

Article

Determining Indoor Parameters for Thermal Comfort and Energy Saving in Shopping Malls in Summer: A Field Study in China

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Abstract: Local data about indoor thermal comfort are in short supply, which are always different from the predicted results produced by models shown in previous studies. Shopping malls that consume substantial energy need to save energy, provided that thermal comfort is maintained. Therefore, this research investigated indoor thermal comfort using field measurements and questionnaires in a typical shopping mall in Danyang, China, with a hot summer and cold winter climate in order to explore local demands and energy-saving potential. The findings are as follows: (1) The average air temperature (T_a) and operative temperature (T_{op}) are 26.7 °C and 26.4 °C, which implies a minor influence from radiation and other factors on T_a . Women are more sensitive to changes in outdoor temperature since clothing insulation (I_{cl}) varies by gender: 0.31 clo and 0.36 clo for male and female individuals, respectively. (2) The thermal neutral temperature (TNT) derived from the thermal sensation vote (TSV) is 25.26 °C, which is significantly higher than the 21.77 °C obtained from the predicted mean vote (PMV) model. (3) There is a wide range of acceptable temperatures for thermal comfort because the highest temperature was identified by the thermal comfort vote (TCV) at 27.55 °C, followed closely by 27.48 °C, 26.78 °C, and 25.32 °C, which were separately derived from the thermal acceptance vote (TAV), TSV, and predicted percentage of dissatisfied (PPD) people; these were based on an upper limit of the acceptable 80% range. (4) In total, 94.85% of respondents accepted the indoor air quality, although the median concentration of CO₂ was 772 ppm, and the neutral relative humidity level was 70.60%. Meanwhile, there is an important relationship between air quality satisfaction and operative temperature; thus, the temperature (26.93 °C) with peak satisfaction can enhance air quality perception and thermal comfort. (5) The energy savings that can be achieved are 25.77% and 9.12% at most based on acceptable thermal comfort compared with baseline energy consumption at 23 °C and 26 °C, respectively.



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1. Introduction

With social and economic development and increases in residents' disposable income, people's attention to indoor environmental quality has shifted from basic temperature and humidity control to more refined demands for thermal comfort [1–5]. Previous studies showed that this shift was directly related to improved living standards: when the gross domestic product (GDP) per capita exceeded USD 10,000, the public was significantly more sensitive to indoor thermal environments and willing to pay extra for comfort [6–9]. Thermal comfort is not only correlated with occupants' physical balance but is also a

potential risk factor for human health [10,11]. For example, long-term exposure to high temperatures may induce cardiovascular disease and respiratory dysfunction, while low temperatures in winter are significantly associated with joint pain and decreased immunity [12–14]. In addition, thermal comfort indirectly regulates psychological states through the neuroendocrine system: experimental data show that when the room temperature deviates from the thermal neutral temperature (TNT) by more than 2 °C, anxiety levels and decision-making error rates increase by 18% and 24%, respectively [15,16]. In commercial and office scenarios, the impact of thermal comfort on productivity is more prominent; American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standards specify that maintaining indoor temperatures within the scientifically calculated range corresponding to predicted mean vote (PMV) values of ± 0.5 can enhance employee work efficiency by 12–15%. Conversely, an excessively hot or cold environment can lead to distractions and longer task completion times [17–19]. In the design of modern commercial spaces, indoor thermal environment management has been upgraded from a basic service to a strategic competitive factor [20]. However, existing studies predominantly focus on severe hot or cold climates, lacking empirical data on localized thermal adaptation behaviors (e.g., humidity sensitivity and clothing insulation differences) in hot summer and cold winter (HSCW) shopping malls, while the PMV model inadequately accounts for these regional factors [21,22]. It was shown that when the indoor temperature is maintained at 22–24 °C and relative humidity is controlled at 40–60%, the PMV value reaches the optimal one, and this microclimate environment can significantly increase the duration of customer stays in shopping malls by over 35% [23,24]. From the perspective of consumer behavior, the probability of impulse purchases increases by 18.7% for every increase of 1 standard unit in thermal comfort, which is due to the release effect of cognitive resources brought about by the reduction in heat stress [21,25]. It should be noted that the energy efficiency of the building must be considered when analyzing the indoor thermal comfort of shopping malls, because high energy consumption will greatly increase the operating costs of the building, waste energy, and cause serious environmental impacts [26,27]. The use of heating, ventilation, and air conditioning systems represents a significant share of global energy consumption, accounting for 60–70% of total building energy consumption [28,29]. The heating, ventilation, and air conditioning systems of shopping malls consume 10–20-times more energy than residential buildings due to their high indoor thermal comfort requirements, large number of air conditioners, extensive ventilation needs, and long operating hours [30,31]. At the same time, with the rapid growth of China's economy and the acceleration of urbanization, the number of shopping malls is also increasing dramatically [24,32], and the energy conservation of shopping malls is particularly important in the context of global energy shortages and global warming [33–35].

At present, according to the national standards for building energy saving (GB50189-2015 [36] and GB55015-2021 [37]) in China, the indoor temperature setting standard for shopping malls is 20–23 °C in spring, 25–27 °C in summer, and 18–20 °C in winter [22]. In order to optimize customers' shopping experience in shopping malls, managers often adopt a seasonal air-conditioning control strategy, such as simply raising the temperature in winter and lowering the temperature in summer. However, most of the above operations focus on the mechanical control of temperature and humidity, and they lack the dynamic adaptation to thermal comfort [21]. On the one hand, the integration of multiple business formats leads to the complexity of spatial circulation (such as atrium voids and floor functional zoning) [38]; on the other hand, the number of customers fluctuates significantly with holidays and time periods, resulting in continuous changes in indoor thermal inertia and energy loads and forming a highly dynamic and nonlinear physical environment system [38–40]. However, current standards are not able to provide specific and local

data references for indoor thermal comfort parameters in different regions since they do not have sufficient localized data and concentrate on the general and unified guidance. Therefore, the thermal comfort in shopping malls in different regions may not be able to meet customers' real and localized needs in the indoor environment by adopting the current unified standard as the settings of comfort parameters. More importantly, mismatching and blind settings lead to serious energy waste at the same time.

In order to reduce energy consumption and improve indoor thermal comfort, studies have investigated and analyzed the indoor thermal environment and thermal comfort in different shopping malls. Surveys on the thermal environment of shopping malls in different regions showed that relevant standards or models cannot accurately predict indoor thermal comfort, and shopping malls tend to be overheating in winter and overcooling in summer, resulting in relatively low thermal satisfaction and huge energy waste [21]. It was also emphasized that temperature discomfort can also directly trigger physiological discomfort reactions from customers or occupants [41], and the most significant one is that the high indoor temperature (above 27 °C) in summer leads to a significant decrease in users' thermal satisfaction [42]. Although the indoor temperature and humidity of shopping malls meet the requirements of civil building standards according to the study on the indoor thermal environment of shopping malls in hot summer and cold winter climate zones of China [43], the indoor temperature range of air conditioning in winter specified in the standard does not actually make users in shopping malls feel comfortable. The thermal resistance of customers' clothing in the shopping mall environment (average 0.6 clo) is significantly lower than that in the office (1.0 clo), and the dynamic activity level (metabolic rate of about 1.6 met) is higher than that in the static space, indicating that shopping malls need to adopt different indoor temperatures to meet the thermal comfort requirements of customers [43–45]. Even if people in different shopping malls have different needs for comfortable indoor temperatures [45], overheating in winter and overcooling in summer are the main reasons why customers feel uncomfortable in shopping malls. Overcooling is quite common in shopping malls in summer since their managers generally have the misconception that “low temperature is a high-quality environment” and believe that a low-temperature environment of 18–22 °C can increase customers' willingness to spend money on shopping. Unfortunately, 26–28 °C is probably the suitable range for both comfort and energy saving [46,47] based on numerous previous findings. In addition, the overall satisfaction of customers in shopping malls is also determined by many other indoor factors, such as air quality, light intensity, ambient odor, and noise [48–51].

Given the urgent need for shopping malls to save energy and improve customers' thermal comfort satisfaction, it is crucial to investigate and study the localized and actual thermal comfort needs of customers in different commercial buildings with different climate characteristics in order to ensure that shopping malls can not only effectively meet customers' needs for the indoor environment but also reduce energy consumption and operating costs. However, previous studies on the thermal environment in shopping malls tended to focus on some big cities/regions with typical climatic conditions, and the number of field investigations was limited. Consequently, shopping malls usually lack the local real data to guide indoor thermal comfort operations so they are unaware of customers' actual thermal comfort needs or strategies to balance energy efficiency with comfort corresponding to different climates. To address these gaps, this study investigated the iconic shopping malls in a typical city named Danyang in Jiangsu Province with a hot summer and cold winter climate and monitored the indoor physical environment of the mall in summer and collected subjective questionnaires about indoor thermal comfort. Thus, the main objectives of this study are as follows:

- To analyze the indoor thermal environment and establish objective benchmarks through measurements of indoor temperature, humidity, CO₂, black globe temperature, and wind speed.
- To identify the thermal comfort characteristics and requirements of occupants in regional shopping malls during summer conditions and obtain localized subjective thermal comfort data, by conducting questionnaire surveys on customers' clothing choices, dwell time, thermal preferences, thermal comfort evaluations, humidity perception, and air quality satisfaction, followed by systematic analysis of the collected responses.
- To develop an integrated model based on the analysis of collected subjective and objective data in order to find optimal ranges for indoor thermal comfort parameters.
- To explore the optimal balance between energy savings and thermal comfort in shopping malls with hot summer and cold winter climate.

