ASSESSING THE DOMESTIC ENERGY USE AND THERMAL COMFORT OF OCCUPANTS IN A POST-WAR SOCIAL HOUSING DEVELOPMENT ESTATE IN FAMAGUSTA, NORTHERN CYPRUS

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A thesis submitted in partial fulfilment of the requirements of the University of East London for the degree of Doctor of Philosophy

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FEBRUARY 2022

Abstract

Efforts to retrofit post-war residential buildings have gained increasing momentum recently, especially after the European Union called for a zero carbon–emission target by 2050. This study presents a novel methodological framework for determining the most effective energy policy for implementing the EPBD mandates and improving the energy efficiency of existing post-war social housing stock in the South-eastern Mediterranean climate of Cyprus. The study examines how energy policy and regulation is carried out in this area through analysis of nationally representative archetype buildings in the coastal city of Famagusta where the weather is subtropical (*Csa*) and partly semi-arid (*Bsa*). The developed empirical framework integrates the socio-technical-systems (STS) approach and provides data about households through field interviews to better understand the relations between sociodemographic characteristics, energy use and thermal comfort. The *in-vivo* experiences of householders' thermal-sensation votes is assessed to predict individual aspects of adaptive thermal comfort and its relevance to overheating. Data is collected from *in-situ* measurements, including recordings of household indoor-air temperatures integrated with thermal-imaging surveys and heat-flux measurements of building fabric elements, along with concurrent *on-site* monitoring of environmental conditions and a review of household energy bills to accurately determine actual energy use. The results reveal that in a non-retrofitted building, cooling and heating comprise the greatest proportion (73%) of total energy consumption. Applications for six passive cooling design strategies are then analysed, and after the life-cycle cost assessment of each is considered, off-site modular building applications are developed. After building optimisation, it is found that approximately an 81% savings related to cooling consumption can be achieved, which suggests that design, ventilation, and servicing strategies, combined with passive shading systems, can improve the energy efficiency and indoor-air quality of residential buildings.

Declaration

I, Bertug Ozarisoy, confirm that the work presented in this doctoral thesis is my own research project. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Nomenclature and Abbreviations

A	Area (m^2)
°C	Degrees Celsius
Clo	Insulation value of clothing
C_v	Air permeability coefficient
CV	Coefficient of variation (%)
df	Degree of freedom
E	Energy (kWh/m^2)
f	Frequency
F	Fuel (MJ)
f_c	Correction factor of thermal mass
$f_{shading}$	Envelope shading reduction factor
G_{value}	Solar energy transmittance
GWH	Giga-watt hour
h	Equation parameter
H	Height (m)
h^{-1}	Air infiltration rate
m	Mass (kg)
M	Mean
M	Thermal conductivity coefficient (kJ/m^2K)
m^2	Square meter
m^3	Cubic meter
met	Metabolic activity
MJ	Mega-joule
N	Number of data
N_s	Number of total simulations
p	Significant level
***P*-set**	Subject respondents
***P*-test**	Parametric (analysis)
q	Heat flux (W/m^2)
Q_{glass}	U-value of windows (W/m^2K)
Q_{op}	Operative air infiltration threshold (°C)
r	Density (kg/m^3)
R	Heat absorptivity coefficient (m^2K/W)
r	Number of elementary effects per parameter
r^2	Coefficient of determination
RC_{facade}	Thermal resistance of façade (m^2K/W)
RC_{floor}	Thermal resistance of floor (m^2K/W)
RC_{roof}	Thermal resistance of roof (m^2K/W)
s	Thickness (m)
sf	Solar-fraction factor
T	Temperature (°C)
t	Time(s)
T_a	Indoor-air temperature (°C)

$T_{ed} - 1$	Daily mean external temperature for previous day (°C)
T_{ed}	Daily mean external temperature (°C)
T_{ground}	Ground temperature (°C)
T_{int}	Indoor-zone temperature (°C)
T_m	Mean air temperature (°C)
T_{max}	Maximum temperature (°C)
T_o	Outdoor-air temperature (°C)
$T_{o/u}$	Total over/underheating hours
T_{op}	Operative air temperature (°C)
T_{pma}	Prevailing mean outdoor-air temperature (°C)
$T_{rm} - 1$	Running-mean temperature for previous day (°C)
$T_{rm} - 2$	Daily -ean external temperature for two days ago (°C)
T_{rm}	Running-mean temperature (°C)
T_{set}	Setpoint-zone temperature (°C)
T_{upp}	Upper limit of threshold temperature (°C)
T_{wall}	Envelope-zone temperature (°C)
U	Heat-loss coefficient (W/m^2K)
V	Wind speed (m/s)
W	Width (m)
W	Wind velocity (m^2s)
W_s	Monthly average wind speed (m/s)
y	Statistical variable

Abbreviations

.epw	EnergyPlus Weather (file format)
.gbxml	Green Building extensible markup language
.xml	Extensible markup language (file format)
A/C	Air conditioning
AMY	Actual meteorological year (weather file)
ANOVA	Analysis of variance
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BEM	Building-energy modelling
BES	Building-energy simulation
BIM	Building-information modelling
BPE	Building-performance evaluation
BPS	Building-performance simulation
BS	British Standards
CEA	Cyprus Electricity Authority
CEN	Comité Européen de Normalisation
CFD	Computational fluid dynamic
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon dioxide
CSV	Comma-separated values (plain-text file)

CY	Cyprus
DBT	Dry-bulb temperature
DECC	Department of Energy and Climate Change
DTS	Dynamic thermal simulation
EA	Electricity Authority
ECM	Energy-conservation measures
EEG	Energy-efficiency gap
EEM	Energy-efficiency measure
EN	European Norm
EPBD	Energy Performance of Buildings Directives (standards)
EPC	Energy performance certificate
EU	European Union
EUI	Energy-use intensity
FLIR	Forward-looking infrared radiometer
GA	Genetic algorithms
GBS	Green Building Studio (Autodesk®)
GHG	Greenhouse gas
GIS	Geographic Information Systems (software tool)
GNP	Gross national product
HSI	Heat-stress index
HSRS	Health and Safety Rating System
IES	Integrated Environmental Solutions (energy-simulation tool)
IHG	Internal heat gain
IPCC	Intergovernmental Panel on Climate Change
IPMVP	International-performance measurement and verification protocol
IR	Infrared radiometer
IRT	Infrared radiometer thermography
LCCA	Life-cycle-cost assessment
MANOVA	Multivariate analysis-of-variance
MET	Metabolic equivalent
MFH	Multi-family house
MkWh	Million kilowatt-hours
MM	Mixed-mode (ventilation)
MO	Multi-objective
NC	Northern Cyprus
NV	Natural Ventilation
nZEB	nearly zero energy building
NZEB	Net zero energy building
OP1	Low occupancy
OP2	Moderate occupancy
OP3	High occupancy
OT	Operative air temperature
PCDS	Passive cooling design strategies
PMV	Predicted mean vote
POE	Post-occupancy evaluation

PPD	Predicted percentage of dissatisfied
RA	Regression analysis
RC	Resistance capacitance
RESNET	Residential Energy Services Network
RH	Relative humidity
RHI	Relative-humidity index
RoC	Republic of Cyprus
RQ	Research question
RTB	Residential tower block
SAP	Standard assessment procedure
SAR	Suggested acceptable range
SCAT	(EU) Smart Controls and Thermal Comfort
SD	Standard deviation
SFH	Single-family house
SME	Small-and-medium enterprise
SP	Set point
SPSS	Statistical Package for Social Sciences (Version 25.0 software)
STS	Socio-technical systems
TL	Turkish Lira
TMY	Typical meteorological year
TPV	Thermal-preference vote
TRNSYS	Transient System Simulation Tool
TRY	Test reference year (weather file)
TSV	Thermal-sensation vote
UCR	United Cyprus Republic
UCTCEA	Union of Cyprus Turkish Engineers and Architects
UHI	Urban heat island (effect)

Superscripts/Subscripts

act	Actual
adj	Adjacent
air	Indoor air
amb	Ambient
av	Average
e	East (building envelope)
eff	Effective
eq	Equivalent
ext	External (ambient air temperature)
in	Indoor
int	Internal
losses	Losses to ambient temperature
min	Minimum value
max	Maximum value
n	North (building envelope)

nom	Nominal
opt	Optimal
percap	Per capita
ppm	Parts-per-million
pred	Predicted
rad	Radiation
s	South (building envelope)
sim	Simulation
t	Top
tot	Total
w	West (building envelope)

Greek Symbols

γ	Linear correlation coefficient
$\propto_e$	Absorptivity of external surface
Δ	Difference, variation
ΔT	Time step(s)
β	Energy performance coefficient
μ	Mean value
θ	Opening/closing windows and doors (°)
ρ	Air density (m^3/kg)
ω	Weight of objective function

Köppen Climate Classifications

Aw	Tropical wet and dry or savanna
Bsh	Semi-arid
BSk	Cold semi-arid
BWh	Hot desert
Cfa	Humid subtropical
Cfb	Temperate oceanic
Csa	Sub-tropical
Dfb	Warm summer humid continental

Acknowledgments

I would like to express my sincerest thanks to the Graduate School for offering me a postgraduate education to pursue doctoral studies and research at the School of Architecture, Computing and Engineering. I especially want to thank Prof. Verity Brown and Dr. Mihaela Anca Ciupala for being seminal in welcoming me to the University of East London (UEL). I truly appreciated the supportive and rigorous research culture they offered to foreign students and their continuous support throughout my research journey in the UK.

Most importantly, I would like to take this opportunity to thank my internal examiner - Emeritus Professor Allan Brimicombe at the UEL for his unprecedented help and guidance under very exceptional circumstances, without which I feel this PhD thesis would not have been able to reach its present standard. Prof. Allan Brimicombe has with his recommendations and guidance, especially in the field of statistics, enabled me to enrich not just the quality of this PhD thesis from the perspective of statistics but also enrich my own knowledge of statistics. This has been a bonus reward for me in my academic career.

I would also like to acknowledge my external examiner, Associate Professor Benjamin Jones at the University of Nottingham, for his valuable contribution to this PhD thesis.

I thank all the tutors and instructors that I had a pleasure to get to know during my stay at the University of East London. Becoming a researcher was a delightful experience and engaging with academics in the UK as a UEL's PhD student. My special appreciation goes to Dr. Thomas Rusbridge whose help and encouragement made it possible for me to continue on my research path. I also thank my colleagues Dr. Sahar Zahiri and Dr. Wei Shi for their advice in the early stages of this study and their critical review of the development process of this PhD research project that inspired me to improve the thesis further. I would like to thank all who have involved themselves and have given up their valuable time to help guide me in these very difficult and challenging times through the process of this PhD journey at the UEL.

I am deeply grateful to my mentor Prof. Hasim Altan whose friendship, professional advice and personal encouragement were instrumental in the development stages of the thesis for me to embark on doctoral studies. This thesis would not have been possible without the support of Prof. Hasim Altan and I am sincerely thankful for his advice on the improvement of the layout of the thesis and the conceptualisation of narrative structure of the chapters to enable me to complete the thesis successfully.

But most of all I want to thank my aunt Dt. Serife Gurkan for her never-ending love, support and understanding throughout my research work. Nevertheless, the continued support and encouragement of my family has given me the strength to strive for excellence and personal growth and hopefully this thesis is a tiny reflection of both.

Dedication

This research work is dedicated to my family.

I would like to acknowledge my aunt Dt Serife Gurkan who supporting me both financially and morally to complete this doctoral thesis at the University of East London. I won't be able to succeed this PhD research timely without her financial support. I also opt enormous dept to my mum Ayse Ozarisoy for providing me an opportunity to study in the UK and her deeply patience at the time of writing up this doctoral thesis.

I would also like to acknowledge my uncle Halil Salkok and his wife Cigdem Salkok alongside my other beloved aunts of Sevilay Salkok and Nilgun Ozarisoy for their support and great help at the time of conducting a questionnaire survey at the post-war social housing development estate in Famagusta, Northern Cyprus. I won't be able to complete all necessary field surveys without their help and guidance. They spent a tremendous amount of time with me for recruiting households and providing necessary contacts/networking in order to achieve sufficient enough sample size for the statistical analyses.

Publications from the Thesis

Ozarisoy, B., & Altan, H. (2021). Significance of Occupancy Patterns and Habitual Household Adaptive Behaviour on Home-Energy Performance of Post-War Social-Housing Estate in the South-Eastern Mediterranean Climate: Energy policy design, *Energy,* Elsevier. *https://doi.org/10.1016/j.energy.2021.122904*
(Deposited to the UEL's repository)

Ozarisoy, B., & Altan, H. (2021). Bridging the energy performance gap of social housing stock in south-eastern Mediterranean Europe: Climate change and mitigation, *Energy & Buildings,* Elsevier. *https://doi.org/10.1016/j.enbuild.2021.111687*
(Deposited to the UEL's repository)

Ozarisoy, B., & Altan, H. (2021). Systematic literature review of bioclimatic design elements: Theories, methodologies and cases in the South-eastern Mediterranean climate, *Energy & Buildings,* Elsevier. *https://doi.org/10.1016/j.enbuild.2021.111281*
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Ozarisoy, B., & Altan, H. (2021). A novel methodological framework for the optimisation of post-war social housing developments in the South-eastern Mediterranean climate: Policy design and life-cycle cost impact analysis of retrofitting strategies, *Solar Energy, 225*, Elsevier. https://doi.org/10.1016/j.solener.2021.07.008
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Ozarisoy, B. (2021). Energy effectiveness of passive cooling design strategies to reduce the impact of long-term heatwaves on occupants' thermal comfort in Europe: Climate change and mitigation, *Journal of Cleaner Production*, Elsevier. https://doi.org/10.1016/j.jclepro.2021.129675
(Deposited to the UEL's repository)

Chapter 1

Introduction

1.1 Knowledge Gap in Energy-Policy Framework and Retrofitting Existing Housing Stock

The concept of retrofitting is an important milestone in the evolution of upgrading the energy efficiency of residential buildings. A significant proportion of the social-housing stock in south-eastern Europe is obsolete in this area, and occupants who represent different socio-demographic profiles require in-depth study (Fokaides *et al*., 2017; Nematchoua *et al*., 2021). Various policy instruments have been introduced to retrofit existing social-housing stock, but many have failed to acknowledge the significance of occupancy patterns in relation to energy use (Santin, 2011).

To address the diversity of each EU nation and the variances of the housing typologies thereof, the EPBD schemes were influenced by many factors, including the diversity of the thermal properties of buildings, the range of occupant behaviour, energy-governance structures and energy-subsidisation goals and schemes adopted by EU countries (Cristino *et al.*, 2021); this is why there are neither stringent building regulations nor any type of control mechanism to determine the effectiveness of energy-efficient subsidisation schemes in Northern Cyprus (NC) and the RoC (Evcil & Vafaei, 2017). This resulted in a shortfall between the full potential of EPBD implementations and awareness of the adoption of energy-efficiency measures (EEMs); in the residential sector, this knowledge gap is referred to as the ‘energy efficiency gap’ (Fokaides *et al*., 2014; Nabitz & Hirzel, 2019).

Several scholarly research endeavours have investigated associations between governmental policies on thermal retrofitting and current-energy efficiency awareness related to the energy use in residential buildings for the development of socio-technical-systems (STS) approach in buildings’ retrofitting, specifically that of EU countries (Bertoldi & Mosconi, 2020; Morton *et al.*, 2020; Thonipara *et al.*, 2019). A lack of control mechanisms and implementation frameworks arose due to the variety of European laws that were enacted in each country, which took the political agendas and international relations of each EU member state into consideration; this led to a communication gap between policy design and community-level energy-subsidisation schemes (Arbolino *et al*., 2019; Buessler *et al*., 2017; Haley *et al*., 2020).

Government initiatives in Cyprus, which is an EU member state, and NC, which is not an EU member state, have attempted to alleviate the burden of the existing housing stock by changing the legislative framework to adopt the EPBD guidelines and nZEB schemes to upgrade the thermal efficiency of existing building stock (Dascalaki *et al.*, 2016; Kylili *et al.*, 2014; Spyridaki *et al.*, 2020). Such legislative frameworks were not devised, however, by taking occupants' habitual adaptive energy-use behaviour into consideration, which would have led to more effective guidelines for the reduction of energy consumption and the optimisation of occupant thermal comfort in the residential sector (Hamborg *et al*., 2020).

The RoC government promoted a multilateral agreement with the EU for implementing energy-efficient systems and other retrofitting interventions that will improve the thermal efficiency of existing housing stock (Panayiotou *et al.*, 2013). This transformational technology and the associated legislation have not been implemented to adopt the European International Organisation for Standardisation benchmark legislation within the development of STS approach in energy use (Baldoni *et al.*, 2019). There is currently no legislative procedure in NC to assess the energy performance of buildings to provide an internationally recognised EPC scheme that can be applied to any type of housing stock.

Several studies recommended a territorial approach to improve energy-subsidisation programmes associated with the economy and implement EPCs that are related to a building life-cycle cost assessment (LCCA), and a review of the feasibility of optimisation studies was also suggested to provide a roadmap to stakeholders and policymakers (Barone *et al*., 2019; Gaspar, 2017; Renner & Giampietro, 2020); these studies asserted that the selection of archetype buildings and nationally representative household population would facilitate the development of a bottom-up energy-policy framework across all EU member states.

The present study considers the Cypriot housing stock, which was not accurately demonstrated in the TABULA/EPISCOPE project developed under the *Horizon 2030* framework; this study was the first to identify social-housing stock as representative building typologies to address the energy-efficiency gap and provide accurate primary data sources to this national online database platform, which is required for the energy-governance development of each EU member state.

Another technical constraint is the lack of available primary databases to record the impact of EPCs on home-energy performance and household energy bills; this dearth of data is evident in many areas, such as legislation and regulations for issuing EPBDs and relevant training materials, which include the development of software tools and an online open-source platform to disseminate the outcomes of each country (Ballarini *et al*., 2014; Cozza *et al*., 2020). In this regard, there is a growing body of the literature that recognises the importance of the integration of EU mandates, because the representativeness of housing stock in NC was not thoroughly classified, primarily because the housing typology classification was based on a random selection of case-study buildings for an archetype analysis of local initiatives and energy agencies. Because of this challenge, a comprehensive energy-performance evaluation of housing stock can only be conducted at the building-level; as such, there is an urgent need for effective nationwide implementation of EPCs and other control mechanisms to achieve policy targets and additional actions related to future holistic retrofitting efforts for urban neighbourhoods, all of which must put into place by stakeholders and government initiatives in NC.

The EPBD developed guidelines for each EU member state, including the RoC, but as of the date of conceptualisation of this research, these recommendations have not been implemented; thus far, the authorities have failed to comply with the EU's *Horizon 2030* recommendations, and an effective methodological framework based on studies that represent the housing stock and households has not yet been developed.

The present study fills this energy-governance gap and creates a roadmap to upgrade the energy efficiency of the housing stock and increase household energy-efficiency awareness; the effect of the absence of retrofit policy design remains unclear, and further research is required. The present study provides a new methodological framework to develop EPC implementation strategies in the Cypriot context, according to the recommendations put forth in the EPBD mandates as part of the EU energy policy. The main aim of this research is to fill the knowledge gap in the area of an evidence-based framework for energy-policy decision-making mechanisms related to the integration and implementation of the EPBD regulations at the conceptual and national levels. The objectives are threefold:

(i) To examine the significance of occupancy patterns and habitual adaptive household behaviour on home-energy performance by conducting feed-forward interviews with social-housing occupants;

(ii) To investigate overheating risks and occupant thermal comfort within representative RTBs and subsequently provide primary data sources to build future performance evaluation studies; and

(iii) To develop and test the applicability of a BES on base-case RTB prototypes to demonstrate a design method based on comprehensive accounting of energy

governance in the EU and to examine the energy-policy framework at the European level and the development of a holistic retrofitting agenda for all EU member states.

The present study focuses on socio-cultural issues deemed to be the most relevant to efforts to improve the thermal efficiency of residential buildings; a number of significant, difficult-to-quantify home-energy-performance factors that are often under emphasised in energy policy, such as the ingrained energy-use habits of different households and the socio-demographic characteristics and degree of thermal discomfort thereof, can facilitate the development and implementation of energy-efficiency schemes, which is why an STS approach that simultaneously considers multiple factors is an effective means to address the EEG. In line with this objective, the present research adopts an STS conceptual framework that concurrently considers retrofitting-related social and technical factors to improve the likelihood of adopting long-term holistic retrofitting schemes that will enhance the energy performance of the domestic built environment.

1.2 Aim and Motivation

The overall aim of the present study is to improve current energy-efficient design methods to develop an effective methodological framework for policymaking decisions and long-term holistic retrofitting schemes for existing buildings enacted in EU members states that considered occupant energy-use behaviour. The motivation was to increase household energy-saving awareness and positively affect occupant behaviour related to home-energy performance to develop energy-efficiency regulations and determine legal standards and benchmarks for the implementation of EPCs that are in line with the EPBD recommendations. This approach provided a good representation of the common drivers in the property market by considering different levels of retrofitting strategies and delineated potential challenges by acknowledging occupant energy-consumption behaviour and building-thermal properties that have noticeable impacts the thermal comfort and actual energy use of occupants in NC post-war social-housing estates.

1.3 Research Questions

The research questions (RQs) in the present study focused on the domestic-energy use and occupant thermal comfort in purpose-built RTBs to determine what information was necessary to properly calibrate building energy performance, to provide guidelines, tools and policy implications to improve the energy efficiency of post-war social-housing estates in NC. The primary RQ that was addressed was: What is the most effective and universally applicable energy-policy framework to implement the EPBD mandates recommended by EU and improve the energy efficiency of existing housing stock in NC?

The following RQs are outlined to develop a bottom-up energy-policy framework to upgrade the thermal efficiency of the existing Cypriot housing stock:

- ***RQ-1:*** How do environmental factors affect occupant thermal comfort and how can neutral adaptive thermal-comfort thresholds be identified in this South-eastern Mediterranean climate?
- ***RQ-2:*** How will this empirical study contribute to and inform the design of net-zero energy buildings in EU countries?
- ***RQ-3:*** What are the main determinants of energy use in archetype RTBs, and to what extent do retrofitting options have the potential to achieve optimum indoor comfort conditions?

Investigating current design methods while developing the STS design approach resulted in energy-policy frameworks and regulations that will enable NC, the RoC and other EU member states to properly address the EEG. To achieve these targets, the present study sought to address the outlined RQs in three conceptual frameworks: First, to analyse the manner in which EPCs can be utilised as energy-planning tools by calculating and verifying average energy consumption; second, to examine the current state of existing research into the validity of EPCs as an effective policymaking tool to accelerate the transformation of post-war social-housing stock into low-energy dwellings; and third, to investigate the technical constraints of building regulations and thermal properties of RTB prototypes in energy-performance developments between NC and EU countries when devising and implementing a universal energy-policy directive.

1.4 Socio-Technical-Systems Approach

An STS approach was used as a theoretical framework to integrate household socio-demographic characteristics related to energy use, the thermal-conductivity level of buildings and environmental factors; and to address the question of how different contexts influence the development of energy-efficiency strategies. Drawing on this approach, the present study investigated domestic-energy use and indications of how much is being used thereof in base-case RTBs to improve the energy efficiency of existing social-housing stock.

It should be noted that the present study focuses on the STS research design approach to integrate a multidisciplinary study into a methodology for building-energy simulation studies. The choice of focus was intentional in light of the fact that decisions associated with post-war social-housing development estates, which seek to improve the energy efficiency of existing housing stock were generally made according to assumptions, overlay general studies or forecasting scenarios that fail to consider human-based factors in building-energy modelling (BEM) stage.

The implications of the present study were exploratory in nature and used a human-based empirical design approach that specifically targeted household energy-use characteristics, the overheating risk of different occupied spaces and the impact thereof on occupant thermal comfort. To fulfil the study research, aim and objectives, the conceptual framework placed social-household occupants at the centre who were influenced by three determinant factors—socio-demographic characteristics, environmental conditions and building thermal properties—as shown in Figure 1.1.

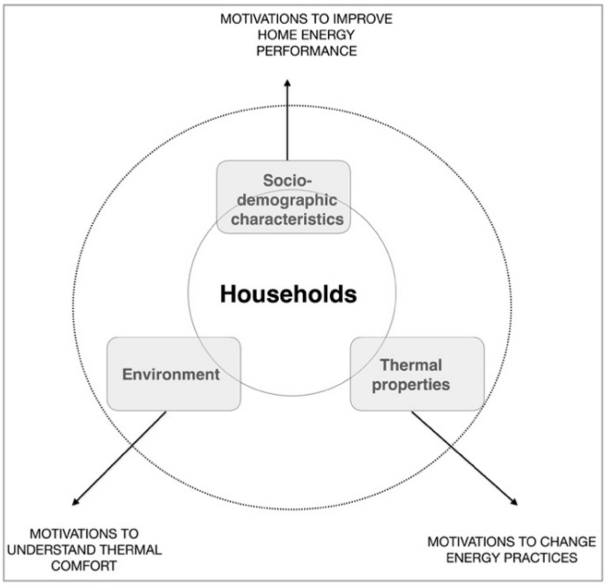


Figure 1.1: Research model based on STS design concept.

This model illustrates the manner in which the STS conceptual framework can be adopted to address EEG, as opposed to measures that simply targeted Famagusta households. Without considering the significance of occupancy patterns on energy use, the empirical studies aim to address vulnerable neighbourhoods steeped in energy poverty may not be as effective (Berger & Höltl, 2019).

The STS model clearly demonstrates that without an understanding of household socio-demographic characteristics, empirical studies conducted to develop the potentialities of the STS approach has found to be that an appropriate method of design to overcome issues in the EEG (Cockbill *et al*., 2020; Guerra-Santin *et al*., 2017). As such, the variants in the model are interlinked (i.e., the inner circle), and they affect home-energy performance (i.e., the outward-moving arrows and dashed outer circle). By investigating the factors that were outlined in the model, all obtained data were concurrently analysed feed-forward, then embedded into each other to inform policymaking decisions related to energy use (Sovacool *et al*., 2020).

The STS approach can be found in previous scholars' work in central European countries and few studies that considered council estates in the U.K., but no other studies adopted the STS and investigated household energy use, occupancy patterns and their degree of thermal discomfort in the south-eastern Mediterranean Europe have been considered (Anderson *et al.*, 2020; Johnstone *et al.*, 2020). Hence, this empirical study is the first to examine the applicability of the STS approach while taking household cultural values, norms and social assets into account.

1.5 Contribution to Knowledge

The main contribution to the body of knowledge is the integration of data to identify the empirical analysis of the STS conceptual framework to develop a new method of design for the EPBD mandates that can be applied to the universal databases, as listed in Table 1.1.

Table 1.1: The Impact of Key Research Areas to the Contribution to Knowledge.

Key Concepts		Contributions
Energy policy	-	EU energy governance by integrating EPCs into building-energy-performance development of social-housing stock
Thermal comfort	-	Donation of the neutral adaptive thermal comfort identified by a thermal-comfort survey of the Cypriot context to the *American Society of Heating, Refrigerating and Air-Conditioning Engineers* (*ASHRAE*) Global Thermal Comfort Database II
	-	Donation of the neutral adaptive thermal comfort identified for the Cyprus climate to the EU *Smart Controls and Thermal Comfort* (*SCAT*) online database
	-	Dissemination of the optimum thermal-comfort level thresholds that were developed as a result of a field investigation in the south-eastern Mediterranean climate and can be applied to the European Norm *EN 15251* standards—which are related to indoor environmental input parameters associated with the design and assessment of building energy performance and address indoor-air quality, the thermal environment, lighting and acoustics—as an updated methodological framework
Energy use	-	Integration of the archetype housing stock into the EU's *Horizon 2030 TABULA/EPISCOPE* national database
Building energy simulation	-	Development of energy-assessment methods for archetype housing stock and analytical BEM with integrated human-based data from the questionnaire survey to demonstrate a policy design tool to the applied sciences field in energy use

1.5.1 Contribution to STS Conceptual Framework Development

The present study provides new insights into the EU energy governance and presents the outcome of comprehensive methodology developed by adopting the STS design approach, which is not found in other EU countries holistic retrofitting projects. Hence, this is the first study to be adopted and developed in the south-eastern Mediterranean climate of Cyprus. Thus, the findings should make an important contribution to the research subject of energy policy in the development of retrofitting schemes.

One of the unique features of the research technique developed in the present study is that it adopts the STS approach to create a novel methodological workflow to assess domestic-energy use and thermal comfort, neither of which is well-defined in traditional building physics or in regression-based forecasting for policy-making decisions. As a result, the BPE remains largely unpredictable when considering real-life occupant energy-use experiences. Moreover, an evidence-based STS approach was developed for the present study to determine the feasibility of the retrofitting design interventions when human-based considerations, including *in-situ* measurements to assess occupant thermal comfort were recorded during the survey, are factored into the BES model.

While the present study makes several important original contributions to EEGs, the retrofitting interventions developed herein may not be economically feasible with current energy-efficiency policy targets, even though the applicability of the research context and the recently recommended EPBD objectives from the EU may lead to an increased demand for domestic-cooling options. As such, it can be asserted that the economic and environmental benefits are mutually supportive of one another and that addressing current design methods related to thermal comfort, overheating risk and building optimisation will eventually lead to a win–win situation.

1.5.2 Contribution to Global Thermal-Comfort Database

Numerous field studies have found that occupant thermal comfort varies with local climate. There is no generally recommended acceptable comfort range for multi-family houses (MFHs), however, nor are there specific thermal-comfort prediction methods, particularly in southern-Mediterranean EU countries. The present study addresses the question of whether the thermal comfort field studies (ASHRAE Global Thermal Comfort Database II) should continue to search for methods to predict neutral thermal-comfort levels or shift the focus toward other applicable adaptive thermal-comfort models that optimise indoor air temperature and consequently lead to a greater human physical body adaptation and a lower dependence on air condition systems for space cooling or intensive energy use.

The study findings gathered via a longitudinal thermal-comfort survey and *in-situ* measurements of households where there is not any data available for the Cypriot context will contribute to the ASHRAE Global Thermal Comfort Database II. Notably, the most up-to-date representative sample that considered the thermal comfort in buildings was developed by Zhang *et al*. (2013); the results were available on the ASHRAE Global Thermal Comfort Database II universal online platform, an open-access site for scholars. The regression forecasting of neutral adaptive thermal comfort could provide a universally accepted benchmarking criterion for the baseline scenario development on thermal comfort in the Mediterranean region.

The *EN 15251* guidelines were 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 *SCAT* database.

1.5.3 Contribution to Energy-Performance Evaluation Studies

To address the knowledge gap of current building diagnostic design methods, the present study delineates the development of a novel methodological framework based on an empirical case-study approach that utilises a field survey, infrared-radiometer-thermography (IRT) and numeric experiments to calibrate BES procedures.

In this exploratory case study, an IRT survey and *in-situ* measurements of environmental conditions were concurrently carried out *in-vivo* with a questionnaire survey that was distributed to the households; household energy bills were obtained from the Cyprus Electricity Authority (CEA) to verify the data derived from the BES analysis. This is the first study to use energy-simulation studies as diagnostic tools to examine the existing post-war social-housing stock in NC and the RoC. This conventional building-diagnostic method was adopted to verify building thermal properties and the impacts thereof on overheating risks and occupant thermal comfort. The aim was to obtain human-based results in the BES to prove that the end result of energy performance analysis is not based in forecasting scenarios, but rather on actual household information related to occupancy patterns and home-energy performance factors embedded in the BES to design effective retrofitting strategies that will improve the thermal efficiency of the existing housing stock.

1.5.4 Contribution to BES Research

The present study is the first to target and conduct BES procedures on existing Cypriot social-housing stock. A BES analysis was integrated into the implementation of EPCs because of the reliable assumptions thereof to assess the energy performance of case-study RTBs. The energy simulation inputs seek to identify the impact of household occupancy patterns and habitual adaptive behaviour of on home-energy performance to provide a basis for the information that is needed to properly calibrate the building-energy performance of targeted households. It also envisages to demonstrate that occupants' real-life energy-use experiences have had a significant impact on calibrating domestic-energy use to simultaneously identify discrepancies between the actual and predicted energy use on the dynamic energy-simulation platform.

This is the first BES prototype model to demonstrate results obtained by a field-study investigation to develop a set of simulation input parameters that are needed for dynamic thermal simulations (DTS). These were evidence-based conclusions, but an examination of design methods that were recommended for BPE studies in the available exemplar projects confirmed that a BES is a steady-state analysis that is premised on testing the thermal efficiency of energy-efficient materials and building technologies without considering human-based data in the model. As such, the present study was developed according to human-based BES input parameters obtained from the questionnaire survey, *in-situ* measurements, the IRT survey and environmental monitoring of the project site to demonstrate real data for energy-use policymaking decisions. This conceptual framework can be applied to efforts to implement the EPBD mandates and to demonstrate the exemplar development framework, policy and regulations as it relates to the social-housing stock of NC and other EU member states.

1.6 Thesis Outline

The contribution of this thesis is a detailed record of the development of an STS conceptual framework. The novel methodological workflow was developed through a comprehensive, interdisciplinary study that informed the applicability of evidence-based retrofitting interventions as energy-policy design tools, and the case-study RTB prototypes delineated in the present study will serve as examples in the development of future BES studies in academia and in practice. The chapters that comprise this thesis will guide the reader through a journey of research that inevitably leads to the conclusions in the final chapter, as listed in Table 1.2.

Table 1.2: The Narrative Structure of the Chapters.

Chapters		Descriptions
Chapter 1	-	It describes the knowledge gap and outlines the research aim, objectives and questions that informed every stage of the STS conceptual framework and the integration thereof into the existing body of knowledge and highlights the novelty of the study.
Chapter 2	-	It details a literature review of overheating risk of buildings and thermal comfort studies across the globe in an effort to provide a comprehensive understanding of occupants' habitual adaptive behaviour on energy use.
Chapter 3	-	It describes the mixed-method research design that was utilised to study the internal, intrinsic motivation embedded in the context of the present study, specifically household socio-demographic characteristics and the influences thereof on thermal discomfort.
	-	The rationale for each of the case-study selections is then given, and the relevance thereof on the framework development for future energy policy is explained; and finally, the research limitations are outlined.
Chapter 4	-	It presents the results of a longitudinal field study that assessed household thermal comfort within the framework of the development of adaptive thermal-comfort theories by previous scholars.
	-	It identifies, in detail, a methodological framework for conducting a field investigation by including human data in the regression-forecasting analysis to develop an empirical case-study approach.
Chapter 5	-	It presents a novel methodology that was developed according to the *in-situ* measurements of the building-fabric thermal performance to assess as-built energy models of case-study RTBs.
	-	The BES studies were investigated according to the recommended international benchmarks and criteria to assess overheating risks and occupant thermal comfort by taking the real-life household energy-use experiences into consideration.
Chapter 6	-	It presents the DTS analysis of six passive cooling design strategies were developed, including the LCCA impact of households' energy use also was discussed.
Chapter 7	-	It makes conclusions based upon the observations of the preceding chapters. It also delineates implications for long-term holistic retrofitting programmes and policy design for evidence-based retrofitting design interventions with the implementation of the EPBDs in NC and other EU countries at the household- and building-levels.

Chapter 2

Literature Review

Introduction

The aim of this chapter is to provide an up-to-date extant review of building overheating risks, occupant thermal comfort, occupant behaviour on energy use and modelling and the current methods of energy-modelling simulation studies to respond to the research questions. The methodology involves a detailed literature review to provide an overview of existing studies of building-fabric thermal performance and a thorough selection and study of review articles, original research papers and conference proceedings to investigate the benefits and challenges of assessing building overheating risks and occupant thermal comfort. The review articles were filtered from a list of journal articles and conference proceedings that were published between 1990 and June of 2019. The source of the selection of articles used for the analysis was the 'Web of Science Core Collection', which is maintained by Clarivate Analytics. The main procedure involves creating a design for a search of the articles. To retrieve articles for the topic 'Building Performance', three title (TI) record files were created, as listed in Table 2.1.

Table 2.1: Search Parameters for Existing Studies.

Concepts	Keyword-Search Selection Criteria	Review Articles	Original Research Papers	Conference Proceedings
Overheating risk of buildings	TI = ('building performance*' OR 'overheating risk assessment')	8	171	25
Thermal comfort	TI = (('building performance*' OR 'thermal comfort' OR 'field investigation') AND (('thermal discomfort*' OR 'environmental monitoring')))	12	187	23
Occupant behaviour	TI = (('building performance*' OR 'occupant behaviour' OR 'occupant patterns') AND (('energy use*' OR 'occupant behaviour')))	7	128	12
Energy modelling	TI = (('building performance*' OR 'energy use' OR 'overheating') AND (('building optimisation*')))	9	175	27

Table 2.1 demonstrates a summary of the search data for articles on BPEs conducted in the Web of Science Core Collection database. The set results of the advanced searches were combined using the 'OR' Boolean operator to obtain 784 articles. This chapter discusses the extant literature to address the issues and proposes research trajectories to resolve the major challenges identified in BES studies.

2.1 Overheating Risk of European Buildings

2.1.1 Building-Energy Performance Gap

Government initiatives at various levels have been made globally, which seek effective solutions to the problems related to household energy consumption and CO_2 emissions, especially for vulnerable households in energy poverty and underlying with health conditions in all spheres of the economy (Government Office of Science, 2016a). Understanding the importance of the energy performance of existing housing stock constitutes a cultural and societal challenge (Government Office of Science, 2016b).

Zero-carbon targets must be achieved to reduce the detrimental impact of greenhouse emissions and mitigate climate change (Arriazu & Monge-Barrio, 2017). Neither developed nor developing societies will be able to meet the range of targets set by the European Union (EU) and other countries related to the design and procurement of built environments to reduce CO_2 emissions to 80% of 1990 levels by 2030, or the mandates set forth in the 2018 U.K. *Climate Change Act* to limit CO_2 emissions to 20% by 2050 (Charmpis *et al.*, 2018). In Northern Cyprus (NC) specifically, there are several post-war residential-housing stocks that must attain the EU's 2030 energy-consumption-reduction targets, all of which are worthy of an investigation.

Various studies have demonstrated the potential benefits of a greater reduction of energy consumption and the increasing value of the built asset (Domínguez-Amarillo *et al.*, 2019; Fernández-Agüera *et al.*, 2019; Österbring *et al.*, 2019). None have attempted to understand the overheating risks in NC residential buildings and the impacts thereof on occupant thermal comfort, and this issue remains unaddressed. Despite this paucity, it is not important to initially evaluate the energy performance of existing housing stock and assess occupant thermal satisfaction, since these variables can have a significant impact on energy use (Escandón *et al.*, 2017; Fernández-Agüera *et al.*, 2016; Terés-Zubiaga *et al.*, 2015).

By exploring different variations of building-energy performance assessments, the *European Union Statistics on Income and Living Conditions Report* and the 2018 *Household Budget Survey* both indicated that different assessment indicators related to energy use, such as whether or not occupants are in arrears on their utility bills or are unable to keep their homes adequately warm, which homes are uncomfortably hot in the summer, hidden energy performance, energy costs that consume a large proportion of one's income and the presence of a leak, damp or rot, should all be considered, as shown in Figure 2.1.

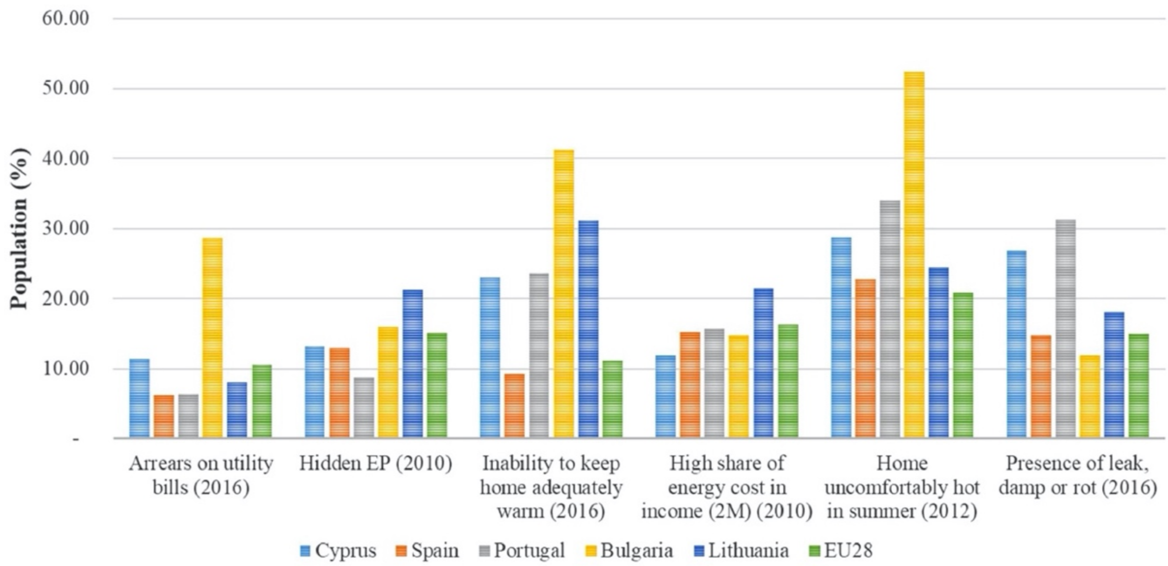


Figure 2.1: Energy-performance assessment indicators in EU member states. ***Source:*** Kyprianou *et al*. (2019).

Alonso *et al*. (2017) and Sánchez-Guevara (2018) argued that energy-performance-assessment indicators undertaken in EU countries are based on households' self-assessment evaluation of their dwellings. To explain the survey results, it can be seen that the case studies showed slightly low-performing indicators in comparison to the EU overall average. Spain was shown to have better home-energy performance than the EU, which enabled respondents to keep their homes thermally comfortable (San Miguel-Bellod, 2018). While many other countries, particularly those in south-eastern Europe that share the subtropical (i.e., *Csa*) and partly semi-arid (i.e., *Bsh*) climate characteristics of Cyprus, showed significant thermal discomfort; Spain showed a similar approximation to the European overall average with respect to maintaining thermally comfortable indoor environments in the summer. It can therefore be deduced from the above graph that 29% is higher than in the EU average of thermal discomfort (Kyprianou *et al*., 2019).

More significantly, Bulgaria had the worst overall thermal-performance for both of the assessment indicators related to the thermal-comfort aspect of residential buildings, including the criterion related to being in arrears on utility bills; Cyprus also showed a higher percentage of arrears on utility bills than in the EU. Nevertheless, it is evident that Portugal had a slightly better performance than many other countries due to stringent policies that were put into place in 2015 to thoroughly implement energy-performance directives; it should be considered, however, that many Portuguese households rely heavily on biomass burning for space heating and are therefore not properly accounted for in the energy-bills assessment. In terms of assessing the influence of the presence of leaks, damp or rot in residential buildings, Bulgaria has the lowest percentage of its population living in such conditions; this is followed by Spain, which also showed lower indicators than the remainder of the EU.

Lithuania was slightly above average, while households in Cyprus and Portugal have faced thermally uncomfortable indoor environments due to absence of thermal insulation on building envelopes and ageing residential-building stocks; these findings strongly correlate with the population consensus, because distinct deviations between these two Mediterranean countries have been observed. Notably, Lithuania was found to be the only country with an energy-performance indicator that was higher than the EU average; this can be further corroborated by the fact that Lithuania was shown to have one of the highest income coefficients, which indicates unequal income distribution across the total sample size in both surveys from which the results were taken as base-case reference indicators of home-energy performance (Guardigli *et al*., 2018).

Couched within this emerging energy debate, the EU Framework Programme for Research and Innovation for 2014–2030 includes an action plan that underscores the need to legislate the policy priorities put forth in the EU's 2030 strategy (Fosas *et al.*, 2018). This plan incorporates long-term aims to address major energy-demand concerns that are shared by citizens of Europe and elsewhere (Kalisa *et al*., 2018). This strategy plan consists of different policy implications related to energy use, including the significance of occupancy patterns and various socio-demographic characteristics that should be considered during the decision-making process for retrofitting efforts of existing housing stock (Page *et al*., 2008; Santangelo & Tondelli, 2017 Erell *et al*., 2018).

2.1.2 Review of Current Overheating Drivers and Definitions

To date, studies related to overheating risks in residential buildings can be broadly categorised as endeavours that involved the long-term monitoring of occupied indoor spaces to identify and quantify the risk of overheating (Beizaee *et al.*, 2013; McLeod & Swainson, 2017; Pathan *et al.*, 2017); endeavours that employed DTS modelling to assess current and future overheating risks in existing and newly built residential buildings in the U.K. (McLeod *et al*., 2013; Sanchez-Guevara *et al*., 2019); and endeavours that utilised empirical data to construct predictive models that are capable of assessing overheating risks by employing an STS approach because of a fundamental when interacting with the occupants (Santamouris & Kolokotsa, 2015; Santamouris, 2016). The findings of these studies highlighted the importance of developing a systemic approach when conducting a DTS analysis in conjunction with a primary data source that was obtained from longitudinal field studies to calibrate a building's energy performance. Some researchers have argued that modelling methods that make use of building-fabric *in-situ* measurements and monitor environmental conditions to explain data variations present advantages over other modelling methods employed in BPE studies (Reeves *et al*., 2010; Serghides *et al*., 2016); this is because many assumptions that were made via DTS elevate the level of uncertainty in energy-calibration results (Gomes *et al*., 2018). Figure 2.2 illustrates an overview of literature studies that considered the impact of climate change on home-energy use, the EPBD implications for the integrity of international assessment criteria on building-thermal performance and occupant thermal comfort and further methodology developed by undertaking a BES analysis for the delivery of effective retrofitting outcomes.

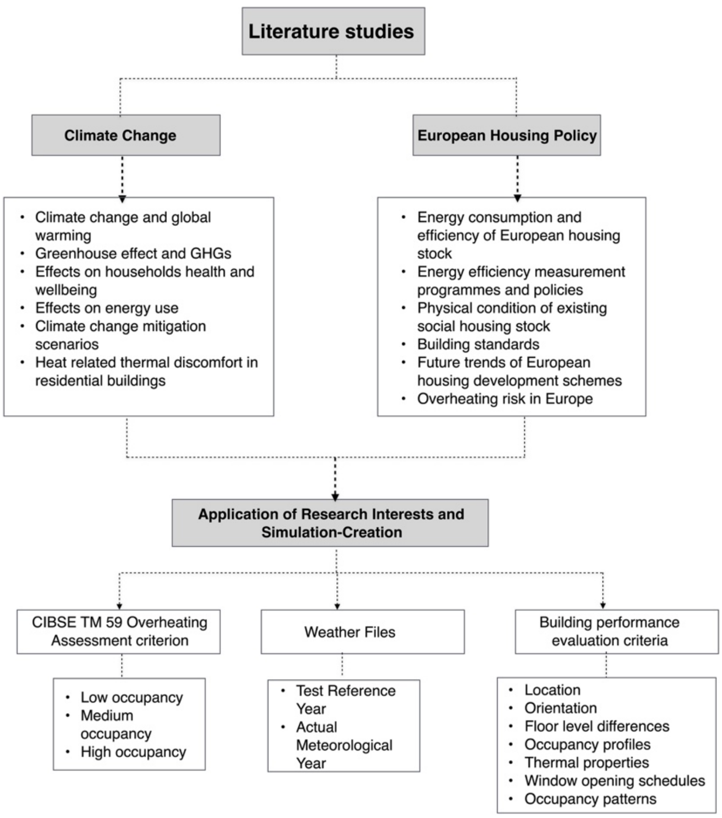


Figure 2.2: Overview of studies included in literature review.

The first pilot study of summertime overheating by Jenkins *et al.* (2011) reported that despite the relatively mild climate in the U.K., there was concern related to increases in the summer air temperatures in airtight low-energy residential buildings due to the effects of high temperatures on occupant thermal comfort. In fact, there is growing evidence of overheating risks in newly built housing stock (i.e., terraced houses, high-density residential estates) that struggle to achieve the requirements recommended by the EPBD together with energy-performance-certificate (EPC) schemes that were put in place to upgrade the energy efficiency of existing building stock in the U.K. and across Europe (Attia *et al.*, 2017; Jenkins *et al.*, 2012; Sharifi *et al.*, 2019). Due to the lack of a conceptual framework to assess the thermal performance of buildings and variations in the implementation mechanisms for each EU member state, these energy-efficient building materials and technologies led to increased indoor-air temperatures in the summer (Guerra-Santin *et al*., 2013; Psomas *et al.*, 2017).

McLeod and Swainson (2017) described overheating that occurred when temperatures made building occupants thermally uncomfortable or heat stressed due to local environmental conditions and low-quality thermal properties of buildings. In a study that set out to define 'overheating', Ren *et al*. (2014) found that with consecutive days of hot weather, including warmer-than-average nights, recorded indoor air temperatures in some homes, specifically newly built energy-efficient homes, started to exceed outdoor air temperatures and no longer provided protection from the heat.

Several studies have revealed a correlation between energy use and building thermal properties (Hens, 2010; Isaacs *et al*., 2010; Hamilton *et al*., 2014); several other studies have linked variations in indoor-air temperature fluctuations to occupant health and wellbeing, particularly during long-term heatwaves (Hatvani-Kovacs *et al*., 2018; Pathan *et al*. 2017). Studies have investigated hazardous effects of summer temperatures on occupant thermal-comfort, including indoor air temperature and relative humidity (RH) monitoring studies (Beizaee *et al*., 2013); building-physics modelling studies (Gupta & Gregg, 2013; Mavrogianni *et al*., 2012; Oikonomou *et al*., 2012; Porritt *et al*., 2012); and epidemiological studies of heat-wave mortalities (Liu *et al*., 2017). Previous research also determined that overheating is linked to household occupancy and behavioural patterns, which has been corroborated to evaluate the building performance of case-study locations, as presented in Tables 2.2(a) and (b).

Table 2.2(a): Pilot Studies That Evaluated Building-Performance.

References	A. Location and Climate	B. Climate-Change Scenarios	C. Methodology	D. Housing and Occupant Characteristics
Karimpour *et al.* (2015)	Adelaide, Australia (*BSk*): Mild temperate climate	Investigated current and future typical meteorological year (TMY) climate TMY for 2070 CC scenario	Energy modelling (AccuRATE); best design based on minimum heating- and cooling-energy consumption	- Entire Australian population was targeted - Multi-family houses (MFHs) - Brick-veneer house (typical house design in Australia)
Tong *et al.* (2010)	Brisbane, Australia (*Cfa*): Subtropical climate (hot and dry in the summer)	Reviewed data for heatwaves in 2004 and data related to air temperatures, air pollutants and health outcomes for period of 2001–2003	Energy modelling (AccuRATE); cooling and heating; base house and modifications with 2,5–7-star energy rating—utilised regression model to explore correlations between air temperatures and occupant health and wellbeing	- Detached brick-veneer residential house - Façades (U=0,75 W/m^{2}K) - Concrete roof tiles - Simple glazing - Holland blinds - Heating set points (SPs): 20°C in the living room and 18°C in the bedroom - Cooling set points vary from 23–26,5°C
Ren *et al.* (2014)	Brisbane, Australia (*Cfa*): hot and dry Melbourne, Australia (*Cfb*): warm summer	Reviewed data for heatwaves in 2004	Energy modelling (AccuRATE); heatwave scenarios for Brisbane (2004) and Melbourne (2009)	Conventional single-family houses (SFHs) without air conditioning (A/C) systems. Steady-state analysis of standardised occupancy profiles
Hatvani-Kovacs *et al.* (2016)	Adelaide, South Australia (BSk) – Subtropical cold and arid	Reviewed data for heatwaves in 2004	Online survey undertaken with representative sample (N = 393); Chi-square, Fisher's exact test and Fisher–Freeman–Halton exact test statistical analyses undertaken; Wilcoxon test performed	Vulnerable population living in energy poverty was targeted. - 90% dwellings with cooling systems (entire dwelling or a single room) - 25% rooms without shading - Most were without insulation and with light mass external walls
Brotas and Nicol (2016b)	- Athens, Greece (*Csa*) - Lisboa, Portugal (*Csa*) - Rome, Italy (*Csa*) - Munich, Germany (*Cfb*) - London, England (*Cfb*) - Moscow, Russia (*Dfb*)	Reviewed climate-change projections for 2020, 2050 and 2080 (CCWorldWeatherGen)	Energy modelling; overheating (CIBSE). - Criterion 1: Hours of exceedance (3%) - Criterion 2: Daily weighted exceedance - Criterion 3: Upper-limit temperature	Mid-storey south- and east-facing flats - U-value (wall) = 0,18 W/m^{2}K - U-value (glass) = 1,4 W/m^{2}K - Pattern-of-use = 24 h^{-1} - Ventilation rate: 0,3–1,0 h^{-1} - Night ventilation - Interior blinds - MFHs

Source: Adapted from Ana-Sanchez and Monge-Barrio (2018)

Table 2.2(b): Pilot Studies That Evaluated Building Performances. (Continued)

References	A. Location and Climate	B. Climate-Change Scenarios	C. Methodology	D. Housing and Occupant Characteristics
Barbosa *et al.* (2015)	Lisboa, Portugal (*Csa*)	M1: 2050–2080 CCWorldWeatherGen weather file generator was used M2: 2003 heatwave—TMY weather files were used for building-performance simulation	- Energy modelling (EnergyPlus with Design Builder); discomfort hours (STAT or ADAPT-15251) - Long-term monitoring for two dwellings; weather station installed to monitor outdoor environmental parameters	Residential building: - Four dwellings per floor; each with eastern or western orientation - Façade: Brick (high mass): $U = 1{,}7$ W/m^{2}K - Double-glazed: $U = 2{,}4$ W/m^{2}K - PVC frame - Concrete slab Vulnerable low-income population was targeted
Santamouris *et al.* (2010)	Athens, Greece (*Csa*): Suburban and rural areas in dense urban zones	2009 summer conditions—night-ventilation techniques were used to assess occupant thermal comfort	Monitored secondary-data collection of energy consumption and operational conditions of each building ($N = 210$ dwellings); and TRNSYS was used for building-performance simulations.	Mechanically air-conditioned. Single houses with high thermal mass: - U-value (walls) ≈ 0,5 W/m^{2}K - U-value (roof) ≈ 0,4 W/m^{2}K Surface ranges from 55–480m^2 high
Santamouris *et al.* (2015)	Athens, Greece (*Csa*): Dense urban zones	Very hot summer of 2007 (i.e., 30–33°C hot spells): Urban Heat Island (UHI) effect	Reviewed article on experimental studies conducted to investigate the impact of UHI effect.	No cooling systems Vulnerable low-income population with underlying health conditions was targeted
Pyrgou *et al.* (2017)	Perugia, Italy (*Cfb*)	Building-thermal energy-efficiency in 2013—Heatwaves (i.e., UHI effect)	Energy modelling and environmental monitoring using RStudio software	Four typical single-family detached houses (SFHs) Italian households were targeted
Fahmy (2014)	Alexandria, Cairo and Aswan, Egypt *(Bwh)*	Examined data for 2020, 2050 and 2080 (CCWorldWeatherGen)	Energy modelling (EnergyPlus with Design Builder)	Two collective buildings: GF and 5F Three typologies or envelopes (GRC)
Saman *et al.* (2013)	M1: - Adelaide and Richmond, Australia (*Bsk*) - Amberley, Melbourne and Hobart, Australia (*Cfb)* - Brisbane and Sydney, Australia *(Cfa)* - Perth, Australia *(Csa)* - Darwin, Australia (*Aw)*	- M1: Heatwave - M2: 2030, 2050 and 2070 data	Energy modelling (AccuRATE) - M1: Heatwaves, overheating (adapted ASHRAE 55:2013); energy model; five case studies - M2: Cooling demand for two dwellings	Different typologies: Mostly single-family and semi-detached houses Vulnerable low-income and ageing population was targeted

Source: Adapted from Ana-Sanchez and Monge-Barrio (2018)

Tables 2.2(a) and (b) present a list of previously undertaken pilot research studies for BPEs, which was retrieved from the collection of research articles in the Clarivate Analytics database. A large body of research has been undertaken on the overheating risks of different building variants that could potentially be used to support retrofitting and design decisions (i.e., housing typology, household socio-demographic characteristics, etc.). As can be seen, several scholars have conducted building-energy modelling and environmental monitoring to assess the overheating risk of these residential buildings, and an exploratory case-study approach was applied to these methodologies to properly understand the building performance of existing housing stock (Beizaee *et al*., 2013; Ballarini *et al*., 2014; Dascalaki *et al*., 2016).

