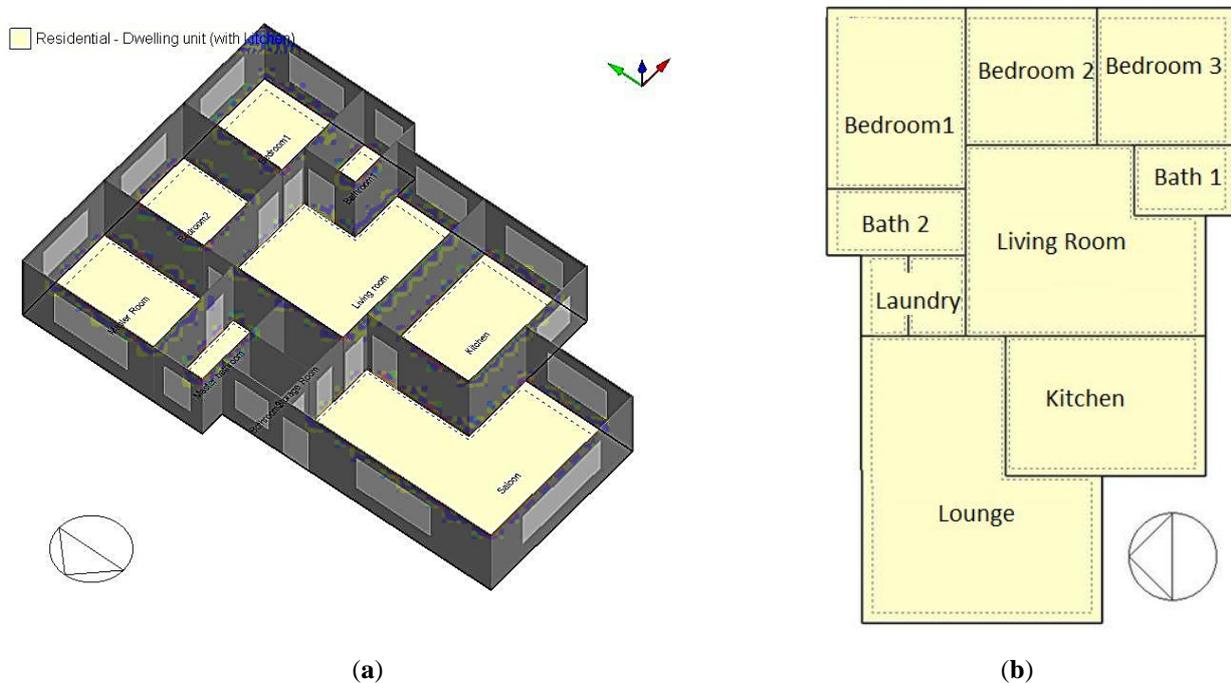
Figure 4. (**a**) 3D model of the building. (**b**) Layout of the building.

The building envelope materials and its specifications were based on typical Jordanian architectural design and followed Jordanian building codes. These were selected and implemented in DesignBuilder, as follows.

2.2.1. Roof, Floor, External Walls, and Internal Walls

Table 1 presents the specifications and configurations of materials for the roof, floor, external walls, and internal walls.

Table 1. Thermal conductivity and thickness of the roof, floor, external walls, and internal walls.

Layers	Width (mm)	Conductivity (W/m.K)	Total U Value (W/m^2.C)
Roof			
Asphalt	20	0.7	
Extruded polystyrene	50	0.03	
Miscellaneous materials—aggregate	100	1.3	0.535
Concrete, reinforced	320	2.5	
Cement plaster	20	1.2	
Floor			
Ceramic/clay tile	30	0.52	
Miscellaneous materials-aggregate	100	1.3	1.877
Concrete	320	1.7	
External wall			
Stone	50	2.2	
Concrete, reinforced	100	2.5	
Extruded polystyrene	50	0.03	0.563
Concrete block	100	1.6	
Cement plaster	10	1.2	
Internal wall			
Cement plaster	30	1.2	
Concrete block	100	1.6	2.5
Cement plaster	30	1.2	

2.2.2. External Windows—Frame and Glazing

Table 2 presents the specifications and configurations of the glazing materials for external windows. Thermal transmittance is indicated by the U-value.