2. Methodology

2.1. Survey Site and Climatic Conditions

The “Thermal Design Code for Civil Buildings” in China classifies the country into five climatic zones: severe cold, cold, hot summer and cold winter (HSCW), hot summer and warm winter, and mild. Danyang (31°44′–32°09′ N, 119°24′–119°54′ E), located in the HSCW zone (as shown in Figure 1), experiences substantial annual precipitation and relatively weak solar radiation along with distinct seasonal contrasts. Its summer is characterized by sultry conditions with daily average temperatures exceeding 25 °C for 49 to 110 days annually and peaking at 25 °C to 30 °C in the hottest month. In contrast, winters are cold and damp, with average temperatures in the coldest month ranging from 0 °C to 10 °C and daily average temperatures at or below 5 °C for 0 to 90 days annually.



Figure 1. Location of the survey site.

The climate in Danyang is characterized by a subtropical monsoon pattern, situated in the eastern sector of the HSCW climate zone. This city exhibits distinctive meteorological features, including elevated humidity levels, substantial solar radiation, abundant annual precipitation, an extended frost-free period exceeding 240 days, and pronounced seasonal variability. Data from the Danyang Meteorological Station indicate that summer winds are predominantly easterly and southerly, while winter winds are mainly northerly with southeasterly and easterly winds dominating annually at an average speed of approxi-

mately 3.2 m/s. The annual mean temperature is 15.8 °C, with monthly average maximum temperatures ranging from 28 °C to 34 °C and monthly average minimum temperatures between −2 °C and 2 °C. Danyang receives a total of 1916.2 h of sunshine annually and experiences an average annual precipitation of 1060 mm while maintaining a mean relative humidity of about 75%.

The survey was conducted in summer when extreme heat and strong solar radiation caused a rapid temperature increase and discomfort. Average nighttime temperatures of around 27 °C created residual heat that contributed to a sultry atmosphere. The monsoon's influence and strong convective air resulted in concentrated summer precipitation that led to frequent heavy rainfall over short periods. Heavy rainfall events often coincided with thunderstorms and high humidity, which intensified the overall feeling of discomfort.

2.2. Data Collection

2.2.1. Objective Data Collection

The thermal sensations of building occupants are influenced by multiple interrelated quantitative and qualitative factors. Four primary factors have been identified: indoor air temperature (T_a), relative humidity (RH), mean radiant temperature (T_{mr}), and air velocity (V_a) [52]. Additionally, the Indoor Air Quality Standard (GB/T 19883-2022) in China specifies a maximum permissible indoor CO₂ concentration of 0.10% (1000 ppm) in public spaces such as shopping malls to ensure adequate air quality and safeguard occupant health and comfort [53].

Measurements of T_a and RH were conducted using a portable thermometer with a measurement range of 0 °C to 60 °C and 0% to 99% RH, achieving an accuracy of ± 0.5 °C and $\pm 5\%$ to evaluate indoor thermal conditions. V_a was recorded with a hot-wire anemometer that measures from 0 m/s to 10 m/s and has an accuracy of ± 0.1 m/s. T_{mr} was determined using a 75 mm black globe thermometer with a range of 0 °C to 80 °C and an accuracy of ± 1 °C. CO₂ concentrations were monitored with a non-dispersive infrared (NDIR) sensor-based instrument that ranges from 400 ppm to 5000 ppm and has an accuracy of ± 50 ppm, selected for its high sensitivity to CO₂ fluctuations. All instruments adhered to ISO 7726 standards for microclimate data acquisition [54], with specifications detailed in Table 1.

Table 1. Monitoring equipment.

Equipment	Function	Size	Range	Accuracy	Resolution	Illustrations
Model LYW5D03MMC small thermometer (Manufacturer: Miaomiaocai Technology Co., Ltd., Beijing, China)	Air temperature	43 × 43 × 12.5 mm	0–60 °C	± 0.5 °C	0.1 °C	
	Relative humidity		0–99%	$\pm 5\%$	1% RH	
Model 8778 black globe thermometers (Manufacturer: Dongguan Hengxin Instrument Co., Ltd., Dongguan, China)	Globe temperature	278.2 × 75 × 75 mm	0–80 °C	15–40 °C: ± 1 °C; other: ± 1.5 °C	0.1 °C/°F	

Table 1. Cont.

Equipment	Function	Size	Range	Accuracy	Resolution	Illustrations
Model 405-V1 hot-wire anemometer (Manufacturer: Testo Instrument International Trading (Shanghai) Co., Ltd., Shanghai, China)	Air velocity	49 × 37 × 36 mm (Wind Speed Probe: diameter 13.5 mm, extendable to 300 mm)	0–10 m/s	±0.1 m/s	0.01 m/s	
Model MHO-H411 CO ₂ concentration monitor with NDIR sensor (Manufacturer: Miaomiaocai Technology Co., Ltd., Beijing, China)	CO ₂ concentration	50 × 50 × 16.3 mm	400–5000 ppm	±50 ppm ±5% reading	1 ppm	

The survey was conducted on the first floor of the shopping mall, which was divided into five zones: east, south, west, north, and central. Measurement points were systematically positioned in high-occupancy areas, including corridors that connect atria and public spaces to capture representative thermal conditions. All sensors, including the globe thermometer and humidity sensors, were calibrated in advance by co-locating with laboratory-grade reference instruments in a controlled environment. In accordance with the Standard for Energy Efficiency Test of Public Buildings (JGJ/T 177-2009) in China, sensors were installed at heights ranging from 1.0 m to 1.5 m above floor level [55]. Each zone was equipped with a compact thermometer to monitor localized temperature variations without disrupting mall operations. A centrally located station on the first floor housed the hot-wire anemometer, black globe thermometer, and CO₂ monitor for integrated data collection. Objective measurements were performed daily from 10:00 to 21:00 throughout the study period, with instantaneous spot readings recorded at 60 min intervals (hourly sharp time points) to capture representative thermal conditions while minimizing operational disruptions.

2.2.2. Subjective Data Collection

The survey was conducted over 19 days from 13 to 31 August 2024, during which 660 questionnaires were collected. Data collection utilized a team-based approach with each team consisting of two researchers, one who operated and monitored the measurement equipment and the other who delivered questionnaires to mall customers and staff. Researchers wore standardized identification badges throughout the process to enhance transparency and reduce potential respondent bias.

The participants primarily included mall customers and staff who were mostly local residents, and their responses were representative of the local population's adaptation to regional climate conditions and the indoor thermal environment of the mall. The survey took place on the first floor where respondents generally stood. Each session lasted approximately one minute and began with a 20 s explanation of this study's objectives, followed by 40 s for questionnaire completion after obtaining informed consent. To incentivize participation, respondents received a small token of appreciation upon submitting their questionnaires. The survey workflow is illustrated in Figure 2.

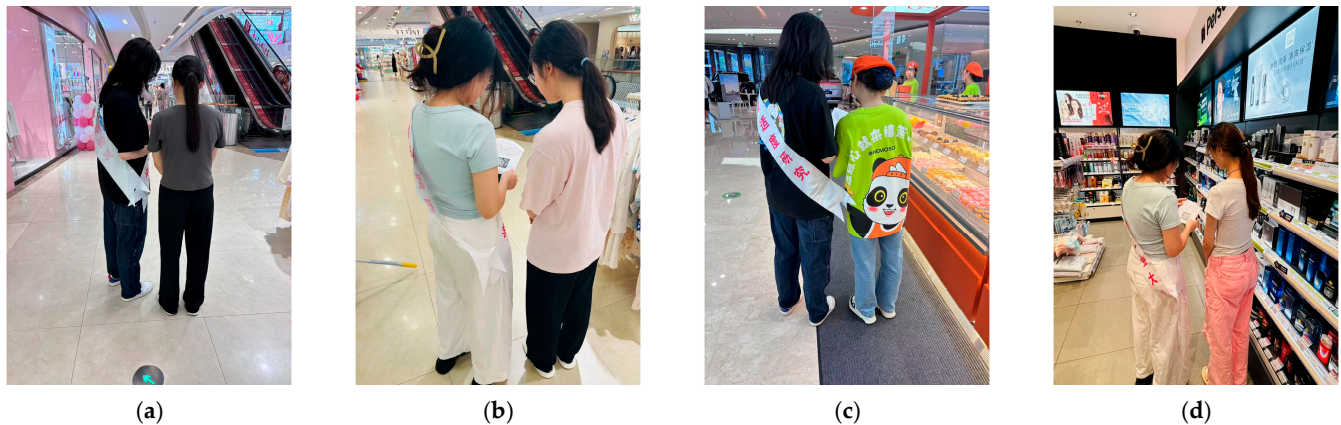


Figure 2. The field survey in the shopping mall: (a,b) introduce the survey objectives and procedures to customers; (c,d) explain the survey content and obtain consent from mall staff. Note: Team members wear identification badges with bilingual slogans (front: “Nanjing Tec h University” in Chinese; back: “Thermal Comfort Survey in Shopping Mall” in Chinese) to ensure transparency and participant awareness.

