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Performance Evaluation and Comparison of Different HVAC Systems for Indoor Temperature Control and Energy Savings

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Abstract

HVAC systems are primarily designed to ensure the thermal comfort of building occupants. Traditionally, HVAC systems regulate the fixed temperature to maintain thermal comfort by constantly monitoring the interior air temperature. ASHRAE 55 is a standard that provides acceptable ranges of operational temperatures for air-conditioned buildings. The HVAC system's set-temperature may be adjusted based on the operational temperature, which is influenced by both indoor air temperature and mean radiant temperature, in order to provide neutral thermal comfort for occupants. This research examines the thermal comfort and energy consumption of two identical HVAC systems that are controlled based on interior air temperature and operating temperature, respectively. Two office rooms with identical architectural arrangements situated in Hong Kong were chosen for a case study. The HVAC systems were controlled according to interior air temperature and operational temperature simultaneously, following occupancy schedules. The study found that an HVAC system regulated by operational temperature provides improved thermal comfort at the expense of a modest increase in energy usage. The study's primary results are valuable for designing energy-efficient HVAC systems and improving comfort in indoor spaces.

Keywords: HVAC systems, Thermal comfort, Indoor air temperature, Energy consumption.

Introduction

Building inhabitants are kept at a comfortable “temperature by heating, ventilating, and air-conditioning (HVAC) systems. The idea relies on multi-parameters, making it often difficult to measure or estimate the thermal comfort. Indoor air temperature (T_i), relative humidity (RH), air velocity (v_a), mean radiant temperature (MRT), clothing value (clo), and metabolic rate (met) are the six characteristics that make up Fanger's Predicted Mean Vote (PMV) index, which is still used by thermal comfort standards like ASHRAE 55 and ISO 7730. The PMV index is based on a temperature scale that goes from -3 (very cold) to +3 (very hot). When the PMV is 0, it indicates that the occupants are completely content with the temperature and humidity levels”. The goal of an HVAC system is to provide a pleasant conditioned atmosphere, and according to ASHRAE 55, a range of ±0.5 of PMV is also considered acceptable.

In order to regulate the functioning of HVAC systems, thermostats often monitor the temperature of the air inside the building. Thermal comfort, however, is a multi-parameter notion that necessitates the inclusion of other factors. One of the important factors influencing thermal comfort is operative temperature (OT), also known as resultant temperature. Because OT is the sum of MRT, Ti, and va, it has a significant impact on the thermal comfort of the occupants. When measuring thermal comfort, several studies used OT instead of T_i. For instance, Kwok and Chun looked at how comfortable it was for students in Japanese schools with air conditioning versus those with natural ventilation. The authors determined OT by measuring the MRT, T_i, and va of the environment. They found that kids' thermal reactions were different in air-conditioned classrooms because of the control they had and the expectations they had of the HVAC system. Since OT stands for both wall temperature and Ti, Nicol and Humpreys discovered a robust correlation between the two variables and thermal comfort in their separate investigation. Outdoor temperature (T_o) is a major determinant of OT, according to the authors.