Table 2. Thicknesses and configuration of glazing layer materials.

Layer Name	Layer Thickness (mm)
Generic BLUE	6
100% Air Gap	6
Generic CLEAR	6
U-value (W/m^2. K)	3.1
Total Solar Heat Gain Coefficient (SHGC)	0.5
Light transmission	0.5

2.3. Simulation Software

EnergyPlus is the simulation engine that was used to simulate the building's energy efficiency using DesignBuilder software (version 6.1, Software company in Stroud, England).

EnergyPlus is a thorough simulation program created to simplify building simulation, and several prior studies have shown its effectiveness [42–44]. Using hourly climatic data files on the study case "shoebox" that refers to the use of a local office, it is feasible to create advanced dynamic simulations using this program in real time. Along with the input for building characteristics and internal loads. The DesignBuilder provides a simple and flexible interface with which to simulate the building construction systems, heating/cooling systems, illumination systems, window types, and so on. It is primarily utilized to analyze the thermal performance and thermal comfort of a building, including cooling and heating loads. It includes a built-in database of building structures in terms of physics (building materials) and weather data. DesignBuilder (DB) is one of the tools that architects and engineers have praised and rated among the best. It is designed to execute EnergyPlus calculations on digital solid modeling, and it is used in this software to mimic heat transfer procedures, climatic factors, and other elements that affect energy usage in structures. Moreover, it is a three-dimensional, all-encompassing platform created on the foundation of EnergyPlus. EnergyPlus is designed to be a precise computation engine, leaving the creation of more user-friendly pre-and post-processing stages to other tools.

Model operational data such as occupant data, lighting systems, and home appliances were defined based on a survey carried out by the Ministry of Energy and Mineral Resources; this survey determined the actual construction properties and pattern of energy utilized in Jordanian buildings [45]. Moreover; the simulation input was determined as follows: the infiltration rate is 0.70 ACH, occupants are six in a family, and ventilation is used on summer nights to benefit from the night breeze to cool the building. The values of simulation parameters—lighting, occupant number, heating set point, and cooling set point—were input according to the function of each space in the most suitable conditions for the constructed model according to the actual operation time in the residential houses and apartments as well as the climate of Amman city. The heating period was chosen to be from November to April, while the cooling period was chosen to be from May to October. The model was examined in four different Jordanian climates (similar to those found in several parts of the world) using the DesignBuilder built-in hourly weather data for each climate. So, each climate zone is determined by a specific location for each zone, as each zone has it is own weather file and settings.

2.4. The Adaptive Thermal Comfort Model

The adaptive model is based on the idea that different climates have an impact on interior comfort because people can adapt to a range of temperatures throughout the year. According to the adaptive theory, building occupants' requirements and needs regarding temperature can be impacted by situational variables, including their access to environmental controls and previous thermal experiences. The adaptive thermal comfort model was utilized in this investigation to create new occupant thermal comfort limits and predict the amount of energy that heating and cooling required. In adaptive models, the desired interior temperature of the inhabitants is predicated on the findings of statistical analysis of empirical field survey data. The adaptive approach to thermal comfort holds that residents' behavior may change depending on a range of variables that go beyond fundamental physics and human biology, including demographics (gender, age, economic status), context (building design, building function, season, climate, semantics, social conditioning), and perception (attitude, preference, and expectations). Because it uses a wider range of operating temperatures and low-energy ways to maintain occupants' thermal comfort instead of mechanical heating and cooling, the adaptive thermal comfort model was chosen above alternative thermal comfort modules (such as PMV and PPD).