The thermal comfort questionnaire was developed in accordance with ISO 10551 [56] and comprised four sections: (1) personal information (age, gender, and present identity), (2) current status (duration of stay, clothing insulation for upper/lower body, and footwear), (3) thermal comfort evaluations (thermal sensation vote, thermal comfort vote, thermal preference vote, and thermal acceptance vote), and (4) air quality perceptions (humidity sensation vote, air quality satisfaction vote, and ventilation sensation vote). The complete structure is summarized in Table 2.

Table 2. Major design of survey questionnaire.

Categories	Questions	Options for Answer
Personal information	Age	<20 or 20–29 or 30–39 or 40–49 or ≥ 50
	Gender	Male or Female
	Present identity	Customer or Mall staff
Present situation	Residence time	<30 min or ≥ 30 min
	Upper garment	Categorize clothing into inner and outer layers, with a total of 15 selection options.
	Underwear	9 selection options
	Shoes and socks	5 selection options
Thermal comfort vote	Thermal sensation vote (TSV)	7-point scale (from -3 “very cold” to $+3$ “very hot”)
	Thermal comfort vote (TCV)	5-point scale (from -2 “fully uncomfortable” to $+2$ “fully comfortable”)
	Thermal preference vote (TPV)	5-point scale (from -2 “cooler” to $+2$ “warmer”)
	Thermal acceptance vote (TAV)	4-point scale (from 0 “fully acceptable” to 3 “fully unacceptable”)
Air sensations vote	Humidity sensation vote (HSV)	5-point scale (from -2 “humid” to $+2$ “dry”)
	Air quality satisfaction vote (AQSV)	5-point scale (from -2 “very satisfied” to $+2$ “very dissatisfied”)
	Ventilation sensation vote (VSV)	5-point scale (from -2 “stuffy” to $+2$ “blowing”)

Thermal sensation vote (TSV) utilized a 7-point scale (-3 to $+3$), anchored by very cold (-3) and very hot ($+3$), with a neutral midpoint (0). Thermal comfort vote (TCV) employed a 5-point scale (-2 to $+2$), ranging from very uncomfortable (-2) to very comfortable ($+2$). Similarly, thermal preference vote (TPV) used a 5-point scale (-2 to $+2$), where -2 indicated a preference for cooler environments and $+2$ denoted warmer environments.

Thermal acceptance vote (TAV) was assessed via a 4-point scale (0 to 3), with 0 representing fully acceptable and 3 indicating fully unacceptable. The questionnaire was designed in Chinese to minimize linguistic ambiguities, as it is the native language of the respondents.

2.3. Data Analysis Methods

2.3.1. Objective Data Analysis

The operative temperature (T_{op}) defined by ASHRAE 55 serves as a comprehensive indicator of the indoor thermal environment because it accounts for both T_a and T_{mr} [57]. T_a does not fully capture the influence of radiant heat, as surrounding surfaces such as walls and display cabinets primarily exchange heat with occupants through radiation in shopping malls. Therefore, T_{op} provides a more accurate representation of the thermal conditions perceived by the human body.

In accordance with ISO 7726, T_{op} can be estimated using Equation (1) under practical conditions where the relative V_a is low (<0.2 m/s) or the temperature difference between T_{mr} and T_a is minimal (<4 °C) [54]:

$$T_{op} = \frac{T_a + T_{mr}}{2} \quad (1)$$

where T_{op} is the operative temperature, T_a is the indoor air temperature, T_{mr} is the mean radiant temperature.

T_{mr} is calculated according to Equation (2) with reference to ISO 7726 [54]:

$$T_{mr} = T_g + 2.44V_a^{0.5}(T_g - T_a) \quad (2)$$

where T_{mr} is the mean radiant temperature, T_g is the globe temperature, V_a is the indoor air velocity, and T_a is the indoor air temperature.

The thermal insulation properties of clothing items are assessed according to methodologies prescribed in ASHRAE 55 [57] and ISO 7730 [58]. Summer apparel data obtained from questionnaires are analyzed using ISO 9920's standardized definitions for clothing material insulation [59]. Total clothing insulation (I_{cl}) is then computed through Equation (3), as defined by ASHRAE 55 [57]:

$$I_{cl} = 0.83 \cdot \sum_i I_{cl,i} + 0.161 \quad (3)$$

where $I_{cl,i}$ represents the clothing insulation of a single garment (clo).

The PMV and predicted percentage of dissatisfied (PPD) are calculated using the ISO 7730 framework [58], incorporating six parameters: T_{mr} , T_a , RH, V_a , I_{cl} , and metabolic rate (MR). As most occupants remained standing during observations, an MR of 1.6 met (93 W/m^2) was applied to reflect typical retail activity levels.

2.3.2. Subjective Data Analysis

Linear regression analysis is adopted to establish separate equations for the measured TSV and the PMV in relation to the T_{op} [58], in which the slopes of these equations indicate the sensitivity of respondents to air temperature [60]. By setting TSV = 0 and PMV = 0, we can determine both the measured TNT and the predicted TNT. Additionally, the ranges of $-0.5 < \text{TSV} < +0.5$ and $-0.5 < \text{PMV} < +0.5$ define two thermal neutral temperature ranges (TNTRs) [61]. This analysis assesses the applicability of the PMV model in evaluating thermal comfort in the surveyed shopping mall during the investigation period, highlighting the distinctions between measured and predicted values.

Thermal acceptability (TA) is assessed using both measured and predicted methods. The percentage dissatisfied is evaluated using measured indicators, such as the TAV, TSV, TCV, and PPD values. Quadratic regression relationship between the percentage dissatisfied and the T_{op} is used to define thermal acceptability ranges at 80% and 90% for each indicator.

This study investigates indoor air quality (IAQ) in shopping malls by analyzing RH and carbon dioxide (CO₂) levels. Firstly, linear regression is performed between humidity sensation vote (HSV) and RH. The neutral relative humidity (NRH) is determined by setting HSV = 0, with the neutral relative humidity range (NRHR) defined based on the criteria $-0.5 < \text{HSV} < +0.5$ [62]. Secondly, IAQ assessment is conducted by examining spatial distribution patterns of CO₂ concentration and occupancy density (OD). Finally, a second-order polynomial regression analysis is employed to establish the relationship between air quality satisfaction rate and T_{op} , identifying the T_{op} value associated with peak satisfaction.

2.4. Analysis of Energy Savings Based on Indoor Thermal Comfort

2.4.1. Energy Consumption

SketchUp Pro 2024 (Trimble Inc., Westminster, CO, USA), a three-dimensional (3D) modeling software leveraging NURBS-based surface modeling and parametric component libraries, was employed to construct high-precision building geometry models [63,64]. Its core advantages include the following: (1) rapid generation of complex spatial forms (e.g., atrium–curtain walls) via the “Push/Pull” tool; (2) iterative definition of envelope layer compositions (e.g., exterior walls = cladding layer + insulation layer + structural layer) using dynamic components; and (3) integration of standardized equipment (e.g., fan coil units) through the open-source 3D Warehouse model repository. Upon completion of geometric modeling, thermal property configurations and space-type classifications were implemented via the OpenStudio plugin (v3.6.0) [65], ultimately exporting the model into the EnergyPlus (v25.1.0)-compatible IDF file format to achieve seamless integration between geometric modeling and energy simulation [66,67]. Previous research has proved the effectiveness of integrating SketchUp with EnergyPlus for building energy consumption studies [68]. In this investigation, the case study mall is digitally reconstructed using SketchUp and simulated its energy consumption in EnergyPlus, as shown in Figure 3. Building envelope thermal properties are configured in compliance with China’s Design Standard Energy Efficiency in Public Buildings (GB 50189-2015) [36], with detailed material specifications provided in Table 3. Climate data utilize the typical meteorological year (TMY3) dataset for Danyang, Jiangsu, embedded in EnergyPlus. Occupant density parameters are established as: 0.35 persons/m² for retail areas and 0.60 persons/m² for food service zones. Equipment loads are defined at 8 W/m² (retail) and 25 W/m² (catering), while lighting power density is 12 W/m² based on the Standard for Lighting Design of Buildings (GB 50034-2013) [69]. The HVAC system employs a constant air volume (CAV) configuration, with operational hours spanning 10:00 to 22:00 local time.

Table 3. Building envelope materials and heat transfer coefficient.

Building Envelope	Materials	Heat Transfer Coefficients (W/(m ² ·K))
Exterior wall	20 mm stone veneers + 80 mm rock wool insulation + 200 mm structural concrete layers	0.65
Roof	5 mm waterproofing layers + 100 mm XPS insulation boards + 150 mm concrete layers	0.50
External window	12 mm double Low-E insulating glass	2.80

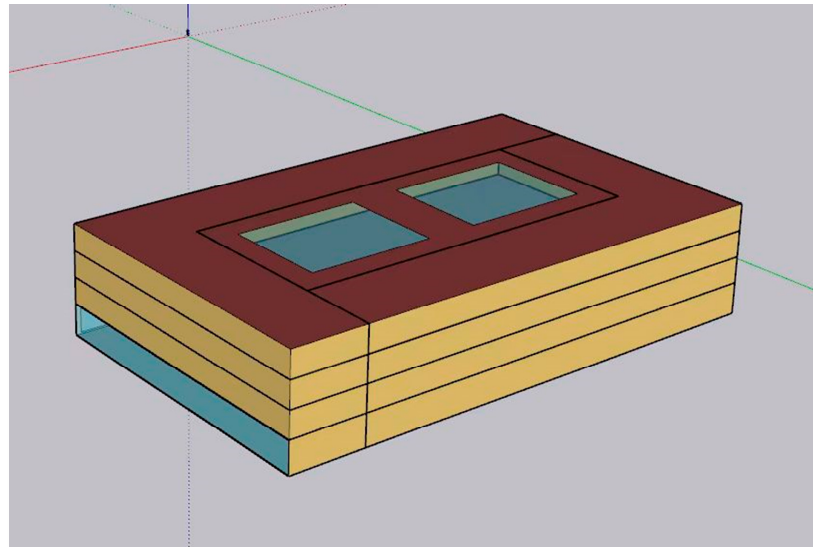


Figure 3. Energy model of the surveyed shopping mall.

