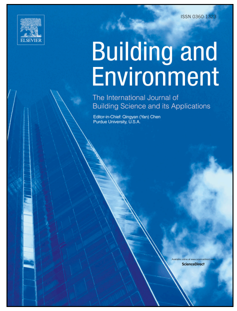

Regression forecasting of ‘neutral’ adaptive thermal comfort: A field study investigation in the south-eastern Mediterranean climate of Cyprus

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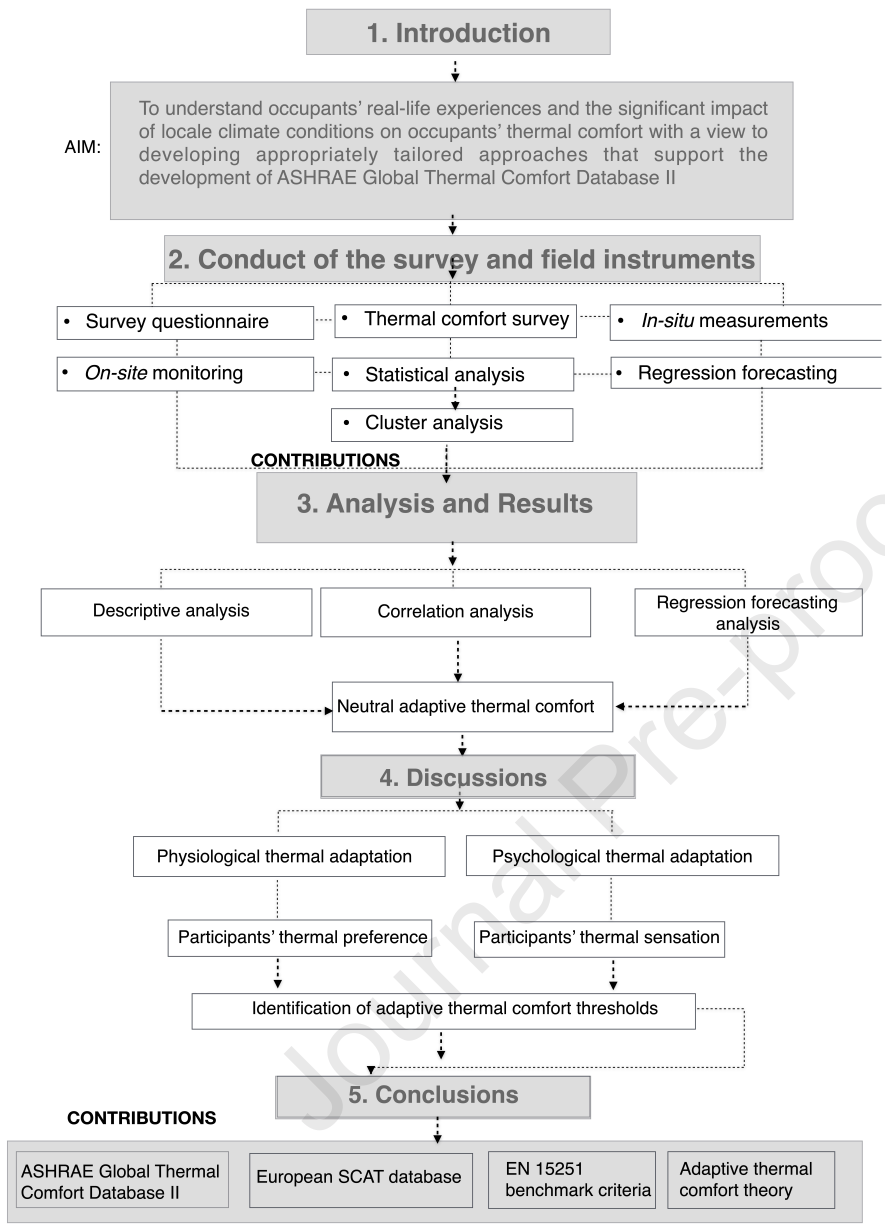
1. Introduction
AIM:
To understand occupants' real-life experiences and the significant impact of locale climate conditions on occupants' thermal comfort with a view to developing appropriately tailored approaches that support the development of ASHRAE Global Thermal Comfort Database II
2. Conduct of the survey and field instruments
• Survey questionnaire
• Thermal comfort survey
• In-situ measurements
• On-site monitoring
• Statistical analysis
• Regression forecasting
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3. Analysis and Results
Descriptive analysis
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Neutral adaptive thermal comfort
4. Discussions
Physiological thermal adaptation
Psychological thermal adaptation
Participants' thermal preference
Participants' thermal sensation
Identification of adaptive thermal comfort thresholds
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CONTRIBUTIONS
ASHRAE Global Thermal Comfort Database II
European SCAT database
EN 15251 benchmark criteria
Adaptive thermal comfort theory

Regression forecasting of 'neutral' adaptive thermal comfort: A field study investigation in the south-eastern Mediterranean climate of Cyprus

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Abstract

Numerous field studies have found that occupants' thermal comfort varies with locale climate conditions. However, there is no generally recommended acceptable comfort range for multifamily residential buildings, nor are there specific adaptive thermal comfort prediction methods, particularly in South-eastern Mediterranean countries. We investigated an *in-vivo* experience of social householders' thermal sensation votes to predict individual aspects of adaptive thermal comfort and influences on its validity in purpose built residential tower blocks of a post-war social housing estate in Famagusta, Cyprus. We conducted field studies, which included *on-site* questionnaire surveys, environmental monitoring and *in-situ* physical measurements, on 36 base-case representative archetype buildings over 288 flats where the weather is subtropical (Csa) and partly semi-arid (Bsh). 118 flats were successfully recruited. A moderate correlation was found between the occupants' thermal sensation and the indoor air temperature ($r = 0.215$, $p < 0.05$), while a negative moderate correlation was found with the outdoor air temperature ($r = –0.325$, $p < 0.01$). The occupants' thermal sensation vote indicated that the 'neutral' temperature was 28.5 °C, and the upper limit of the comfort range in warm indoor air temperature conditions was 31.5 °C. This suggests that, in hot and dry climates in which thermally uncomfortable indoor environments occur, particularly in summer, occupants appear to tolerate a warmer condition than at other high and medium altitudes. The outcome of this study contributes to the development of the ASHRAE Global Thermal Comfort Database II where there is not any data available for the Cypriot context.

Keywords: Adaptive thermal comfort; Environmental monitoring; Field studies, Questionnaire survey, Regression forecasting, Social housing

Nomenclature	
°C	Celsius
p	Significant level
r	Number of elementary effects per parameter
R^2	Coefficient of determination
Ta	Indoor air temperature (°C)
To	Outdoor air temperature (°C)
Abbreviations	
A/C	Air-Conditioning
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BS	British Standards
CEN	Comité Européen de Normalisation
CIBSE	Chartered Institution of Building Services Engineers
DBT	Dry Bulb temperature
DTS	Dynamic Thermal Simulation
EPBD	Energy Performance of Buildings Directives
.epw	Energy Plus Weather file format
EN	European Norm
FLIR	Forward-looking infrared thermometer
GHG	Greenhouse gas
MFH	Multi-family House
MM	Mixed-mode Ventilation
NV	Natural Ventilation
PPD	Predicted Percentage of Dissatisfied
PMD	Predicted Mean Vote
RQ	Research question
RA	Regression analysis
RTB	Residential tower block
RH	Relative humidity
SC	referred to Space conditioning (heating + cooling)
SCAT	(EU) Smart Controls and Thermal Comfort
SD	Standard deviation
SMEs	Small-and-medium enterprises
SPSS	Statistical Package for the Social Sciences
TPV	Thermal preference votes
TSV	Thermal sensation votes
UHI	Urban Heat Island (effect)
WBT	Wet-bulb temperature

1. Introduction

The notion of 'thermal comfort' identifies that the reaction of human body to the changing indoor environment conditions by means of exploring physiological, psychological and environmental parameters [1]. The design and physical characteristics of this environment describe the microclimate, which interacts with people's habitual adaptive behaviour to adjust to a thermally comfortable indoor air environment according to their thermal expectations [2]. In fact, there is an intrinsic interrelation between the physiology of human body and the indoor air environment which can also attribute to interact with the outdoor environmental conditions [3]. Up-to-now, many scholars have pilot longitudinal field studies to identify the adaptive thermal comfort threshold levels which are included both into the ASHRAE Global Thermal Comfort Databases I and II . Thus, indicating the variation of these input parameters have shown determinant factors to explore the acceptability range of predicted mean vote in accordance with these parameters namely, building type; climate; activity levels etc. Humphreys and Nicol described thermal comfort as a situation in which the exchange of heat between a person and their environment has a neutral balance [4].

Nicol et al. concluded that the subjectivity of population size is underestimated and that a broad range of parameters satisfies individuals, thereby making the term qualitative and introducing behavioural aspects that not only differ among people from different locales, but also among people from the same area. This set of thermoregulations help us to outline differences between occupant behaviour and their settings within the built environment [5]. Another definition of 'thermal comfort', provided by experts from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), has been accepted globally and used repeatedly by many scholars in this field. In parallel with these definitions, Brager and de Dear stated that people's expectations about thermal comfort led to an undetermined sensation in the investigation of 'neutral' thermal comfort level [6]. Table 1 demonstrates the previous scholars' work on thermal comfort which is available at the ASHRAE Global Thermal Comfort Database II.

Table 1. Review of ASHRAE Global Database II.

References	Year	Country	Benchmarking criteria	Main findings
[7]	1993	San Francisco, U.S.	- ASHRAE 462-RP data - ASHRAE Standard 55-92 - ASHRAE Standard 55-81	Approximately 12% PPD in occupied space, compared to 5% minimum PPD
[8]	2002	Western Iran	- ISO 7730-1994 - Griffiths Thermal comfort equation	Adaptive thermal comfort temperatures in the summer ranged from 26.7–28.4°C
[9]	2004	Tunisia, North Africa	- ISO 7730-1994 - ASHRAE Standard 55-92 ASHRAE Standard 55-81	More than 80% of participants reported comfortable temperatures from 16–26.5°C
[10]	2008	Central/ Southern China	Fanger's PMV model	Neutral summer OT: - Urban residence: 14.0°C - Rural residences: 11.5°C
[11]	2010	Beijing China	- Brager and de Dear's adaptive model - Fanger and Toftum's PMV model	Neutral summer OT was 26.8°C; PMV-predicted temperature was 25.7°C
[12]	2013	Malaysia	De Dear's adaptive thermal comfort model based on the ASHRAE RP-884 database	Predicted adaptive thermal comfort temperature was nearly 30°C
[13]	2017	Central Slovakia	- ISO 16017-2 Standard - ISO 16000-4 Standard	18% of apartments non-renovated buildings did not fall in optimum thermal comfort range (i.e., 20–24°C)

Many pilot studies have been conducted by the Nicol, McCartney and de Dear to design an international database by conducting longitudinal field surveys in various climate zones across the world. One of the prominent focus of this study is to search correlations between the adaptive neutral temperature and locale climate characteristics of the pilot case study locations were chosen to demonstrate representativeness of data in optimisation of 'neutral' thermal comfort [14-17]. Following a similar approach, this literature study also considers the adaptive thermal comfort theory which is developed by well-known scholars such as de Dear and Nicol. These studies highlight the fact that identification of optimum 'neutral' thermal comfort threshold plays a vital role for the international thermal comfort database. This pilot project seeks to explore correlations between the occupants' behaviour and environmental factors in order to provide occupants' *in-vivo* experience on the development of 'neutral' thermal comfort, particularly in the South-eastern Mediterranean Island of Cyprus where there is little research undertaken.

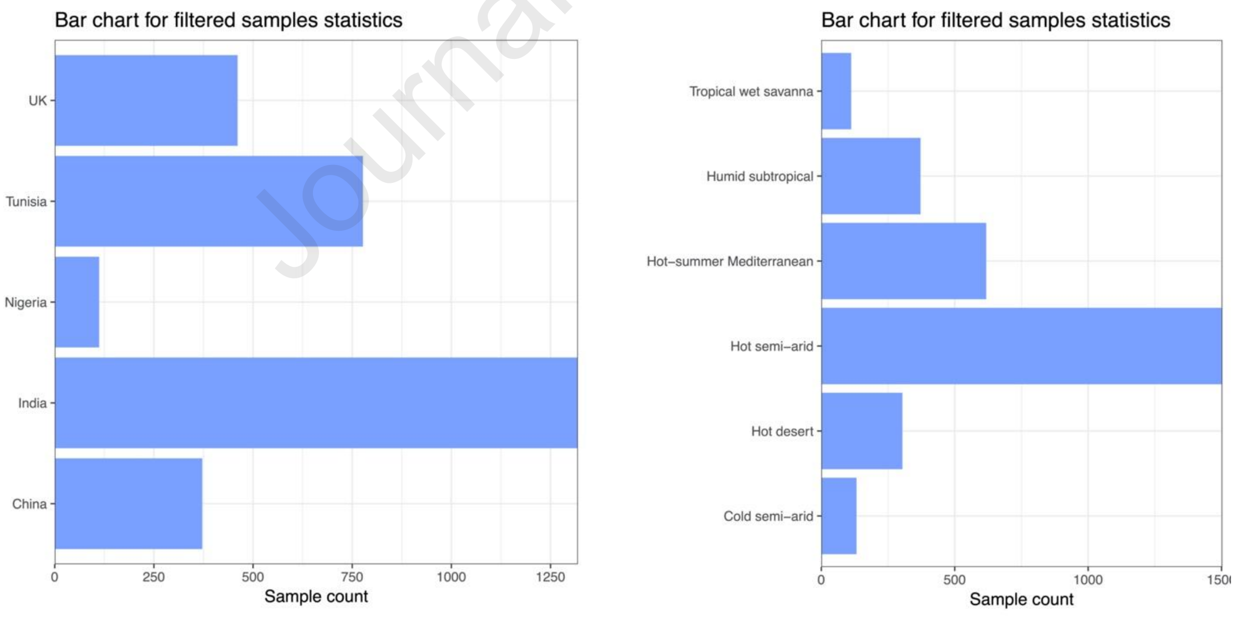
Occupants' thermal discomfort is linked with both the thermal properties of buildings and environmental conditions of the field study sites [18,19]. The pilot study conducted by Nicol et al, explain that the thermal discomfort is linked with three types of human related adaptation namely: behavioural, physiological or psychological [20]. To date, previous pilot study projects' findings highlight the importance of the effects of occupants' interactions on assessing their degree of thermal discomfort [21-22]. To accomplish the assessment of the optimal indoor conditions for occupants' thermal preferences, several comfort models have been proposed. Many scholars have adopted Fanger's 'static' heat balance model, which predominantly considers occupants' behaviour as containers that passively undergo building management [23]. The reason is that the adaptive comfort model allows occupants to adjust their thermal comfort to the outdoor environment according to their preferences and sensations [24].

According to Fanger's adaptive thermal comfort theoretical study, the optimum thermal comfort temperature level is identified in accordance with the adaptive theory [25,26]. This approach includes references from the notion of 'thermal comfort', human body's reactions to the building thermal properties thereof it excludes the subject respondents' social factors and their psychological impact on the identification of 'neutral' thermal comfort [27,28]. It must be stressed that the equation formula is developed for the regression forecasting of 'neutral' thermal comfort should be a steady state to control the dependent variables are selected for the sampling criteria [29]. According to a study by Nicol and colleagues begun in 2002, adaptive approach could be accepted an alternative theory to inform the outcomes of the filed study investigation in various climates for the development of international database [30,31]. From this study, it was found that monitoring of outdoor environmental conditions is the prominent factor on the identification of households' thermal preferences with taking into account indoor air temperatures of each occupied space concurrently. Table 2 delineates the literature review undertaken on field investigation of occupants’ thermal comfort in various of climate zones, including the Asia Pacific region to compare the regression analysis results with research studies from other countries with similar climate.

Table 2. Pilot studies that adopted EN 15251 adaptive thermal comfort criteria.

References	A. Studied Locations	B. Climate Zones	C. Building Type and Ventilation Strategy	D. Methodology	E. Main Findings
[1]	Worldwide	ASHRAE Global Database I	Free-running and NV buildings	ASHRAE RP-884 dataset was used; field-validation experiments in various climate zones were considered; specified laboratory-grade instrumentation was used; statistical derivation of adaptive models was conducted for 160 buildings in the database; and statistical analysis was conducted.	80% (or 90%) acceptability limit equations for the adaptive model were programmed into a hybrid building-management system as critical thresholds to switch the building between passive and active modes.
[32]	China: Chongqing	Köppen Climate: Cfa (hot in the summer and cold in the winter)	Free-running buildings	Black Box theory was adopted to develop adaptive model of thermal comfort; questionnaire survey and environmental monitoring campaign were used; and statistical analysis was used to determine coefficient for the study area.	Adaptive coefficient for warm and cool conditions using data obtained from subject respondents were 0.293 and −0.125, respectively.
[33]	U.K. and China	Köppen Climate: - Cfb (temperate oceanic) - Cfa (hot in the summer, cold in the winter)	NV buildings	Group analytic hierarchy process was adopted; longitudinal field surveys were conducted; a total of 41 (U.K.) and 33 (China) subjects participated; pair-wise comparison strategy was adopted; and sensitivity analysis was conducted.	Reduction of the current weight of psychological adaptation by 17.54% reversed the rankings between the physiological parameters and personal physical factors for the U.K. case.
[34]	Chennai, Kolkata and Hyderabad, India	Köppen Climate: tropical (hot and humid)	NV buildings; air conditioning	Five different adaptive-comfort equations were computed; field-study approach was adopted; multiple surveys were conducted; and ASHRAE TMY2 weather file was used.	When fans were used during the warm months, 2°C was able to be added to the upper limit of comfort zone in NV buildings.
[35]	Worldwide	ASHRAE Global Database II	NV and mix-mode buildings; air conditioning	ASHRAE RP-884 database was used; R studio IDE was used for statistical analysis; and study included historic climatic averages from 27,593 records.	‘Neutral’ comfort temperatures in the Asian subset trended 1–2°C higher than in Western countries.
[36]	Worldwide	ASHRAE Global Database II and studies conducted in past 21 years	NV and mix-mode buildings; air conditioning	Explanatory adaptive-comfort models were reviewed; ASHRAE RP-884 database was used; and regulatory documents and standards on adaptive comfort were reviewed.	None of the published attempts explained the discrepancy between the heat-balance comfort-model predictions and the actual observations.

With regards to the adaptive thermal comfort theory, little research has addressed to explore correlations between physiological factors and addressing the thermal history of subject respondents' thermal preferences [37,38]. The previous scholars' work predominantly have conducted numerical experiments by using the climatic chamber in laboratory environments in order to test actual weather conditions and its influence on the human's thermal history which was investigated by Humphreys and Nicol in 2003 [23,24,28]. Numerous field studies have found that occupants' thermal comfort varies with local climate [39-41]. However, there is no generally recommended acceptable comfort range for existing residential buildings, nor are there specific thermal comfort prediction methods, particularly in south-eastern Mediterranean countries in Europe. Fig. 1(a) & (b) demonstrate previous scholars work on investigating 'neutral' adaptive thermal comfort in multi-family residential buildings, which is available on the ASHRAE Global Thermal Comfort Database II [42].



(a) (b)

Fig. 1. (a) The sample of adaptive thermal comfort studies by country; **(b)** The TSV configuration of field studies by climate type. **Source:** Data is extracted from thermal comfort visualisation tool: available at https://cbe-berkeley.shinyapps.io/comfortdatabase/ [42].

This is the first study to undertake a longitudinal analysis of field investigation on the development of adaptive comfort of households in the south-eastern Mediterranean climate where the weather is subtropical (Cfa) and partly semi-arid (Bsh) - hot and dry in the summer [43]. This empirical analysis was aimed to inform the evolution of human body's adaptation according to the changing environmental conditions. It sits on the grounds of informing the outcomes of deterministic approach was adopted. Notably, these experiments were seeking to identify the benchmark criteria for the 'neutral' adaptive temperature which is commonly accepted by the sampling size. One of the main constraints of this pilot study project was not to consider the psychological and cultural aspects of comfort, and therefore, it can be questioned, and this is the knowledge gap should be addressed by the further pilot studies on the adaptive thermal comfort theory.

In early 1990's Griffiths developed an equation formula to consider semantic analysis of the experimental questionnaires in various of climatic zones to gather instances of feedbacks from subject respondents through a field investigation. Here-to-say that this benchmark criteria were purely evidence-based because of the inclusion of human data into the test chamber for numerical experiments were adopted sequentially [44]. According to a pilot study on adaptive thermal comfort, one of the frontier research limitation was the validity of primary inputs data included for the regression forecasting analysis on 'neutral' thermal comfort. For example, the outdoor environmental conditions or hybrid environments could be considered 'warm' in the summer without the presence of an actual representative sample into the test chamber [45]. To avoid discrepancies between actual and simulated environmental conditions, multi-level questionnaires were developed to reduce this risk factor in the regression forecasting analysis [46]. Many previous pilot study projects indicate that there are three different questionnaire types were developed on the Likert scale assessment namely; 'sensation', 'acceptability' and 'preferences', in order to verify the coherence of the different answers given by the subject respondents [47-49].

Over the past decade, most research in thermal discomfort has emphasised the use of several metrics and methods to assess occupants' thermal perception of the indoor environment and their thermal response to different diagnostic of degree of thermal discomfort experienced by the households [50,51]. Similarly, in the last decade, the development of nationwide thermal comfort index database is gaining momentum by the scholars [52]. These studies were aimed to identify thermally comfortable benchmark threshold level for each country in order to demonstrate the significance of long-term thermal indices at the time of developing policy design for the development of the ASHRAE Global Thermal Comfort Database II [53].

The outcomes of these pilot projects recommended an evidence-based scientific literature on adaptive comfort, standards and guidelines for the optimisation studies on occupants' thermal comfort [54,55]. Remarkably, most of the studies' findings indicate that variations between human body's physiology and subject respondent's cultural asset was disregarded by the scholars [56-58]. However, it is worth pointing out the need to evaluate all available current methods of design for long-term evaluation of thermal conditions in residential buildings and for thermal risk assessment to take into account the environmental conditions of the study areas under investigation [59–61]. This is because building regulations and assessment criteria for a building's performance evaluation of an appropriate standard on the assessment of indoor air quality are clearly specified in the European directives on improving buildings' thermal resilience and assessing energy performance of the existing housing stock as regulated by the European Norm (EN) - EN 15251 standard [62]. This is a policy design recommended in line with the EPBD mandates to consider indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. [63,64]. It therefore makes sense to adopt similar international assessment benchmarking criteria to assess participants' thermal comfort in residential buildings. This is the reason that the EU norms are recommended to adopt the assessment criteria for mixed-mode buildings. Table 3 illustrates the summary of cooling and heating temperature ranges according to the criterion recommended by the International

Standard Organisation (ISO) - 7730:2005 for mechanically conditioned residential buildings [65,66].

Table 3. PPD and PMV indexes for naturally ventilated buildings.

Criteria	Description	PPD	PMV	Temperature range for heating °C clothing — 0.5 clo
I	High level of thermal preference expectation required for vulnerable people with disabilities and underlying with health conditions.	<6	–0.2 < PMV < +0.2	23.5–25.5
II	Neutral thermal preference expectation recommended for new and existing buildings.	<10	–0.5 < PMV < +0.5	23.0–26.0
III	Moderate thermal preference expectation recommended for existing buildings.	<15	–0.7 < PMV < +0.7	22.0–27.0

As noted in Table 3, the low heating set points in the winter range from 18-21 °C, and high cooling set points in the summer range from 25.5-27 °C; this corresponds with the international thermal-comfort criteria laid out in EN 15251, depending on whether the level of thermal expectation is associated with vulnerable residents (i.e elderly population with underlying health issues, people with disabilities) or moderately associated with *U-values* of buildings' properties [67]. Here, it is noteworthy to mention that these recommended set points are the maximum and minimum temperatures in the recommended threshold level. The EN 15251 criteria also highlight, however, that with respect to adapting to a neutral thermal-comfort setting, these temperature ranges vary according to building codes, thermal regulations, energy-saving targets and occupant influences on energy use [68].

Surveys such as those conducted by top-notch scholars, such as Fergus Nicol and his research consortium in 2012, have shown that Fanger's work is recommended as best methodological approach for conducting longitudinal and transverse surveys on thermal comfort in residential buildings [2,5,16]. One of the main reasons is that his universally recognised valid conceptual framework was chosen for the building performance evaluation studies. Moreover, many critics ultimately accepted his formulation due to the discrepancies found between monitored environmental conditions and simulated indoor air environment for assessing occupants' thermal comfort [69,70]. Previous research findings into thermal comfort assessment have found that there are inconsistent and contradictory parameters that could affect the accuracy of statistical analysis on field survey data [71,72]. This is partially due to the preliminary experimental tests conducted in the representative laboratory environments in order to explore the dependent variables included in the equation formula for the thermal comfort assessment [73]. Therefore, many studies have criticised this evaluation criterion, since the numerical experiments cannot develop actual environmental conditions [74-76]. In addition, one of the pilot study's findings indicated that considering occupants' interactions and their votes on both thermal preference and sensation could lead to more realistic assumptions to validate the field survey findings [77].