The use of appropriate control mechanisms, on the other hand, may reduce the energy consumption of HVAC systems. Buildings' energy usage rises due to HVAC system adjustments that aren't correct. For instance, Kusiak et al. looked at how HVAC control settings correlated with energy use. By optimizing HVAC management, the authors were able to save 7.6% of energy when the system was managed only according to the T_i. Nevertheless, the study suggested that other variables, such T_o and MRT, which cannot be controlled, should be included in future research. Jain et al. proposed OT-driven control for HVAC systems in highly-glazed buildings to achieve this goal. According to the authors, energy usage is significantly impacted by summertime window pane temperatures. The research did not, however, look at the thermal comfort of the inhabitants. Using modulation of T_i and OT, Olesen et al. replicated three distinct HVAC systems: a fan-coil system, a floor-based radiant system, and an overhead radiant system. The introduction of an OT-driven control system to a fancoil system improved thermal comfort, according to the findings. Nevertheless, the research did not provide experimental data as it relied on simulations. In a similar vein, Wang et al. recommended OT-driven thermostat control for radiant systems in offices and T_i-driven thermostat control for fan-coil systems based on their simulation findings. Furthermore, in their building energy modeling systems, Niu and Burnett used OT rather than T_i. The researchers found that OT and T_i-based simulations used significantly different amounts of energy. In contrast, Turhan and Akkurt used a T_i-based controller to study the thermal comfort of office workers in a Mediterranean climatic zone. Even though the research was carried out in an office setting, the impact of the OT-driven controller on thermal comfort was not assessed. Most HVAC systems modify the set temperature based on the T_i, even though HVAC systems are typical non-linear multiparameter systems. Additionally, because of the radiation between human bodies and wall surfaces, the thermal comfort of inhabitants is greatly affected by the wall temperatures. So, to improve thermal comfort, it may be preferable to measure OT rather than T_i. While models are useful, in-situ measurements are essential for a complete understanding of energy usage.

As far as the author is aware, there have been just a handful of simulation studies that directly compare HVAC system controllers that use OT with those that use T_i. In contrast to other research, this one compares thermal comfort and energy usage in real-world settings for HVAC systems driven by OT and T_i. To accomplish this, we will use two identical HVAC systems in two identical office rooms; one will be T_i-driven (in Office A) and the other will be OT-driven (in Office B). Using the same occupancy schedules, each office room is filled by one person.

HVAC system energy consumption analysis

In a central air conditioning system, the cold and heat sources, the transmission and distribution systems, the air handling equipment, and the end devices are the primary components that make up the system. In order to generate the necessary amount of energy to either cool or heat, the cold and heat sources, which are also referred to as the host or outside unit, are accountable. In order to ensure that the cold and hot water or wind that is produced by the sources of cold and heat are delivered to the right area, the air duct system or the water pipe system is responsible for doing so. For the purpose of producing the required air, several pieces of machinery such as air conditioning boxes, fresh air units, and air handling units are used. Radiators, a variety of air supply outlets, fan coils, and floor radiation heating and cooling all make up the end equipment, which is the last link in the chain that brings heat or cold into the room. Radiators are the most common form of end equipment. Building strategies and infrastructure development need to work together in order to achieve zero carbon emissions. This is because the selection and implementation of energy-efficient technology in buildings should ideally be coordinated with a variety of other components or parts which make up the infrastructure. It is hard to ignore the amount of energy that is used by machines that are used for air conditioning and refrigeration. The rated power of a refrigeration unit, the load rate, and the period of time that the unit is actively operating all have an impact on the amount of energy that it consumes. It is noteworthy that the conveyancing system has a somewhat high rate of energy consumption.Approximately seventy percent of the entire electrical power consumption is accounted for by the building's ventilation, heating, and cooling systems. The resulting form of an air conditioner has a considerable influence on the amount of energy that it consumes. Altering the location of the end units allows you to change the load in the room at the same time. Maintaining a room temperature that is continuously low will result in an increase in energy use. It is possible to ensure the overall quality of the system by ensuring that this particular component of the building process is sufficiently safe and stable. This, in turn, has an effect on the amount of energy that the HVAC system consumes. The reason for this is because the quality of the water circulation has a significant impact on the amount of energy that the HVAC system consumes.

Case Building

Hong Kong, where the case building is situated, is within the Köppen-Geiger climatic Classification system's Csb climatic zone. The average yearly outdoor temperature is 12ºC, according on statistics from 1927 to 2023. As shown in Figure 1, we will be using two identical office rooms (Office A and B) as our case study.