2.4.2. Energy Efficiency

Utilizing the PMV-PPD model and the Global Thermal Comfort Database, ASHRAE 55 takes human thermal adaptation into consideration in various climate zones, and it recommends a summer comfort range of 23–26 °C for air-conditioned environments to optimize the balance between thermal comfort and energy conservation [57]. However, the local thermal comfort demand is probably different from each other in different cities and areas due to various climatic conditions and so there is a gap between the recommended and the required temperature. The following three steps are employed to evaluate the potential energy savings caused by the above gap based on the investigated data: energy consumption (E_b^t) is gained by the ASHRAE-recommended temperature boundaries (23 °C and 26 °C, respectively), which is regarded as the baseline of energy use in the shopping mall; the optimized energy consumption (E_{opt}) is produced by the real thermal comfort demand involved in the investigation. Finally, energy savings ratios are calculated using Equation (4) to identify the most energy-efficient setpoint that meets acceptable thermal comfort criteria.

$$\eta = \frac{E_b^t - E_{opt}}{E_b^t} \times 100\% \quad (4)$$

where η represents the energy efficiency rate. E_b^t represents the baseline energy consumption according to the temperature specified by the ASHRAE 55, where t represents the temperature, which, in this study, could be either the maximum or minimum temperature, and E_{opt} represents the optimized energy consumption corresponding to acceptable indoor thermal comfort.

3. Results and Discussion

3.1. Results of Investigated Objective Data

3.1.1. Indoor Thermal Environment

A longitudinal field investigation yielded 3135 environmental measurements, encompassing both indoor and outdoor parameters. As shown in Table 4, these parameters refer to outdoor air temperature (T_{out}), outdoor relative humidity (RH_{out}), T_a , globe temperature (T_g), RH, V_a , and CO₂ concentration. Additionally, derived thermal comfort indices T_{op} , PMV, and PPD, which are systematically computed from these measurements based on ISO 7730 standards, are contained [58].

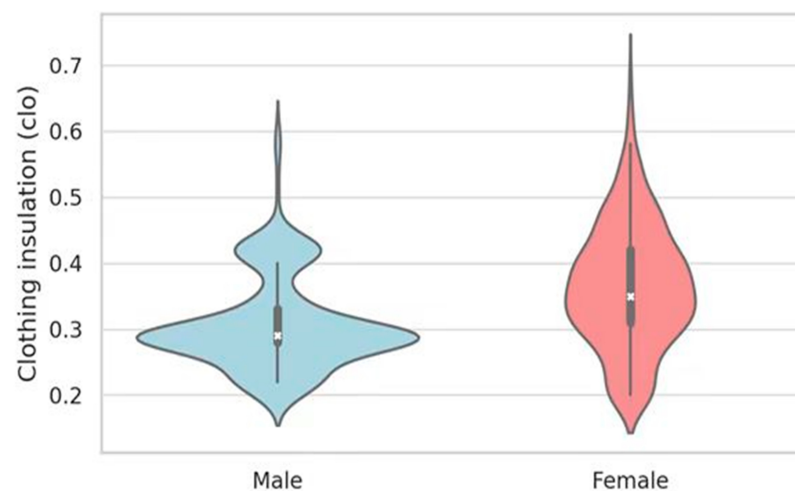
Table 4. Objective measurement data.

	T_{out} (°C)	RH_{out} (%)	T_a (°C)	RH (%)	V_a (m/s)	T_g (°C)	CO_2 (ppm)	T_{op} (°C)	PMV	PPD
Maximum	36.0	92.0	27.8	75.4	0.20	27.4	886	27.3	1.44	47.65
Minimum	27.0	23.0	26.3	58.0	0.03	25.1	620	25.5	0.63	13.33
Average	32.4	66.3	26.7	64.6	0.08	26.3	766	26.4	1.01	26.80
Standard deviation	1.9	13.9	0.3	3.4	0.04	0.4	62	0.4	0.13	5.63

The monitored outdoor environment exhibited a mean temperature of 32.4 °C and relative humidity of 66.3% in Danyang, reflecting the summer features of its subtropical monsoon climate marked by thermal intensity and precipitation dominance. Indoor measurements displayed thermal stabilization, with air temperatures averaging 26.9 °C (26.3–27.8 °C) and humidity levels of 64.6% (58–75.4%) persistently exceeding the ISO 7730 [58] comfort threshold (30–60%). Airflow velocities remained constrained to 0.03–0.20 m/s alongside globe temperature variations of 25.1–27.4 °C, while CO_2 concentrations consistently met the GB/T 18883-2022 [53] air quality standard (<1000 ppm). Notably, the operative temperature (26.4 °C) aligned with both ISO 7730 [58] summer comfort criteria (22–27 °C) and measured air temperatures, confirming minimal radiative impacts.

3.1.2. Clothing Insulation

The violin plot in Figure 4 delineates gender-specific thermal insulation patterns in summer apparel, revealing distinct distributional characteristics between male and female respondents. Male participants exhibited a more constrained distribution, evidenced by a narrower interquartile range (IQR) and reduced whisker span. Bimodal clustering around 0.29 clo and 0.42 clo indicates standardized male attire dominated by short-sleeved shirts combined with either shorts or trousers. Conversely, female respondents revealed greater variability, with a unimodal concentration centered at 0.35 clo. This dispersion reflects diverse sartorial preferences, including selecting long-sleeved garments for solar protection that inherently increase insulation values.

**Figure 4.** The distribution of clothing insulation for males and females.

Empirical evidence presents a stronger correlation between outdoor temperatures and I_{cl} compared to indoor thermal conditions [70,71]. Figure 5 illustrates the linear association between I_{cl} metrics and mean outdoor temperatures across gender groups. Table 5 summarizes the gender-specific regression models, revealing an average I_{cl} of 0.31 clo for male participants compared to 0.36 clo for females. These results are consistent with the established literature documenting gender-based differences in thermal adaptation

strategies, where females tend to adopt higher I_{cl} levels than males under comparable environmental conditions [71,72]. The attenuated correlation observed in male participants suggests reduced variability in male summer clothing selection patterns. The steeper negative regression slope observed in female respondents, measured at -0.02 compared to -0.01 for males, suggests that female summer clothing ensembles exhibit greater sensitivity to outdoor temperature.

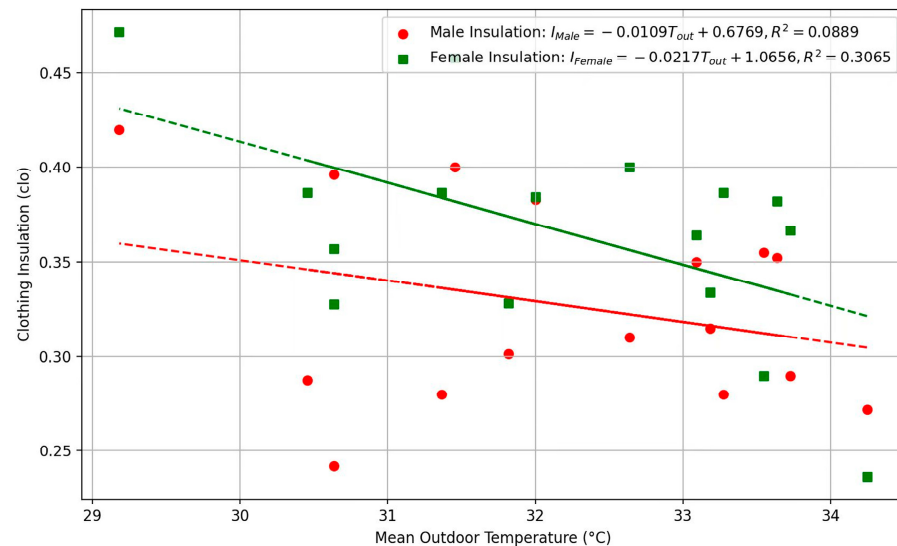


Figure 5. Clothing insulation in relation to mean outdoor temperature for male and female. Note: Solid lines denote the regression lines fitted to the data points. Dotted lines represent the extensions of these regression lines beyond the observed data range.

Table 5. Clothing insulation for male and female.

Gender	Average	Regression Models	R ²
Male	0.31	$y = -0.01x + 0.68$	0.09
Female	0.36	$y = -0.02x + 1.07$	0.31

3.2. Results of Investigated Subjective Data

3.2.1. Subjective Thermal Responses

Figure 6 discloses normal distribution patterns in all six thermal perception indices (TSV, TAV, TPV, TCV, HSV, VSV) with standard deviations below 1.0, indicating low variability in participant responses and tight clustering of data points around their respective means.