In this study, we therefore investigated potential correlations between the households' thermal sensations against to the *on-site* environmental monitoring and *in-situ* measurements of subject respondents' occupied spaces in order to explore the determinant factors on the development of adaptive thermal comfort (see **Graphical Abstract** – The methodological workflow developed for the empirical study). In so doing, we determined the significance of environmental conditions' effect on occupants' thermal preference votes (TPVs) and thermal sensation votes (TSVs) for assessing the indices of long-term thermal discomfort benchmarks through longitudinal surveys in this particular Mediterranean climate.

2. Conduct of the survey and field instruments

2.1. Climate

The climate of a region is determined by its geographical position in the north-east corner of the Mediterranean Sea, the morphological characteristics of ground plains and the meteorological variations of the regions. According to the Köppen-Geiger climate classification, Cyprus has climate characteristics that are typical of the Mediterranean region [78]. The Köppen -Geiger climate data shows that the overall climate type of Cyprus is subtropical (Csa) and partly semi-Arid (Bsh) in the northeast part of the island, as illustrated in Fig. 2.

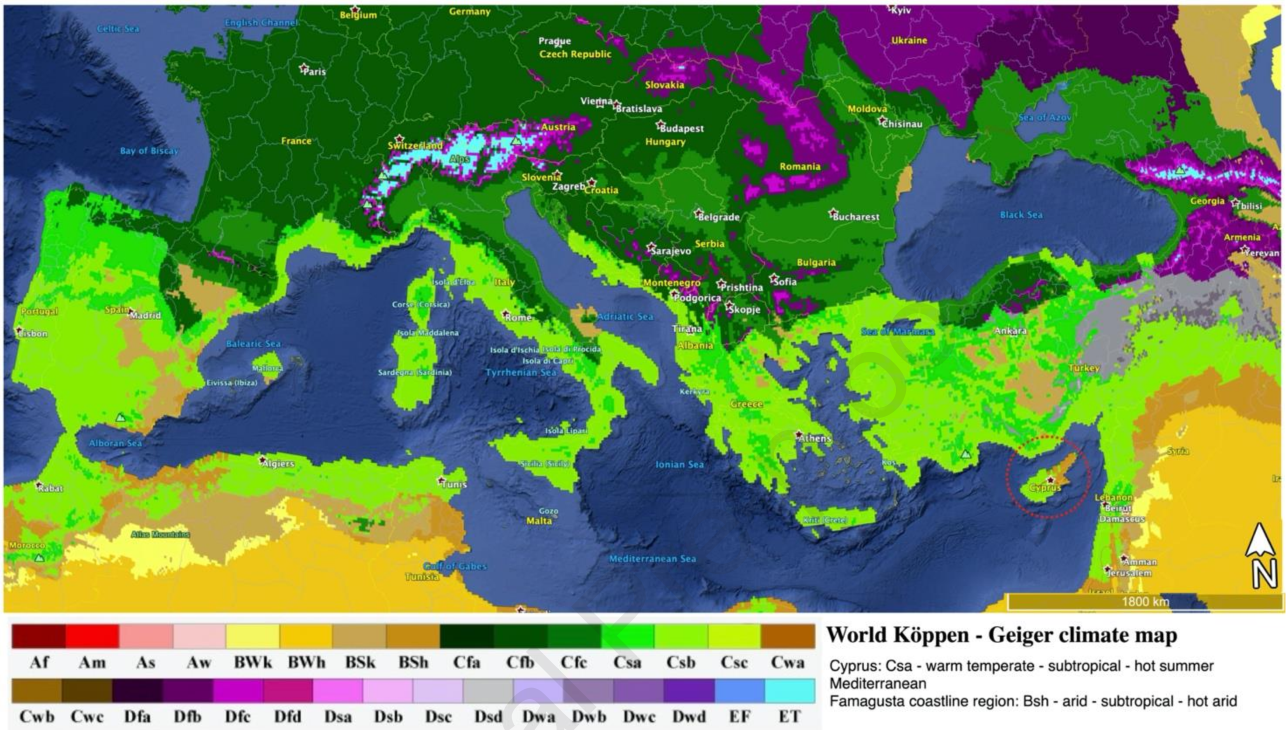


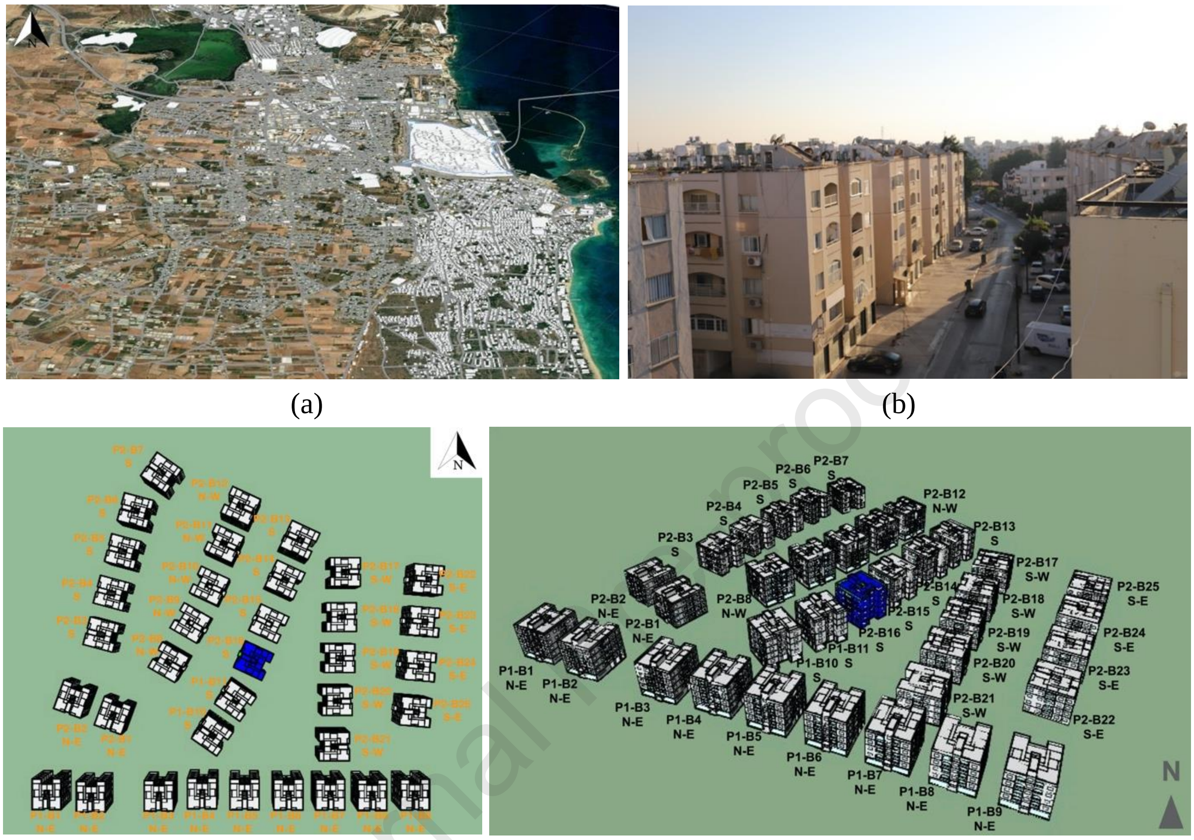
Fig. 2. The map of Köppen-Geiger climate classification in the Mediterranean region [79][1].

2.2. Selection criteria of field study location and representativeness of housing stock

To investigate 'neutral' adaptive thermal comfort level, this study employed a questionnaire survey, *on-site* environmental monitoring and *in-situ* measurements of 118 flats in 36 RTBs in high density social housing estate in Famagusta, Cyprus. By developing a longitudinal field study investigation, environmental conditions were monitored concurrently when the questionnaire surveys were carried out with householders of the case study in the hottest summer of August in 2018. The primary focus was on vulnerable neighbourhoods as they have a high number of social housing developments that were constructed during the mid 1980s and early 1990s, which were

[1] Permission to use Figure 2 was granted by Franz Rubel on April 14, 2021. Accessible at http://koeppen-geiger.vu-wien.ac.at

located both in urban and suburban areas and included neither stringent town planning regulations nor considerations of the climate of the built sites at the time of construction, as shown in Fig. 3(a)-(d).



(a) (b)

(c) (d)

Fig. 3. (a) The map of the coastal city of Famagusta and its location of the post-war social housing development estate. **Source:** The map was extracted from the ArcGIS Pro version 2019.01 software suite developed by Esri in the UK; **(b)** The orientation of the RTBs in the social housing development estate without taking into account any type of environmental design principles in architecture during the decision-making process of the social housing scheme during the mid-1980s and early 1990s. **Source:** The image was taken by the author of this article in 2018 while conducting the field study; **(c)** The site map of the RTBs within the demonstrating RTB orientation; **(d)** 3D rendering of a model of the RTBs. **Sources (c)–(d):** The images were extracted from the Integrated Environmental Solutions software suite's VistaPro platform – version 2020.1.0. *P1-B1-11: Phase 1 – Block 1-11, **P2-B1: Phase 2 – Block 1-25, ***N-E: North-east, N-W: North-west, S-W: South-west, S-E: South-east, S: South.

Through the adopted explanatory case-study approach, the types of buildings in each construction era were analysed and evaluated in relation to a number of environmental factors, including an analysis of the different contextual layers, to ascertain the existing strength of the urban block-development configurations and evaluate the shortcomings thereof under the threat of urban sprawl.

As is shown in Fig. 4, Archetype 1 demonstrates the first social-housing scheme developed during the British Colonial administration in the early 1990s with a combination of single-storey row houses. This was the first pilot housing scheme in Cyprus, and it led to an increasing demand to build mass-scale housing schemes, which are indicated as Archetypes 2 and 3. Notably, urbanisation in Cyprus started in the mid-1980s as a result of growth in the population, which prompted a simultaneous increase in demand in the residential-building sector. High-density social-housing developments in urban and suburban areas resulted in a surge in the construction of low-, mid- and high-rise apartment blocks across five major cities and urban agglomerations in Cyprus.

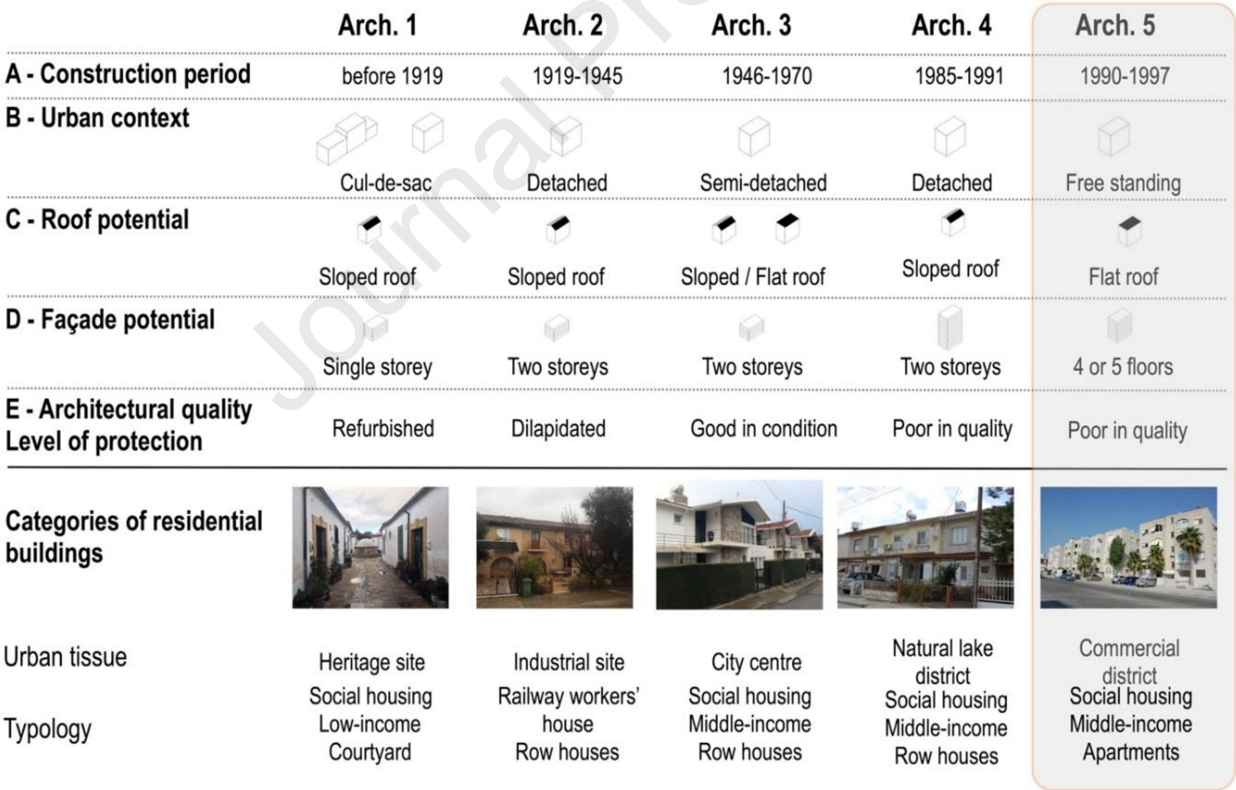


Fig.4. Taxonomy of existing Cypriot housing stock to identify archetypes for case-study location and sampling criteria. **Source:** Images from the first author's personal archive.

In Fig.4., Archetypes 4 and 5 demonstrate the government social-housing estates, which were built between 1984–1996 to address the housing shortage for young people. Notably, within a decade of implementing the same residential-building typology, these types of housing estates were repeated in all five major cities across the country (See **Supplementary Material**). All of these RTBs lacked planning for a social-housing structure scheme, which led to poor air quality and high thermal conductivity in the summer and caused an overheating risk and thermally uncomfortable indoor environments. Fig.4 outlines the stages of mass-housing estate construction in Cyprus and reveals that starting with 4–5-storey RTBs (Archetype 5) in the mid-1980s and early 1990s, which ultimately led to changes in construction practices in NC. The development stages had no defined planning schemes for the implementation of EPBD mandates, no governmental policy and no control mechanisms, all to detriment of the environment and the thermal comfort of residents.

Key criterion in the case study building selection was that the sample would be representative of the post-war social housing stock. The selection of buildings was based on typology, geometry, construction period, construction material, supply system type, the number of occupants and hours of use [80]. Additionally, it was necessary to have sufficient existing building data and define the scope for the survey and *on-site* monitoring to ensure a comprehensive study. Table 4 summarises the characteristics of the dwellings [81].

Table 4. Key characteristics of base case RTBs investigated.

Technical features of dwellings	Three exposed surfaces flat units
Type and date of construction	Perforated hollow brick wall (20 cm thickness) without any type of insulation, mid 1980s and early 1990s.
Number of storeys	4 and 5
Number of occupants (mean)	Three occupants per dwelling.
Layout	Living room, kitchen, 3 bedrooms, pantry, corridor, wet-closet, bathroom, 2 semi-open terraces in living room/kitchen.
Conditioned net floor area [m^2]	90 m^2 of each flat unit in a RTB prototype.
Area-to-volume ratio [m^{-1}]	0.33

U-value [W/(m^{2}K)]	External walls 3.47 Internal walls 3.18 Roof 2.8 Windows 5.20
Windows	The majority (90%) have single-glazed aluminium-framed windows with a 50% opening ratio. The rest have a mix of single and double glazing.
Heating system	There is no off-grid heating infrastructure installed in Cyprus.
Cooling system[s]	Predominantly wall-mounted air conditioning and portable domestic appliances.

To provide a comprehensive overview of the national representative of housing stock and highlight the importance of the demand for housing projects and the impact thereof on occupants' thermal comfort in multi-family residential buildings, statistical data were obtained from the Statistical Office of Cyprus and are illustrated in Fig.5 & 6.

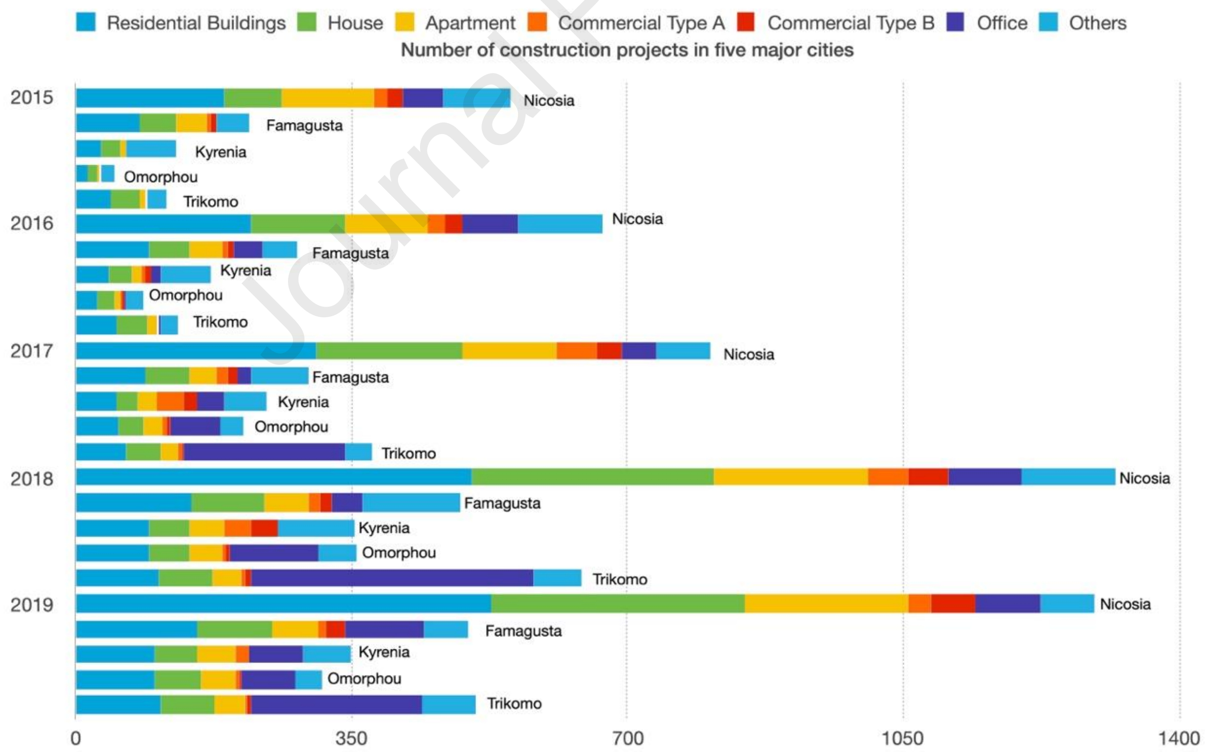


Fig.5. Number of buildings constructed between 2015-2019 in five major cities: Nicosia, Famagusta, Kyrenia, Omorphou and Trikomo.

Fig.5 shows the number of construction projects within the distribution of building typology between 2015–2019. It can be observed that in all five major cities, the majority were the residential buildings comprised of 1–5-storey RTBs, followed by apartments (i.e., medium- and high-rise RTBs) comprised of as many as 23 storeys. According to the Annual Report of Housing statistics in 2020, the number of buildings steadily increased; Famagusta is comprised of 568 residential buildings, 336 houses, 232 apartments that were built between 2015–2019. Therefore, the graph clearly demonstrates that there was a consistent increase in construction activity due to one-third of the population—approximately 110,201 people—living in the capital city of Nicosia. At the same time, The State Planning Organisation statistics in 2019 indicates that the Famagusta population was estimated at 76,000 [82]. The graph demonstrates that the number of construction projects were increased steadily in all cities. A gradual increase in construction projects in Trikomo between 2018–2019 can be observed.

Housing statistics demonstrate that 214 residential buildings, 139 self-built houses and 75 apartments were constructed between 2018–2019, when this area became an attractive location for foreign investors to construct mass-scale high-density RTBs. Fig.6 demonstrates the overall square metres of built space according to building typology. Peak completion of construction projects took place in residential buildings in 2018, when approximately 1.3 billion square metres of space was built. Notably, there no data were available for residential structures that were built in 2019 due to stringent town-planning measures that led to the withdrawal of construction-project proposals, and a policy gap in the implementation of those measures affected SMEs and large foreign investors in Cyprus.

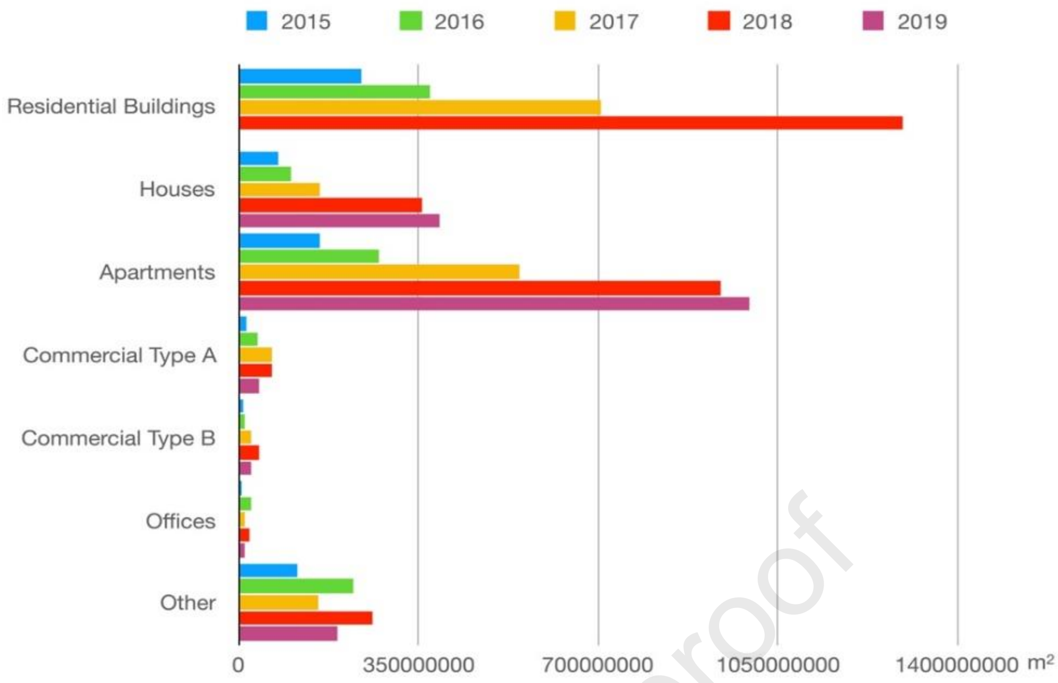


Fig.6. Total number of buildings constructed in urban areas between 2015-2019.

It can also be observed that approximately 937 million square metres of apartment-type housing stock were built in 2018, with an increase in the total footprint in 2019 of approximately 1 billion square metres. It should be emphasised that these housing types were built by SMEs, which served as the dominant factor for the construction of medium- and high-rise RTBs, compared to self-built housing projects. According to the 2020 Annual Report of Housing, self-built houses comprised 159 million square metres of space in 2015, and this figure steadily rose to more than 392 million square metres of space in 2019. In observance of this market trend, it appears that a priority was given to the construction of purpose-built apartments and residential buildings to obtain a high profit margin by privately owned construction companies. This underscores the fact that that the dominant building characteristics in Cyprus are residential buildings and apartments. This is why the present study focused on investigating high-density medium-rise RTBs as a representative housing typology in Cyprus.

In Cyprus, there are a total of 833,700 buildings, and the majority (approx. 70%) are used for residential purposes. Of 583,590 residential buildings, the medium-rise RTB structure of four or five storeys is predominant. About 385,000 are residential buildings with two-storey detached, semi-detached or terraced houses, and 198,000 are RTB buildings with five or more than ten storeys, located in densely populated cities across the island [82]. The most representative morphological building typologies are rectilinear block and H-shape, to which more than 38% of the total housing units belong. Notably, residential building-stock comprises approximately 6,646 representative buildings which consists of 2,712 dwellings constructed under the government's social housing scheme and 659 dwellings completed in collaboration with local co-operative establishments between 1984-1996. Additionally, 3,275 dwellings were built by privately-owned construction companies to fulfil the absence of social housing scheme between 2000-2005 [83]. A total of 36 RTBs with the same floor-plan layout, construction materials and architectural style were selected to conduct a field study and recruit social households in accordance with these criteria, as illustrated in Fig. 7(a)-(f).