This paper applied and compared two methods to determine the operating temperature of the air conditioner for both cooling and heating. The first method involved setting a constant temperature (18 °C and 24 °C) for the air conditioner when the internal air temperature was no longer within this range. The second method detected the operative temperature utilizing an adaptive thermal comfort model. It improves the building's

economic and environmental performance when people tolerate higher indoor air temperatures since mechanical temperature control may be reduced. This results in lower energy consumption and operating expenses. However, mechanical cooling or heating systems must be built and operated in accordance with the set-point conditions determined by the Fanger comfort model if the outdoor running indicates the temperature is beyond the range of the adaptive thermal model.

The comfort temperature of the adaptive model can be calculated using the ASHRAE 55 standard equation [46], Equation (1):

$$T_c = 0.31 \cdot T_\circ + 17.8 \tag{1}$$

where

Tc: outdoor mean temperature for the past 30 days (°C);

$T_\circ$: operative temperature (°C).

The adaptive thermal comfort 80% acceptability limits inside the building, where at least 80% of the people feel at ease with these temperature ranges, were determined using Equation (2) [46]:

$$80\% \text{ acceptability limits imply } Tc \pm 3.5 \,°C \tag{2}$$

In order to use the adaptive thermal approach, people must dress correctly. The basic requirements for using this module are that the mechanical cooling or heating system has not been established and that the inhabitants are assumed to be inactive. Additionally, the metabolic rates should be between 1.1 and 1.3 Met (exercise will warm the body in winter, but will make it feel hotter in summer). Clothes insulation (Clo) was used in these calculations and ranged from 0.5 m² °C/W for hot days to 1.3 m² °C/W for cold days. However, the effect of air and movement was not considered [47]. The adaptive thermal model was applied for every month of the year in each climate.

3. Validation

In order to evaluate the impact of the adaptive thermal comfort model, several studies were carried out, either by comparing it with structural retrofit strategies or by comparing it to the predicted mean vote model, using surveys, calculation methods, the multiple scenario strategy, experimental results, and simulation.

According to Spanish research that was done to assess the energy demand in an office building using an adaptive thermal comfort approach, the results not only show that the energy demand can be reduced by using adaptive set point temperatures by up to 69.91% for the least restrictive category and by 31.34% in the category with the highest level of user expectation, but they also show variations in demand that might occur under various conditions. The prediction model is validated when it is applied to a real-world scenario and results in minimum differences of between 3 and 10% [48]. Another study compares the outcomes of two important thermal comfort models (adaptive thermal comfort and the predicted mean vote (PMV) adjusted by the expectancy factor) to examine their influence on the prediction of the energy consumption for several full-scale housing experimental modules built on the campus of the University of Newcastle, Australia. This study demonstrates the advantages of using the adaptive thermal model for building structures. It demonstrates how well this approach works to save energy use, raise thermal comfort in buildings, and lower greenhouse gas emissions [49]. Research studies demonstrate that people who cannot adjust their indoor climate are less comfortable and suffer health issues. Broadening temperature bands may be a useful strategy for reducing energy use, boosting enjoyment, and, as recently demonstrated, reducing health issues associated with our way of life. According to the adaptive approach to thermal comfort, people's perceptions of thermal comfort change depending on the typical indoor and outdoor climatic conditions they encounter. The findings show that the adaptive approach has the capacity to adjust the indoor environment in actively conditioned buildings in cold and temperate regions [50]. In addition, a survey conducted in 100 common areas of five nursing homes in the Mediter-

ranean climate served as the basis for field research on adaptive thermal comfort models for nursing homes in the region. The study involved simultaneous measurements of indoor and outdoor environmental factors and a questionnaire-based assessment of the subjects' perceptions of thermal comfort. Two adaptive thermal models are included in the research for nursing homes that will allow for increased use of natural ventilation and the adoption of setpoint temperatures when air conditioning is required, resulting in less demand for heating and cooling [51–53].