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Figure 1. Selected offices for the case study (a) Office A (b) Office B

Every office has three walls, one window, and a total size of three meters by five meters by two and a half meters. The orientation of the offices is all towards the south. Throughout the year, the air conditioners in each workplace are adjusted to a temperature of 22 degrees Celsius, ensuring a comfortable interior climate (Fig. 2). Maintaining a steady temperature in the workplace helps employees work as efficiently as possible. Because of its ease of demodulation and controllability using an IR receiver and transmitter, a portable air conditioner is chosen as the HVAC system. Table 1 lists the characteristics of the air conditioner.

Table 1. Specification of air-conditioners

Heating	8700 Btu/h
Cooling	8900 Btu/h
Remote Controller Unit	38 kHz
Energy Supply	220 Volt
COP-heating	3.11
COP-cooling	2.90

Between 8:30 a.m. and 12:30 p.m. and 1:30 p.m. and 5:00 p.m. on weekdays, a guy occupies each office. No visitors or guests are permitted in the offices, and tenants are asked to maintain the same level of use and ventilation schedule. This will help keep the offices at a comfortable temperature during the measurements, which may be caused by internal heat gains. You may find the residents' personal details in Table 2.

Table 2. Occupants' physiological parameters

	Office A	Office B
Gender	Male	
Age	35	35
Body Mass Index (kg)	22.6	22.8

The air-conditioners are operational just during office hours. Each office is considered to have an airtightness of 0.5 ACH (air changes per hour) based on the standard value for naturally ventilated buildings in ASHRAE 55. The exterior wall has an overall heat transfer coefficient (U-value) of 0.90 W/m2K. The roof and ground are considered adiabatic due to the presence of other air-conditioned office spaces. The U-values for the window and door are 1.447 W/m2K and 1.69 W/m2K, respectively. To prevent internal heat sources, the radiators, computers, and gadgets like photocopiers in the office rooms are closed during trials.

Figure 2. Selected HVAC system for the office rooms

Materials and Methods

The approach is comprised of three primary components: the development of control algorithms for heating, ventilation, and air conditioning (HVAC) systems, the execution of a measurement campaign, and the evaluation of the results in terms of thermal comfort and energy need. In Figure 3, a flow chart depicting the methodology that was used in the study is shown.

Developing Control Method

1. Disassemble the HVAC system's infrared codes
2. Make controllers that are powered by Ti and OT available via software and mobile applications.
3. Builts a network of wireless sensors
4. Send IR codes again to change the HVAC system's set temperature.

Measurement Campaign (Office A)	Measurement Campaign (Office B)
1. Measure T_i in Office A	1. Measure OT in Office B
2. Hold Ti at 22°C in Office A	2. Hold OT at 22°C in Office B
3. Obtain thermal comfort for subjective measurements via mobile application	3. Obtain thermal comfort for subjective measurements via mobile application
4. Measure energy consumption of HVAC system	4. Measure energy consumption of HVAC system

Comparison of the Results

1. Compare thermal comfort
2. Compare energy consumption of HVAC system

Figure 3. Overview of the methodology

Developing control methods

In order to make adjustments to the temperature that has been established, the HVAC systems in Office A and Office B are managed utilizing fundamental PID control methods. Adjustments to the heating, ventilation, and air conditioning system are made by PID controllers as a result of the temperature departure from the setpoint that they calculate. It is ensured that the temperatures of each HVAC system are kept at 22 degrees Celsius. The temperature in Office A is managed via T_i readings, but the temperature in Office B is controlled in a different manner. In “the case of Office A,for instance, the controller will transmit infrared signals to start the heating, ventilation, and air conditioning system once the temperature falls below 22 degrees Celsius. In a similar manner, the controller will cease operation of the HVAC system if the temperature rises over 22 degrees Celsius. The identical procedure is being applied to Office B, but this time the system is being run based on the values of the OT measures. The fact that the software for controllers is built in the C programming language is something that should be mentioned thoroughly.