(a)

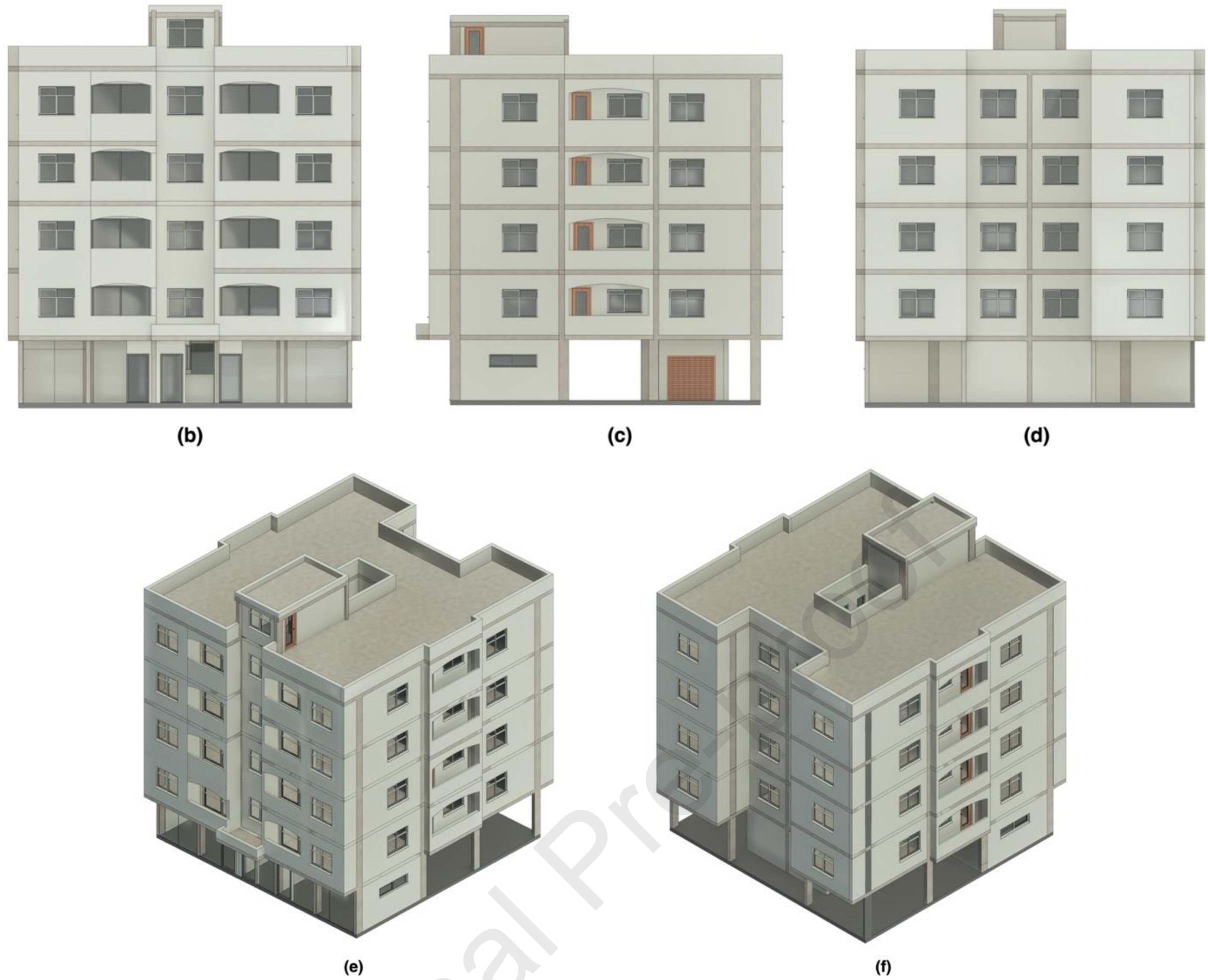


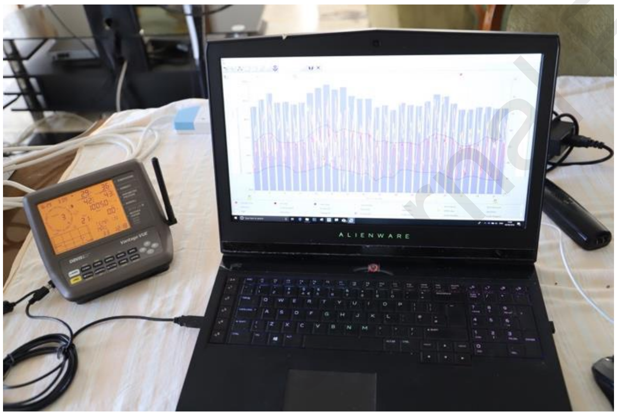
Fig. 7. (a) Details of floor-plan layout of the RTBs; **(b)** Front elevation view; **(c)** Side elevation view; **(d)** Back elevation view; **(e)** 3D Rendering model of front-side views; **(f)** 3D Rendering model of back-side views.

Sources (a)-(f): Autodesk® Revit® Version 2021.1.0.

2.3. Physical measurements

The outdoor air temperature and relative humidity (RH) levels of the environmental conditions were monitored from 28 July to 3 September 2018 to investigate the 'neutral' adaptive thermal comfort for the south-eastern Mediterranean climate of Cyprus which contributes to the development of the ASHRAE Global Comfort Database II. The outdoor environmental conditions, including the outdoor air temperature, RH and heat stress index, were monitored with a Wireless Vintage Pro 2 weather station from Davis Instruments Corporation (Hayward, CA, USA) [84]. The indoor environmental conditions were recorded using a thermometer (resolution 0.1 °C), the globe temperature was recorded with a 15-cm-diameter globe thermometer of thin-walled copper sphere painted black (resolution 0.1 °C), the RH was recorded with the 2400 Heat Stress WBGT (Wet Bulb Globe Temperature) Meter (Extech Instruments, Nashua, NH, USA) (resolution 0.1 °C) and black globe temperature (BGT) was recorded [85].

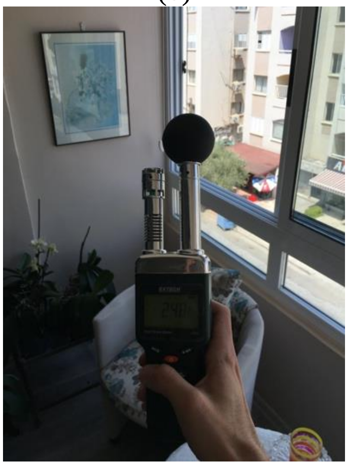
To validate the findings from the monitoring campaign, additional *in-situ* measurements of indoor air environment were carried out using a forward-looking infrared radiometer (FLIR) infrared thermographic camera to assess the occupants' decisions on TPVs and TSVs. With regards to assessing the building fabric thermal performance, the indoor air temperature and RH of 118 participants' living rooms were measured concurrently with a questionnaire survey to cover the hottest summer period for assessing overheating risk and occupants' thermal comfort. Fig. 8(a)-(d) illustrate the setups for the weather station and indoor air temperature measurement instrument.



(a)

(b)

(c)



(d)

Fig. 8. (a) The environmental conditions were recorded and computed with highly efficient engine to reduce the risk of data loss during the survey; **(b)** The custom-made data logger compartment was built by specialist weather software company and this device was integrated into the computer engine to allow the researcher for a continuous environmental monitoring; **(c)** The *in-situ* measurements of indoor environment was recorded while the wall mounted A/C system was in use late in the afternoon on a hot summer day; **(d)** The indoor air environment was recorded while the large-glazed windows were open early in the morning on a hot summer day. **Sources (a)–(b):** The images were collected from the first author's field survey diaries and archival photographic documentation of the case study buildings in Famagusta, Cyprus. **Image credits (c)–(d):** on courtesy of the households participated for the questionnaire survey and monitoring campaign recruited by the lead researcher.

2.4. Questionnaire survey

In our research, we adopted a methodology that included questionnaire surveys for the residents of the RTBs with different orientations in social housing development. To collect adequate primary data from the social householders about cooling energy use and thermal comfort assessment in the sample of flats, we developed a standardised questionnaire survey (see the questionnaire survey proforma in **Appendix A.1-A.7** – Investigation of household heating- and cooling-energy-consumption patterns and thermal comfort). A total of 200 households out of 288 flats were randomly selected, covering the social housing stock within various states in Cyprus [86]. Out of 200 households, only 118 participants were successfully recruited from 28 July to 3 September 2018.

The questionnaire was designed to obtain predominantly quantitative feedback from the respondents, using random sampling criteria to identify a nationally representative archetype buildings in order to represent dominant housing typology in Cyprus. The sampling criteria was selected to identify social householders' socio-demographic characteristics, ownership status, length of residency, including base case RTB orientations and flat floor level differences of each apartment units in the social housing estate, as shown in Fig.9. In order to assess occupants' degree of thermal discomfort, the questionnaire pro-forma was distributed to the subject respondents by adopting the 7-point ASHRAE thermal sensation band was used [87].

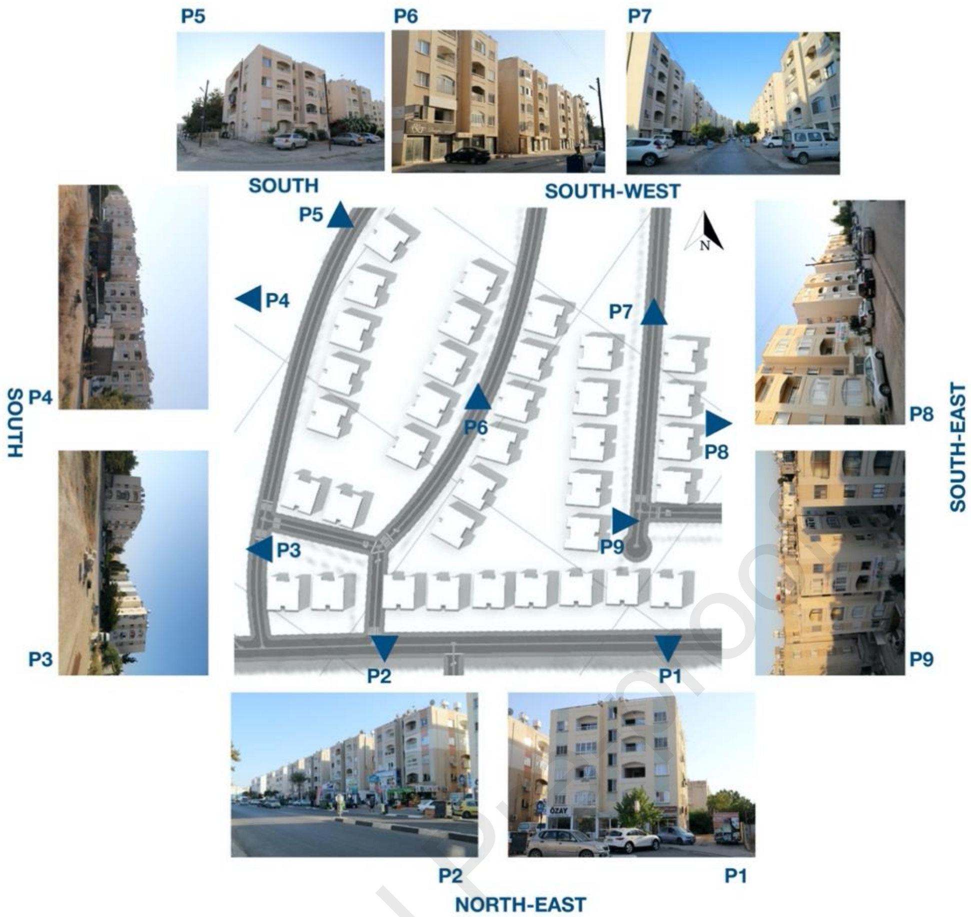


Fig. 9. The point-by-point walk through survey of the case study location, the field investigation was undertaken on door-to-door-survey of 36RTBs in the social housing estate.

In this study, a thermal comfort sheet that was devised in conjunction with the questionnaire. The questionnaire design process was iterative and involved extensive collaboration with the social householders. This data collection method looked at selected RTBs with owner-occupied and privately-rented apartment units to measure the indoor thermal comfort conditions while concurrently conducting *on-site* environmental monitoring by asking them to answer questions. Respondents in the survey completed a face-to-face semi-structured interview, which lasted around 25 minutes. The respondents were people who did not identify themselves as vulnerable (i.e., people with disability or dyslexia).

Each participant was given a questionnaire to complete and was also interviewed by the lead researcher. An analysis was guided by a preliminary thematic analysis of key concepts prompted during the interviews with respondents. The semi-structured interviews were conducted with households across 36 RTBs so that the findings of the study could be generalised to represent entire social housing stock in Cyprus in five major cities *(i)* Famagusta – coastal, *(ii)* Nicosia – inland, *(iii)* Kyrenia – coastal & semi-mountainous, *(iv)* Omorphou – coastal & mountainous, Trikomo – coastal climates where represent the subtropical (Cfa) and partially semi-arid (Bsh) climate of Köppen-Geiger climate classification.

2.5. Parametric data analysis

Correlations amongst multiple parameters were obtained from the findings of the longitudinal field survey to investigate the relationship amongst different parameters, using Statistical Package for the Social Sciences (SPSS) version 25.0 (IBM, Armonk, NY, USA) [88]. First, for the descriptive analysis, we used the interview findings to report the households' socio-demographic characteristics and their thermal comfort level, and then we used correlation analysis of these findings to evaluate the correlation amongst the different parameters.

Inferential statistics, also referred to as inductive statistics, are techniques employed for the purpose of making generalisations or inferences about the sample size [89]. The main inferential statistical techniques used in this study included Pearson's correlation coefficient and linear regression analysis. For running the parametric tests between the dependent and independent variables we adopted the statistical conventions were as follows: 95% is the assumed degree of confidence, 0.05 is the level of confidence interval, and 0.000 is the significance level (p). Notably, a total of 188 households were successfully recruited, but a 100-sampling size was included in the SPSS dataset, because it was determined that 18 households did not provide accurate information at the time that the questionnaire survey was distributed; to avoid a biased interpretation of the field-survey results and to run a parametric-statistical analysis for the present study, these households were disregarded in the dataset.

3. Analysis and Results

3.1. Descriptive analysis

The findings are presented according to the narrative order that questions were distributed to the household members[2]; firstly, the descriptive data for each different orientation (north-east, north-west, south-east, south-west, and south) and floor level of the respective flats are discussed. This is followed by the results of statistical testing using Pearson's rank correlation test to investigate the relationship between the households' socio-demographic characteristics and its impact on thermal comfort assessment (**Data set A:** The raw data of the statistical data set was designed with the SPSS version 25.0, including an .sav file for other scholars to access for further research work). The decision to use these tests was made based on the statistics decision chart for parametric tests discussed in section 3.2. In this study, field investigation was carried out only in summer, and the measured indoor occupied spaces were analysed. Table 5 presents a descriptive analysis of the monitored and measured environmental parameters during the summer period surveyed.

Table 5. Data of outdoor and indoor climatic parameters in representative interviewed/measured flats.

Environmental parameters	Minimum °C	Maximum °C	Mean °C	SD
Indoor air temperature	25.40	34.10	30.595	1.76860
Indoor relative humidity	31.10	75.00	57.838	8.75611
Outdoor air temperature	23.70	36.00	32.118	2.17015
Outdoor relative humidity	19.60	78.00	59.166	11.76264
Outdoor heat stress index	33.00	43.00	36.700	2.33766

The results of environmental monitoring findings showed the typically warm conditions of the environment during the survey period in summer. The maximum indoor and outdoor air temperatures peaked at 34.10 °C (SD = 1.76) and 36 °C (SD = 2.17), respectively. Additionally, it was observed that the RH levels of the indoor environment were not excessively high on hot summer days, with a mean of 57.83%, a maximum of 75%, and a minimum of 31.10% (SD = 8.75). However, the outdoor environment had a mean humidity level of 59.16% (SD = 11.76). Moreover,

[2] The households represent the flats recruited for the present study. Throughout the questionnaire survey, the researcher requested that the households nominate one of their family members who felt confident responding to the questions.

we observed that, during these six weeks, the external temperatures were above 23 °C for 95% of the time [90] (**Data set B:** Outdoor environmental monitoring recordings in .csv file).

The mean indoor air temperature for 100 occupied spaces of each flat recruited for the study. It was found that the indoor air temperatures were ranged from 25.4 °C to 34.10 °C which was significantly higher than the acceptable upper thermal comfort threshold of 28 °C indicated by Chartered Institution of Building Services Engineers (CIBSE) Guide A [91].

The results reveal that all 36 RTBs' households suffered from uncomfortably indoor air environment conditions which is worthy for an investigation to predict 'neutral' adaptive thermal comfort by undertaking regression analysis. Notably, we identified that the low quality of building materials and significant heat losses through building envelopes have led to increase the indoor air temperatures, particularly intense solar radiation on the top floor flats.

Moreover, the air velocities were also considered, whereas they are significant to restore the thermal comfort. In this field study, the air speed frequency was recorded. Therefore, the occupants were not asked to record their thermal perception with considering the air movement and its impact on adaptive thermal comfort at the time of voting. The readings were only taken into consideration to avoid bias on the subject participants' responses both on the TPVs and TSVs. Notably, the participants were recruited different time of day which directly influences on the results of their TPVs and TSVs. In this study, this determinant factor was taken into consideration to identify the most accurate findings on investigation of 'neutral' adaptive thermal comfort where the weather is hot and dry in summer. The findings of the regression analysis were developed based on this technical detail which is neglected by other previous scholars' work on thermal comfort.

The extensive statistical analysis was undertaken between time of day and on-site environmental monitoring conditions to prove the validity of regression analysis findings in section 3.3 (**Data set C:** Scripts of statistical analysis were conducted on exploring influences between time of day and locale climate conditions in .xls file). Moreover, the air movement factor has appeared to affect the participants' decisions on thermal comfort with taking into account their habitual adaptive behaviour on window opening schedules which are discussed in section 4.1. Fig. 10(a)&(b) illustrate the readings on the ventilation rate of outdoor environmental conditions monitored concurrently with the questionnaire survey.

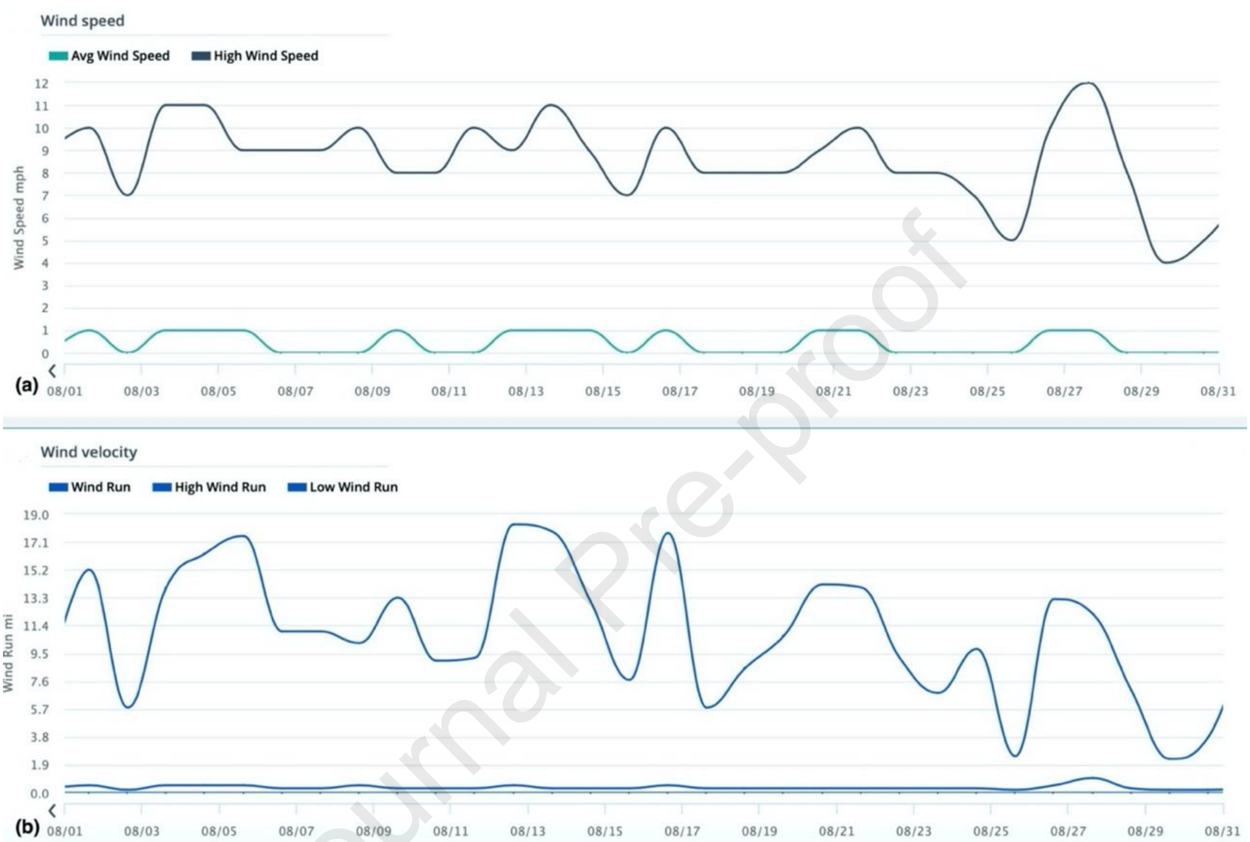


Fig. 10. **(a)** The air movements with average and high-speed recordings; **(b)** The wind velocity frequency recordings.

As can be seen in Fig.10(a) & (b), the average recorded wind speed throughout the field survey period was 0.2 m/s. Hence, the Cyprus Meteorological Service data indicates that In Cyprus, the minimum and maximum wind speeds in December are 2.98 m/s and 6.16 m/s, respectively, whereas in the month of August they tend to be 3.75 m/s and 7 m/s, respectively [92]. The environmental monitoring studies reveal that the fluctuations of airspeed within the other environmental parameters recorded at the time of survey have led to impact on occupants' habitual adaptive behavior to adjust their thermal comfort due to the acclimatization of high indoor air temperatures.

The statistical analysis related to locale climate conditions are not only limited with the *on-site* environmental monitoring, the *in-situ* measurements of participants' occupied space were also investigated to reduce the risk of bias on their TSVs and TPVs. (**Data set D:** Scripts of statistical analysis were conducted on exploring influences between time of day and indoor air environment quality in .xls file).

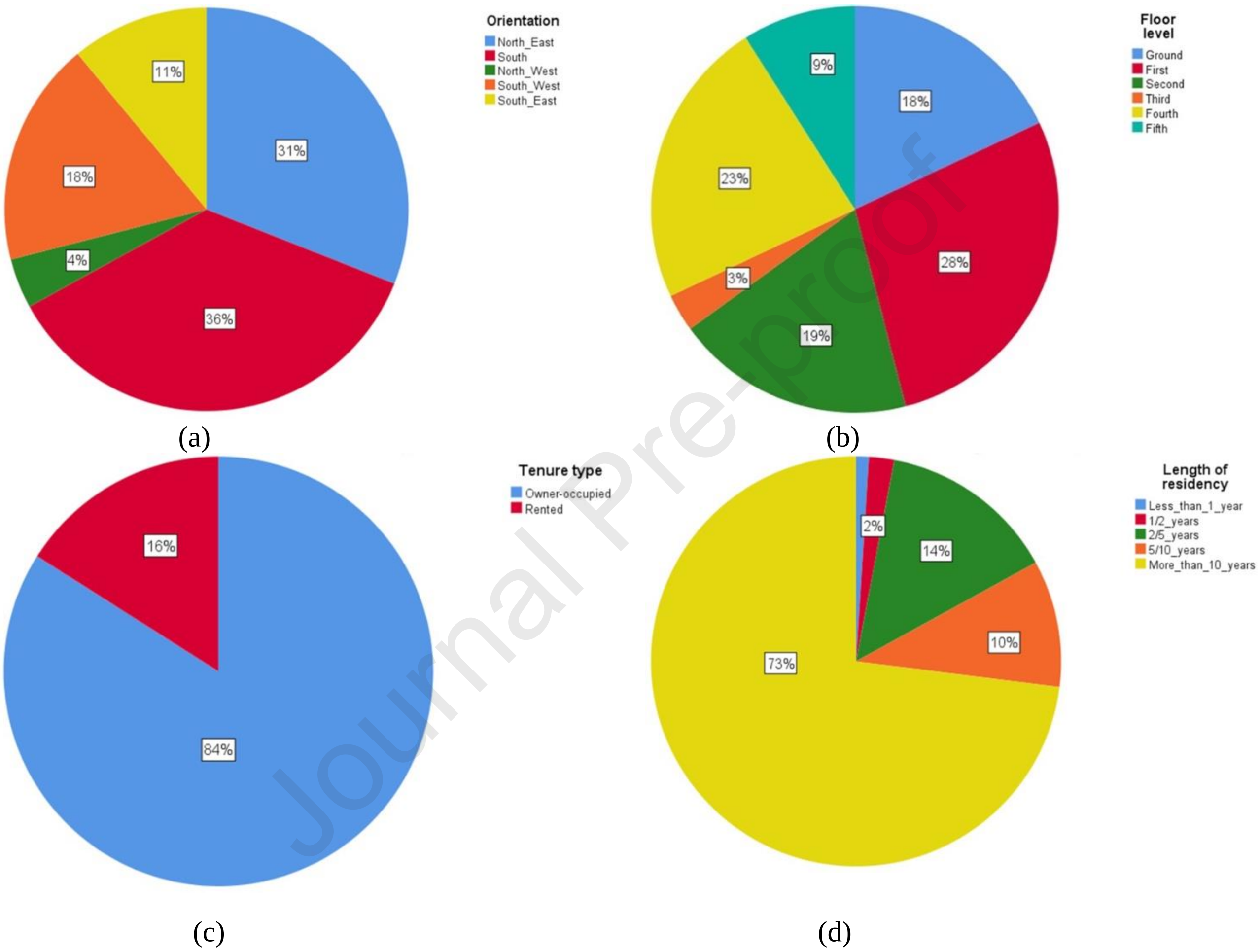


Fig. 11. Descriptive analysis of questionnaire survey: **(a)** number of participants recruited by different orientation of RTBs; **(b)** number of participants recruited by floor level difference; **(c)** tenure type; **(d)** length of residency.