4. Results and Discussion

Figure 5 presents the energy required to maintain heating and cooling using air-conditioning so that it remains within constant temperature limits (18 °C and 24 °C) in various climatic zones. The annual energy consumption for heating and cooling in climate zones one, two, three, and four was 5226, 7791, 8136, and 4965 kWh, respectively. The heating demand was high in climate zones one and three but decreased in climate region four and was almost non-existent in climate zone two. The cooling consumption was significant in climate zone two and to a lesser extent in climate zones four and three, respectively. Although climate zone one had the lowest cooling demand, the amount of cooling required was still notable.
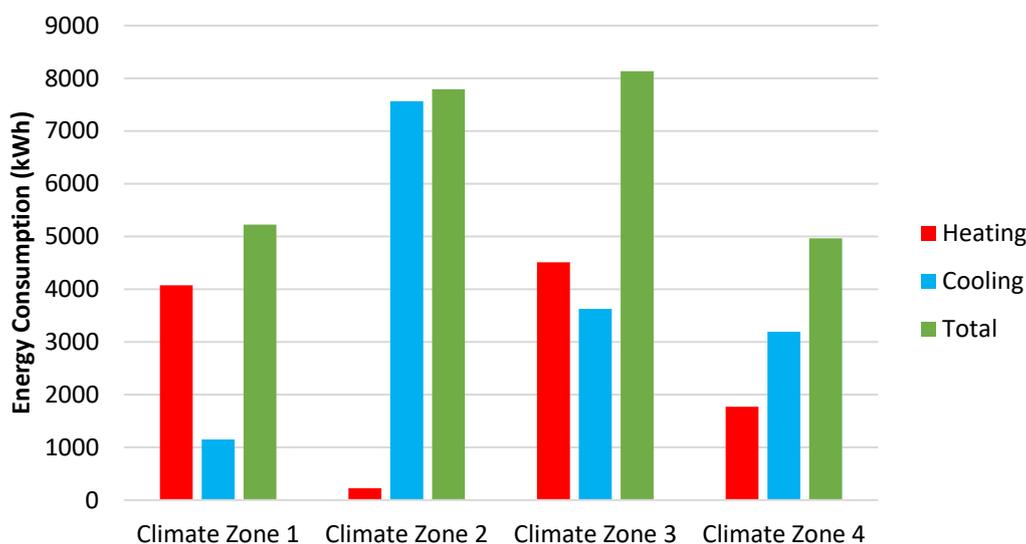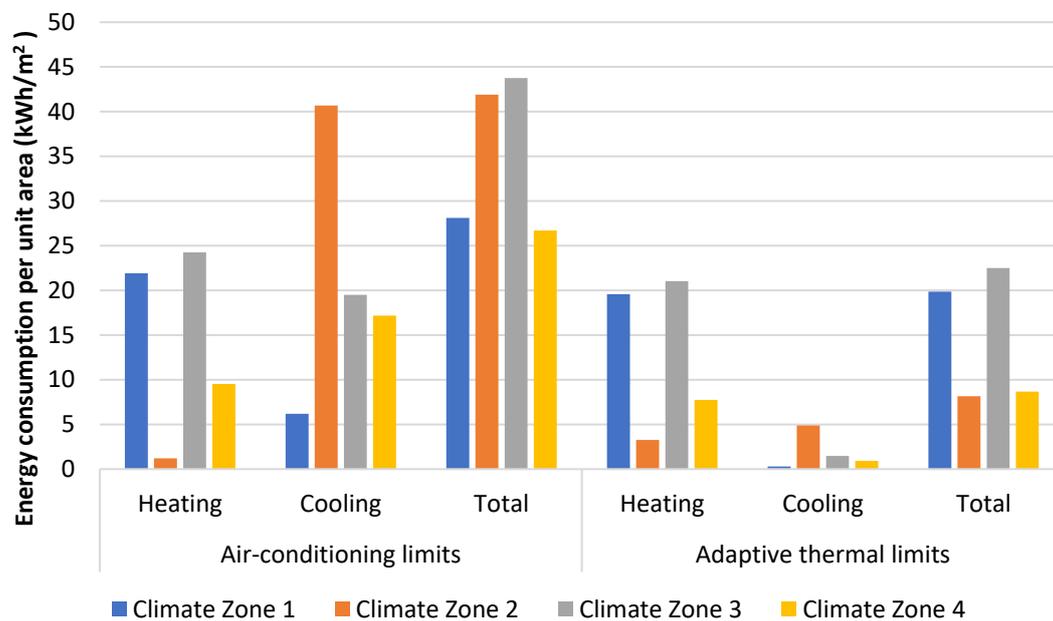

Figure 5. Annual energy consumption needed for space heating and cooling using air conditioning limits in different Jordanian climates.