These studies were reviewed to understand the current design methods that are available to assess building overheating risks and the relevance thereof to the development of a new adaptive conceptual framework through an exploratory case-study approach undertaken in a post-war social-housing development estate in NC for purposes of a comparative analysis. It is therefore important to search for a new conceptual framework that can better explain occupants' real-life energy-use patterns and experiences. For this reason, these studies were limited because they only explored the impact of climate change on building overheating risks, but did not consider human-based factors in their future energy-forecasting scenarios.

Gupta and Gregg (2018) provided an in-depth analysis of the work of Oliveira Panão (2014) and revealed the relevance of Panão's work when identifying the main parameters of overheating risks experienced in the summertime; these parameters can be correlated with heat gain from high external temperatures, direct solar gains on exterior surfaces or penetrating glazing and internal heat gains (IHGs).

Gupta and Gregg's (2018) study also highlighted the developed conceptual framework to increase awareness of issue resolutions related to overheating risks at the local and national levels by promoting a participant-led research design process. This indicates that constraints related to BPEs are not limited to buildings and that studies should consider community awareness when attempting to provide a universal design approach in the implementation of energy-efficient materials and retrofitting technologies.

2.1.3 Overheating Thresholds

Previous studies on overheating risks found that under current and future climates, NV could potentially reduce indoor-air temperatures, but only to a limited degree (Lomas & Kane, 2013; Moazami *et al.*, 2019). Because of this and according to climate-change projections, the future increase in external temperatures is expected to diminish the effectiveness of NV as a cooling strategy (Dino & Akgul, 2019; Mata *et al.*, 2019). Various criteria have been developed to assess when occupied rooms in base-case representative flats under investigation in long-term monitoring studies measure summertime overheating in the U.K. and across Europe (Mavrogianni *et al*., 2012; McLeod & Swainson, 2017; Escandón *et al.*, 2019); these include the static CIBSE criteria, which suggest that the operative air temperatures (OTs) in living rooms should not exceed 28°C for more than 1% of the occupied hours throughout the year, while the criterion for bedrooms is 1% of hours over 26°C (Chartered Institution of Building Services Engineers, 2006). More recently, a move to use adaptive overheating thresholds that show variations according to outdoor-air temperatures has gained increasing interest for risk assessments in free-running (i.e., naturally ventilated) buildings (CIBSE, 2013).

It is essential to specify information requirements and exchange procedures to devise effective implementation of the EPCs in the decision-making process for energy-use policies (Psomas *et al*., 2016). This is why, in terms of legislation, the Health and Safety Rating System (HSRS) Operating Guidance stated that there is a significant increase in the risk of strokes and mortality when temperatures exceed 25°C (Gupta & Gregg, 2013). In line with this statement, the HSRS provided the only statutory definition of overheating risks related to morbidity and mortality in U.K. residential properties to reduce the death toll as a consequence of frequently observed long-term heatwaves in summer across the continental Europe (McLeod & Swainson, 2017).

Attention has also been focused on the provision of effective NV and the positive impact that this will have on overheating risks in conjunction with other building-fabric elements, such as thermal insulation, thermal mass and shading, in addition to the potential for temperature stratification in the summer (Guerra-Santin *et al.*, 2017; Porrit *et al.*, 2011, 2012). Some researchers have emphasised that occupants in NV buildings have the benefit of being able to adjust their indoor-air temperatures according to their individual thermal-comfort expectations and that this control facility is also known to make occupants more tolerant of their environment (Baker & Standeven, 1996; Brager & de Dear, 1998).

Several investigations of overheating-risk-assessment criteria have investigated people's adaptive thermal comfort at home (Encinas & de Herde, 2013; Gunawardena & Steemers, 2019). Nicol and Humphreys (2002) argued that the temperature that constitutes overheating in naturally ventilated buildings is higher than in mechanically ventilated structures. To date, longitudinal and transverse survey methods have both been utilised to assess occupant thermal comfort with some degree of integration with the British BS: 15251:2007 standard and ASHRAE 55 standard (van Hoof & Hensen, 2007).

Factors thought to influence overheating-risk issues have been explored in several studies (Peacock *et al*., 2010; Rodrigues & Gillot, 2013; Pathan *et al*., 2017); these studies predominantly employed the CIBSE TM52 technical memorandum on building overheating-risk-assessment criteria. In these scholarly investigations and according to the *CIBSE Guide A* (2006), indoor comfort temperatures in the summer are 25°C for living rooms and 23°C for bedrooms, and overheating occurs if over the course of one year, 1% of the occupied hours exceeds 28°C in living rooms and 26°C in bedrooms; the *CIBSE Guide A* (2006) also noted that temperatures that are higher 24°C can impair sleeping, which suggests that it is important to differentiate when peak temperatures occur.

Significant research has been conducted to identify different assessment methodologies to evaluate occupant thermal comfort (Schweiker & Wagner, 2015; Singh *et al*., 2011). Many of these projects primarily adopted the STS design approach into efforts to develop BES models and monitoring campaigns to evaluate long-term general-thermal-comfort conditions in naturally ventilated buildings (Åkerman *et al*., 2020; Barone *et al*., 2019; López-González *et al*., 2016). These pilot-study projects considered different assessment criteria to evaluate the overheating risks in residential buildings and occupant thermal comfort.

One of the most commonly used methodologies is the CIBSE TM52, which was the first set of criteria based on dry-resultant temperature (CIBSE, 2015) As it relates to assessing overheating risks caused by the abovementioned factors, D'Oca *et al*. (2018) emphasised that the role of occupant behaviour is significant when indoor air temperatures are assessed by embedding the CIBSE TM52 overheating memorandum into the BES model. Moreover, in separate reviews of vulnerable households in social-housing developments, Pretlove and Kade (2016) and Santangelo and Tondelli (2017) pointed out that existing assessment criteria do not account for the influence of buildings on solar exposure risk and are not reliant on actual representative occupancy patterns in terms of disseminating energy use to vulnerable individuals. To date, no study has employed a dynamic measure to analyse representative housing stock in NC to consider overheating risks and occupant thermal comfort.

Mavrogianni (2012) modelled domestic space-heating demands and heatwave vulnerability within the London urban island heat island (UHI) effect. This case-study presented the outcomes of two developed housing-stock models: a heat-demand model that was based on steady-state energy-use calculation techniques and a multiple linear-regression overheating-risk meta-model of an existing dynamic thermal simulation programme. The conceptual framework was developed on input parameters that were collected after monitoring representative flats, which is a well-known, conventional tradition to demonstrate aggregate BES models; the study conducted by Mavrogianni (2012) did not take human-based data into account in the energy-forecasting analysis, because the questionnaire-survey approach was not adopted to obtain household socio-demographic characteristics via semi-structured interviews. Table 2.3 demonstrates the developed thermal-comfort assessment criteria and methodology to assess building overheating risks and occupant thermal comfort.

Table 2.3: Long-Term Evaluation Indices of General Thermal-Comfort Conditions.

	Based on Comfort Models				**Based on Reference Temperatures**		
Family of Indices	**Year**	**Index Name**	**Comfort Model**	**Standard/ Author(s)**	**Year**	**Index Name**	**Standard/ Author(s)**
Percentage	2005	Percentage outside PMV* range	Fanger	ISO 7730	2002	*CIBSE Guide J* Criterion	CIBSE
Cumulative	2005	Percentage outside range	Fanger	ISO 7730	2006	*CIBSE Guide A* Criterion	CIBSE
	2005	Percentage outside range	Adaptive EU	EN 15251			
	2005	PPD** weighted criterion	Fanger	ISO 7730			
	2005	Accumulated PPD	Fanger	ISO 7730			
	2005	Degree-hour criterion	Fanger	ISO 7730			
	2005	Degree-hour criterion	Adaptive EU	EN 15251			
	2010	Exceedance PPD	Fanger	Borgeson -Brager			
	2010	Exceedance Adaptive	Adaptive U.S.	Borgeson -Brager			
Risk	2008	Overheating risk	Adaptive EU	Nicol *et al.*	2007	Overheating Risk	Robinson-Haldi
Averaging	2005	Average PPD	Fanger	ISO 7730			

***PMV** = Predicted mean vote
****PPD** = Predicted percentage of dissatisfied
Source: Adapted from Nicol *et al.* (2008)

Regarding different assessment criteria recommended by different regulations and researchers in this field, the international ISO 7730 standard introduced five methods that were developed according to Fanger's comfort model; three of these five indices were repurposed in the EU's EN 15251 standards by extending their scope to also include the adaptive-comfort model (Nicol, 2004). This proposed methodology enabled researchers to assess thermal comfort while considering different lower- and upper-limit overheating thresholds to develop more accurate information for use in subsequent simulation analyses.

After reporting on analysed data that was measured in free-running buildings during the EU Smart Controls and Thermal Comfort (SCAT) project, Nicol *et al.* (2009) introduced the overheating-risk-assessment criteria. In their review, Nicol and Humphreys (2002) introduced a novel methodology to estimate the cooling consumption of buildings when seeking to achieve thermally comfortable indoor conditions during hot summer spells by adapting degree hours to assess overheating risk of each occupied space, which can be applied to different base-case temperatures as a reference point to assess long-term discomfort indices. Notably, these indices are weighted to consider overheating risks in the 'Exceedance index', which weighs discomfort hours by the hourly average occupancy in buildings (Liu *et al*., 2012). As it relates to the previously mentioned overheating risk criteria, this criterion is recommended in the CIBSE TM52 technical memorandum to assess overheating risks in European dwellings and increase understanding of the importance of assigning base-case representative occupancy profiles in building modelling simulations as an assessment methodology (Lomas & Porritt, 2017). Many scholarly articles mentioned a performance gap between the predicted and actual energy use when adopting the CIBSE TM52 criteria (CIBSE, 2013); for this reason, the design methodology to assess the overheating risk in homes that was put forth in CIBSE TM59 recommended the adoption of representative dominant occupancy patterns as an assessment criterion to calibrate the predicted and actual energy performances of buildings. Several studies concluded that the CIBSE TM59 criteria facilitated more accurate energy-use predictions because of real occupancy patterns that are assigned in the course of building modelling simulations (Pisello & Asdrubali, 2014; Pignatta *et al*., 2017; Petrou *et al*., 2018). To date, no study has analysed multiple factors related to the adoption of CIBSE TM59 assessment criteria while taking dominant representative occupancy profiles obtained from the longitudinal field surveys in the South-eastern Mediterranean climate into consideration (Abela *et al*., 2016; Serghides *et al*., 2017).

2.2 Thermal Comfort

2.2.1 Definition of Thermal Comfort

The notion of 'theral comfort' identifies that the reaction of human body to the changing indoor environment conditions by means of exploring physiological, psychological and environmental parameters (de Dear & Brager, 2001). 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 (Nicol & Humphreys, 2010). Many scholars have conducted 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 acceptable PMV range in accordance with these parameters namely, building type; climate; activity levels etc. Table 2.4 demonstrates the previous scholars' work on thermal comfort which is available at the ASHRAE Global Thermal Comfort Database II.

Table 2.4: Review of ASHRAE Global Database II.

References	Location	Benchmarking Criteria	Main Findings
Brager *et al.* (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
Heidari and Sharples (2002)	Western Iran	- ISO 7730-1994 - Griffiths Thermal comfort equation	Adaptive thermal comfort temperatures in the summer ranged from 26,7–28,4°C
Bouden and Ghrab (2005)	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
Han *et al.* (2009)	Central/ Southern China	Fanger's PMV model	Neutral OT: - Urban residence: 14,0°C - Rural residences: 11,5°C
Cao *et al.* (2011)	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
Djamila *et al.* (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
Földváry *et al.* (2017)	Central Europe, Slovakia	- ISO 16017-2 Standard - ISO 16000-4 Standard	18% of apartments in unrenovated buildings did not fall in optimum thermal comfort range (i.e., 20–24°C)

Humphreys and Nicol (1998) described thermal comfort as a situation in which the exchange of heat between a person and their environment has a neutral balance. Another conceptual definition of thermal comfort, which was provided by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), has been globally accepted and frequently used by scholars in this field. In conjunction with the universal thermal comfort criterion, Brager and de Dear (1998) asserted that people's expectations related to thermal comfort led to an undetermined sensation in the investigation of neutral thermal-comfort level.

Contrarily, Hoes *et al*. (2009) considered Brager and de Dear's definition of thermal comfort to be more descriptive of a 'psychological approach' to exploring correlations between occupant thermal-sensation votes (TSVs) and thermal-preference votes (TPVs). For this reason, an exploratory approach would be needed to identify the complexity of the physiological, psychological and environmental parameters during an analysis of longitudinal surveys (Kalmár, 2016; Mishra & Ramgopal, 2015).

Nicol *et al*. (2008) 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. Additionally, Yao *et al*. (2009) explored the influences of different parameters, such as people's expectations and preferences related to environmental conditions, on their thermal comfort; this is considered to be the 'adaptive model' approach to optimise occupant thermal comfort via field surveys and, in turn, allows an understanding of behavioural and subjective assessments of individuals in real settings that reflects more than the physical relationship between people and their environment. Tables 2.5(a) and (b) delineate the literature review that was undertaken on field investigations of occupant thermal comfort in various of climate zones, including available data on the ASHRAE Global Thermal Comfort Database II.

Table 2.5(a): Field-Investigation Studies on Adaptive Thermal Comfort.

References	A. Study Location	B. Primary Aim of Model	C. Methodology	D. Main Findings
Tuck *et al.* (2019)	Kuala Lumpur, Malaysia	To conduct a comparative analysis of OTs recorded with predicted temperature using adaptive thermal-comfort equation in hot and humid climates	Two-storey corner terraced house selected for exploratory case-study approach. Field measurements conducted; weather station installed in front yard of case-study house; thermal recorders and hot-wire anemometer installed in each occupied space; CO_2 measurements recorded.	According to ASHRAE Standard 55, recorded air temperature was 1,8°C higher than the same parameter defined by EN 15251 and 0,9°C higher than the same parameter defined by ACE hot-humid environment conditions.
Pastore and Andersen (2019)	Switzerland	To analyse the thermal performance of 'Minergie'-labelled buildings	Post-occupancy evaluation (POE) conducted on four Swiss green buildings with 'Minergie' label. POE protocol recruited for winter and summer; long-term environmental monitoring campaign recruited; *in-situ* measurements recorded; extensive online surveys undertaken to collect long-term occupant thermal-comfort options.	According to occupants, indoor conditions never attained commonly used 80% satisfaction threshold.
Nghana and Tariku (2016)	Burnaby and Vancouver, Canada	To demonstrate the energy effectiveness of implementing PCM onto apartment building envelopes to prove the thermal-comfort effect and energy consumption of mechanical system	Field experimental study conducted: - Two prototype buildings built on-site for experimental study: One had PCMs implemented on building envelopes, the other had no PCMs. - Energy Plus software used for numeric validation; ASHRAE 62.2 requirements used as international assessment criterion	PCM decreased peak indoor air temperature by as much as 0,6°C and increased trough temperature by 0,8°C.
Zhang *et al.* (2017)	Guangdong Province, Southern China	To demonstrate climate-design adaption of rural folk houses and the impact thereof on household thermal comfort in hot and humid climate	Yearlong thermal-comfort survey conducted: Eleven traditional folk-house residents selected for sample size. Questionnaire survey conducted concurrently with documentation of *in-situ* measurements; ASHRAE Standard-55 adopted to identify neutral thermal-comfort assessment; statistical analysis conducted with SPSS v22.0 software suite, and all differences at 0,05 level were accepted as significant.	Thermally neutral temperature was 0,6–1,3°C lower; upper limit of 80% acceptable temperature was decreased by 0,8–4,7°C in semi-open spaces.

Table 2.5(b): Field-Investigation Studies on Adaptive Thermal Comfort. (Continued)

References	A. Study Location	B. Primary Aim of Model	C. Methodology	D. Main Findings
Vellei *et al.* (2017)	ASHRAE Global Thermal Comfort Database II	To determine a clear explanation for lack of humidity signal or convincing formulation of the effect of humidity on adaptive thermal-comfort development	Global thermal-comfort datasets investigated, including meta-analysis of summary data from 63 field studies and field data from 39 naturally ventilated buildings in eight climate-types; experimental study established from ASHRAE RP-884 data	The new adaptive thermal-comfort model increased the comfort envelope of naturally ventilated buildings because its overheating prediction was 30% lower than that of the current model
Ličina *et al.* (2018)	ASHRAE Global Thermal Comfort Database II	To document origins, scope, development, contents and accessibility of ASHRAE Global Thermal Comfort Database II	Dataset created from field studies conducted from 1995–2016; 81,846 rows of paired subjective comfort votes and objective instrumental measurements data included in global database development framework; Query Builder used with Javascript to develop visual tool	Web-based interactive thermal-comfort visualisation tool that allows end-users to quickly and interactively explore the data was developed.
Jin *et al.* (2019)	Harbin, Northeast China	To explore gender-related thermal-comfort differences in severely cold regions	Physical measurements conducted; thermal-comfort questionnaire survey distributed to pedestrians; correlations among psychological parameters explored	In transitional seasons, female neutral temperature was 23,2°C, and male neutral temperature was 19,8°C.

A significant proportion of the current literature on thermal comfort specifically focuses on the physical environment and physiological conditions to predict comfort levels and quantitatively produce a number of thermal indices to thoroughly assess occupant thermal-comfort levels (Liu *et al*., 2012; Taleghani *et al*., 2013; Toe & Kubota, 2013). Nicol *et al*. (2012) explained that these models, known as 'heat-balanced models', are predominantly based on physics and physiology and are able to rationally analyse the heat flow between the human body and its surroundings.

Humphreys and Nicol (2000) insisted that occupants' thermal sensations strongly correlate with age, gender, economic and cultural aspects and location and climatic conditions. In an analysis of the influences of dependent and independent variables on occupant thermal preferences and sensations, Humphreys (2005) identified specific groups of people with more demanding needs—such as children, the elderly, people with disabilities and people who are sick—who are more likely to be vulnerable. This led to a significant contribution toward the assessment of thermal comfort in different climate regions under investigation by many other scholarly articles in this field (Nicol & Humphreys, 2010).

2.2.2 Adaptive Thermal Comfort Theory

Significant research has been conducted to ensure comfortable indoor conditions and to accurately predict the comfort level of a room that is in line with the references provided by the European BS EN 15251 standards (CIBSE, 2016); and a considerable amount of literature evaluated assessment methods of the summer performances of un-air-conditioned residential buildings has been published (Ferrari & Zanotto, 2009; Haldi & Robinson, 2010; Nicol & Roaf, 2012; Nicol, 2017).

What is known about optimising occupant thermal comfort is largely based upon empirical studies that investigated the overheating risk in indoor spaces in light of climate change, which anticipates an increase in temperatures and a greater frequency of extreme weather events, such as heatwaves (Kottek *et al*., 2006; Kovats *et al*., 2014; Nikolopoulou & Lykoudis, 2006). Furthermore, several studies documented the lack of benchmarking assessment criteria among the input parameters and occupant behaviour intended to measure occupant thermal comfort and assess building overheating risks (Brager & de Dear, 1998; Halawa & Van Hoof, 2012; Guerra-Santin *et al*., 2013).

Research revealed an increased interest in assessing the calculations of the PMV and PPD indices, in addition to information that is needed to estimate certain localised effects, such as shading and NV (Humphreys & Nicol, 2003). The CIBSE TM52 Overheating Task Force identified a new approach to define overheating that considers occupants' thermal comfort and wellbeing as essential, especially in residential buildings without mechanical cooling systems (Mann *et al.*, 2012; Olesen, 2012); this follows the methodology and recommendations put forth in the BS EN 15251 guidelines to determine whether an existing occupied residential building can be susceptible to becoming overheated, especially in the summer.

It should be stressed that studies within the south-eastern Mediterranean climate revealed both of these effects on high overheating risk of buildings and high proportion of the PPD index. In addition to increasing population and rapid urbanisation, changing climate conditions present a need for cities to adapt to new conditions and develop resilience to provide thermally comfortable buildings (Aydin & Jakubiec, 2018; Gupta & Gregg, 2012; Synenefa *et al.*, 2018).

Many field studies have been conducted in various climates around the world, which demonstrated that comfortable temperatures are closely linked to local climate conditions (Brager & de Dear, 1998; McCartney & Nicol, 2002; Nicol, 2017; Tuck *et al*., 2019). By following a similar approach, the adaptive thermal-comfort theory explains this phenomenon as it relates to occupants who actively engage with their indoor environments (de Dear & Brager, 1998; Nicol *et al*., 2012). If an environment causes occupant discomfort, then those residents are likely to take responsive actions to restore their comfort (Nicol *et al*., 2006); these responsive actions are said to be rooted in one of three types of adaptation: behavioural, physiological or psychological (Nicol, 2008). Table 2.6 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 in Chapter 4.

Table 2.6: Pilot Studies That Adopted EN 15251 Adaptive Thermal Comfort Criteria.

References	A. Study Location	B. Climate Zones	C. Building Type and Ventilation Strategy	D. Methodology	E. Main Findings
de Dear and Brager (2001)	Worldwide	ASHRAE Global Database I	Free-running and NV buildings	ASHRAE RP-884 dataset used; field-validation experiments in various climate zones considered; specified laboratory-grade instrumentation used; statistical derivation of adaptive models conducted for 160 buildings in database; statistical analysis 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.
Yao *et al*. (2009)	Chongqing, China	Köppen Climate: *Cfa* (hot in the summer, cold in the winter)	Free-running buildings	Black Box energy model adopted to develop adaptive model of thermal comfort; questionnaire survey and environmental monitoring campaign used; statistical analysis used to determine coefficient for study area	Adaptive coefficient for warm and cool conditions using data obtained from subject respondents were 0,293 and –0,125, respectively.
Liu *et al*. (2011)	U.K. and China	Köppen Climate: - *Cfb* (temperate oceanic) - *Cfa* (hot in the summer, cold in the winter)	NV buildings	Group analytic hierarchy process adopted; longitudinal field surveys conducted with 41 U.K. and 33 Chinese subjects; pair-wise comparison strategy adopted; sensitivity analysis 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.
Mishra and Ramgopal (2014)	Chennai, Kolkata and Hyderabad, India	Köppen Climate: tropical (hot and humid)	NV buildings; air conditioning	Five adaptive-comfort equations computed; field-study approach adopted; multiple surveys conducted; ASHRAE TMY2 weather file used	2°C was able to be added to the upper limit of comfort zone in NV buildings When fans were used during the warm months.
Parkinson *et al*. (2019)	Worldwide	ASHRAE Global Database II	NV and mix-mode buildings; air conditioning	ASHRAE RP-884 database used; RStudio IDE used for statistical analysis; 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.

Several studies have investigated the effects of occupant interactions on energy use (Hitchcock, 1993; Bonte *et al*., 2014; Buso *et al*., 2015); and several comfort models have been proposed to address this aspect of assessing optimal indoor conditions as they relate to occupant thermal preferences (Balslev *et al*., 2015; Evola *et al*., 2013). Many scholars adopted Fanger's 'static' model, which considers occupant behaviours as containers that passively undertake building management (Gagge *et al*., 1986; Jeong *et al*., 2016). This is because the adaptive-comfort model offers occupants the ability to adjust their thermal comfort in the outdoor environment according to their preferences and sensations.

According to Fanger *et al*. (1970), suitable indoor temperatures are commonly defined according to the thermal-comfort theory; this approach bases its definition of thermal comfort on physics and ignores the social and psychological aspects of thermal perception, and its formulation is entirely steady-state and determines a narrow range of allowable temperatures throughout the year without regard for outdoor conditions. According to a study by Nicol *et al*. (2002), an alternative approach to defining comfortable temperatures is the adaptive approach, which stems from the results of a wide range of field studies (McCartney & Nicol, 2002; Nicol, 2017; Nicol & Humphreys, 2002); the study by Nicol *et al*. (2002) found that occupant thermal expectations are related to the outside climatic conditions on a variable basis.

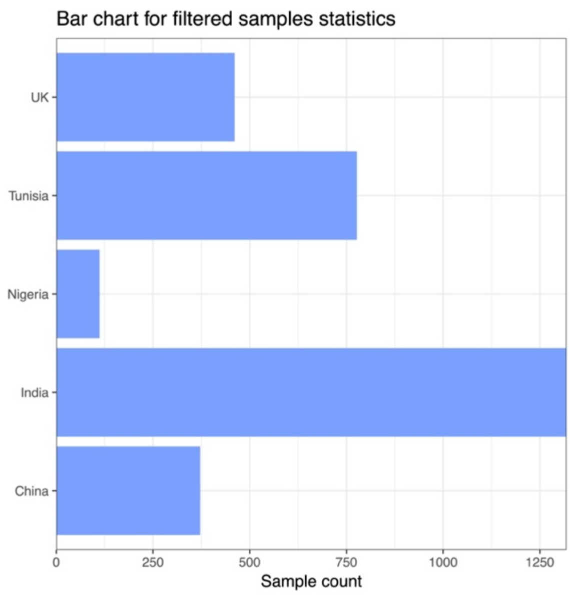
Despite the fact that adaptation is a fundamental component of the adaptive thermal-comfort theory, little research has addressed the nature of adaptation or the influence of thermal history on current thermal preferences (Pastore & Andersen, 2019). A majority of the studies that have addressed thermal history were conducted by Humphreys and Nicol (2002). The theory behind adaptive thermal comfort underscores the idea that defining the ideal thermal environment as neutral is based on a deterministic approach, which does not take the psychological and cultural aspects of comfort into account and should therefore be questioned.

Many studies have considered a semantic analysis of experimental questionnaires and detected the influence of underlying culture on the deep meaning of the words used in those surveys (Griffiths, 1990; McCartney & Nicol, 2002; Nicol *et al*., 2012; May *et al*., 2017).

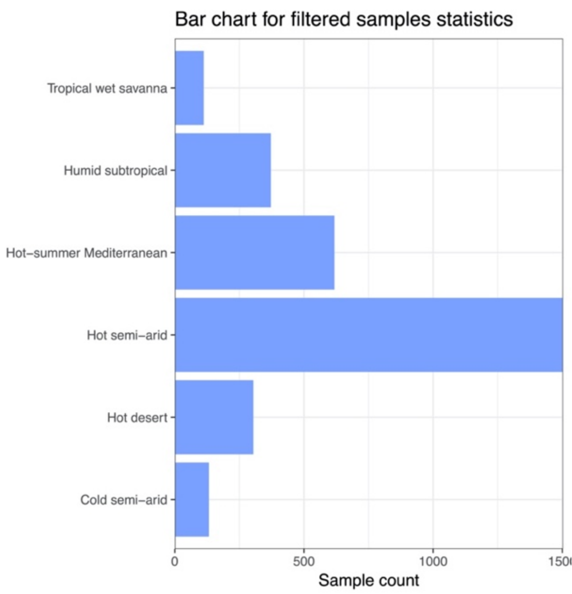
According to Michael *et al*. (2018), this problem is especially valid when referring to outdoor or hybrid environments, such as environments that can be considered 'warm' in the summer without the actual presence of discomfort. This is why multi-level questionnaires were developed to differentiate between 'sensation', 'acceptability' and 'preferences' to thoroughly verify the coherence of the various answers (Ghahramani *et al*., 2015; Mishra & Ramgopal, 2013). Investigations by Naylor *et al*. (2018) and Murtagh *et al*. (2019) included discussions of previous studies and new experimental data and found that there is a tendency for occupants to adapt to the conditions they normally encounter to measure their discomfort.

It is important to note that little is known about night-time thermal comfort (CIBSE, 2013). Studies have shown that sleep deprivation due to night-time overheating serves as a major motivation to buy domestic-cooling systems (Artmann *et al*., 2008; Della Valle *et al*., 2018); this trend is particularly problematic in the urban context, where there is less air movement and the urban heat island (UHI) effects are most noticeable after dark (Santamouris *et al*., 2007; Oikonomou *et al*., 2012; Santamouris & Kolokotsa, 2015).

Numerous field studies have found that occupants' thermal comfort varies with local climate (Nikolopoulou & Lykoudis, 2006; Yao et al., 2009; Carlucci *et al*., 2018). 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. Figures 2.3(a) and (b) demonstrate previous scholars work on investigating neutral adaptive thermal comfort in MFHs, which is available on the ASHRAE Global Thermal Comfort Database II (Földváry *et al*., 2018).



(a)



(b)

Figure 2.3: (a) Sample adaptive thermal comfort studies by country; **(b)** TSV configuration of field studies by climate type. ***Source:*** Data extracted from thermal comfort visualisation tool; available at https://cbe-berkeley.shinyapps.io/comfortdatabase (Földváry *et al.*, 2018).

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*) (Rubel et *al.,* 2017).

Consequently, in urban areas of Famagusta, the stringent policy regulations for adopting globalised housing-design standards and the lack of ability to integrate a thermal-comfort assessment when evaluating BPEs for RTBs means that apartment projects were planned and designed without considering the climatic aspects of the built environment. Overall, evidence indicates an urgent need to more closely examine critical reflections on the integration of the adaptive thermal-comfort theory into the BES to concurrently assess building overheating risks and occupant thermal comfort.

2.2.3 Long-Term Evaluation of General Thermal-Discomfort Indices

Most research on thermal discomfort has emphasised the use of several metrics and methods to assess occupants' thermal perceptions of their environment and their thermal responses to different climate conditions (Castellano *et al*., 2016; Földváry Ličina *et al*., 2018). Similarly, a new type of discomfort index was developed that aimed to describe the importance of considering long-term thermal indices in residential buildings in the scientific literature and related standards and guidelines (Borgeson & Brager, 2011). While most of these new indices summarise the thermal performance of a building in a single value, existing indices need to be analysed as part of a long-term evaluation of the thermal conditions in residential buildings and as part of a thermal-risk assessment that considers the environmental conditions of the study areas under investigation.

Surveys, such as those conducted by Kovats *et al*. (2014), showed that the indoor temperatures of most dwellings range from 17,2–30,5°C and those occupants indicated that they do not feel thermally comfortable outside of this range, with individual tolerance in elderly occupants being on the lower side despite their capacity to adapt their physiological human body to high outdoor temperatures. A strong correlation between the energy consumed for space conditioning and the type of building and services offered to various population groups has also been emphasised (Kwok *et al*., 2017); this is due to the fact that according to an appropriate standard of annual indoor environment quality, building regulations and assessment criteria for a BPE are inherent in the European Directives on buildings energy-efficiency guidelines that were issued by the EPBD (EPBD, 2010) and regulated by the EN 15251 standards (EN 15251, 2007).

Notably, Nicol and Humphreys (2002) drew on an extensive range of assessment criteria to investigate occupants' thermal comfort. To be viewed as credible, an evaluation method should be based on sound scientific evidence and a clear understanding of the psychological and physiological aspects of the decisions that occupants are making (Wang *et al*., 2018). For this reason, different categories of indoor thermal environments that are dependent upon occupant expectations were recommended; these assessment criteria reveal that the highest degree of thermal expectation is applied to buildings inhabited by infants, people with disabilities and ill or elderly occupants—that is, in places where people are the most vulnerable. Table 2.7 describes these categories in line with the recommendation of the EN 15251 assessment criteria.

Table 2.7: Applicability of Indoor-Environment Categories.

ASHRAE 55 Category	Scope	PPD	Fanger PMV	Adaptive Δop (°K)
90%	Utilised when a higher standard of thermal comfort is desired	< 10%	−0,5 < PMV < +0,5	±2,5
80%	Utilised for typical applications and when other information is unavailable	< 20%	−0,85 < PMV < =0,85	±3,5

Source: EN 15251 (2008)

With this in mind, adopting similar international assessment benchmarking criteria to assess occupant thermal comfort in residential buildings seems like a common-sense decision. This is why the design and evaluation of indoor thermal environments in mechanically cooled and heated buildings were assessed using the following criteria based on the PMV and PPD indices, which were detailed in the EN ISO 7730 standards (EN ISO 7730, 2006). Table 2.8 illustrates the summary of cooling and heating temperature ranges according to criteria recommended for mechanically conditioned residential buildings in the EN 15251standards.

Table 2.8: PPD and PMV Indices for Naturally Ventilated Buildings.

Criteria	**Description**	**PPD**	**PMV**	**Temp. Range to Heat Clothing (0,5 *clo**)**
I	High level of thermal-preference expectation required for vulnerable people with disabilities and underlying health conditions	< 6	−0,2 < PMV < +0,2	23,5–25,5°C
II	Neutral thermal-preference expectation recommended for new and existing buildings	< 10	−0,5 < PMV < +0,5	23,0–26,0°C
III	Moderate thermal-preference expectation recommended for existing buildings	< 15	−0,7 < PMV < +0,7	22,0–27,0°C

**clo*: Clothing and thermal insulation value
Source: EN 15251 (2008)

As noted in Table 2.8, the low heating set points in the winter range from 18–21°C, and high cooling set points (SPs) 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 the degree of association related to vulnerable residents or moderately associated with existing buildings (Haldi & Robinson, 2010); 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 (Wang *et al*., 2019).

The recommended EN 15251 benchmark criteria serve as an evaluation standard for the thermal environment in naturally ventilated residential buildings, which indicates an expectative adaptation level that is strongly correlated to the outdoor environment. At the same time, the ASHRAE 55 standard (2017), which involves similar conceptual approaches to assess occupant thermal comfort in underlying international norms, can also be incorporated within the adaptive approach. Nicol and Humphreys (2010) pointed out that some parameters lack information, which creates a gap in databases that were developed through different projects, classifications for applicable buildings, derivations of acceptable neutral temperature by respondents and outdoor-air temperatures recorded at the time of longitudinal surveys to assess occupant thermal comfort.

Notably, the proposed thermal-comfort assessment model recommended by the EN 15251 standards is largely based on the EU SCAT pilot-study project, which created a reference database to properly understand occupant thermal preferences and sensations in different climate regions across Europe (Schweiker *et al.*, 2020). It is also important to mention that the ASHRAE 55 criteria (2017) are only applicable to naturally ventilated buildings; while the EN 15251 can be applied to any free-oscillation building-type, with or without space-conditioning installations (O'Brien *et al.*, 2020).

On a different note, these standards are applicable for metabolic rates that range from 1,0–1,3 MET, because they allow occupants some flexibility to adapt to their clothing. ASHRAE 55 (2017) and EN 15251 benchmark criteria include recommendations for acceptable lower and upper threshold limits for outdoor- and indoor-air temperatures (Hellwig *et al.*, 2019). According to ASHRAE 55 criteria (2017), prevailing mean outdoor-air temperatures can vary from 10–35°C, while the EN 15251 asserts that running mean outdoor-air temperatures can vary between 10–30°C; both indicated that 25°C is the upper limit of acceptable occupant thermal-comfort levels in naturally ventilated buildings and in structures that use mechanical ventilation.

Previous research on thermal-comfort assessments utilised inconsistent and contradictory parameters, which affected the accuracy of the statistical analysis that was conducted on field-survey data (Halawa & Van Hoof, 2012; Haldi & Robinson, 2010). This is partially due to the preliminary experimental tests that took place in climatic chambers to closely control the physical variables involved in the equation (Ascione *et al*., 2015). Many studies also criticised this evaluation criteria, because tests in climatic chambers cannot produce the conditions of a real environment (Liu *et al*., 2012; Ascione *et al*., 2016). Additionally, Barbosa *et al*. (2015) and Brotas and Nicol (2015) argued that considering occupant interactions and their TPVs and TSVs could bring about more realistic assumptions to validate field-survey findings. The generalisability of the research on this subject is problematic (Indraganti & Rao, 2010; Teitelbaum *et al.*, 2020). Many studies have confirmed the validity of Fanger's long-term discomfort index; in fact, Nicol and Humphreys (2010) suggested that longitudinal field surveys should consider employing the heat-balance model to define comfort.

In summary, none of the reviewed indices have been fully supported by relevant studies, which intended to provide a long-term evaluation of the general thermal-comfort conditions in buildings. This suggests that all boundary conditions that affect respondents' decisions on TPVs and TSVs should be made explicit to produce reliable results that can then be clearly interpreted.

2.3 Building-Energy Simulations

2.3.1 Precedent of Longitudinal Field Studies to Analyse Energy Policy Design

Many field studies have been conducted in various climates across the world, which demonstrated that household energy consumption and occupant thermal comfort are closely linked to the local climate (Stazi *et al*., 2014; Frederiks *et al*., 2015; Schweiker *et al*., 2018). A previous study by Andersen *et al*. (2009), for example, conducted longitudinal surveys with vulnerable Danish households highlighted that the heat coefficient factor of building envelopes are the main causes for high level of thermal discomfort. Therefore, this survey was being conducted to one case study building only.

It is deemed to indicate that the findings which were intended to demonstrate the nationally representativeness of Danish housing stock cannot be generalised for the whole region due to the respondent limitation which can generate result bias. According to a study by Schrubsole *et al*. (2014), an alternative approach to defining representative occupancy profiles is not limited to the integration of standardised assessment criteria for a BES study, which stem from the results of a wide range of steady-state analyses of energy-calibration studies. The present study underscores the importance of identifying the representative housing stock and the manner in which it is integrated into the energy-calibration analysis; Table 2.9 delineates the integration of a BES into the development of an STS approach for policymakers.

Table 2.9: Previously Developed BES Frameworks.

References	A. Study Location	B. Primary Aim of Model	C. Methodology	D. Selected Software
Pasichnyi *et al*. (2019)	Stockholm, Sweden	To develop a novel approach to use rich datasets to improve the energy efficiency of different building archetypes based on specific urban energy challenges	Urban BEM workflow developed to estimate energy savings for 5.532 buildings; aggregated energy models developed for building retrofitting and electric heating	- RStudio IDE - gridExtra Metrics - Tidyverse - UpSetR and VennDiagram - Energy Plus - Design Builder
Yang *et al*. (2018)	Florida, U.S.	To develop an experimental validation of an early-design 3D dynamic thermal model	Exploratory case-study approach at Off-Grid Zero Emissions Building at Florida State University; mathematical equations utilised; BES conducted	- Early-design stage 3D dynamic thermal simulation tool - vemBUILDING - Mathematical modelling tool - Fortan
Rouleau *et al*. (2019)	Quebec City, Canada (located in ASHRAE Climate Zone 7, a cold climate)	To develop an assessment method to determine energy-consumption robustness and dwelling thermal comfort related to occupant behaviour	High-performance multi-residential building selected for exploratory case-study approach	- TRYNSS used to construct thermo-physical models - A total of 1.000 annual occupant profiles were stochastically generated
D'Agostino and Parker (2018)	Fourteen locations in the European Union	To develop a simulation-based optimisation framework of cost-effective choices and EEMs for new buildings	Detached SFHs in 14 European locations selected as archetypes; BES conducted	- EnergyPlus and TRNSYS used to run DTS - BEopt energy-simulation software used for economic evaluation of optimisation
Ascione *et al*. (2019)	Italy	To develop a multi-objective (MO) optimisation approach to address building-envelope energy designs in different climate zones: Palermo (Zone B), Naples (Zone C), Florence (Zone D) and Milan (Zone E)	Genetic algorithm (GA) approach adopted; newly built five-storey residential building chosen for BES	- MATLAB used to build optimisation studies - EnergyPlus used for DTS

Another pilot study conducted by Indraganti and Rao (2010) was the largest housing survey to date due to the quota sampling method that was implemented to conduct the questionnaire survey in a hot and dry climate. The present study identified five underlying determinant factors related to occupant behaviour and energy use: the type of domestic-cooling appliances that are used, the hours when cooling appliances are turned on, window-opening schedules, household size and occupants' socio-demographic characteristics. The appliance factor is related to more use of space conditioning (Wallace *et al*., 2010); The frequency of cooling appliances uses and window-opening schedules are related to behaviour that leads to even more energy use; household size is related to calculating the internal heat gains of each occupied space; and the socio-demographic factor is related to personal preferences for a warmer indoor environment and understanding the reasons for thermal discomfort, as shown in Figure 2.4.

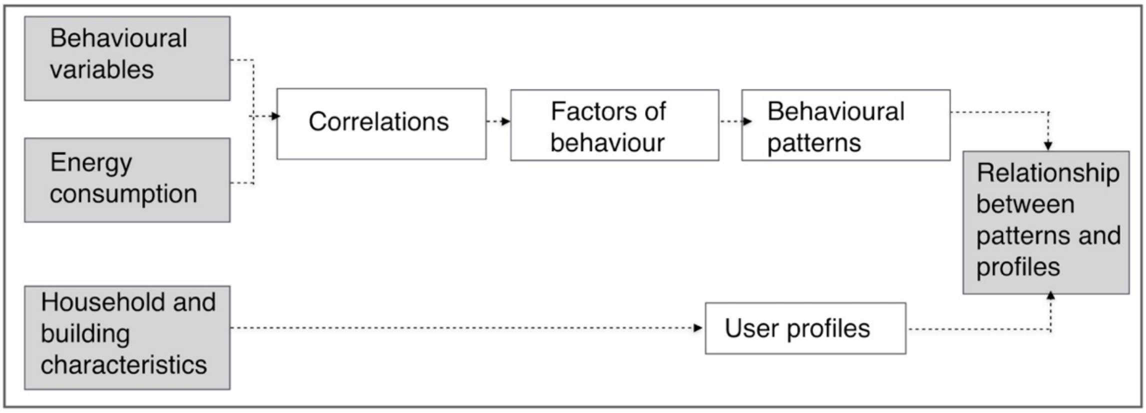


Figure 2.4: STS approach adopted for this study.

Based on building-energy performance and to validate the findings of their questionnaire survey, Tink *et al*. (2018) suggested that monitoring comfort levels on a room-by-room basis would be an effective methodology to investigate biases in the responses of the sampling population. Table 2.10 lists literature that considered the relevance of habitual adaptive energy-use occupant behaviours, while also considering environmental conditions that were observed during longitudinal and transverse surveys of home-energy performance.

Table 2.10: Conceptualisation of Building-Energy Simulation to Develop STS Approach.

Oladokun (2015) and Motawa and Oladokun (2015)	**Moustakas *et al.* (2011)**	**Tenget *et al.* (1990)**	**Zhang *et al.* (2014)**	**Wei *et al.* (2018)**	**Walsh *et al.* (2013)**	**Martinez-Moyano and Richardson (2001)**	**This Study**
Conceptualisation	Problem definition	Diagram construction and analysis	Problem identification and definition	Problem articulation	Problem identification and definition	Problem identification and definition	Problem identification and definition
	System conceptualisation	Simulation procurement	System conceptualisation	Dynamic hypothesis	System conceptualisation	System conceptualisation	System conceptualisation
Formulation	Model representation	—	Model formulation	Formulation	Model formulation	Model formulation	Model formulation
	Energy-performance model	—	Energy-use analysis	—	—	—	Energy-performance analysis
Testing	Model evaluation	Simulation procurement	Model evaluation	Testing	Simulation and validation	Model testing and validation	—
	—	—	Policy analysis	—	Policy analysis and improvement	Model use, implementation and dissemination	Energy-efficient retrofitting interventions
Implementation	Policy analysis and model use	Policy analysis and evaluation	Model use and implementation	Policy formulation and evaluation	Policy implementation	Design of learning strategy, energy efficiency	Policy formulation and analysis

Another thought-provoking study by Moore *et al*. (2019) emphasised challenges in building-energy-calibration studies that are derived from the failure of regulatory provisions to capture occupants' real-life energy-use experiences. This research investigated five high-performance state-of-the-art prototype houses in Australia for the purpose of assessing the thermal performance thereof to meet relevant regulatory housing standards and was similar to a research project by Rouleau *et al*. (2018) that assessed the thermal performance of residential buildings in Canada. Moore *et al.* (2019) concluded that targeted regulatory concepts have failed to meet expectations due to occupants' behavioural activity, which were not considered during the BPE; another reason for this failure was that generic occupancy profiles that did not consider the climate and other localised effects on energy consumption were assigned in the simulation model.

It should be noted, however, that the standards and regulations in question were unable to predict the comfort levels of occupants and low zero-energy-consumption targets (Symonds *et al*., 2017; Sempirini *et al*., 2017; Agliardi *et al*., 2018). The aforementioned study findings further emphasised the fact it is essential that a thorough understanding of current lifestyles of different socio-demographic groups to develop an effective assessment methodology. The methodological framework developed for the present study and the findings thereof will provide a pathway to better understand current problems with existing post-war social-housing stock and residents' thermal satisfaction with their indoor environmental conditions.

2.3.2 Current Validation Techniques

Several researchers have investigated the development of energy-calibration methods in BES that were employed to determine occupant thermal comfort by optimising indoor-air temperatures on a broad scale and reducing energy consumption with the aim of diminishing the overheating risks in residential buildings (Lomas & Kane, 2012; Tweed *et al*., 2014; Tardioli *et al.*, 2015). Furthermore, a significant number of steady-state analyses of BES studies have been conducted to assess the thermal performance of existing housing stock (Toftum *et al*., 2009; Evans *et al.*, 2018). Only a few studies, however, have sought to provide a better understanding of the importance of considering human-based factors in the DTS model and to properly calibrate the BES by using primary data sources gathered from longitudinal field studies (Williamson *et al*., 2010; Colclough *et al.*, 2018).

Asadi *et al.* (2014) concluded that the selection criteria of building-simulation input parameters increased the environmental socio-economic value of accurately forecasted energy scenarios. Additional evidence put forth by Emmerich *et al.* (2008) supported this assertion and demonstrated that incorporating a real-time series of climate files, actual occupancy patterns and household window-opening schedules into the black-box simulation model for the DTS analysis could provide an overview on home-energy performance. With this in mind, it is evident that the potential benefits of a greater reduction in energy consumption and the value of the built asset will increase (Fokaides *et al*., 2014; Giorgio *et al*., 2018).

Recognition of the limitations and inherent contradictions of the development of a black-box model for the DTS analysis led a few studies to fully understand overheating and the impact thereof on occupants' thermal comfort, particularly in south-eastern Mediterranean EU member states, even though this issue remains unaddressed (Ascione *et al*., 2019; Tejero *et al*., 2018). Despite the decisive role of these factors in demonstrating variations of simulation input parameters and detecting uncertainty in the datasets for energy-calibration analysis, the results reveal that a high accuracy for the nearly zero energy building prototype. It was found that the analytical energy model offers a prediction accuracy of 2,2% and 7,03% for the energy use and indoor zone temperature, respectively. (Hart & de Dear, 20014).

A pilot case study by Kavgic *et al*. (2010) tested the efficiency of various retrofitting technologies and concluded that it was difficult to quantify weather profiles that are concurrently assigned in the black box model with occupancy patterns gathered through a questionnaire survey. A notable analysis and discussion on this subject by Kylili *et al*. (2016) mentioned that social-housing RTBs often underperform when compared to design specifications because of discrepancies in building-fabric thermal performance, system efficiency and occupant behaviour.

Even though Agliardi *et al*. (2018) proposed a building-optimisation study, only a steady-state analysis that embedded future climate scenarios into the black-box model was conducted to assess the validity of the assumptions for the subsequent research phase, as shown in Table 2.11. The results show that an acceptable reduction in cooling-energy consumption in the representative housing typology was achieved during the summer, but additional studies are needed for a more-comprehensive understanding of the implications of considering human-based factors in BES models in retrofitting efforts for residential buildings.

Table 2.11: Validation Techniques to Assess Overheating Risks and Analyse Model Calibrations.

Technique	Description	Application
Comparison to other models	Various validated simulation-model results compared to results of other valid models	Applied to validate simulation model
Worst-case scenario development	Analytical energy-model structures and outputs for extreme and unlikely factor-level combinations in system viewed as plausible	Applied as comparative study of worst-case scenario, such as implementation of CIBSE TM59 overheating-assessment criteria and EN 15251 thermal-adaptive theory, to assess overheating risks and occupants' thermal comfort
Face validation	Individuals knowledgeable about system (i.e., practitioners and energy consultants) asked if model and/or behaviour thereof are reasonable	Applied to validate model input data
Historic data validation	If historic data exist, or if data are collected to build and/or test system model, some are used to build the model, and remainder are used to determine (i.e., to test) whether model behaved in the same manner as the system.	Applied to validate simulation model
Historic methods (i.e., rationalism, empiricism and positive economics)	Empirical method used to develop study's validation technique, because method requires empirical validation of every assumption and outcome.	Applied to validate simulation model
Multi-stage validation	- Model assumption developed according to theories, observations and general knowledge - Model assumptions validated by empirically testing whenever possible - Model input–output relationship compared (i.e., tested) against real system	Applied to validate simulation model

Schneider *et al*. (2016) conducted an exemplar study that addressed summertime overheating, wherein the authors described overheating risks and delineated methods to assess the likelihood of overheating in a base-case representative-building typology during long-term heatwave peaks in the summer. In addition to this study, Symonds *et al*. (2017) proposed an index to predict summer overheating risks caused by heat-stress-index factors that were found to influence occupants' thermal comfort.

Roaf *et al*. (2009) used the 'Percentage Outside Range' index, which facilitated an assessment of cooling-degree days in several building-envelope retrofitting strategies that were implemented in social-housing apartment units throughout Europe. Another pilot study was undertaken by Corrado and Ballarini (2016), in which the significance of adopting the 'Exceedance: PPD' and 'Exceedance: Adaptive' indices were explored, and the aforementioned indices were utilised by employing black-box models for the DTS analysis (Fokaides *et al*., 2011; Pignatta *et al*., 2017; Santangelo *et al*., 2018). One of the main goals of these studies were to investigate the prevalence of summer thermal discomfort in naturally ventilated dwellings located in 16 different climate zones to fully comprehend the impact of climate-related factors on the thermal preferences and sensations of the study participants.

There is a growing recognition that the overheating phenomenon in a variety of field-assessment procedures could be deployed in different experimental studies to corroborate the thermal properties of buildings, occupant behaviour and the physical environment and aid in the development of national adaptive thermal-comfort indices for the European Survey of Thermal Comfort database. In the name of this endeavour, Schweiker and Wagner (2015) adopted the 'Percentage Outside Range' methodological approach, which is based on the European adaptive-comfort model, to reduce the impact of overheating that is created by an increase in thermal mass.

The present study outlines the development of the thermal-comfort indices of previous studies and the outcomes thereof to fully understanding overheating risks and household domestic-energy use and accurately assess occupant thermal comfort. It should be emphasised at this point that energy-calibration studies should be considered in relation to representative *in-vivo* experiences of household energy consumption and the building-fabric thermal performance of buildings, which align with intergenerational occupants, rather than with the state of the buildings.

2.3.3 Review of Available Energy-Simulation Software Packages

There is a growing interest in the use of energy-simulation tools to conduct a BPE, which has led to a wide range of simulation software suites that are accessible to practitioners and designers (Coakley *et al*., 2014; Harish & Kumar, 2016; Østergård *et al*., 2016). Analytical tools are classified according to the level of computational script that was developed and the complexity thereof, including steady-state, computational fluid dynamic (CFD) and dynamic tools (Loga *et al*., 2016). This classification is limited to the resolution of the digital model, the number of user inputs and the time that is needed to successfully develop BES models. Steady-state tools provide detailed daily or seasonal performances and visualisations of energy flows over a two- or three-dimensional domain that help to refine the design at later and more advance design stages (Yang *et al.*, 2018). To properly conceptualise the analytical-energy model that was developed for the present study, commonly used BES packages reviewed globally, as shown in Table 2.12.

Table 2.12: Summary of Data-Processing Capabilities of BES Software and Plug-Ins.

Software Plug-In	Software Package	Open Source	Supports Optimisa-tion	Supports Calibration	BIM* Interoper-ability	Weather Data Handling	Fast Processing Capability
IESVE	IESVE		✓	✓	✓	✓	High
IDA ICE	IDA ICE		✓		✓		Medium
eQUEST	DOE-2						Low
Design Builder	EnergyPlus		✓		✓		Medium
Open StudioPAT	EnergyPlus	✓	✓	✓	✓	✓	High
Ladybug & Honeybee	EnergyPlus	✓			✓	✓	Medium
jEplus	EnergyPlus	✓	✓				High
Modclkit	EnergyPlus						Low
MLE+	EnergyPlus	✓	✓				Low
EpXL	EnergyPlus	✓	✓				Medium
Eppy	EnergyPlus	✓	✓				High

*BIM: Building-information modelling

Source: Adapted from Ma *et al*. (2012)

Table 2.12 presents a list of BES software suites and plug-in components that were utilised to calculate numeric experiments. This section examines the Integrated Environmental Solutions (IES) software engine, which is used as part of design process of buildings to predict energy performances of public buildings or high-density residential estates to improve the efficiency of recommended building materials; this software suite is a commercial tool that can be used between designers and their clients.

Several studies employed the IES software to assess the energy performance of archetype buildings and create an overview of household energy use and associated CO_2 emissions for energy-policymaking decisions (Pasichnyi *et al.*, 2019; Stojiljković *et al.*, 2015). In a study conducted by Kristensen *et al.* (2018), Dutch residential buildings were selected as sampling strategy of existing housing stock.

The IES software is widely used for commercial purposes, and a few exemplar research case studies utilised the IES software suite as part of their methodologies. Balvedi *et al*. (2018) insisted that the IES software should be widely used by scholars to demonstrate the universal validity of this BES platform in large-scale residential projects to eliminate research bias and uncertainty related to the results obtained from DTS analyses; this research gap should be addressed.