A breakdown of the completed questionnaires shows that 36% of the questionnaires were returned from south-facing blocks, 31% from north-east-facing blocks, 18% from south-west-facing blocks, 11% from south-east-facing blocks and 4% from north-west-facing blocks, as shown in Fig.11(a). Of the households, 18% were recruited from ground floor flats, 28% from the first floor, 19% from the second floor, 3% from the third floor, 23% from the fourth-floor flats and 9% from the top-floor level flats, as shown in Fig.11(b). Of the completed questionnaires, 33% male and 67% female responses were received. An analysis of age distribution votes across the interviewed households showed that 48% of the respondents were from 55 to 65 or over 65. Table 6 displays the frequency and age distribution for the administered questionnaires.

Table 6. Age distribution of the thermal comfort survey questionnaires returned from the RTBs.

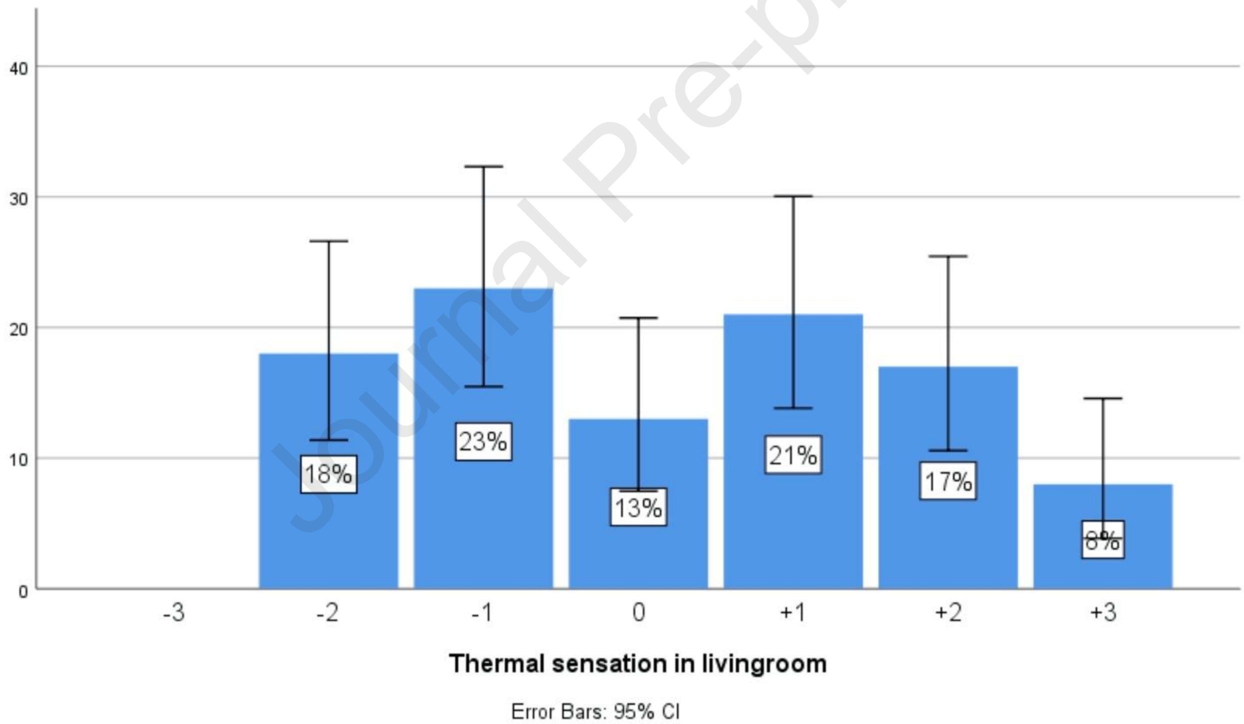
	Age frequency distribution					
Orientation	**20–25**	**25–35**	**35–45**	**45–55**	**55–65**	**65 or over**
North-east	1	8	4	4	9	5
South	0	6	8	9	6	7
North-west	0	0	0	0	3	1
South-west	0	0	2	4	10	2
South-east	0	1	2	3	4	1
Total	1	15	16	20	32	16

Floor level	**20–25**	**25–35**	**35–45**	**45–55**	**55–65**	**65 or over**
Ground	0	1	2	2	10	3
First	1	2	3	7	9	6
Second	0	4	5	3	3	4
Third	0	1	1	0	0	1
Fourth	0	5	3	4	9	2
Fifth	0	2	2	4	1	0
Total	1	15	16	20	32	16

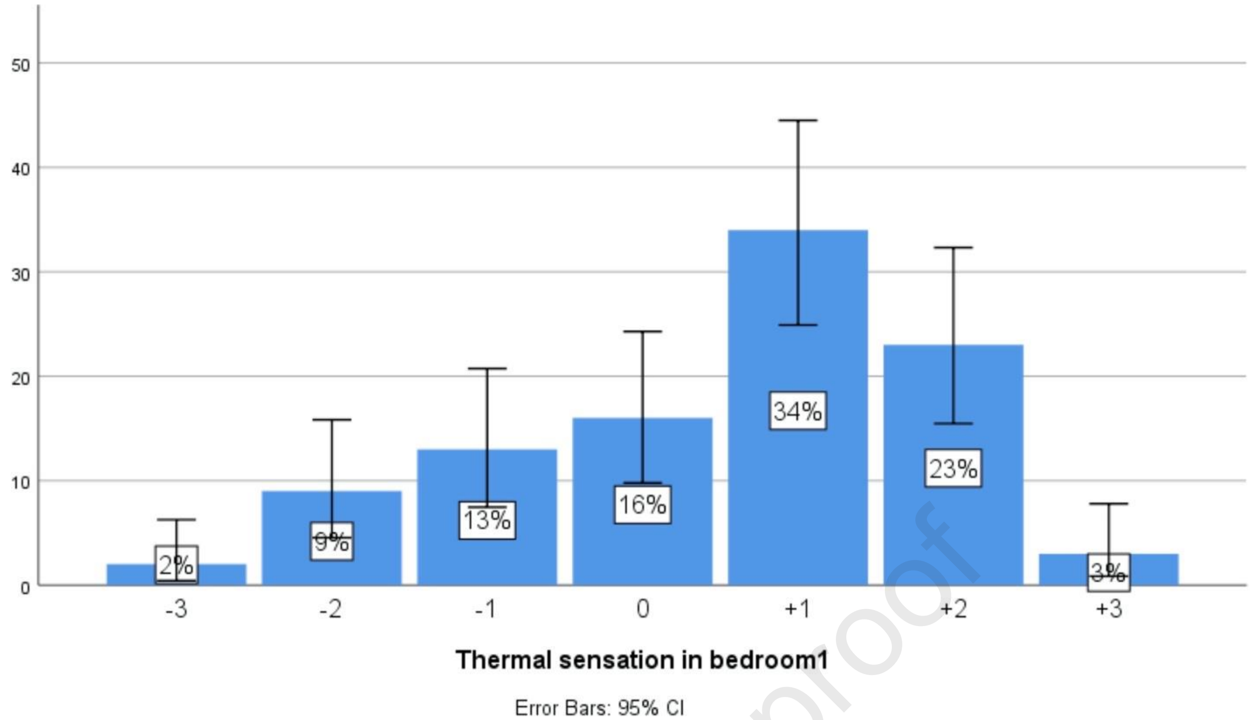
Note: The frequency distribution of the households' age band takes into consideration the flats' floor level differences. The households' age band scale runs from 0 for 20–25 to 5 for 65 or over; the recruited households from different orientations with the age band scale runs from 0 for North-east to 4 for South-east; the recruited households from the floor level differences with the age band scale runs from 0 for Ground to 4 for Fifth.

Notably, the distribution of occupancy type and responses indicated 84% ownership status and 16% private tenancy status, as shown in Fig.11(c). These response rates, according to the different tenure types, indicate that ownership status may influence the occupants' perceptions of the thermal environment. The length of residency of the subject participants in the measured flats indicates that 14% of the households had been living in their flats from 2 to 5 years, while the majority (73%) of the residents in the social housing estate had been living there for more than 10 years at the time of the survey, as shown in Fig. 11(d).

To fulfil the research objective, we investigated the occupants' TSVs in accordance with their socio-demographic characteristics, including gender and age, and the physical structure of the RTBs was also taken into consideration in terms of the orientation and floor level differences of the flats. The TSVs were rated using the ASHRAE 7-point thermal sensation scale: cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (+1), warm (+2) and hot (+3). The TSVs of very dissatisfied, slightly dissatisfied, neutral, slightly satisfied, satisfied and very satisfied with the indoor environment were also assessed using a 7-point scale from −3 to +3 [35]. Fig. 12(a)–(d) illustrates the findings of the occupants' TSVs in each occupied space across the surveyed sample size.

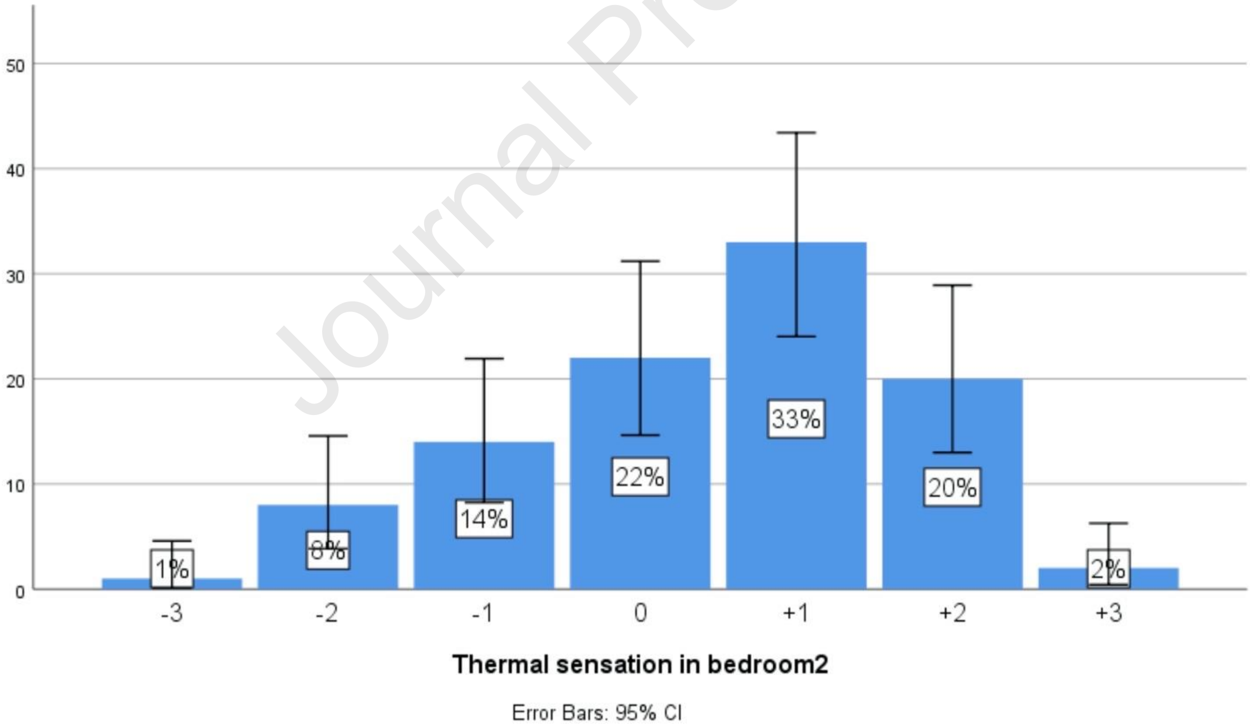


(a)

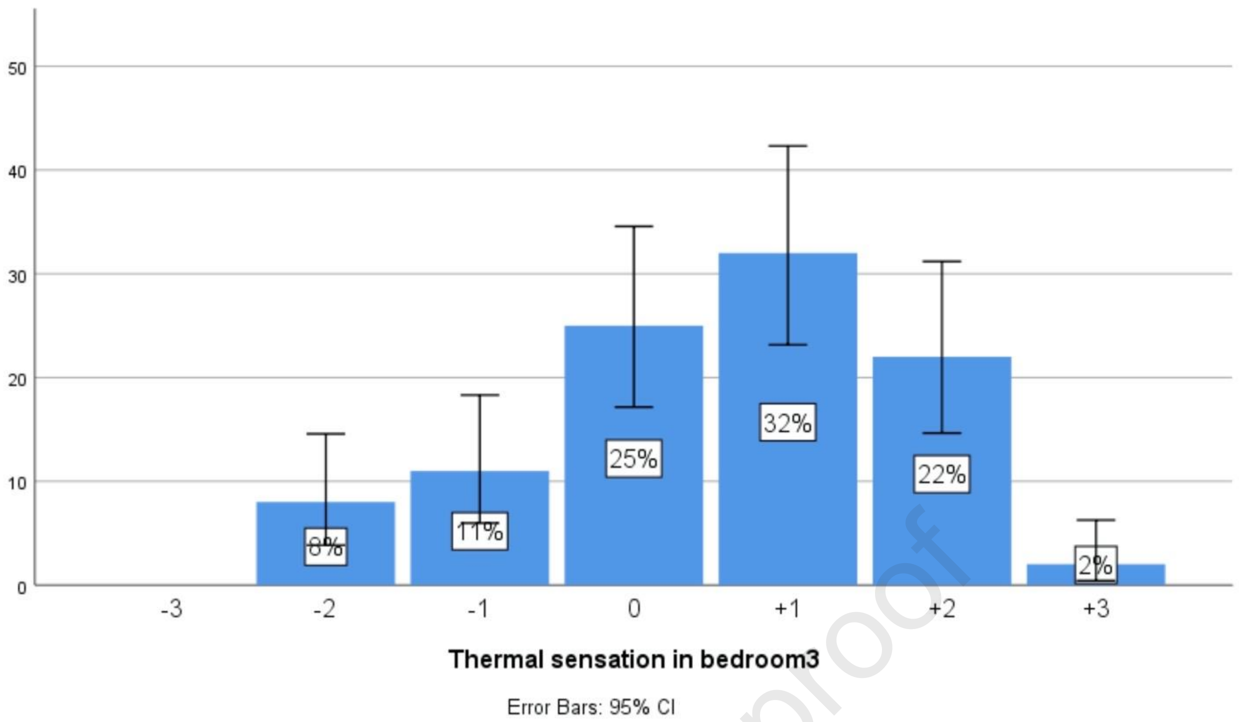


(b)

Fig. 12. Percentage distribution of occupants' TSVs in **(a)** the living room; **(b)** bedroom 1. (To be continued)



(c)



(d)

Fig. 12. Percentage distribution of occupants' TSVs in **(c)** bedroom 2 and **(d)** bedroom 3.

As shown in Fig. 12(a), 23% of the respondents reported that they felt comfortably cool, 21% felt comfortably warm, and 18% felt too cool. On the other hand, 17% of the respondents found the environment too warm, 13% were comfortable, and 8% were much too warm. A further 41% of the respondents reported that they felt comfortably cool and too cool in their living rooms. However, 46% expressed feeling comfortably warm and much too warm in summer due to the RTBs' orientation.

Fig. 12(b) shows that 34% of the respondents found the environment comfortably warm, 23% found it too warm, and 3% expressed feeling much too warm. On the other hand, 13% of the respondents reported that they were comfortably cool, 9% were too cool, and 2% felt much too cool. Finally, 16% indicated that they were comfortable in their bedroom 1 spaces in summer. Thus, approximately two-thirds (60%) of the participants voted comfortably warm and much too warm.

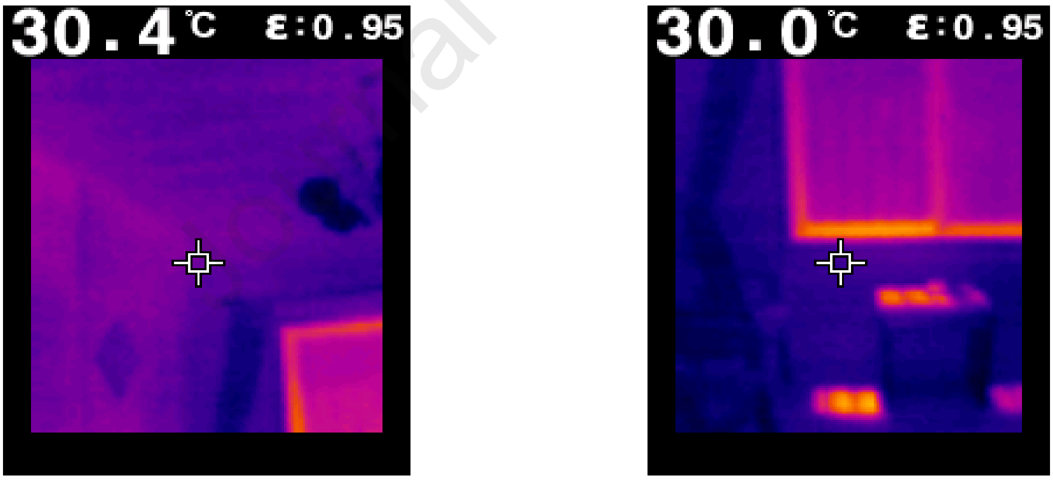
As illustrated in Fig. 12(c), 33% of the households reported that they felt comfortably warm, 20% were too warm, and 2% were much too warm, whereas 14% expressed that they felt comfortably cool, 8% were too cool, and only 1% felt much too cool. On the other hand, 22% of the respondents indicated that they were comfortable in their bedroom 2 spaces. Over half (56%) of the participants reported that they preferred to feel comfortably warm or much too warm. However, 22% of the participants expressed feeling thermally comfortable. This may be directly related to the RTBs' orientation and floor level differences.

According to Fig. 12(d), 32% of the respondents said they found their environment comfortably warm, 22% found it too cool, and 2% found it much too warm, while 11% found their environment comfortably cool, and 8% found it too cool. Finally, 25% of the participants indicated that they felt comfortable. These TSV results for bedroom 3 spaces show more or less the same patterns as the bedroom 1 and 2 spaces (**Data set E:** Occupants' TSVs scripts by using Whisker's statistical test in .xls file).

As previously mentioned, this may have been due to the RTBs' orientation and the floor levels of the measured flats. The findings revealed that there were signs of thermal discomfort in all of these indoor spaces, which were probably caused by the deficient building envelopes and high solar absorptivity of the RTBs, based on their orientation. It also emerged from the findings that most of the occupants experienced slightly high indoor air temperatures in their living room spaces due to the lack of natural ventilation and the effect of direct solar radiation. This highlights the fact that the occupants' TSV ranking scale distribution included a lot of variation, thus indicating relatively thermally uncomfortable conditions in summer (**Data set F:** Scripts of statistical analysis were conducted on exploring influences between time of day and participants' thermal sensation in .xls file). Table 7 illustrates the recordings of indoor air temperature by using infrared radiometer thermography to explore correlations between the impact of solar radiation on building envelopes and occupants' thermal comfort, with taking into account the *wet-bulb* and *dry-bulb* temperature readings consecutively.

Table 7. *In-situ* measurements of building envelopes and indoor air temperature parameters' recordings.

Frequencies		*In-situ* measurements	Indoor WET	Indoor DEW
N (Normality)	**Valid**	100	100	100
Mean (°C)		33,64	24,35	21,48
Std. Error of Mean		0,23545	0,32722	0,33602
Median (°C)		32,90	24,60	21,90
Std. Deviation (SD)		2,35445	3,27217	3,36021
Skewness		0,840	3,844	-0,0567
Std. Error of Skewness		0,241	0,241	0,241
Kurtosis		-0,036	29,640	3,067
Std. Error of Kurtosis		0,478	0,478	0,478
Minimum (°C)		29,10	18,70	11,40
Maximum (°C)		39,80	48,50	32,40
Percentiles (°C)	**25th**	32,10	23,00	20,20
	50th	32,90	24,60	21,90
	75th	34,80	25,57	23,40



(a) (b)

Fig. 13 (a) & (b). Sample of *walk-in* survey analysis of infrared radiometer thermography was used concurrently with the questionnaire survey.

Fig. 13(a) shows the thermal performance of ceiling surface measured 30.4 °C on intermediate floor southeast-facing flat's living room on peak day, 1 August 2018, at 10:05a.m. The outdoor temperature was 29 °C. The wall-mounted air conditioner had been in use for approximately two hours at the time of the thermography survey, set at 19 °C. Thermal anomalies of regular shapes and clearly identified boundaries are associated with the underlying structure and even temperature distribution within the pattern. This image shows an area of ceiling where the flat located above was constructed without using any insulation material on the building envelope.

Fig. 13(b) shows the thermal performance of the side wall measured 30.0 °C in intermediate floor southeast-facing flat's living room. The side (southeast) wall shows greater heat gains coming through the aluminium-framed single-glazed windows. In addition, air leakage causes thermal anomalies with more irregular shapes; deficiencies in window-frame structure and large temperature variations were detected forming characteristic streaks or ray patterns.

In this image, air leakage through the deficient window frame causes significant heat loss. This accounts for slightly uncomfortable indoor air temperatures, despite air conditioning use during morning occupancy hours. In those surveys, signs of significant conductivity heat loss through the ceiling surfaces were observed. In summary, internal walk-through thermography was found to be much more successful at detecting a broad range of thermal lag of building materials which has attributed to the investigation of 'neutral' adaptive thermal comfort through a longitudinal field investigation in this south-eastern Mediterranean climate.

3.2. Correlation analysis

This analysis primarily explores the reasons for thermal discomfort in respect to the households' age, the orientation of the RTBs and the floor-level differences of flats in each occupied space based on the collected data from the respondents. The reason for conducting this analysis was that socio-demographic characteristics are a significant factor in people's behaviour in any setting. The main reason for considering the age band in this Pearson's rank correlation analysis was that almost half (48%) of the households were in the 55–65 and 65 or older age groups, and we believed that it was important to consider the impact of age on thermal comfort in these measured flats.

A moderate negative correlation (r = −0.229, $p < 0.05$) was found between the households' age and the occupants' complaints about thermal discomfort. This is because 48% of the household members were elderly. In conjunction with this socio-demographic analysis, the RTBs' orientation and floor level differences were taken into consideration. As mentioned in the general survey findings section, 24% of the occupants complained about high humidity in the south-west-facing RTBs in summer, and another 17% complained about incoming sun.

The findings revealed that the occupants may have experienced thermally uncomfortable conditions due to the high outdoor air temperatures and humid conditions in this climate. This became clear when we determined the positive relationships between the reasons for thermal discomfort and RTB orientation differences, as shown in Table 8.

Table 8. Means, SDs and correlations between the reasons for thermal discomfort (M = 3.2, SD = 2.64) and household age band (M = 3.15, SD = 1.34), orientation (M = 1.42, SD = 1.37) and floor level (M = 2.03, SD = 1.52).

Research question & Other parameters		**Discomfort**	**Age band**	**Orientation**	**Floor level**
Q 35: How would you best describe the source of this discomfort?	Pearson's correlation	1	–0.185	–0.030	0.218*
	Sig.		0.065	0.767	0.029
Age band	Pearson's correlation	–.0185	1	0.178	–0.229*
	Sig.	0.065		0.076	0.022
Orientation	Pearson's correlation	–0.030	0.178	1	–0.078
	Sig.	0.767	0.076		0.441
Floor level	Pearson Correlation	0.218*	–0.229*	–0.078	1
	Sig.	0.029	0.022	0.441	

Note: The recruited households' age band scale ran from 0 (20–25) to 5 (65 and over). The orientation of the RTB scale ran from 0 (North-east) to 1 (South), 2 (North-west), 3 (South-west) and 4 (South-east). The recruited flats' level difference scale ran from 0 (Ground) to 1 (First), 2 (Second), 3 (Third), 4 (Fourth) and 5 (Fifth). The recruited households' age band scale ran from 0 (20–25) to 5 (65 and over).

*Correlation is significant at the 0.05 level (two-tailed).

The results of the orientation analysis showed that, although there was no significant correlation between floor level differences and reasons for thermal discomfort, there was a moderately positive relationship ($r = 0.218$, $p < 0.05$). This was due to the poor window design in the RTBs, which prevented natural ventilation into the indoor occupied spaces. This led to a difference of 2–3 °C between the ground and top floor flats due to a lack of natural ventilation and as a result of the upper floor receives the intense horizontal radiation on the roof. Thus, it appeared that occupants' habitual adaptive behaviour in window opening patterns also played a crucial role in their TSV decisions, which are discussed in section 4.1.

According to the survey findings, 55% of the respondents reported opening windows for more than eight hours in summer, which highlighted the fact that most of the respondents preferred to open windows for cooling purposes. This possibly reflected a positive and moderate relationship between the households' socio-demographic characteristics and the RTBs' physical position, partly because the occupants had experienced relatively uncomfortable indoor air temperatures in their occupied spaces in summer. From this analysis, we found that the flats' floor level differences played a crucial role in the households' habitual adaptive behaviours in respect to thermal comfort. What was notable from this correlation analysis was that there was no significant factor for orientation and occupants' gender across the sample size.

The relationship between the occupants' TSVs for each occupied space and the RTBs' physical position was found to have moderate to strong positive correlations amongst the variables, as shown in Table 9. In questions 22–25, the occupants were asked to evaluate the overall quality of the indoor air temperature in an open-ended question form (see the questionnaire survey proforma in **Appendix A.1-A.7**). The question concerning the respondents' rating of the quality of the indoor air environment was intended to assess the degree of thermal discomfort in summer. Table 9 illustrates the Pearson's rank correlation analysis between the households' TSVs in summer and the physical position of the RTBs, taking into account orientation differences.