The comfort temperature of the adaptive model can be calculated using the ASHRAE 55 standard equation [46], equation number one. The comfort temperature ranges for the adaptive thermal model for a 90% acceptability limit were calculated for all climates. These ranges were extended from 25.4 °C to 27.9 °C, 24.2 °C to 29.7 °C, 22.6 °C to 27.6 °C, and 25.3 °C to 30. 2 °C in summer and 16.9 °C to 19.4 °C, 16.4 °C to 21.4 °C, 16.8 °C to 20.8 °C and 15.9 °C to 20.9 °C in winter for climate zones one, two, three, and four, respectively. The simulation model was then utilized to calculate the energy required for heating and cooling, as illustrated in Figure 6. The energy required for mechanical heating or cooling was 3693, 1515, 4185, and 1612 kWh per year for climate zones one, two, three, and four, respectively.
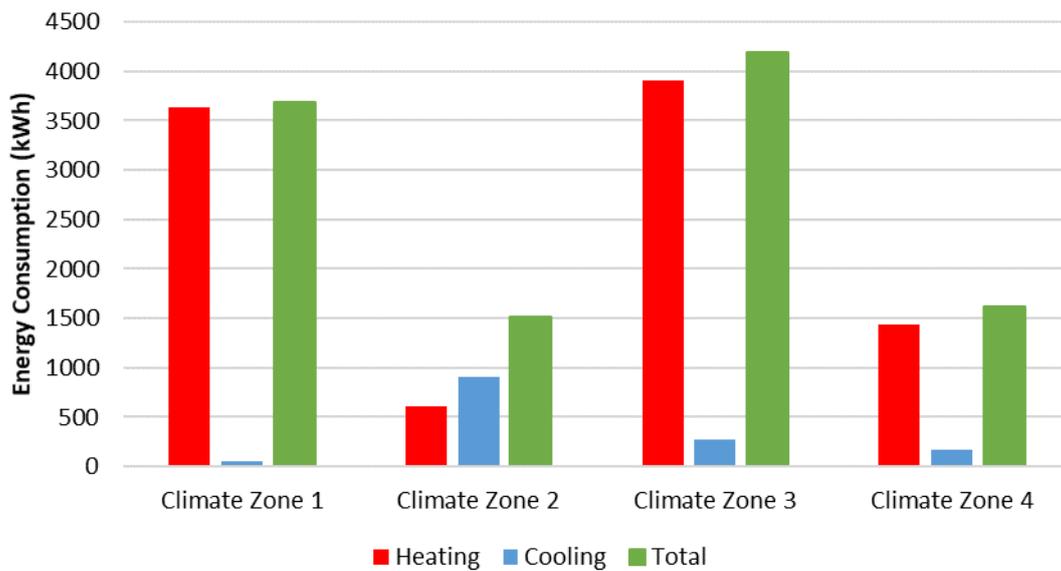
Figure 6. Annual energy consumption needed for space heating and cooling using adaptive thermal comfort model limits in different Jordanian climates.

Figure 7 presents the energy required for heating and cooling per unit of the area using fixed sets of operative temperatures for air-conditioning and the adaptive comfort operative temperature limits.

Figure 7. Annual energy consumption using wider ranges for air-conditioning extracted from the adaptive comfort operative temperature limits.