In order to conduct the investigation, we have designed two controllers. There are two microcontrollers for measuring T_i and OT and controlling the HVAC system based on the results, as well as a Wi-Fi Module for wireless communication between OT and T_i sensors, the controller, and mobile applications”. The controller also includes an infrared receiver for demodulating the infrared codes of the HVAC system, an infrared transmitter for sending signals to the HVAC system, and an infrared transmitter for sending signals to the HVAC system.

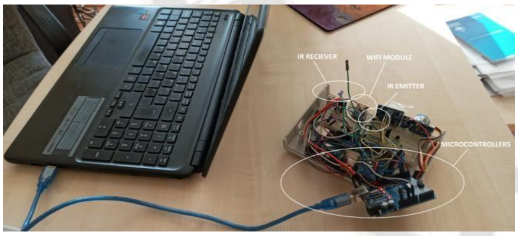

Figure 4. Hardware of controllers

Measurement campaigns

During the period beginning on August 1st, 2022 and ending on January 21st, 2023, the controllers were installed in two different office rooms. These controllers covered both heating and cooling modes. As a consequence of this, a research study is carried out in order to investigate the differences between T_i-driven and OT-driven HVAC systems with relation to thermal comfort and energy consumption. For the purpose of evaluating the interior environment in different office settings, the ISO 7730 standard, which is developed from ASHRAE 55, is applied. All of the offices, including T_o, T_i, and OT, participate in the measurement process. T_i and OT values have been included into the design of the controllers so that they may be used to operate the HVAC systems in Office A and Office B. The temperature of heating, ventilation, and air conditioning (HVAC) systems, to be more exact, air conditioners, is initially set at 22ºC in order to handle both the heating and cooling seasons. After that, a DHT22 sensor is employed in order to collect data about the temperature of the air within Office A (Fig.5). The controller performs an analysis on the outcomes of the measurements, and thereafter, it makes adjustments to the HVAC system by adjusting T_i.

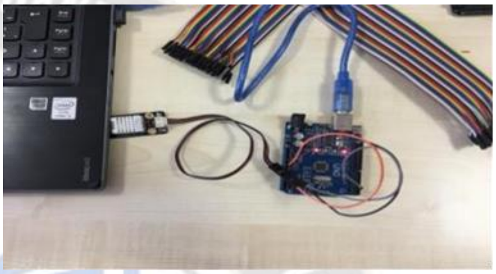

Figure 5. Objective measurements for Office A

Office B uses a specially calibrated globethermometer, created by the author, to continually measure OT (Fig.6). OT is calculated based on Equation 1 from ASHRAE 55 for air velocity at or below 0.1 m/s due to the absence of mechanical ventilation in the office rooms.

$$OT = (T_i + MRT)/2 \qquad (1)$$

A k-type thermometer is placed in the middle of a hollow copper sphere in the globe thermometer that was manufactured. This thermometer is used to calculate the "Mean Radiant Temperature" (MRT). The temperature that is received from the "globe thermometer" (Tg) is kept on a server, and the Mean Radiant Temperature (MRT) is calculated by the controller using Equation 2 in an automated manner. The diameter of the copper sphere, which is matte black in color, is 150 millimeters, and its emissivity is 0.95.

$$MRT=\left[(T_g - T_i)^4 x \frac{0.25 \times 10^8}{\varepsilon} x \left(\frac{|T_g - T_i|}{D}\right)^{\frac{1}{4}} (T_g - T_i)\right]^{\frac{1}{4}} - 273 \qquad (2)$$

The accuracy of the developed sensors is ensured when they demonstrate proper calibration. For this purpose, a designed globe thermometer is calibrated using a well-known commercial globe thermometer.