Table 9. Means, SDs and correlations between the occupants' TSVs for each occupied space in summer: living room (M = 3.45, SD = 1.71), kitchen (M = 2.83, SD = 1.67), bedroom 1 (M = 3.66, SD = 1.38), bedroom 2 (M = 3.53, SD = 1.29), bedroom 3 (M = 3.55, SD = 1.23), orientation (M = 1.42, SD = 1.37) and floor level (M = 2.03, SD = 1.52).

Thermal sensation		**Living room**	**Kitchen**	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**	**Orientation**	**Floor Level**
Living room	Pearson's correlation	1	0.565^{**}	0.409^{**}	0.302^{**}	0.297^{**}	−0.188	−0.052
	Sig.		0.000	0.044	0.002	0.003	0.062	0.611
Kitchen	Pearson's correlation	0.565^{**}	1	0.349^{**}	0.364^{**}	0.270^{**}	−0.126	−0.156
	Sig.	0.000		0.000	0.000	0.007	0.211	0.122
Bedroom 1	Pearson's correlation	0.409^{**}	0.349^{**}	1	0.824^{**}	0.765^{**}	-0.220^{*}	−0.005
	Sig.	0.000	0.000		0.000	0.000	0.028	0.963
Bedroom 2	Pearson's correlation	0.302^{**}	0.364^{**}	0.364^{**}	0.805^{**}	0.805^{**}	−0.132	−0.070
	Sig.	0.002	0.000	0.000	0.000	0.000	0.191	0.491
Bedroom 3	Pearson's correlation	0.297^{*}	0.270^{**}	0.765^{**}	0.805^{**}	1	-0.244^{*}	−0.036
	Sig.	0.003	0.007	0.000	0.000		0.014	0.725
Orientation	Pearson's correlation	−0.188	−0.126	-0.220^{*}	−0.132	-0.244^{*}	1	−0.78

	Sig.	0.062	0.211	0.028	0.191	0.014		0.441
Floor level	Pearson's correlation	−0.052	−0.156	−0.005	−0.070	−0.036	−0.078	1
	Sig.	0.611	0.122	0.963	0.491	0.725	0.441	

Note: The occupants' TSVs for each occupied space in summer: living room, kitchen and bedrooms 1, 2 and 3 scale runs from 0 (−3) to 1 (+3); the orientation of the RTB scale runs from 0 (north-east), 1 (south), 2 (north-west), 3 (south-west) and 4 (south-east); the recruited flats' level difference scale runs from 0 (ground), 1 (first), 2 (second), 3 (third), 4 (fourth) and 5 (fifth).

**Correlation is significant at the 0.01 level (two-tailed).
*Correlation is significant at the 0.05 level (two-tailed).

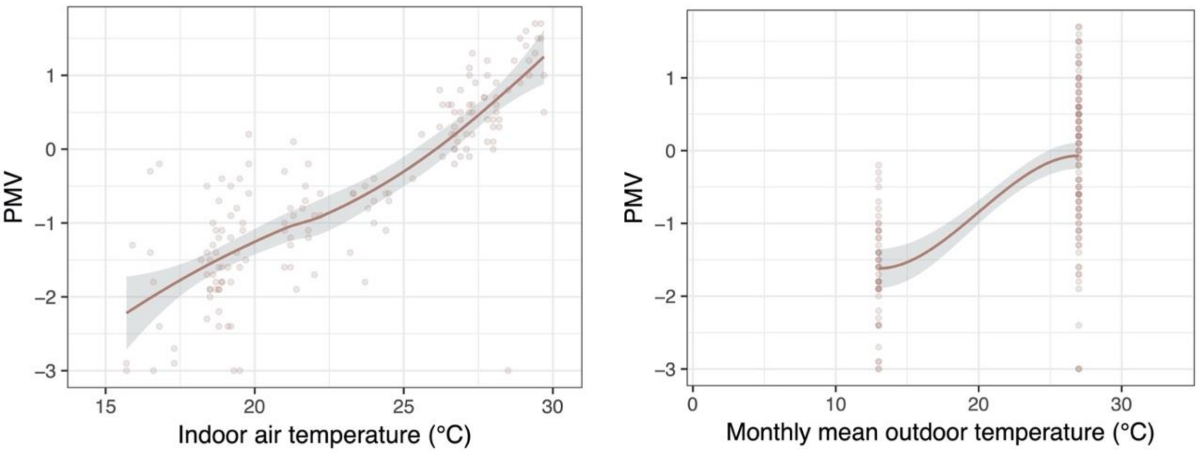
Regarding the occupants' decisions on TSVs in summer, several positive strong and moderate correlations were found. A strong correlation was noted between the TSVs in the living room and kitchen spaces ($r = 0.555$, $p < 0.01$). A correlation also existed between TSVs and the occupation of these spaces in terms of the number of hours both on weekdays and on weekends. We also found that there was a moderate positive correlation between TSVs ($r = 0.257$, $p < 0.01$) and weekday cooling consumption patterns as well as a moderate positive correlation ($r = 0.358$, $p < 0.01$) with weekend cooling consumption patterns.

Significance was also noticed between occupancy density and the effect of heating system control type used. Another positive moderate relationship appeared between occupants' TSVs and the living room and bedroom 1 ($r = 0.409$, $p < 0.01$) and moderate relationship between TSVs and the kitchen and bedroom 1 ($r = 0.349$, $p < 0.01$). This was probably due to the small floor area of these spaces, which means the physical condition of the RTBs can lead to thermally uncomfortable indoor air temperatures due to the poor window design in the interviewed flats.

Concerning the problem of overheating experienced in bedroom 2 in summer, several positive-moderate, strong and very strong correlations with the TSVs were associated with the living room ($r = 0.302$, $p < 0.01$), kitchen ($r = 0.364$, $p < 0.01$) and bedroom 1 ($r = 0.824$, $p < 0.01$). In the bedroom 3 spaces in summer, several more positive moderate correlations were found with the living room ($r = 0.297$, $p < 0.01$), and the kitchen ($r = 0.270$, $p < 0.01$). It should be noted that, a positive strong correlation was found with the bedroom 1 ($r = 0.765$, $p < 0.01$). This seemed to be consistent in spite of the high electricity bills, and in particular, the problems of overheating strongly related to high electricity bills, where the houses gained heat at high rates due to the deficient building envelopes. However, a positive and very strong correlation was also found with bedroom 3 and bedroom 2 ($r = 0.805$, $p < 0.01$), which was due to the effect of the RTBs' orientation on the occupants' TSVs. Finally, we found that there was a moderate negative correlation with bedroom 3 ($r = -0.244$, $p < 0.05$) and bedroom 1 ($r = -0.220$, $p < 0.05$), which indicated that the position of the rooms in the flats had to be taken into account in order to assess the occupants' thermal comfort to provide a basis for regression analysis which is discussed in the following section.

3.3. Regression forecasting analysis

This section comprises the analyses of question 34 concerning occupants' overall thermal sensation for each occupied space in summer (see the questionnaire survey proforma in **Appendix A.1-A.7**). The linear regression analysis was conducted by calculating numerical values of PMV results to identify the neutral thermal comfort benchmarking level. In the comparison of the validating the subject respondents' TSVs with the PMV predictor model, it must be stressed that almost all statistical tests related to slightly warm conditions ranged outside the acceptable thermal environment for comfort ($–0.5 < PMV <0.5$), with a 10% [42]. However, if PMVs were normalised into a 7-point scale of TSV ($–0.5 < PMV < 0.5$ set as 0/neutral, $0.5 < PMV < 1.5$ set as +1/slightly warm etc.), 80% of the results produced by the heat-balance model were in the 'warmer than neutral' region (> +1) [93]. Fig. 14(a)&(b) demonstrate the development of adaptive model to identify world global thermal comfort benchmarking criteria for multi-family residential buildings.



(a) (b)

Fig.14. The scatter plot distribution of adaptive model of multi-family residential buildings; **(a)** indoor air temperature; **(b)** outdoor air temperature. ***Source:*** The ASHRAE – Global Thermal Comfort Database II[3].

Fig. 14(a) shows that the PMV index ranged between 16 °C and 29 °C in naturally ventilated buildings included into the ASHRAE Global Thermal Comfort Database II. Hence, the PMV index depicted between 12 °C and 28 °C while the outdoor environmental conditions selected to identify adaptive model, as shown in Fig. 14(b). For the data acquisition, the satisfaction metric was chosen to develop baseline for the regression forecasting analysis in Cyprus climate.

This section presents the results of households' TSVs for each occupied space against indoor air temperature recorded by undertaking *in-situ* measurements. Additionally, the occupants' TSVs were paired with the indoor relative humidity whether exploring its impact on the 'neutral' sensation threshold level. At the same time, the regression coefficient analyses were undertaken between the subject respondents' TSVs for each occupied space against outdoor air temperature recorded by installing the weather station at the time of conducting semi-structured interviews in the social housing estate.

In the questionnaire, participants were asked, 'How would you rate the overall thermal satisfaction of indoor air temperature for living room spaces?'. The responses were evaluated according to the 'thermal sensation' scale to identify optimum indoor air temperatures in summer.

[3] These graphs were extracted from the thermal comfort visualisation tool's 'PMV' index interface. The tool is an open access source which is available at https://cbe-berkeley.shinyapps.io/comfortdatabase/

Fig. 15 shows the subject respondents' TSVs plotted against operative air temperature recorded during the field survey period.

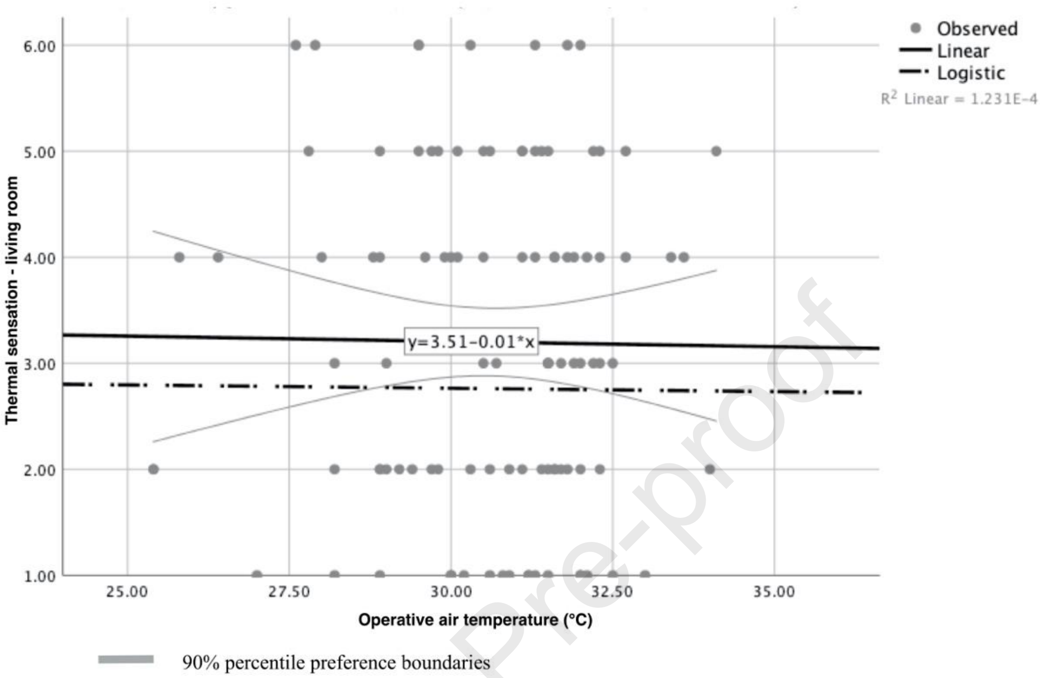


Fig. 15. Relationship between occupants' thermal sensation and operative air temperature in the living room spaces.

The occupants' preferred temperatures for the living room spaces are shown in Fig. 15. A negative perfect regression coefficient was found between occupants' thermal sensation and operative air temperature ($R^2 = 1.231$, $p < 0.001$). The graph indicates that the respondents were 'slightly uncomfortable' when the indoor air temperature ranged from 25 °C to 35 °C in the living room spaces. As can be seen in Fig. 10, 18% of respondents felt 'too warm' (Ta from 28 °C to 34 °C ± 3 °C and ± 9 °C), 23% felt 'comfortably warm' (Ta from 26 °C to 33 °C ± 1 °C and ± 8 °C), and 13% felt 'comfortable' (Ta from 28 °C and 32.50 °C ± 3 °C and ± 7.50 °C), while 21% of respondents voted for feeling 'comfortably cool' (Ta from 26 °C to 33 °C ± 1 °C and ± 8 °C), 17% voted for feeling 'too cool' (Ta from 27 °C to 33 °C ± 2°C and ± 8 °C) and 8% voted for feeling 'much too cool' (a pattern similar to that of the 'much too cool' thermal sensation). The results show that thermal sensation differences significantly influenced occupants' thermal comfort. They also indicate that occupants felt ‘uncomfortable’ at 32.50 °C and ‘very uncomfortable’ at 35 °C [94].

In the questionnaire, participants were asked, ‘How would you rate the overall thermal satisfaction of indoor air temperature for the bedroom 1 spaces in summer?’. Their responses were evaluated on the thermal sensation scale to assess their degree of thermal discomfort and predict acceptable comfort temperatures in summer. Fig. 16 shows the TSVs plotted against operative air temperature. To avoid discrepancies on the statistical data, the dataset was computed within each half-degree bin in summer.

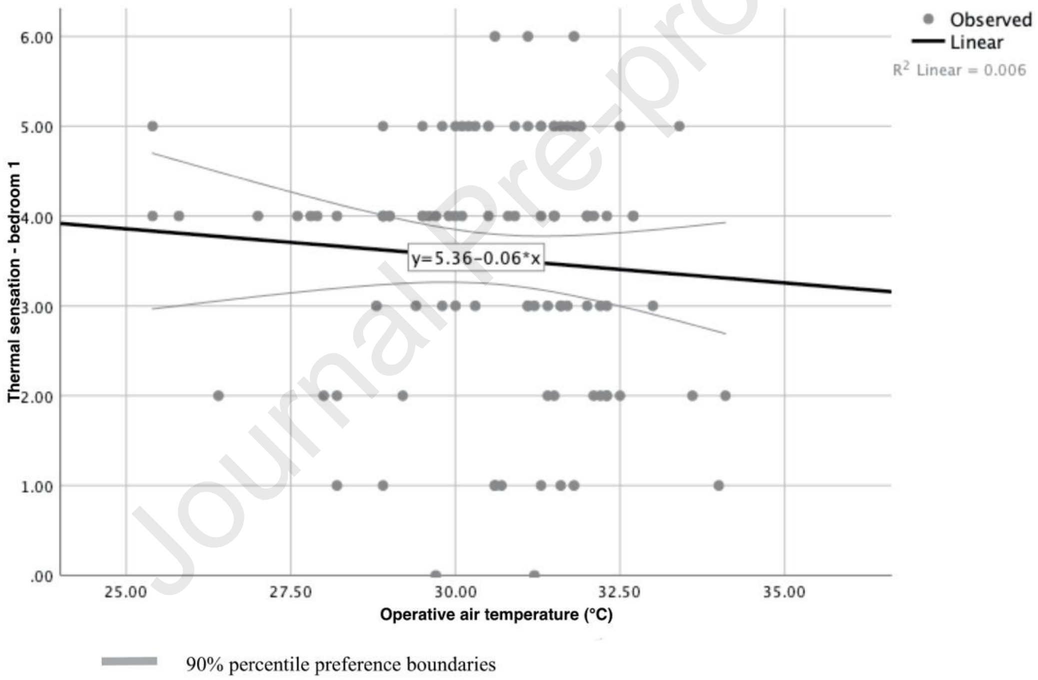


Fig. 16. Relationship between occupants’ thermal sensation and the operative air temperature in the bedroom 1 spaces.

A negative weak regression coefficient appeared between occupants’ thermal sensation and operative air temperature (R^2 = 0.006, p < 0.001). As seen in Fig. 16, 3% of respondents felt ‘much too warm’ (Ta from 31 °C to 32 °C ± 6 °C and ± 7 °C), 9% felt ‘too warm’ (Ta from 26 °C to 33 °C ± 1°C and ± 8 °C) and 13% felt ‘comfortably warm’ (Ta from 25.50 °C to 33 °C ± 0.50 °C and ± 8 °C), while 16% voted for feeling ‘comfortable’ (Ta from 28 °C to 33 °C ± 3°C and ± 8 °C), 23%

voted for feeling ‘too cool’ (Ta from 28 °C to 34 °C ± 3 °C and ± 9 °C) and 3% voted for feeling ‘much too cool’ (Ta from 29 °C to 32 °C ± 4 °C and ± 7 °C). Further, the graph indicates that the 90% percentile preference boundaries ranged from ‘comfortable’ to ‘comfortably warm’. The thermally acceptable indoor air temperatures were from 26 °C to 28 °C, which were from +1 °C to +3 °C higher than the upper thermal comfort threshold recommended by CIBSE Guide A [95].

A quantitative scale ranking of data was gathered on the occupants’ TSVs towards exploring the influences of the environmental parameters recorded concurrently with a questionnaire survey by asking them, ‘How would you rate the overall thermal satisfaction of indoor air temperature for the bedroom 2 spaces in summer?’ Fig. 17 shows the participants TSVs plotted against operative air temperature.

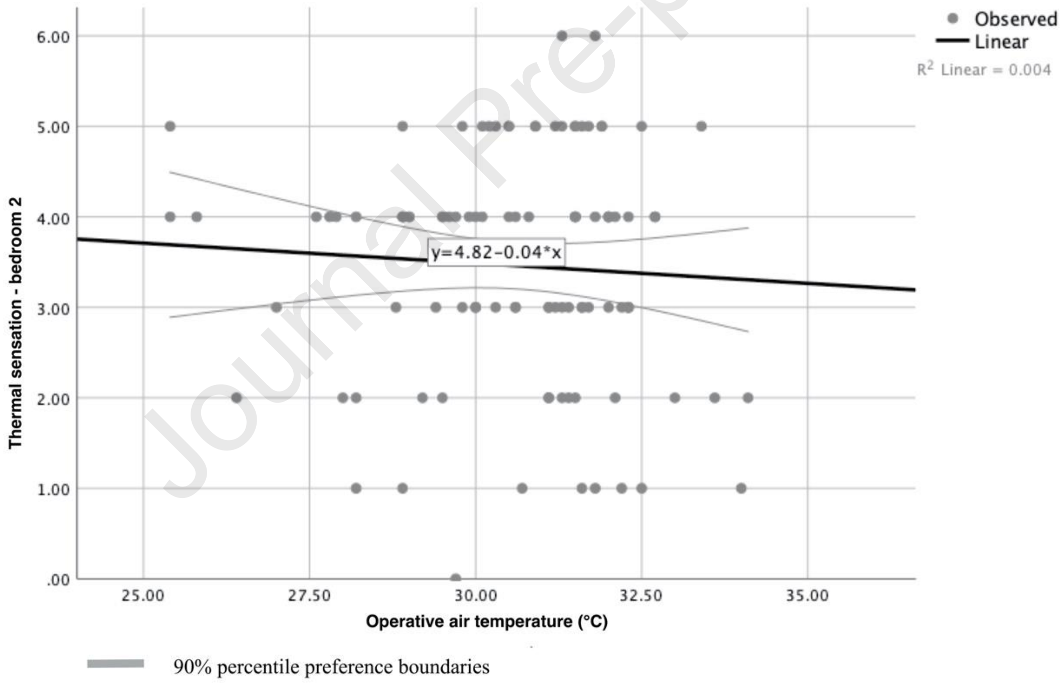


Fig. 17. Relationship between occupants’ thermal sensation and operative air temperature in the bedroom 2 spaces.

A weak negative regression coefficient was found between occupants’ thermal sensation and operative air temperature ($R^2 = 0.004$, $p < 0.001$). As shown in Fig. 17, 2% of respondents felt ‘much too warm’ (Ta from 31 °C and 32 °C ± 6 °C and ± 7°C), 8% felt ‘too warm’ (Ta from 26 °C to 33 °C ± 1 °C and ± 8 °C), 14% felt ‘comfortably warm’ (Ta from 26 °C to 32.50 °C ± 1°C and ± 7.50 °C) and 22% voted for feeling ‘comfortable’ (Ta from 27 °C to 32 °C ± 2 °C and ± 7 °C), while 32% voted for feeling ‘comfortably cool’ (Ta from 26 °C to 34 °C ± 1 °C and ± 9 °C), 20% voted for feeling ‘too cool’ (Ta from 28 °C to 33 °C ± 3 °C and ± 8 °C) and just 1% of respondent voted for feeling ‘much too cool’ (Ta at 29 °C ± 4 °C).

Based on the linear regression equation, we concluded that, in summer, the thermally ‘comfortable’ indoor air temperatures showed patterns similar to those for the bedroom 1 spaces. However, the scattered regression plot demonstrated that the thermally acceptable outdoor air temperatures were from 33 °C to above 35 °C [96].

In order to determine the optimum thermal comfort level in relation to a range of thermal sensations predicted by the PMV, participants were asked, ‘How would you rate the overall thermal satisfaction of indoor air environment for the bedroom 3 spaces in summer?’. Fig. 18 shows the participants’ TSVs plotted against operative air temperature. The thermal sensation graphs were obtained by plotting participants’ TSVs against the environmental parameters.

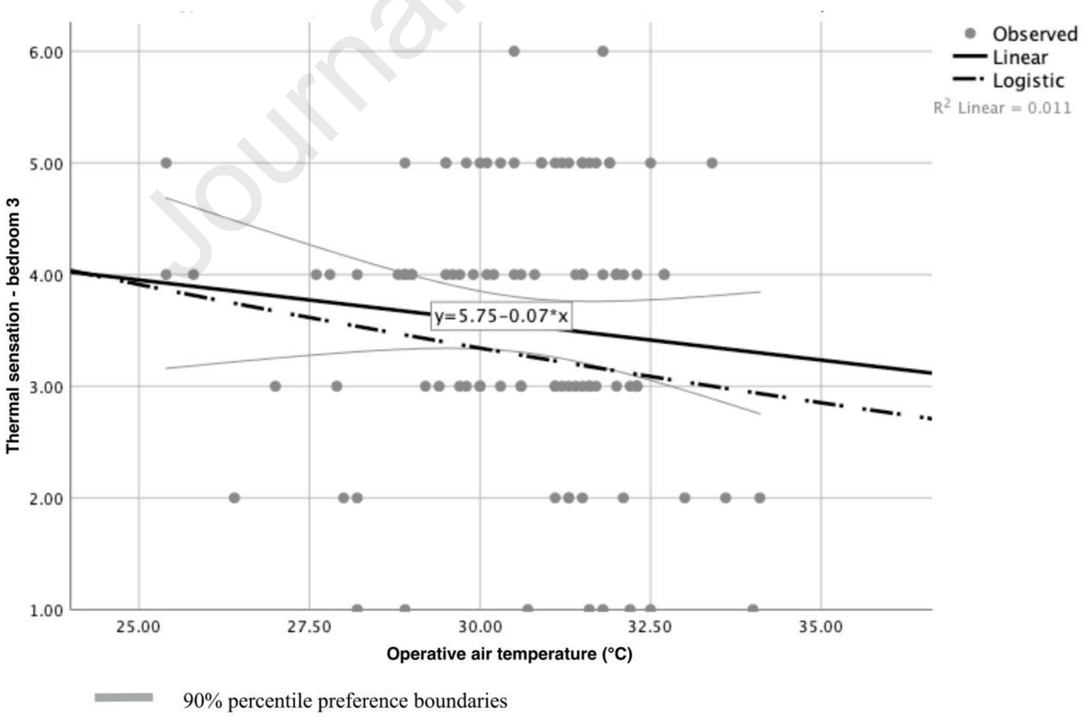


Fig. 18. Relationship between occupants’ thermal sensation and operative air temperature in the bedroom 3 spaces.

A weak negative regression coefficient was found between occupants' thermal sensation and operative air temperature ($R^2 = 0.011$, $p < 0.001$). As shown in Fig. 18, 8% of respondents felt 'too warm' (Ta from 28 °C to 32.50 °C ± 3°C and ± 7.50 °C), 11% felt 'comfortably warm' (Ta from 26 °C to 34 °C ± 1 °C and ± 9 °C) and 25% felt 'comfortable' (Ta from 26 °C to 32 °C ± 1 °C and ± 7 °C), while 32% voted for feeling 'comfortably cool' (Ta from 26 °C to 33 °C ± 1 °C and ± 8 °C), 22% voted for feeling 'too cool' (a similar pattern as for the 'comfortably cool' sensation) and 2% voted for 'much too cool' (Ta from 31 °C to 32 °C ± 6 °C and ± 7 °C).

According to the regression analysis findings, the thermally 'comfortable' temperatures in living room spaces ranged from 26 °C to 28 °C during the summer [97]. Considering that the influence of outdoor air temperature on occupants' thermal sensation in living room spaces ranged from 23 °C to 35 °C, the results indicated that higher adaptation ranges occurred across the measured flats in summer [98].