The TSV distribution had a mean of 0.34 and exhibited mild positive skewness while remaining close to thermal neutrality (Figure 6a). The predominant clustering of responses within the -1 to $+1$ range peaked at neutral and substantiates effective environmental thermal regulation, while extreme thermal perceptions represented by $|TSV| = 3$ were statistical outliers. The TAV results had a mean of 1.97 and approached the theoretical maximum of $+2$ (Figure 6b), while 83.6% of responses concentrated in the 1–3 range, confirming high environmental acceptability.

The TPV analysis revealed bimodal distribution characteristics (Figure 6c), with a mean value of -0.63 , reflecting a predominant preference for cooler conditions as 96.8% of respondents selected values between -2 and 0 . In contrast, TCV measurements showed a mean of 0.26 and 89.8% of participants reported neutral to comfortable experiences (Figure 6d), aligning with adaptive comfort theory. Humidity perception data had a mean of -0.17 and displayed remarkable consensus as 99.4% of responses fell within

the ± 1 scale range (Figure 6e). Ventilation perception patterns had a mean of -0.37 and indicated dichotomous responses between “moderate” (49.6%) and “slightly stuffy” (39.2%) perceptions (Figure 6f), suggesting differential airflow sensitivity across population subgroups.

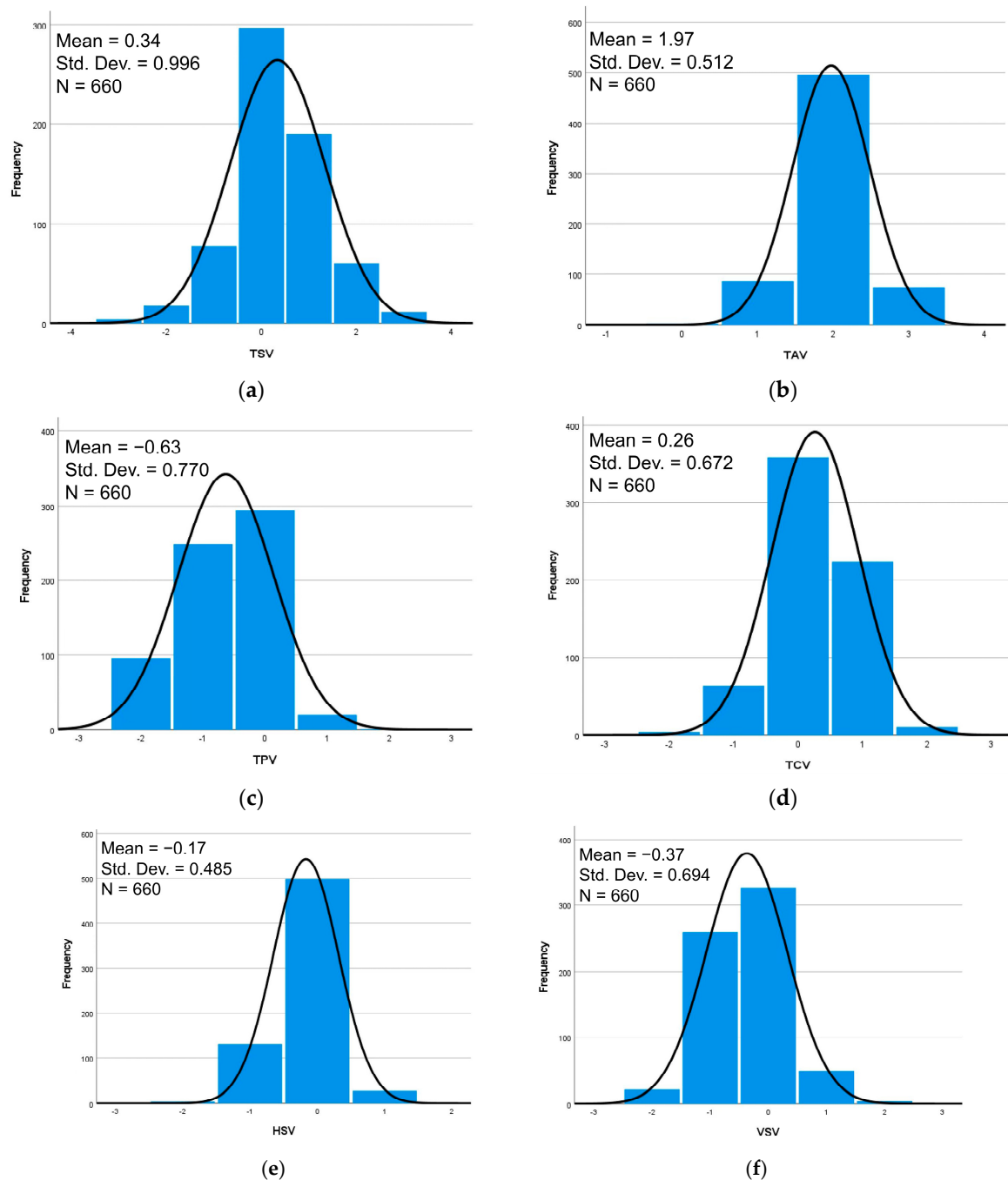


Figure 6. Normal distribution of (a) TSV, (b) TAV, (c) TPV, (d) TCV, (e) HSV, and (f) VSV. Note: Black curves indicate theoretical normal distributions fitted to the data.

3.2.2. Thermal Preference and Comfort Votes

Figure 7 illustrates the percentage distribution of thermal preference votes (TPVs) as a function of respondents' thermal sensation votes (TSVs). In detail, 44.55% of respondents indicated that there was no need to alter the current thermal environment, whereas 37.73% expressed a preference for a slightly cooler environment. For respondents with TSVs categorized as “warm” (+3 and +2), nearly all indicated a preference for cooler temperatures.

Conversely, respondents with TSVs classified as “cold” (−3 and −2) did not exhibit a symmetrical preference for thermal adjustment. In particular, when TSV was −2, 72% of respondents preferred the thermal environment to remain unchanged or become cooler, whereas for TSV = −3, 25% desired no change, and another 25% expressed a wish for cooler conditions. Furthermore, when respondents experienced a “slightly warmer” sensation (TSV = +1), 83% preferred a cooler thermal environment. These findings suggest that during the survey period, respondents consistently favored cooler conditions, regardless of their distinct thermal sensations.

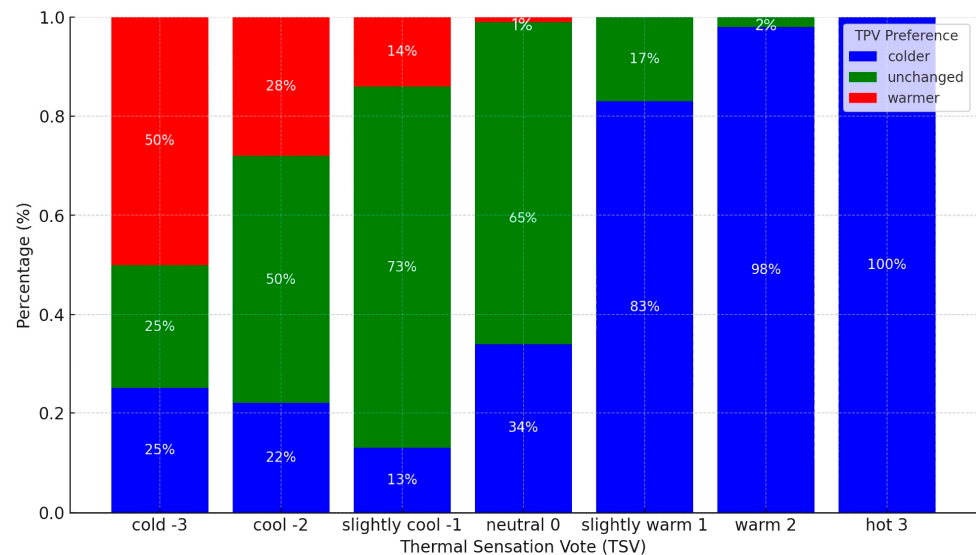


Figure 7. Results of TPV corresponding to TSV.

Figure 8 shows the distribution of TCVs with respect to respondents' TSVs. As depicted in the figure, when respondents reported feeling cooler (i.e., cold, cool, or slightly cool), the vast majority reported being comfortable, with only a small proportion indicating discomfort. However, respondents were more likely to report thermal comfort at lower temperatures and increased discomfort as temperatures rose. When respondents experienced warmer conditions (i.e., slightly warm, warm, or hot), the proportion reporting discomfort increased significantly, while the proportion reporting comfort decreased. This trend reinforces the notion that a cooler thermal environment is preferred in the shopping mall setting.