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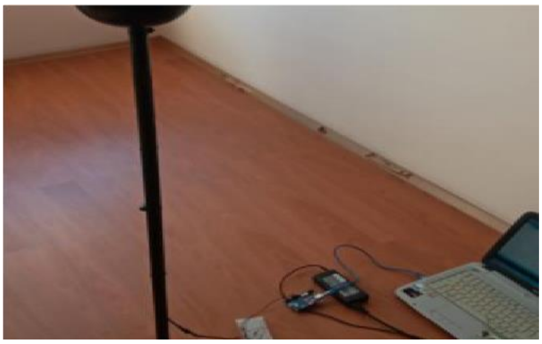

Figure 6. Built an office-specific globe thermometer to track OT

In accordance with the recommendations provided by ASHRAE 55, each measuring sensor is positioned in the same manner and at a height of 1.1 meters directly above the ground. In order to reflect the amount of energy that is expended during ordinary work while sitting in an office, the metabolic rate of the occupants has been set at 1 metabolic equivalent (M = 57.9 W/m2). In the process of subjective measurement, the Thermal Sensation Vote (TSV) is gathered from the people who are using the space. For the purpose of avoiding disturbances in TSV, participants are selected on the basis of their age and body mass indices that are similar to one another. When it comes to subjective evaluation, an Android smartphone application is developed (Fig. 7). The software in the initial interface makes a request for the location of the tenant in order to ascertain the thermal preferences that are linked with various workplaces. Following this, the occupants are required to evaluate their sensation of temperature using the ASHRAE seven-point scale that has been devised. During the course of the office hours, the renters periodically use the smartphone application at intervals of ten minutes.

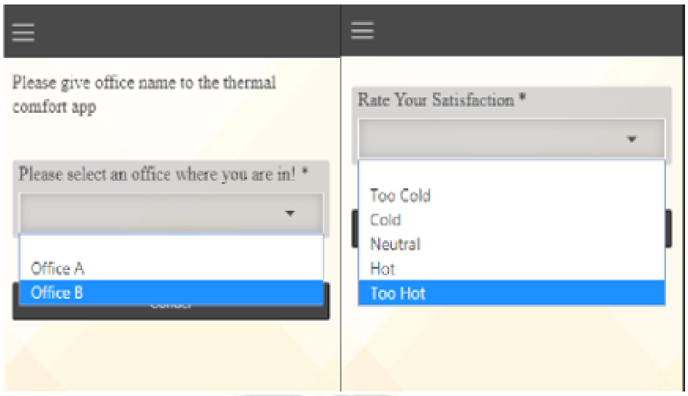

Figure 7. Mobile app screenshots created for the research

The air-conditioners' energy usage is quantified in kilowatt-hours using a three-phase power analyzer. Table 3 provides a list of the instruments utilized and their respective levels of accuracy. The data representing the objective and subjective measurements are stored in a web server, and the microcontrollers that are situated in both of the office rooms are responsible for carrying out mathematical calculations.

Table 3. Specifications of the instruments

Instrument	Measured parameter	Accuracy
DHT 22	T_i, T_o	< 1 ºC
Globe-Thermometer (developed by the author)	OT	< 1 ºC
Extech Power Analyzer	Energy consumption in kWh	± 2% for kWh

Comparison of the results

The findings are compared based on thermal comfort and energy usage. Power analyzers monitor the energy consumption of HVAC systems, while a mobile application is used to determine the TSV of the occupants. The purpose of comparing T_i and OT-driven HVAC systems is to determine which approach is more effective in achieving thermal comfort and energy efficiency.

Results and Discussions

During the time period beginning on August 1, 2022 and ending on January 21, 2023, encompassing both the summer and winter seasons, objective parameters (T_i, T_o, and OT) and subjective parameters (TSV) are monitored and stored. This is in accordance with the information provided in Section 3.2. It is important to take notice that October is considered to be part of the cooling season since the average temperature throughout the month is higher than usual.

The total number of measurement days, together with the values for T_o, T_i, and OT, are shown in Table 4. This table also includes the heating and cooling modes.