The IES software offers structural engineers a versatile range of energy modelling techniques when they are undertaking a calibration analysis to validate available data sources (Choi, 2017). The platform provides effective tools to construct an actual building geometry and assign building thermal properties, occupancy profiles, ventilation schedules for each room to undertake various of numeric experiment targeted for BPE studies (Bateson, 2014). The IES software consists of standardised occupancy profiles and infiltration rates for naturally ventilated buildings, and users are able to adapt an analytical energy model to their own purpose-built design and simulation input parameters, such as occupancy profiles, window-opening schedules, clothing value and metabolic rates, to assess household energy performance (Ben & Steemers, 2014; Fokaides *et al*., 2016).

A thorough analysis of previous scholarly work on BPEs revealed that Design Builder software was commonly used as an analytical energy-simulation tool (Hoes *et al*., 2009). Design Builder, which is an open-source dataset available in EnergyPlus, is interoperable with the EnergyPlus software suite, and it assigns weather files in the simulation platform (Hong *et al*., 2021); this software is limited to using interoperable large-scale weather datasets to assess the overheating risk of buildings.

As can be seen in Table 2.12, the IES software allows large-scale weather files to be uploaded onto the simulation platform and an edit time series is included in the datasets before the DTS analysis is run (Chen *et al*., 2016). This is the most advantageous factor in comparison to select the Design Builder, EnergyPlus, TRNSYS as a research tool to demonstrate representativeness of archetype building selection for the development of base-case scenario in energy policy (Aldossary *et al*., 2014; Ioannou *et al*., 2018).

The IES computational platform provided the most accurate data related to solar-exposure analyses of buildings (Habibi, 2017); this is because large-scale weather files can demonstrate the solar-diffusion frequency of building thermal properties for the initial overheating risk analysis. The main advantage of employing the IES software for a solar-exposure analysis is that it incorporates computational script that was developed to calculate the diffuse parameters of building envelopes. A solar-exposure analysis that was conducted by Kokaraki *et al*. (2019) led to a better understanding of the solar-irradiance factor and the impact thereof on building envelopes, and the findings of this study were validated by a thermal-imaging survey.

Contrarily, Design Builder does not provide the opportunity to undertake a solar-exposure analysis in conjunction with weather files that are assigned in the simulation model; it only applies industry benchmarks of ASHRAE 55–90.1 standards and CIBSE TM52 for the purpose of an overheating analysis (Jenkins *et al*., 2013). There is a limited amount of time to develop a new method to implement building EPCs, which do not exist in NC while the IES software applies benchmarking assessments.

The dearth number of studies considered the adoption of industry benchmarks or local standard assessment protocols to report the dynamic thermal simulation findings while assessing energy performance of buildings (Dodoo *et al*., 2017). Therefore, the most of studies are neglected to consider human-based approach into the energy simulation which is worthy for an investigation. In addition, the IES software allows an assessment of the life cycle cost assessment (LCCA) of buildings and integrates the results into a building regulation-compliant plug-in interface to demonstrate accurate economically viable studies (Mostavi *et al*., 2017).

The interface of the IES software and Design Builder claim to be able to undertake building-optimisation studies for building retrofitting efforts (Juan *et al*., 2009; Sierra *et al*., 2018). The results obtained from Design Builder allows the data to run a parametric analysis by using Genetic Algorithms (GAs) to demonstrate the energy efficiency of retrofitting design strategies.

In the BPEs, the IES software and Design Builder platform were compatible with each other for a DTS analysis and able to use human-based data in the simulation model and to assign weather files for a building-fabric thermal-performance analysis. Both are able to incorporate the ASHRAE 55–90.1 and CIBSE TM52 industry benchmarks to concurrently assess building overheating risks and occupant thermal comfort (Crawley *et al*., 2008; Zakula *et al*., 2019). Even though the CIBSE TM59 guidelines were included in the IES interface in 2020 for overheating-risk assessments by incorporating dominant representative occupancy profiles, this was not included in Design Builder. Figure 2.5 presents a list of energy-simulation software packages that were initially tested to better understand the efficiency of the IES software suite for the present study.

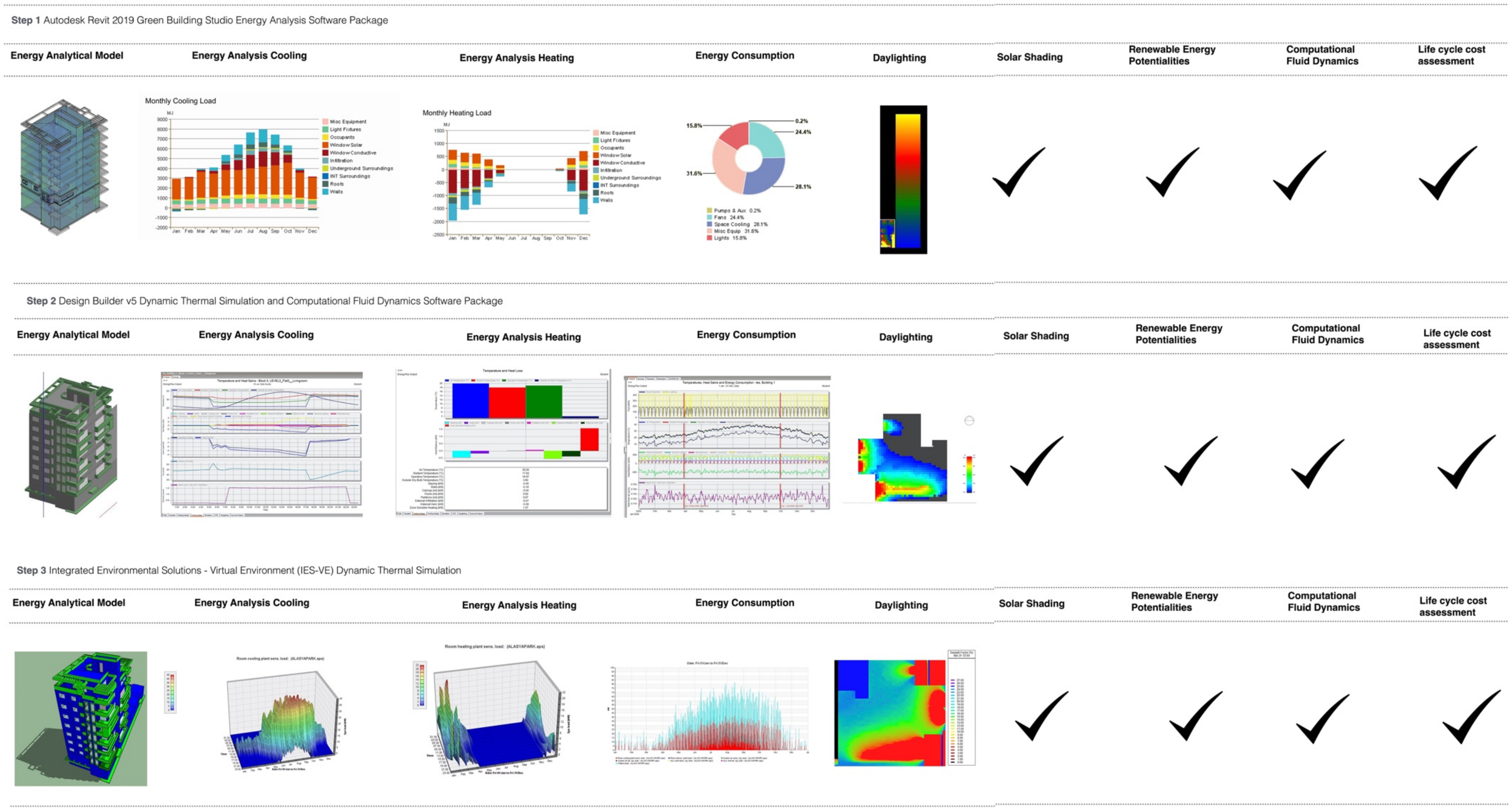


Figure 2.5: Preliminary analysis of energy software tested to explore strengths and weaknesses of IES software.

A few studies reported that data obtained from the Energy Plus weather datasets, which are available in the EPW format, were incompatible with the computational script that was developed for the IES software (Hopfe & Hensen, 2011; Tian *et al.*, 2018). To avoid discrepancies, the EPW datasets were corrected with the Weather Analytics software, which is interoperable with the IES simulation platform. Evidence suggests that unlimited data can be obtained from the IES software; any data can be formatted into the gbXML format, which is compatible with the computational script of Design Builder, EDSL Tas, Autodesk® Revit® Green Building Studio® and SketchUp (Abanda & Byers, 2016; Wang & John, 2016); this adaptability can be used to develop a new simulation framework that will assess the energy performance of buildings.

One of the constraints of using the gbXML analytical building geometry constructed in the IES platform is that the available and designed thermal properties of a case-study building in the thermal-properties-template manager platform are incompatible with the other simulation software engines (Ferrari *et al*., 2019). As with other energy-simulation engines, the thermal properties of building materials should be manually adjusted in the standardised templates that were previously designed in these software suites to avoid this discrepancy.

The building geometry shown in Figure 2.5 was constructed in the IES platform, and a gbXML file was generated to test the interoperability of the software with Design Builder and Autodesk® Revit® Green Building Studio® by using a steady-state analysis of the thermal performances of buildings. A taxonomy analysis determined that all three software engines provide cooling, heating, energy consumption, overall electricity use, daylight and solar-shading analyses, renewable energy potentialities, a CFD analysis and the LCCA of buildings (Magnier & Haghighat, 2010; Nwodo & Anumba, 2019). After a thorough analysis of all three software platforms, the IES software suite provided detailed time series that were extracted from a DTS analysis through a steady-state BES; it can also be used to conduct a dynamic thermal analysis by including secondary datasets, such as sub-metering data, in the simulation model (Mata *et al.*, 2019). The IES software links to the LCCA plug-in that is available on the IES platform to test the cost effectiveness of building-optimisation studies.

Design Builder provided simulation targets that were similar to the IES software, except when the obtained data were not detailed; discrepancies were frequently detected due to the lack of available time series for the DTS analysis included in the weather files. Notably, Autodesk® Revit® Green Building Studio® can also be used in BES studies by integrating the gbXML file that is constructed in the IES platform. Revit® is compatible with the Geographic Information System (GIS) software suite when identifying the location of a case-study building; unlike Design Builder and IES, however, weather files cannot be assigned in the Revit® energy-analysis plug-in interface to generate an analytical energy model, and the data obtained with this platform for an energy analysis are based on the standardised online dashboard platform in Green Building Studio®, which provides an overview of building energy performance without actually including human-based data in the model (Machete *et al.*, 2018). This is why Revit® is not preferred for research purposes. The IES simulation interface, the computational script that was developed to conduct a solar-exposure analysis of buildings and the integration thereof to develop building regulations proved to be determinant factors in the decision to use the IES software suite as the BES tool in the present study.

2.4 Conclusions

This chapter delineated the extent literature review that was conducted to properly identify the knowledge gap related to the integration of an STS conceptual framework in a BES study; to address the energy-efficiency gap related to building overheating risks, the thermal comfort of occupants and the energy use of households; and to explore the novelty of integrating energy-assessment studies with an energy audit and thermal imaging, an area where little research has been undertaken. The literature reviewed in this chapter outlined three key areas relevant to filling the knowledge gap in BPEs: overheating-risk assessment, thermal comfort and occupant behaviour in energy modelling. The IES software suite was selected for an energy-assessment analysis due to its accuracy.

The literature review demonstrated that integration of the STS into energy-modelling studies is not clearly understood, and that a longitudinal field-study investigation to calculate and assess the PMV and PPD indices would be worthwhile. Moreover, the CIBSE TM59 Overheating Task Force noted in 2017 that a new design method was needed to define overheating as it relates to occupant thermal comfort, especially in residential buildings without mechanical cooling systems; this approach must follow the methodology and recommendations of BS EN 15251 to determine whether an occupied residential building should be classified as being in danger of becoming overheated, particularly in the summer. The literature review also revealed a lack of data that resulted in a gap between the as-designed and as-built performances of existing housing stock. Consequently, a novel methodology should be developed according to *in-situ* measurements, which include household indoor-air-temperature records integrated with thermal-imaging surveys and heat-flux measurements of building-fabric elements, in addition to concurrently monitored environmental conditions and a review of households' energy bills.

Chapter 3

Methodology

Introduction

This chapter presents the research methodology by explaining the rationale for the present study and the conceptual framework that was developed to address the energy-efficiency gap (EEG) while optimising occupant thermal comfort. The case-study residential buildings are described and the research design model that was adopted to conduct field surveys is explained. The present study employed a mixed methodology of qualitative and quantitative data analyses to examine the influence of the socio-technical-systems (STS) approach through a building modelling simulation based on the archetype residential buildings to develop energy policies that are in accordance with the Energy Performance of Buildings Directive (EPBD) objectives. Furthermore, the selection criteria of base-case representative residential tower blocks (RTBs) are explained and the data-collection methods that were used, field-work procedures and data analysis and interpretation are presented. The mixed-method research approach that was developed through a comprehensive, multidisciplinary research design model is described, and some limitations of the present study are delineated. Finally, issues related to building-energy modelling and validation techniques are discussed.

3.1 Rationale for the Present Study

Northern Cyprus (NC) is marked by a lack of construction standards, codes of practice and building regulations associated with a thorough investigation of the building-energy performance of existing housing stock, which does not help to resolve the issue of high energy demand in the residential sector. Debates on the energy-performance of social housing in EU member states have revealed considerable shortcomings in the integration of current design methods that concurrently assess building overheating risks and optimise occupants' thermal comfort to develop an effective conceptual framework for each member state that considers variations in climate characteristics, building codes and regulations and household types during the decision-making process.

The importance of developing an evidence-based energy-policy framework to assess robust energy-performance evaluation-and-certification schemes in south-eastern Mediterranean EU countries has not yet been addressed. A theoretical investigation of the STS design model and the integrity thereof in a multi-criteria decision-making process have gained momentum in research endeavours related to energy and the social sciences. A thorough empirical analysis of the energy-planning systems and energy-efficiency investments were the result of strategic policies and political issues that arose because of multi-disciplinary research and were developed within the scope of the EPBD mandates. To address the knowledge gap in current energy-efficiency frameworks, the present study adopted the STS design approach to develop a new adaptation of building-energy performance assessment criteria and to identify the neutral thermal-comfort thresholds of households through a longitudinal field survey.

3.2 Stages of Development of STS Conceptual Framework

3.2.1 The Theory of Socio-Technical-Systems Approach

The theoretical foundation of the Socio-Technical-Systems (STS) approach dates to the 1950s when Jay W. Forrester first introduced a new method of design that bridged engineering and management; this theory was then developed and applied by a group of researchers from the Massachusetts Institute of Technology (MIT). Forrester defines STS as "a way of combining all available information including the written description and personal experience with computer simulation to yield a better understanding of social systems" (Forrester 1976). The rationale of the present study is to provide a detailed record of the development of an STS conceptual framework, as shown in Figure 3.1.

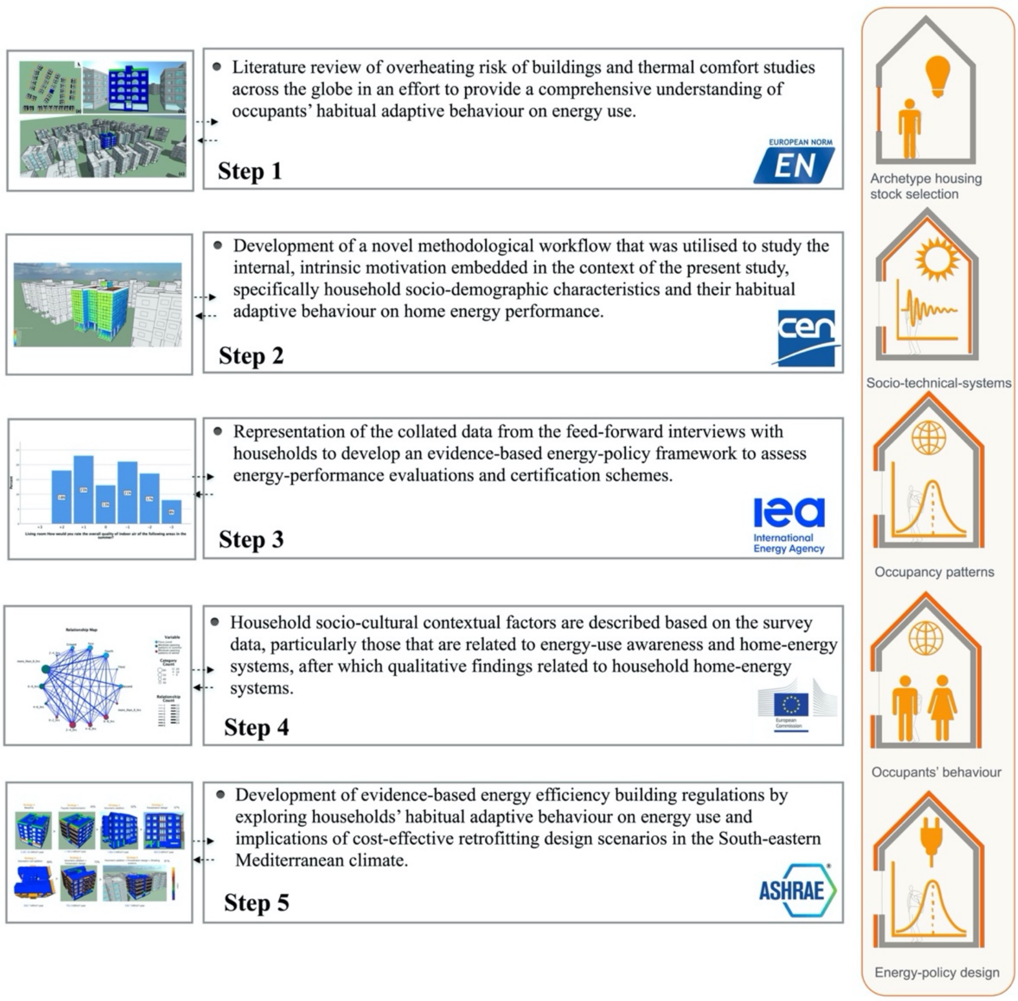


Figure 3.1: Stages of development of the STS conceptual framework of the present study.

What Forrester developed in the 1950s was an early stage of an economic modelling and forecasting design approach that could be applied to the other disciplines; this method of design re-emerged in the 1970s to become an approach commonly applied by scholars both for research and for developing energy forecasting scenarios for policymakers (Forrester, 1971). In 1975, Forrester explained the constraints of the method he had developed and reported on its limitations after two decades of experimenting with his own methodological approach in system dynamics (SD).

First, Forrester (1975) outlined that he found there to be a failure to develop adequate sampling to represent the loop structure that makes up economic systems: this was due to the discrepancies detected when analysing closed loops in purpose-built experimental analyses, which led to changes in the loop structure and the overlapping of multiple datasets and time constraints when undertaking energy modelling simulations. He also found that shortcomings of the STS approach include an inability to include flows of goods, issues with secondary data sources of information, and the fact that labour intensive work is required to identify each parameter to be correctly included in simulation models. Finally, the STS model is constrained by not being able to produce a null result, if, for instance, there isn't enough data for the model to work. Additionally, the STS model is that it cannot conduct an analysis that recognises its own failure to forecast economic analysis in the field of business and management.

It should also be noted that one of the constraints of the early-stage STS model was a restriction in building energy models: these were constrained by their capacity for manipulating numerical data. These technical constraints caused research bias and manipulation in many scientific papers that were published at the time. In this same 1975 work, Forrester stresses that the early stage of the STS model predominantly relied on only undertaking multiple regression analysis for obtaining coefficients for equation models that define behavioural analysis in the SD approach. Forrester also noted that the early STS model showed a lack of representativeness on identifying assumptions related to the behavioural models developed by scholars.

Later, after identifying the above shortcomings in the early models developed between 1946 and 1976, Forrester revised his theory and in 1998 published an instruction manual entitled "Designing the Future" to provide a new approach to understanding the efficacy of variables included in energy simulation for forecasting energy policy design scenarios. In this 1998 manual, Forrester proposes a series of new methods of design that incorporate *(i)* dynamic structure; *(ii)* information flows; *(iii)* benchmarking; *(iv)* nonlinear systems; *(v)* differential equations; *(vi)* discontinuous changes in variables; *(vii)* model complexity; *(viii)* representativeness and integration with evidence-based data collection; and *(ix)* a workflow for coefficient accuracy. A review of these step-by-step development stages demonstrates that Forrester provided advancements on his technique, and with these improvements considered, it can be said that Forrester provided a significant contribution with his article entitled "Industrial Dynamics: A Major Breakthrough for Decision Makers" in the *Harvard Business Review* in 1958.

Ansari and Seifi (2013), Oladakun and Odesola (2015) and Wolstenholme (1990) all indicate that Forrester's developed multidisciplinary SD approach has become a powerful and well-established methodology and tool for energy forecasting modelling and for understanding the integration of attitudes in the development of parametric energy models. Coyle (1977), conversely, criticises the STS approach. Coyle stresses the definition of the STS conceptual framework in his criticism, saying that it "deals with the time-dependent behaviour of managed systems with the aim of describing the systems and understanding through qualitative and quantitative models how information feedback governs STS's behaviour and designing robust information feedback structures and control policies through simulation and optimisation" (Coyle, 1977). According to Coyle, the STS dynamic model offers new insight for the mixed-method design where the data was fed by *in-vivo* experiences or real-time historic data series integrated into energy modelling. In light of this, Coyle argues that the STS conceptual framework consists of complex parameters and that it requires further experimental validation techniques to provide reliable outputs in the decision-making process.

In 2007, Forrester reviewed the past fifty years of experimental studies conducted within the STS conceptual framework since he developed the field of system dynamics and provides guidance for the next fifty years. In this latest work, Forrester stresses that "a model can be useful if it represents only what we believe to be the nature of the system under study… we are forced to commit ourselves on what we believe is the relative importance of various factors. We shall discover inconsistencies in our basic assumptions… Through many of these we learn" (Forrester, 2007). In light of this statement, it can be understood that there will be a high likelihood of identifying discrepancies in datasets when predicting energy and economic models. Despite the shortcomings of his approach, Forrester highlights the advantages of adopting the STS conceptual framework and integrating the systems dynamic approach in the matter of exploring statistical analysis in the building engineering field, as shown in Figure 3.2.

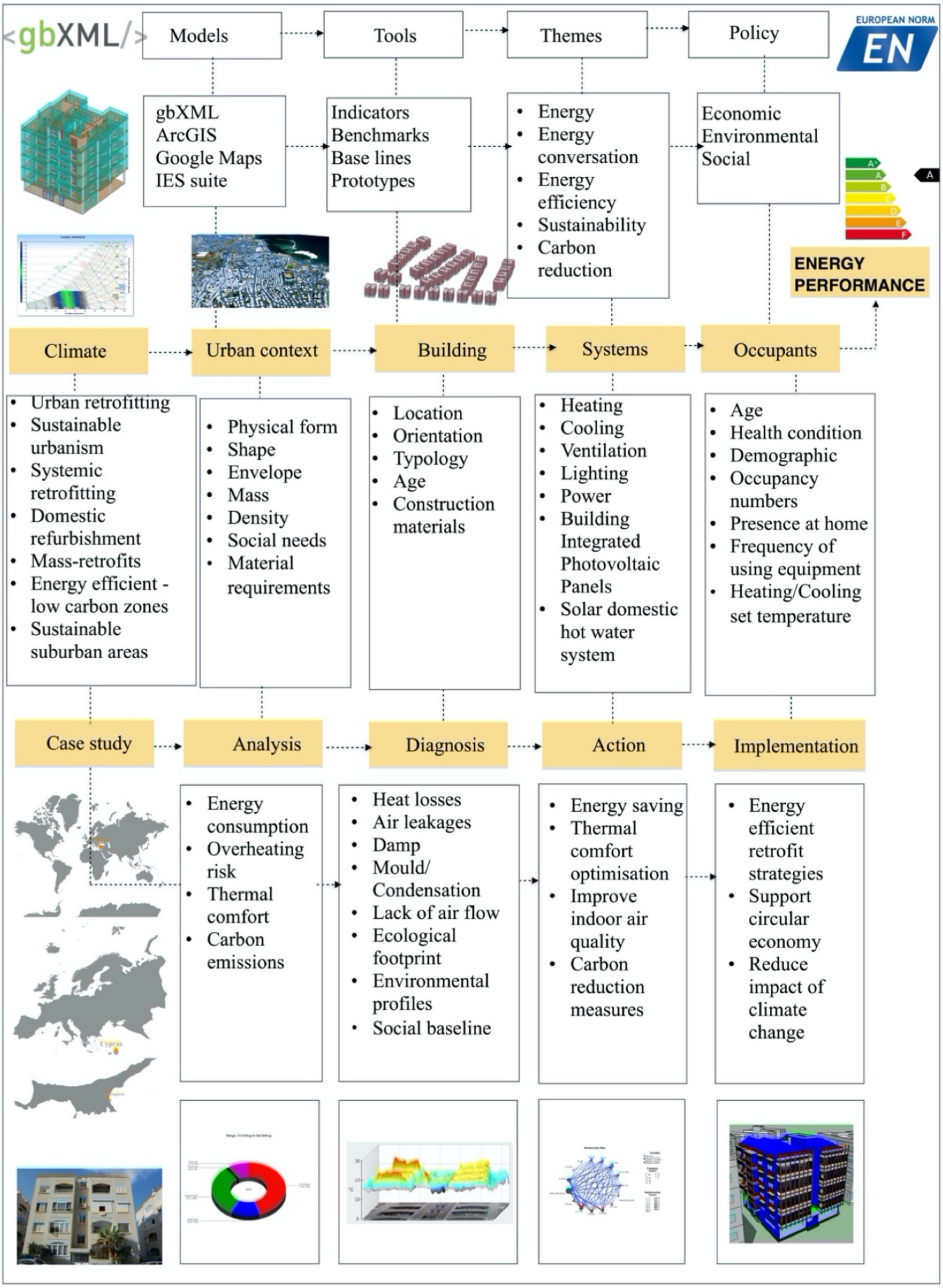


Figure 3.2: Steps for developing an evidence-based energy policy framework that considers the effects of household adaptive behaviour on home energy performance.

In the same 2007 paper, Forrester outlines the advantages of using the STS conceptual framework based on a review of the past fifty years of experimental studies and their outcomes, and provides nine main conclusions about STS, which are outlined in the following paragraphs.

(i) Forrester finds that the integration of STS provides a clear description of the methodological approach used by scholars. Using STS also enables them to improve shortcomings in their models so that they can integrate a comprehensive methodological framework to conduct their experiments accurately.

(ii) Forrester indicates that STS provides a compact model that can demonstrate how inaccuracies are resolved in a model and how researchers can deal with complex parameters in their own fields, as shown in Figure 3.3.

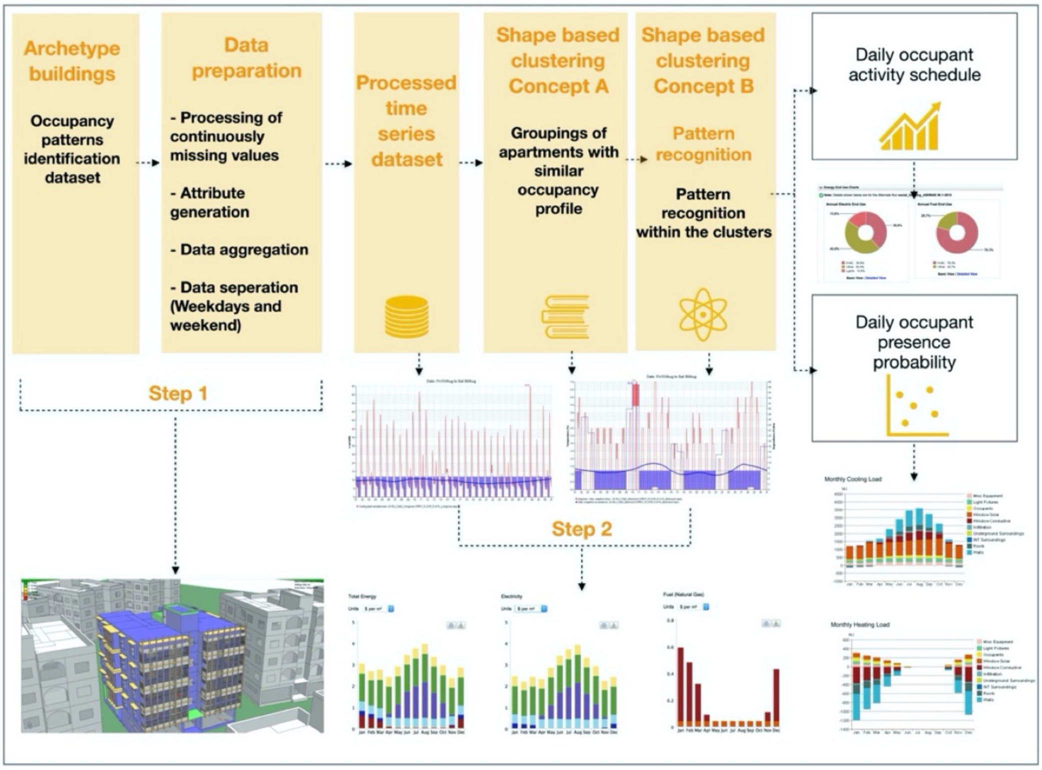


Figure 3.3: Adoption of the STS conceptual framework into energy modelling research.

(iii) STS provides a reduction in the time constraints of energy modelling approaches where it requires the inclusion of time-series data for the validation of research outcomes.

(iv) Forrester (2007) argues that STS requires generic models, and while researchers set out the baseline model for benchmarking assessments, the descriptive assessment of results is required to interpret the findings of research outcomes.

(v) Forrester indicates that the attributes of the developed models require the integration of evidence-based datasets so that the system model allows researchers to generate more realistic assumptions while developing energy policy design scenarios. At the same time, Forrester stresses that energy policy design scenarios should be tested with dependent variables that are gathered through survey sampling to validate research outcomes. Figure 3.4 demonstrates the influence of adopting the STS conceptual framework in the 1980s.

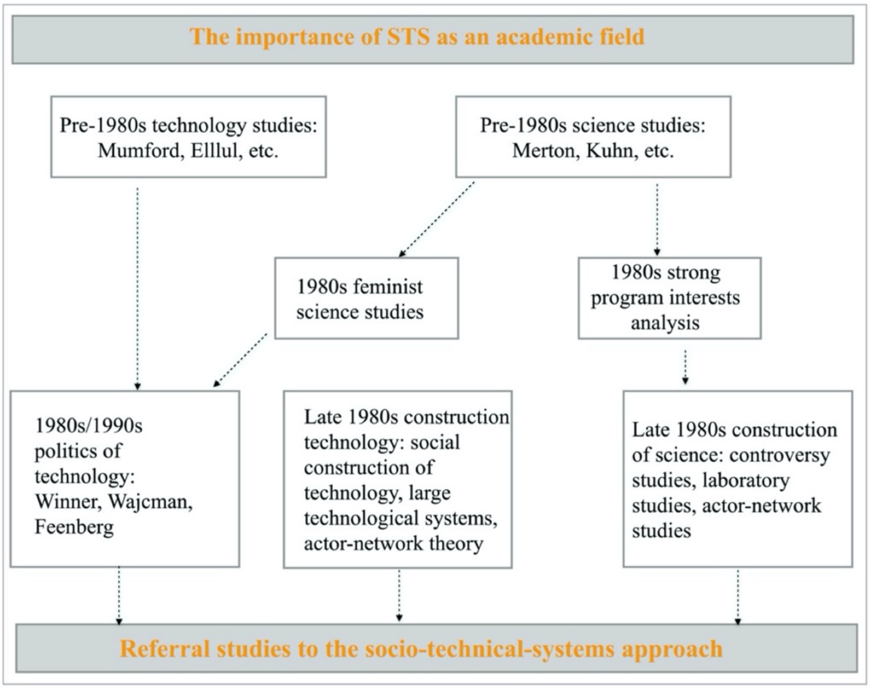


Figure 3.4: Adoption of the STS conceptual framework by multidisciplinary studies in the 1980s.

(vi) Forrester (2007) recommends that energy policy design scenarios require policies that support criticism by applicable theories. One of the reasons for this is that the STS model can be applied to multidisciplinary studies.

(vii) Forrester discusses the difference between current and past studies so that the developed STS design approach can demonstrate the inaccuracies and shortcomings of each experimental model. This technical aspect can also provide a guidance to future scholars in thoroughly identifying their own knowledge gaps while designing a comprehensive methodological framework for their own studies.

(viii) Forrester clearly outlines that the STS model examines developed energy-design policies by including households' *in-vivo* experiences in energy use, and he also highlights that this developed STS design approach provides a way to reduce any research bias while conducting the statistical analysis.

(ix) Forrester outlines the STS model and provides a reliable methodological design approach for researchers to deal with research bias and develop evidence-based energy models for SD in the engineering field.

After reviewing all these advantages, Forrester (2007) states that as the STS conceptual framework has developed over time, it has enabled researchers to continue to use similar design approaches in their own fields without the need for applying new advances in system dynamics. Therefore, Forrester indicates that if researchers decide to use the STS conceptual framework, a high quality of work is required to determine realistic assumptions in the decision-making process that is shown in Figure 3.5. Forrester stresses that if scholars fail to apply all these approaches under the framework of STS, they should not be criticised as they may not have had the opportunity to receive the education to fully train themselves in the engineering field.

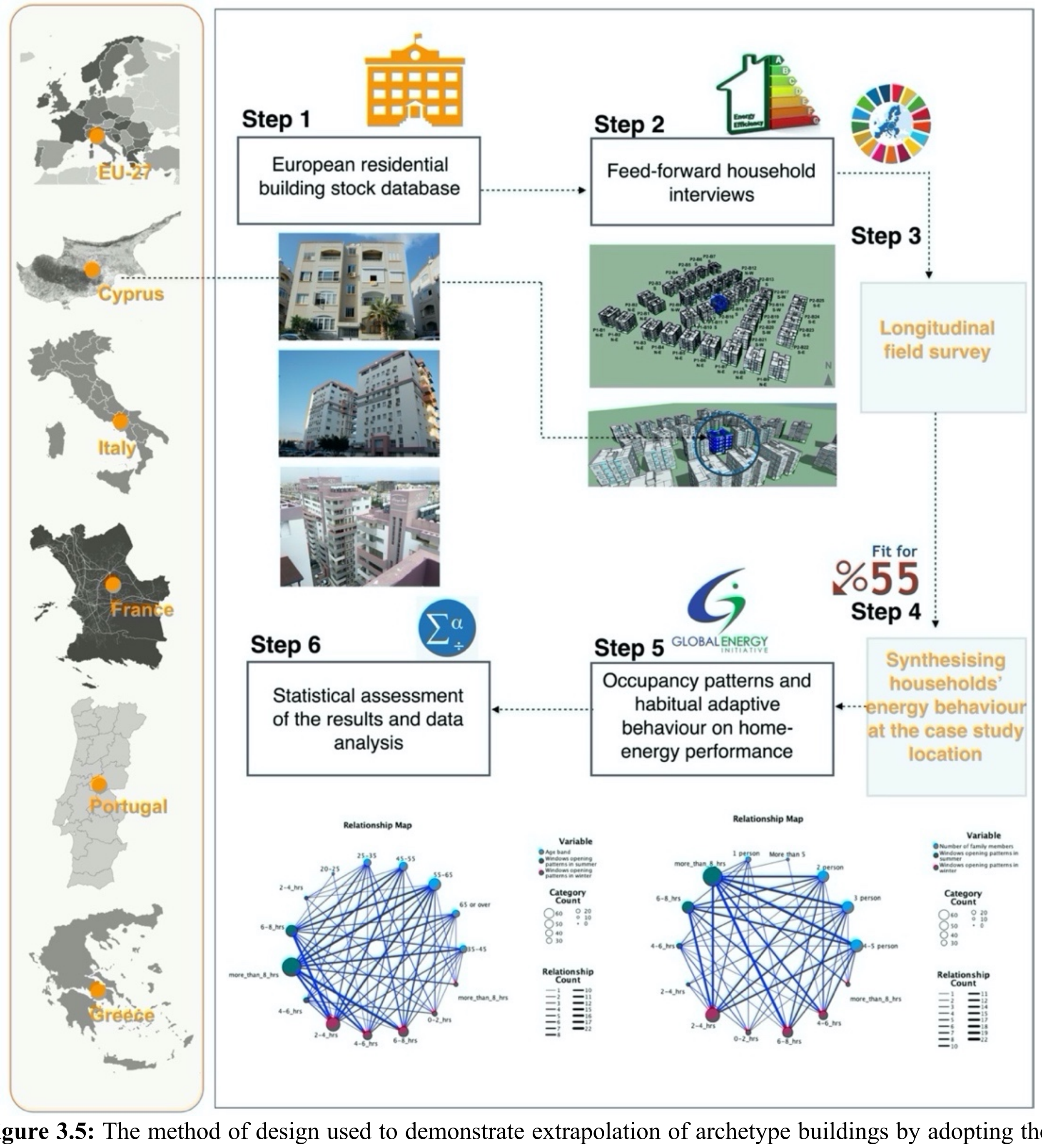


Figure 3.5: The method of design used to demonstrate extrapolation of archetype buildings by adopting the STS conceptual framework for effective policymaking decisions in energy use.

In his paper entitled "System Dynamics – The Next Fifty Years", Forrester (2007) outlines guidelines for researchers for the next fifty years of integrating the STS design approach, and strongly recommends that researchers consider the complexity of the STS design. To reduce shortcomings in SD, Forrester indicates that more established energy models should be set out in accordance with the research hypotheses so that the results can generate effective energy policy design mechanisms for stakeholders. Forrester also indicates that the main advantage of integrating STS is that it leads to a non-linear relationship and multi-loop feedback system in the SD approach, which in turn enables researchers to go beyond the established settings when conducting experimental analysis. Finally, Forrester notes that the STS design approach will always remain complex and may be difficult for scholars to understand and apply to their own methodologies.

In summary, the STS conceptual framework provides a multidisciplinary modelling approach. It is a well-known and widely-accepted theory that has been widely applied by scholars in many fields to develop evidence-based energy design scenarios. Balnac *et al.* (2009) refer to STS as the common approach in energy and environment. Morecroft (1988) and Milstein *et al.* (2010) indicate that STS allows researchers to conduct evidence-based longitudinal studies to assess energy consumption. The STS approach has also been widely used by Davis and Durbach (2011), Motawa and Banfill (2010) and Dyner *et al.* (1998) in the development of other energy-efficiency decision-making criteria. These studies highlight the importance of the effective applications that could be developed through identification of the “energy efficiency gap”: this theory should be further developed by other scholars to fill knowledge gaps due to changes in energy building regulations, and to tackle climate change. Forrester (2007) also mentions that the integration of STS is not only limited to conducting experimental studies in energy efficiency.

In the present study, the STS design approach is adopted and further developed in view of the technical constraints and strengths indicated by Forrester in 2007. The present study consists of a comprehensive methodology used to gather data on household energy-efficiency awareness in order to optimise thermal comfort within the integration of conventional thermal comfort assessment indicators for benchmarking, as shown in Figure 3.6. The present study examines households’ subjective attitudes through thermal sensation votes gathered through a questionnaire survey, and assesses household energy use by establishing an energy-simulation approach in the South-eastern Mediterranean climate of Cyprus. This subject can be accepted as applicable for an STS design model, and the research can be applied to develop further guidance for energy efficiency research.

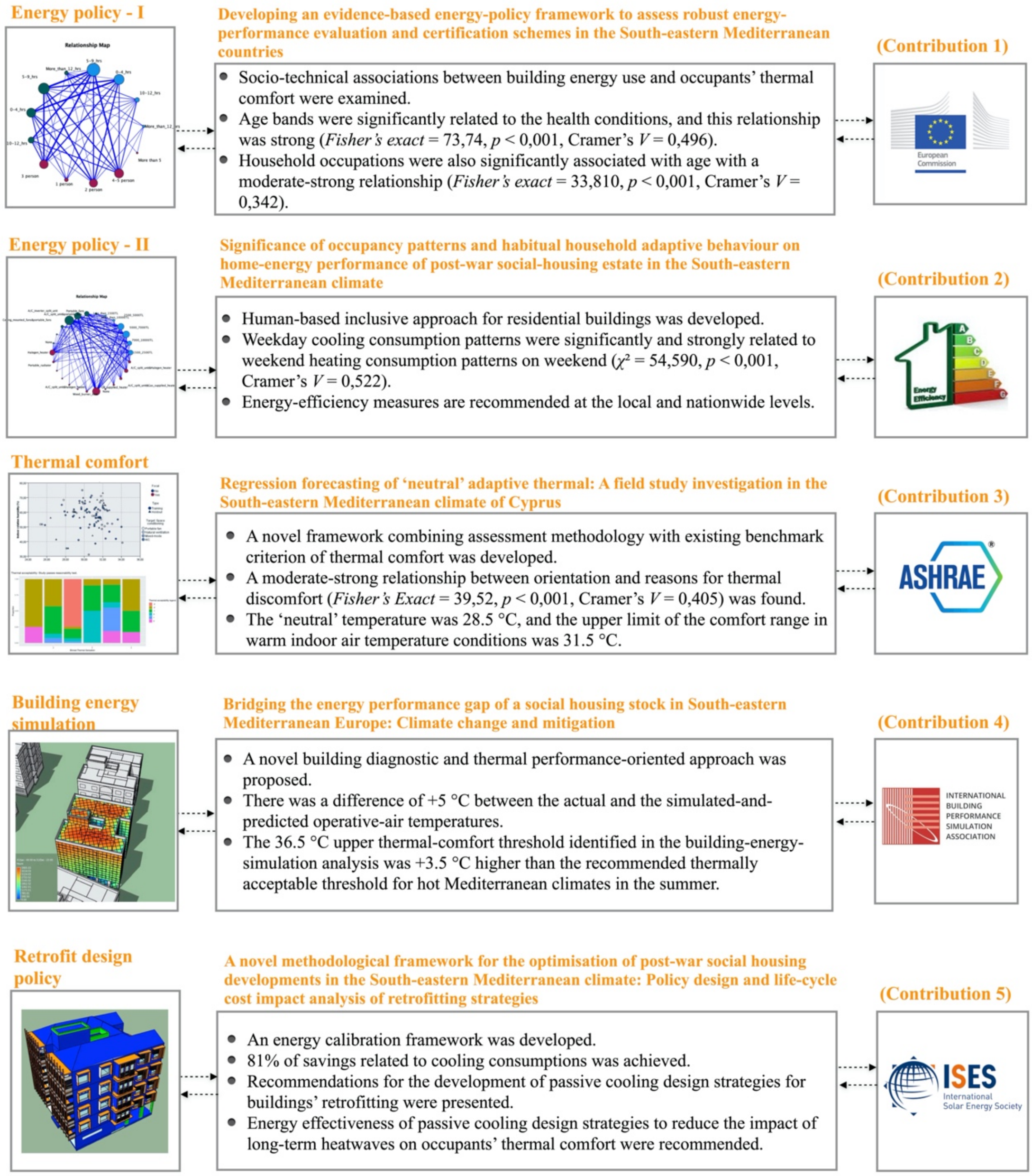


Figure 3.6: The implications of the integration of the STS conceptual framework and its impact on the research outcomes of the present study.

In the present study, use of the STS model allows the researchers to apply a comprehensive method of design to their own studies in the building engineering field; this use of the STS model could have long-term implications for building energy performance development. Table 3.1 delineates the critically evaluation of the STS approach and its impact on developing an effective method of design in retrofitting energy policy design. Additionally, Forrester (2007) indicates that the use of the SD approach enables scholars to achieve reliable energy policy measures by simplifying the complex parameters in multilinear loop systems. This enables scholars to provide energy design implications for policymakers, including economic feasibility and forecasting scenarios to foresee the cost-effectiveness of energy efficient design scenarios in the residential sector. Figure 3.7 demonstrates the integration of the STS conceptual framework with the energy efficiency objective.

Table 3.1: Evaluation of the STS Concept in Key Research Areas.

STS Concepts	Benchmarking Indicators	Occupants' behaviour	Thermal comfort	Overheating risk	Energy modelling
Occupants *(Users and aspects)* - *Data functional inputs*	**People detection**				
	Presence of users	√	■	Δ	Δ
	Average count of users	Δ	Δ	⊕	Δ
	Actual count of users	√	√	√	√
	Occupants' position in a room	Δ	√	⊕	⊕
	Ability to analyse each user data	■	Δ	Δ	√
	Behavioural pattern				
	The behaviour of occupant in space	√	Δ	⊕	⊕
	Configuring occupancy patterns	Δ	⊕	√	√
	The different modes of users	Δ	■	Δ	Δ
	The usual actions occur by user	Δ	■	Δ	Δ
	Metabolic activity (*met*) level	√	√	√	√
	Clothing insulation (*clo*) level	√	√	√	√
	Thermal sensation	■	■	Δ	√
	Comfort temperature degree need	⊕	⊕	Δ	■
	Predicted mean vote	■	■	Δ	√
	Predicted percentage of dissatisfied	Δ	Δ	√	√
Technical parameters	**Green resilient design**				
	Increase airtightness	⊕	Δ	Δ	■
	Adjust glazing by orientation	■	Δ	√	■
	Apply passive solar design	⊕	■	Δ	■
	Provide thermal mass	⊕	⊕	■	√
	Use high-transmittance glazing	⊕	⊕	⊕	√
	Sustainability				
	Combine vernacular design practices with modern materials	Δ	■	■	Δ
	Use locally available materials	Δ	⊕	⊕	√
	Orient building to optimise wintertime solar gain	Δ	√	⊕	√
	Block unwanted solar gain	Δ	Δ	Δ	√
	Energy-policy design				
	Technology maturity	⊕	⊕	⊕	■
	Efficiency	Δ	Δ	Δ	Δ
	Distribution grid availability	■	■	Δ	√
	Reducing peak demand	√	⊕	√	√
	Energy input-output ratio	Δ	⊕	■	Δ
	Technical feasibility	■	⊕	√	⊕
	Local technical knowledge	⊕	⊕	⊕	■
Systems Modelling	**Building conditions and Climate data**				
	Weather data	Δ	√	√	√
	Natural daylighting information	⊕	⊕	⊕	√
	Natural ventilation information	■	■	Δ	√
	Occupancy schedules	Δ	Δ	■	■
	Miscellanies parameters				
	Space principles	Δ	■	Δ	√
	Geo fencing upon users' habits	Δ	Δ	⊕	■
	Lighting schedules	√	Δ	Δ	Δ
	Use of appliances	⊕	⊕	⊕	■
	Air flow				
	Outside temperature	√	√	√	√
	Operative air temperature	Δ	⊕	⊕	■
	Demand response	■	Δ	Δ	■
Legend: *(Assessment criteria)*	√ Meet criterion	■ Knowledge gap			
	Δ Meet criterion with expectations	⊕ Does not meet criterion			

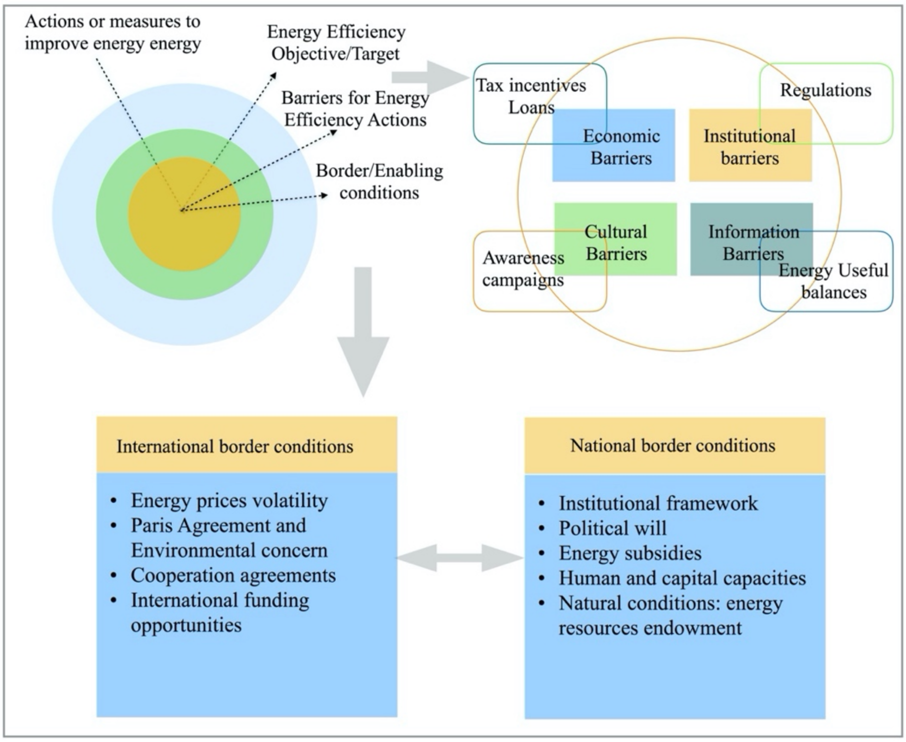


Figure 3.7: Distribution of strengths, constraints and opportunities between the STS conceptual framework and energy efficiency.

This section has reviewed the power of the STS design approach and its implications for the development of energy policy design scenarios. Robert *et al.* (1983), Richardson and Pugh (1981) and Ranganath and Rodrigues (2008) suggest that the inclusion of problem identification, system conceptualisation, reliable energy modelling for simulations, analysis of SD model behaviour, energy performance evaluation, policy analysis, and improvement and policy implementation processes should be considered when conducting any kind of experimental analysis using the STS conceptual framework. These scholars also stress that the energy efficiency gap should be addressed if scholars are able to apply the theory of STS in their research hypothesis. This is the reason that the aim of the present study is to investigate the significance of energy efficiency in filling the knowledge gap in energy use. The following section, 3.2.2, discusses the terminology of the energy efficiency gap and its implications for the development of energy policy design scenarios.

3.2.2 Theory of the Energy Efficiency Gap

This section reviews the theoretical and empirical research studies that have been aimed at identifying terminology around the energy efficiency gap (EEG). For this analysis, first the most well-known and widely-accepted EEG terminology is defined and then critical analysis is undertaken to provide a guide to the changing notions around EEG as it relates to political events, changing climate conditions and on-going trends in energy efficiency. Figure 3.8 demonstrates the stages of development in energy-policy design scenarios that affect EEG in the residential sector.

Figure 3.8: Procedure of energy-efficiency implementations recommended by the Energy Performance of Buildings Directive (EPBD) under the Horizon 2030 framework.

The conventional terminology of EEG was defined by Jaffe and Stavins: "The energy efficiency gap is described as the gap that exists between the current or expected future energy use of homes and the optimal current or future energy use" (Jaffe & Stavins, 1994). Jaffe and Stavins then further describe the EEG in order to provide a foundation of theoretical information to guide policymakers in the implementation of energy policy design in the residential sector. However, the starting point of a well-established meaning for EEG dates to the 1970s. A pilot study project entitled "Drivers and Barriers to Improving Energy Efficiency and Reducing CO_2 Emissions in the Private Housing Sector" states that in the UK little action had been taken towards energy conservation through the method of considering existing housing stock that was built in the UK pre-1973 (Altan, 2004). This pilot study demonstrated the relevance of the rapid increase in energy prices in 1970s. Figure 3.9 demonstrates the timeline of fuel poverty (FP)-related policy regulations implemented between 1970 and 2018 by the British government.

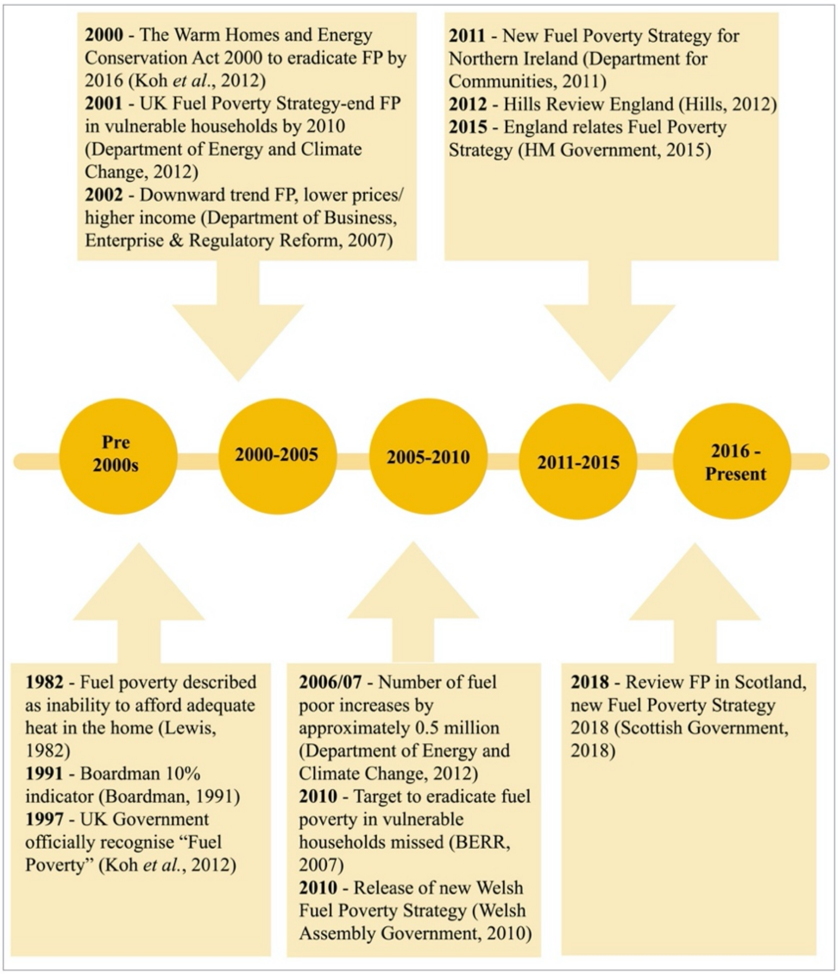


Figure 3.9: Timeline of policy directives implemented to fulfil the fuel poverty-related policies in the UK.

Altan (2004) recommends that in energy efficiency studies aiming to identify the EEG, international attention should be given to the energy conservation of households and the habitual adaptive behaviours of households. Following on to the study conducted by Altan, Pelenur (2013) presented a study outlining the importance of analysing households' sociodemographic characteristics alongside barriers to the adoption of domestic energy efficiency measures in large UK cities. The aim of the study was to better understand the EEG and to improve the effectiveness of future energy efficiency initiatives. This study shows distinct differences to the pilot study conducted by Altan (2004) in terms of researching a tool for the identification of the EEG. Figure 3.10 shows a conceptual diagram of energy efficiency literature from the past fifty years.