Notably, the living rooms that were measured concurrently with the questionnaire survey also suggested that comfort was experienced in temperatures well above the recommended international benchmarking criteria for the spaces, with high values indicating a strong relationship. Regarding respondents' TSVs for their bedroom 1 spaces, the indoor air temperature at which they expressed being thermally 'comfortable' within the interviewed flats ranged from 26 °C to 28 °C, while we observed that the outdoor air temperature was not in the range of the 90% percentile preference boundaries. This was partially due to occupants' higher thermal comfort preferences and to the position of the bedroom spaces in the flats [99]. The results suggest that occupants can adapt to the thermal environment within a wide range of thermally comfortable threshold levels better than to slightly warmer indoor air temperatures.

Similar patterns were found for occupants' thermal sensations regarding their bedroom 2 spaces. On the regression plot, the study's thermally 'comfortable' sensation votes were not scattered within the 90% percentile preference boundaries. This indicated that the occupants also experienced overheating risk in their bedroom 2 spaces. However, the thermally 'comfortable' outdoor air temperature ranged from 33 °C to above 35 °C [100]. The results revealed that a significantly high outdoor temperature peaked at 36 °C, suggesting a preference for higher indoor air temperature in the bedroom 2 spaces in summer.

Concerning the influence of indoor air temperature on occupants' thermal sensation for bedroom 3 spaces, we found that the thermally 'comfortable' temperatures ranged from 26 °C to 28 °C, while the thermally 'comfortable' outdoor air temperatures ranged from 28 °C to 30 °C [101]. The analysis indicated a preference for a temperature that was 2 °C higher in the bedroom 2 and 3 spaces than in the bedroom 1 spaces. The findings also revealed a significant difference of 5 °C between the preferred indoor and outdoor air temperatures in all the bedroom spaces. It must be stressed that a positive moderate correlation was found with the bedroom 2 ($r = 0.282$, $p < 0.001$) and another positive strong correlation was found with the bedroom 3 ($r = 0.799$, $p < 0.001$) spaces, thus validating the regression coefficient findings to identify the accuracy of PMVs. In addition, a positive moderate correlation was found with the bedroom 1 spaces ($r = 0.202$, $p < 0.05$).

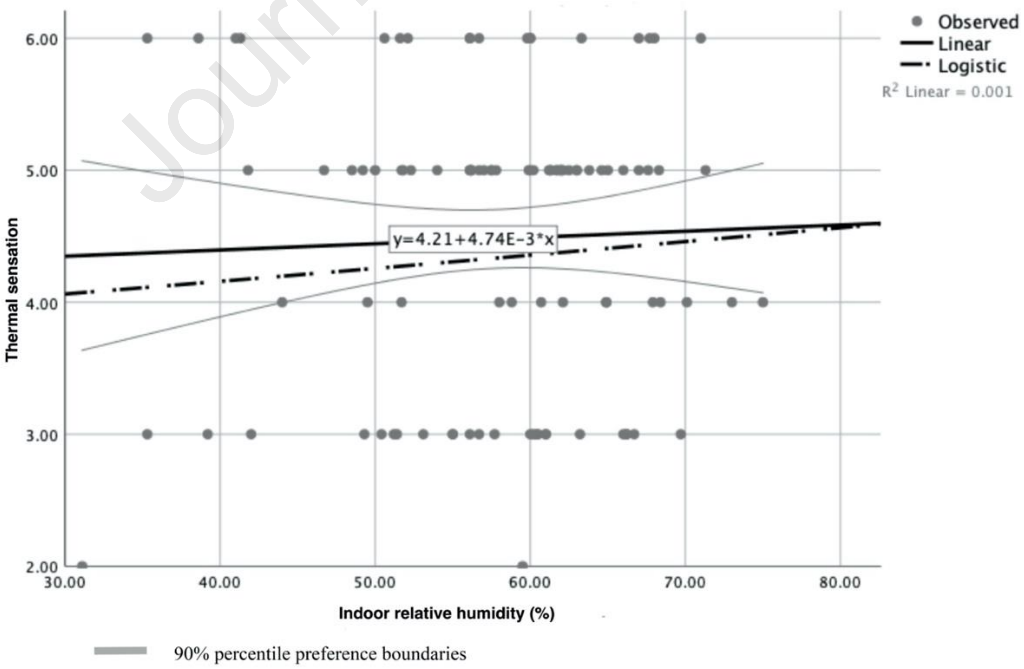


Fig. 19. Relationship between occupants' overall thermal sensation votes and the indoor relative humidity.

Fig. 19 shows the relationship between the occupants' overall thermal sensation votes and the indoor relative humidity conditions of the interviewed flat units. 41% of respondents expressed a 'cool' preference (RH ranged between 42% and 71% at ±0.2% and ±11%), 25% felt 'neutral' (RH between 43% and 74% at ±0.3% and ±14%), 18% felt 'cold' (RH fell between 32% and 71% at ±8% and ±11%), 14% voted for feeling 'slightly cool' (similar to patterns for the 'cold' preference) and 2% preferred feeling 'warm' (RH between 31% and 59% at ±9% and ±1%). The results reveal that at the time of the survey, the occupants had experienced thermally uncomfortable indoor environment due to high humidity levels. A positive weak regression coefficient was noticed between the occupants' thermal comfort preference and the indoor RH ($R^2 = 0.001$, $p < 0.001$). Further analysis highlighted that the mean RH levels corresponding to group thermal sensations of +1 and -1 ranged from 35% to 72%. This may well indicate a reason for thermal discomfort across the interviewed flats. Fig.20(a) through (h) illustrate the climate characteristics of eight cities in Cyprus, which represent the generalisation of applied thermal-comfort threshold levels were identified through the regression forecasting analysis.

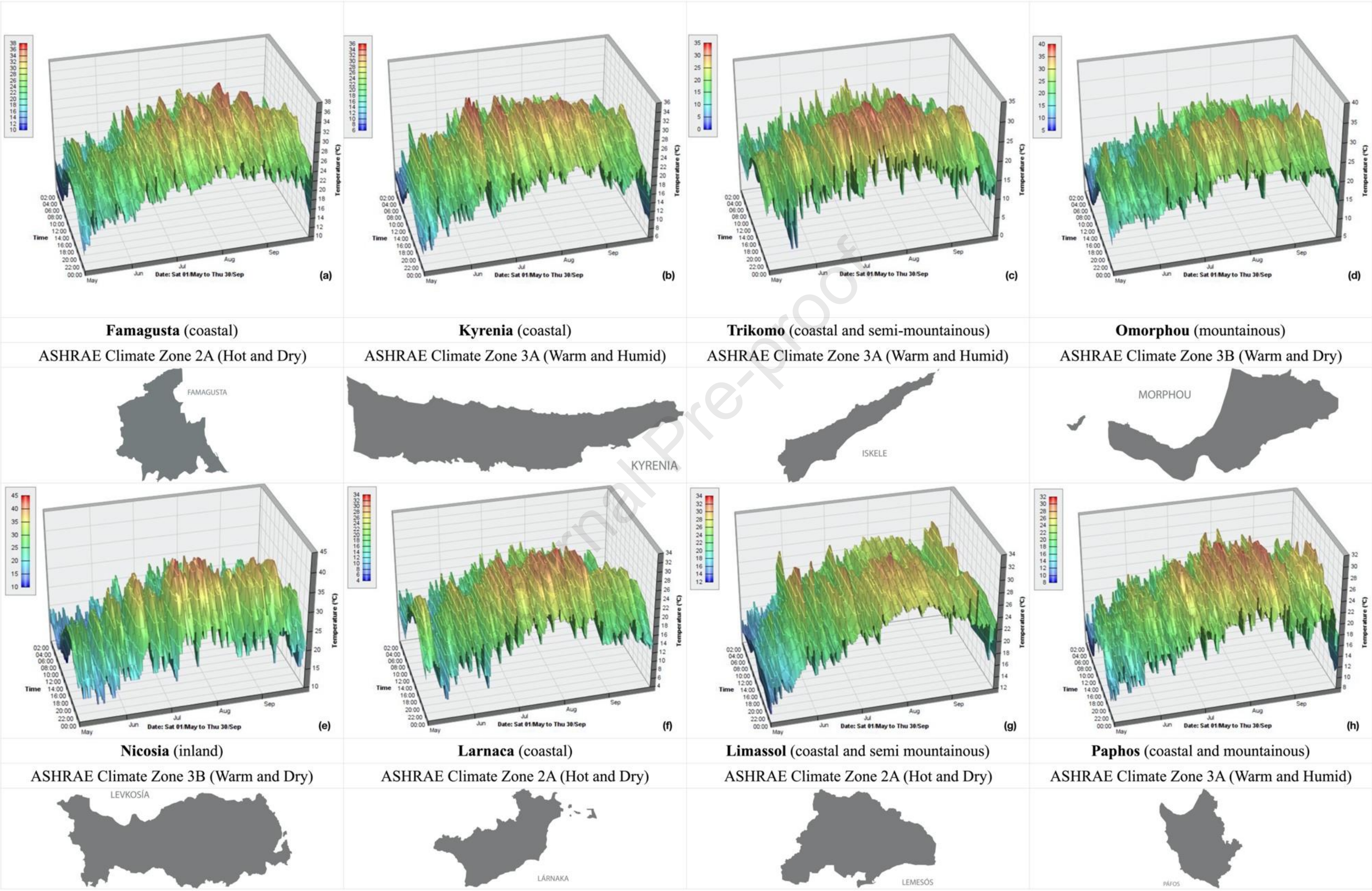


Fig.20. (a)-(h) Mapping of climate variations of eight cities in Cyprus.

The present study investigates the effects of local climate conditions on the psychological adaptation of human thermal comfort. This pilot case study was conducted in the coastal city of Famagusta, which was selected as the baseline model to represent the climate conditions of all major Cypriot cities. One of the primary reasons this study was not conducted in a climatic chamber within the constraints of a laboratory environment was to ensure that the experiment parameters were properly identified so the findings could be applied to the wider climate zone of the south-eastern Mediterranean basin.

The climate datasets of eight cities in Cyprus were extracted with the EnergyPlus program and formatted as an .epw weather file, then this information was sourced into the IES software suite weather datasets, and dynamic thermal simulations were conducted to generate the climate patterns of each city with the aim of assessing the results generated from the building-energy simulation platform to confirm the validity of the field study findings. The climate characteristics of these cities were then examined to understand the representativeness of the neutral adaptive thermal-comfort threshold levels and prove the general applicability of the proposed benchmark criteria to all cities in Cyprus. The results revealed a discrepancy between the *in-situ* physical measurements and the building-energy simulation results; while the neutral adaptive thermal-comfort threshold in the case-study location was 28.5–31.5°C, the building-energy simulation indicated that the climate in the representative cities showed variations of ±10–15°C.

As is shown in Fig.20(a), air temperatures in Famagusta in May through September, which is the cooling period of this south-eastern Mediterranean island, fluctuated between 28–38°C. Air temperatures peaked at 36°C in the second week of June, then oscillated between 26–32°C until the third week of August, when temperatures rose as high as 38°C, only to decrease and fluctuate between

28–32°C until the end of September. These climate-pattern variations were found to be within the thermally acceptable neutral adaptive thermal-comfort thresholds that were developed through the field study of the present study.

Fig.20(b) demonstrates that air temperatures in the coastal city of Kyrenia varied between 24–28°C, peaked at 36°C in the middle of June, then steadily decreased to 25°C in the third week of June. Temperatures reached 35°C at the end of the first week of July, then fluctuated between 28–32°C until the end of August. Temperatures were predicted to be in the thermally comfortable range of 22–28°C throughout the month of September; the present study concluded that the neutral adaptive thermal-comfort threshold level were within this benchmark criterion. Notably, climate patterns observed in the simulation prediction were within the top 30°C of the upper thermal-comfort limit by ASHRAE based off of information in the database.

Fig.20(c) illustrates warm air temperature patterns in the coastal, semi-mountainous city of Trikomo, which fluctuated between 30–35°C during the peak cooling period in July and August. A difference of ±3.5°C was identified when neutral adaptive thermal-comfort threshold level was selected as the benchmark criterion. Steady, continuous warm air temperatures were observed through most of the summer months. Notably, air temperatures reached 30°C in the third week of September, which is the upper thermal-comfort limit, according to the ASHRAE Global Thermal Comfort Database II requirements.

In Fig.20(d), the pleasant air temperature patterns in the mountainous city of Omorphou fluctuated between 20–25°C from May to the first week of June, then temperatures increased to 32°C and vacillated between 25–28°C until the first week of August, at which time they peaked at 40°C; temperature variations between 28–32°C were then observed until the end of September. When taken as a whole, there was a ±8.5°C variance of the upper limit of neutral adaptive thermal-comfort threshold level that was developed for the Cypriot climate in the present study.

Fig.20(e) demonstrates the slightly cool environment conditions in the inland city of Nicosia, which ranged between 10–25°C until the end of first week of June; temperatures rose to 35°C during the second and third weeks of this month, then steadily decreased to 30°C between the final week of June and the second week in July. Air temperature peaked at 45°C in the second week of July and fluctuated within the 40–45°C range until the middle of August, when air temperatures decreased to 36°C and stayed within the range of 36–42°C until the third week of September, then decreased again to 34°C at the end of September. Temperatures did not fall below the 35°C upper thermal-comfort limit between the first week of July and the third week of September.

There was a significant ±15°C difference between day-time and night-time temperatures in area, which is due to the inland geographical location of Nicosia and the city's position between two mountains that block breezes from the coastline regions; this caused the urban heat island (UHI) effect, which results in thermally uncomfortable indoor-air environment conditions. There was a ±3.5°C difference in the upper neutral adaptive thermal comfort limit of the simulation prediction, which was determined to be 31.5°C. These results suggest that there should be a higher adaptive thermal-comfort threshold limit for multi-family residences in Nicosia.

Figure 20(f) demonstrates the air temperatures in the coastal city of Larnaca, which ranged between 22–24°C in the first week of May, then fluctuated between 10–16°C until the third week of May; from the third week of June to the first week in September, temperatures vacillated between 24–34°C. Notably, peak air temperatures were observed on several temperature oscillations. Even though pleasant air temperatures of 20–26°C were predicted until the end of September, the upper thermal-comfort limit was determined to be between 30–32°C from the middle of July to the first week of September; this threshold level fell within the 28.5–31.5°C neutral adaptive thermal-comfort benchmark that was developed in the course of the present field-study investigation. Continuous air-temperature fluctuations that were above the upper thermal-comfort limit recommended by the ASHRAE Global Thermal Comfort Database II were observed for a prolonged period of time; however, these climate patterns fell within the 30–33°C range of thermally acceptable air temperatures that are recommended for Mediterranean countries with hot and dry summer climates.

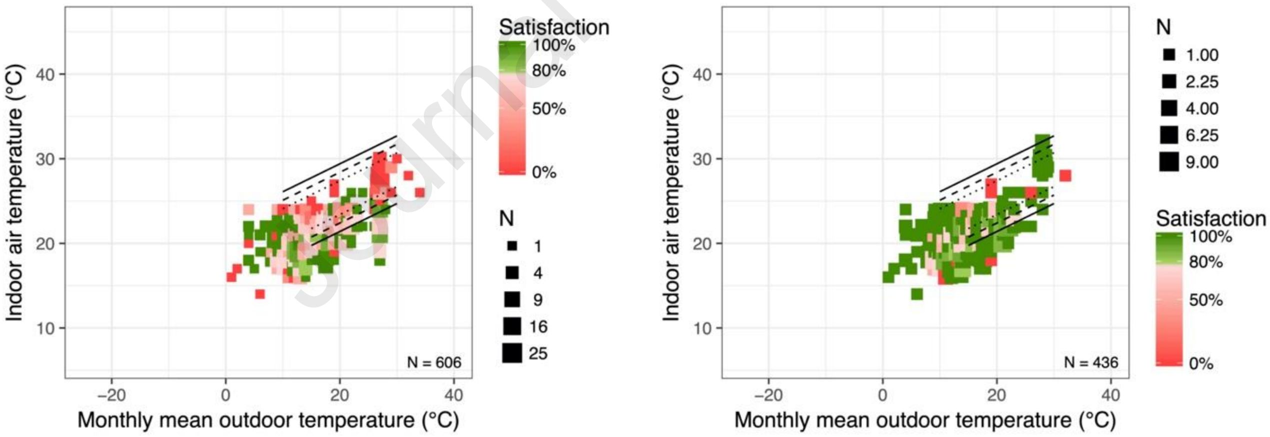
Fig.20(g) depicts temperature fluctuations in the coastal, semi-mountainous city of Limassol, which ranged from 8–23°C until the first week of June, when air temperatures steadily rose to 32°C, then decreased to 30°C in the second week of this same month. The curvilinear weather patterns demonstrate the 25–32°C temperature ranges experienced in this area until the end of August; air temperatures peaked at 34°C in the second week of September, then steadily decreased to 22°C by the end of September. Overall, peak air temperatures were between 26–30°C, which fell within the neutral adaptive thermal-comfort threshold that was developed for the present study.

Fig.20(h) demonstrates reasonably comfortable air temperatures in the coastal, semi-mountainous city of Paphos, which fluctuated between 12–22°C from the beginning of May until the last week of June, then rose to 29°C in the first week of July. Air temperatures oscillated between 30–32°C from mid-July to mid-September, with a peak temperature of 32°C in the second week of August, then significant temperature fluctuations that ranged from 18–30°C were observed until the end of September; the predicted air temperature fell within the neutral adaptive thermal-comfort threshold level that was developed for the baseline coastal city of Famagusta. Notably, the temperature fluctuation differences between Paphos, which is a coastal city, and the baseline city is due to the geographical location of the former, which is located at the south-western corner of the island and benefits from breezes off of the eastern Mediterranean Sea; this demonstrates that the frequency of the outdoor-air-movement factor is a determinant environmental effect that ensures pleasant thermal conditions during the peak cooling period and suggests that lower neutral adaptive thermal-comfort threshold benchmarks are needed in this part of the island.

In the baseline model, which is represented in Fig.20(a), slightly warmer temperature fluctuations between 32–38°C were recorded, and the benchmark criteria ranged between 28.5–31.5°C; this represents the thermal comfort of multi-family residential buildings in Cyprus. It should be noted that the neutral adaptive thermal-comfort threshold developed through the longitudinal field study represents 80% of the climate zones of Cyprus and includes 52% of the low-, medium- and high-rise RTBs in the country.

The matrix presented in Fig.20(a) through(h) demonstrates the national representativeness of the investigated housing stock by exploring the neutral adaptive thermal comfort in areas throughout Cyprus; the results of the present study can be extrapolated to other south-eastern Mediterranean cities with climate characteristics that are similar to the Cypriot climate. Moreover, this matrix could provide a roadmap of the methodological workflow that was developed in the course of this empirical study, which is not limited to exploring the thermal comfort of multi-family social-housing units, but can also be generalised to different housing typologies in other areas of the Mediterranean basin that experience hot, dry summers.

It was also noted that the temperatures of the proposed model were higher, 2°C on average, than the temperatures of the EN 15251 (2007) recommended for naturally ventilated buildings. Notably, the thermal sensation votes that fell within the parameters for the recommended benchmark of the EN 15251 adaptive model were plotted against the 80% and 90% upper and lower acceptability limits. Fig.21(a)&(b) demonstrate the acceptability of thermal sensation available on the ASHRAE Global Thermal Comfort Database II.



(a) (b)

Fig.21. The scatter plot distribution of thermal sensation by **(a)** building typology[4]; **(b)** climate type[5]. ***Source:*** The ASHRAE – Global Thermal Comfort Database II[6].

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[4] The naturally ventilated multi-family residential buildings were selected by using the Query Builder on the ASHRAE Global Comfort Database II.

[5] The hot summer Mediterranean climate was selected to extract the graph.

[6] These graphs were extracted from the thermal comfort visualisation tool by using the satisfaction metric – Acceptability (TSV +-2). The tool is an open access source which is available at https://cbe-berkeley.shinyapps.io/comfortdatabase/

Fig. 21(a) shows that the subject participants' TSVs ranged between 20% and 30% acceptability while the monthly mean outdoor temperatures were between 25 °C and 30 °C in naturally ventilated multi-family residential buildings. To identify baseline model for the identification of 'neutral' adaptive thermal comfort, the study was examined the acceptable thermal comfort levels available for the hot summer Mediterranean climate on the ASHRAE Global Thermal Comfort Database II. Fig. 21(b) demonstrates that the acceptable thermal sensation was fell between 19 °C and 33 °C, where the weather is subtropical (Csa) and partly semi-arid (Bsh). It can be seen that significant proportions of these votes fell outside the upper and lower limits, indicating that occupants found a wider range of thermal sensations conditions comfortable than the adaptive model describes.

It can be concluded that the difference between preferred temperature and neutral temperature among two different recorded environmental conditions demonstrates the occurrence of thermal adaptation. On validating questionnaire variables, comparing neutral temperature and preferred temperature could explain which group is better adapted to its thermal environment. Thus, it appears that the differences between neutral temperature and preferred temperature in summer are ±0.4°C and ±9°C. The results prove that the study's participants had the best ability to adapt (the remarkably highest difference between neutral temperature and preferred temperature) to their indoor thermal environment in summer.

4. Discussions

4.1 Physiological thermal adaptation

Adaptive comfort is a subject worthy of investigation in purpose to reduce energy consumptions for heating and cooling. Because of the differences between the populations in their climate, culture, behaviour, acclimatisation and other factorial variables, standard ranges of thermal comfort must be abolished. In order to capture the wider types of occupants and not create direct generalisation which introduce higher bias, the cluster analysis was conducted to validate the field investigation findings in thermal comfort.

The cluster analysis will result in better mapping of the thermal comfort and occupants' habit in relation of their energy spending. With this cluster groups, analysis can be one within clusters to form more uniform data. If needed, the general conclusion can be drawn using the comparison against cluster. With this approach, the study presents that the result will have less bias if the case is generalised for the whole region. The following discussion is structured according to the research question that guides the findings obtained through feed-forward interviews: (*RQ*) how environmental factors affect occupants' thermal comfort to identify 'neutral' adaptive thermal comfort thresholds in this south-eastern Mediterranean climate.

As our research aim was to test the factors that affect occupants' thermal sensations, we performed a statistical test to determine the relationship between occupant decisions on TSVs and environmental parameters. A positive moderate regression coefficient was found with the indoor air temperature ($R^2 = 0.398$, $p < 0.001$), and a positive weak regression coefficient was found with the outdoor air temperature ($R^2 = 0.159$, $p < 0.001$). The TSV findings indicate that the minimum threshold for adaptive indoor air temperature was 28.5°C and the upper threshold was 31.5°C. This may indicate that the statistical value of R-squared ($R^2 = 0.398$, $p < 0.001$) was extrapolated by the slightly weak regression coefficient factor to optimise indoor air temperature, which strongly correlates with TSV. Table 10 demonstrates the effects of between-subjects tests to validate the findings between space conditioning and length of residency.

Table 10. Regression coefficients.

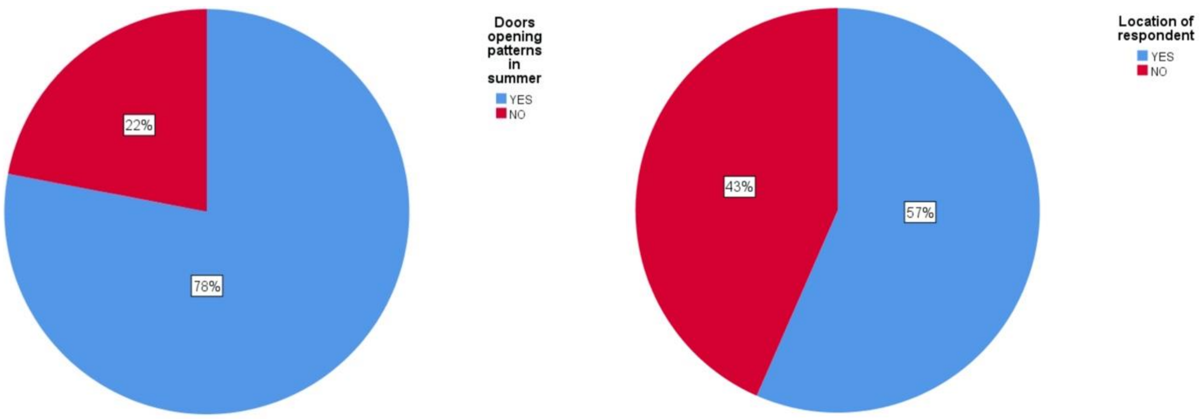
Source	**Dependent Variable**	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected model	Space conditioning	65,113[a]	31	2,100	1,336	0.160
	Length of residency	41,669[b]	31	1,344	2,590	0.001
Intercept	Space conditioning	15,394	1	15,394	9,793	0.003
	Length of residency	17,454	1	17,454	33,630	0.000
Feeling preference	Space conditioning	1,685	1	1,685	1,072	0.304*
	Length of residency	2,864	1	2,864	5,519	0.022

Type of cooling system	Space conditioning	7,979	6	1,330	0,846	0.539*
	Length of residency	7,951	6	1,325	2,553	0.027

a. R-Squared = 0.379 (Adjusted R-Squared = 0.095)
b. R-Squared = 0.541 (Adjusted R-Squared = 0.332)

As shown in Table 10, to reduce bias on TSV, the participants' TSVs and their type of cooling systems were associated with the length of residency and the space conditioning type. The findings demonstrate a positive moderate correlation between space conditioning and feeling preference ($r = 0.304$, $p < 0.001$). This indicates that the room condition is the determinant factor in identifying the 'neutral' adaptive thermal comfort level. Table 10 also shows that there was a positive strong correlation between space conditioning and type of cooling systems ($r = 0.539$, $p < 0.001$). This indicates that adaptive thermal comfort is related to household income level.