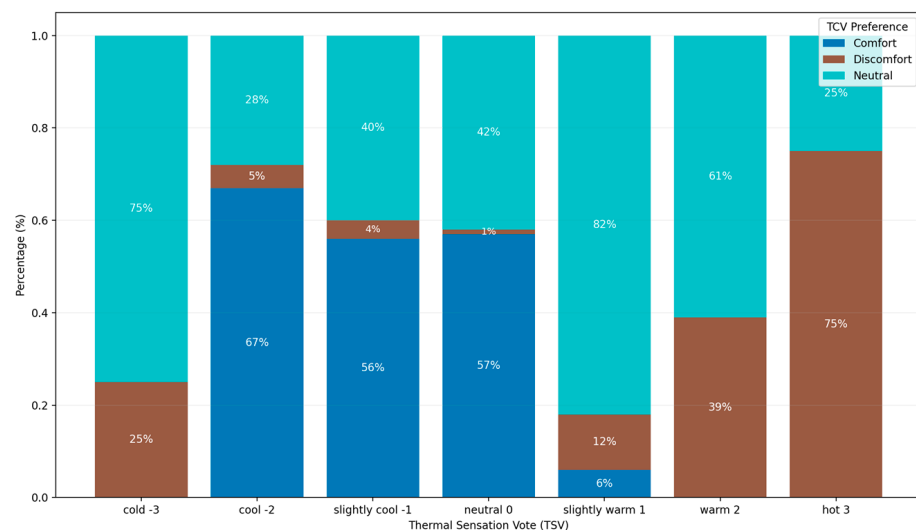


Figure 8. Results of TCV corresponding to TSV.

3.3. Profiling of Comfort Temperature Indicators

3.3.1. Neutral Temperature

Linear regression between TSV and T_{op} was performed to elucidate changes in residents' perceptions induced by variations in indoor climatic conditions [73]. Figure 9 reveals the linear regression relationships between TSV- T_{op} and PMV- T_{op} for respondents in the shopping mall. The test data were aggregated into 0.3 °C intervals to address limited indoor thermal variability, where each point in the figure represents mean TSV and PMV values per interval.

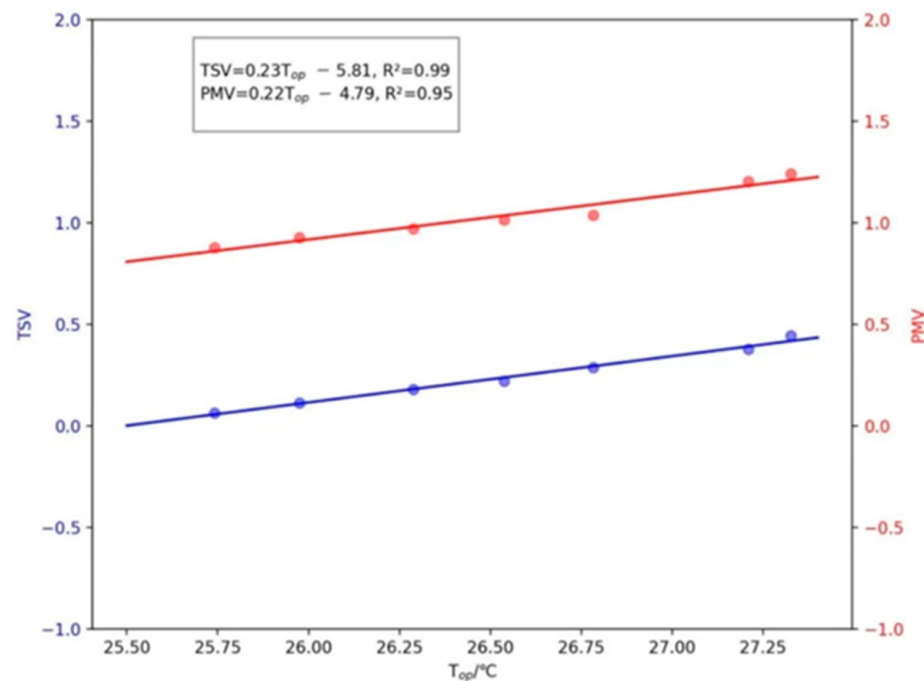


Figure 9. TSV and PMV in relation to operative temperature.

The figure reveals a strong positive correlation between both TSV and PMV with T_{op} . However, a bias is observed between TSV and PMV because the regression line for PMV is consistently higher than that for TSV, which indicates that the PMV model overestimates actual thermal sensation. Table 6 summarizes the regression models for both TSV and PMV, showing that the slopes of the regression equations are approximately 0.23 unit/°C for TSV and 0.22 unit/°C for PMV, which represent respondents' sensitivity to T_a [60], suggesting that both models have comparable predictive capabilities regarding temperature sensitivity.

Table 6. Regression models of TSV and PMV.

Indices	Average	Regression Models	R ²	TNT (°C)	TNTR (°C)	Interval Width (°C)
TSV	0.34	$TSV = 0.23T_{op} - 5.81$	0.99	25.26	19.95–23.59	3.64
PMV	1.01	$PMV = 0.22T_{op} - 4.79$	0.95	21.77	23.13–27.39	4.26

To further assess the differences between PMV and TSV, thermal neutral temperatures (TNTs) were determined by setting TSV and PMV to zero. This resulted in values of 25.26 °C and 21.77 °C, respectively. By applying the criteria $-0.5 < TSV < +0.5$ and $-0.5 < PMV < +0.5$, TNTRs were determined to be 19.95–23.59 °C for TSV and 23.13–27.39 °C for PMV. The comparison of TNT and the thermal neutral temperature range (TNTR) for TSV and PMV further illustrates the tendency of the PMV model to overestimate the environmental thermal sensation.

In this study, the PMV model systematically overestimated respondents' thermal sensations, which is consistent with the findings of Yan et al. [74]. These observations lead to the conclusion that the PMV model is not suitable for assessing thermal comfort in the test mall during the survey period.

3.3.2. Acceptable Thermal Comfort

Thermal acceptability (TA) can be predicted using various methods, including TAV, TSV, TCV, and PPD [75,76], which are summarized in Table 7. In this study, quadratic regression models were developed by calculating the percentages of dissatisfaction for TAV, TSV, TCV, and PPD and correlating these percentages with the T_{op} . The results for these four indices are presented in Figure 10, where each point represents the percentage of dissatisfied respondents during the survey period. Figure 10 illustrates that the percentage of dissatisfaction predicted by the PPD method is the highest, followed by TSV, TAV, and TCV. Furthermore, as T_{op} varies, the percentage of dissatisfaction associated with TSV shows the largest variation, while TCV shows the smallest.

Table 7. Summary of methods for determining thermal acceptability.

Method	Percentage of Dissatisfied
Thermal acceptance vote (TAV)	Percentage of TAV = {0,1}
Thermal sensation vote (TSV)	Percentage of TSV = {−3, −2, 2, 3}
Thermal comfort vote (TCV)	Percentage of TCV = {−3, −2}
Predicted Percentage of Dissatisfied (PPD)	PPD

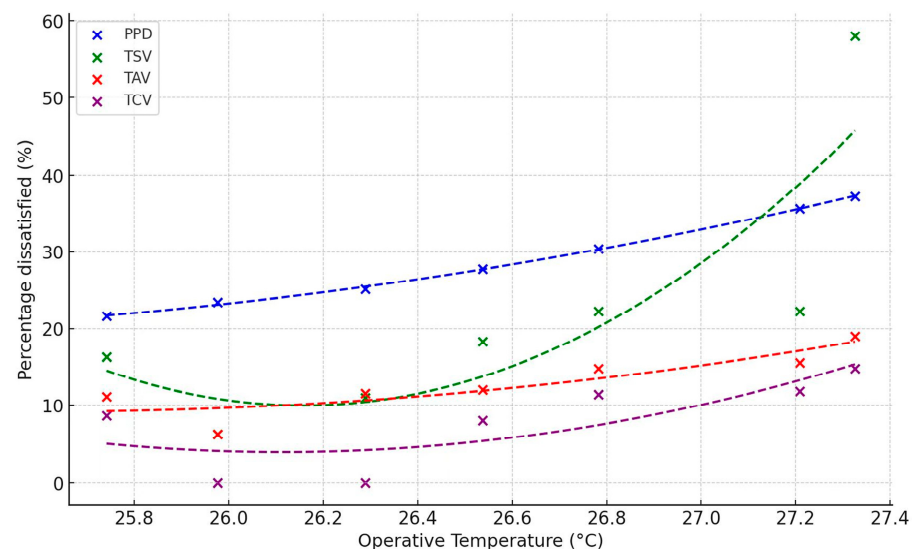


Figure 10. The relationship between percentage of dissatisfaction and operative temperature.

According to ASHRAE 55, a dissatisfaction threshold of 10% or 20% is used as a standard for assessing environmental comfort [57]. Showing a good fit with the T_{op} across all indices, Table 8 presents the quadratic regression equations and associated acceptance ranges (80% and 90%) for each methodology. As shown in the table, PPD determines the smallest acceptable temperature range, with no temperature pickup in the 90% acceptability range. The next widest acceptable temperature ranges were identified by TSV, TCV, and TAV. Regarding the upper limits of the 80% acceptability temperature range, TCV identified the largest value (27.55 °C), followed by TAV (27.48 °C) and TSV (26.78 °C). The smallest value was determined by PPD (25.32 °C), which falls within the summer comfort zone (24–28 °C), as defined in GB 50736 [77]. All the above values exceeded the TNT (based on

TSV) of 25.26 °C, with differences of 2.29 °C, 2.22 °C, 1.52 °C, and 0.06 °C, respectively. All other values differed from TNT by more than 1.5 °C, except the upper limit value determined by PPD. Therefore, occupants have a high thermal acceptability for the indoor environment, even if the indoor environment is warm, indicating there is a big energy conservation potential in shopping malls.

Table 8. Regression models of TA determined by TAV, TSV, TCV, and PPD.