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Table 4. Duration of measurement for T_o, T_i, and OT values

			Office A	Office B
Experiment Days	Heating		60	
	Cooling		71	
To (oC)	Heating	Min	-1.5	
		Max	20.9	
		Average	3.5	
	Cooling	Min	20.4	
		Max	26.4	
		Average	22.8	
Ti (oC)	Heating	Min	21	21.4
		Max	22	23.1
		Average	21.4	22.4
	Cooling	Min	21.8	21.4
		Max	22.5	23.6
		Average	22	22.2
OT(°C)	Heating	Min	16.1	21.2
		Max	21.1	22
		Average	17.4	21.6
	Cooling	Min	21.4	21.9
		Max	24.5	22.4
		Average	22.6	22

According to the information shown in Table 4, the values of T_o run the gamut from -1.5 to 26.4 degrees Celsius. To further complicate matters, T_i and OT are both greatly impacted by To, which leads to an increase in the amount of energy that is required to attain the target temperature for both controllers. An illustration of the daily average values of T_i, T_o, OT, and TSV for Office A can be seen in Figure 8. A representation of the TSV values of the renter is shown by the black lines.

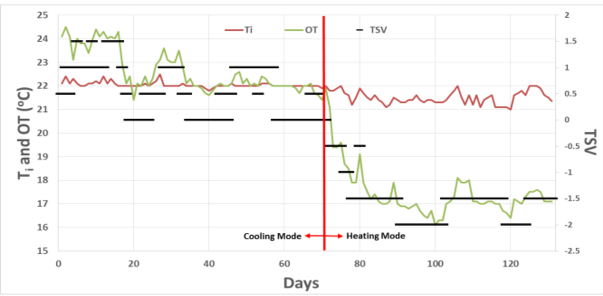

Figure 8. Measurement results for Office A

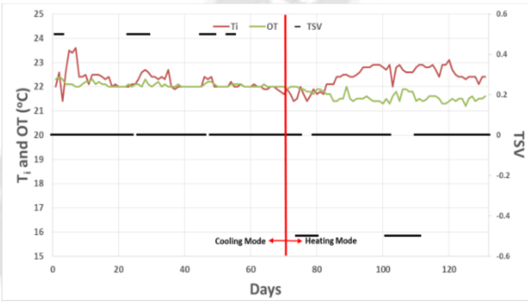

Figure 9. Measurement results for Office B

A smartphone app is used to get the TSV values of the people living there. Comparing the TSV of the two control systems is also shown in Figures 8 and 9. In contrast to T_i-driven HVAC systems, OT-driven systems have TSV values that range from -2 to 1.5. When the OT-driven HVAC system is in use, the tenant reports feeling neutral 82% of the time. For a T_i-driven HVAC system, this number is only 26%.

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The energy usage of two separate controllers is shown in Figure 10. Energy consumption for OT-driven HVAC systems is 2.4% higher than that of T_i-driven systems. On the other hand, OT-driven HVAC systems used 539.6 kWh of energy over the 131-day trial, whereas T_i-driven systems used 526.8 kWh. In any case, it bears repeating that occupants in an OT-driven HVAC system do not feel anything.

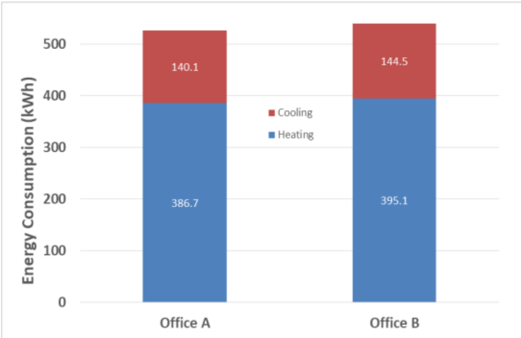

Figure 10. Comparison of energy consumption of OT and T_i-driven HVAC systems

Temperature variations within the same workplace might be the cause of the OT-driven HVAC system's increased energy use. For instance, in various parts of an office that are exposed to abundant radiant heat from building components like windows and walls, the OT may differ from T_i. Also, in structures with lots of windows, the OT is different from T_i since the window temperature isn't the same as the measured T_i. There is a noticeable disparity between the OT and T_i spaces because to the case office's very high window-to-wall ratio of 3.6. Accordingly, to achieve the specified temperature, the OT-driven HVAC system uses somewhat more energy than the T_i-driven one.