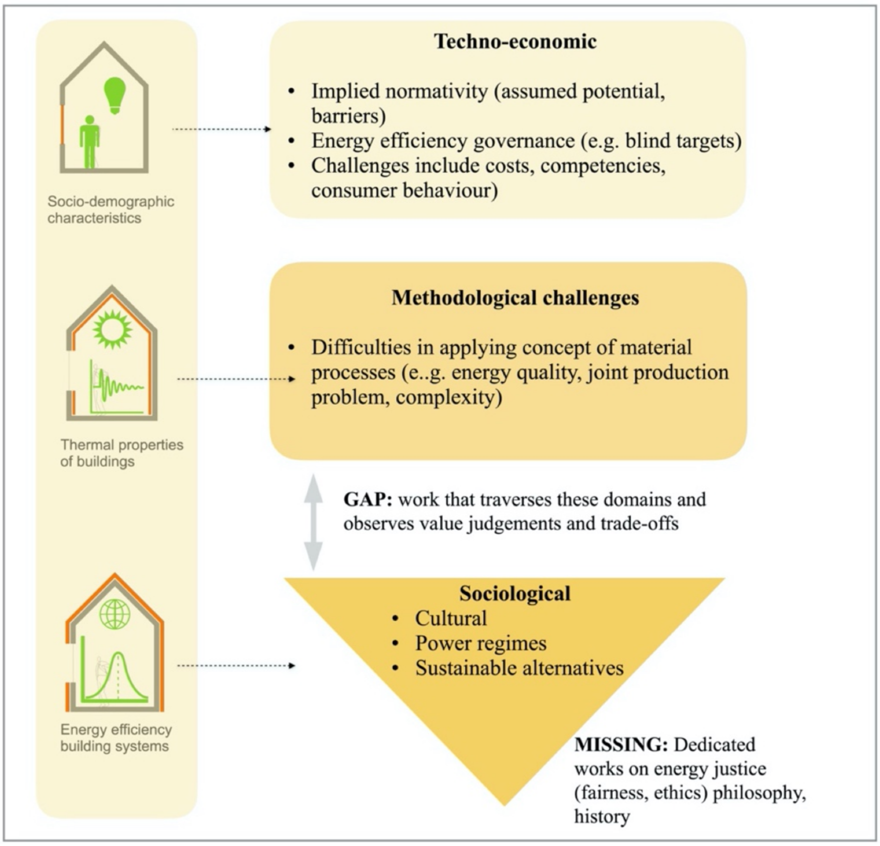


Figure 3.10: Conceptual diagram of energy efficiency literature.

Pelenur (2013) investigated the type of methodological advances required in order to improve household energy efficiency awareness in Cardiff and Manchester, while Altan (2004) developed a novel study to examine the energy efficiency standards, CO_2 emissions and energy ratings of the existing housing stock in Sheffield. Both of these studies predominantly focused on a regional scale, on interviewing households, on modelling existing housing stock to understand households' energy use behaviour and on analysing energy efficiency standards, particularly examining the worst housing conditions in the UK.

In the last seventy years, there has been a rapid increase in world energy use, partly because of the availability of easily extractable fossil fuels (coal, gas and oil), though awareness of the limited nature of these reserves has existed since the 1970s. While industrialised nations depend heavily upon fossil fuels for their industrial processes, developing nations also desire to increase their technological capabilities and their use of energy in various forms. Although it is unlikely that the world will completely run out of fossil fuels in the next fifty years, the majority of easily extractable reserves are located in a small part of the world and the prices are due to increase. This significant energy crisis in the 1970s opened a pathway for scholars and policymakers to find alternative practical solutions for improving energy efficiency in housing. From the 1970s up to the present, scholars in many fields have conducted both theoretical and experimental studies to identify the knowledge gap in energy efficiency research, as shown in Figure 3.11.

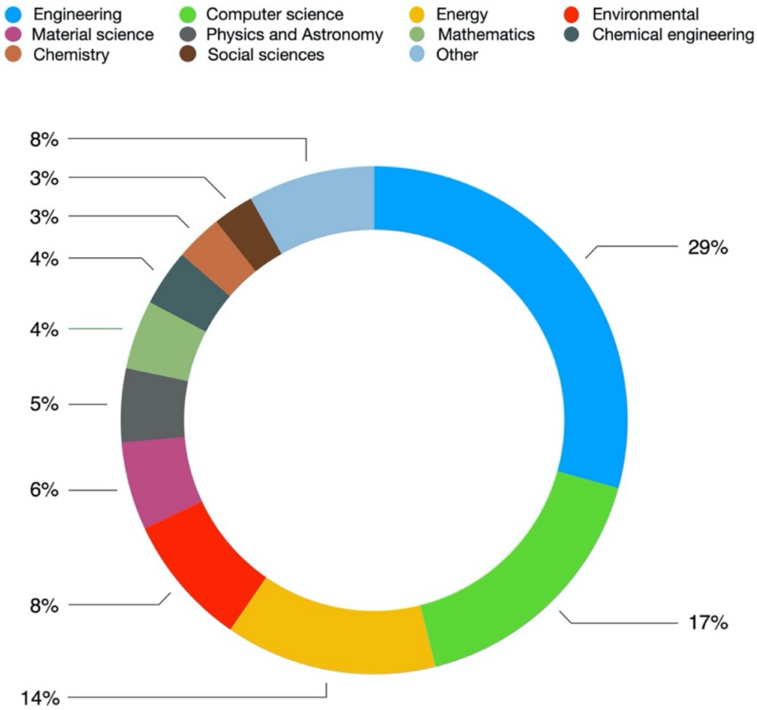


Figure 3.11: Fields of research articles discussing "energy efficiency" in either the title, abstract or keywords from 1970 to 2019 in Scopus.

Pelenur and Cruickshank (2012) indicate that the EEG is a well-researched topic across a wide range of disciplines in terms of both the availability of previously developed energy efficiency studies and its popularity amongst scholars for developing energy efficiency design scenarios both in the UK and EU-27 countries.

To identify the feasible integration of the EEG into energy research, Wilson and Dowlatabadi (2007) describe four diverse disciplinary approaches that can help scholars develop an STS conceptual framework without altering the conventional definition of the EEG: *(i)* conventional and behavioural economics, *(ii)* technology, *(iii)* adoption attitude-based decision making, and *(iv)* social and environmental psychology. Wilson and Dowlatabadi highlight that there are theoretical preferences across different conventional traditions in energy efficiency, and that can lead to a research gap that allows the integration of the STS conceptual framework when developing energy design policy, as shown in Figure 3.12.

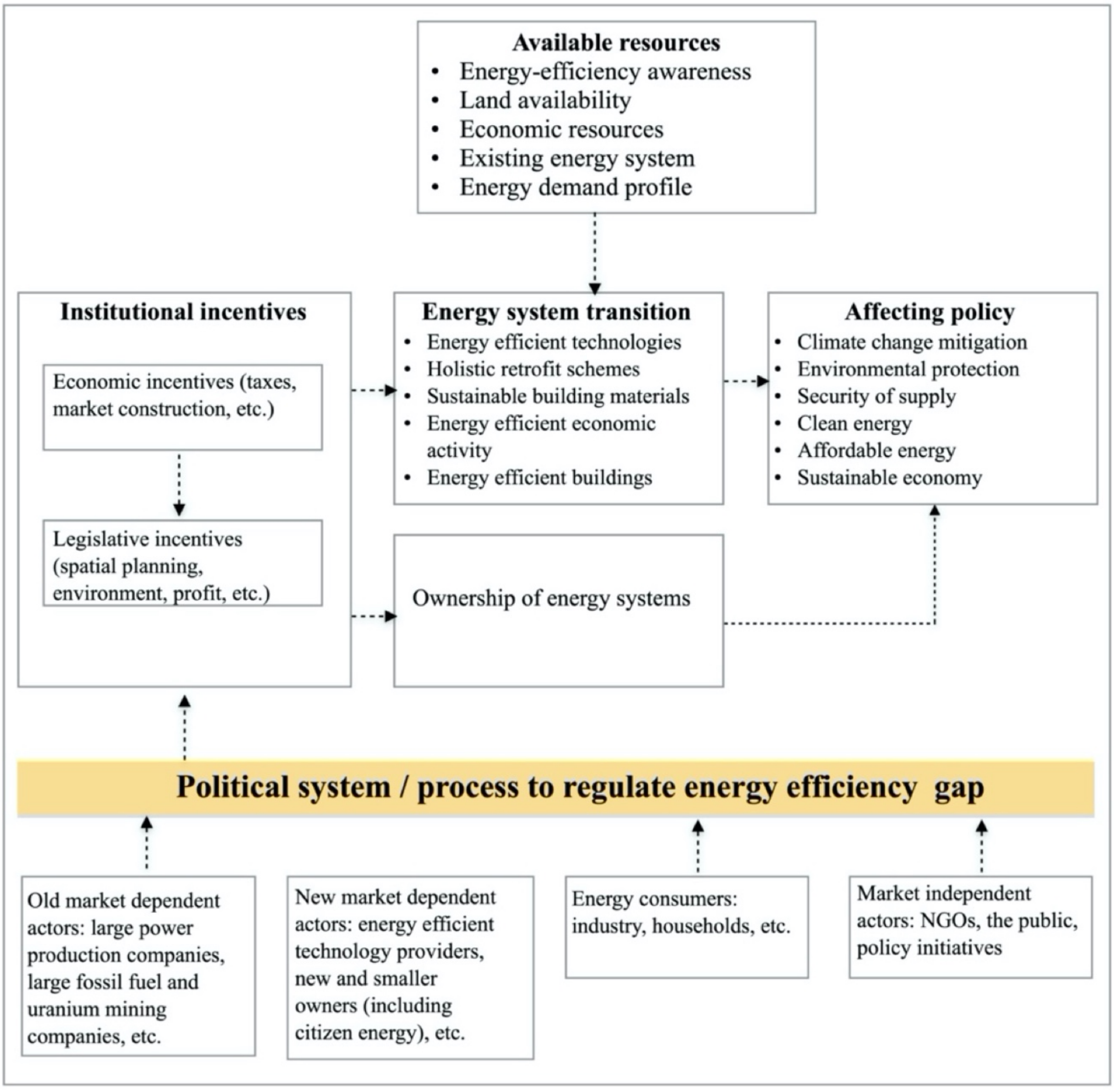


Figure 3.12: Theoretical approach for understanding the significance of EEG for regulating effective energy performance policies.

Weber (1997) stresses that the energy efficiency gap is a complex issue, where technical, institutional, organisational and behavioural barriers all play a significant role during the decision-making process, and that all these aspects are interconnected. In light of this complexity, Pelenur and Cruickshank (2012) form a new outline of the causes of EEGs: these scholars describe the EEG problem formulation from an interdisciplinary perspective that offers a general overview for improving energy efficiency awareness (specifically in UK households), as shown in Figure 3.13.

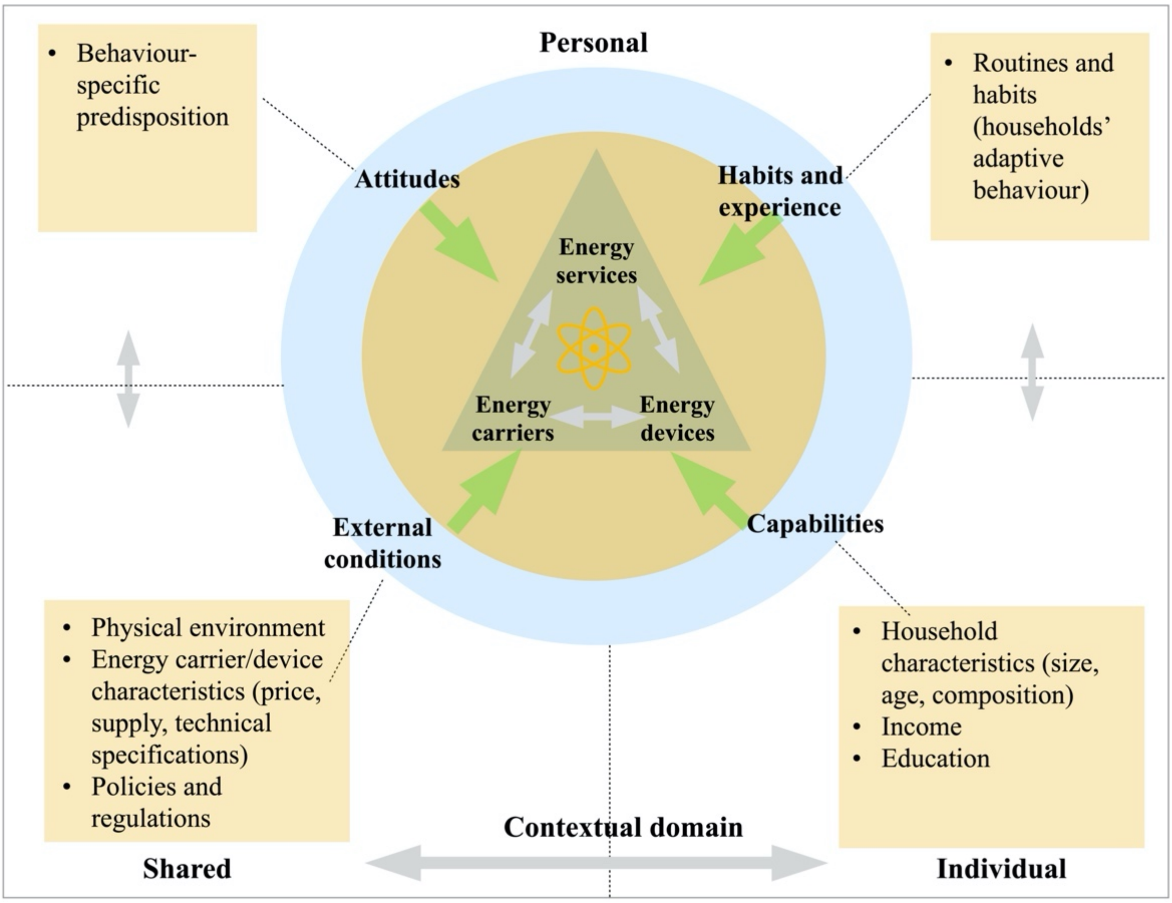


Figure 3.13: Factors influencing household energy consumption.

Conversely, Jaffa and Stavins (1994) argue that the reason for the EEG is a lack of transparent information about the strength of implementing energy efficient technologies. They posit that uncertainty regarding the up-front costs of adopting energy efficient materials and also inaccuracies in the calculation of discount rates by households has led to a negative impact on implementing energy efficient retrofit decisions. Stern (2006) clearly outlines that the constraints of the EEG are interconnected with household attitudes regarding energy use, the financial burden of implementing energy efficient technologies and a lack of awareness around energy conservation, as shown in Figure 3.14.

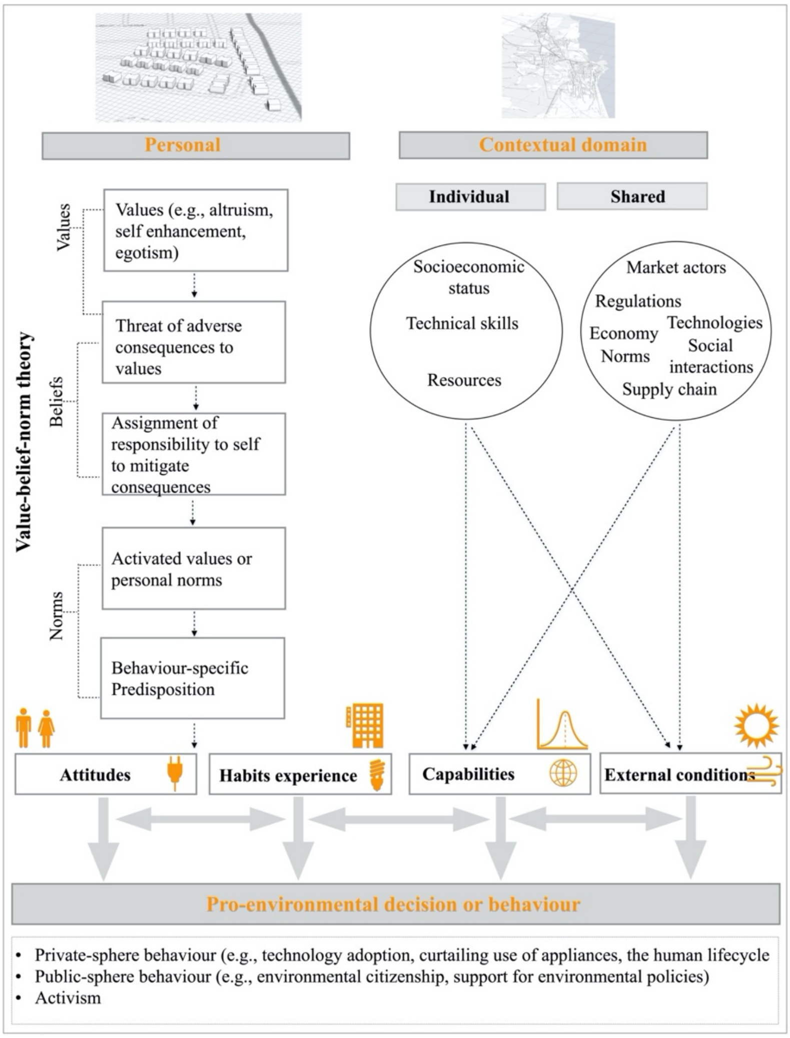


Figure 3.14: An integrated model for defining the forces behind the EEG in Europe.

Pelenur (2013) also stresses that one of the main constraints of the EEG is that many stakeholders did not accept householders as rational actors at the time of developing energy efficiency scenarios. Lutzenhiser (1992) indicates that household interaction with energy is subjective and energy use behaviour is generally left to chance. Although Lutzenhiser highlights the importance of effective control mechanisms for regulating energy incentives and subsidisation schemes, most scholars have failed to address this knowledge gap by considering households' *in-vivo* experiences on energy use. This concern in EEG research has been investigated by many scholars, but so far none of them has been able to define this aspect of EEG enough to use it to inform policymaking decisions regarding energy use. The aim of the present study is therefore to apply science insights to an energy engineering problem, specifically to an investigation of Cypriot post-war social housing, using householders as demographic variables who are associated with empirically-identifiable barriers to affecting the implementation of evidence-based retrofit design solutions. Table 3.2 delineates the critically evaluation of the EEG and its impact on key research areas discussed in Chapter 2.

Table 3.2: Evaluation of the EEG in Key Research Areas.

Energy efficiency gap	**Benchmarking Indicators**	**Occupants' behaviour**	**Thermal comfort**	**Overheating risk**	**Energy modelling**
Energy efficiency	Embodied energy in construction materials	Δ	⊕	⊕	√
	Embodied energy in materials for maintenance	Δ	Δ	⊕	Δ
	Efficient HVAC distribution systems	■	■	Δ	√
	Energy performance	⊕	■	Δ	■
	Water heating system (solar/any)	Δ	Δ	√	√
	Energy-efficient equipment	⊕	⊕	Δ	√
	Energy metering	⊕	⊕	√	√
	Efficient lighting system	Δ	Δ	⊕	√
	Thermal efficiency of building system	⊕	⊕	⊕	√
	Good fenestration design	■	■	■	■
	Air infiltration	⊕	⊕	Δ	√
Energy-policy design	GHG emissions from energy use	Δ	Δ	⊕	Δ
	Primary energy uses per capita	⊕	Δ	Δ	⊕
	Annual energy consumption per capita	⊕	⊕	Δ	⊕
	Ratio of energy-related jobs to population	⊕	⊕	⊕	⊕
	Active public participation	⊕	Δ	Δ	■
	Household energy intensity	Δ	Δ	√	√
	Share of household income spent on fuel and electricity	⊕	⊕	Δ	⊕
	Awareness raising campaigns on energy issues	⊕	⊕	⊕	⊕
	Local authority advice	⊕	⊕	⊕	⊕
	Assistance to the citizens on energy use	⊕	⊕	⊕	⊕
Energy optimisation	**Optimisation**				
	Construction cost & Energy	Δ	Δ	■	√
	Thermal & Lighting performance	Δ	Δ	⊕	√
	Life-cycle-cost	Δ	Δ	■	■
	Thermal performance	Δ	■	Δ	⊕
	Solar energy utilisation	Δ	Δ	Δ	Δ
	Specify reflective, high-emissivity roofing	Δ	Δ	⊕	√
	Provide operable windows	⊕	⊕	■	■
	Retrofitting				
	Post-occupancy evaluation	√	√	⊕	√
	Energy audit	√	⊕	■	√
	Building commissioning	Δ	Δ	⊕	⊕
	Life cycle assessment	Δ	Δ	■	Δ
	Cost analysis	⊕	⊕	Δ	Δ
	Energy benchmarking	⊕	⊕	■	■
	ASHRAE Guidelines	Δ	■	Δ	Δ
	Measurement and verification	⊕	⊕	■	■
Affordable and clean energy ***# SDG Call 7***	**Energy-planning**				
	Energy produced from resources	√	√	⊕	Δ
	Level of energy distribution	⊕	⊕	Δ	Δ
	Raise of energy-efficiency awareness	⊕	⊕	⊕	⊕
	Supporting energy initiatives	⊕	■	⊕	■
	Clean energy research & Development	⊕	■	⊕	⊕
Legend: ***(Assessment criteria)***	√ Meet criterion	■ Knowledge gap			
	Δ Meet criterion with expectations	⊕ Does not meet criterion			

Many field studies conducted by scholars from different climate zones across the globe have investigated correlations between households' habitual adaptive behaviours and their sociodemographic variables (Shipworth *et al.*, 2010; Pelenur, 2010; Pelenur and Cruickshank, 2013). These studies highlight that household behaviour is one of the factors that can affect the EEG.

Pelenur (2013) suggests that the forces behind EEGs can be further identified through comprehensive research on both the psychological and sociological aspects of households. These are factors that require further investigation in terms of their relationship to the EEG, and this is a knowledge gap that other scholars have failed to fill with previous multidisciplinary studies, as outlined in Figure 3.15. After thoroughly reviewing other pilot studies, the present study finds that researching the EEG can be integrated with the STS conceptual framework in order to provide reliable research outputs in energy policy. The present study therefore reviews previous scholars' work to discuss the strength of EEG theory.

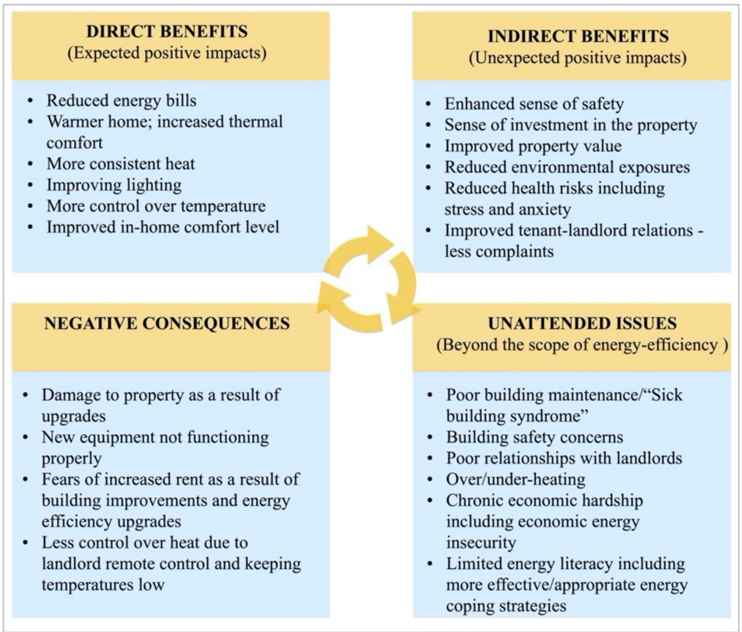


Figure 3.15: Strengths and constraints of identifying the EEG and implementation solutions.

The importance of identifying the EEG began at policy level with the regulatory innovation introduced by Directive 2010/31/EU (Economidou *et al*., 2020; Bertoldi and Mosconi, 2020). This policy regulation is also known as the Energy Performance of Buildings Directive (EPBD). The EPBD has become a mandatory policy regulation to assess the energy performance of buildings through a multi-decade process. After the implementation of the EPBD, most scholars have changed their research focuses to conducting comprehensive research studies aimed at improving the energy efficiency of existing housing stock. The outcome of EPBD implementation has been a positive impact on integrating the concept of the EEG as an energy policy tool.

Copiello (2017) indicates that there is a strong correlation between the rationale of the EPBD and the subject matter of the EEG. Copiello stresses that the EPBD has had a linear effect on improving energy efficiency awareness across households. Kerr *et al.* (2017) indicate that EPBD implementation, when considering the EEG, could provide an effective mechanism for establishing policy tools and supporting non-governmental organisations (NGOs) to further develop energy subsidisation schemes. Ma *et al.* (2012) note that the presence of the EPBD mandates has opened a new pathway for an evolutionary process of methodological approaches in the building engineering field. Tian (2013) highlights that the implementation of the EPBD has enforced households' need to apply for energy performance certificates (EPCs) for their buildings, which in turn has enabled people to better understand the energy performance of their buildings. This is because the concept of the EEG has a direct impact on understanding energy efficiency and assessing the energy performance of existing housing stock.

Hitchcock (1993) states that "households" can be viewed as systems being defined by both physical and social variables for developing evidence-based energy design solutions. It should be noted from the above scholars' statements that the implementation of the EPBD mandates in both central Europe and in the South-eastern Mediterranean region of the EU has had a positive effect in increasing households' awareness of energy use, but there are still shortcomings in implementing energy efficient technologies, particularly as the human behaviour factor has largely been neglected by scholars (Gonzales-Cacenas *et al.*, 2020; Organ, 2020). Knight *et al.* (2021) stress that the EEG has been debated for decades by scholars because they are still questioning whether or not investing in energy efficiency is worth it. Reviewing all these views on the EEG, it appears that scholars do not agree on a single research pathway for determining the EEG. Figure 3.16 demonstrates a developed step-by-step system for integrating the STS conceptual framework with the concept of the EEG.

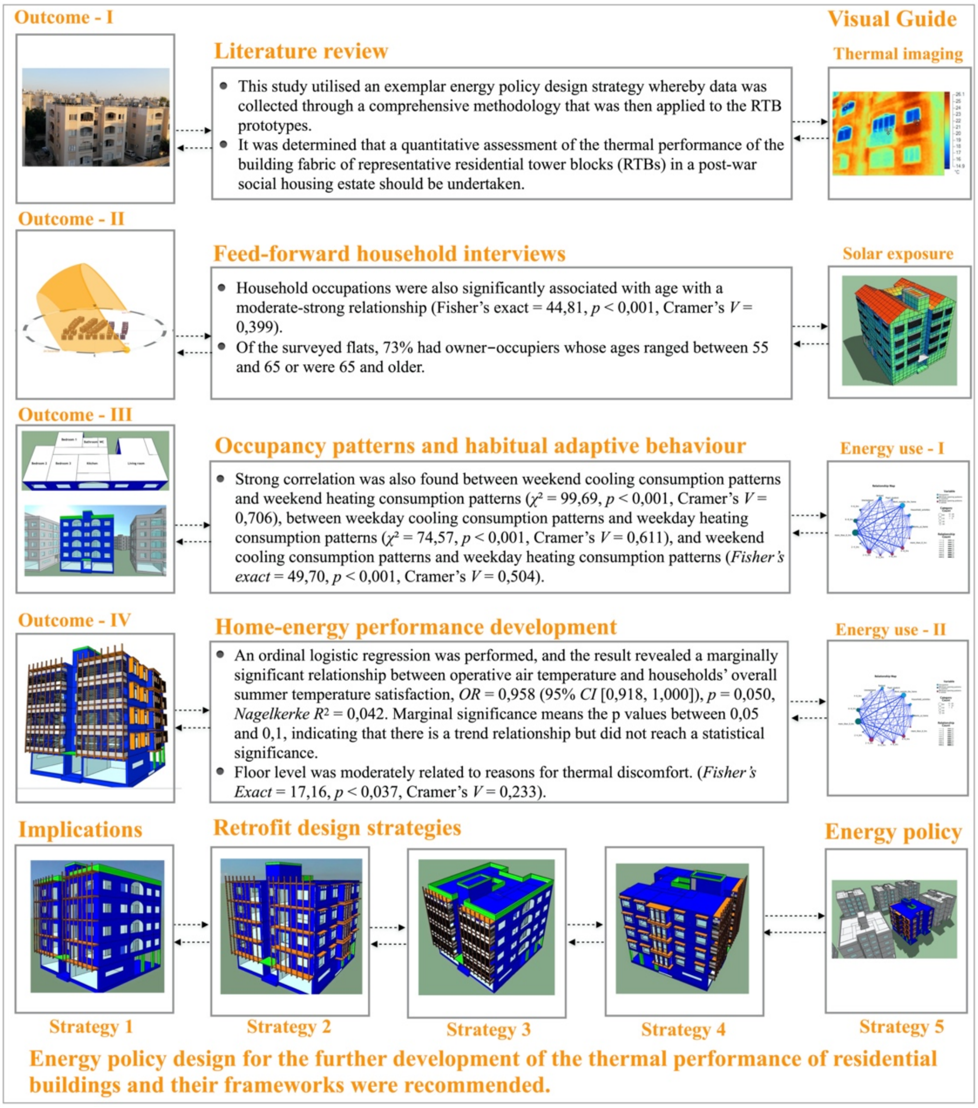


Figure 3.16: Comprehensive research framework applied to develop a retrofit policy design.

A review of other scholars' work in the EEG field is necessary for integrating the STS conceptual framework into EEG research to avoid research bias and provide reliable energy efficiency measures. All the referred pilot studies conducted extensive research to understand the factors that create the EEG. Despite constraints reported by earlier studies after the implementation of the EPBD, there is great potential for considering the EEG when taking into account energy efficiency, energy performance development and energy policy design.

The starting point for the present study was the human-based data that enabled a triangulation of the findings from the collected data, which were further enriched and verified by a field investigation. To ensure a systematic analysis of the key aims and objectives, this study adopted a mixed-method research design approach by conducting a building-energy performance evaluation with the use of dynamic thermal modelling and simulations, which was then validated by a comprehensive questionnaire survey, thermal imaging and *in-situ* measurements of the base-case prototype RTBs in the post-war social-housing development estate in NC. In general, each phase was carried out in a sequential order to facilitate a discussion of the literature review that was conducted as part of the main research scope. Table 3.3 outlines the development of a novel STS conceptual framework.

Table 3.3: Step-by-Step Development of STS Conceptual Framework.

STS Development Structure	Guidance to Develop a Method for Current Design Approach
Step 1: ***Literature review***	To undertake a literature review based on selected key terms—'overheating risk', 'thermal comfort', 'occupant behaviour and energy modelling' and 'building-energy simulations'—to address the knowledge gap in the field of energy efficiency and to develop a new design method for the STS approach.
Step 2: ***Questionnaire survey***	To conduct a questionnaire survey that will assess household-energy performance and the energy-use patterns of occupants prior to and following the energy-saving measures implemented in the selected archetype buildings.
Step 3: ***Thermal-comfort survey***	To make recommendations that will support successful delivery of current and future policy schemes related to retrofitting efforts for existing residential buildings that take occupant thermal comfort into consideration to promote evidence-based retrofitting interventions.
Step 4: ***Measurements and Monitoring***	To concurrently conduct *in-situ* measurements and *on-site* monitoring through semi-structured interviews with households to assess the degree of overheating risk that they experienced and to thoroughly identify their thermal-comfort preferences.
Step 5: ***Building-energy modelling***	To model and simulate the base-case representative RTBs to test the current energy performance of the structures before implementing retrofitting design strategy phases for energy policy. In line with the overheating and thermal-comfort assessments, the CIBSE *TM59 Design Methodology for the Assessment of Overheating Risk in Homes*, which was embedded in the building modelling simulation phase of the present study.
Step 6: ***Building performance evaluation***	To test the validity of environmental monitoring and modelling outcomes in the IES software suite by using actual meteorological year (AMY) weather files, occupancy patterns and the occupants' habitual adaptive behaviours and window-opening schedules in the summer.
Step 7: ***Retrofitting policy design***	To develop a novel design guideline for retrofitting efforts in post-war housing stock and to demonstrate the feasibility of implementing passive-cooling design systems and energy-consumption-reduction measures during pre- and post-retrofitting phases

3.3 Method of Design Applied in Statistics

3.3.1 The Concept of Statistical Representativeness

In order to provide a background analysis for developing the concept of statistical representativeness, this section presents a review of selected theoretical information and exemplar pilot projects and their applicability. Table 3.4 delineates the original research articles that were reviewed to identify the most appropriate concept of statistical representativeness for the present study.

Table 3.4: Reviewing the Concept of Representativeness in Statistics.

References	Concept(s)	Method(s)	Outcome(s)
Chasalow and Levy (2021)	Law, social and behavioural sciences	- Stratification of population sample size - Generalisability of research findings	Equal representation of each subgroup of the user population was recommended
Hirsch and O'Donnell (2017)	Education, social and behavioural sciences	- A multiple-choice test-based survey was distributed - Descriptive statistics - 4 x 2 chi-square test of independence	A unique set of test questions to identify students who hold common representativeness was developed
Schmill *et al.* (2014)	Global change sciences (i.e., human factors, climate, remote sensing)	- Pearson's chi-square tests - Heat mapping - Histograms - Kullback-Leibler *f*-divergence test - Multivariate analysis	Implementing a variety of methods for making assessments about the representativeness of a collection of case studies across the globe
Schouten *et al.* (2009)	Social and behavioural sciences	- Population R-indicators - Chi-square statistics used to test independence and goodness-of-fit - Logistic regression models	A mathematically rigorous definition and perception of representative response was developed

Hama *et al.* (2020) and Hu and Kohler-Hausmann (2020) highlight the importance of the integration of the STS approach into using the conceptual analysis of sampling size to test associations gathered through various experimental statistical analyses. Chasalow and Levy (2021) discuss the STS approach providing a multidisciplinary integrated conceptual framework that enables both statisticians and engineers to interrogate taken-for-granted terms and categories while developing benchmarks in energy-policy design. These studies indicate that representativeness of sampling size shows differences between one pilot study and another, due to demographic structures, geography and the political conditions of each research context.

Chasalow and Levy (2021) explain their own representativeness concerns while developing a novel methodological framework for representativeness in statistics, politics and machine learning. In this theoretical study, these scholars contribute a sense of the variety of meaning and values associated with representativeness in order to prove the validity of chosen sampling sizes. Chasalow and Levy indicate that they did not select a large sampling to develop their own representative study. In their pilot research project, these scholars predominantly focused on sampling in Europe and the United States more than other parts of the world. According to Chasalow and Levy, it is difficult to identify the limitations of their own selected sampling size representativeness because of the geographical extent of their research context. To avoid a research bias and provide a generalisation of their research findings, their study set out to offer reliable and statistically representative sampling criteria that would allow the targeted reader group to understand their research outcomes.

Garett (1942), Jensen (1926), Kurksal and Mosteller (1980) and McNemar (1940) all discuss the issue of how to check a particular sample for representativeness. Kiaer (1976) states that "the representative method can be applied in several ways". To explain this claim, Kiaer develops two different sample types. His first method is an arbitrary filtering of the variables gathered from the sampling. Kiaer explains that this selection should be done in a "haphazard or random way" to avoid giving preference to subject respondents in certain occupations or belonging to particular social strata. This method of selection highlights that the representativeness of sampling size results from the absence of selective discretion. His second method involves allocating representativeness in a mechanical procedure that can provide a feasible method of design to undertake statistical analysis faster and provide an opportunity to detect discrepancies in the sample.

In previous studies that develop the concept of statistical representativeness of sampling size, one of the main strengths of the selection of a random sampling method is that it enables the use of all available data to ensure a proportionate match on known relevant variables. This was proven by Kiaer in 1976 in a population study that consisted of surveyors in rural areas and used census data to allocate counts per country and then selected districts within the countries to "represent the main industry groups within the country as well as its various geographic conditions" (Kiaer, 1976). This method of design demonstrates that it can be applicable to choose a single geographic domain to develop the concept of statistical analysis by integrating census data and applying outcomes to other geographic domains that have been shown to have similar demographic structures, political assets and cultural norms.

Hirsch and O'Donnell (2001) used a 4 x 2 chi-square test of independence to determine whether performance on a test was dependent on students' experience. For the statistical analysis, Cramér's V was chosen to measure the association between variables; this study reported findings with low *p*-values by selecting the conventional measurement of $p < 0.001$. Shaughnessy (1992) and Konold (1991) identify a knowledge gap for overestimating students' understanding of probability by using applicable test instruments to identify the representativeness of a sample size. This also creates some concern about the consistency, reliability and calculation of adequate sampling size for statistical analysis.

Hirsch and O'Donnell (2001) have developed a scientific method of design that measures the reliability of datasets and the applicability of concepts of statistical design to provide an understanding of conceptual change that can have a long-term impact on conceptual-level analysis. Schmill *et al.* (2014) developed a theory of analytics for assessing global representativeness in social science studies to guide future scholars that was aimed at addressing sampling bias and providing a public domain for similar pilot projects. This pilot study aimed to reduce the gap between local and global researchers in providing analytical methods of design that could help scholars assess the representativeness of a sampling size and assist in correcting any bias for the interpretation of statistical findings. Schmill *et al.* (2014) recommend the chi-square test as the most appropriate statistical method that allows scholars to apply to their own hypothesis testing. In the Schmill study, Pearson's chi-square tests were used for testing the independence of two samples using a model function defined over a contingency table of observed versus expected values.

Schmill *et al.* (2014) clearly highlight that the chi-square test is useful in computing representativeness, which gives the degree of extent for the global representativeness of case studies included in the dataset. Schmill *et al.* also indicate that the chi-square analysis is the standard and most applicable practice in many disciplines and it allows researchers to provide a reliable result without requiring any research limitations at the time of addressing their own research hypotheses. However, Schmill *et al.* recommend that the chi-square test is not an applicable test for sample sizes of less than 50, or when the expected frequency for more than one category is less than 5. These statistical criteria provide a reasonably representative sample size that should be considered to prevent any research bias. Schmill *et al.* (2014) also indicate that Fisher's exact test can help in cases where there is an expected frequency of zero to avoid any research bias in relatively small sample sizes.

The concept of using a statistical method allows researchers to avoid research bias while undertaking multinominal logistic regression analysis to determine benchmarking criteria for their own research hypothesis. Schouten *et al.* (2009) have developed benchmarks for the representativeness of survey responses in order to reduce the risk of non-response when developing a statistical dataset extracted from field survey responses. Schouten *et al.* propose that the R-indicator, which is related to Cramér's V, be used as a measure for the association between response and non-response variables. Their study indicates that the R-indicator was selected as a lack-of-association measure for a given sampling size. Schouten *et al.* highlight that for assessment of the R-indicator, the weaker the association the better; this implies that there is no evidence related to the issue of no-response rate and this issue has not affected the composition of the observed data.

Little and Rubin (2002) describe the concept of representative response as closely related to missing-data mechanisms, such as Missing-Completely-at-Random (MCAR), which is a standard method of design applied to multidisciplinary studies globally. Schouten *et al.* (2009) stress that the applicability of the MCAR test should be considered for longitudinal field surveys, particularly where the target group is householders, to provide a statistically representative sample size. Schouten *et al.* also indicate that chi-square test statistics are often used to test independence and goodness-of-fit for exploring discrepancies between any survey items and the missing-data-mechanism.

To prove the representativeness of a sample size, Schouten *et al.* (2009) developed a benchmarking criterion where researchers can apply chi-square statistics to χ in order to measure the reliability between true response behaviour and the response behaviour that is expected when response is independent of χ. This concept of statistical benchmarking criteria indicates that Cramér's V is an association measure that enables a transformation of chi-square test statistics to the [0, +1] interval. It should be noted that Cramér's V provides a universal design approach to other researchers that they can apply to test associations gathered through longitudinal field surveys.

Goodman and Kruksal (1979), Bentler (1990) and Marsh Bella and McDonald (1988) indicate that there are many applicable association measures developed by earlier statisticians to identify representativeness of sample sizes. Therefore, these scholars recommend that R-indicators have a strong relation to response parameters. Goodman and Kruksal (1979) outline that R-indicators are for measuring in a multivariate setting to avoid any discrepancies at the time of undertaking statistical analysis.

To test the reliability of their statistical analysis, Schouten *et al.* (2007) conducted logistic regression models to predict the type of responses expected. In a further study conducted by Schouten *et al.* (2009), the researchers developed an advance indicator to identify the concept of statistical representativeness of sample sizes. In this pilot study, the researchers found that the field survey approach gave more accurate results regardless of the limitation of only being able to recruit relatively small sample sizes. As an outcome of this pilot study, Schouten *et al.* (2009) recommend that in multinominal logistic regression models, variables give a significant contribution at the 5% level, and where this cannot be done, these variables should be excluded from the sampling size.

In conclusion, the reviewed papers inform us about the theoretical aspects of the development of relevant statistical backgrounds globally. Through the review of these papers, it was found that Cramér's V tests allow researchers to measure associations gathered through longitudinal field surveys, thus allowing researchers to develop an evidence-based benchmarking criterion. While this section discusses theoretical information around the concept of statistical representativeness, further exemplary pilot studies are reviewed and discussed in Section 3.3.2.

3.3.2 References to the Works of Other Scholars on Representativeness

This section presents a review of pilot studies that have examined different methods in statistics to avoid research bias and develop a reliable concept of statistically representative sampling sizes. This section supports the selection criteria of conventional statistical analysis for non-parametric or parametric tests, and also provides guidance to readers developing their own statistical methods in the building engineering field. Table 3.5 delineates the original research articles that were reviewed to understand the development of a statistically representative population sample.

Table 3.5: Reviewing Pilot Studies to Develop the Concept of Representativeness in Statistics.

References	Concept(s)	Method(s)	Outcome(s)
Beresewicz (2017)	Business, economics and information technology	- Self-selection survey - Domain-level data - Deterministic and probabilistic approaches	Advantages and disadvantages of measuring representativeness by using individual and aggregated data is outlined
Bertino (2006)	Statistics	- Power function and coverage probabilities used to calculate representative population sample size - Cramér–von Mises criterion	The utilisation of the representativeness function in many standard statistical constraints is outlined through experimental statistical techniques
Marsh *et al.* (1988)	Statistics	- Goodness-of-Fit indicators - Stand-alone indexes - Incremental-fit indexes	Guidance on the effects of sample size and data set on the fit indexes distributed
Barratt *et al.* (2017)	Social and behavioural sciences	- Web-survey method - Global drug survey developed - Descriptive statistics - Identification of continuous and categorical variables - Adjusted R-square for the probabilistic analysis	Opt-in web surveys of hard-to-reach populations are an efficient way of gaining in-depth understanding of stigmatised behaviours and are appropriate
Cornesse and Bosnjak (2018)	Business, economics and information technology	-General sample-based R-indicators	Probability-based samples are more representative
Li and Brimicombe (2008)	Geo-information and statistics	- Small area population modelling approach was adopted - The raw datasets of local scenarios were cleaned and then checked with each other in order to control data quality	The findings were implemented to support local social infrastructure planning in the Thames Gateway London boroughs in the UK
Li and Brimicombe (2011)	Geo-information and statistics	- Average weighted distance by small area geography method was applied - Regression analysis conducted to explore the effect size of an average weighted Euclidean and network distance	The Euclidean distance approach has less computational load and is generally applicable, particularly where rapid “what-if” analyses are required for decision support in a planning context
Brimicombe and Mungroo (2018)	Health, geography and social sciences	- Locally available secondary data sources - Welch's two-sample t-test - Correlation-tree analysis - Euclidean distance method	Visualisation map to demonstrate the distances between GP practices by using the conventions of various statistical methods could provide an effective mechanism for policymaking decisions

Beresewicz (2017) developed a two-step procedure to measure representativeness of internet data sources. In this study, Beresewicz focuses on representativeness and non-sampling errors to avoid any research bias while developing the dataset for parametric analysis. Several types of surveys and their pros and cons are also discussed. Beresewicz's analysis is in line with the survey recommendations provided by Bethelehem and Biffignadi (2011). The Bethelehem and Biffignadi study stresses that a self-selection survey can provide a true response and also avoid any bias in research outcomes.

On the contrary, Kruksal and Mosteller (1979a, 1979b, 1979c) argue that there is no straightforward definition of a statistically representative sample size. These scholars tabulate a list of definitions used in the conventions of statistical dataset preparation and interpretation, as follows: *(i)* unjustified obtained data, *(ii)* absence of dependent variable, *(iii)* lack of population sample, *(iv)* typical archetypes, *(v)* general representativeness of sample population, *(vi)* clarification of vague terms, *(vii)* dominant representativeness of targeted population sample, *(viii)* precise estimation obtained from precise population sample, *(ix)* reasonable fraction of a population sample for a particular purpose. Kruksal and Mosteller claim that all these stated types of population samples could be counted as representative samples.

Beresewicz (2017) discusses the importance of selection of actual data to avoid any errors during the data preparation stage; his study implements a referred statistical convention to measure representativeness of sampling size by using both individual and aggregated data. As an outcome of this pilot study, Beresewicz recommends that to assess the representativeness of new data sources, the time series of historical data should be considered by future scholars. He also suggests that data collated over time may reveal similarities to existing data sources.

To follow this recommendation, in the present study, time-of-day factor was used to present *in-situ* measurements of environmental parameters in order to foresee the benchmark indicators when undertaking the building performance evaluation. The statistical convention Beresewicz developed proved to be an appropriate statistical convention to use in this study.

Bertino (1998) defines the representativeness of a random sample as "the degree of capacity of the sample to demonstrate the typical or dominant characteristics of the targeted sample population". In light of this theory, Bertino conducted an empirical study to measure the representativeness of a sample population to provide a reliable source for inferential purposes. In this experimental study, the Cramér's V statistical method was used to identify measures for the observed values. The study set out to assess the degree of efficiency of several conventional techniques (i.e., power function, coverage probabilities) in order to support the representativeness function of the selected sample population. Bertino conducted hypothesis testing to measure the sample population and to renumerate the representativeness index, which can be used in a similar design approach to the Cramer–von Mises test.

Marsh *et al.* (2006) developed a novel goodness-of-fit index in a confirmatory factor analysis to assess the effect of sample size. In this pilot study, observed variables were selected to provide a background for a multivariate distribution. Marsh *et al.* considered large sample sizes to include for their statistical analysis. To assess the degree of associations in large sample sizes, in this pilot study the chi-square test was chosen because this method of design can be applied to testing the efficiency of the goodness-of-fit base of the stratified data on a large sample size while interpretating statistically significant chi-square outcomes.

To prove the empirical analysis developed by Marsh *et al.* (2006), the present study examines a theory developed by Hoelter (1983). This is in order to understand how the present study has been impacted by previous scholars' statistical methods in terms of applicability and in terms of bringing theory into practice to enable the development of benchmark criteria and energy policy implications in the residential sector. Hoelter states that "sacrificing the power of a test by utilising small sample sizes simply blinds the researcher to significant differences between a model and the data" (Hoelter, 1983). To avoid this mistake, the present study aims to avoid bias and develop a set of methods as outlined by Bertino (2006) above.

Marsh *et al.* (2006) indicate that the interpretation of Cramér's V findings will generally fall between 0 and +1, but their experimental study shows that it is also possible to detect negative findings for relatively small sample sizes. Marsh *et al.* report that higher values reflect more reliable outcomes for all benchmarking indexes and most outputs are positively intercorrelated. This finding may support the hypothesis testing model developed by Bertino (2006) discussed above. Marsh *et al.* discuss the indexes used to calculate what sample size is adequate to conduct a relevant statistical analysis. To this extent, no absolute criterion has been found to be acceptable for sample limitation. Bentler and Bonett (1980) found that $N = 90$ was an acceptable minimum population size to conduct their parametric analysis, while Hoelter (1983) found that $N = 200$ was an acceptable sample size. The variance in these studies shows that there have been many acceptable conventional theories developed by previous researchers, and an inability to apply conclusions to other scholars' research hypotheses may be due to both the constraints and strengths of analytical methods and the implications of individual studies. Table 3.6 delineates the strengths and constraints of using both individual and domain data at the time of developing a statistically representative population sample size.

Table 3.6: Strengths and Constraints of Measuring Representativeness in Statistics.

Aggregation level	Strengths	Constraints
Individual data	1. Measuring representativeness at any level 2. Detection of the selection mechanism 3. Control over data processing and cleaning 4. Linkage with units or objects from statistical and non-statistical data sources 5. Assessment of uncertainty of estimates	1. Limited access to individual data 2. Time consuming data cleaning process 3. Linkage uncertainty 4. Linkage may be legally prohibited or impossible
Domain data	1. Alternative when individual data is not available 2. Overall information about consistency with official and non-official data 3. May provide a general overview of the data without time-consuming data cleaning processes 4. May indicate whether the use of such data is possible for official statistics	1. Limited possibilities of measuring representativeness and the selection mechanism 2. Requires historical timeseries data for comparison 3. Requires harmonisation with available domain-level data 4. Lack of a measure of uncertainty of estimates

Source: Pelenur (2013)

Barrat *et al.* (2017) conducted a global drug survey in order to determine a representative sample. Their data was gathered through a call-back survey. To identify the representativeness of this global database, Barrat *et al.* discuss the theory of representativeness developed by Kruksal and Mosteller between 1979 and 1980, discussed above. Barrat *et al.* also highlight that the representativeness of a sampling size may show differences due to the research hypotheses of each survey and the response rate of sampling to be included in the dataset.

Gobo (2007) argues that a household survey with 100 variables will create weights on variables that can be matched to population distributions. In line with this theory, Barrat *et al.* (2017) proves that for the statistical representativeness of household surveys, a minimum of $N = 100$ is required to provide reliable research outputs.

In the 2017 global drug survey conducted by Barrat *et al.*, age was pre-coded as a categorical variable with indicators for categories of participant age as follows: 15–19, 20–24, 25–34, 35–44, 45–54, 55–64, 65–74 and 75+. However, the sample from the Australian database used age factor as a continuous variable, and the researchers gathered the continuous variable from the Australian context as a categorical variable. This present study shows a similar design approach in terms of exploring households' sociodemographic characteristics: the conceptual data preparation strictly considered age as a categorical variable, but the gathered information from households was numeric and was counted as a continuous variable to understand the standard deviation (SD) and mean of the selected household populations.

Cornesse and Bosnjak (2018) investigated an association between survey characteristics and representativeness in order to provide a reliable conceptual framework to conduct an appropriate statistical test. This pilot study also referred to the previous experimental analysis conducted by

Kurksal and Mosteller (1979a, 1979b, 1979c). One of the main parallels is that these studies refer to the success and also reliability of survey estimates as mirroring the "true" parameters of a target population. Cornesse and Bosnjak recommend that random survey sampling is an applicable method of design to develop the convention of statistical analysis.

Cornesse and Bosnjak (2018) recommend that a mixed-mode survey can increase the representativeness of a sample size and enable researchers to conduct a statistical analysis in accordance with their research hypotheses. Kreuter (2013) identifies the term "auxiliary data", by which he means combining all available data from both respondents and non-respondents to enhance post-survey adjustments and provide an effective method of design for the data preparation stage.

Brick and Kalton (1996) and Kreuter and Olson (2011) argue that accurate identification of aggregated data shows limitations for constructing sampling from data, survey pro-data and data linked to survey data, when considering a particular population sample. One of the main constraints is the lack of aggregated data available on municipality and district levels to construct accurate and reliable datasets that can represent collated data on a national level.

Schouten *et al.* (2009) highlight the importance of using representative sample-based R-indicators to measure the effect sizes between dependent and independent variables to identify the national representativeness of sample sizes and their effects on a developed research hypothesis. To support this theory, Cornesse and Bosnjak (2018) stress the importance of using logistic regression models of propensity to identify accurate effect-size measures for parametric tests. These studies predominantly discuss the concept of statistically representative sample sizes and how this concept enables researchers to decide on appropriate statistical methods of design for their statistical analyses.

After thorough review of these pilot research projects, this present study finds the assessment using global representativeness of heat mapping to foresee global patterns conducted by Schmill *et al.* (2014) to be one of the best exemplar studies. It provides a synthesis of pilot studies and brings the findings of local case studies out by demonstrating globally representative sample sizes in the public domain. The technical effectiveness of this study is due to the use of Pearson's chi-square tests to measure the independence of two samples. Additionally, the study uses a function defined over a contingency table of observed versus expected values. This selected conventional method of design enables the researchers to set a common design approach that can be applied by other scholars when developing nationally representative sample sizes.

Another pilot study, conducted by Schouten *et al.* (2009), clearly outlines the benchmarking indicators for the representativeness of survey responses; the study stresses the use of R-indicators related to Cramér's V measures for the association between dependent and independent variables. To this extent, Schouten *et al.* recommend that random sampling surveys require the use of well-known chi-square statistics because of the need to use the independence test and goodness-of-fit. These technical details relate to the development of conventional statistical analysis and can provide reliable effect-measure sizes.

Alvarez and Mossay (2006), Griffith and Wong (2007) and Oshungade (1986) discuss the effectiveness of the integration of administrative datasets by using limited geographic regions to develop an appropriate method of design for statistical analysis. This convention enables researchers to conduct population modelling in agreement with frequently updated regional administrative datasets. In line with this concept of statistical detail, Li and Brimicombe (2008) conducted a scenario-based small area population model for social infrastructure planning in London. This study set out to investigate the population of each individual borough to propose effective solutions for modelling multiple data sources and included a wide range of local administrative datasets applied to small-area geography. By contrast, the pilot studies conducted by Schmill *et al.* (2014) and Schouten *et al.* (2009) discuss the applicability of the development of a universal design approach to provide more reliable outputs for their own statistical analyses.

In the study conducted by Li and Brimicombe (2008), a small area of a particular location was selected intentionally by collecting secondary data resources from administrative datasets to conduct a statistical analysis for modelling proposed design scenarios. In like manner, the selection of a particular case study location and conducted statistical analysis could be applied to the other regional pilot studies that aim to integrate particular households, demographics and cultural assets for their own scenario-based modelling approaches.

Li and Brimicombe (2011) investigated a new variable for spatial accessibility measurement in social infrastructure planning. In this study, UK census data was used to develop their statistical analysis. For the concept of statistical representativeness, an average weighted distance method was applied by selecting small-area geography. The London Borough of Haringey and the Uttlesford district were selected as case study locations and the Euclidian distance method was applied to measure network distances for a regression analysis. To understand the method of design applied by Li and Brimicombe, we looked back at the theoretical study conducted by Chasalow and Levy (2021) on representativeness in statistics, politics and machine learning, and found that a representative method of stratification could be applied at the time of developing a dataset where the data gathered from municipalities or local administrative resources enables the generalisation of the research outputs for decision-making criteria.

Brimicombe and Mungroo (2018) conducted a statistical analysis to explore geographical variation in general practice (GP) drug prescriptions for schizophrenia and similar psychoses in England. This pilot study used monthly files on GP's prescribing practices for England, which were downloaded from the National Health Service (NHS) digital database. This data was then aggregated by the 326 local authorities in England. Brimicombe and Mungroo used the Euclidian distance method by using GP survey postcode data to measure the effect-size differences between urban and rural locations.