In this study, *in-situ* measurements of indoor air temperatures were recorded. In fact, indoor air movement will significantly influence neutral thermal sensations. Indoor air movement can make the occupants feel comfortable despite relatively high indoor temperatures. In response to research question 19, the occupants were asked to report their door opening habits when A/C was not used, as illustrated in Fig. 22(a). Additionally, in the questionnaire proforma (see **Appendix A.1**), the physical conditions and respondent locations within their living rooms were recorded to assess the occupants' thermal discomfort and identify 'neutral' adaptive thermal comfort. Respondent location is illustrated in Fig. 22(b).



(a) (b)

Fig. 22. (a) Distribution of household internal door opening patterns in summer; **(b)** Location of participants in their living rooms at the time of the survey.

Fig. 22(a) shows that 78% of the respondents kept internal doors closed when using air conditioning while 22% kept internal doors open. The reason that more than three-fourths of the respondents kept their internal doors closed was to keep the internal space cool in the summer. One interviewee with health problems preferred to keep the doors open to dissipate pollutants when the air conditioning was in use. On the other hand, less than one-third (33%) of the occupants kept the doors open because they used portable fans to cool indoor spaces. Fig. 22(b) shows that 57% of respondents were interviewed near an open window and 43% near a closed window, across 36 RTBs in the social housing estate.

To accurately assessing the occupants' thermal comfort votes concurrently with the *in-situ* measurements, it is important to consider the respondents' locations. This research method implies that the occupants' TSVs directly correlate with the locale climate conditions and thermal properties of their flats. Fig. 23 illustrates the percentage distribution of the respondents' room conditions to show the effect of this information on occupants' *in-vivo* experiences associated with thermal comfort.

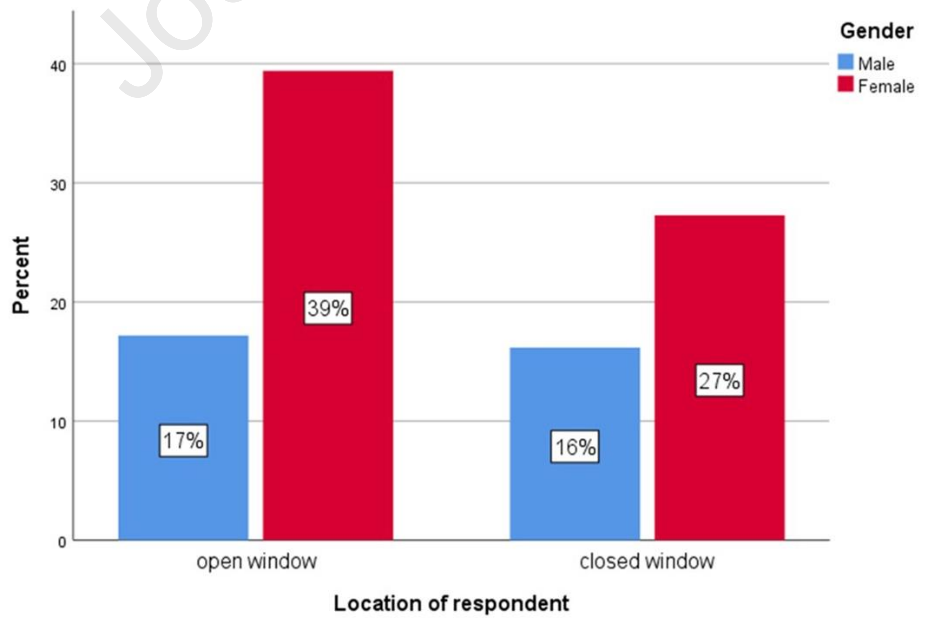


Fig. 23. Distribution of household living room conditions.

One significant factor in evaluating thermal comfort was whether sitting near an open or a closed window had an effect on questionnaire responses. During the survey, 39% of the female and 17% of the male respondents were surveyed near an open window while 27% of the female and 16% of the male respondents were surveyed near a closed window. These results show that the occupants either received natural ventilation or used portable fans when the windows were open (57%), or they used an air-conditioning system when the windows were closed (34%). It is important to consider the effect of RTB orientation and the floor-level differences of the RTB flats. In this study, these variables were found to significantly affect occupants' TSVs, which is helpful for identifying the 'neutral' adaptive thermal comfort.

With question 36, the study examines different room conditions, taking into account RTB orientation. The analysis reveals some potential challenges that arise with the RH and outdoor heat stress index factor, which has caused thermally uncomfortable summer indoor air environments. When the effects of operative air temperature and RH are considered, their impact on indoor thermal comfort conditions is notable and can potentially affect the occupants' TSVs. Fig. 24(a) illustrates household living room conditions, taking into account RTB orientation.

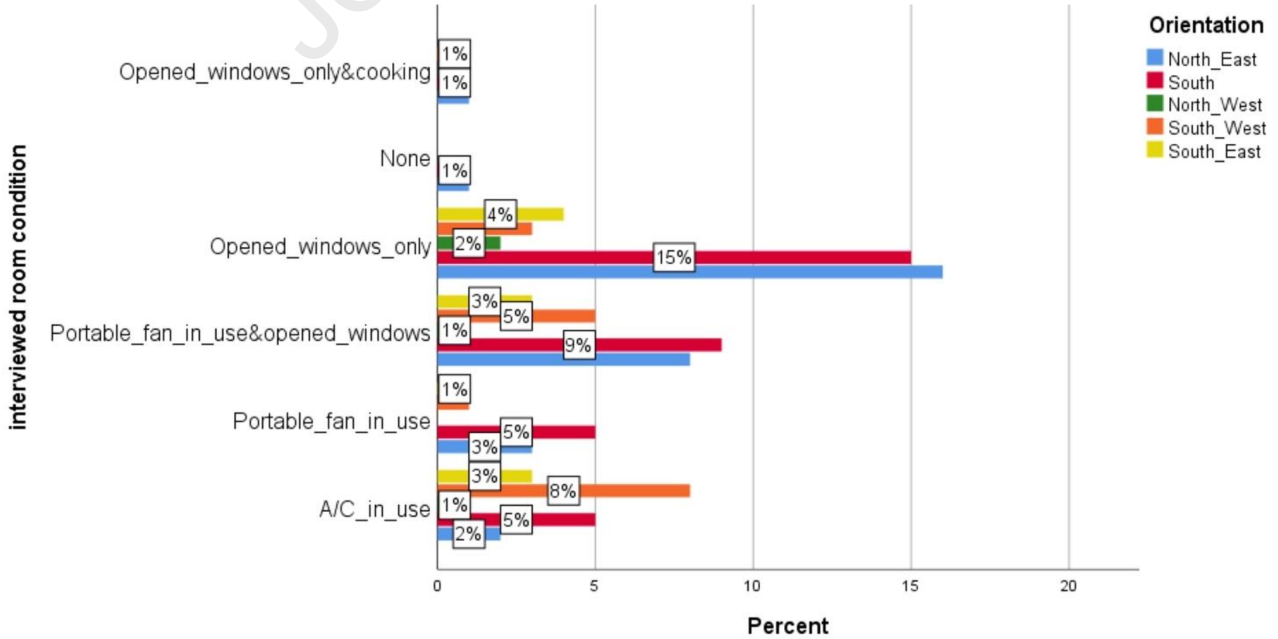


Fig. 24. (a) Household room conditions and RTB orientation.

As seen in Fig. 24(a), in the northeast-facing flats, 16% had only the window open, 8% had windows open and a portable fan in use, 3% had only a portable fan in use, and 2% had an A/C system in use. In the south-facing flats, 15% had only the window open, 9% had windows open and a portable fan in use, 5% had only a portable fan in use, and 5% had wall-mounted A/C systems in use and the windows closed. In the northwest-facing flats, 3% had only the window open, 1% had windows open and a portable fan in use, and 1% had A/C systems in use with the windows closed. In the southwest-facing flats, 8% had A/C systems in use and the windows closed, 5% had a portable fan in use and the windows open, and 3% had only the windows open. In the southeast-facing flats, 4% of the had the windows open, 3% had the windows open and a portable fan in use, and 3% had only an A/C system in use and the windows closed.

It can be concluded that the observed dominant factor in the surveyed rooms was found in the south-facing flats, where 26% majority of respondents had the windows open and portable fans in use. Additionally, it was observed that a greater percentage (44%) of the south-facing flats had only a window open. This is because the interviews were conducted in the afternoon, when outdoor air temperatures peak. This is also why 5% of respondents had A/C systems in use. Furthermore, the dominant factor was observed in the southwest-facing flats, where 8% of respondents used A/C systems and 5% used portable fans with the windows open. This indicates the importance of solar angulation on the building, which causes a high degree of thermal discomfort.

Question 36 examines the households' room conditions, taking into account the floor-level differences of the flats. It was found that RTB orientation plays a crucial role in assessing occupants' thermal comfort in summer. However, it is also important to examine the effect of floor-level differences to provide more reliable information in determining the 'neutral' adaptive thermal comfort level. It seems that both the physical position and thermal properties of the RTBs had a significant influence on occupants' TSVs.

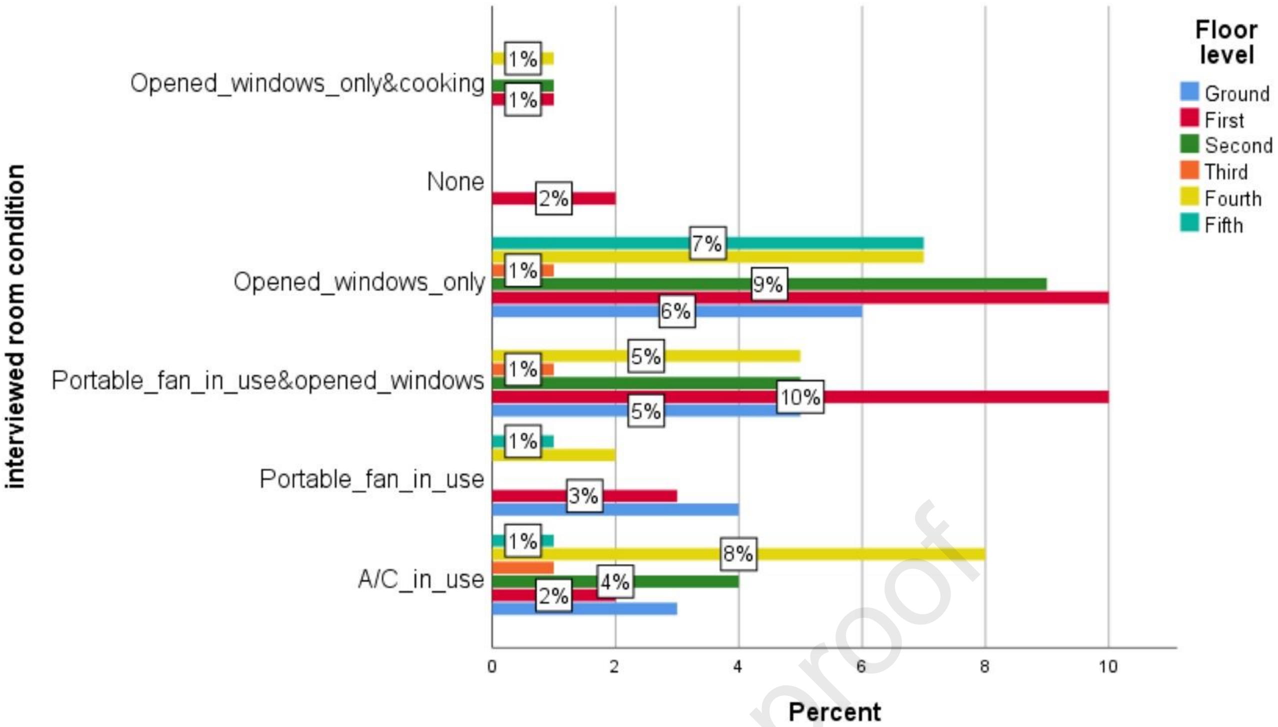


Fig. 24. (b) Household room conditions, taking into account floor-level differences.

Fig. 24(b) illustrates occupants' habitual adaptive behaviours for thermal comfort, taking into account the flats' floor-level differences. In the ground-floor flats, 6% of the households were interviewed while the windows were open, 5% had a portable fan in use and the windows open, 4% had a portable fan in use and the windows closed, and 3% had only an A/C system in use.

In the first-floor flats, 10% had the windows open, 10% had a portable fan in use and the windows open, 3% had a portable fan in use, and 2% of the respondents had A/C systems in use. In the second-floor flats, 9% had the window open, 5% had a portable fan in use with the windows open, and 4% had an A/C system in use with the windows closed. For the third-floor flats, 1% had the windows open, 1% had portable fans in use with the windows open, and another 1% had an A/C in use. In the fourth-floor flats, 7% had the windows open, 8% had an A/C system in use, 5% had a portable fan and the windows open, and 2% had portable fans with the windows closed. In the fifth-floor flats, 7% had open windows, 1% had portable fans and the windows closed, and only 1% had an A/C system in use. It was found that the most dominant factor was a portable fan with the windows open. These findings confirm that, contrary to expectations, the first-floor flats also showed strong indications of thermal discomfort. This is due to the RTB orientation and the closeness of the blocks to each other, which decreases ventilation.

This might also show that, in subtropical (Csa) and partly semi-arid (Bsh) climates in which thermally uncomfortable indoor environments occur, particularly in summer, occupants' physiological adaptations are more tolerant of slightly warmer indoor environment conditions than at high and medium altitudes [102-104]. This implies that long-term acclimation and more tolerant physiological adaptations to warming climate conditions could explain the acceptability criterion on the development of adaptive thermal comfort, which also contributes to the ASHRAE Global Thermal Comfort Database II. It also could explain why households expressed a neutral thermal feeling in spite of observed temperatures over 31.5°C, the upper for overheating risk in residential buildings [105].

4.2 Psychological thermal adaptation

The findings of this study revealed that, when the indoor air temperature ranged from 25.0°C to 27.5°C, all the participants' TSVs fell within the acceptable comfort zone, and occupants indicated that they were mostly satisfied with the indoor air temperature. Notably, 6% of participants reported feeling thermally uncomfortable while 94% of participants reported feeling thermally comfortable in the range from 27.5°C to 30.0°C. Additionally, in circumstances when the indoor operative air temperature increased to 2.5°C, which is slightly above the neutral temperature range of 30.0°C to 32.5°C, the predicted percentage dissatisfied (PPD) with the indoor air temperature rose to 23%. It was found that occupants' PMV increased to 41% when temperatures ranged from 32.5°C to 35.0°C. When the outdoor air temperature exceeded 35.0°C, no respondents felt thermally comfortable. Fig. 25 (a) through (d) demonstrate the cluster analysis between the interviewed room conditions and environmental factors to reduce bias on the subject participants' TSVs investigated for this empirical study.

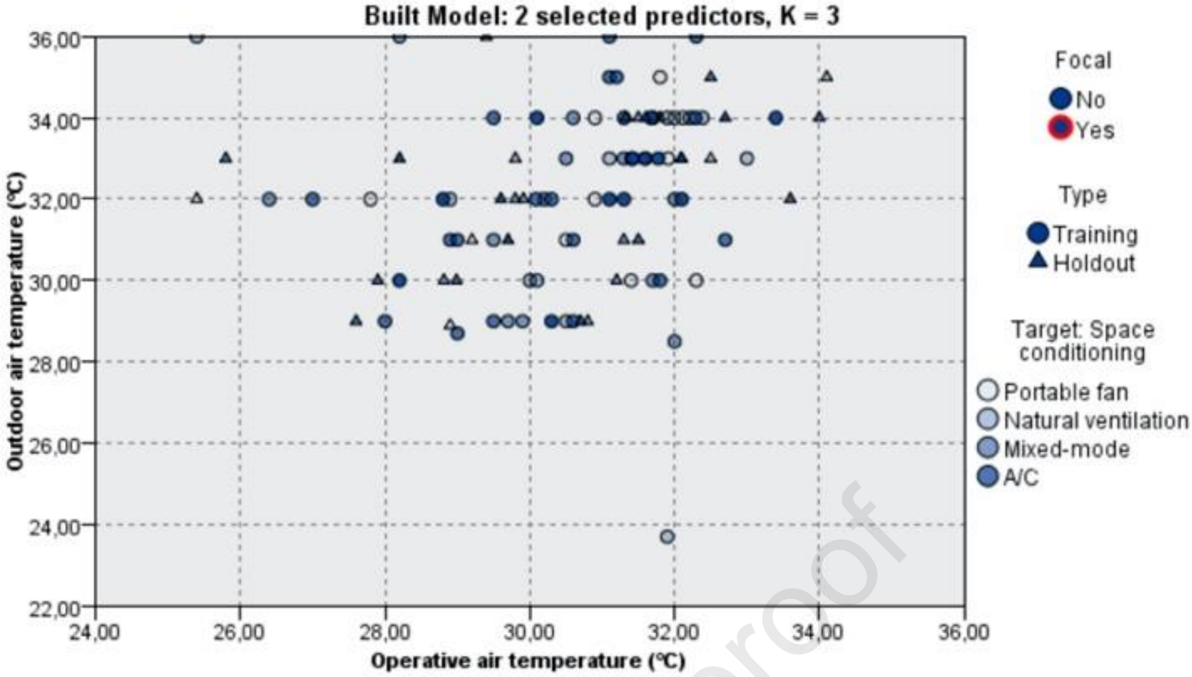


Fig. 25. (a) Cluster analysis of space condition type between outdoor air temperature and operative air temperature.

Fig. 25(a) illustrates the analysis of patterns between the space conditioning and environmental conditions at the time of the survey. Participants used both A/C and mixed-mode ventilation between 28°C and 36°C. The most notable pattern was that mixed-mode ventilation was used to optimise indoor air temperatures between 32°C and 34°C. This trend is followed by the use of A/C systems between 34°C and 36°C. The graph shows that only one participant preferred to use a portable fan when the outdoor temperature was 24°C, which is 1°C below the thermally acceptable comfort level. The indoor air was recorded at 32°C, a thermally uncomfortable indoor air temperature. These findings demonstrate that the thermal properties of the buildings and the poor window design of the flats were the reason that high indoor air temperatures were observed while the outdoor air temperature was thermally acceptable.

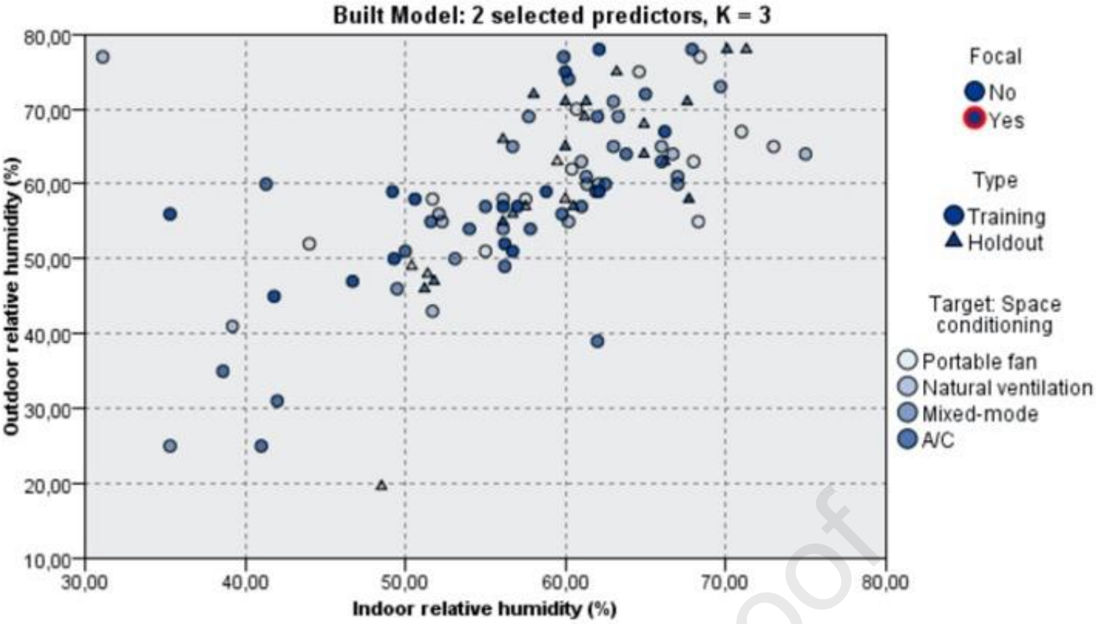


Fig.25. (b) Cluster analysis of space condition type between outdoor relative humidity and indoor relative humidity.

Fig. 25(b) illustrates the test of subjects between the space conditioning and the influences of both indoor and outdoor RH conditions. It was found that most of the participants used A/C systems between 50% and 60% outdoor RH levels. This demonstrates that these participants' bodies were not thermally adaptable to slightly humid environmental conditions. The results reveal that the thermal discomfort of these types of social housing residents is not within the recommended lower thermal comfort threshold level at 40% and upper comfort threshold level at 60%. This is why most of the households relied on A/C systems to optimise their thermal comfort. The study also found that the households used both A/C and mixed-mode cooling strategies between 60% and 80% outdoor RH levels. This indicates that the outdoor RH was the determining factor in the occupants' thermal comfort.

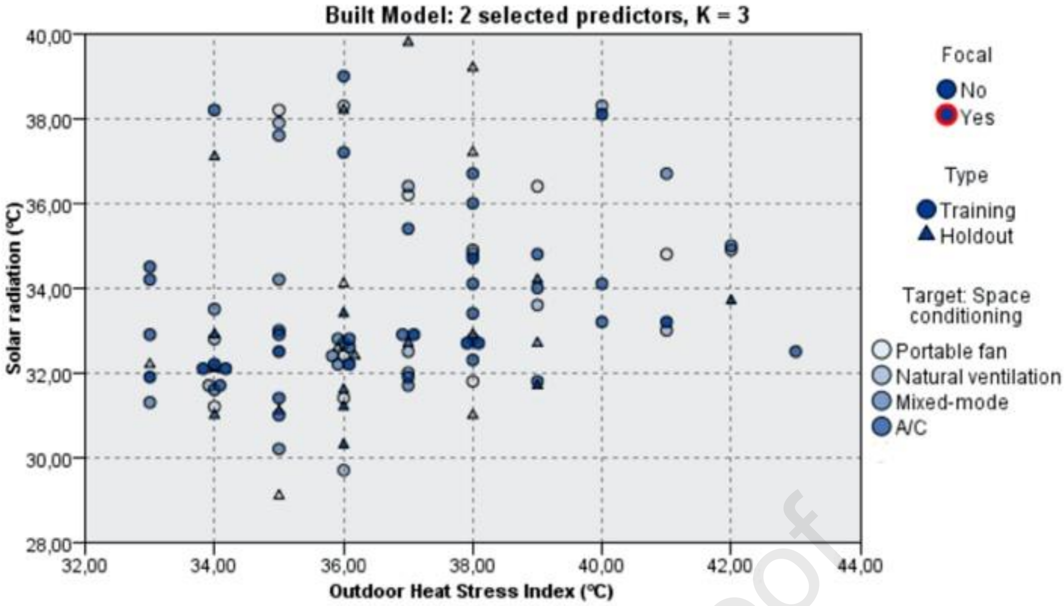


Fig. 25. (c) Cluster analysis of space condition type between solar radiation and outdoor heat stress index.

Fig. 25(c) illustrates the relationships between the space conditioning and the *in-situ* measurements of building envelopes and the *on-site* measurements of environmental conditions. It was found that most respondents relied on A/C systems between 32°C and 34°C indoor air temperatures while the outdoor heat stress factor ranged between 34°C and 38°C. This indicates that solar mask is determined by the outdoor heat stress index. One reason for this is that solar irradiance on the building envelopes caused high indoor air temperatures. This is due to the low quality of construction materials used across all 36 RTBs and the hot summer climate of Cyprus. Also, the respondents used portable fans between 36°C and 40°C indoor air temperatures to optimise thermal comfort. The reason for this is the income level of the participants. Notably, it was observed that these types of participants aged between 55-65 and 65 or over, used natural ventilation while portable fans were in use.