Indices	Regression Models	R ²	90% Acceptable T_{op} (°C)	80% Acceptable T_{op} (°C)
TAV	$y = 0.03x^2 - 1.55x + 19.92$	0.79	[25.06, 26.12]	[23.70, 27.48]
TSV	$y = 0.26x^2 - 13.70x + 179.22$	0.72	[26.13, 26.19]	[25.54, 26.78]
TCV	$y = 0.08x^2 - 4.04x + 52.85$	0.64	[25.23, 26.99]	[24.67, 27.55]
PPD	$y = 0.03x^2 - 1.43x + 17.95$	1.00	-	[24.33, 25.32]

3.4. Perceived Indoor Air Quality Assessment

This study investigated IAQ in the shopping mall from two perspectives: humidity sensation and CO₂ concentration. The relationship between HSV and RH is illustrated in Figure 11. Given the minimal fluctuations in indoor humidity within the shopping mall, RH was categorized into nine groups at 2% intervals. The 2% binning strategy, though smaller than the instrument precision ($\pm 3\%$ RH), was selected to prioritize capturing overarching trends in humidity–satisfaction relationships rather than relying on precise differences within individual intervals. The HSV values for each RH interval were averaged, revealing a linear relationship with an R² value of 0.76, as described by the regression equation in Equation (5). This result indicates a strong linear correlation between HSV and RH. The slope of the equation is 2.43 unit/%, which suggests that respondents exhibit high sensitivity to humidity levels in the mall. When HSV reaches zero, the corresponding humidity defined as NRH is 70.60% among the respondents. The HSV range from -0.5 to $+0.5$ corresponds to the NRHR calculated as 50.00–91.20%. Notably, this NRHR range exceeds the recommended comfortable RH range of 25% to 70%, as stipulated by ASHRAE 55 [57]. This observation may be attributed to the long-term adaptation of local residents to environments with high humidity in the HSCW climate zone [78]. Furthermore, the broad NRHR indicates that individuals are less sensitive to humidity variations compared to temperature changes.

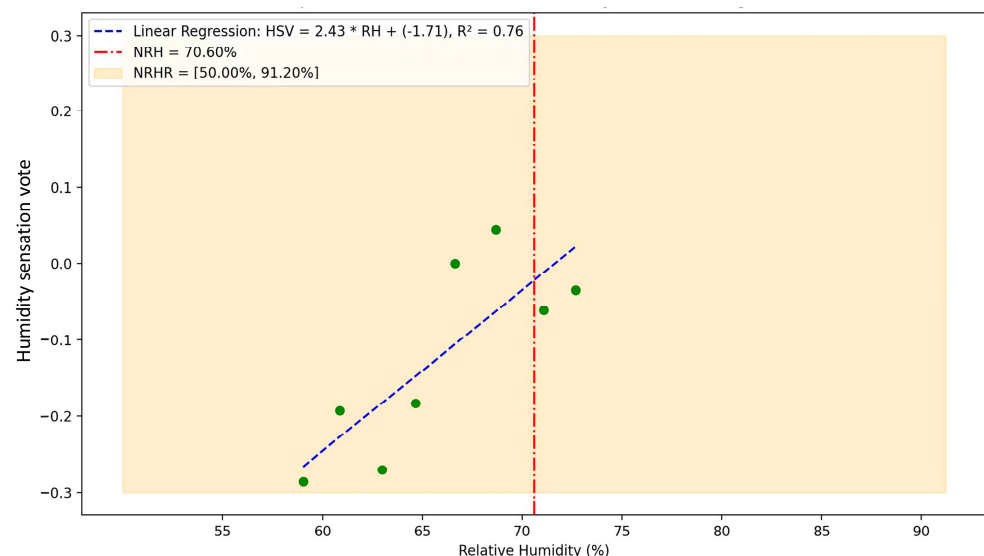


Figure 11. Linear regression correlation between HSV and RH.

The high NRH indicates that, while occupants may tolerate high humidity levels, it necessitates an effective ventilation system capable of managing varying humidity levels and preventing discomfort. This suggests that the mall's HVAC system should be designed not only for temperature control but also for humidity regulation, ensuring the removal of excess moisture in peak humidity conditions. The increased awareness of resident tolerance allows for more adaptive control strategies, balancing energy use efficiently while maintaining acceptable air quality.

$$\text{HSV} = 2.43\text{RH} - 1.71 \quad R^2 = 0.76 \quad (5)$$

Figure 12a shows a box plot of CO₂ concentration in the shopping mall during the survey period. While the median CO₂ concentration (772 ppm) remained below the 1000 ppm threshold established in GB/T 18883-2022 [53], the instrument's inherent accuracy limits precise quantification. However, the observed stability in CO₂ levels (709–823 ppm) suggests adequate ventilation under typical occupancy conditions. OD, defined as the surface area per occupant (m²/person), has been shown in previous studies to correlate strongly with CO₂ concentration [79]. Figure 12b presents a box plot of OD, showing a median value of 78.95 m²/person and a distribution range from 64.42 m²/person to 84.68 m²/person. This density is significantly higher than the 8 m²/person OD recommended for shopping mall buildings in GB50189-2015 [36]. This is likely due to the extensive public areas such as atria and corridors present in the mall.

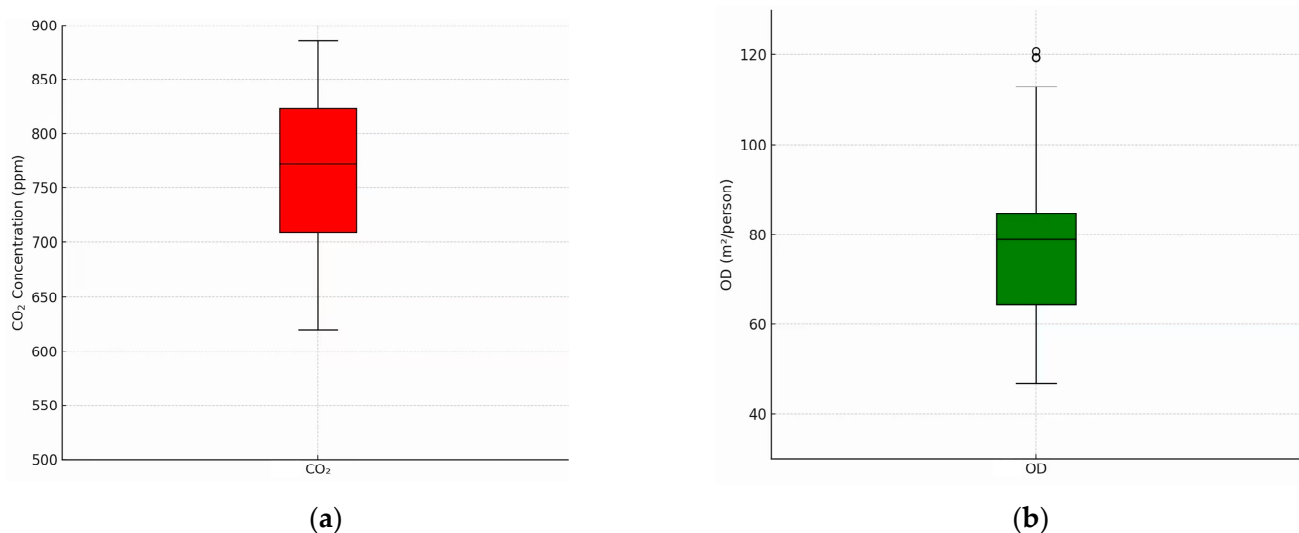


Figure 12. Box plots of average (a) CO₂ concentration and (b) OD in the shopping mall.

The positive correlation between CO₂ levels and occupancy suggests that during peak hours, the ventilation system must be sufficiently responsive to fluctuations in OD. Implementing a demand-controlled ventilation (DCV) strategy could be advantageous in such settings, adjusting airflow rates dynamically based on real-time occupancy data to ensure both energy efficiency and indoor air quality. This approach may help reduce energy consumption while maintaining compliance with air quality standards.