According to the benchmark indicators for the representativeness of survey responses, Schouten *et al.* (2009) recommend that the concept of representative response be closely related to missing-data mechanisms, such as MCAR, and their theoretical study also suggests that randomly sampling criteria by using a population sample to conduct statistical analysis is the most appropriate statistical method of design.

In conclusion, the pilot studies conducted by Li and Brimicombe (2008, 2011) and Brimicombe and Mungroo (2018) highlight that the selection of particular small-area geographies, such as local case study locations in a given country, requires a representative sampling criterion to develop a feasible and nationally representative statistical analysis. While, conversely, Schmill *et al.* (2014) and Barratt *et al.* (2017) discuss the efficacy of developing globally statistically representative datasets by using survey samples gathered through random sampling data collection instruments.

With these methods in mind, the present study aims to use the method of small-area geography by undertaking a questionnaire survey to develop a statistically representative sample size; findings are supported by census data and national housing survey datasets to avoid any research bias and provide applicability of research outcomes to other EU-27 countries when developing evidence-based energy policy design scenarios.

3.3.3 Sample Size Calculation Criteria

This section reviews other scholars' work in multidisciplinary studies on determining the applicable method of design for establishing sampling size. This section also reports on the statistical representativeness of sample size to provide background information on the identification of margin of error; this enables the study to provide acceptable and more reliable benchmarking criteria. To calculate sample size criteria, first the margin of error was calculated using an online calculator[1] in accordance with the suggested conventions in statistical analysis. After thorough calculation of the sampling criteria, power estimator analyses were conducted in order to establish the validity of the Fisher's exact tests and the Pearson's correlation tests.

The online calculator findings report that – with the confidence level set at 95%, sample size set at 100, population proportion set at 50%, and population size set at 1,440 – the margin of error is 9.46%. This means, there is a 95% chance that the real values are within ±9.46% of the measured/surveyed value. Figure 3.17 demonstrates the applicable calculation method for the present study.

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[1] ***Source:*** https://www.calculator.net/sample-size-calculator.html

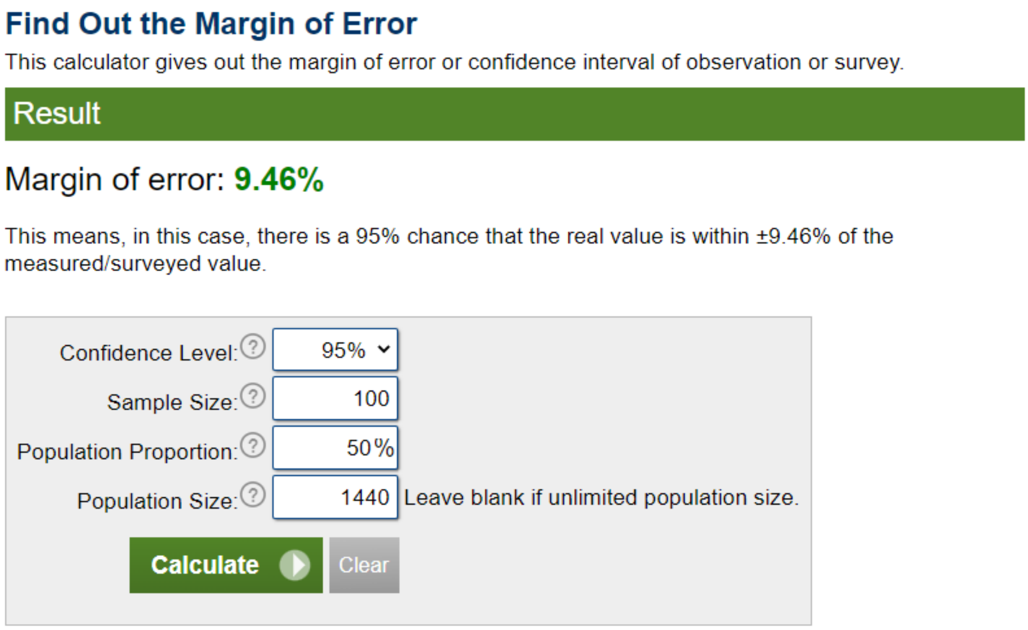

Figure 3.17: Calculation of margin error in the present study.

As shown in Figure 3.17, the margin of error was found to be 9.46%. However, the conventional recommendation for a margin of error calculation is that it should be 5% with a population proportion set at 50%. Many scholars indicate that 5% is the generally accepted benchmark criteria for developing a statistical analysis. The reason for this 5% threshold is that it is necessary to interpret statistical findings and to explore their impact on the outcome of research projects. For example, the traditionally acceptable interventions of the Fisher's exact test and Pearson's correlation analysis findings require the identification of a 5% threshold level in order to provide a reliable statistical interpretation and level of frequency to determine the significance of the statistical findings.

In the present study, the margin of error was found to be 9.46% and this is not within the traditionally acceptable threshold limit. However, many scholars indicate that a threshold level in the 10–20% range can be accepted to demonstrate statistical representativeness of sample size. Tables 3.7(a) and (b) introduce other scholars' works that contain sampling size criteria within the range of 10–20%. After thorough analysis of previous scholars' work on the identification of a sufficient sample size, it appears that some studies recommend a margin of error between 10–20% as a traditional threshold level in the building engineering field. This is the reason that, in the present study, the identified 9.46% margin of error is considered to provide a reasonably acceptable sample fraction for undertaking statistical analysis.

On further questioning the identified 9.46% margin of error, a *priori* power analysis using G*Power 3.1.9 was conducted to determine the minimum sample size. With the power set at 0.08, alpha level set at 0.05, a moderate effect size of 3.5 (odds ratio) and with the proportion of the control group at 0.5, results indicate that a total of 104 participants would be needed in order to reach an adequate sample size for running crosstabulations using Fisher's exact tests, as shown in Figure 3.18(a). This sample size was also sufficient when running the correlation analysis, as shown in Figure 3.18(b).

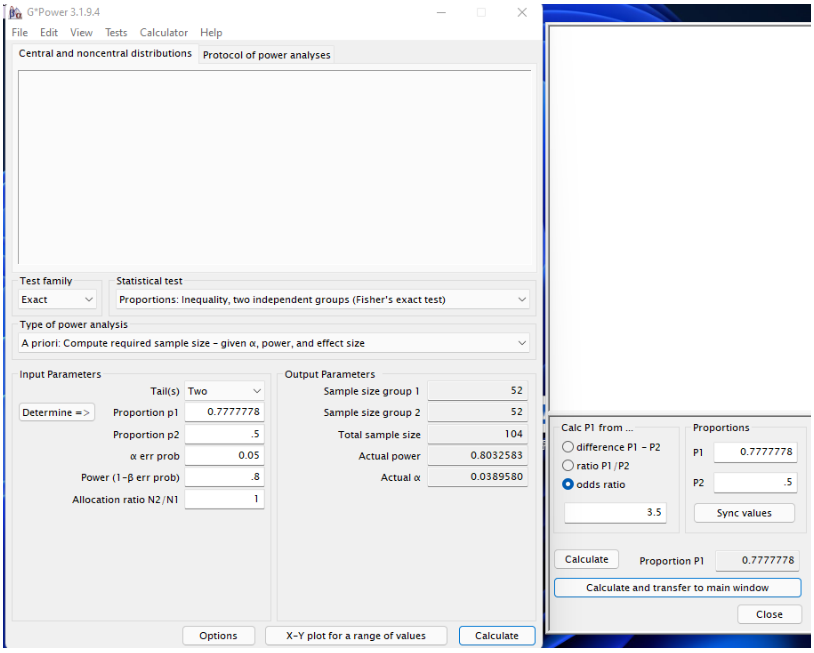

Figure 3.18(a): The step-by-step calculation to prove the validity of using Fisher's exact test.

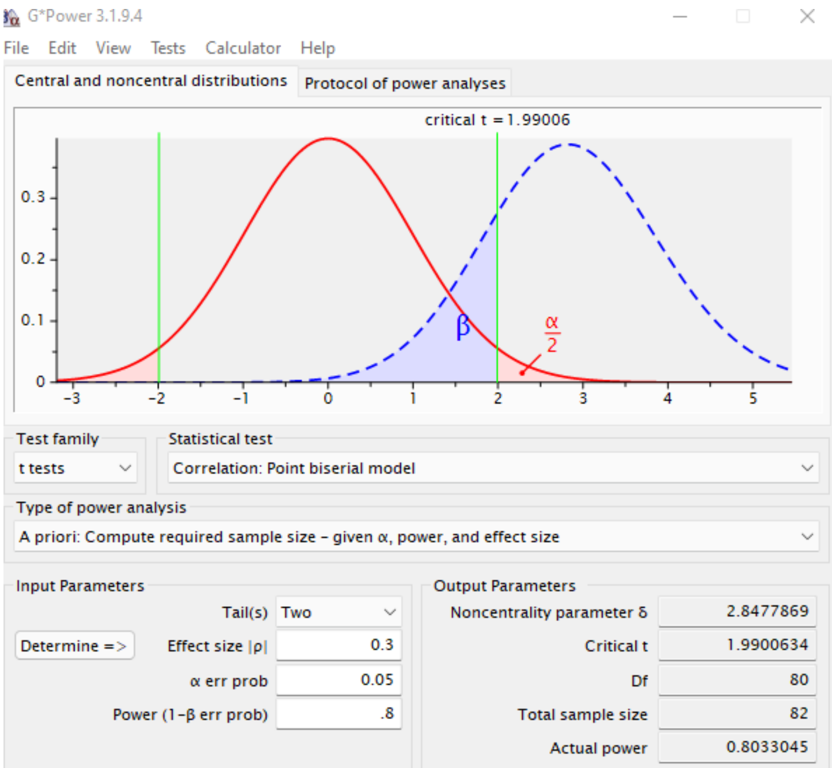

Figure 3.18(b): The step-by-step calculation to prove the validity of using correlation analysis.[2]

[2] G*Power is a tool used to compute statistical power analyses for many different *t*-tests, *F*-tests, *z*-tests and χ^2-tests. G*Power can also be used to compute effect sizes and to graphically display the results of power analyses. ***Source:*** https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower

In the present study, both the conventional online calculator and power analysis were used. One of the reasons for this was to provide an exact clarification regarding the power of the sampling size because the sufficiency of sampling size plays an important role in explaining the significance of research outcomes (see both **Appendix F** – Sample of Validation Results for the Statistical Analyses and **Appendix G** – Sample of Outliers Test). Previous scholars' work indicates that using the online calculator may lead to inaccuracies because the researcher may have misinterpreted the population. To avoid any research bias, the present study also conducted power analysis to foresee the impact of the population size for interpretating the statistical analysis.

Theoretical information on power analysis recommends that the acceptable threshold level should be 80% in order to determine statistical findings. This means that the use of Fisher's exact test and Pearson's correlation analysis could provide effective and more reliable research outcomes at the time of developing an evidence-based energy-policy design (see **Appendix I** – Development Stages of the Statistical Analysis – Part 2).

To develop the concept of statistical representativeness of sample size, the present study reviews other scholars' work to provide an evidence-based statistically representative sampling criteria that sets out to determine the threshold range between 10–20% used by previous scholars. This review aims to demonstrate that a margin of error between 10% and 20% can be an applicable threshold level in the building engineering field. Tables 3.7(a) and (b) delineate the review of exemplar studies.

Table 3.7(a): Reviewing the Theoretical Approach in Representativeness.

References	Concept(s)	Method(s)	Outcome(s)
Al-Momani (2000)	Construction management	- Descriptive statistics - Bar-chart representation - Regression analysis	Guidance to help construction managers in establishing reliable evaluation criterion
Owen *et al.* (2006)	Social and behavioural science	- Exploratory factor analysis - Descriptive statistics -Missing data and outliers tests conducted - Data missing at random (MAR) - Confirmatory factor analyses – cross validation technique	Exploratory and confirmatory factor analyses formed the central portion of this reappraisal of the psychometric properties developed The conducted questionnaire survey could be successfully shortened from 27 to 14 items
Saka and Chan (2020)	Architectural engineering and design management	- A pilot survey was carried out by administrating the questionnaire proforma - Descriptive statistics - Mann-Whitney U test	Guidance on knowledge, skill and functionality requirements for quantity surveyors in building information modelling

Table 3.7(b): Reviewing the Theoretical Approach in Representativeness. (Continued)

References	Concept(s)	Method(s)	Outcome(s)
Willcoxon and Chatham (2006)	Business management and social science	- Longitudinal survey - Descriptive statistics - Pearson's correlation analysis	Guidance on testing the accuracy of the representativeness of sample size selected to develop effective policymaking decisions
Borrego *et al.* (2009)	Education and building engineering	- Descriptive statistics - Chi-square test - Pearson's correlation - ANOVA - MANOVA	Guidance on the applicable representative sampling criteria Evaluation criteria for quantitative, qualitative and mixed-methods research

Al-Momani (2000) conducted a survey of 130 public projects constructed in different regions of Jordan between 1990 and 1997. To provide a roadmap for policymakers, descriptive statistics, correlation coefficients and linear regression analysis were used to measure the effect of the selected sampling size on the research outcomes.

Owen *et al.* (2006) developed a psychometric re-evaluation of the Women in Science Scale to determine an exploratory factor analysis. In this pilot study, 1,439 middle and high school students were recruited to participate in the statistical analysis. In the questionnaire survey proforma, 27 items were asked to the participants to explore the correlations between dependent and independent variables.

In this pilot study, Owen *et al.* asked the students to circle a number on a 6-point Likert scale that reflected their true feelings for each item. The response format ranged from Strongly Agree (1) to Strongly Disagree (6), with no option of a neutral response. The variables that were set out to measure the students' responses on the Likert scale were included as "ordinal" to run an appropriate statistical analysis. Owen *et al.* used the factor analysis method as their main conceptual method of design to generate research outcomes in accordance with their research hypotheses. In this pilot study, every confirmatory factor analysis (CFA) was inspected for potential multivariate outliers, defined as those with significance ($p < 0.001$). One-way ANOVA was used to probe the multivariate results. Table 3.8 demonstrates the lists of variable scaling requirements for several widely used statistical procedures.

Table 3.8: Selecting a Statistical Procedure Based on Variable Scaling.

	Scale of Criterion	
Scale of Predictor	**Categorical**	**Continuous**
Categorical	Logistic regression or log-linear analysis	ANOVA
Continuous	Logistic regression or discriminant analysis	Ordinal logistic regression (OLS)
Categorical or continuous	Logistic regression	Ordinal logistic regression (OLS) with dummy coding

Note: The table is not meant to be exhaustive. When faced with all categorical variables, for example, a chi-square test of independence could be applied. However, log-linear analysis is preferable due, in part, to its ability to include interaction terms in the model.

Source: Adapted from King (2011)

Saka and Chan (2020) conducted a longitudinal survey on the knowledge, skill and functionality requirements for quantity surveyors in the building information modelling (BIM) environment, using a case study in Delphi. A pilot survey was carried out by administrating a questionnaire to 25 target experts, including researchers and practitioners. While the chosen sampling size was relatively small, the questionnaire survey items were sufficient to gather data that was representative of the sampling size of the study. In the Saka and Chan study, the statistical methods of analysis used to determine the significance of questionnaire survey items include the Cronbach's alpha reliability test, mean score ranking, the Mann-Whitney U test and quartile deviation. Notably, the power analysis test was conducted to test the effect size of the sampling survey recruited for the study. It was found that the value ranges from 0 to 1 and a value of at least 0.7 was an acceptable threshold level to conduct the statistical analysis.

Willcoxon and Chatham (2006) investigated profiling information technology (IT) managers' personality and behavioural characteristics to outline significant differences. The questionnaire survey was conducted with 130 IT senior managers to develop a statistically representative sample size; multiple surveys with relatively large indicators related to each survey item were then distributed to target groups. This method of design allowed Willcoxon and Chatham to analyse the statistical findings within a margin of error between 10% and 20% to provide a reliable benchmarking criterion.

To provide an evidence-based theoretical approach for the use of a margin of error in the 10–20% range, Borrego *et al.* (2009) outlined a set of guidelines for scholars in engineering education to develop quantitative, qualitative and mixed-methods analyses by considering the significance of the benchmarking criterion for each discipline in the engineering field.

For undertaking ordinal logistic regression analysis, Schumacker (2017) describes a logistic regression coefficient to be estimated and then interpreted as the increase in the log-odds of the outcome per unit increase in the value. Table 3.9 demonstrates the interpretation of the odds ratio recommended by Schumacker.

Table 3.9: Selecting a Statistical Procedure Based on Variable Scaling.

Effect size range	Description
OR = 1	The effect size/variable does not affect the odds of the outcome
OR > 1	The effect size/variable is associated with higher odds of the outcome
OR < 1	The effect size/variable is associated with lower odds of the outcome
Source: Schumacker (2017)	

According to Borrego *et al.* (2009), in any type of engineering field, descriptive statistics should be conducted in the case of research topics about which little is known. This is also known as the deterministic approach, as it does not address any relationships between variables or groups. However, Borrego *et al.* recommend that for hypothesis testing, researchers should seek to examine the relationships between and among various indicators to report statistically significant findings.

To conduct an accurate correlation analysis between variables, Thorne and Giesen (2002) outline a required conventional method of design, as shown in Table 3.10.

Table 3.10: Identification of the Appropriate Use of Variables.

Variables	Analyses	Predictive Analyses
Categorical	Contingency tables, chi-square	Logistic regression, discriminant analysis
Continuous (i.e., scale, ordinal, ratio)	ANOVA, MANOVA, t-tests, Pearson's correlation	Linear regression, multiple linear regression
Note: This table only includes statistical analyses used to examine relationships between variables in the engineering field.		
Source: Adopted from Thorne and Giesen (2002)		

It should be stressed that the identification of the accurate variable type plays an important role in testing associations between study variables. According to Borrego *et al.* (2009) there is a strong association between variable type and the convention of the statistical method chosen for analysis. Borrego *et al.* also highlights the importance of using the appropriate design type and the relevant interpretation of each statistical analysis to provide reliable research outcomes, as shown in Table 3.11.

Table 3.11: Applied Convention to Undertake a Mixed-Methods Research Design.

Design Type	Timing of quan and qual phases	Relative weighting of quan and qual components	Mixing – when quan and qual phases are integrated	Notation
Triangulation	Concurrent	Equal	During interpretation or analysis	QUAN + QUAL
Embedded	Concurrent or Sequential	Unequal	One is embedded within the other	QUAN (qual) or QUAL (quan)
Explanatory	Sequential, quan then qual	Usually quan is given priority	Phase 1 informs phase 2	QUAN > qual
Exploratory	Sequential, qual then quan	Usually qual is given priority	Phase 1 informs phase 2	QUAL > quan
Abbreviations: quan = quantitative; **qual** = qualitative				
Source: Adopted from Creswell and Clark (2007)				

According to Creswell and Clark (2007), a researcher-adapted mixed-methods study involves the collection and analysis of both quantitative and qualitative data in a single study to interpret statistical analysis in accordance with conventional methods (i.e., Cramér's V and Phi test, Pearson's correlation, Chi-square test, Fisher's exact test). Their conventions for undertaking a mixed-methods research design are presented in Table 3.12. To develop statistically representative research outcomes related to households' socio-demographic characteristics and their habitual adaptive behaviour on home energy performance, Cramer's V tests were applied by using both Chi-squared and Fisher's exact tests. These statistical analyses are presented in **Appendix I** – Development Stages of the Statistical Analysis – Part 2. Additionally, contingency tables are also presented in **Appendix H** in order to add weight to those results.

Borrego *et al.* (2009) stress that using the triangulation design method plays a crucial role in any type of engineering research in order to validate survey findings from any type of data collection method (e.g., *in-situ* measurements, *on-site* environmental monitoring, energy modelling). Borrego *et al.* also discuss the strengths and constraints of both quantitative and qualitative research methods, as shown in Table 3.12.

Table 3.12: Qualitative and Quantitative Research Criteria.

Quantitative Research Criteria	Qualitative Research Criteria
Validity: project and instruments measure what is intended to be measured	**Credibility:** establishing that the results are credible or believable
Generalisability: results are applicable to other settings, achieved through representative sampling	**Transferability:** applicability of research findings to other settings, achieved through limited description
Reliability: findings are replicable or repeatable	**Dependability:** researchers account for the ever-changing context within which the research occurs
Objectivity: researcher limits bias and interaction with participants	**Reflexivity:** researchers examine their own biases and make them known
Source: Adopted from Borrego *et al.* (2009)	

Borrego *et al.* (2009) state what is one of the main reasons for the margin of error being set at 5% to identify whether a gathered sample size is sufficient or not. However, many scholars have adopted a mixed-methods research design approach to represent statistical findings, and in these scholar's engineering studies, a margin of error can be acceptable within the 10–20% threshold level. This means that in the engineering field, it is not necessarily compulsory to use the conventional method that is applied when using the online sampling calculator tool.

In summary, this section demonstrates the significance of identifying statistically representative sampling criteria for benchmarking evaluation studies by considering several multidisciplinary studies' findings and providing a general overview on the subject matter. The present study concludes that scholars should use the power estimator analysis method to identify a sufficient sampling size before determining what type of statistical method should be applied in accordance with their questionnaire survey items. It should also be noted that this present study recommends that scholars in the building engineering field use both the online sample size calculator tool and undertake the power analysis method concurrently to avoid any research bias when interpreting statistical findings, particularly in energy research.

3.3.4 Selection Criteria for Thermal Comfort Assessment

This section reviews previous scholars' thermal comfort assessment criteria to provide thorough guidance for the development of "neutral" adaptive thermal comfort thresholds in the South-eastern Mediterranean climate of Cyprus. Scholars have applied and developed different methods of design to measure occupants' thermal sensation in order to identify their predicted mean vote (PMV), but none of these scholars have clarified the differences between the selection of thermal sensation as either an ordinal or continuous variable type, or they haven't accurately undertaken parametric statistical analysis in the building engineering field.

In the present study, throughout the development stages of the statistical analysis, it was found that the differences between ordinal and continuous variable types of thermal sensation should be addressed. This is supported by the conventional methods of design applied by previous studies on thermal comfort, as listed in Table 3.13.

Table 3.13: Worldwide Studies on Thermal Comfort Assessment.

References	Sample Size	Statistical Method	Thermal Comfort Assessment
Rupp *et al.* (2021)	Data extracted from the ASHRAE Global Thermal Comfort Database II (*n* = 107,583)	Regression coefficient	Griffiths constant/occupant's thermal sensitivity theorem applied
Wang *et al.* (2018)	Three different experiments conducted in the climate chamber by using a discrete scale of 2 votes per subject, a discrete scale of 5 votes per subject, and a continuous scale for thermal sensation and satisfaction with 5 votes per subject	- Frequency statistics - Normalised standard uncertainty - Descriptive statistics - Box plot distribution - Bar chart distribution	Humphreys and Nicol's (2002) theorem was applied by investigating subject respondents' PMV and PPD
Haldi and Robinson (2008)	- A dataset of some 5,908 entries from 60 participants was used. - The dataset was built on a comprehensive longitudinal field survey conducted during the warm summer of 2006	- Histograms were used for the distribution of temperature measurements in the database - Logistic regression techniques were used. - G-statistics differences were reported by using Nagelkerke's statistical tradition	Nicol and Humphreys's (2004) theorem was applied to assess occupants' thermal comfort votes
Haghighat and Donnini (1998)	A total of 877 subjects participated in the questionnaire survey during the summer and winter of 1996	- Descriptive statistics - Pearson's correlation coefficient - Bar chart diagram distribution	ASHRAE Standard 62-89R and ASHRAE Standard 55-92 were used for the benchmarking criteria
Brager *et al.* (2004)	A total of 1,000 survey responses were integrated into the dataset	- Descriptive statistics - Scatter plot diagrams - Bar chart distribution - Linear regression analysis - Histograms	ASHRAE RP-884 and ASHRAE RP-1161 datasets were used for the benchmarking criteria

Many scholars have debated the identification of accurate statistical analysis criteria for the convention of the initial thermal comfort assessment scale that was developed by Bedford in 1936. This assessment used a 7-point Likert scale and was later applied and proved by Fanger in the 1970s; it has since become the widely used conventional method of design, and was applied, among others, by Griffiths in the 1990s. Its scale was also made popular by Nicol in the 2000s and since then many top-notch scholars in thermal comfort research, such as Brager in 2008, de Dear in 2010 and Parkinson in 2016, have continued developing this reliable thermal comfort assessment criteria based on the conventional methods of design applied and developed by previous scholars.

De Dear in 2010 and Parkinson in 2016, as well as their colleagues in thermal comfort studies, established the ASHRAE Global Thermal Comfort Database I and II. This open-source international global database allows researchers to identify the appropriate method of thermal comfort assessment criteria for their studies (i.e., using thermal sensation as either an ordinal or continuous variable).

Rupp *et al.* published an article in 2021 entitled "The Impact of Occupants' Thermal Sensitivity on the Adaptive Thermal Comfort Model". In this paper, 107,583 samples were extracted from the ASHRAE Global Thermal Comfort Database II to conduct a regression analysis using a *p*-value of < 0.001 to determine the significance factor within the variables. Rupp *et al.* (2021) used the [-3, +3] thermal comfort assessment criteria as a continuous variable to run statistical analysis with *in-situ* measurements (i.e., indoor operative temperature, indoor air temperature). Figure 3.19 demonstrates the presentation of the statistical findings of the study conducted by Rupp *et al.* (2021).

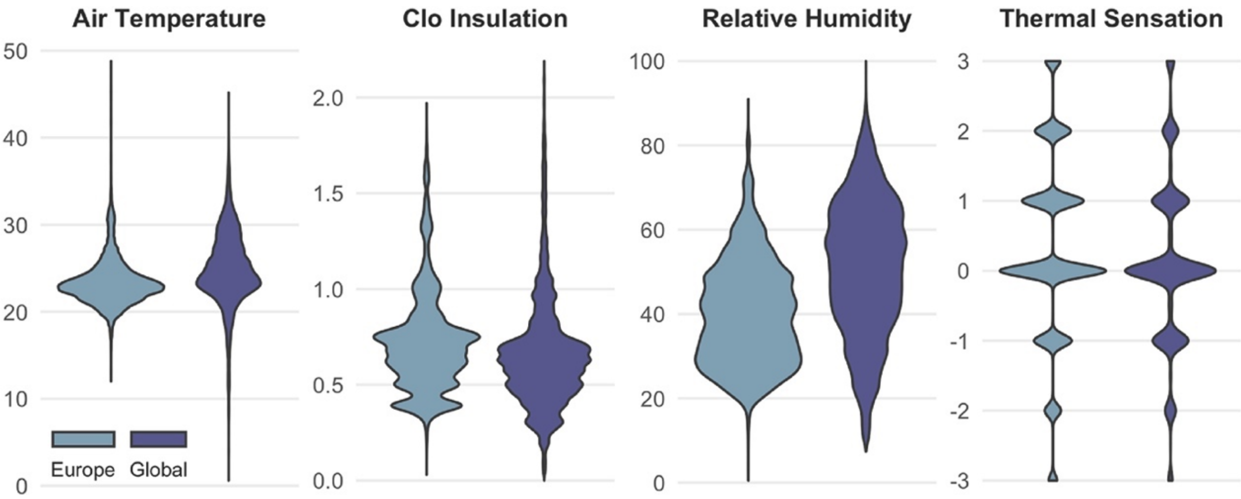

Figure 3.19: Violin plot diagram representation of the sample extracted from the Global and European datasets from the ASHRAE Database II for indoor air temperature, clothing (*clo*) insulation, relative humidity and thermal sensation vote. ***Source:*** Rupp *et al.* (2021)

In Figure 3.19, the thermal sensation variable is represented in the continuous variable formatting style [-3, +3] which was identified by Wang *et al.* (2018). The Wang study discusses the uncertainty of subjective thermal comfort measurement criteria to provide guidance to scholars in thermal comfort studies. Many scholars have applied different measurement criteria by using the point ranking of the Likert scale assessment that was developed between 1936 and 2016.

Wang *et al.* (2018) stress that the use of different measurement criteria in thermal comfort studies has led to misunderstandings when interpretating the findings in accordance with statistical conventions. To avoid any further misunderstanding by the scholars who are not experts in thermal comfort studies, Wang *et al.* (2018) recommend the most appropriate thermal sensation assessment criteria to be that shown in Figure 3.20.

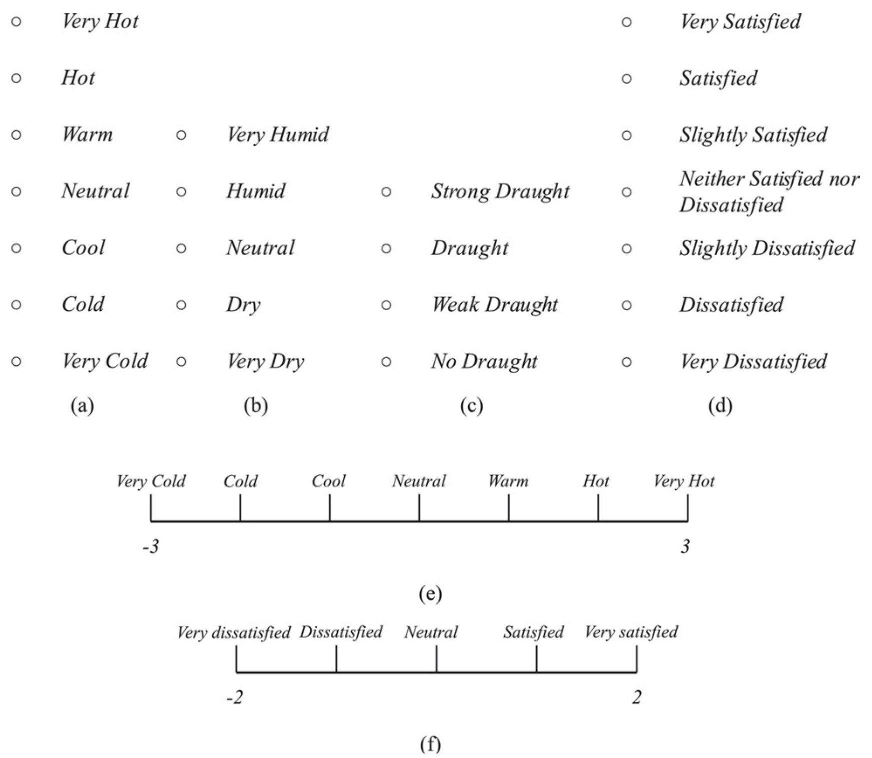

Figure 3.20: Thermal sensation scale on the questionnaire. **(a)** 7-point discrete thermal sensation scale; **(b)** 5-point discrete humidity sensation scale; **(c)** 4-point discrete draught sensation scale; **(d)** 7-point discrete thermal sensation scale; **(e)** 7-point continuous thermal sensation scale; **(f)** 5-point continuous thermal sensation scale. ***Source:*** Wang *et al.* (2018)

Wang *et al.* (2018) used a climate chamber to control thermal variables and determine the most appropriate design for their thermal sensation scale. They provide a list of the acceptable variable types to be used when assessing any type of variable related to thermal comfort studies, which is shown in Table 3.14.

Table 3.14: Variables for Thermal Comfort Assessment.

Subjective thermal indicators	Points on rating scale	Subjective rating scale
Thermal sensation	Fig.3.20 (a)	Discrete
Humidity sensation	Fig.3.20 (b)	Discrete
Draught sensation	Fig.3.20 (c)	Discrete
Thermal satisfaction	Fig.3.20 (d)	Discrete
Thermal sensation	Fig.3.20 (a)	Discrete
Thermal satisfaction	Fig.3.20 (d)	Discrete
Thermal sensation	Fig.3.20 (e)	Continuous
Humidity sensation	Fig.3.20 (b)	Discrete
Draught sensation	Fig.3.20 (c)	Discrete
Thermal satisfaction	Fig.3.20 (f)	Continuous

Source: Adapted from Wang *et al.* (2018)

Haldi and Robinson (2008) conducted a longitudinal field survey to assess occupants' thermal comfort. They conducted a multiple logistic regression analysis to identify neutral adaptive thermal comfort; the assessment criteria were presented by using the thermal scale band [-3, +3]. Another pilot study was conducted by Haghighat and Donnini (1998) to investigate the psycho-social factors affecting occupants' thermal sensation by using *in-situ* measurements of indoor air environment conditions. Haghighat and Donnini used descriptive statistics to report the monitored indoor air environment conditions by using the continuous variable type. Haghighat and Donnini also used Pearson's correlation analysis to measure occupants' thermal sensation and the measured/recorded variables for their statistical analysis. In their study, occupants' thermal sensation was coded by using the conventional tradition of [-3, +3] parameters. Additionally, Haghighat and Donnini (1998) presented the questionnaire survey items set out as ordinal variables in bar chart formatting to demonstrate the survey findings according to their research hypothesis.

Brager *et al.* (2004) conducted a longitudinal survey by using a sample size of 105 for the warm season and 93 for the cool season to assess occupants' thermal sensation. By using this method, they were following a similar method of design to that developed by Haghighat and Donnini (1998) to report *on-site* measurement findings by using the environmental monitoring dataset as a continuous variable and occupants' thermal sensation votes coded as a continuous variable ranging between -3 and +3 for accuracy in their linear regression analysis.

The present study follows the conventional method of design that was developed and conducted by previous scholars. To identify the neutral adaptive thermal comfort thresholds in the South-eastern Mediterranean climate of Cyprus, the present study codes thermal sensation as [-3, +3] and conducts a Pearson's correlation analysis. Figure 3.21 includes the stages of data collection undertaken to assess domestic energy use and occupants' thermal comfort in this longitudinal field study.

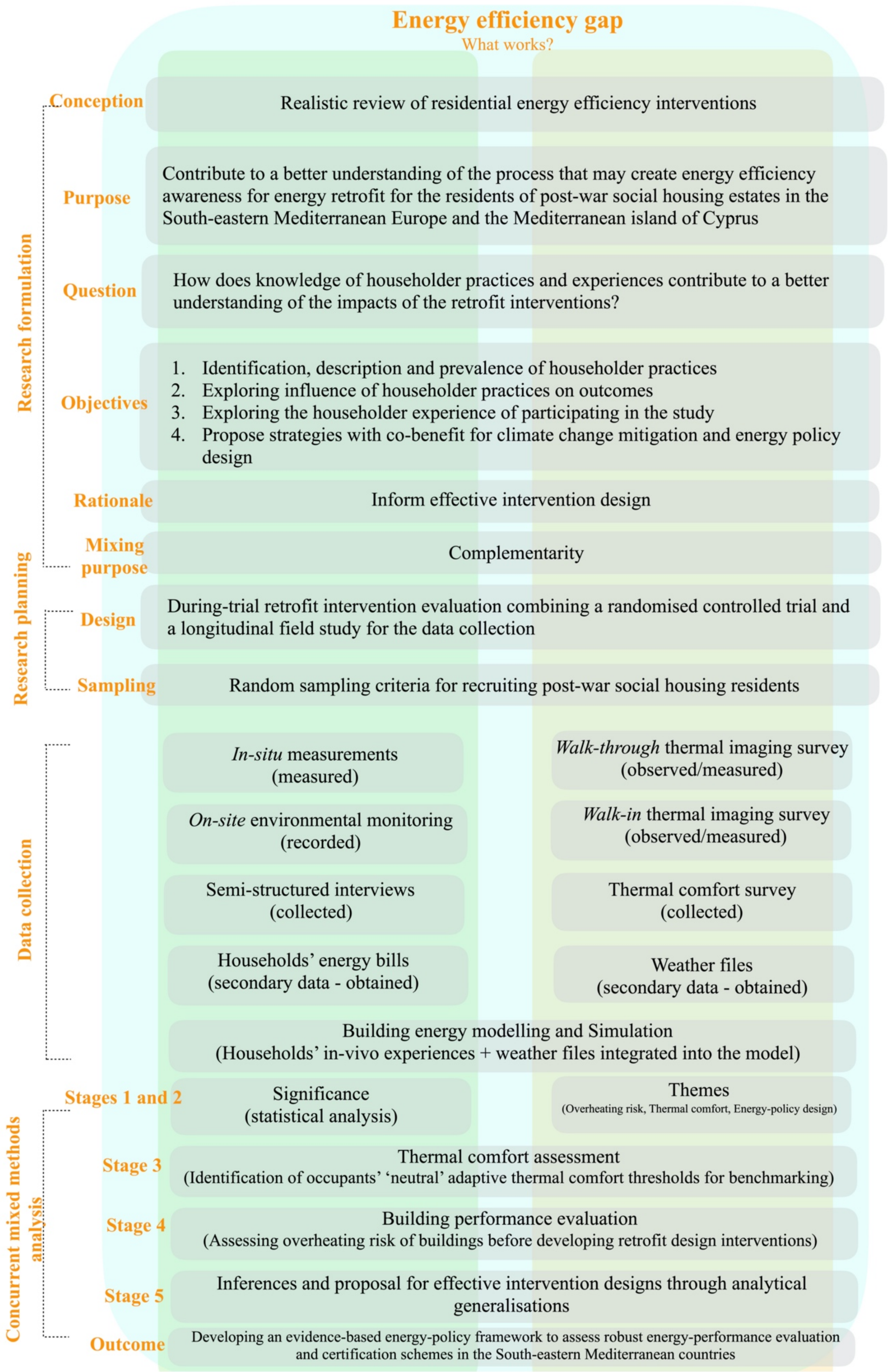

Figure 3.21: Framework for addressing EEG in terms of energy use and occupants' thermal comfort.

As shown in Figure 3.21, for exploring the relationships between the *in-situ* measurements of environmental conditions and occupants' thermal sensation votes in order to calculate the acceptable "neutral" thermal comfort threshold level, the present study uses the [-3, +3] assessment criteria. According to Wang *et al.* (2018) thermal sensation variables can also be used as an ordinal variable type for thermal comfort studies. This is the reason that the present study coded the variables that were asked of the subject respondents on a 7-point Likert scale as ordinal variables and conducted the Fisher's exact test for the statistical analysis. It should be noted that the present study adopted and applied the most recommended tradition in thermal comfort studies to provide a universal design approach to contribute to the ASHRAE Global Thermal Comfort Database II (see **Appendix J**).

3.4 Archetype-Building Typology Selection

3.4.1 Socio-Demographic Structures

The first census data for Cyprus were recorded in 1901, at which time the island population was 51.309 (Statistical Service of Republic of Cyprus, 2014). The RoC was established on August 16, 1960 with the involvement of two major ethnic communities: the Turkish and Greek Cypriots. After declaring independence from the Great Britain, the first census data were recorded on December 11, 1960, at which time the overall population was 104.942 with an annual growth rate of 1,9% (Moeschberger & Phillips, 2014; SPO, 2020). After NC declared itself a *de facto* state in 1983, the first census data were recorded in 1996, at which time the overall population was 200.587. A second nationwide census survey was conducted in 2006, and at that time, the population was 256.644 with a 2,6% annual population growth rate.

As a consequence of a property boom and high demand for housing by foreign buyers wishing to take over control of the construction industry, the most-recent nationwide census data were collected by the NC government in 2011; this effort was intended to provide necessary figures on housing-stock data to the Union of Cyprus Turkish Engineers and Architects (UCTCEA). At that time, the overall population was 286.257 with a 2% annual population growth rate (SPO,2011).

Currently, this background information is used every year to estimate population projections; the most recent population and housing-unit census data were updated on December 31, 2019 (SPO, 2020). According to this census data, the NC population was 382.230 in 2019; the male population was 207.149, and the female population was 175.081, as shown in Figure 3.22. As can be seen, there were 62.299 individuals in the 20–24 age group, which comprised a large proportion of the overall population; there were 37.972 males and 24.372 females in this age group. The 70–74 age group consisted of 9.465 individuals: 4.551 males and 4.914 females.

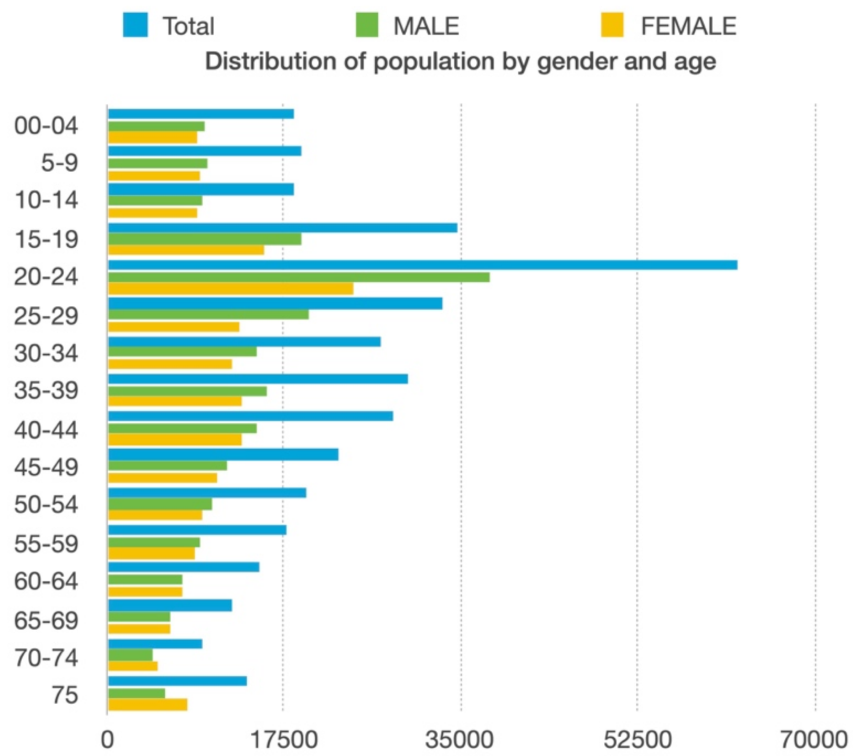

Figure 3.22: Distribution of NC population by gender and age. ***Source:*** *Annual Statistical Report for 2019*, published by the Northern Cyprus Statistical Office.

The 2019 demographic statistics in the RoC indicate that the estimated population was 888.000, compared to 875.000 at the end of 2018, with an increased annual growth rate of 1,4% (Statistical Office of the RoC, 2019). The census data were distributed according to gender and age in an effort to foresee birth rates and determine the percentage of the ageing population. The data show that the proportion of children who were 0–4 and 10–14 years of age were both estimated to be 16%; the proportion of age groups older than 65 years of age increased to 16,3% in 2019, compared to 22,3% and 11,3%, respectively, in 2000. These results indicate that there was a notable increase in the proportion of age groups 65 years of age and older and a decrease in the proportion of age groups younger than 15 years of age, which suggests that the size of the ageing population will increase in the RoC over the next few decades.

3.4.2 Residential-Building Stock Characteristics

In developing countries where urban growth and rapid urbanisation occurring, urban sprawl, a lack of planning related to land use and the absence of the EPBD mandates has impacted the current state of the housing stock (Bartels, 2007; Fokaides *et al*., 2017). As it relates to NC, changing the physical layout of the land combines with a lack of regulatory bodies for town planning are two major factors that have resulted in architectural, urban and environmental devastation (Oktay, 2007; Varoglu *et al*., 2018). It is difficult to compare the urban settlements of NC with other European countries, because they are smaller in size, both in land use and in terms of overall population (Attia *et al*., 2017; Yorucu, 2003).

In NC, the rapid urbanisation of cities, rampant construction activity in suburban areas and the structure of the housing sector are connected; within the construction industry, these processes had an impact on land use and the explosive growth in energy use through the lack of control mechanisms in policy design in the urban and suburban systems (Balkiz & Therese, 2014; Savvides, 2017).

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.

In Figure 3.23, Archetype 1 demonstrates the first social-housing scheme developed during the British Colonial administration in the early 1900s with a combination of single-storey row houses (Vehbi & Hoskara, 2010; Yildiz & Manioğlu, 2015). This was the first pilot housing scheme in Cyprus, and it led to an increasing demand to build mass-scale housing schemes, which are illustrated as Archetypes 2 and 3 in Figure 6. Gazioglu (1996) stated that 19% of the mass-housing estates were built in the British Period (i.e., prior to 1960); 3,8% in the RoC (i.e., 1960–1963); 12,7% in the fenced-off Varosha territory during the outbreak of civil war (i.e., 1963–1974); 8,9% in the Cyprus Turkish Federation (i.e., 1974–1983) and 55,7% when NC declared itself a *de facto* state[3] (Hoskara *et al*., 2009). Notably, urbanisation in NC 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 (Ghafoor & Yorucu, 2006). 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 NC (Safakli, 2011).

According to the 2018 annual report for the Department of Social Housing detailed, from 1984–1996, the NC government implemented three different social- and private-housing schemes—row

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[3] Data included housing that was built under governmental social-housing schemes and housing projects built by local cooperatives in NC between 1984–1996.

houses, medium-rise RTBs and a combination of the two—which were intended to address the housing shortage that was a consequence of the division of island (SPO, 2011).

A total of 2.712 dwellings were built during the rise of post-war social-housing estate developments under the governmental social-housing scheme (Yorucu & Keles, 2007); an additional 659 dwellings were built in collaboration with local cooperatives in NC. After the completion of mass-scale housing projects, the government did not construct any other social-housing developments (Cogaloglu & Turkan, 2019). It should be noted that during the late-1990s and early 2000s, mass-scale housing projects were largely regulated by the SMEs (Goharddini *et al.*, 2013); according to housing statistics, an additional 3.275 dwellings were built by privately owned construction companies to fill the void in social-housing structures implemented between 2000–2005 (SPO, 2011).

Figure 3.23: Taxonomy of existing Cypriot housing stock to identify archetypes. ***Source:*** Images from author's personal archive.

In Figure 3.23, Archetypes 4 and 5 demonstrate the government social-housing estates, which were built between 1984–1996 to address the housing shortage for young people, as shown in Table 3.15. 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 (Günçe *et al.*, 2008; Hoskara *et al.*, 2009). All of these RTBs had the same floor-plan layout (i.e., two flats located on each floor) and the same building-envelope materials, which did not consider local climate conditions and topographical conditions of the project sites.

Table 3.15: Government Social-Housing Development Projects in NC.

Phase	Type	Nicosia (Urban)	Famagusta (Urban)	Kyrenia (Urban)	Omorphou (Rural)	Lefke (Rural)	Total
Phase I (1984–86)	Duplex	96	80	40	32	10	258
	Apartment	40	—	—	—	—	40
	Total	*136*	*80*	*40*	*32*	*10*	*298*
Phase IIA (1985–87)	Duplex	60	80	40	32	—	212
	Apartment	48	—	—	—	—	48
	Total	*108*	*80*	*40*	*32*	—	*260*
Phase IIB (1986–88)	Duplex	128	56	60	—	—	244
	Apartment	56	—	—	—	—	56
	Total	*184*	*56*	*60*	—	—	*300*
Phase IIC (1987–89)	Duplex	292	116	—	—	—	408
	Apartment	56	8	—	—	—	80
	Total	*348*	*124*	—	—	—	*488*
Phase III (1990–92)	Duplex	—	—	—	—	—	—
	Apartment	104	88	—	16	16	240
	Total	*104*	*88*	—	*16*	*16*	*240*
Phase IV (1993–96)	Duplex	—	—	—	—	—	—
	Apartment	608	336	112	64	16	1136
	Total	*608*	*336*	*112*	*64*	*16*	*1136*
Totals for all four phases (1984–96)	Duplex	576	332	140	64	10	1122
	Apartment	912	432	112	80	32	1568
	Total	***1488***	***764***	***252***	***144***	***42***	***2690***

Source: Data obtained from the Ministry of Housing, Dept. of Rural Affairs and Development

The housing typology classification reveals that these RTBs were built without informed decision-making related to land use and planning. 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. Figure 3.23 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.

3.4.3 Housing Stock

Rapid construction during the 'property boom' led to a revived interest in the property market (Yorucu, 2013). The expectations of the Annan Plan and changing market conditions throughout the world was evidence that people from such countries as Russia, Turkey, Greece, the U.K. and Germany began to show significant interest in buying a second home in NC (Yorucu *et al*., 2010). Increasing energy demands from the residential sector were mostly observed in rapid construction activities and a renewed focus on economic improvement (Moutsiou, 2020; Zachariadis, 2010); in NC, the rapid and varied activity throughout the construction sector resulted in economic growth (Aloala, 2019).

The 2008 State Planning Organisation statistics showed that in the pre-construction period of 1997–2001, the average Gross National Product (GNP) rate was 1,8% (SPO, 2008). During the 2002–2006 accelerated construction activity period, this rate soared to 11% per annum; it should also be noted that during this same period, the construction industry in NC accounted for 8,1% of GNP. The results show the manner in which construction activity stimulated interest in other construction projects. This situation changed after 2010, however, due to the priority that was given to property investors from Russia, Israel, Iran and Turkey wishing to secure their money in NC to only construct medium- or high-rise RTBs on vacant land.

According to the State Planning Organisation, NC is characterised as a market economy that is dominated by the construction sector, which contributes 11% toward the GNP; only 8% was contributed by the private sector and 6% by the transportation sector (SPO, 2017). The data indicate that the first-time home-buyer rate was 4% in 2017 and 5% in 2019. A sharp decrease in the annual growth rate of the construction sector of 4% can be observed in 2019 (SPO, 2019); at this time, a stringent land-use planning policy and town-planning regulations were put in place by the government to discourage invasive construction activities in Famagusta and its agglomerations, especially rural villages with a close proximity to the shoreline and Trikomo and its waterfront regions. Nationwide lockdown measures that were sue to the COVID-19 global pandemic and political turmoil in the early months of 2021 negatively impacted the construction sector in NC. To provide a comprehensive overview of the construction sector and highlight the importance of the demand for housing projects and the impact thereof on energy use, statistical data were obtained from the Statistical Office of NC and is illustrated in Figures 3.24 through 3.28.

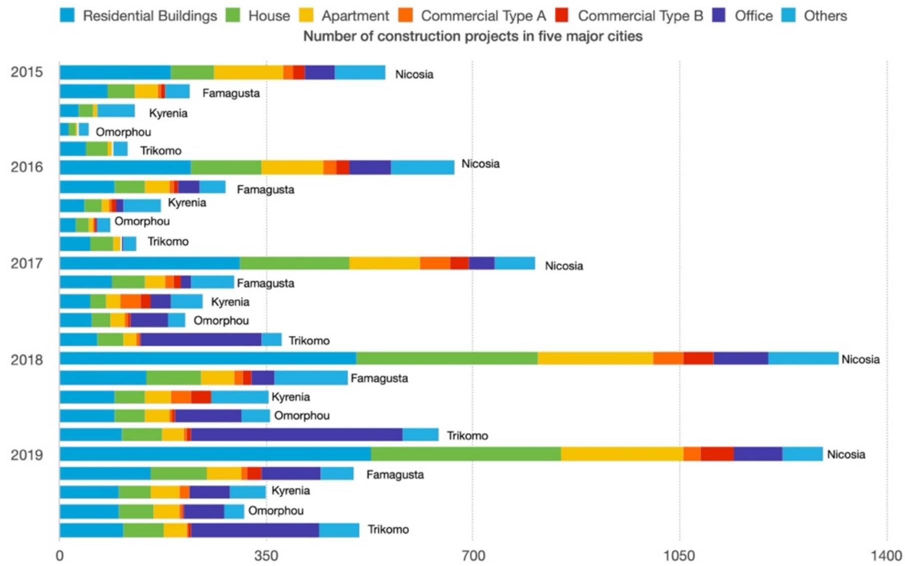


Figure 3.24: Number of buildings constructed between 2015–2019 in five Cyprus cities: Nicosia, Famagusta, Kyrenia, Omorphou and Trikomo.

Figure 3.24 shows the number of construction projects within the distribution of building typology between 2015–2019. It can be observed that in all five 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 (SPO, 2019). 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 from Israel, Russia and Azerbaijan to construct mass-scale high-density RTBs. The statistical results reveal that the current housing stock in NC exceeds local demand and is predominantly considered to be a foreign-buyer property market; this is because there are no stringent building regulations to control construction activity or to inspect the thermal quality of building stock (Ouria & Sevinc, 2018). Due to the policy gap in residential buildings and in the construction sector, SMEs and large investors relied on internal loans to build these mass-housing estate developments (Becher, 2014).

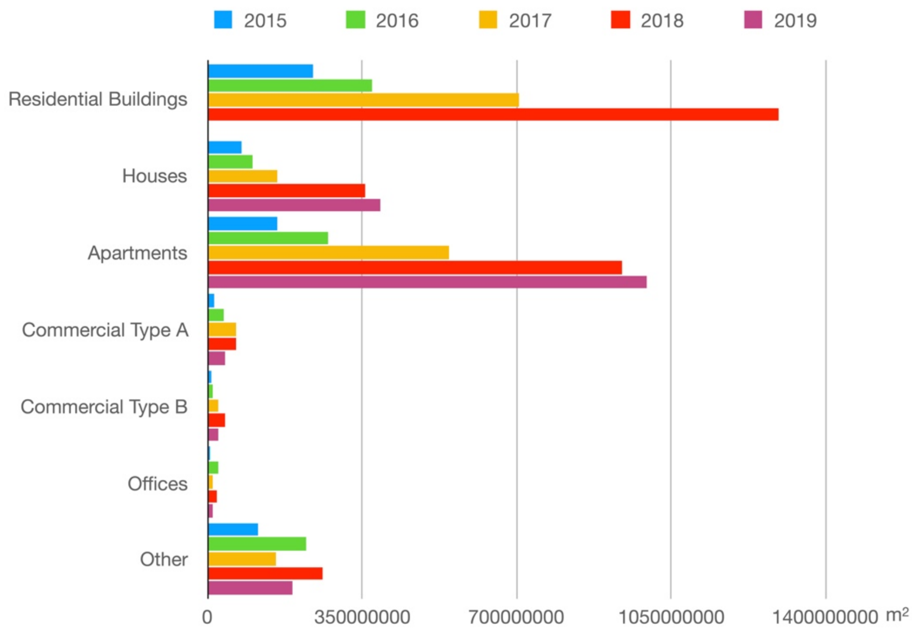


Figure 3.25: Total number of buildings constructed in urban areas between 2015–2019.

Figure 3.25 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 NC (Alola, 2020).

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 NC 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 NC.