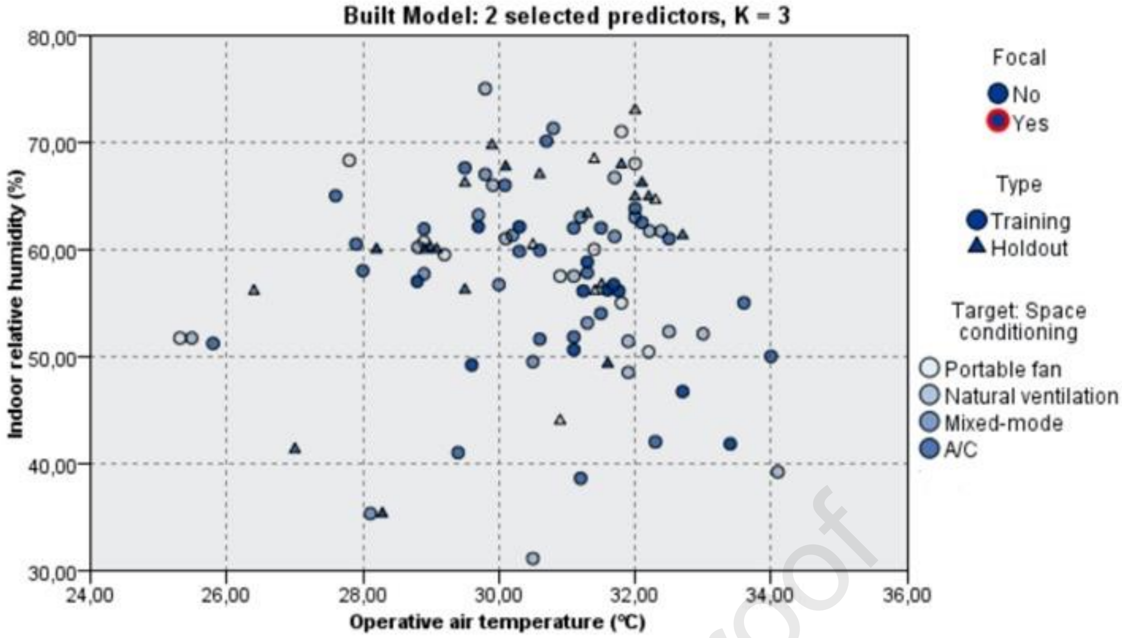


Fig. 25. (d) Cluster analysis of space condition type between indoor relative humidity and operative air temperature.

Fig. 25(d) illustrates the relationships between the space conditioning and indoor environmental conditions. It was found that a majority of participants used all types of available space conditioning systems when the indoor RH was between 50% and 70% and the operative air temperature was between 28°C and 33°C to create a thermally comfortable indoor air environment. The results indicate that the identification of 'neutral' adaptive thermal comfort has found variations between space conditioning and environmental conditions. The graph depicts that the type of space conditioning systems has a direct impact on occupants' TSVs.

In order to reduce the risk of bias on the households' TSVs, this graph shows that social housing residents prefer using all available sources for space conditioning in summer in this Mediterranean climate. Hence, the regression analysis finds that the 'neutral' adaptive thermal comfort temperature was between 28.5°C and 31.5°C while the space conditioning was observed between 28°C and 33°C. It can be concluded that the identification of the adaptive thermal comfort threshold level is not only limited by environmental conditions, but the thermal properties of buildings and household space conditioning preferences should be considered as the determinant factors to reduce research bias on thermal comfort studies.

The strong correlations found between the optimum thermal comfort threshold level and operative air temperature were shown more clearly in the regression analysis findings. The results revealed that 80% of the study's respondents were slightly comfortable in a temperature ranging from 28.5°C to 31.5°C. What is notable is that the acceptable identified comfort range was considerably higher than Fanger's adaptive thermal comfort level and the industrial benchmark of the EN 15251 recommendations for naturally ventilated buildings. It was found that when the indoor air temperature was 5°C higher than the recommended benchmark criterion, the vast majority of respondents reported feeling thermally comfortable across the 100 flats recruited for this pilot study [105].

Moreover, the range of thermally comfortable indoor air temperatures could have been extrapolated by 2°C or 3°C if respondents had used either portable fans or air conditioning. This can be explained by the decrease in the number of TSVs if any type of cooling system was used. In this case, if acceptable thermal comfort were observed when temperatures fell from 30.0°C to 32.5°C, the PPD index of participants might rise to 90%. The results of a questionnaire showed that 23% of respondents were using a portable fan or an air conditioning system during the time of the survey. This could be explained by a combination of both behavioural adjustments and physiological adaptations [105,106]. The results of the field survey in conjunction with a linear regression analysis revealed that the neutral temperature was 28.5°C, and the upper acceptable limit was 31.5°C.

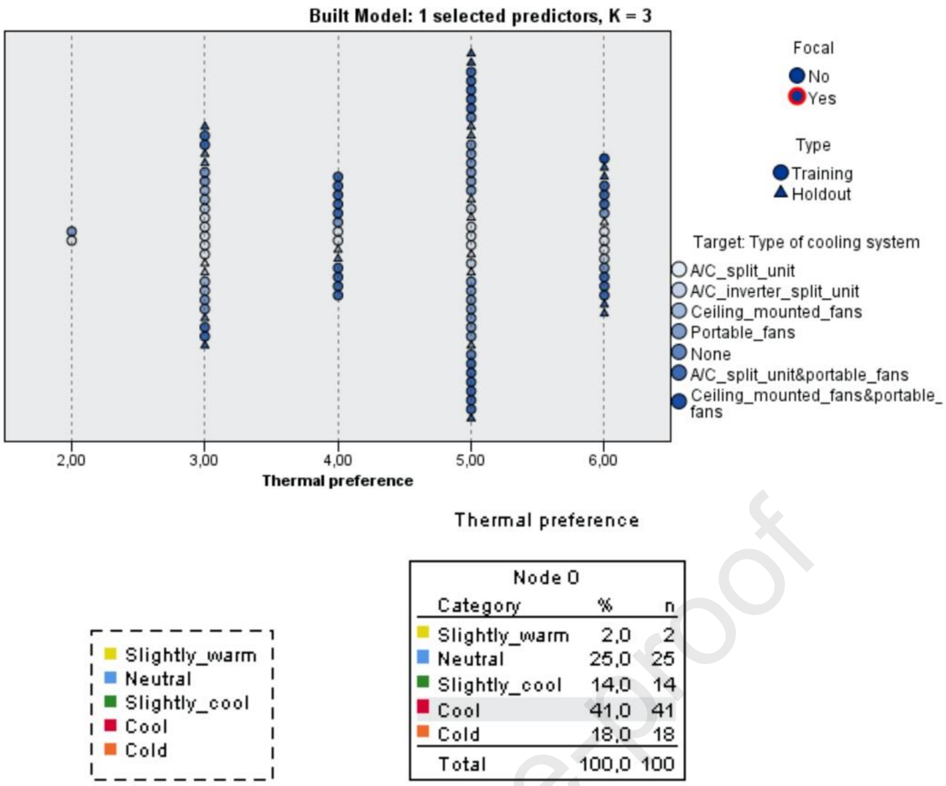


Fig. 26. Cluster analysis of household TSVs taking into account space conditioning types.

Fig. 26 illustrates the relationship between space conditioning and occupants' thermal preferences. It was found that 25% of occupants felt thermally comfortable. Additionally, it was observed that these participants used all types of space conditioning systems at the time of the survey. The graph depicts that these participants predominantly used both ceiling-mounted and portable fans to optimise their thermal comfort. The most notable finding was that 41% of participants reported feeling cool in their environment. Fig. 26 shows that this group used all types of space cooling systems to lower indoor air temperatures.

The results are consistent with data obtained on optimising occupant thermal comfort by considering *on-site* monitoring and *in situ* measurements. According to the survey analysis, nearly three-fourths (73%) of the total sample size who reported feeling 'slightly cool to cold' were more likely to experience a thermally comfortable indoor air environment at 26.0°C (M = 25.7°C, SD = 1.2°C). Regression forecasting revealed that the lowest (23.6°C) and highest (27.1°C) operative air temperatures were achieved, resulting in PMV values of –0.64°C (which was closer to the 'slightly cool' sensation) and –1.64°C, respectively. The results suggest that achieving desired indoor air environment temperatures improved occupant thermal comfort and possibly reduced cooling energy consumption in summer [108,109]

In this field study, all of the *in-situ* measurements and *on-site* environmental monitoring findings depicted in the graph were observed from *in-vivo* experiences of households' TSVs and their influences on the identification of 'neutral' adaptive thermal comfort while taking into account participants' habitual adaptive behaviours. A plurality of participants (41%) preferred to use all types of domestic cooling appliances. The findings reveal that 25% of households also used all types of space conditioning systems to acclimatise to the indoor air environment. These findings indicate that the households' TSVs are strongly correlated with observed indoor environmental conditions (i.e., space conditioning type, *in-situ* measurements and *on-site* environmental monitoring). This study explores all possible determinant factors and their influences on the development of adaptive thermal comfort threshold levels in this south-eastern Mediterranean climate.

5. Conclusions

This research sought to draw conclusions about optimising occupant thermal comfort in order to explore the influences of environmental parameters in a post-war social housing development in Famagusta, Cyprus, where the climate is subtropical (Csa) and partly semi-arid (Bsh) – hot and dry in summer. To investigate the degree of thermal discomfort experienced in the summer, statistical analyses were used to determine the factors that influence occupants' thermal sensation votes. The analyses in this research were explanatory in nature, and the objective was to determine the relationships amongst different variables (e.g., respondent age, RTB orientation, floor-level differences, indoor operative temperature and outdoor air temperature), which will then deepen our understanding of the relative influence and interaction amongst the variables. This analysis will pave the way for assessing the thermal comfort levels of certain groups, taking into account the effect of orientation and floor-level differences.

This empirical study is the first of its kind to target social households to assess the degree of thermal discomfort of each occupied space and occupant thermal comfort by employing a questionnaire survey. The present study enhances the understanding of the complex interrelationships between household socio-demographic characteristics, thermal properties of buildings and occupants' habitual adaptive behaviour on thermal comfort in heat-vulnerable multifamily residential buildings.

The present study makes a major contribution to research on the development of a thermal-comfort assessment benchmark criteria that the present study was used to systematically evaluate the results obtained from the questionnaire survey, *on-site* environmental monitoring and *in-situ* measurements of indoor air environment. The primary data demonstrates actual numeric experimentation of statistical analysis to identify adaptive thermal-comfort indices for this research context. The methodological framework developed for the present study was novel in that it adopted industry benchmarks from the Comité Européen de Normalisation (CEN) Standard EN 15251, which is based on adaptive thermal-comfort conventions developed by Fanger in 1976 and a scientific conceptual framework developed by Nicol and Humphreys in 2002.

It should be noted that the EN 15251 guideline was last updated in 2007; the present study contributes to the development framework of the EN 15251 with such a methodology. One of the main reasons is that a statistical tool was used for the purpose of regression forecasting to validate the field-survey findings and identify neutral adaptive thermal-comfort thresholds. to obtain accurate data and eliminate research bias, discrepancies in the findings of the regression-forecasting analysis and limitations related to the adoption of several thermal-comfort assessment benchmark criteria, the present study was employed all applicable methodologies currently available to ensure that the results of this field investigation would be accurate and suitable for inclusion in the EU's Project Smart Controls and Thermal Comfort (SCAT) database.

It can be concluded that occupant adaptation to slightly warmer indoor environments and outdoor air temperatures would significantly contribute to the ASHRAE Global Thermal Comfort Database II in terms of outlining a set of methods to conduct on a longitudinal field survey in this south-eastern Mediterranean climate and forecasting the ‘neutral’ adaptive thermal comfort by use of regression analysis. The study also provides a roadmap to the EN 15251 thermal comfort assessment criteria if industry-based temperature design criteria were not to be met with the ASHRAE Global Thermal Comfort Database II compliances, as these would conflict with the occupants’ adaptive comfort temperatures.

Declaration of Competing interest

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Graphical Abstract: The methodological workflow developed for the empirical study.

Supplementary Material: Mapping of the post-war social housing estates in the South-eastern Mediterranean Island of Cyprus

Data set in Mendeley

Data set to this article can be found online at –

Data set A: The raw data of statistical data set was designed in the Statistical Analysis in Social Science (SPSS) version 25.0, including .sav file for other scholars' further research work.

Data set B: Outdoor environmental monitoring recordings in .csv file

Data set C: Scripts of statistical analysis were conducted on exploring influences between time of day and locale climate conditions in .xls file)

Data set D: Scripts of statistical analysis were conducted on exploring influences between time of day and indoor air environment quality in .xls file)

Data set E: Occupants' TSVs scripts by using Whisker's statistical test.

Data set F: Scripts of statistical analysis were conducted on exploring influences between time of day and participants' thermal sensation in .xls file)

Appendix A.1 Pro-Forma Questionnaire Survey

External temperature	°C	Block/Flat No			Type of apartment unit				
Internal temperature	°C	Level			☐ Penthouse	studio	1+1	2+1	3+1
Location of tower block	S-W ☐	N-W ☐	N-E ☐	S-E ☐	☐ Corner flat (flat in the corner of the block)	studio	1+1	2+1	3+1
Location of respondent	Near an open window?		YES	NO	☐ Flat (sharing both walls with other flats)	studio	1+1	2+1	3+1
Kitchen design layout			OPEN	CLOSED	☐ Flat (sharing a wall with a flat)	studio	1+1	2+1	3+1

SECTION 1

HOUSEHOLD

We would like to know some facts about your households. Fill in the following table: start with yourself (respondent) and continue with the rest of your household.

1. What is the gender, age, occupation and highest level of education for you and all occupants in your house?

	Gender (Male/Female)	Age	* Occupation (Full time/Part time)	** Level of Education
☐ Respondent				
☐ Person 2				
☐ Person 3				
☐ Person 4				
☐ Person 5				
☐ Person ___				
* Occupation:	**a.** Works outside the home, **b.** works at home, **c.** household activities, **d.** pupil/student, **e.** other, (please specify); ______			
** Level of Education:	**a.** None, **b.** elementary school, **c.** secondary school, **d.** high school, **e.** undergraduate, **f.** postgraduate (PhD, MSc, MA) **g.** other (please specify); ______			

Remember the order you listed your household members above and use this order for the rest of the questionnaire.

2. How many years have you lived in this flat?
☐ Less than 1 year ☐ 1-2 years ☐ 2-5 years ☐ 5-10 years ☐ < 10 years

3. Do you own or rent your dwelling?
☐ Owner-occupied ☐ Rented property

4. Do you check your use of electricity by taking the meter reading frequently?
☐ Yes ☐ No

5. How much electricity (in kWh) did you consume (May-September) according to this last overview?
Low rate (rate or meter 1)________________kWh

High rate (rate or meter 2)________________kWh

Fig. A.1. Questions intended to record physical and environmental parameters and household socio-demographic characteristics.

Appendix A.2 Pro-Forma Questionnaire Survey

6. Do you know anything about energy-saving methods?
☐ A lot ☐ Some ☐ A little ☐ Nothing

7. Have you received advice on how to reduce your energy bills? ☐ Yes ☐ No
If you answered 'yes', from where did you receive the advice?______________

☐ Famagusta Municipality ☐ The Electricity Authority (KIB-TEK) ☐ Other, please specify:

8. How many people generally stay in these specific rooms on a typical weekday?

Room/Number of people	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
☐ Living room																								
☐ Kitchen																								
☐ Bedroom 1																								
☐ Bedroom 2																								
☐ Bedroom 3																								

9. How many people generally stay in these specific rooms on a typical weekend day?

Room/Number of people	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
☐ Living room																								
☐ Kitchen																								
☐ Bedroom 1																								
☐ Bedroom 2																								
☐ Bedroom 3																								

COOLING SUPPLY AND CONSUMPTION

10. What type of cooling system do you have? Specify numbers of each.
☐ Central cooling system ☐ A/C split unit ☐ A/C inverter split unit ☐ A/C portable unit____
☐ Ceiling-mounted fan ☐ Portable fans ☐ None ☐ Other, (please specify):

We are interested in how you use your cooling system during the **SUMMER** months. Consider a summer day very hot and humid; last year the average temperature on a summer day was 32.5°C.

TEMPERATURE REGULATION

11. Mark how you control the indoor air temperature at home in the summer:

☐	Remote control		☐	Smartphone application	
☐	Wall-mounted thermostat		☐	N/A	

Fig. A.2. Questions related to household occupancy patterns and types of cooling systems.

Appendix A.3 Pro-Forma Questionnaire Survey

COOLING DEVICES USE

We would like to know when you turn on/off your cooling device(s) in different rooms on **weekdays** and at **weekends**.

12. Where and when do you turn on the cooling device(s) on **weekdays**?

Room	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Living room																								
Kitchen																								
Bedroom 1																								
Bedroom 2																								
Bedroom 3																								

13. Where and when do you turn on the cooling device(s) at **weekends**?

Room	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Living room																								
Kitchen																								
Bedroom 1																								
Bedroom 2																								
Bedroom 3																								

HEATING SUPPLY AND CONSUMPTION

14. What type of heating system do you have? Specify numbers of each.

☐ Central heating system ☐ A/C split unit ☐ A/C inverter split unit ☐ Wall-mounted heating fan
☐ Portable external fans ☐ Radiator ☐ Gas-supplied heater ☐ Oil-supplied heater
☐ Halogen heater. ☐ None. ☐ Other, (please specify) ____

We are interested in how you use your heating system during the **WINTER** months. Consider a winter day very cold and dry; last year, the average temperature on a winter day was 11°C.

TEMPERATURE REGULATION

15. Mark how do you control the indoor air temperature at home:

☐	Radiator taps		☐	Smartphone application	
☐	Wall-mounted thermostat		☐	Remote controller	
☐	Automatic thermostat		☐	N/A	

Fig. A.3. Questions related to household cooling-energy-use patterns and types of heating systems.

Appendix A.4 Pro-Forma Questionnaire Survey

HEATING DEVICES USE

We would like to know when you turn on/off your heating device(s) in different rooms on **weekdays** and at **weekends**.

16. Where and when do you turn on the heating device(s) on **weekdays**?

Room	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Living room																								
Kitchen																								
Bedroom 1																								
Bedroom 2																								
Bedroom 3																								

17. Where and when do you turn on the heating device(s) at **weekends**?

Room	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Living room																								
Kitchen																								
Bedroom 1																								
Bedroom 2																								
Bedroom 3																								

WINDOW SCHEDULES

Now we will follow some questions about the use of the windows during the **SUMMER** (average temperature approximately 32.5 °C, not too much wind). Where when do you open and close your windows on an average day during the **SUMMER**?

If you use doors for ventilation (like doors to the garden or balcony) please considers your doors as windows.

18. Where and when do you open your windows in the **SUMMER**?

Room	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Living room																								
Kitchen																								
WC																								
Bathroom																								
Bedroom 1																								
Bedroom 2																								
Bedroom 3																								

19.In general, do you keep room doors open in the summer when you don't have cooling on?

☐ Yes ☐ No

20. Why do you open the windows? Multiple marks possible.

☐ To get fresh air ☐ To cool down (i.e., adjust temperature)

☐ To remove condensation ☐ To dissipate dirty air (e.g., smoking, cooking smells)

21. Why do you close the windows? Multiple marks are allowed.

☐ Against draft ☐ Against the warm air/cool air ☐ Block sounds from outside

☐ Block smells from outside. ☐ For safety reasons ☐ Other, (please specify);________

Fig. A.4. Questions related to household heating-energy-use patterns and habitual window-opening behaviour and schedules in summer.

Appendix A.5 Pro-Forma Questionnaire Survey

22. How would you rate the overall thermal sensation of the following areas in the **SUMMER**?

Living room	Cold	1	2	3	4	5	6	7	Hot
Kitchen	Cold	1	2	3	4	5	6	7	Hot
Bedroom 1	Cold	1	2	3	4	5	6	7	Hot
Bedroom 2	Cold	1	2	3	4	5	6	7	Hot
Bedroom 3	Cold	1	2	3	4	5	6	7	Hot

Now we will follow some questions about the use of the windows during the **WINTER** (average temperature approximately 11 °C, not too much wind). Where and when do you open and close your windows on an average day during the **WINTER**?
If you use doors for ventilation (like doors to the garden or balcony) please considers these doors as windows.
23. Where and when do you open your windows in the **WINTER**?

Room	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Living room																								
Kitchen																								
WC																								
Bathroom																								
Bedroom 1																								
Bedroom 2																								
Bedroom 3																								

24. In general, do you keep room doors open in the winter when you don't have heating on?

☐ Yes ☐ No

25. How would you rate the overall thermal sensation of the following areas in the **WINTER**?

Living room	Cold	1	2	3	4	5	6	7	Hot
Kitchen	Cold	1	2	3	4	5	6	7	Hot
Bedroom 1	Cold	1	2	3	4	5	6	7	Hot
Bedroom 2	Cold	1	2	3	4	5	6	7	Hot
Bedroom 3	Cold	1	2	3	4	5	6	7	Hot

APPLIANCES INVENTORY

26. Which and how much of the following appliances is present your home, and for how many hours each day?

Rooms	Equipment	Number of hours
Living room	☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐
Kitchen	☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐
Bedroom 1	☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐
Bedroom 2	☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐
Bedroom 3	☐☐☐☐☐☐☐☐☐	☐☐☐☐☐☐☐
*Appliances:	**a.** Television set, **b.** computer monitor; **c.** computer laptop; **d.** smartphone/tablet; **e.** video game console;	

f. home cinema; **g.** refrigerator/freezer; **h.** cooker/oven; **g.** dishwasher; **j.** washer/dryer; **k.** toaster; **m.** kettle; **n.** coffee machine; **p.** microwave; **r. h**air-dryer **s.** others, (please specify); ________

Fig. A.5. Questions related to built-environment factors that impacted household TSVs.

Appendix A.6 Pro-Forma Questionnaire Survey

27. How much light bulbs are being used in per room and how many hours a day?

Type of Light Bulb Numbers of Hours	Livingroom	Kitchen	WC	Bathroom	Bedroom 1	Bedroom 2	Bedroom 3
☐ Low-energy light bulb	☐	☐	☐	☐	☐	☐	☐
☐ Halogen light bulbs	☐	☐	☐	☐	☐	☐	☐

HEALTH

28. How is your health general?

	Very Poor	Poor	Mediocre	Good	Very Good
☐ Respondent					
☐ Person 2					
☐ Person 3					
☐ Person 4					
☐ Person 5					
☐ Person ___					

INCOME

29. What is your monthly income?

☐ less than 9,500 TL ☐ 9,500, - 2,850 TL ☐ 2,850 -1,800 TL

Fig. A.6. Questions related to household health and income.

Appendix A.7 Pro-Forma Questionnaire Survey

SECTION 2

30. How do you prefer to feel? (Check the most appropriate response)

☐	☐	☐	☐	☐	☐	☐
Hot	Warm	Slightly Warm	Neutral	Slightly Cool	Cool	Cold

31. Using the list below, please check every item of clothing that you are wearing right now; this is an indication of the thermal comfort level of your interior space:

Top

☐ Short-sleeved shirt
☐ Long sleeved shirt
☐ Walking Shorts
☐ Jeans
☐ Athletic sweat pants.

Bottom

☐ Trousers
☐ Knee-length skirt
☐ Suit vest
☐ T-shirt
☐ Ankle-length skirt

☐ Other: (Please note if you are wearing something not described above, or if you think something you are wearing is especially heavy): ____________

32. How would you describe your activity level just prior to completing this survey? (Check the one that is most appropriate)

☐ Reclining
☐ Relaxed, standing
☐ Medium activity, standing
☐ Reclining
☐ Cooking, standing
☐ Medium activity standing

☐ Seated
☐ Light activity, standing
☐ High activity
☐ Seated
☐ Light activity standing
☐ High activity

33. In the **summer** months, how satisfied are you with the temperature in your space now?

Very Satisfied	1	2	3	4	5	6	7	Very Dissatisfied

34. In the **winter** months, how satisfied are you with the temperature in your space?

Very Satisfied	1	2	3	4	5	6	7	Very Dissatisfied

35. How would you best describe the source of this discomfort? (Check all that apply):

☐ Humidity too high (damp)
☐ Air movement too high
☐ Incoming sun
☐ Drafts from windows
☐ Thermostat is inaccessible.

☐ Humidity too low (dry)
☐ Air movement too low
☐ Heat from home appliances
☐ Draft from vents
☐ Thermostat is adjusted by other household members

☐ N/A

☐ Heating/cooling system does not respond quickly enough to the thermostat
☐ Heat/cold surrounding surfaces (floor, ceiling, walls or windows)
☐ Deficient window (not operable)
☐ My room is hotter/colder than other rooms

36a. Please describe any other issues related to being too hot or too cold in your room:

Fig. A.7. Thermal-comfort assessment.

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Highlights

- Questioning of existing adaptive thermal comfort models for naturally ventilated residential buildings and households were investigated.

- A novel framework combining assessment methodology with existing benchmark criterion of thermal comfort was developed.

- In vivo experience of subject respondents' thermal sensation votes was demonstrated.

- A negative moderate correlation was found with the outdoor temperature at $r = -0.325$, $p<0.01$.

- The results revealed that 80% of the study respondents were slightly comfortable in a temperature ranging from 28.50 °C to 31.50 °C.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

To the readers' information:

This paper presents the outcomes of self-funded PhD research project undertaken at the University of East London, United Kingdom. The paper is devised after the completion of the research project. Therefore, at the time of writing up the research paper related to this case study location due to the project period is extended slightly beyond the targeted timeframe, the author has provided additional financial flow from his own budget to complete this project successfully. **Dt. Serife Gurkan** fully funded this PhD research project undertaken at the Graduate School, School of Architecture, Computing & Engineering, University of East London between 26/09/2016 – 29/09/2020. She also supported the researcher (**Bertug Ozarisoy**) financially at the time of developing this research paper proposal, conceptualising, data collection and writing up processes. She provided substantial amount of financial investment throughout the research progress. Additionally, **Dt. Serife Gurkan** paid the researcher's travel expenses to enable him to conduct the field survey in Cyprus.

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