The adaptive thermal model was used, and it resulted in a considerable reduction in cooling consumption compared with fixed air-conditioning thermostat settings during the summer months. This was due to the broader scope of temperatures mentioned previously. The reduced percentage of cooling load reached an astonishing ratio of 95%, 88%, 92%, and 95% for climate zones one, two, three, and four, respectively. Simple supplementary actions should be taken by the occupants of buildings during the summer to reclaim the thermal

comfort within the acceptance limit, including night-time natural ventilation, movable shading to prevent undesirable sun radiation, and appropriate clothes.

In the winter months, the adaptive thermal model reduces the heating demand slightly as opposed to the fixed temperatures of the air-conditioning unit. This is owing to the lower adaptive thermal comfort limits of 18.2 °C, 18.4 °C, and 18.1 °C in climate zones one, three, and four, respectively, compared with 19 °C for the fixed air-conditioning system. An exception to this is the second climatic zone, where a rise in heating demand was observed when using the adaptive thermal model where the lower limit is 20.6 °C. Operating the air conditioners using the acceptable temperature limits of the adaptive thermal model decreased the total energy usage for mechanical heating and cooling from 5226, 7791, 8136, and 4965 kWh per year to 3693, 1515, 4185, and 1612 kWh per year for climates zone one, two, three, and four, respectively, as illustrated in Figures 8 and 9.
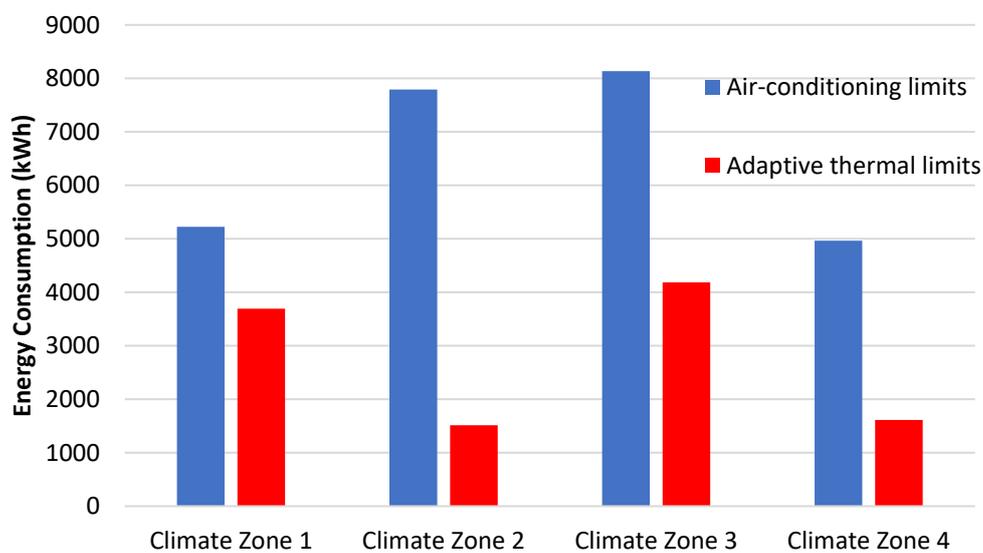