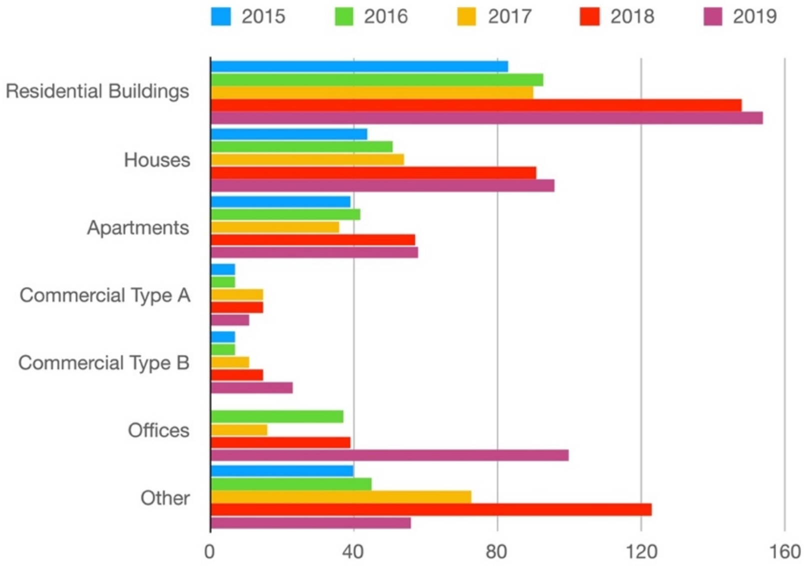


Figure 3.26: Total number of buildings constructed in Famagusta between 2015–2019.

Figure 3.26 shows the total number of construction projects in Famagusta that were completed between 2015–2019; the highest number of construction projects were recorded in residential buildings. According to the housing data, residential buildings that were completed in 2019 consisted of 154 housing units, followed by 148 condominiums in 2018; the second-most-dominant housing typology was self-built houses, which showed a steady increase between 2015–2017. A total of 149 house projects were completed by either building contractors or private construction companies (i.e., single-storey bungalows, two-storey detached or semi-detached houses). Between 2018–2019, there was a notable increase in the number of this type of housing projects as a consequence of uncertainty due to the implementation of new town-planning regulations and stringent measures related to the protection of rural villages and shorelines in Famagusta and Trikomo.

According to the Annual Report of Housing Census, 187 self-built houses were completed between 2018–2019. As it relates to apartment construction, 117 apartment buildings were completed between 2015–2017, then a slightly decrease in the number of built apartments can be observed between 2018–2019, during which time 115 projects were completed; these apartment projects were 5–23-storey standalone buildings that were built on vacant land or wherever close-proximity to the shoreline to attract foreign second home buyers.

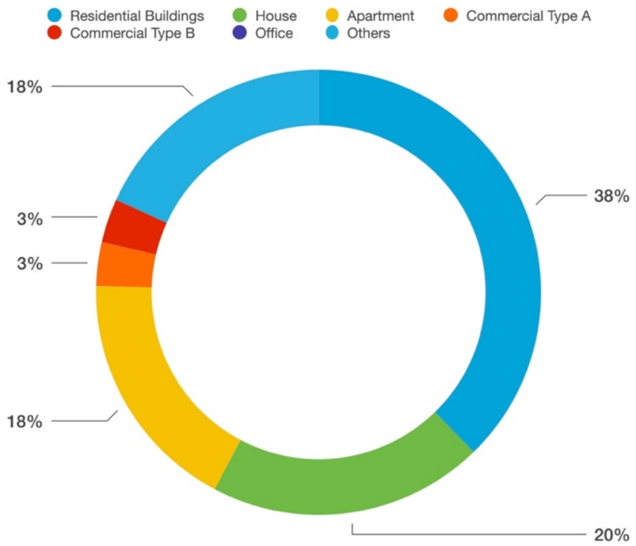


Figure 3.27: Proportional percentages of building types constructed in Famagusta between 2015–2019.

Figure 3.27 clearly shows that the dominant housing typology in Famagusta was residential buildings, which comprised 38% of the overall building stock; this was followed by 20% that were self-built houses, 18% that were apartments and 6% that were commercial properties. Notably, the residential buildings were purpose-built 2-to-5-storey RTBs with more than two flat units on each floor. The analysis suggests that the RTB archetypes are the nationally representativeness of the housing stock, which were built in large quantities in all the major cities in NC (Ciftcioglu, 2017). It should be noted that in all types of housing classifications reveal that the absence of EPBD mandates led to the construction of residential buildings and apartments that were built without any type of energy-efficient technology or building materials (Ince, 2019). This also relates to the cost of the buildings, except self-built houses for which the houseowners implemented energy-efficient materials that were within their budget at the time of construction.

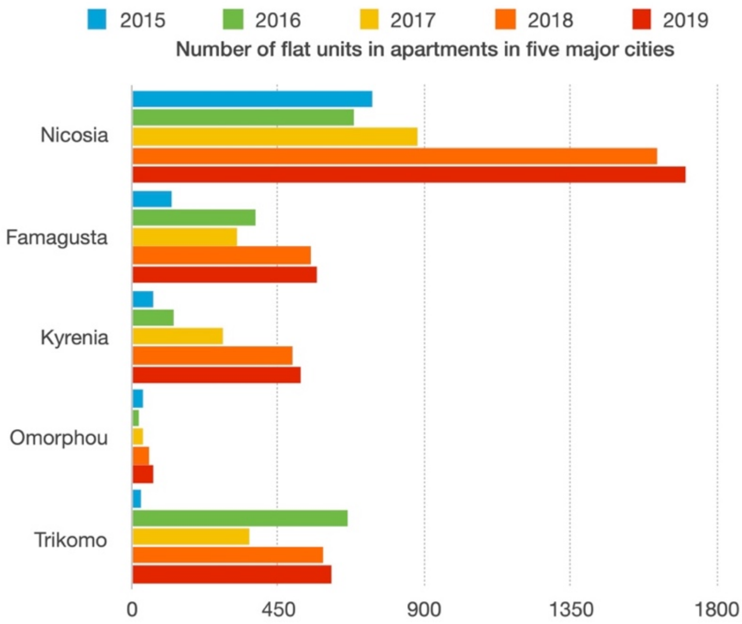


Figure 3.28: Total number of flat units completed in five major cities in NC between 2015–2019.

Figure 3.28 shows the number of apartment units built between 2015–2019 in five major cities in NC. A majority of the housing projects in 2019 were built in the capital city of Nicosia; approximately 1800 apartment units were completed within that year. This is due to land shortages and a high demand from the population of homebuyers who were 20–24 and 25–29 years of age. A significant rise in the number of completed flat units in Famagusta and Trikomo due to demands on the property market from the large foreign enterprises can also be observed; approximately 2500 apartments were constructed between 2015–2019. The analysis reveals that the trend of building apartments was always significant in Nicosia because it is the capital city and has a large population; hence, the demand for new housing projects is always on the rise. In comparison, the construction of apartment housing stock in Famagusta only steadily increased between 2018–2019, but this is still remarkably high, considering the local population numbers.

To conclude, most of the residential buildings are of the RTB typology with a mean gross floor area of 105 m^2; this corresponds to an average of 75 m^2 per occupant (SPO, 2019). According to 2018 EU Housing Statistics, the equivalent average numbers are significantly lower than those recorded for Cyprus and are equal to 84,5 m^2 and 33,8 m^2 per occupant, respectively (Eurostat, 2018).

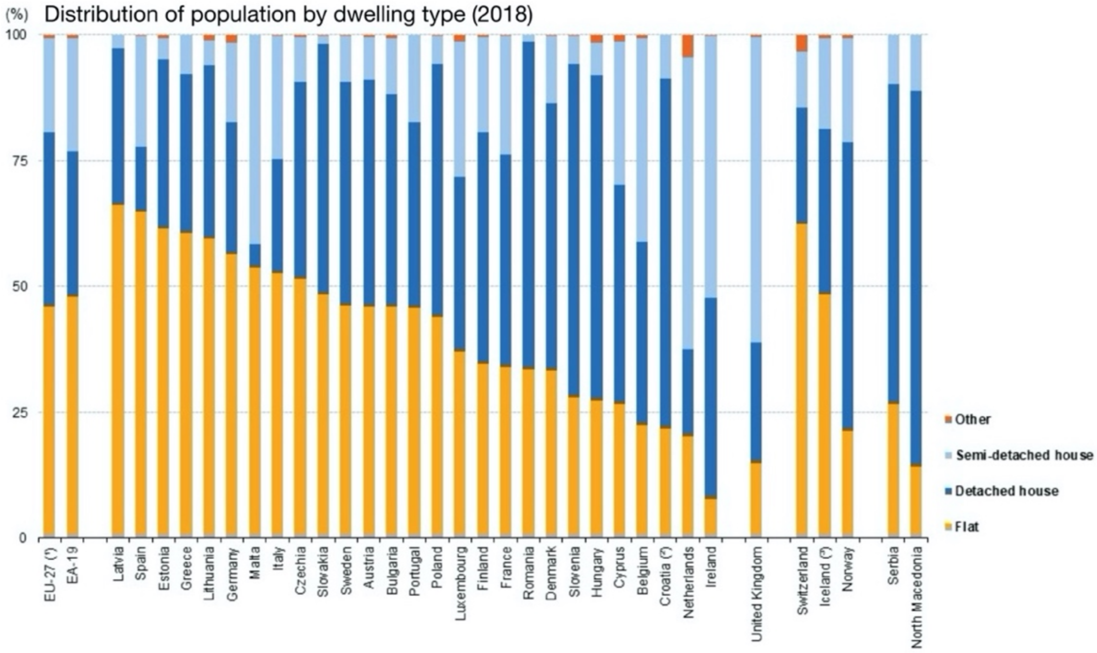


Figure 3.29: Distribution of population by dwelling type in EU member states in 2018.[4]

To compare the NC housing stock with that of the RoC and other EU countries, the study examined the 2018 housing statistics available via Eurostat. Figure 3.29 shows that in 2018, 46% of EU citizens lived in flats, 18,6% lived in semi-detached houses, and 34,7% lived in detached houses. Among the EU member states, the proportion of people living in flats in 2018 was 66,2% in Latvia, 64,9% in Spain, 61,5% in Estonia, 60,6% in Greece, 59,5% in Lithuania, and 62,5% in Switzerland. In the RoC, 27% of people lived in the flats; the present study found that 56% of people in NC lived in flats between 2015–2019, which was significantly higher than in the RoC. The findings prove that political events and demand on the property market by foreign investors led to a notable increase in housing stock in NC. To properly understand the composition of NC housing stock, a sample distribution according to the housing typology classification was presented in Figure 3.23.

Medium-rise RTBs (i.e., Archetype 5) constructed between 1984–1996 were the dominant representative housing typology of the residential-building stock in NC. Currently, the construction projects undertaken by SMEs and large foreigner investors in large quantities utilise similar floor-plan layout designs and scale-of-construction projects, all of which were first introduced under government social-housing schemes. This RTB typology was chosen for the present study to represent a reasonable proportion of the overall housing stock, and the statistical results prove that RTBs comprise a majority (i.e., 56%) of housing stock in NC.

[4] Data on the distribution of population by degree of urbanisation, dwelling type and income group extracted from 2018 EU SILC survey in Eurostat database. Data only represents population and housing stock in the southern territory of the RoC; NC housing stock is not included due to being an isolated *de facto* state.

3.4.4 Representative Archetype Post-war Social Housing Estate

Famagusta is an exposed waterfront city that is subject to constant changes in the construction industry due to rapid economic growth and increasing housing demands. This coastal city, a map of which is shown in Figure 3.30, is an exemplar model for the selection of a high-density social-housing estate development that was built in the heart of the city centre and in close proximity to the old walled Venetian city without considering the value of the historic urban tissue or any bioclimatic environmental design principles at the time of construction.

Figure 3.30: Location of base-case social-housing estate between old walled city and city centre in Famagusta. ***Source:*** Map extracted from ArcGIS Pro Version 2019.01 software suite; developed by Esri (U.K.) in 2019.

Medium-rise residential tower blocks are the most common structures in the district; this housing estate contains 288 apartment units in 36 RTBs that have the same floor-plan layout design, as shown in Figure 3.31; the blocks are 15 m × 16 m and 4–5 storeys high. The conditioned gross floor area of the case-study multi-family apartment unit is 90 m^2; and the original U-values were 3,47 W/m^{2}K for the external walls, 1,23 W/m^{2}K for the internal walls, 1,2 W/m^{2}K for the roof and 2,10 W/m^{2}K for the doors and windows. There are two types of RTBs in NC: four-storey structures without communal amenities and five-storey structures with commercial premises located beneath the flats, as shown in Figures 3.32(a) through (c).

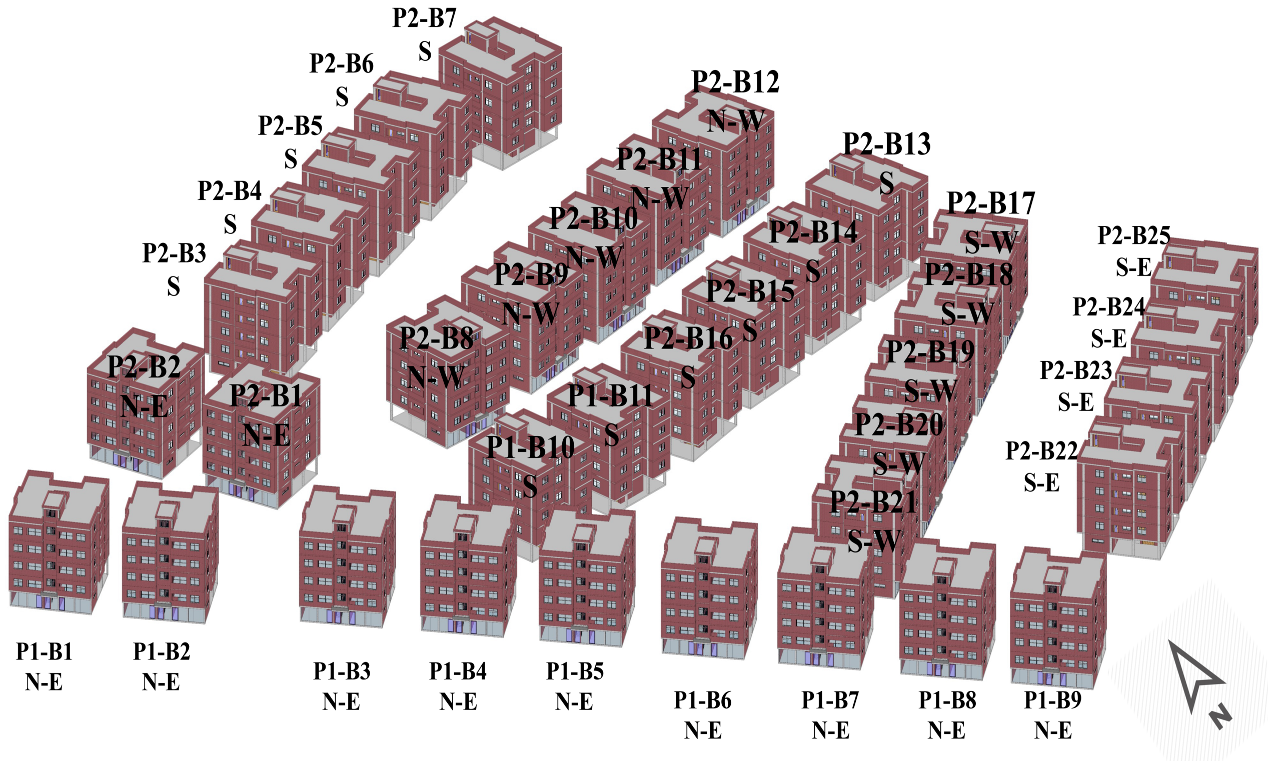


Figure 3.31: The location map of interviewed RTBs in the social housing development. *P1-B1-11: Phase 1-11, **P2-B1-25, ***N-E: Northeast, N-W: Northwest, S-W: Southwest, S-E: Southeast, S: South

(a) (b) (c)

Figure 3.32: (a) High-density medium-rise post-war social-housing development estate; **(b)** current condition of prototype RTB and southwest-facing RTB; **(c)** building façade designed without considering climate characteristics.

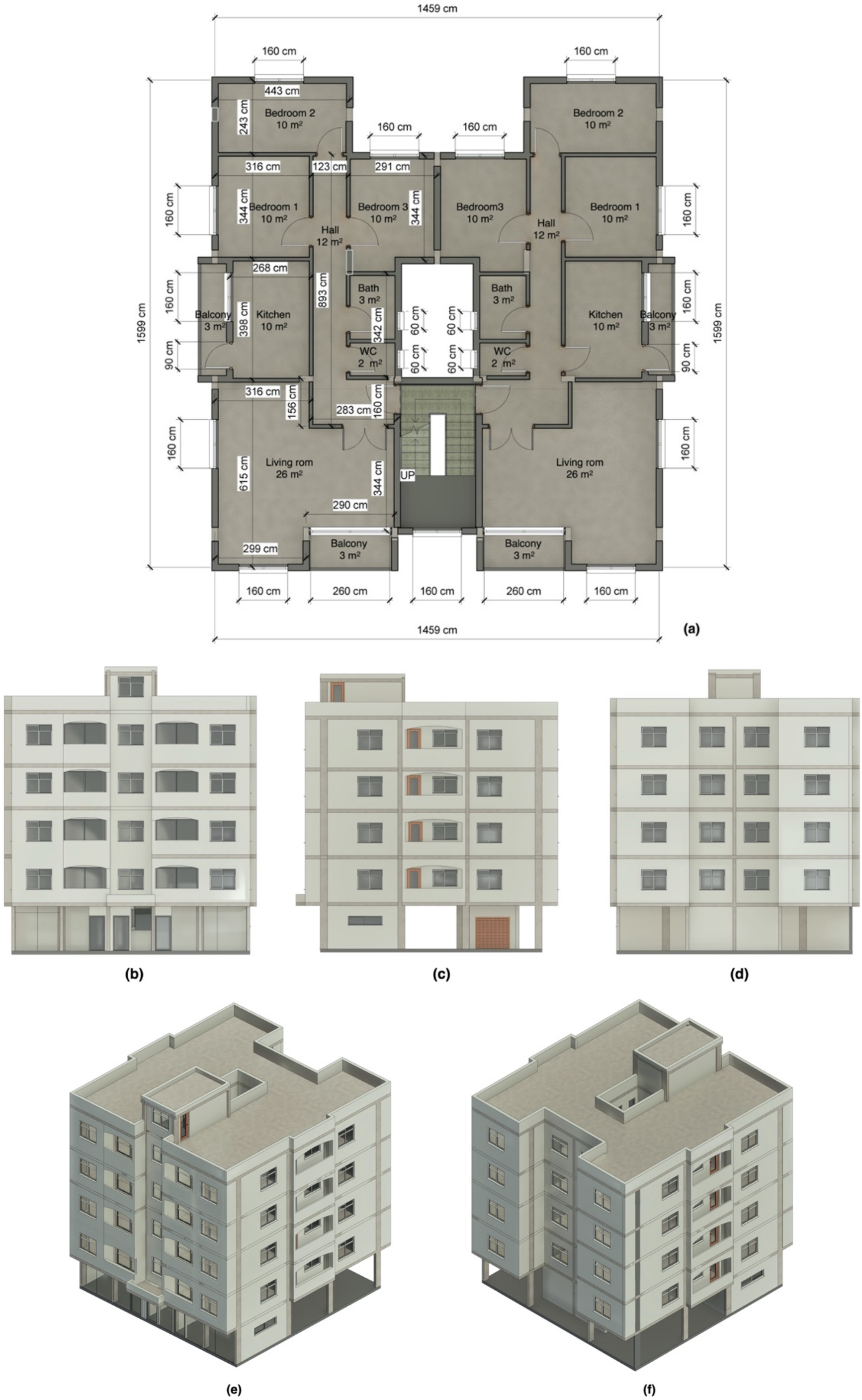


Figure 3.33: **(a)** Details of floor-plan layout of the RTBs; **(b)** Front elevation view; **(c)** Side elevation view; **(d)** Back elevation view; **(e)** 3D Rendering model of front-side views; **(f)** 3D Rendering model of back-side views. **Sources (a)-(f):** Autodesk® Revit® Version 2021.1.0.

As shown in Figures 3.33(a) through (f), the key criterion for the representative case-study building selection in the present study was that the sample needed to be representative of the post-war social-housing estates that were built in the mid-1980s and early 1990s. 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 households according to these criteria, as illustrated in Figures 3.34(a) through (d).

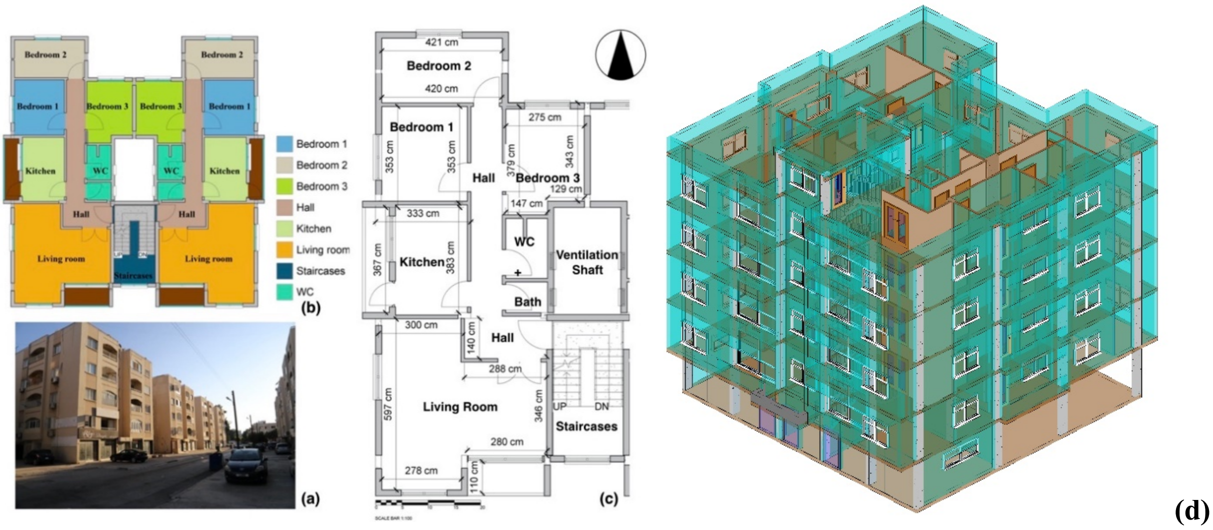


Figure 3.34: (a) Base-case medium rise residential-tower development built in the 1990s; **(b)** 3D urban-block model of social-housing estate; **(c)** floor-plan layout details and **(d)** analytical 3D model of RTB. ***Source:*** Floor plans and 3D model produced with Autodesk® Revit® Version 2020.1.0

The definitions of the 36 representative RTB typologies that referenced the year of construction, the urban/suburban morphology of the block, the number of floors in the building and the number of dwellings per floor were derived; sub-typologies were also identified to understand the impact of rapid construction activity on the transformation of the urbanisation and land-use characteristics of the city. Figures 3.35(a) through (e) demonstrate the typical physical deterioration of the building envelopes. The physical conditions of the building envelopes at the time of this study can be seen in Figures 3.36(a) through (d); due to the lifespan of the buildings, these were not constructed according to any kind of building regulations that complied with recommendations from the Chamber of Architects. The buildings that were constructed under the governmental social-housing scheme can be described by three newly defined variables—the energy-consumption patterns of the occupants, the thermal performance of the buildings and the thermal-comfort level of occupants—all of which are worthy of investigation.

Figure 3.35 (a) through (e): Major decay observed on building envelopes and cracks in wall junctions of all base-case RTBs.

Figure 3.36: **(a)** Kitchen balconies and double-glazed, aluminium-framed window systems installed by occupants; **(b)** wall-mounted A/C systems installed on building envelope; **(c)** kitchen balcony closure on upper-floor flat; **(d)** structural failures in junction details between columns and beams on roof.

In summary, the buildings that were constructed under the governmental social-housing scheme can be described according to the occupants' energy-consumption patterns, the building's thermal performance and the occupants' thermal-comfort levels. The long-term viability of these RTBs will require the incorporation of energy-efficient and -saving features within the methodologically planned energy-policy framework.

3.4.5 Building a Stock Model for Energy Policy Design

To fill the energy-efficiency gap, improvements in the physical quality of housing stock that are directly related to human-based factors are needed. This need led to the development of a novel methodological framework for assessing domestic energy use, as shown in Figure 3.37.

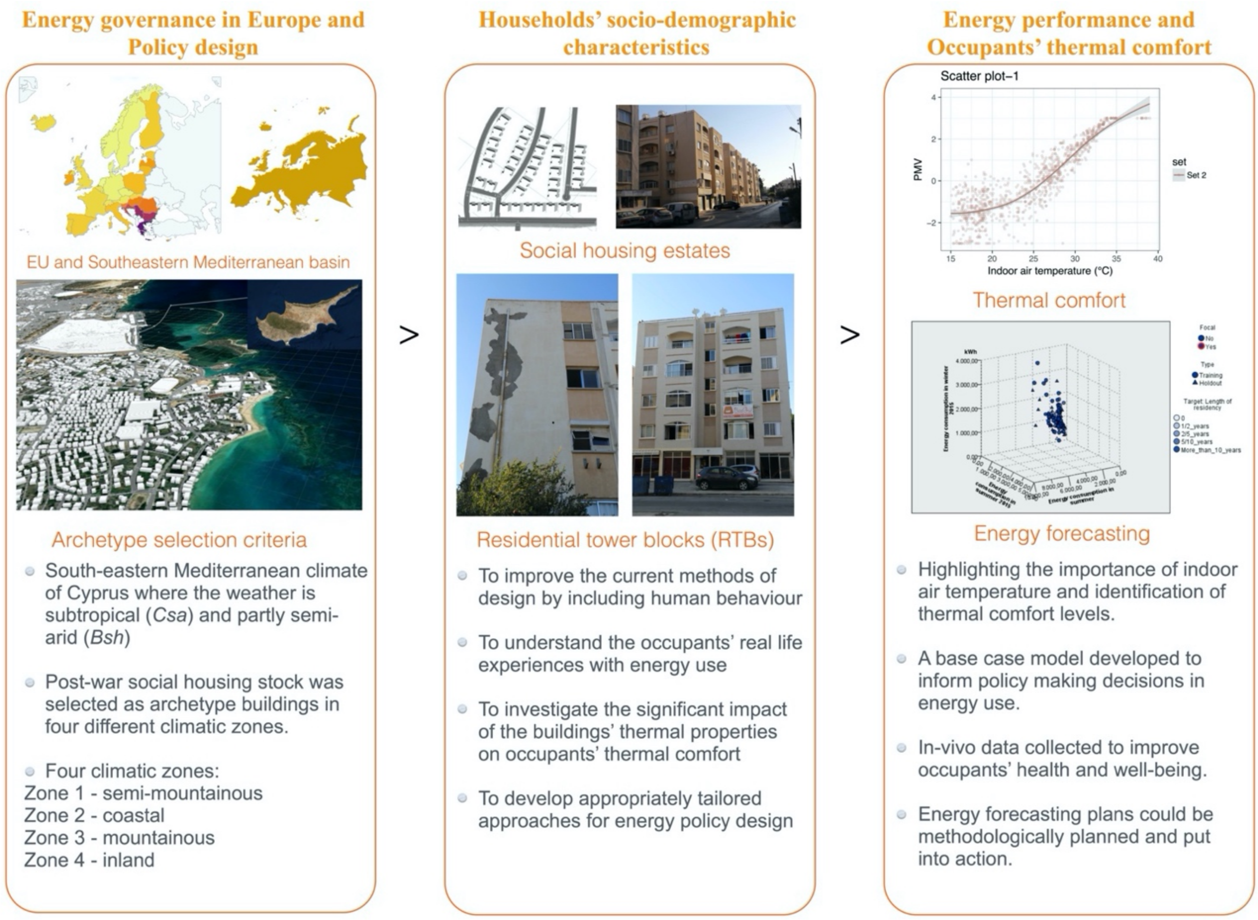


Figure 3.37: Stages of development of the STS conceptual framework.

One of the main goals of the present study was to encourage social housing occupants to assess and adopt principles of retrofitting design policies to improve the extant mass-housing stock. This approach will investigate buildings that were built under the governmental social housing scheme, but that have not yet undergone any refurbishments to make the structures more energy efficient and adapted to the local environment. The present study revealed an urgent need for governmental bodies to devise effective policies for the mass-housing sector so that the construction industry applies necessary retrofitting strategies on a rapid and large-scale basis to reduce energy consumption. Tables 3.16(a) through (c) delineate previous scholars' work on the development of statistically representative housing archetypes across the world.

Table 3.16(a): The Literature on Building Stock Aggregation through Archetype Buildings.

References	A. Study Location	B. Building Type	C. Sampling Size	D. Primary Aim of Model	E. Methodology	F. Main Findings
Mata *et al.* (2014)	France, Germany, Spain and the UK	Single-family dwellings (SFD); terraced houses (T); multi-family dwellings (MFD)	France – 99 archetypes (54 R, 45 NR), Germany – 122 R archetypes Spain – 120 archetypes (40 R, 80 NR) UK – 252 archetypes (168 R, 84 NR)	To assess the possibility of describing the European Union (EU) building stock for the purpose of forming a basis for analysing the effect and costs of applying different energy efficiency intensity (EEI) measures to the entire EU building stock	A dynamic Building Stock Model was used; archetype buildings were selected to represent the building stock of the country; the segmentation was applied to both residential (R) and non-residential (NR) buildings; a total of 593 archetype buildings were investigated; census data and national reports were used; the 3CL-DPE Method was used to define building geometry and *U*-values of building envelope parameters	A final total energy demand that differs by -6% to +2% from statistics for the four countries investigated; the share of space heating of the total energy demand ranges from 59% to 82% in R buildings
Ballarini *et al.* (2014)	Thirteen EU countries, representation of Italian building typology in three different climatic zones	Single-family houses (SFHs; detached or semi-detached); terraced houses; multi-family houses (MFHs); apartment blocks	Six SFHs; six MFHs; six apartment blocks built between 1901–1920 and 1991–2005	Development of methodology to identify reference buildings for assessing energy-saving potentials; to design a harmonised structure for 'European building typologies' in order to estimate the energy demand; to identify a national 'Building Typology' according to the IEE-TABULA project	The Building Typology Matrix was developed by region/climate area; The Real Example Building (*ReEX*), The Real Average Building (*ReAv*) and The Synthetical Average Building (*SyAv*) approaches were developed; statistical data was used to support the archetype housing stock analysis; the building energy assessment model was developed; a quasi-steady-state monthly model was chosen in order to meet the consistency both with European standards and with national standards; retrofitting interventions applied to the national building stocks were considered	Annual primary energy need for space heating and domestic hot water ranged from 41% (Czech Republic) to 75% (Italy, Middle Climatic Zone); on average, more than 40% of energy savings could be obtained by the whole analysed European residential stock just applying a 'standard' retrofitting scenario
Wang *et al.* (2015)	Stockholm, Sweden	Swedish low-rise residential buildings	2-3–storey low-rise MFHs purpose-built housing estates built between 1965 and 1975	To investigate energy effectiveness of retrofit measures applied onto building envelopes by an exploratory case-study analysis	A typical Swedish multi-family archetype was selected; the IDA ICE 4.6 (indoor climate and energy performance simulation programme) was applied for the simulation of thermal performance	Adding insulations on roof and improving air-tightness level achieved a 16% and 18.4% energy consumption reduction, respectively

Table 3.16(a) identifies representative housing typologies for the development of bottom-up energy policy frameworks in European countries. The study by Mata *et al.* (2014) investigates the implementation of energy-efficiency strategies by aggregating 593 archetype buildings to represent the entire housing stock, using the national housing databases of France, Germany, Spain and the UK. The sampling population was extracted from the Eurostat database in 2011. This dataset consists of the building characteristics, energy consumption levels and CO_2 emissions of each country and provides a benchmark for the validation of the final energy demand for a reference year. By contrast, the present study only includes data on medium-rise residential tower blocks (RTBs), which represent 56% of the dwellings in Northern Cyprus (NC). The two studies show differences in terms of the development of methodology for building stock aggregation. Mata *et al.* (2014) primarily investigates the building thermal properties of both single family houses (SFHs) and multi-family houses (MFHs) and the energy use of these dwellings was validated through measures of indoor-air temperature, while, in the present study, the nationally representative housing stock data was gathered from the Housing Construction Statistics from 2015 to 2019 and applied to the most representative medium-rise RTBs and the energy simulations were validated by integration of human-based data through a questionnaire survey.

In the present study, 100 households' data was integrated into the building energy model to develop an evidence-based energy policy framework, and the findings were generalised across eight cities in Cyprus; this method of design provides a universal design approach that could be extrapolated to other South-eastern Mediterranean countries. To prove the validity of the methodological framework developed as an output of this field study investigation in Cyprus, the analysis of the archetype presented here also considers the work of Ballarini *et al.* (2014). In this study, three different archetype housing typologies were selected to represent the entire the Italian housing stock and three different climatic zones were considered: *(i)* the Mediterranean zone up to 2,100 heating degree days; *(ii)* the middle climatic zone from 2,100 to 3,000 heating degree days and *(iii)* the Alpine zone, having more than 3,000 heating degree days.

In the present study, the representative archetypes selected from the urban context enable the research findings to be applied to other post-war social housing estates located in other major cities in NC. This chosen method allows identification of both the upper- and lower-neutral adaptive thermal-comfort thresholds of each city across the island; this also contributes to an ability to benchmark to the ASHRAE Global Thermal Comfort Database II.

Another study, that of Ballarini *et al.* (2014), only considers the development of a method of design for the identification of building typology according to the Typology Approach for Building Stock Energy Assessment (TABULA), Intelligent Energy Use (IEE), European Union project. Additionally, the pilot study conducted by Ballarini *et al*. used secondary data sources for the development of aggregate energy models, and the occupants' thermal comfort was neglected in the project's assessment of the energy-saving potentials of European residential building stocks. This indicates that the study conducted by Ballarini *et al.* has shortcomings in terms of applying the research outputs to other EU countries' energy policy frameworks. In contrast, this present study provides a universal design approach in terms of integrating a household's *in-vivo* experiences in energy use and validating the findings with the statistical analysis of data collected through a questionnaire survey.

Wang *et al.* (2015) only considers low-rise residential buildings as nationally representative archetype houses in Stockholm, Sweden. In the present study, by contrast, post-war social housing estates were selected as an archetype housing typology to represent the demand on government social housing schemes in the mid-1980s and early 1990s in NC. The study included 6,646 buildings that were constructed during this era and the building typology was extrapolated with the most reliable housing stock data from between 2015 and 2019 to identify a nationally representative housing stock that accounts for 56% of the low-, medium- and high-rise RTBs in NC, as shown in Figure 3.38.

The pilot study conducted by Wang *et al.* (2015) used building energy modelling approach by integrating the statistically representative of Swedish housing stock for energy policy design. Additionally, this study investigates building fabric thermal performance of case-study buildings by testing energy efficiency measures (i.e., thermal bridge, air-tightness retrofitting (S1), ventilation retrofitting (S2), window retrofitting (S3), attic/roof retrofitting (S4) and external wall insulation (S5) applied on the existing state of building envelopes while in the present study six passive cooling design strategies were developed and applied on the base-case scenario by considering bio-climatic design elements of the Cypriot context and testing energy effectiveness of each strategy with integration of the questionnaire survey outputs into the building energy model.

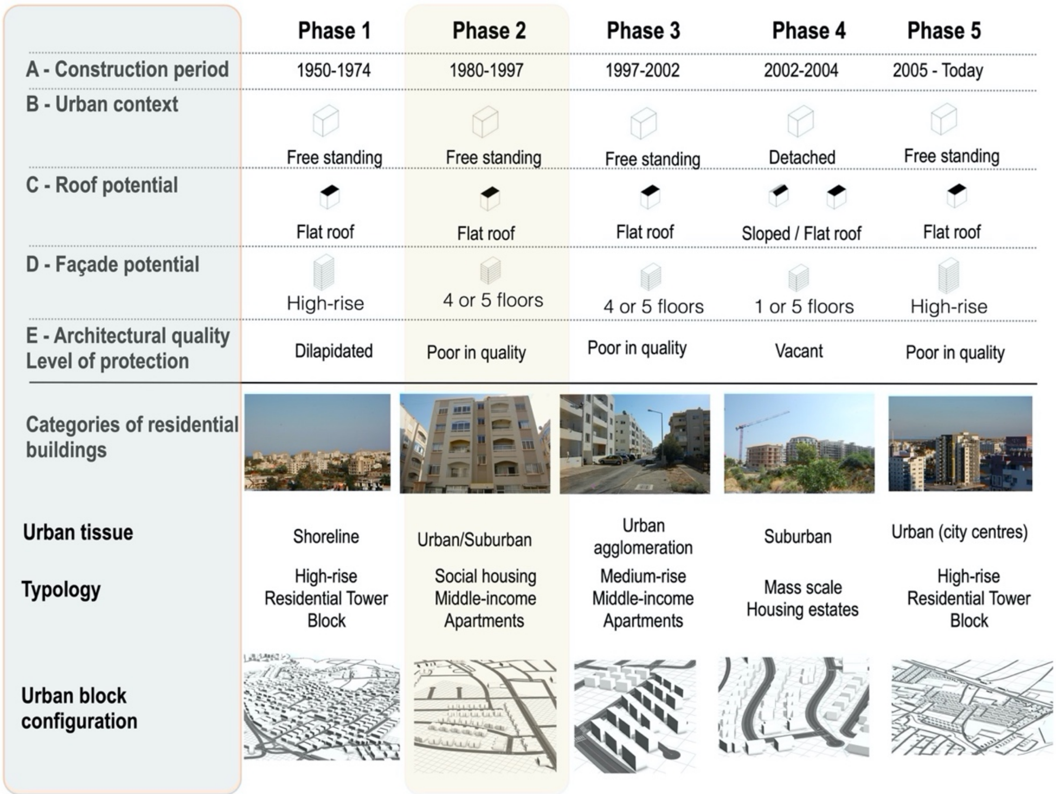


Figure 3.38: National representativeness of high-, medium- and low-rise residential tower blocks in NC.

It should also be noted that Wang *et al.* considers the traditional method of design for testing energy effectiveness of state-of-the-art retrofit interventions applied onto building envelopes without the integration of actual data collection or any other research instruments to measure building fabric thermal performance. The outputs of the *Wang et al.* study predominantly represent the assumptions of energy consumption profiles. In the present study, however, the data collected through 100 samplings of questionnaire survey outputs and *in-situ* recordings of indoor environmental conditions were integrated into the building energy model to validate the findings from dynamic thermal simulations (DTS). The output from the DTS analyses can be extrapolated to assess building performance of post-war social housing estates both in urban and rural locations across the island. Table 3.16(b) delineates the development of statistical sample criteria for archetype housing stock analyses.

Table 3.16(b): The Literature on Building Stock Aggregation through Archetype Buildings. (Continued)

References	A. Study Location	B. Building Type	C. Sampling Size	D. Primary Aim of Model	E. Methodology	F. Main Findings
Dineen *et al.* (2015)	Ireland	2-storey semi-detached houses; 1-storey apartments; 2-storey detached houses; 2-storey terraced buildings; 1-storey detached houses (representing 87% of all dwellings)	The National Administration System (NAS) database was used, which contained details of 253,875 dwellings that represent 19% of the total dwelling stock of 1.6 million housing units	To demonstrate a novel bottom-up approach to modelling the energy-saving potential of energy efficiency improvement measures applied through the retrofit of existing dwelling stock	Archetype housing stock analysis was selected; the housing census data of 2011 was used for the calibration analysis; 145 archetypes were used for the model calculations; Global Sensitivity (GA) analysis was conducted; six retrofit measures were examined; energy demand analysis was conducted	There was approximately a 7.5% change in energy consumption for every 1° C internal temperature fluctuation; the energy model underestimated the heat energy demand of the 2011 stock by just 1.2%
Belpoliti and Bizzarri (2015)	Emilia Romagna, Italy	More than 2-storey and up to 8-storey standalone apartments	70 buildings that were constructed under the Italian social housing scheme between 1991 and 1995.	To develop an effective method of design for the energy performance audit of the social housing stock; to elaborate a parametric calculation protocol to boost effectiveness of the energy audit analysis	A bottom-up energy policy development approach was chosen; national housing census data was used; energy performance analysis was conducted; carbon emission profiles were assessed; three retrofit energy interventions were applied onto the building envelope	Replacing the heating system and single-pane windows with double-pane ones was characterised by a sustainable cost/benefits ratio that ensures a 39.5% reduction in energy consumption
Julia *et al.* (2016)	Cambridge, Massachusetts, United States of America	Low-rise residential buildings with 1-4 dwelling units	A training set of 339 homes was assessed, then a larger test set of 2263 homes was assessed	To develop a methodology for probabilistic Urban Building Energy Modelling (UBEM) archetype characterisation	Archetype dwellings representing housing data between 1970 and 1990; measured energy data was used; a Bayesian calibration approach was adopted; an hourly weather dataset was created; six high-uncertainty variables were chosen for the calibration analysis	Using a calibration error based on monthly energy resulted in 16.5% of the buildings being compared to 0.03% when using annual error margins
Serrano-Lanzarote *et al.* (2016)	Valencia, Spain	Terraced buildings; isolated linear buildings; isolated building towers	1,698.470 dwellings were built between 1960 and 1980, representing 12 climatic zones	To quantify the energy-saving potential and the related CO_2 emissions of the housing stock	A top-down approach was used by splitting the actual energy consumption of the regional building stock among the total number of buildings; building energy simulations were conducted	Energy consumption could be reduced up to 2% in 10 years, representing a savings of 247,871 Mwh

Dineen *et al.* (2015) adopted bottom-up modelling by integrating the statistical power of housing census data available for Ireland from 2011. Representative datasets were gathered from the national energy balance datasets as part of Energy Performance Certificate (EPC) calculations. To define the aggregate energy models, 253,875 dwellings were selected from the National Administration System (NAS), representing 19% of the total dwellings in Ireland. In the present study, the nationally representative data obtained from the *Annual Statistical Report* published by the Northern Cyprus Statistical Office in 2019 represents approximately 11,512 dwelling units consisting of residential tower block projects built on mass scale across the island between 2015 and 2019. This statistical data, extrapolated with the total dwellings, shows that these buildings represent 56% of the building stock in NC.

The study conducted by Dineen *et al.* included a step-by-step development of energy demand calculations and model calibrations by using secondary data sources. In the present study, the building-energy-simulation set-input parameters were developed through a questionnaire survey and *in-situ* physical measurements for environmental conditions were used to validate research findings. There is also of note in the Dineen *et al.* study, the Global Sensitivity analysis approach was used to determine energy-saving measures and rebound effect calculations for each retrofit measure applied onto the building envelope. Whereas in the present study, overall energy-efficient implementation measures of six passive cooling design strategies and their life-cycle cost assessments were examined to demonstrate implications for energy policy design.

One study that shows a similar design approach to the present study is that conducted by Belpoliti and Bizzari (2015). That study investigates the existing social housing stock in the Emilia Romagna region of Italy and adopts only the nationally representative standalone RTBs that were built in the 1990s. This type of social housing stock represents 19.5% of the buildings in Italy. For the present study, the post-war social housing stock was identified as a nationally representative building typology and outcomes were extrapolated using the same design approach as that used by Belpoliti and Bizzari. A main difference between these two studies is that where the Belpoliti and Bizzari study only considers a steady-state analysis of energy retrofit strategies tested to calculate energy savings in the residential sector, the present study sets out to demonstrate the DTS of each of six passive cooling design strategies applied onto the existing state of the archetype buildings. The present study also validates the building energy simulations with use of household energy bills and the socio-demographic characteristics of households gathered through a questionnaire survey.

The study of Julia *et al.* (2016) develops the Urban Building Energy Modelling (UBEM) design method for exploring energy efficiency solutions on urban or district scales. In this territorial exploratory case-study approach, 339 low-rise residential buildings were selected as an archetype housing typology in Cambridge, Massachusetts, USA. In this pilot study, the Energy Use Intensity

(EUI) of the archetype dwellings was assessed to calibrate data with the electricity and gas use of the households. The error margins between the predicted and measured data were calculated to demonstrate annual energy calibration for the region, but the selected sample size does not represent the entire population of this region. To avoid research bias and provide a generalisation of research outputs, the available dataset was multiplied with a larger test set of 2,263 dwellings, applied to measure the accuracy of the validation of the methodology. In the present study, an even larger dataset of 6,646 dwellings were used. These dwellings were identified as nationally representative archetype buildings in both an urban district and also in rural locations in NC. The urban district of Famagusta was selected as a baseline to extrapolate research findings to other cities, as shown in Figure 3.39. The main methodological difference between the pilot study conducted by Julia *et al.* and the present study involves the questionnaire survey used in the present study. In the present study, the statistical method of bootstrapping method was used to increase the sample size to test associations between households' actual energy bills and their socio-demographic characteristics gathered through a questionnaire survey. Additionally, DTS were undertaken to predict the energy use of the identified archetype housing stock by integrating dominant representative occupancy profiles gathered through a questionnaire survey.

A top-down energy policy design approach was utilised by Serrano-Lanzarote *et al.* (2016) in Valencia, Spain. In this pilot study, four different archetype housing typologies were studied that represented 1,698.470 dwellings built between 1960 and 1980 in 12 climatic zones in Spain. Only steady-state analyses of energy-efficiency measures were calculated through use of the aggregated data of households' actual energy consumption, the census population and dwellings, national statistics regarding the energy consumption of the residential sector, and 500 surveys about the actual energy consumption for this region referenced to climatic zones.

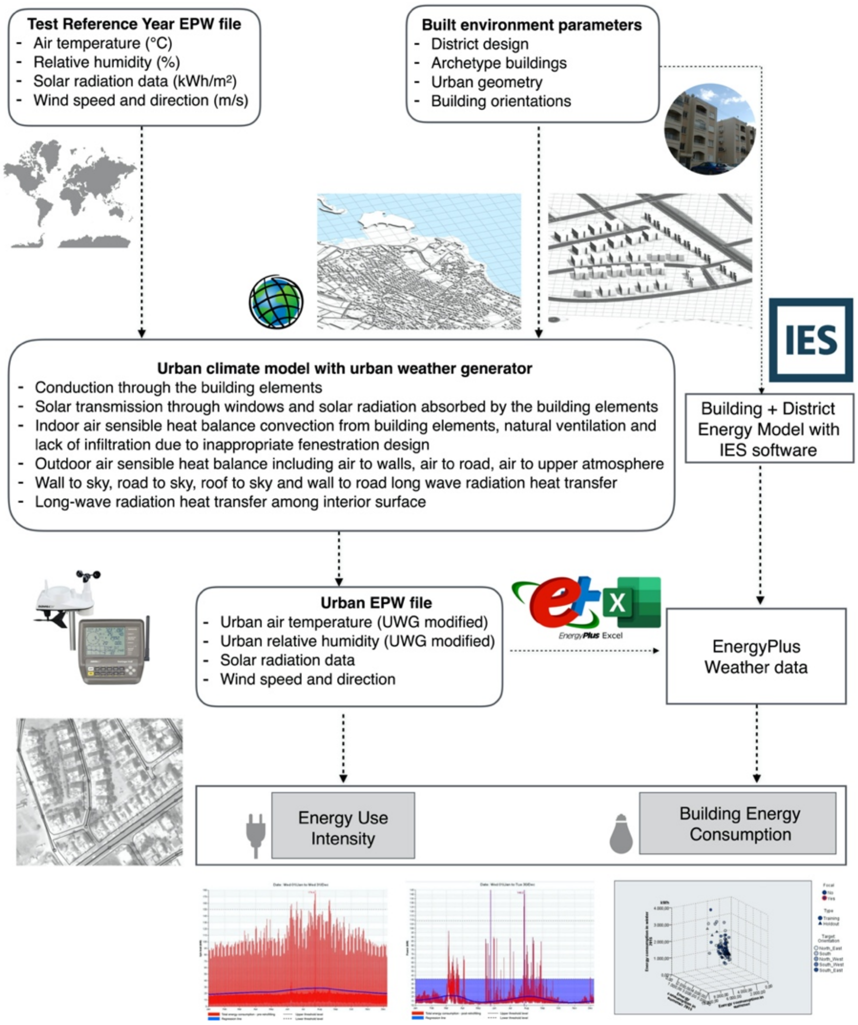


Figure 3.39: The method of design used to demonstrate extrapolation of archetype buildings.

The traditional method of design used by Serrano-Lanzarote *et al.* was also used in this present study, after being adopted for the development of a district-scale retrofitting design approach suitable for NC. It should be noted that the study undertaken by Serrano-Lanzarote *et al.* developed a top-down design approach as these scholars were testing the energy-saving measures of building retrofitting design strategies. In contrast, the present study uses a bottom-up design approach that was developed by integrating the socio-technical-systems (STS) conceptual framework within the extrapolation of field study investigation findings on energy use. The methodological framework developed as an outcome of the present study takes the study conducted by Serrano-Lanzarote *et al.* one step further by developing an evidence-based energy policy framework to assess robust energy-performance evaluation and certification schemes in South-eastern Mediterranean countries. Table 3.16(c) demonstrates the development of statistical methods to aggregate building energy model studies.

Table 3.16(c): The Literature on Building Stock Aggregation through Archetype Buildings. (Continued)

References	A. Study Location	B. Building Type	C. Sampling Size	D. Primary Aim of Model	E. Methodology	F. Main Findings
Loga *et al.* (2016)	20 European countries	SFHs; end-terraced houses; mid-terraced houses; MFHs; apartment blocks; tower buildings	16 EPISCOPE case studies at national, regional and local levels were used; the sample fraction consisted of more than 600 datasets	To develop a common methodological framework with the aim to enable a quantitative comparison of the energy performance of the exemplary buildings; to develop a standardised classification scheme for residential buildings by using an open-access web tool	Cross-country comparisons of building and supply system features were analysed; bottom-up building stock models were used; the energy balance of 'average buildings' was calculated by use of standard energy rating software; *U*-values of both existing buildings and new-build dwellings were gathered; thermal envelope areas were calculated for improvement of building energy models; heating supply systems were identified	Supporting national energy advice activities for illustrating the impact of policy instruments; development of strategies for tracking and understanding actual energy performance achievements
Stefanovic and Gordic (2016)	Kragujevac, Serbia	Free standing tower block; high-rise buildings; apartment blocks; city block; staggered blocks	10,771 multi-family residential buildings were selected in six different construction periods	To improve awareness of energy performance of buildings at the city level	Energy modelling for archetype buildings was constructed; 86 staggered block buildings built between 1981 and 1990 were identified as archetype buildings; a bottom-up design approach was used; a building geodatabase was identified; EnergyPlus software suite was used to undertake building energy simulations	Implementation of polystyrene thermal insulation achieved 17.91%, 21.20% and 22.70% annual heating energy consumption reductions
Cerezo *et al.* (2017)	The residential district of AlqQadisyah, Kuwait	Villa-type multi-family residential buildings	336 dwellings built in the 1980s and 1990s under the 1983 Energy Conservation code, representing 42% of the housing stock	To propose a new method for the characterisation of occupant-related parameters in building archetypes using Bayesian calibration with annual energy data	Both deterministic and probabilistic approaches were adopted; urban data gathering; archetype characterisation; UBEM model generation; archetype Bayesian calibration; energy demand simulation; uncertain and probabilistic archetype parameters explored	EUI of archetypes showed a reduction of percentage errors for the 10 and 90 percentiles of 13%-45% against deterministic methods
Pittam and O'Sullivan (2017)	Cork City, Ireland	End-of-terrace (ET) and mid-terrace (MT) MFHs	1551 asset-rating surveys were used	To use the extracted geometrical building information to demonstrate the effects of using default settings	Representative thermal construction properties were identified; 43 variables were identified that were deemed necessary to represent a detailed disaggregated housing stock database	There is a mean 21.5% variation in the predicted annual energy performance of EUI measures

Loga *et al.* (2016) reviewed the European housing database to develop a common methodological framework for the holistic retrofitting of existing residential buildings. In this statistical analysis method, 600 samples were used for each included EU country across 16 pilot case studies that are available in the TABULA Web Tool. This open-source database offers researchers the ability to extract only those national datasets that were developed under the EPISCOPE-European Union research project to determine the development of EPCs for EU countries. This database consists of the *U*-values of building properties for each nationally representative housing typology identified for each EU country available in the database. In the present study, 36 RTBs that were built under the government's social housing scheme in four major cities across NC were identified as archetype housing stock for conducting the statistical analysis. The Housing Census and Construction Statistics, in conjunction with the most-up-to-date statistical data available from 2015 to 2019, were used to extrapolate representativeness of post-war social housing estates. The data was examined to validate the representativeness of archetype buildings and to provide subsequent background information for the development of a black-box energy model to undertake building energy simulations.

For this study, 100 households were recruited across 36 RTBs in a post-war social housing estate located in the coastal city of Famagusta where the climate is subtropical (*Csa*) and partly semi-arid (*Bsh*), according to the Köppen-Geiger climate classification data. This densely urban district was selected as a base-case scenario where the statistical findings could be generalised and applied to other cities in Cyprus. To prove that the chosen archetypes were statistically representative, this study first examines statistical data for the construction sector by region, as available in the Eurostat data. The findings demonstrate that 7.9% of the gross domestic product (GDP) of the Republic of Cyprus (RoC) and an average of 5.3% of the GDP for the 27 EU countries was accounted for by investment in housing in 2019. The housing census statistics demonstrate that 38% of residential building stock in NC consists of multi-family residential buildings, SFHs and apartments. These statistical findings further validate the national representativeness of the archetype selected for this study, as shown in Figure 3.40.