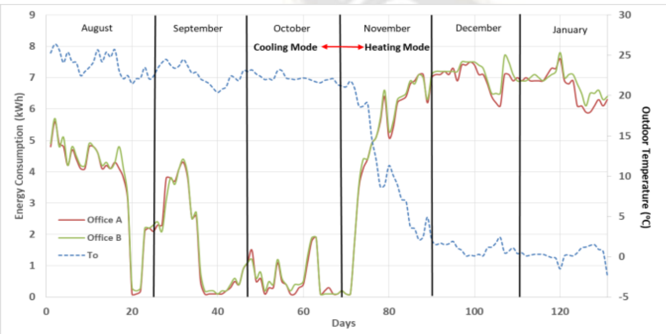

Figure 11. Daily energy consumption of offices

When comparing the heating modes of OT-driven and T_i-driven HVAC systems, Figure 11 shows that the former uses more energy. The chilly weather in Ankara might be the reason why the walls are colder than T_i. Table 4 shows that both offices' average T_i and OT values are below their set-temperatures. Because of this, during the heating season, the energy consumption of an HVAC system powered by OT rises.

To summarize the study's main points, we found that:

1. After using an OT-driven HVAC system, most people report feeling neutral.
2. In a Ti-driven HVAC system, the TSV value is zero for just 26% of the entire measurement days. The occupants may be experiencing discomfort because to temperature changes between the walls and windows from Ti.
3. Energy consumption increases with an OT-driven HVAC system. The little energy savings of a Tidriven HVAC system (2.4% of the total) is insignificant when compared to the increased comfort experienced by occupants.

Results pertaining to the uncertainty analysis of the measurements are further detailed in the section that follows.

Uncertainty Analysis

The Monte-Carlo approach, which is dependent on measurement mistakes, is used in uncertainty analysis. Consequently, the analysis is carried out by assuming mean values for the measurement findings, with minimum and maximum values derived from the precision of the measuring equipment for each measurement. Table 5 shows the energy consumption findings of the investigation.

Table 5. Energy usage compared using the Monte-Carlo technique

Office Type	Maximum (kWh)	Average (kWh)	Minimum (kWh)
Office A	547.1	526.8	501.6
Office B	549.3	539.6	529.1

Energy consumption of OT-driven HVAC systems is higher than that of T_i-driven systems even when measurement mistakes are included into the experiment. One thing to keep in mind is that these findings can be different when using equipment with lower precision. The Monte-Carlo approach also seems to help validate the data used to compare two HVAC systems, which is useful when dealing with uncertainty and modeling mistakes.

Conclusions

This paper's objective is to examine thermal comfort and energy usage as they pertain to HVAC systems that are driven by T_i and those that are driven by OT. For the purpose of this case study, two identical office rooms will be considered. In order to manage the set-temperatures of the HVAC system in the office rooms, two separate systems were created and put into use: one that use OT and another that uses T_i. One guy occupies each office room and measurements are taken throughout office hours. We use objective sensors to measure T_i, T_o, and OT, and we use a custom-built mobile app to calculate TSV. While there was a little increase in energy usage, the findings demonstrated that the thermal comfort was greater with an OT-driven HVAC system.

One occupant provides the TSV values used in the research. With a bigger occupancy, however, the findings may be confirmed. Even though the research used two occupants with almost identical physiological characteristics, factors like psychology may influence TSV and energy usage habits.

However, the case office is housed in a modest office building. Wall and window temperatures have a greater impact on thermal comfort in smaller workplaces than in bigger ones. In order to achieve this goal, trials will be carried out in various types of workplaces that have higher occupancy rates in future studies.

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