Figure 8. Total energy consumption for each climate zone.
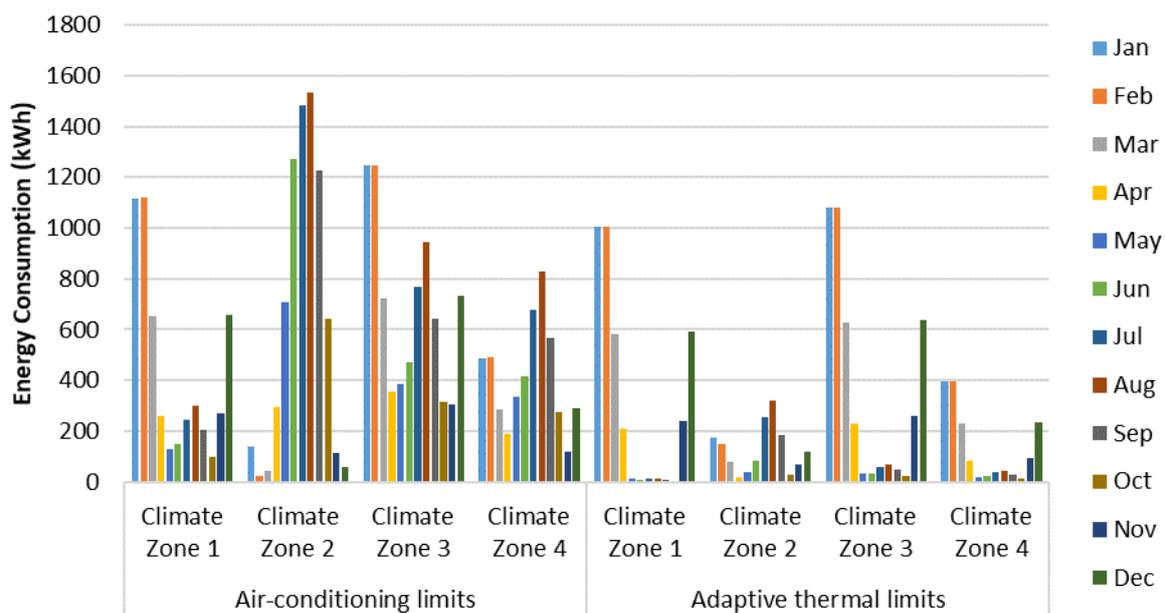

Figure 9. Energy demand for each month in different climate zones.

A significant energy saving was achieved using the temperature limits of the adaptive thermal model instead of the constant temperature settings of an air-conditioning unit. These energy savings reached 1533, 6276, 3951, and 3353 kWh, which represent 29.3%, 80.5%, 48.5%, and 67.5% of the total energy utilized in heating and cooling in climate zones one, two, three, and four, respectively, as presented in Figure 10. As a result, the findings indicate that the adaptive process and human behavior have a huge impact on energy savings, which impacts the future of energy efficiency and the reduction of GHG emissions due to less dependency on the use of AC, and more on the adaptation to the weather circumstances.
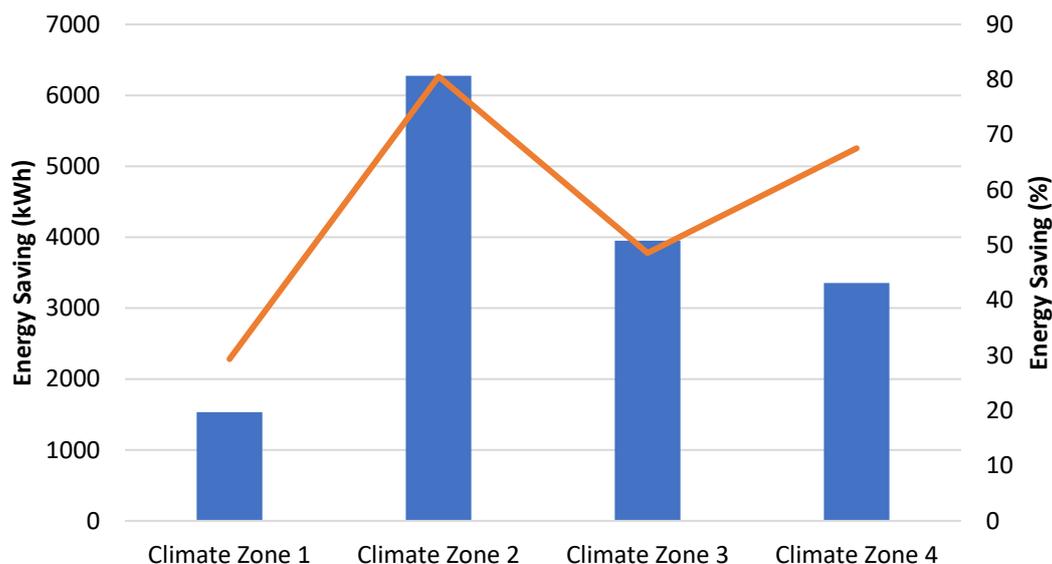
Figure 10. The annual amount and percentage of energy saved using the thermal adaptive comfort approach in different climates.