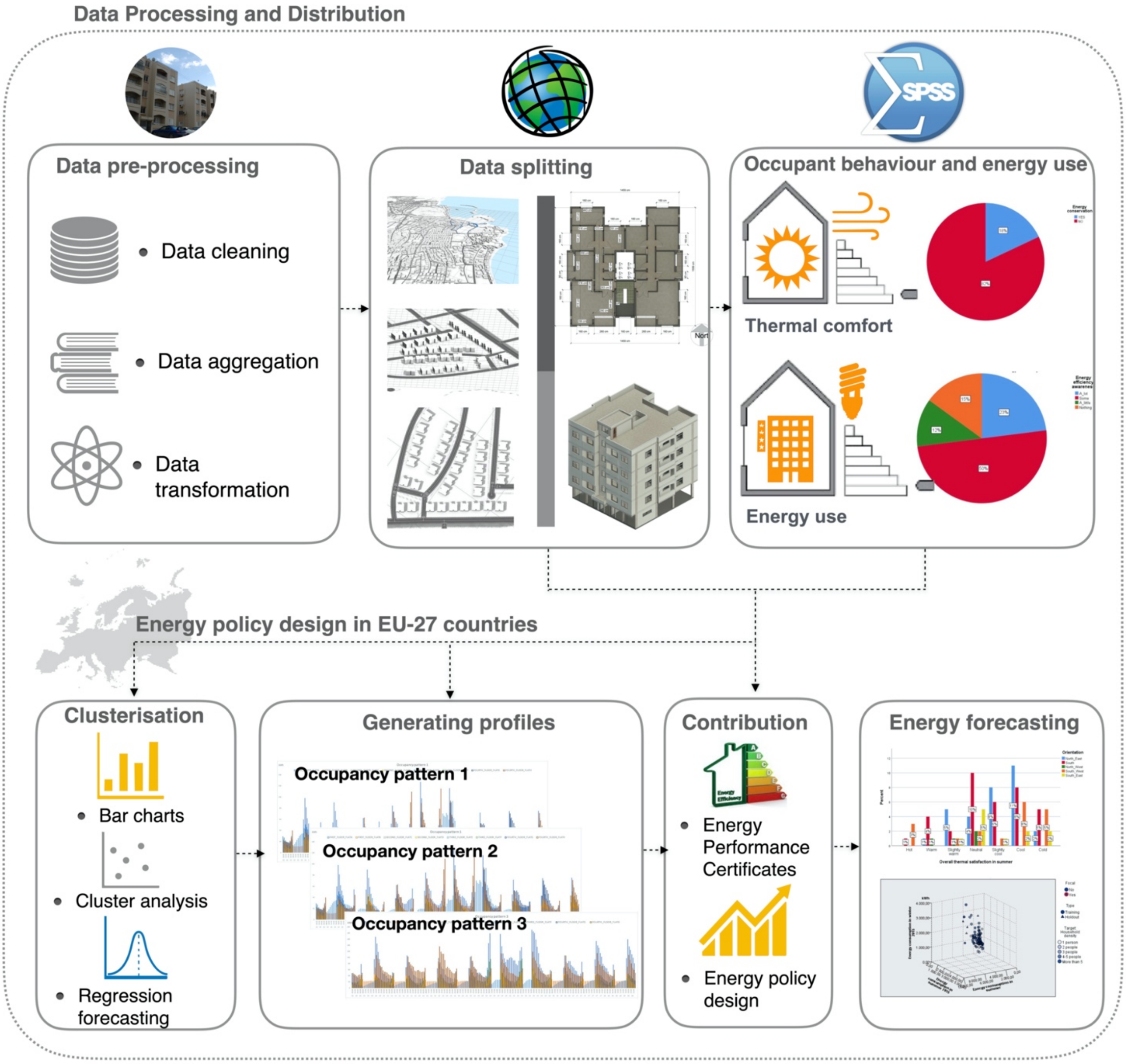


Figure 3.40: Aggregation of archetype building stock for energy policy design.

The study conducted by Loga *et al.* (2016) considered a relatively large sample size for statistical analysis. The international database they used includes the building typology and *U*-values of representative archetypes, offering cross-country validation for the development of effective EPC development schemes in EU-27 countries. By comparison, in the present study, the sample size was relatively small. It consists of 100 households' *in-vivo* experiences in energy use that were collected across 36 RTBs in the same region; however, these findings could be applied to other post-war social housing estates in the four different climatic zones in Cyprus (see **Appendix A**) because RTBs have similar floor plan layout designs and *U*-values of thermal properties. The dataset that was the output of this empirical case study can therefore contribute to the development of bottom-up energy modelling in the South-eastern Mediterranean region, as shown in Figure 3.41.

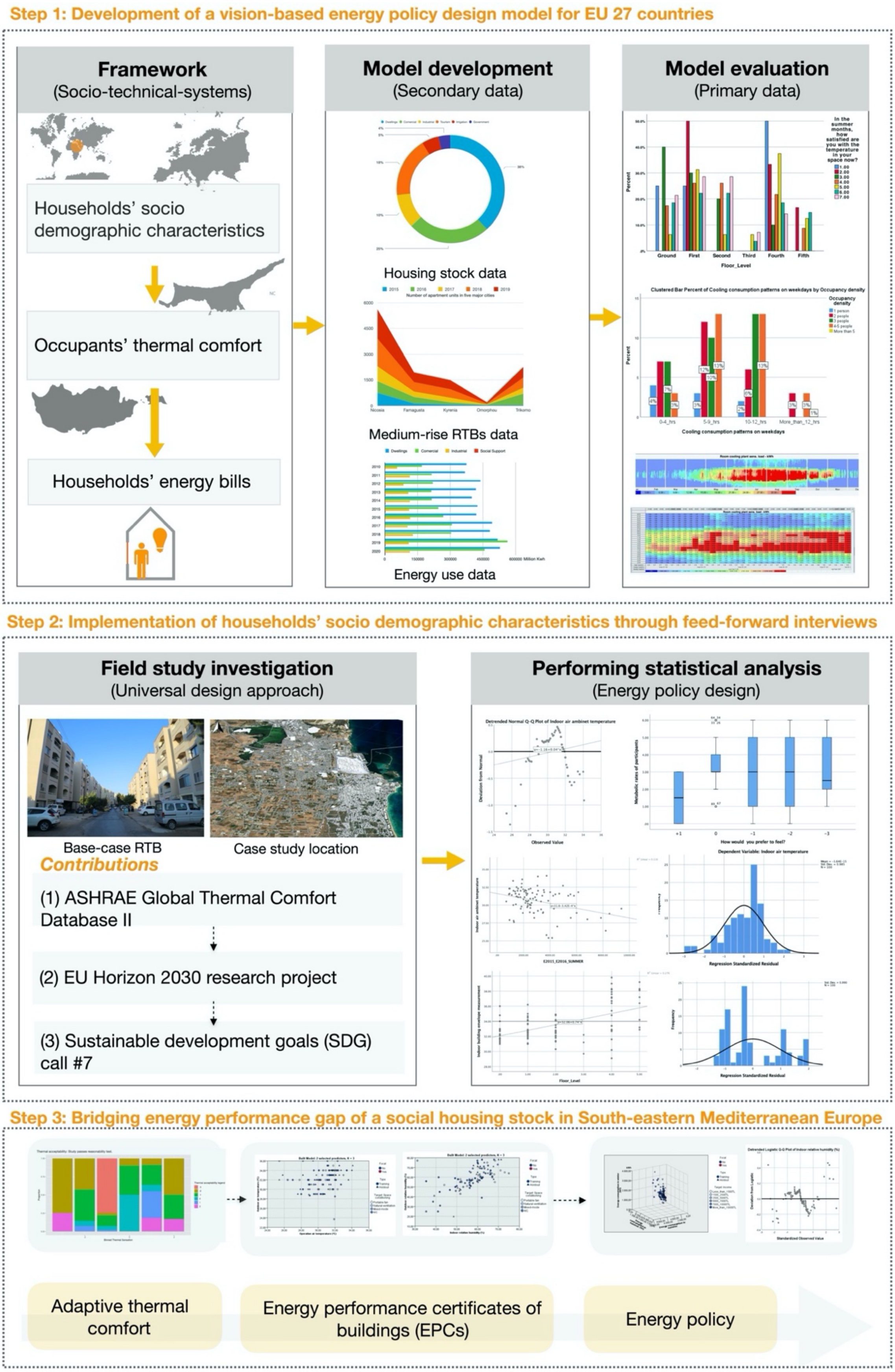


Figure 3.41: Steps for developing an evidence-based energy policy framework that considers households' adaptive thermal comfort.

Stefanovic and Gordic (2016) identified 10,771 multi-family residential buildings, including free standing RTBs and high-rise apartments, in densely built urban districts in Serbia. In the Stefanovic and Gordic study, 86 RTBs were identified as archetype buildings to develop a method of design for improving energy efficiency in the housing stock. The methodological framework developed by Stefanovic and Gordic shows a similar design approach to the present study by investigating potential thermal improvements in the building envelopes of residential multi-family staggered block buildings constructed between 1981 and 1990. However, Stefanovic and Gordic study only considered assumptions generated through building energy modelling and simulations.

In the present study, the building-energy-simulation model was developed by gathering 100 households' socio-demographic characteristics, their habitual adaptive behaviours on home-energy performance, occupancy patterns, and thermal-sensation votes on occupants' indoor-air environments, all to feed black-box model while undertaking DTS. The findings were validated with occupants' actual energy bills. The methodological framework was set to develop simulation set-input parameters and was evidence-based; it predominantly relied on the responses of 100 households across 36 RTBs in a post-war social housing estate, as illustrated in Figure 3.42.

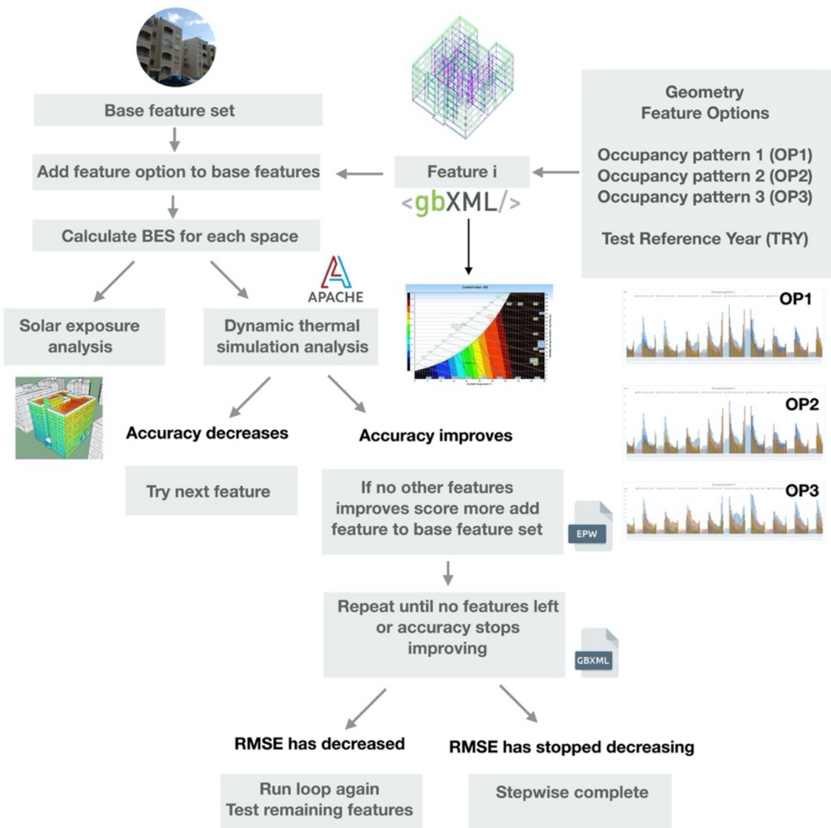
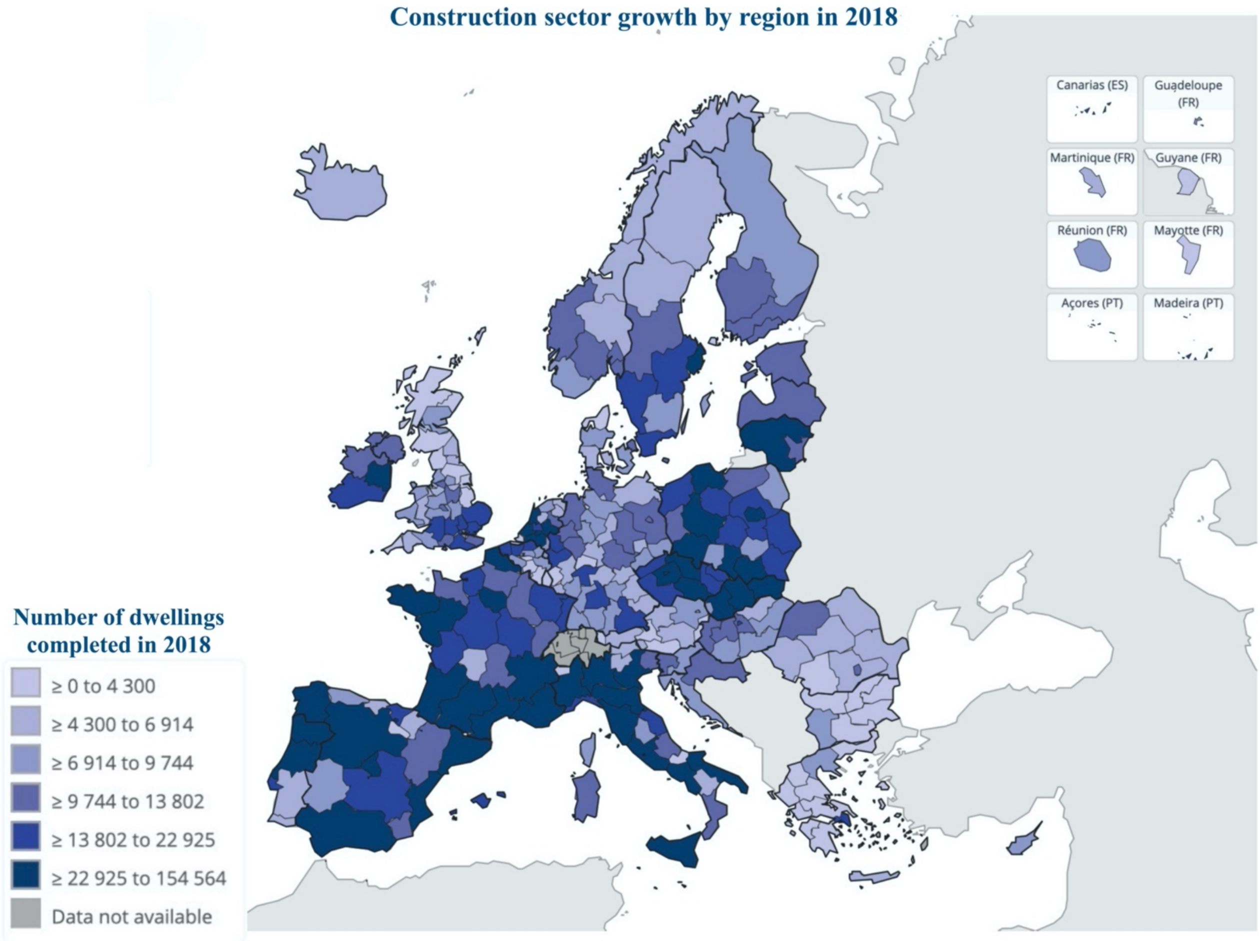


Figure 3.42: Inquiry strategy of the archetype analysis for developing an evidence-based energy policy.

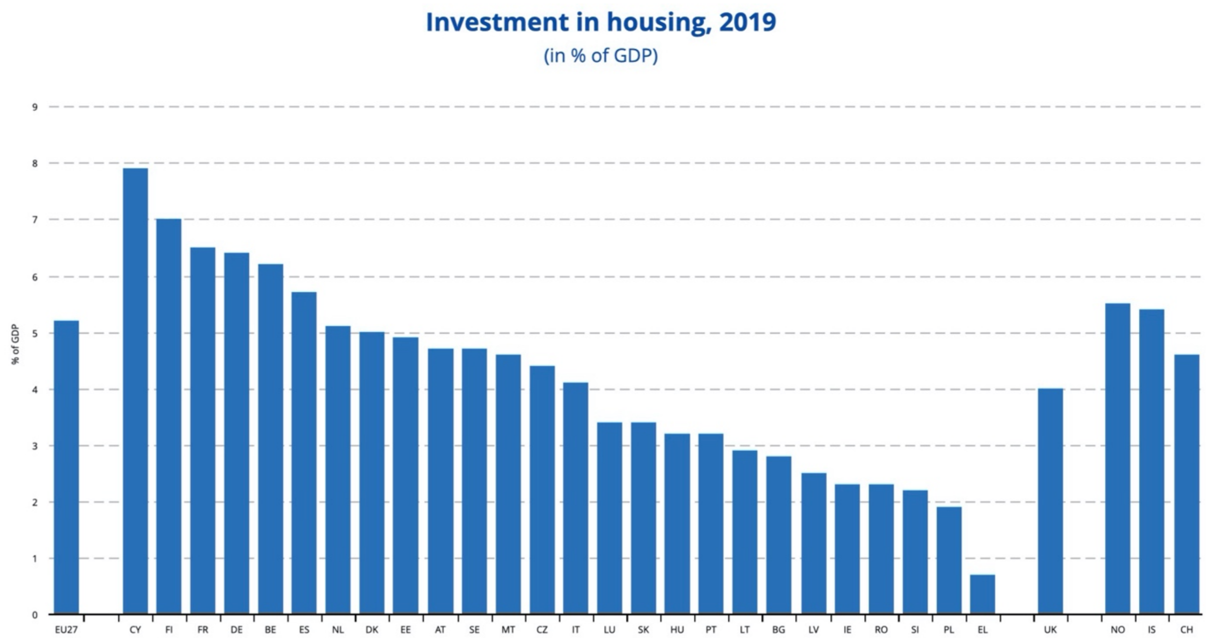
One another similar methodological framework to that used in this study is that of Cerezo *et al.* (2017). This study identified 336 villa-type multi-family residential buildings built between 1980 and 1990 in an urban setting in Kuwait as an archetype building. In this pilot study, the authors set out to demonstrate an energy assessment method with households' actual energy bills to identify discrepancies between metered- and simulated-EUI distributions of the housing stock. In the present study, an evidence-based model analysis was developed to aggregate building energy simulations by using 36 RTBs as a base-case scenario that could be extrapolated to other post-war social housing estates in four different climatic zones in Cyprus. To prove the validity of the universal design approach for the STS conceptual framework, the study examines the pilot research project conducted by Pittam and O'Sullivan (2017). This pilot study used 1,551 samples gathered from the available EPC database to measure the building-energy performance of residential terraced housing stock (identified as an archetype building typology) for aggregating energy performance of base-case archetype buildings before and after retrofitting.

To validate the energy model, a reasonably large sample size was identified by using *U*-value parameters of building elements to use the power of statistical analysis, with the goal of impacting the research for local policymakers and practitioners. In the present study, Housing Census and Construction Statistics were used to identify the national representativeness of archetype housing stock in four different climatic conditions in Cyprus; the findings were then extrapolated to determine the base-case post-war social housing estate by undertaking a longitudinal field study investigation to create the building energy simulations. It should be noted that there is no EPC data available for NC, and this study set out to develop an evidence-based energy policy framework to assess robust energy-performance evaluation and certification schemes in South-eastern Mediterranean countries.

After reviewing the extant worldwide literature on the identification of archetype building typologies and their integration in the development of building energy models for determining effective energy policy design, it can be concluded that a method of design that undertakes a parametric analysis by integrating collated data gathered through a questionnaire survey and field measurements can play an important role in decision-making criteria regarding domestic energy use. To reflect the statistical methods used by previous scholars, the present study examined the EU's construction statistics by using the geo-mapping cluster method, as shown in Figure 3.43(a), and the findings were validated with the available housing census data for the EU countries, as shown in Figure 3.43(b).



(a)



(b)

Figure 3.43: (a) Distribution of dwellings built in EU member states in 2018; **(b)** Distribution of investment in housing in 2019 in percentages of GNP.

As shown in Figure 3.43(a), there is a high demand for construction projects in the South-eastern Mediterranean region. While Portugal, Spain and Italy accounted for the highest number of residential buildings built in 2018, (for these EU countries, it was found that number of dwellings constructed was between 22,925 and 154,564 annually), these figures were followed by Greece and Cyprus were the number of dwellings built ranged from 9,744 to 13,802 annually (Eurostat, 2018).

The Eurostat data figures present those South-eastern Mediterranean countries offer a wide range of SFHs and MFHs for both locals and foreign buyers. According to the Eurostat data, in 2018, 60% of Spanish households lived in flats, 53% lived in flats in Italy and 47% lived in flats in Portugal. In Greece, while the number of dwellings built in 2018 was slightly less than in these other EU countries, about 57% of Greek households lived in flats. While about 27% of Cypriot households live in flats, the population of the island is relatively smaller than most other EU countries in the South-eastern Mediterranean basin, so that 27% of residency in flats is high for the Cypriot context. For the 27 EU countries overall, it was found that 47% of residents live in flats. The obtained average of 27% can be classified as a reasonable fraction to represent the archetype building typology for the RoC. It should be noted that the Housing Census and Construction Report statistics in NC reveal that the low-, medium- and high- rise RTBs account for 56% of the overall residential building stock. This generated statistical data proves that the NC housing stock was slightly above the EU-27 average.

Interestingly, the NC housing stock data is not included in the Eurostat database due to NC being only a *de-facto* state. Northern Cyprus is also underrepresented by the RoC, which does not give a reliable representation of any type of housing stock data for the island of Cyprus. From this statistical analysis, it can be deduced that 56% of high-density residential buildings are nationally representative for NC. This data confirms that high-rise apartments are the representative archetype to be investigated as part of the bottom-up energy policy design. To prove the demand for housing projects, this study investigated housing projects in 2019 by assessing the GNP rate for each of the 27 EU member states, as shown in Figure 3.43(b). It was found that the island of Cyprus accounted for the highest share rate at 7.2% of GDP spent on housing. These figures were followed by 6.6% in Finland, 6.4% in Germany, 2.3% in both Slovenia and Ireland, 2.2% in Poland, 2.0% in Greece and 0.7% in France.

As the EU-27 average was found to be 5.3% of GNP spent on housing, Cyprus's rate was relatively higher than that of other EU countries. This demonstrates that there is high demand in Cyprus for housing projects. It should be noted that Cyprus's population is smaller than other EU countries, and yet the GDP rate shows that the economy is dominated by the construction sector in Cyprus. This statistical data proves that the selected archetype housing typology is appropriate for developing aggregate energy models to validate the data collection findings integrated into the black-box energy model for this study. In the present study, the representative archetype buildings were selected from four different regions and then one of these post-war social housing estates was chosen to extrapolate data to other dwellings in Cyprus, as shown in Figure 3.44.

To identify the representativeness of each post-war social housing estate, both the census data and Housing and Construction Report statistics were investigated to provide a reliable representation rate for each of the cities where the government's social housing estates were built between 1984 and 1997. An up-to-date statistical analysis was undertaken to comply with the most reliable data available for the housing stock between 2015 and 2019.

It was found that in the coastal city of Famagusta where the base-case post-war social housing estate is located, in urban areas, 62% of dwellings are residential buildings, 28% are apartments and 10% are houses. In suburban areas in Famagusta, 44% of dwellings are residential buildings, 37% are apartments and 19% are houses. It should be noted that according to the Statistical Annual Report in 2019, 38% of the overall buildings represent all housing typologies in NC. In mapping representativeness of post-war social housing estates, it was found that apartments in suburban areas in Famagusta represent 37% of dwellings, which proves the appropriateness of the representative archetype of RTBs for the study.

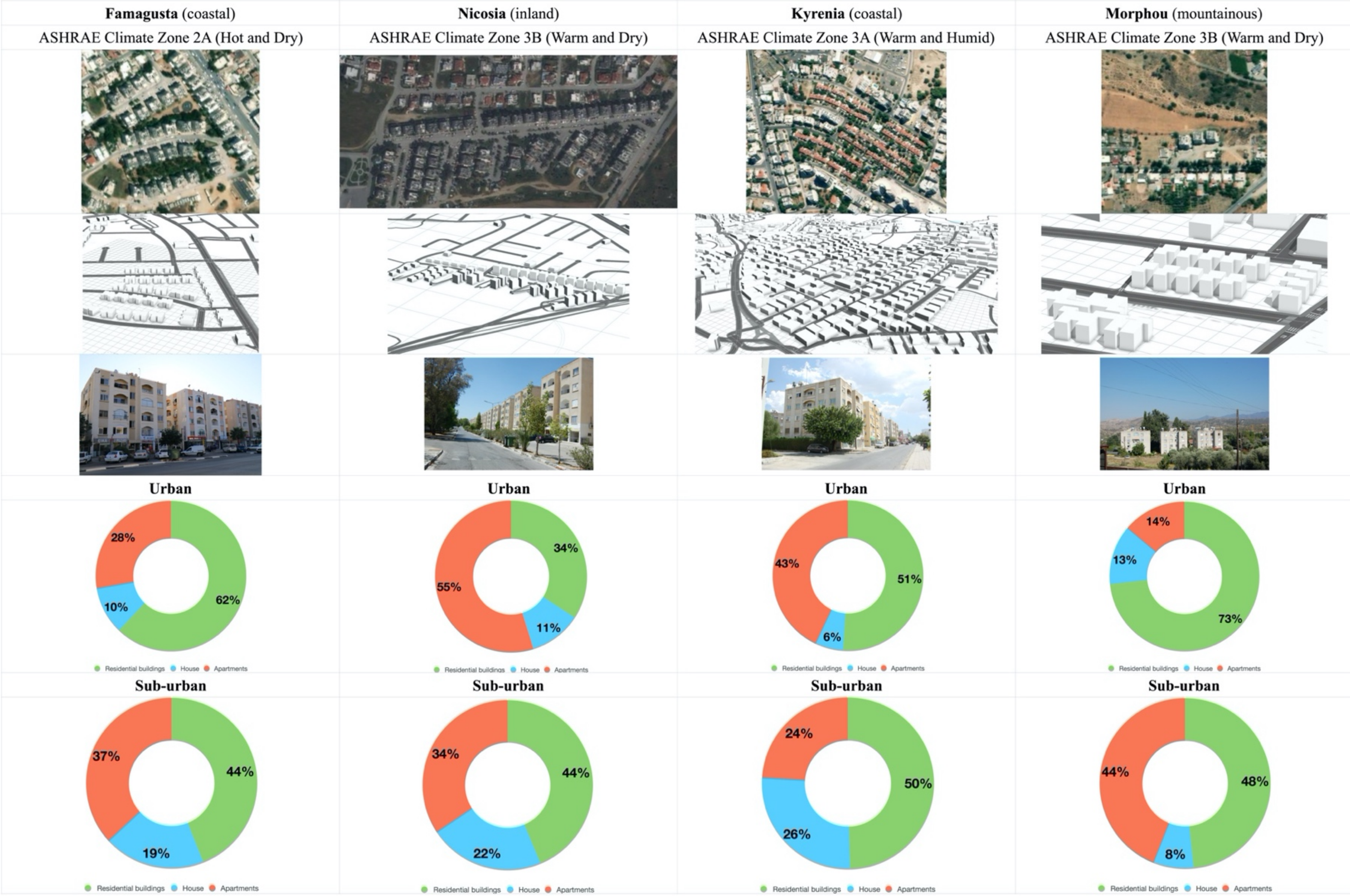


Figure 3.44: Distributions of representativeness of post-war social housing estates.

In the inland region of Nicosia, apartments comprise the highest share of the overall housing stock at 55% in urban areas, followed by 34% residential buildings and 11% houses. In suburban regions, 44% of housing stock is residential buildings, 34% is apartments and 22% is houses. The vast majority (78%) of housing stock is either residential buildings with two to four storeys, or apartments buildings that are more-than-four-storey high-rise MFHs.

In the coastal city of Kyrenia, 51% of dwellings are residential buildings, 43% are apartments and 6% are houses in the densely built urban region, but recent rapid construction activity has had an impact and in suburban regions 50% are residential buildings, 24% are apartments and 26% are houses. Overall, in Kyrenia, 95% of housing stock is residential buildings and apartments, which proves the applicability of research findings in the coastal city of Famagusta to this context where the climate is warm and humid in the summer.

As shown in Figure 3.44, in the mountainous region of Morphou, it was found that the housing stock is 73% residential buildings, 14% apartments and 13% houses in the urban region. Noticeable in this region is a hit record of residential buildings that accounts for 48% of overall housing stock, followed by 44% apartments and 8% houses in the suburban area. It should be noted that this region shows the highest percentage of apartments built amongst the suburban regions of the other cities, as illustrated in Figure 3.44. It can be deduced that both residential buildings and apartments are nationally representative archetypes, which allows an extrapolation of research findings gathered in the base-case post-war social housing estate in the coastal city of Famagusta to an evidence-based energy policy framework for the South-eastern Mediterranean basin.

3.5 Methods and Tools

3.5.1 Literature Review

The aim of the present study was to review literature related to building overheating risks, thermal-comfort assessments, occupant behaviour and modelling and design methods developed by previous scholars to undertake a BES. Furthermore, the most commonly used energy-simulation tools related to building-performance evaluation were derived. To fill the EEG and address the RQs outlined for the present study, the bottom-up approach was adopted to analyse the energy performance of the archetype buildings and to validate the field study findings with the *in-situ* measurements and BES study.

A search was conducted using the traditional review method; the Scopus platform was the main engine used for this search. The literature survey resulted in 784 documents, which included review articles, original research papers and conference proceedings that were collated between 1990 and 2019. Abstracts of the documents were reviewed using the meta-analysis method; this was followed by an analysis of the research context, methodology, archetype-building selection, research instruments used, sampling size and novelty of each empirical study. Figures 3.45(a) and (b) present an overview of the search results, and Table 3.17 lists the top 11 sources that were included in the literature review for the present study; four additional conference proceedings were included to review extant literature that is within the objective of the present study.

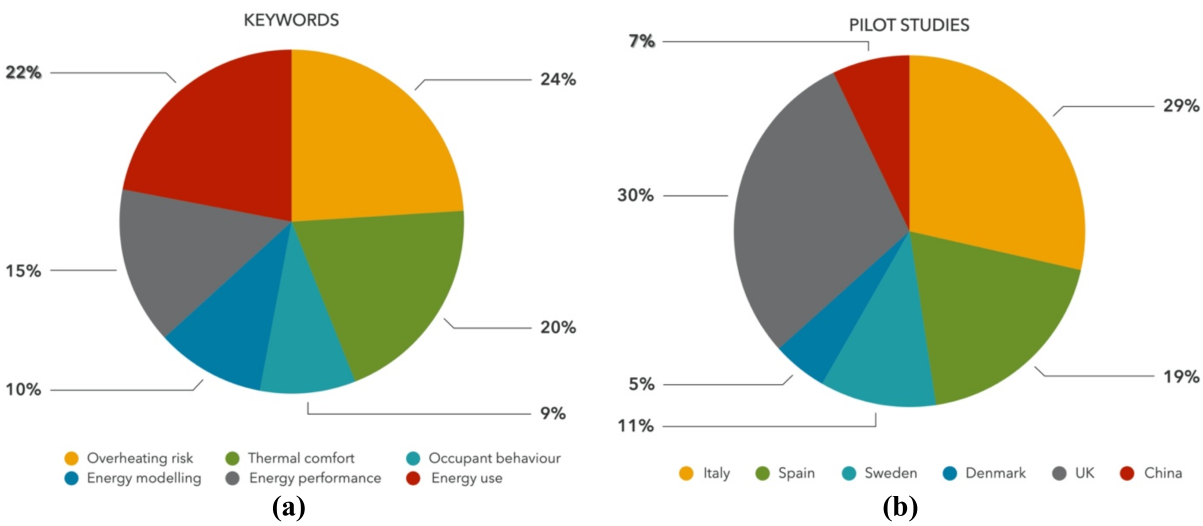


Figure 3.45: **(a)** Keywords and percentage distribution related to appearance; **(b)** countries of pilot studies according to keyword selection criteria.

Table 3.17: Journal Articles and Conference Proceedings Included in Literature Review.

Top 11	Source	Number of Documents	Source IF	Source SNIP	Source SJR
	Selected Journals				
1	*Energy and Buildings*	154	4,867	2,334	2,061
2	*Building and Environment*	124	5,20	2,604	1,879
3	*Energy*	81	6,082	2,012	2,166
4	*Applied Energy*	38	9,27	2,865	3,455
5	*Energy Research and Social Sciences*	54	5,45	1,869	2,138
6	*Energy Policy*	87	4,039	1,931	1,988
7	*Renewable and Sustainable Energy Reviews*	43	12,110	4,351	3,632
8	*Solar Energy*	23	4,608	1,651	1,539
9	*Journal of Building Engineering*	32	2,890	1,777	0,682
10	*Journal of Building Performance Simulation*	56	3,458	1,764	1,329
11	*Sustainable Cities and Society*	13	5,268	1,987	1,356

Selected Conference Proceedings: *(i) Building Simulation Optimization 2018* (30 papers in total); *(ii) Windsor Conference Proceedings 2012–2018* (23 papers in total); *(iii) Zero Energy Mass Custom Housing Proceedings 2016–2018* (7 papers in total); *(iv) IBPSA Conference Proceedings 2016–2018* (27 papers in total)
Note: Journal metrics updated on March 23, 2021.

Reviewing these study findings provided an opportunity to identify a new design method for an STS approach that could be developed to address the EEG and assess occupant thermal comfort via a longitudinal field survey, which is outlined in Sub-section 3.5.2.

3.5.2 Survey Design and Data Acquisition

Survey. A standardised questionnaire survey was developed to collect subjective data from the building occupants related to their domestic cooling-energy use and to evaluate the thermal-comfort levels in specific orientations (Dornyei, 2003); a total of 200 households from 288 flats were randomly selected, which represented the social-housing stock in other municipalities in NC (Black, 2006). A number of research methods were employed in the present study to collect and analyse the research data (Campell & Fiske, 1959; Creswell, 2010; Goodchild *et al.*, 2017).

In this study, the questionnaire survey with structured questions and open-ended questions was intended to collect quantitative and qualitative data throughout the standardised means to further probe the details of specific questions. Notably, the data gathered during the qualitative phase of the present study informed the findings of the quantitative phase (Creswell & Clark, 2011). Similarly, the quantitative results demonstrated outcomes related to household energy use and the thermal comfort reported by participants to assist in the findings from the qualitative data (Kieft *et al*., 2020). 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 households, as illustrated in Figure 3.46.

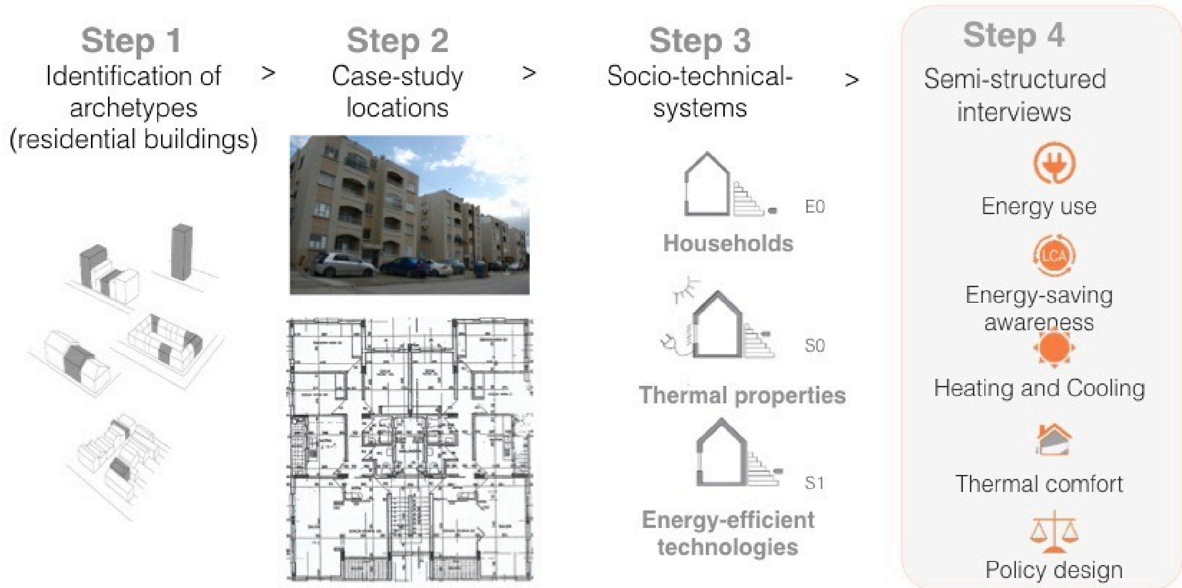


Figure 3.46: Step-by-step identification of representative RTBs to develop base-case scenario.

To conduct an in-depth analysis of the RTB thermal properties that considered household socio-demographic characteristics and environmental conditions of the social-housing project sites, the aforementioned location was selected as a representative application of the described methodology (Ramsden, 2020; Wittmayer *et al*., 2020). In this way, the most dominant representative urban-built stock was studied, and the results of the present study could be extrapolated to the remainder of the social-housing stock, which was intended to represent post-war social-housing stock in Europe.

Participants. The subject respondents (*P*-set) for the development of an STS conceptual framework were drawn from all 36 RTBs in the post-war social-housing estate in Famagusta, Cyprus, as was shown in Figure 3.31. The area boundaries were defined by the demographics and housing-stock datasets associated with the national census of the Office for National Statistics State Planning Organisation. These secondary-data resources were utilised to determine the representativeness of sampling criteria included in the statistical model; 118 households[5] were recruited through a field investigation, which was then extrapolated to represent NC households. All variable differences were calculated to identify the worst-case scenario, and the medium-rise RTB estate with the highest total number of flats was selected; this area represented typical neighbourhoods in Nicosia (i.e., urban), Kyrenia (i.e., urban), Omorphou (i.e., rural) and Lefke (i.e., rural), rather than randomly selected neighbourhoods. The census variables are shown in Table 3.18.

Table 3.18: Household Socio-Demographic Characteristics Collected from the Questionnaire Survey.

Socio-Demographic Variables	
Tenure type	Year of construction
Housing stock with the council tax band	Household occupancy type (i.e., OP1, OP2 and OP3*)
Housing type	
Space conditioning and different floor-levels	Household energy bills

*Occupancy Patterns: Low occupancy (OP1), moderate occupancy (OP2) and high occupancy (OP3)

Source: Restructured in 2018 according to data from the Office for National Statistics.

As can be seen in Table 3.18, all variables were related to household socio-demographic characteristics and the type of housing stock that was chosen. To design standard development models and compare them to the city average, the best approach was to only select one case-study location to represent the entire social-housing stock as a base-case scenario (Muresan & Attia, 2017). This deliberate sampling was undertaken to meet the research objective of investigating the effect of household socio-demographic characteristics on home-energy performance in a typical representative neighbourhood (Cross *et al*., 2017). Each variable was integrated into the statistical model to predict the energy-policy forecasting design scenarios is briefly described below:

i. Ownership status referred to the overall percentage of social-housing stock who were homeowners or private renters.

ii. RTB age referred to the five different archetypes that represented a nationwide sampling for a fraction of overall household population.

iii. Housing typology classification was based on to council tax band in accordance with the council tax rating indicators obtained from the Famagusta municipality.

[5] 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.

iv. Household occupancy type referred to the number of family members lived in the same property.

v. Space conditioning of occupied spaces included natural ventilation, mixed-mode ventilation, mechanical ventilation heat-recovery systems and A/C split units installed in the property.

vi. Actual household electricity bills obtained from the Cyprus Electricity Authority.

These variables include all available physical built-form and demographic information related to the home at the local level to provide subsequent information for the development of an evidence-based STS conceptual framework. Data collection was guided by a preliminary thematic analysis of key concepts prompted during the interviews with participants. The applied methodology considered the post-war social-housing stock by exploring correlations between the household socio-demographic structure, the actual environmental conditions of the built environment and the thermal-conductivity level of building thermal properties. It should also be noted that semi-structured interviews were only conducted with occupants in selected building typologies so the findings of the present study could be generalised and applied to other post-war social-housing stock in the Republic of Cyprus and in Europe.

Questionnaire Design and Household Recruitment. This research adopted a methodology that included questionnaire surveys distributed in RTBs with different orientations to assess overheating risks, optimise occupant thermal comfort and determine whether different floor levels have a substantial impact on the energy use of households in a post-war social-housing development estate. A thorough review of the present study was conducted, including several instances of feedback that were obtained during the pilot study. The survey was conducted with members of 118 households between July 28 and September 3, 2018. The questionnaire included 28 questions and adopted a combination of open-ended, partially closed-ended and mostly closed-ended questions (Creswell, 2012); it was designed to predominantly obtain quantitative feedback from respondents by utilising housing census data obtained from Famagusta Municipality to generate a nationally representative sample of Cypriot households (Darnton, 2008; Doukas, 2020).

The *pro-forma* questionnaire survey was contrived according to the cultural values of the research context, specifically the cultural barriers that prevent a man from entering premises in which only the woman is present (see **Appendix B**); for this reason, the researcher was accompanied by a female throughout the survey processes. The survey was specifically devised to take ethnicity, cultural values, climate characteristics and building codes into account to obtain effective responses from the households. The design structure of this *pro-forma* questionnaire is itself a contribution to the body of knowledge; the *pro-forma* questionnaire survey is an exemplary pilot-survey model that can be applied in other field studies where the climate is shown to be subtropical (*Csa*) and partly semi-arid (*Bsh*).

Importantly, the manner in which the field survey was conducted included going door-to-door with the survey to recruit households. The *pro-forma* questionnaire survey was completed in the form of semi-structured, face-to-face interviews to obtain the most accurate data from the subject respondents; due to the nature of the interviews and discussions, the researcher was able to collect quantitative data to validate the obtained data that included *on-site* monitoring and *in-situ* measurements of the environmental conditions, which is the contribution; this thesis presents the human-based data that were extracted from the questionnaire survey for the BES studies.

Data Analysis. Semi-structured interviews and participant feedback were transcribed and translated. The Statistical Package for Social Sciences (SPSS) Version 25.0 software (IBM: Armonk, NY, U.S.) was utilised to conduct the quantitative analysis; and tests-of-associations were conducted between the numeric factors and the questionnaire responses to join the questionnaire results with the statistical analysis (see **Appendix I** – Development Stages of the Statistical Analysis). Previous studies used analysis-of-variance (ANOVA), Pearson's correlation and ordinal regression and multinominal logistic regression analyses, and these statistical tests effectively explored correlations within a set of variables designed in the dataset. To interpret the statistical analysis the conventional method was used for the interpretations between two continuous variables. Table 3.19 demonstrates the guidelines are generally in agreement with Cohen's recommended guidelines[6].

[6] For the interpretations of statistical findings, the six possible combinations of variables encountered by researchers are as follows: *(i)* continuous-continuous; *(ii)* continuous-ordinal; *(iii)* continuous-nominal; *(iv)* ordinal-ordinal; *(v)* ordinal-nominal; *(vi)* nominal-nominal. For each of these combinations of variables, one or more measures of association that accurately assess the strength of the relationship between the two variables are discussed in the contribution Chapters where it is necessary to determine the influences of statistical findings for the development of evidence-based energy policy framework.

Table 3.19: Measures of Association.

r	**Interpretation of Linear Relationship**
0,8	Strong positive
0,5	Moderate positive
0,3	Weak positive
0,0	No relationship
-0,2	Weak negative
-0,5	Moderate negative
-0,8	Strong negative

$|r| < 0{,}3 \rightarrow$ Weak relationship
$0{,}3 \le |r| \le 0{,}5 \rightarrow$ Moderate relationship
$|r| > 0{,}5 \rightarrow$ Strong relationship
Source: Khamis (2008)

3.5.3 Questionnaire Survey

Design Methods. The present study primarily relied on a questionnaire-based survey to investigate household characteristics and the habitual adaptive behaviour of occupants as it relates to home-energy performance. The questionnaire gauged each household's level of knowledge about their heating and cooling systems in an attempt to determine what the respondents considered to be energy when it came to their cooling systems, and how they adapted heating and cooling systems to their personal thermal comfort in changing climate conditions. Table 3.20 presents the questionnaires that included household socio-demographic information in the interviewed RTBs while taking the orientation and floor-level differences thereof into account. A set of questions was developed to inquire about the socio-economic characteristics and tenancy status of each household, including the length of residency at the property.

Another set of questions focused on the household energy-saving awareness and advice received on information on energy-efficient practices that were provided to each household by the Famagusta Municipality or local energy-networking service, because the questionnaire survey was conducted in the summer and the occupants were asked to retrospectively indicate on various multi-factorial home-energy performance indicators from the previous winter. As was already indicated, the *pro-forma* questionnaire survey was designed to consider the cultural assets, values and norms of the research context and ensure an accurate statistical analysis; a condensed version of the questionnaire is provided in **Appendix B**.

Table 3.20: Questionnaire Details.

Developmental Stages	Questions
Step 1: ***General background information***	- Number of interviewed RTBs - Unit orientation - Floor level
Step 2: ***Socio-demographic information***	- Gender - Age - Tenancy status and length of residency - Number of household members, including non-family members - Employment activity - Income - Education - Ethnicity - Health status
Step 3: ***Energy-saving awareness***	- Did respondent receive energy advice from any type of public or private institution? - Availability of electricity meter readings and frequency of checks - Did the respondents consider any type of energy-saving methods in their daily activities?
Step 4: ***Household energy use and performance***	- Types of domestic heating appliances, available heating-system controls and frequency of use - Types of domestic cooling appliances, available cooling-system controls and frequency of use
Step 5: ***Occupancy patterns***	- Weekday and weekend heating-consumption patterns - Weekday and weekend cooling-consumption patterns - Window-opening patterns in the summer and winter
Step 6: ***Energy consumption***	- Average amounts of monthly utility bill

Household Selection Criteria and Recruitment. To provide subsequent background information related to household socio-demographic characteristics and the validity of the questionnaire survey in the south-eastern Mediterranean climate, the survey participants were selected from among 36 RTBs, all of which had similar floor plans, layout designs and construction characteristics; there was a total of 288 flat units in the social-housing estate, and each had a different orientation and household characteristics, as shown in Figure 3.47.

Figure 3.47: Point-by-point walk-through survey of case-study location; field investigation was conducted via door-to-door survey of base-case RTBs.

A quota-sampling decision-making criterion was adopted in the present study to demonstrate a nationally representative sample of Northern Cypriot post-war social-housing stock. The extant literature on field-study investigations of social-housing estates in Europe and in the U.K. recommended that the quota sampling that is needed to investigate correlations between different variables should be gathered through a questionnaire survey, which suggests that issuing a set of quota characteristics (i.e., tenure type, orientation, different floor levels and occupant energy-use patterns) to interviewers and conducting a corresponding number of multi-decision criteria analyses in every category of every household socio-demographic characteristic.

The aim of this technique was to validate the multi-variate statistical analysis that was conducted to demonstrate the representativeness of the sample size and reflect the household socio-demographic overview for which the interviews were sought. To avoid bias when considering the households' responses to the distributed set of questions and minimise the risk of discrepancies in the statistical analysis, the quota sampling approach offered inclusive primary-data output; one reason for this is that it is not possible to determine the exact representatives of a given sample because of potential sampling bias during respondent selection.

Throughout the *pro-forma* questionnaire survey, the present study developed 10 interview questions to gather the following binary categories: owners versus renters, length of residency, awareness of energy saving, type of heating and cooling systems used, type of heating- and cooling-control systems utilised, occupancy patterns during the weekdays and on the weekends in the winter and summer, window-opening schedules in the winter and summer and the reasons for thermal discomfort—all of which took into account the different orientations of the RTBs and the different floor levels of each flat. These classifications were selected because the aforementioned factors strongly correlate with the significance of energy-consumption patterns in overall energy use. The sample was based on gathering background information on the overall occupancy of every unit in the RTBs, rather than obtaining individual information of the subject respondents.

To fulfil this research objective and avoid the risk of bias on the household responses related to knowledge of energy use at the household level, the survey method was pilot-tested. A questionnaire-based survey was prepared, partly to hear occupant views on patterns that impacted their home-energy use, and also to collect evidence-based examples of identifying dominant representative occupancy profiles that could be further corroborated in the decision-making process of retrofitting design interventions.

3.5.4 Thermal-Comfort Survey

Design Methods. To assess the occupants' degree of thermal discomfort, the *pro-forma* questionnaire was distributed to the subject respondents, the seven-point ASHRAE thermal-sensation band was employed. A thermal-comfort survey was concurrently carried out with *on-site* monitoring and *in-situ* measurements to understand the significant impact of environmental conditions on the occupants' thermal comfort at the time of the survey administration.

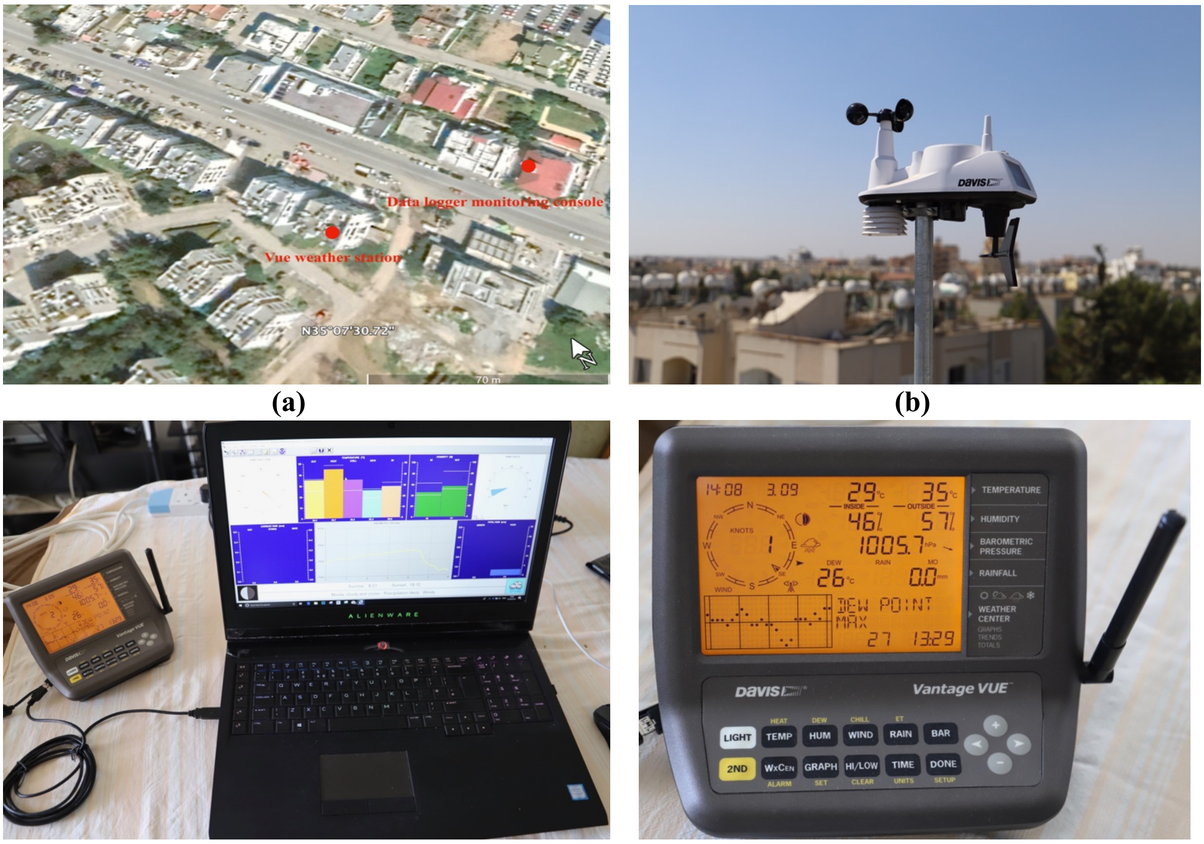
Physical Measurements. The outdoor-air temperatures and relative humidity (RH) levels of the environmental conditions were monitored between July 28, 2018 and September 3, 2018 to assess the overheating risk issues of the *in-situ*-measured flats. The outdoor environmental conditions, including the outdoor air temperature, RH and heat-stress index, were monitored with a Wireless Vintage Pro 2 weather station from Davis Instruments Corporation (Hayward, CA, U.S.), as shown in Figure 3.48(a). Indoor environmental conditions were recorded with a thermometer (resolution 0,1°C); globe temperature was recorded with a 15 cm-diameter globe thermometer with a thin-walled copper sphere that is painted black (resolution 0,1°C); RH was recorded with a 2400 Heat Stress WBGT Meter (resolution 0,1°C) (Extech Instruments: Nashua, NH, U.S.), as shown in Figure 3.48(b).

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 related to their TPVs and TSVs, as shown in Figure 3.48(c). With regard to the overheating-risk assessment, the indoor air temperature and RH of 100 participant living rooms were concurrently measured with a questionnaire survey to cover the hottest period in summer to assess overheating-risk and occupant thermal comfort. Figures 3.48(a) through (c) illustrate the setups for the weather station and indoor air temperature measurement instrument.

(a) **(b)** **(c)**

Figure 3.48: **(a)** Vantage Vue weather station; **(b)** wet bulb temperature recorded with Heat Stress WBGT meter; **(c)** indoor ambient-air temperature measured with FLIR. ***Source:*** Images collected from the author's field-survey diaries and archival photographic documentation of case-study buildings in Famagusta, Cyprus. ***Image Credits:*** Courtesy of households participating in questionnaire survey and monitoring campaign.

To identify neutral adaptive thermal comfort and validate the findings from the BPEs, outdoor thermal conditions, including the outdoor-air temperature, RH levels and the HSI, were monitored with a Wireless Vantage Pro weather station. As illustrated in Figures 3.49(a) and (b), the weather station was installed on the roof of the northwest-facing RTB Block Number 3, which was built in Phase 1; specifically, as shown in Figure 3.49(b), the weather station was mounted on a pole that was approximately 2 metres long. It was equipped with a set of continuously monitored thermocouples that recorded temperature variations throughout the questionnaire survey period, as shown in Figures 3.49(c) and (d).



(a) (b)

(c) (d)

Figure 3.49: (a) Location map of weather station and monitoring console; **(b)** Vantage Vue weather station; **(c)** daily data monitoring during field survey; **(d)** monitoring console dashboard showing data.

The temperature measurements were collected at 15-minute intervals over a one-month period. According to the manufacturer specifications, the accuracy of the thermocouples is rated at ±0,05°C, to ensure that reliable datasets are recorded and to assess the current thermal performance of the case-study building. The environmental monitoring study was concurrently undertaken with the semi-structured household interviews; in addition to the monitored data, meteorological data gathered from the Department of Meteorological Service in NC were collected to compare the accuracy of the monitoring results. The meteorological weather station was located approximately 16 km away from the case-study location, which ensured that the outdoor weather observations were representative of the local climate. The details of the instrumentation used in the field studies are summarised in Table 3.21.

Table 3.21: Technical Properties of Weather Station at Case-Study Location.

Climate Variables	**Accuracy**	**Resolution**	**Measurement Range**	**Instrument for *On-Site* Measurements**
Air temperature	±0,5° above −7°C	0,1°C or 1°C	−40°C to +65°C	
Relative humidity	±3% for 0–90% and ±4% for 0–90-to-100%	1%	1–100%	
Wind speed	1 m/s	0,4 m/s	1–80 m/s	

As can be seen in Table 3.21, the weather station recorded the abovementioned parameters in 10-minute intervals each day. Data for the relevant days were downloaded, processed and merged using a specific weather-analysis software suite developed for the Vue weather station. It should be mentioned that the outdoor air temperature was used to calculate the 80% acceptable operative-temperature range in accordance with the ASHRAE Standard 55 specifications (2017); the upper and lower limits of the 80% acceptable range are presented in Equations 1 and 2. Per to the ASHRAE Standard 55 (2017), variable T_{rma} is defined as the prevailing mean outdoor air temperature and is calculated based on the arithmetic average of the mean daily outdoor air temperatures to calibrate the correlations between the outdoor and indoor environmental conditions that were recorded.

$$\text{Upper 80\% acceptability limit (°C)} = 0{,}31\ T_{rma} + 21{,}3\text{°C} \qquad \text{(Eq. 1)}$$

$$\text{Lower 80\% acceptability limit (°C)} = 0{,}31\ T_{rma} + 14{,}3\text{°C} \qquad \text{(Eq. 2)}$$

3.5.5 On-Site Measurements

Design Methods. While the questionnaire surveys were being conducted, the indoor environmental parameters were also being recorded; this included air temperatures and the RH levels of the measured apartment units. The accuracy of the instrumentation utilised in the field studies met the 2015 *CIBSE-AM11: Building Energy and Environmental Modelling* requirements (Fox *et al.*, 2014). The details of the instrumentation utilised in the field studies are summarised in Table 3.22.