Figure 13a depicts the distribution of respondents' satisfaction with the air quality in the shopping mall during the survey period. The data show that the highest percentage of respondents rated the air quality as "satisfactory" (AQSV = −1) and "average" (AQSV = 0), with proportions of 50.15% and 44.70%, respectively. This indicates a general perception of good air quality among respondents. The air quality satisfaction votes of "average (0)", "satisfied (+1)", and "very satisfied (+2)" were classified as satisfied with the air quality. Figure 13b presents the results of a parabolic regression analysis of the percentage of satis-

fied respondents versus T_{op} , with the shaded area indicating the 95% confidence interval. The relationship is expressed in Equation (6), revealing a strong parabolic correlation between air quality satisfaction and T_{op} . The satisfaction rate peaks at the T_{op} of 26.93 °C, which is 1.67 °C higher than the TNT (based on TSV) of 25.26 °C. On one hand, the increased air mobility at higher temperatures may still play a role in the subjective perception of IAQ. However, given the lack of evidence for ventilation changes, the observed association is more likely to reflect the interactive influence of thermal comfort, olfactory experience, and perceived IAQ. It may also reflect a common cognitive pattern in which people tend to associate improved thermal conditions with better air quality. The 95% confidence interval for the regression model in Figure 13b fully contains the observed data, suggesting reasonable agreement between the fitted curve and empirical measurements. However, extrapolation beyond the central temperature range (26.0–27.4 °C) remains speculative due to sparse extreme-temperature data. This finding indicates a potential divergence between the TNT and the temperature associated with improved perceived air quality.

$$y = -0.24x^2 + 13.08x - 175.04 \quad R^2 = 0.69 \quad (6)$$

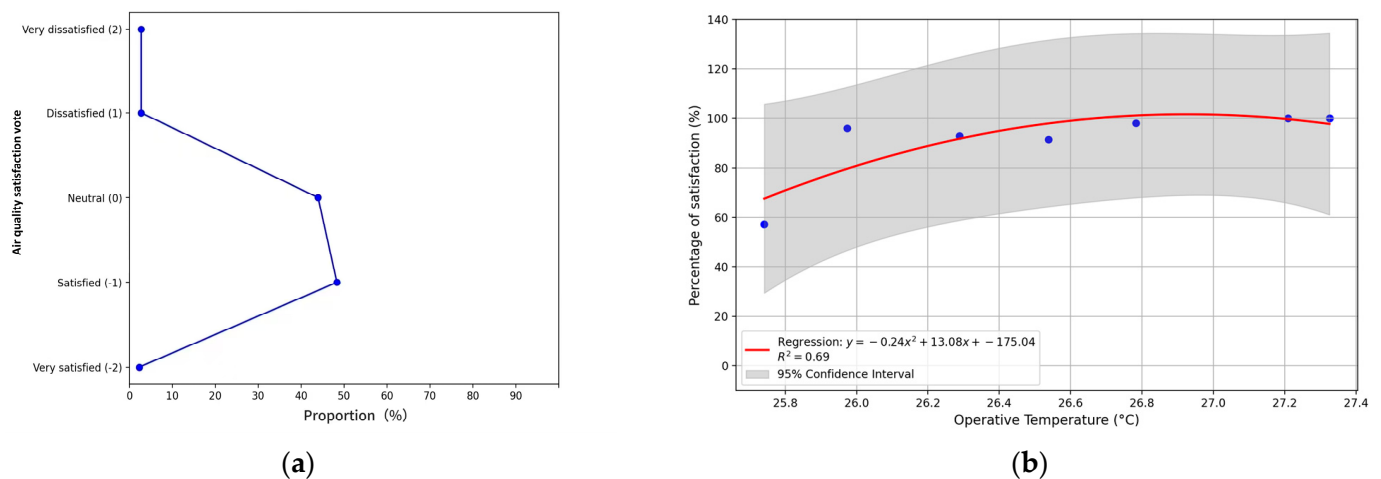


Figure 13. (a) The frequency distribution of air quality satisfaction vote; (b) the relationship between percentage of satisfied air quality and operative temperature.

3.5. Energy Savings of the Surveyed Shopping Mall

The energy consumption analysis for the surveyed shopping mall is conducted based on the baseline temperature and each optimized temperature derived from the thermal comfort survey. Annual energy consumption and energy-saving rates for different temperature settings are presented in Table 9. The optimized temperatures based on TNT (derived from TSV) and the upper limits of the 80% thermal acceptability temperature ranges (determined from both TSV and TAV) are more energy efficient than the minimum temperature (23 °C) recommended by the ASHRAE 55-2023 [57]. These optimized temperatures achieve energy savings of 12.47%, 23.26%, and 25.77%, respectively. Using the upper limit of 26 °C as a baseline, the temperatures based on the upper limits of the 80% thermal acceptability ranges remain energy-efficient, with energy savings of 6.06% (based on TSV) and 9.12% (based on TAV).

Table 9. Energy consumption values and energy saving rates of the surveyed shopping mall at different optimized temperatures.

Temperature (°C)	Simulated Energy Consumption (MWh/a)	Energy Saving Rate Based on 23 °C	Energy Saving Rate Based on 26 °C
23.00	1195	Baseline (0)	−22.44%
25.26 (TNT based on TSV)	1046	12.47%	−7.17%
26.00	976	18.33%	Baseline (0)
26.78 (80% upper limit of TSV-based thermal acceptable range)	917	23.26%	6.06%
27.48 (80% upper limit of TAV-based thermal acceptable range)	887	25.77%	9.12%

These findings reveal that a moderate relaxation of the temperature setting is practically significant for energy savings while ensuring thermal comfort. Additionally, adjusting the temperature within the respondents' acceptability range reduces energy consumption without significantly affecting comfort. Therefore, increasing the summer air-conditioning temperature significantly reduces energy consumption in the tested mall while ensuring thermal comfort. This approach not only provides economic benefits to the mall's operations but also contributes to environmental protection by reducing energy waste.

4. Conclusions

In this research, we studied the indoor thermal comfort and energy savings of shopping malls in summer, focusing on a field investigation conducted in Danyang in China. The findings provide critical insights into the relationships among thermal comfort parameters, IAQ, and energy savings. The appropriate ranges of key indicators, such as the PPD, TNT, and NRH, were addressed, which can offer strong support to quantitatively identify the potential for optimizing the indoor environment while achieving significant energy savings. The main conclusions are as follows:

- T_a in the shopping mall ranged from 26.3 °C to 27.8 °C with a mean value of 26.7 °C, indicating a relatively stable thermal environment. The average T_{op} was 26.4 °C and closely aligned with T_a , which implied a minor influence of radiation and other factors on T_a . V_a was low, ranging from 0.03 m/s to 0.20 m/s. The average PMV was 1.01, while the average PPD was 26.80%. I_{cl} varied by gender, with males averaging 0.31 clo and females averaging 0.36 clo; notably, women were more sensitive to the change in outdoor temperature.
- The TNT derived from the TSV was 25.26 °C, which is significantly higher than the 21.77 °C obtained from the PMV model. This comparison indicates that the PMV model tends to overestimate thermal sensation, suggesting that it is not suitable for analyzing indoor thermal comfort in shopping malls with a hot summer and cold winter climate.
- The PPD determined the smallest acceptable temperature range, while the TAV resulted in the largest span. For the upper limit of the 80% acceptable temperature range, the highest temperature was identified by the TCV at 27.55 °C, followed closely by 27.48 °C derived from TAV, 26.78 °C from TSV, and 25.32 °C from PPD. Significantly, all values obtained through actual observations differed from the TNT (based on TSV) by more than 1.5 °C, except for the upper limit value determined using the PPD prediction method. This shows that there is a wide range of acceptable temperatures for thermal comfort in the surveyed area, even if the indoor environment is relatively warm.

- A strong linear correlation exists between HSV and RH, and the neutral relative humidity level is 70.60%. The median concentration of CO₂ was 772 ppm, which remained below the 1000 ppm threshold and manifested adequate ventilation. Air quality satisfaction votes revealed that 94.85% of respondents rated the air quality as satisfactory or average. Parabolic regression analysis showed that a significant relationship between air quality satisfaction and operative temperature and peak satisfaction occurred at 26.93 °C, which means that this temperature can enhance both air quality perception and thermal comfort.
- Taking the lower temperature limit of 23 °C recommended by the ASHRAE 55-2023 as the baseline, the energy savings achieved are 12.47%, 23.26%, and 25.77% when the temperature is raised to 25.26 °C (TNT based on TSV), 26.78 °C (upper limit of the 80% thermal acceptability range based on TSV), and 27.48 °C (upper limit of the 80% thermal acceptability range based on TAV), respectively. If taking 26 °C as the baseline, the upper limits of the temperature range with 80% thermal acceptability can still achieve energy savings of 6.06% and 9.12% based on TSV and TAV, respectively.

In light of these findings, we recommend that architects and engineers consider the following suggestions to enhance thermal comfort and energy efficiency in shopping malls:

- Architects should design shopping malls with flexible layouts that can adapt to the changing needs of customers throughout different seasons. Such configurations allow for the reconfiguration of spaces, which not only enhances customer experience but also leads to a reduction in energy consumption. Incorporating elements of natural ventilation and lighting into the design can further improve the indoor environment quality while harmonizing with nature.
- Engineers must consider local comfort requirements, climatic conditions, and the energy efficiency needs of the building when designing HVAC systems. This includes implementing systems that can dynamically adjust indoor temperature and humidity based on real-time occupancy data, thereby ensuring optimal thermal comfort for customers while minimizing energy usage. Furthermore, the design should account for the unique characteristics of the building, allowing for the effective management of thermal inertia and energy loads, promoting an efficient balance between energy savings and occupant comfort.

This study has several limitations: (1) This study is a case study that addresses specific localized issues within the HSCW climate zone, which may limit the generalizability of the findings to other regions or contexts outside of this particular area. (2) The sample size, while inclusive of all age groups, is not very large, which could impact the robustness of the results. (3) Data were collected exclusively during the summer season, omitting winter or transitional periods, thus not capturing potential variations in thermal comfort across different seasons. (4) Finally, while comprehensive, this study's focus on subjective comfort evaluations may not fully account for all physical variables influencing thermal perception, indicating that further investigation with objective measures could enhance our understanding.

Future studies should expand to multi-regional validation across diverse climates (e.g., tropical, arid) to generalize the findings, incorporate year-round monitoring to assess seasonal variations, integrate high-resolution physiological and environmental data for objective comfort analysis, and employ demographic-adaptive modeling with larger, heterogeneous samples. These steps would enhance the robustness and applicability of thermal comfort strategies in global commercial building contexts.

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Data Availability Statement: Data will be made available on request.

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