The main climate zones and energy savings are shown in Table 3.

Table 3. Different Jordanian climate zones and the adaptive model savings.

Climate Zone	Total Saving in kWh	Energy Savings (%)
Climate zone 1	1533	29.3%
Climate zone 2	6276	80.5%
Climate zone 3	3951	48.5%
Climate zone 4	3353	67.5%

It was clear that climate zones two and four were better suited for the adaptive model. The adaptive model works better (saves significant amount of energy) with these two climates, followed by climate zone three, and the least influence of the adaptive model was noticed in climate zone one.

5. Limitation and Future Considerations

(a) This type of research could be done on more than one architectural design layout and characteristics that suit each climate to determine exactly the effect of the adaptive thermal comfort for each zone individually.

(b) This investigation could be more beneficial if we could establish an equation for the adaptive thermal comfort specified for the investigated region, as it could be more accurate through surveys and simulation using more than one software.

(c)   The simulation process could be combined with surveys to enhance and establish more precise information about the thermal comfort of each individual.

(d)   This study can be extended to examine the impact of climate change on energy saving potentials of natural ventilation and ceiling fans in mixed-mode buildings or mixed-mode ventilation and air conditioning as an alternative for energy savings.

(e)   There are different types of adaptive models that could be implemented on a similar study in the future.

6. Conclusions

This research aimed to evaluate the effect of the adaptive thermal comfort model in the Mediterranean climate, considering four climate zones in Jordan, as this region and its climate is of great importance for similar studies. This investigation was conducted using the DesignBuilder software, considering four weather profiles. One of the most useful studies in the area of human thermal comfort is the research of the thermal comfort model. It offers a technique for forecasting and assessing the level of human thermal comfort as well as a foundation for establishing the building environment. The process by which the human thermal comfort model has developed progresses from straightforward to intricate, from abstract to concrete, and from the entire body to minute details. Applying the thermal comfort model to a building can play a significant role in forecasting operational heating and cooling demands. The adaptive thermal method provides more extensive ranges of comfortable temperatures and takes into consideration the variety of temperatures during the same season; this results in a meaningful saving of energy. The inhabitants of buildings can sustain their coveted thermal comfort by taking simple actions such as shading windows, ensuring good nighttime ventilation, and wearing proper clothes rather than running artificial air conditioning. Using the acceptable limits of the adaptive thermal model results in a slight increase in energy usage in the building, notably in the summer months. This was the result of the broader temperature ranges of the adaptive approach (28.1–31.6 °C) compared with the cut-off point of 24 °C for the fixed air-conditioning system.

Applying the adaptive thermal comfort reduced the overall energy required for heating or cooling by 29.3%, 80.5%, 48.5%, and 67.5% in climates zone one, two, three, and four, respectively, compared with the constant temperature limits of the air-conditioning units. This will result in a significant decrease in energy usage that limits GHG emissions and the cost of running the building. The outcomes strongly supported using adaptive restrictions as a strategy to save energy for nearly no cost. Over any type of adaptation to the original building, these adaptive restrictions increase sustainability. The scope of this work could be expanded to involve more accurate data about people's thermal comfort in more than one situation, such as during sleeping, working out, and many other activities. In addition, the emergence of different models using machine learning techniques in recent years has increased the number of model construction research topics. The development of the various populations' thermal comfort standards has been the main focus of research over the last 50 years. A research opportunity seeks to produce a thermal comfort model of people due to the big data trend. Data-driven models may forecast an individual's thermal comfort accurately and effectively by combining data with an effective prediction algorithm. This makes the thermal comfort model more usable and has more real-world applications.

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Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CEN	European Committee for Standardization
CFD	Computational Fluid Dynamics
GHG	Greenhouse Gas Emissions
ISO	International Organization for Standardization
PMV	Predicted Mean Vote Models
PPD	Predicted Percentage Dissatisfied Models

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