Table 3.22: Measurement Range and Accuracy of Instruments Used in Field Studies.

Parameter	Instrumentation Model	Range	Accuracy	Accuracy Requirements*	Image
Air temperature	Fluke TIS20 Thermal Camera	−40°C to +85°C	±1°C for 150°C	±0,5°C	
Relative humidity	Fluke TIS20 Thermal Camera	0–100%	±4%	±1%	
Air temperature	Fluke 63 Infrared Thermometer	−25°C to 85°C	±0,5°C for 0–40°C	Minimum: ±0,5°C Ideal: ±0,2°C	
Relative humidity	Fluke 63 Infrared Thermometer	0–95%	±3% at 25°C	±5%	

*Per the 2015 CIBSE Guide A benchmarks

The physical measurements covered the entire period of the questionnaire surveys. The *in-situ* measurements were conducted with the FLIR camera during the field study in August of 2018. In addition to the subjective thermal-sensation responses, these measurements permitted the calculation of comfort temperatures embedded within the Griffiths Method related to adaptive thermal comfort to identify occupant optimum thermal-comfort threshold level, which are presented in Chapter 4.

As it relates to a thermal-comfort analysis, Griffiths suggested that there was a linear relationship between comfort votes and operative temperature (OT) with a constant gradient (Griffiths, 1990). The assessment calculation can thus be interpreted in Equation 3:

$$Cv = T_{op} + h \tag{Eq. 3}$$

where Cv is the comfort vote, T_{op} is the OT and h is the constant. This equation model was adopted to assess the results of the building-energy performance studies and gather evidence-based data to develop an STS conceptual framework.

The present study selected a specific methodology—the pass-by thermography method—to speed up the inspection process, so the research consortium could investigate more buildings in each survey period (Theodosiou *et al*., 2021). The methodology adopted for walk-through surveys in the present study followed the principles established by the American Society for Testing and Materials, the Residential Energy Services Network and British Standard BS EN 13187: 1999 (BR-497:2007, 2007).

3.5.6 Building-Energy Simulation Parameters

Design Method. To determine the input parameters for the simulation set, the present study adopted the STS approach, which considers the socio-demographic characteristics of the energy use of each household, the environmental conditions that were monitored and the thermal-conductivity properties of each building as an empirical study, as shown in Figure 3.50. A bottom-up approach was integrated into the comprehensive methodology in the conceptual framework of the present study to achieve the objectives of the building-performance evaluation and the optimisation of existing housing stock that was not previously carried out in order to inform policy-making decisions related to energy use.

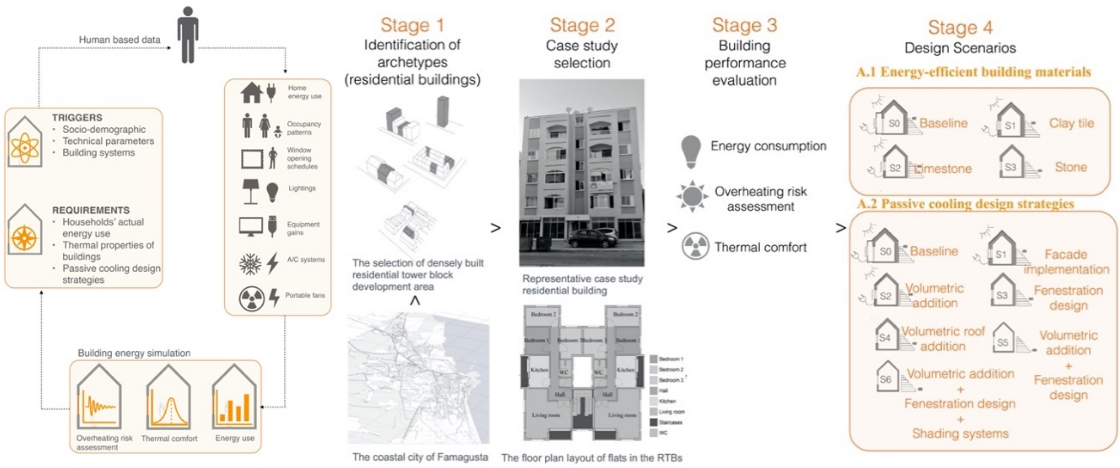


Figure 3.50: Flow diagram demonstrating novelty of STS approach.

In the present study, retrofitting design strategies developed as a result of information obtained from the surveyed occupants' semi-structured interview responses associated with each household's energy-use awareness and the main findings of the building-performance evaluation study to design these buildings systems were used in conjunction with the human-based data. This multivariate research approach led to the development of evidence-based design strategies for effective energy-use policy-making decisions. An overview of the step-by-step energy-performance assessment of base-case RTBs is shown in Figure 3.51.

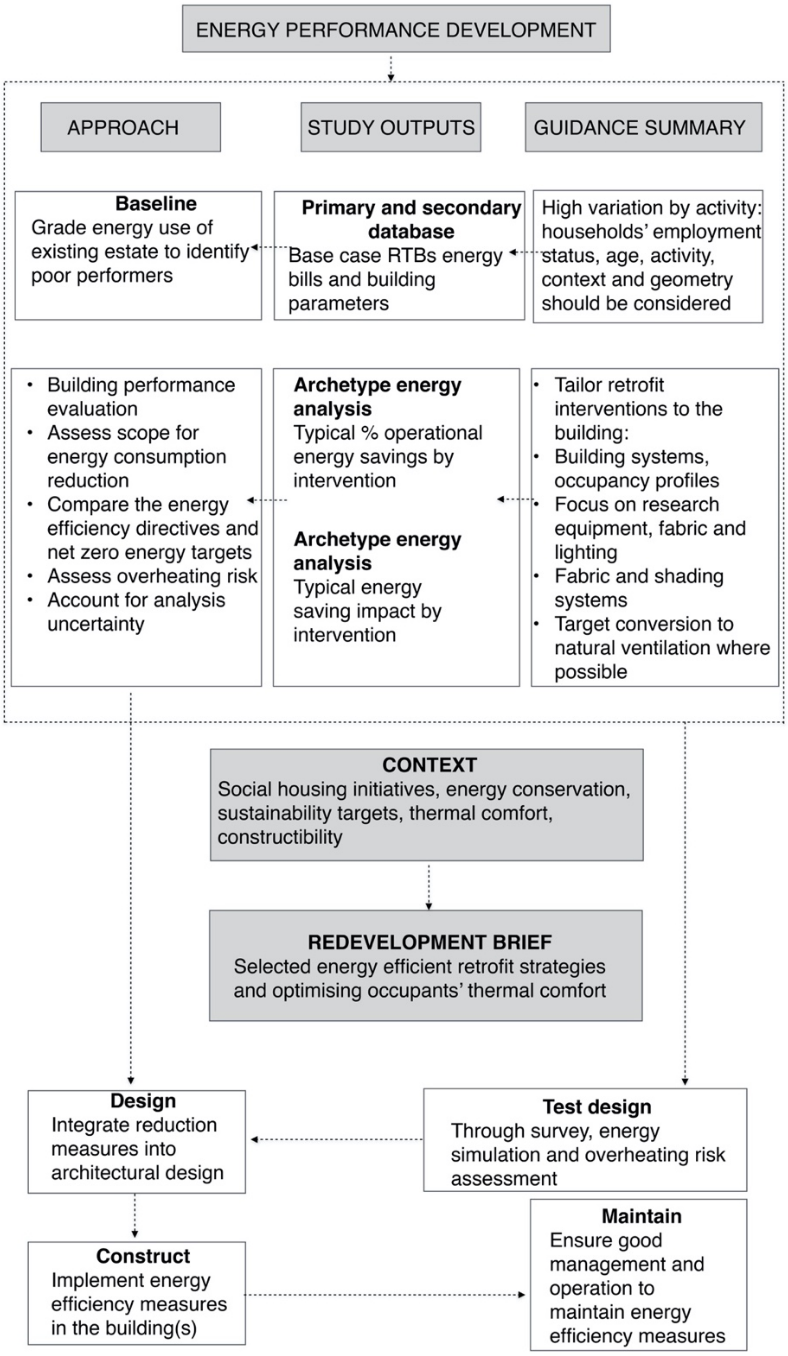


Figure 3.51: Strategy of inquiry for STS conceptual framework development.

To feed into the building-performance simulation analysis, target outputs from the data were utilised to describe the overall building construction and technical systems, a broad set of energy-use data and a room-schedule data that described the characteristics of occupied spaces in representative RTB flat units. The data-collection method for the present study was designed to maximise the detail and accuracy of the record of the base-case representative RTBs within the time frame and the resources available for data collection, as shown in Figure 3.52.

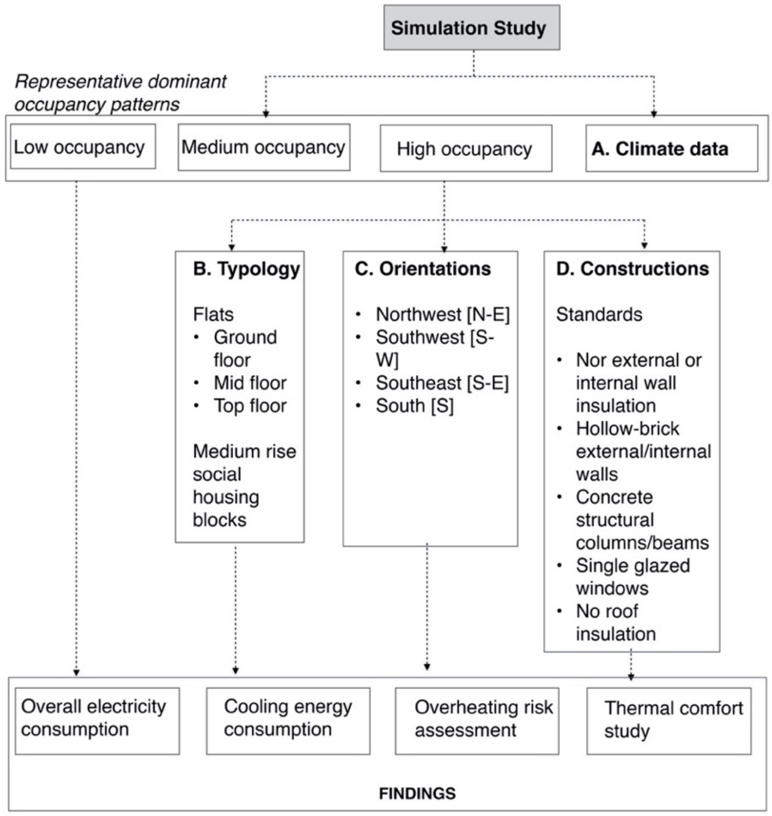


Figure 3.52: Development of archetype housing typology selection for this study.

For each RTB, an initial familiarisation exercise was carried out. This involved a review of building plans, construction materials, construction of room-data schedules and preliminary walk-through and extensive *on-site* photographic documentation. A thorough site walk-round was then performed in each building to diagnose the thermal vulnerability of building envelopes that are susceptible to overheating across the sample of representative flat units. Occupied spaces were also placed in standard space categories according to the floor-plan layout design and the orientation of the units. The present study sought to identify building-envelope thermal performance and to assess the overheating risk of the representative flat units to calibrate domestic-energy use. To ensure a literature analysis of the key aims and objectives, the research adopted a quantitative research design by undertaking a building-performance evaluation based on dynamic thermal modelling and a simulation thereof, and IRT was validated by monitoring indoor and outdoor environmental parameters in the prototype base-case RTBs, including air temperature, RH and household energy bills, as shown in Figure 3.53.

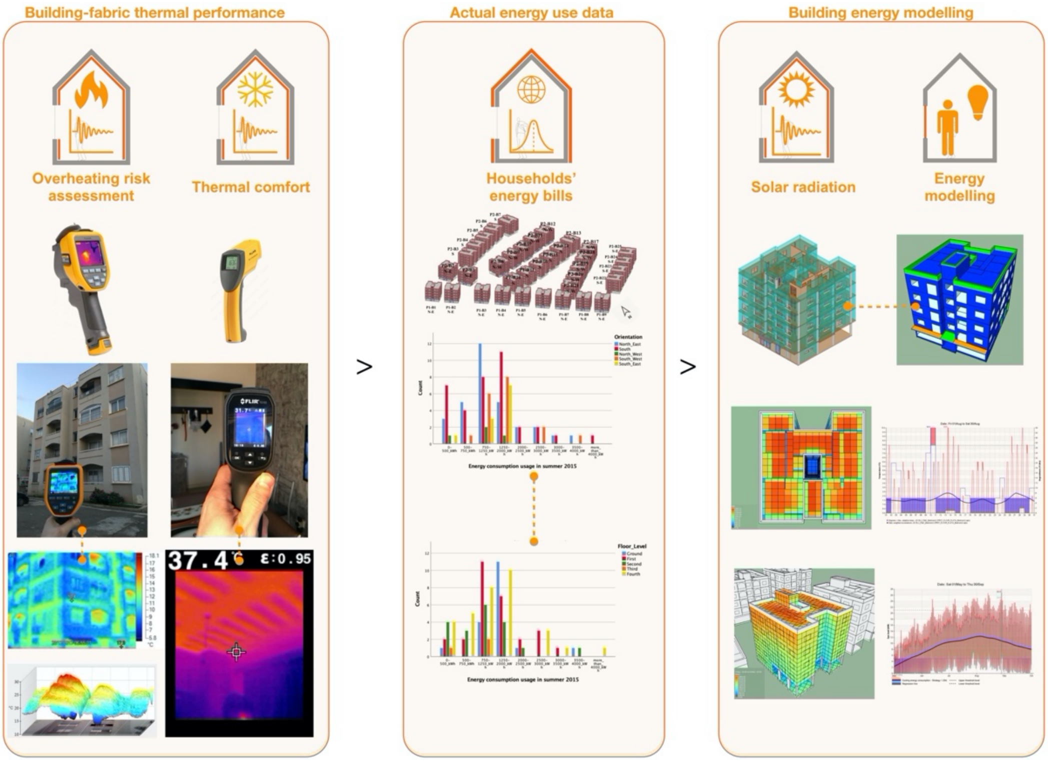


Figure 3.53: Development of methodological workflow to assess building-thermal performance.

The investigation of the case-study RTBs determined that they modelled the cooling-energy demand of the representative medium-rise housing typology and assessed the thermal comfort of occupants during a long-term heat wave while taking the thermal transmittance principles of the U-value of the properties into account. In Chapter 2, the literature review indicated that this step-by-step analysis provided necessary background information to develop a new design method for the STS approach as a tool for policymakers. To develop an effective energy-design policy and improve the current design methods in building-energy simulation studies, the methodological workflow was conducted in the following manner; all of these are discussed in Chapter 5:

i. Thermal imaging
ii. *In-situ* measurements
iii. Household energy-bill analyses
iv. Building-energy simulations

Household Energy Bills. To gather reliable data to assess the energy consumption of the occupants and to compare the building-modelling simulation results to the utility-bill analysis, the present study evaluated the occupants' energy consumption in the winter of 2015–2016 and the summer of 2016. These data served as the basis for a real-energy-consumption dataset that could be used in the building-modelling simulation. These data also enabled us to evaluate the existing energy performance of the surveyed RTBs to assess the overheating issues experienced in each flat. The household electricity bills were obtained from the Cyprus Electricity Authority database with consent from the householders.

3.6 Analytical Energy Simulation Model Development

3.6.1 Heating and Cooling Profiles

Heating profiles were assigned from generic templates because measurements were not recorded in the heating season, but the cooling profiles used data that were measured during the defined cooling-and-monitoring season in August of 2018. For these purposes, only two set-point temperatures for the microclimate control of the active energy systems were defined during operating hours: 20°C during the heating period and 26°C for space-cooling. When possible, the RH control was fixed at a set-point of 50% for the heating and cooling sessions. Moreover, the base-case building was located in the ASHRAE Climate Zone 2A, where a conventional heating period from November 16 to March 31 was established by law (EN 15251, 2007). It should be noted that the cooling period was not fixed, but typically began when indoor temperatures exceeded 26°C for 146 consecutive days; this period usually runs from May to September, and cooling hours are sometimes needed on certain days in October.

The natural ventilation settings were based on temperature control, which was determined to be when indoor temperatures were higher than the 25°C set-point of the A/C system and the outdoor temperatures were below this temperature; otherwise, natural ventilation was used. In empty spaces (i.e., corridors, water closets and bathrooms), only the natural ventilation rate was considered. Moreover, a thermal performance of the representative flats was conducted to compare the comfort delivered by natural ventilation when no A/C system was used.

3.6.2 Ventilation Variation Profiles

The comfort requirements in international standards, such as the 2007 EN 15251 specifications, were expressed in terms of the OT, and the representative case-study RTB set-point regulation was performed according to this value. Consequently, per to the EN 15251 guidelines for normal level-of-comfort expectations, T_{op} values of 26°C for cooling were established for the energy-needs analysis of the representative RTB. In this regard, since the CEN adaptive method provided in EN 15251 is valid for outdoor reference temperatures up to 30°C, only the running mean-temperature equation, which can be applied up to 33,5°C and is therefore more applicable in a Mediterranean climate context, was considered for the present study. The parameters for the building simulation are summarised in Table 3.23. From the records of outside air temperature, the running mean outdoor temperatures were calculated using Equations (4) and (5), which were included in CEN Standard EN 15251 (2007):

$$T_{rm} = (1 - \propto)\ T_{ed} - 1 + \propto T_{rm} - 1 \quad \text{(Eq. 4)}$$

$$T_{rm} = (T_{ed} - 1 + 0{,}8\ T_{ed}\ 2 + 0{,}6\ T_{ed} - 3 + 0{,}5\ T_{ed} - 4 + 0{,}4\ T_{ed} - 5 + 0{,}3\ T_{ed} - 6 + 0{,}2\ T_{ed} - 6 + 0{,}2\ T_{ed} - 7)\ /\ 3{,}8 \quad \text{(Eq. 5)}$$

where T_{rm} is the running mean temperature for today, $T_{rm} - 1$ is the running mean temperature for the previous day, $T_{ed} - 1$ is the daily mean external temperature for the previous day, $T_{ed} - 2$ is the daily mean external temperature for the day before and so on, and is an $\propto$ constant between 0 and 1 (0,8 is recommended).

Table 3.23: Ventilation Variation Profiles Assigned in Simulation Model.

Parameter		**Values**	
Maximum daytime ventilation rate when Q_{op} **> 23°C**		3 h^{-1} from 06:00–23:00	
Maximum overnight ventilation rate when Q_{op} **> 23°C**		2 h^{-1} from 23:00–06:00 200 W/m^2: north, northeast, northwest 300 W/m^2: all other directions	
Infiltration	0.1 h^{-1}	**Cooling Set-Point (Comfort Levels)**	
Internal Heat Gains	4 W/m^2	First Floor	24°C
Façade Short-Wave Reflectivity	0.5 d_f	Intermediate Floor	25°C
		Upper Floor	26°C

In the present study, requirements for standard air-discharge rates in residential buildings were assigned in the DTS interface as follows: the global discharge rate was 1,40 l/m^2s for naturally ventilated buildings; this corresponded to 1,90 h^{-1}, which is what should be experienced in the living spaces during peak occupancy hours. At other times, such as when the flat was unoccupied during the weekend, the European Norm (EN) recommended a discharge rate of 0,10–0,20 l/m^2s to provide adequate indoor-air quality during occupancy hours. Importantly, these rates adhered to conventional values for NV through the building envelope. The simulation model adopted a constant infiltration rate of 0,2778 l/m^2s, which corresponded to 0,1408 h^{-1}. For indoor environmental input parameters related to the design and assessment of energy performance, which addressed indoor-air quality, the thermal environment and lighting benchmarks, night ventilation was modelled for the period between 23:00–07:00 during hot weather, and only when the indoor OT exceeded the cooling SP with a 0,5 h^{-1} increase in the air exchange rate, which is a low-but-consistent recommended ventilation rate that is naturally achievable through single-sided openings (ISO:7730, 2005).

3.7 Limitations

The goal of the present study was to provide effective responses to the RQs with the use of available data and resources, even though this resulted in certain limitations that should be considered. A new STS conceptual framework could provide contributions that would consider real-life occupant energy-use experiences in the decision-making process for future retrofitting interventions. Tables 3.24 demonstrates the summary of research limitations to delineate the technical constraints that are related to key concepts, which should be addressed by future scholars and Figure 3.54 articulates the strengths and constraints of the STS approach to determine and diagnose potential problems of high expenditures on energy use.

Table 3.24: List of Limitations.

Key Concepts	Limitations
Sampling Size	A large sample is required to conduct TSVs and evaluate the collected data, which could affect the generalisation of the results to provide an overall understanding of home-energy performance. A call-back survey was carried out to increase the response rate, but due to time constraints, only five households were successfully recruited; as such, the sampling size was not considered in the statistical analysis.
Statistical Analysis	The ranking system of subject participant responses were estimated from self-reported behaviours and were expected to vary; this lack of integration prevailed, despite evidence that some errors were detected in the parametric (P-test) analysis. This is because the respondents did not provide an accurate vote of the thermal-comfort assessment criteria.
Questionnaire Survey	The use of a *pro-forma* questionnaire to conduct semi-structured interviews with certain households meant that other households could not be reached; for example, those who were illiterate, or who did not read or write Turkish, which is the *lingua franca* of the research context; elderly households with disabilities; subjects who were on long-term breaks; and unoccupied sample flats that were not contacted in the door-to-door survey. There is a degree of uncertainty as to whether ethnic minorities were fully represented, because some respondents might not have understood Turkish or English. No direct question was asked about household income, mostly to increase response rates. The researcher identified the respondents' income levels by considering their age and employability.

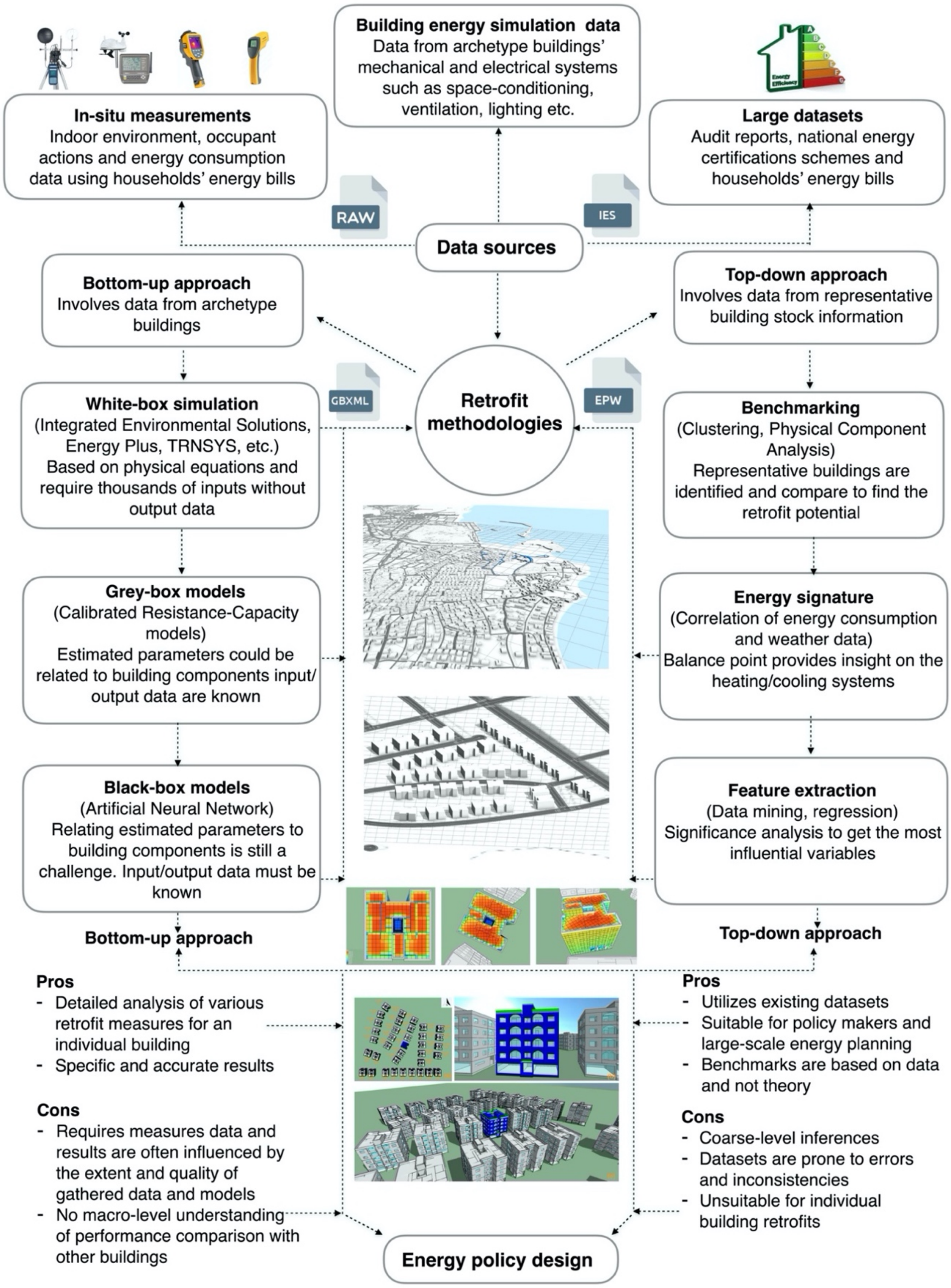


Figure 3.54: The developed STS conceptual framework for the retrofit energy policy design.

Additional research is required to better understand the possible link between occupant behaviour and energy consumption. Significantly more work still needs to be done to investigate specific climate conditions and different housing typologies, as well as relevant subjective measures, such as the socio-demographic characteristics, backgrounds and social structures of different households. Moreover, other novel methodologies that include advanced modelling features related to occupant behaviour when evaluating the energy performance of buildings (i.e., stochastic and deterministic models) should be developed. Finally, the empirical analysis for this study revealed that the energy assessment processes still require additional user input.

Validation measures are essential to improve the accuracy of the simulation results. One of the most important technical aspects of the present study was the adoption of robust methods; international benchmark criteria must be assigned to the analytical-energy models for further data validation. This could lead researchers and designers to develop better models and improve the comparisons of different variables in energy-simulation models.

3.8 Summary

This chapter developed an empirical model that demonstrated a new STS conceptual framework integrated with information obtained in the literature review analysis; the analytical building-energy model used data extracted from the questionnaire survey. The empirical model developed for the present study is the most applicable design method to corroborate the human-based factors in the BES model. Due to uncertain parameters and technical constraints to measure the differences between actual and predicted home-energy performance of case-study RTBs, a methodological workflow was employed in the following manner:

i. Questionnaire survey
ii. *On-site* monitoring
iii. *In-situ* measurements
iv. Analysis of household energy bills
v. Building-energy simulations

This design was established to validate the findings of the questionnaire survey and to integrate evidence-based data into the STS conceptual framework. Any discrepancies detected in the statistical analysis will also appear in the DTS result and the energy-assessment method that was applied to minimise this risk. The IRT survey will also provide good representative indicators to assess the thermal vulnerability of building envelopes. The empirical model was shown to perform well with industry benchmarks adopted to assess building overheating risks, and the adaptive thermal-comfort theory was employed to identify the optimal occupant thermal-comfort levels. Before developing energy-forecasting scenarios, the present study explored the influence of household socio-demographic characteristics on energy use; the households' length of residency, which was considered to understand the adaptability of the human body as it relates to thermal comfort, was also examined. The results obtained from the field investigation to conduct a regression forecast of neutral adaptive thermal comfort will be discussed in Chapter 4.

Chapter 4

Results and Discussions: Regression Forecasting of Neutral Adaptive Thermal Comfort

Introduction

An analysis of the respondents' thermal-sensation votes (TSVs) for the measured living room spaces in the flats recruited through a questionnaire survey is presented in this chapter, and a discussion of the manner in which the occupants of the RTBs evaluated their thermal environment in relation to the *on-site* monitoring and *in-situ* measurements recorded in the hottest summer month is presented. An investigation of the *in-vivo* experiences related to household TSVs to predict individual aspects of adaptive thermal comfort and influences the validity of neutral adaptive thermal comfort thresholds, in the south-eastern Mediterranean climate, where the weather is subtropical (*Csa*) and partly semi-arid (*Bsh*) is described.

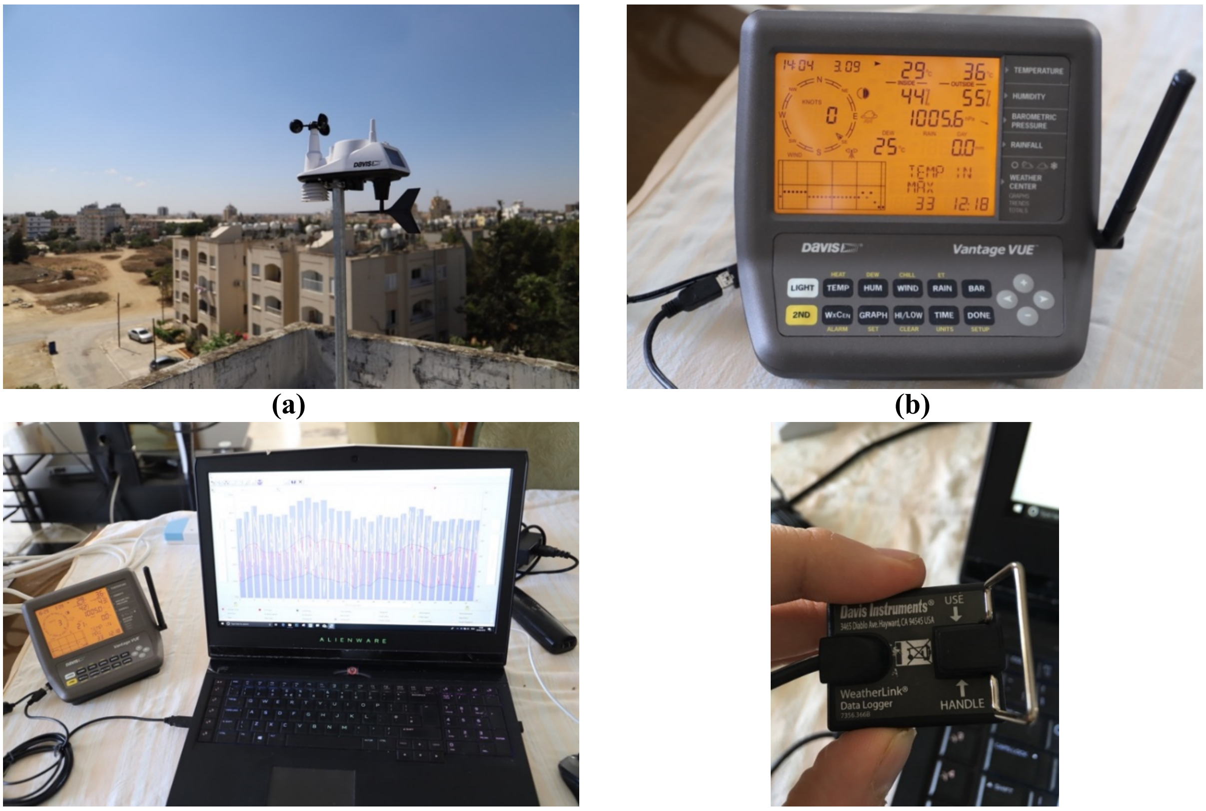
The findings of the environmental monitoring that concurrently assessed overheating risks and the occupants' thermal comfort with a one-point time survey are presented. The occupants' TSVs, which were ascertained during the questionnaire survey, are discussed to understand and convey the environmental conditions of measured flats. The findings of the subject participants TSVs were used to measure the indoor-air temperature and relative humidity (RH) to undertake a regression forecasting analysis for the purpose of determining what constitutes neutral adaptive thermal comfort. Bar charts depicting relationships between indoor- and outdoor-environmental conditions and the occupants' TSVs are considered, and the overall results are presented.

4.1 Physical Measurements

The field instruments were recruited to investigate absolute accuracy measures related to the degree of thermal discomfort experienced in the summer in this south-eastern Mediterranean climate. In this study, physical measurements were carried out in the summer, and the measured indoor occupied spaces were analysed in Sections 4.1.1, 4.1.2 and 4.1.3.

4.1.1 On-Site Monitoring

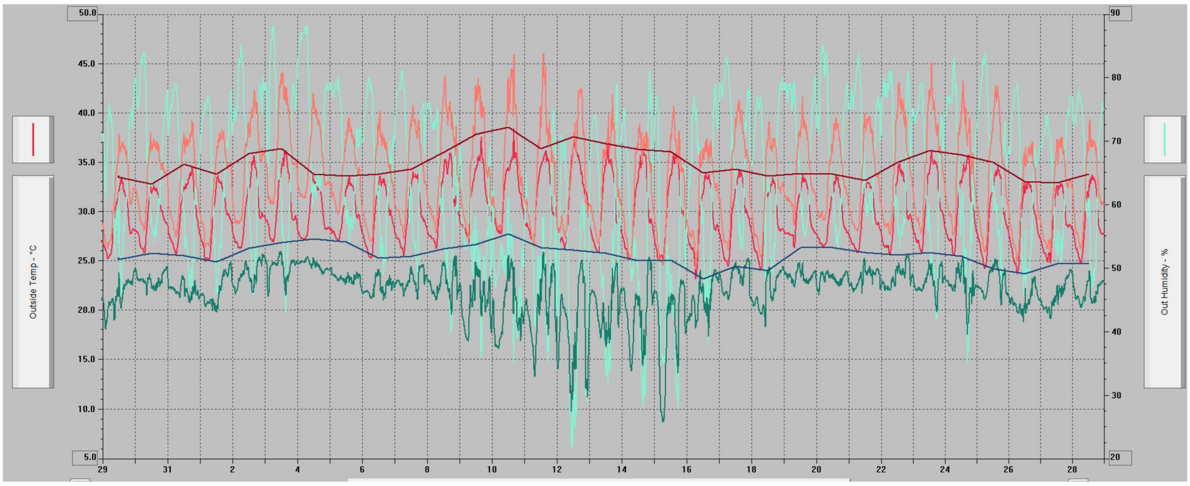
A Vantage Vue weather station was installed on the roof of the RTB, and the monitoring console of the weather station was plugged into the specialist weather software suite. Temperature measurements were collected at 15-minute intervals over a period of one month. Figures 4.1(a) through (d) illustrate the setups for the weather station and data collection of *on-site* environmental monitoring.



(a) (b) (c) (d)

Figure 4.1: (a) Weather station in social-housing estate; **(b)** monitoring console integrated into computer to track environmental readings during questionnaire survey; **(c)** environmental conditions recorded and computed to reduce risk of data loss; **(d)** custom-made data logger compartment integrated into computer engine to allow continuous environmental monitoring.

External weather data were collected from the ASHRAE Climate Zone 2A weather station at Larnaca Airport, Cyprus to compare the outdoor environmental readings with the actual meteorological year (AMY) weather file. In the study context, the period of monitoring occurred during the field survey period in August of 2018. A hot spell was observed from August 9–12, during which outdoor temperatures reached a maximum of 38,7°C at the Larnaca Airport weather station and averaged 28,7°C during the daytime and 25,4°C at night. The monitoring results of the weather data that were extracted from the weather station in August of 2018 can be seen in Figure 4.2.



Outside temperature | Dew point temperature | Highest temperature
Heat stress index | Lowest temperature | Relative humidity

Figure 4.2: *On-site* environmental monitoring readings between July 29 and August 29, 2018.

Figure 4.2 demonstrates fluctuations in the outdoor-air temperature, RH, heat-stress index (HSI) factor, maximum and minimum outdoor-air temperatures and dew point temperatures for the duration of a hot summer at the case-study location. As the graph depicts, the outdoor-air temperature ranged from 27–36°C on August 1–4, fluctuated from 26–36°C on August 5–11 and reached its final peak of 38°C on August 11. Outdoor-air temperatures fluctuated between 25°C and 34°C on August 17–23, then slightly increased to 37°C on August 24. It should be noted that along with the findings from epidemiology, which considered an external temperature of greater than 23°C to constitute a critical threshold, these data represent increased health risks for occupants in their homes (Nicol *et al.*, 2012).

The findings demonstrate that the average daily temperature for the remaining days of the monitoring period was above 23°C, which is the lower limit of acceptable thermal-comfort levels (CIBSE, 2016). As can be seen in Figure 4.2, outdoor-air temperatures fluctuated between 24°C and 35°C on August 25–30; this resulted in a high heat-stress index factor for the occupants at the time the survey was conducted. Furthermore, the external temperature during the final two days of the monitoring period, August 29 and 30, rose above 25°C; temperatures were over 25°C for 21 hours each day.

It must be stressed that, the running mean temperature of the measured external temperature, T_{rm} 23°C, as defined in BS EN 15251 (BSI, 2007), reached the 23°C benchmark for the entire month. The results suggest that the overall monitored period was significantly warmer than the recommended lower thermal-comfort threshold level described in the CIBSE

Guide A (CIBSE, 2016). Notably, the Meteorological Office of Cyprus reported that August temperatures in previous years were lower than the average monthly temperature of 27,1°C that was recorded in 2018 at the Larnaca Airport weather station.

It can therefore be deduced that in the first week of August 2018, which was the peak of the heatwave, heat-stress temperatures fluctuated between 29°C and 44°C before peaking at 46°C on August 11. Notably, the highest outdoor-air temperatures were recorded between August 9–13, and reached 38°C on August 11. As such, it can be observed that the heat stress index and the outdoor-air temperatures both had similar fluctuation patterns, even though a 44°C heat-stress index temperature is considered to be a highly unacceptable outdoor-air temperature when considering the occupants' thermal comfort.

Figure 4.2 further shows that from August 14–17, the heat stress-index temperature ranged between 36°C and 44°C before slightly rising to 45°C on August 23, then decreased to 36°C on August 26. Between August 27–30, the heat stress-index temperature ranged between 36°C and 40°C; this reveals a pattern that is similar to outdoor-air temperature fluctuations, even though the outdoor temperatures were much higher due to the long-lasting heatwave period across the continental Europe in 2018. The highest outdoor-air temperature of 37°C was recorded on August 11, and the highest heat stress-index temperature of 46°C was also recorded on that day; the lowest outdoor-air temperature of 24°C was recorded on August 16.

Figure 4.2 shows the manner in which the fluctuation patterns in outdoor-air temperatures affected the outdoor RH fluctuations during the heatwave of August 2018: In the first week, the outdoor RH reached a 48% relative humidity index (RHI) level, and the RH fluctuated 65–87%; the RH fluctuated between 60–80% through the second and third weeks, then dropped to 25% on August 12.

It should be highlighted that the final week of August included a heatwave, and the RH fluctuated between 60% and 80% in this period. RH plummeted to 35% on August 24 and then remained stable—between 60% and 80%—for the remainder of the month, notwithstanding external air temperature fluctuations. The findings demonstrate that the RHI recorded throughout the monitoring period was above the range of acceptable limits of RHI recommended by the *CIBSE Guide A* criteria for occupant thermal comfort (CIBSE, 2016). The results reveal that thermally uncomfortable indoor-air environment conditions were observed due to the high outdoor RH recorded at the case-study location.

Figure 4.2 shows that on August 1–12, the dew point temperature fluctuated between 20°C and 25°C, then it plummeted to 10°C on August 12 and to 8°C on August 15, before significantly increasing to 24°C on August 18. It was observed that from August 13–30, the dew point temperature fluctuated between 21°C and 25°C; this shows that hot and humid outdoor weather conditions affect the indoor comfort level of occupants. The overall monitoring results indicated that indoor space temperatures increased during the peak time of the heatwave to levels that created a high degree of thermal discomfort for the occupants.

Air velocities were also considered, because they are important to restore the occupants' thermal comfort; as such, the air speed frequency was recorded. The occupants were not asked to record their thermal perceptions while considering the impact of air movement on their adaptive thermal comfort at that time. The readings that were obtained were taken into consideration to avoid bias in the subject participants' responses related to their TPVs and TSVs. Figures 4.3(a) and (b) illustrate the ventilation rate readings for outdoor environmental conditions that were concurrently monitored as the questionnaire survey was being conducted.

Figure 4.3: (a) Air movement with average- and high-speed recordings; **(b)** wind-velocity-frequency recordings.

As can be seen in Figures 4.3(a) and (b), the average recorded wind speed throughout the field-survey period was 0,2 m/s. The Cyprus Meteorological Service data indicate that the minimum and maximum wind speeds in Cyprus in December are 2,98 m/s and 6,16 m/s, respectively; while they tend to be 3,75 m/s and 7,0 m/s, respectively, in August (Cyprus Meteorological Service, 2020). The environmental monitoring studies revealed that the airspeed fluctuations that were noted within the other environmental parameters that were recorded at the time of survey affected the occupants' habitual adaptive behaviour that led them to adjust their thermal comfort levels due to the acclimatisation of high indoor-air temperatures, which direct impacted the participants' TSVs and TPVs.

4.1.2 In-Situ Measurements

The field investigation in the present study was carried out in the summer, and the measured indoor occupied spaces were analysed; indoor-environment conditions were recorded with a Model HT200 Heat Stress WBGT Meter from Extech Instruments (resolution 0,1°C); to validate these findings, *in-situ* measurements were performed using a forward-looking infrared radiometer (FLIR) infrared thermographic camera to assess the occupants' TSVs. Table 4.1 presents a descriptive analysis of the monitored and measured environmental parameters during the summer period surveyed.

Table 4.1: Outdoor and Indoor Climate Parameter Data in Representative Interviewed/Measured Flats.

Environmental Parameters	Minimum (°C)	Maximum (°C)	Mean (°C)	Standard Deviation
Indoor-air temperature	25,40	34,10	30,595	1,76860
Indoor RH	31,10	75,00	57,838	8,75611
Outdoor-air temperature	23,70	36,00	32,118	2,17015
Outdoor RH	19,60	78,00	59,166	11,76264
Outdoor HSI	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 the summer. Maximum indoor- and outdoor-air temperatures peaked at 34,1°C (*SD* = 1,76) and 36°C (*SD* = 2,17), respectively. It was further 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); and it was found that outdoor temperatures during these six weeks were above 23°C for 95% of the time.

The mean indoor-air temperature was recorded for 100 flats in the present study, and it was found that the indoor-air temperatures were ranged from 25,4–34,1°C, which was significantly higher than the 28°C acceptable thermal-comfort upper threshold cited in the *CIBSE Guide A* (CIBSE, 2016). The results revealed that all 36 RTB households suffered from uncomfortably indoor-environment conditions that should be further investigated to predict neutral adaptive thermal comfort by way of an ordinal regression analysis (RA). Notably, the low quality of building materials and significant heat losses through building envelopes were found to increase indoor-air temperatures, particularly intense solar radiation on the top floor flats.

Table 4.2 delineates the indoor-air temperature recordings that were obtained by using infrared radiometer thermography (IRT) to explore correlations between the impact of solar radiation on building envelopes and the occupants' thermal comfort, while concurrently taking both the wet- and dry-bulb-temperature readings into account.

Table 4.2 : *In-situ* Measurements of Building Envelopes and Indoor-Air Temperature Parameter Recordings.

Frequencies		***In-Situ* Measurements**	**Indoor WET**	**Indoor DEW**
***N* (normality)**	**Valid**	100	100	100
Mean (°C)		33,64	24,35	21,48
Standard Error of Mean		0,23545	0,32722	0,33602
Median (°C)		32,90	24,60	21,90
Standard Deviation (*SD*)		2,35445	3,27217	3,36021
Skewness		0,840	3,844	−0,0567
Standard Error of Skewness		0,241	0,241	0,241
Kurtosis		−0,036	29,640	3,067
Standard 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

As can be seen in Table 4.2, when the occupants responded to the questionnaire survey, a limited range of thermal conditions that could be considered slightly warm or very warm according to the thermal-sensation scale recommended by the BS EN ISO 7730:2005 standard (ISO, 2005). The mean indoor-air temperature for the 100 living room spaces that recorded at the time that the participants responded to the questions ranged from 25,4–34,1°C, which is significantly higher than the acceptable upper thermal-comfort threshold of 28°C indicated by the *CIBSE Guide A* (CIBSE, 2016); this implies that local climate conditions are the determinant factor that influences adaptive thermal-comfort levels. It was therefore necessary to pair the humidity value to the occupants' thermal sensations, especially neutral sensations that were associated with 28,5°C. Neutral temperature was explored in the present study to better understand the relationship between the occupants' TSVs and indoor operative temperatures (OTs). Figures 4.4(a) through (d) depict the indoor-air temperatures, RH, outdoor-air temperatures and RH fluctuations during the heatwave in August of 2018 heatwave.

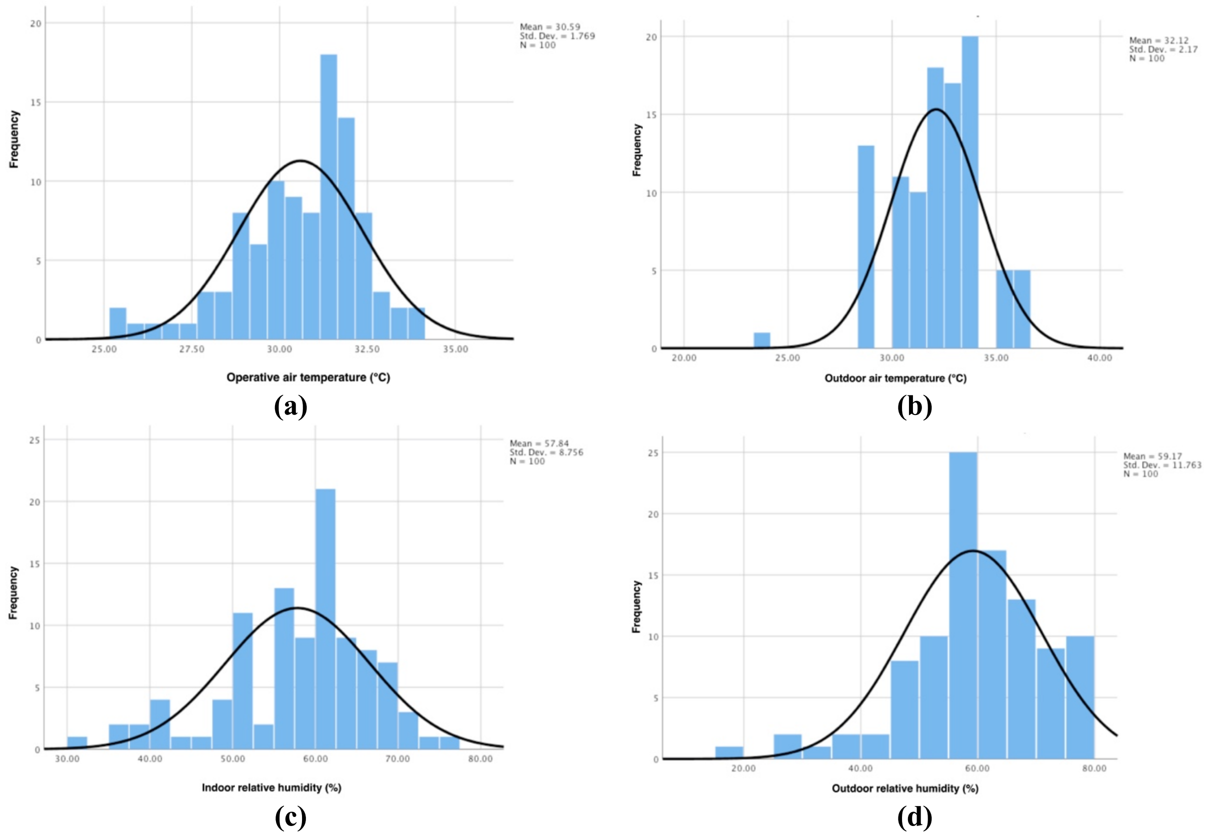


Figure 4.4: Distribution of environmental conditions: **(a)** operative air temperature, **(b)** outdoor-air temperature, **(c)** indoor RH and **(d)** outdoor RH.

According to Figures 4.4(a) through (d), the recorded temperatures were above the acceptable benchmark of 25°C that was determined to maintain the occupants' thermal comfort (BSI, 2005; CIBSE, 2017; CEN, 2007). Additionally, the average mean temperatures that were recorded across the indoor measurement results and the outdoor monitoring results were ranged from 30,59–32,12°C, which is above the recommended thermal-comfort level of 23–25°C indicated by the CIBSE TM52 Overheating Task Force. It is worth noting that recorded daily running mean outdoor temperatures reflected the thermal experiences of the occupants more accurately than the monthly mean temperatures, because the outdoor mean temperatures sometimes changed in significantly shorter intervals (Nicol *et al*., 2012). Even though the monthly mean temperature was taken as an average temperature of the month as a whole in the present study, the occupants' TSVs were found to be correlated with their thermal experiences and their ability to adapt their physiological body temperatures to changing summer climate conditions.

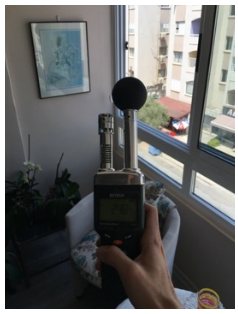
4.1.3 On-site Observations

To investigate how the occupants' thermal perceptions of their indoor occupied spaces can be explained by a physiological approach, subjective thermal sensations need to be compared with the heat-balance model. Brager and de Dear (1998) indicate that the thermal comfort of each occupied space is perceived using the physical factors of the space as well as the occupants' impressions of thermal sensation.

To identify adaptive thermal-comfort thresholds for the case-study location, the research instruments were used to investigate the significance of the physical factors and their influence on thermal comfort. This section illustrates the field equipment that have been used to deal with subjective sensations of thermal comfort. Figures 4.5(a) through (f) demonstrate the field survey diaries and archival photographic documentation of the surveyed flats, taking into consideration the different orientations of the RTBs in the social housing estate.


South-west
(a)


South-east
(b)


North-west
(c)


South
(d)


South-west
(e)


North-east
(f)

Figure 4.5: *In-situ* measurements recorded while **(a)** wall-mounted A/C system was in use in late afternoon; **(b)** single glazed aluminium-framed window was open in late afternoon; **(c)** double-glazed window was open in early morning (participant was interviewed in balcony); **(d)** internal doors were open in early morning (participant was interviewed in balcony, and portable fan was in use during survey); **(e)** windows were open; and **(f)** inverter A/C system was in use.

In Question 33, occupants were asked how satisfied they were with the temperature in their living rooms; the reason for this question was so that the answers could be correlated with the building orientation to identify the overheating risk of the occupied spaces, as illustrated in Figure 4.6.

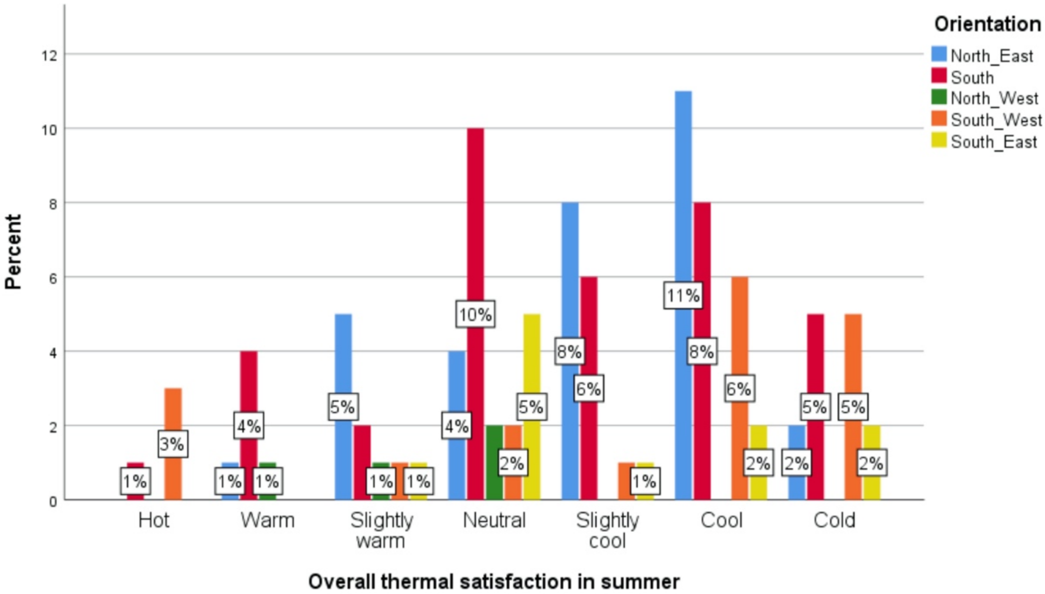


Figure 4.6: Percentage distribution of household thermal-comfort satisfaction votes in the summer according to different building orientations.

According to Figure 4.6, 2% of the occupants in the northeast-facing RTBs stated that they felt cold, 11% felt cool, 8% felt slightly cool, 4% felt neutral, and 5% felt slightly warm. In the south-facing RTBs, 5% of the respondents stated that they felt cold, 8% felt cool, 10% felt neutral, 2% felt slightly warm, 4% felt warm, and 1% felt hot; this is due to the south-facing RTBs absorbing a high level of solar radiation throughout the day in the summer, which resulted in high indoor-air temperature fluctuations that prompted these households to rely on domestic cooling systems to adjust their indoor-air temperatures.

In the northwest-facing RTBs, 2% of the respondents reported that they felt neutral, 1% felt slightly warm, and 1% felt warm. In the southwest-facing RTBs, 6% of the respondents felt cool due to the fact that most of these participants lived in ground-floor flats, and the shading factor from adjacent buildings had a significant impact on their TSVs; in addition to these respondents, 5% of the participants in these RTBs felt cold, 1% felt slightly cool, and 1% felt slightly warm. In the southeast-facing RTBs, 2% of the respondents expressed that they felt cold, 2% felt cool, 1% felt slightly cool, 5% felt neutral, and 1% felt slightly warm.

The findings reveal that the households in the south-facing RTBs experienced high levels of discomfort in the summer: Overall, 23% of the total participants asserted that they felt between slightly cool and slightly warm, which emphasises the fact that the risk of overheating is most likely to occur in the south-facing RTBs. One interviewee who suffered from asthma reported that the high indoor-air temperatures lead to thermally uncomfortable conditions for their family members. The interviewee also commented that due to his health issues, he preferred to open windows and use a portable fan to cool down the indoor-air temperature.

It is important to note that during the field survey, it was observed that some households had enclosed their balcony spaces and installed large, double-glazed aluminium frames that worked as window systems to allow natural ventilation (NV) into their living rooms more effectively. Additionally, some respondents were interviewed in their converted balcony spaces, where they expressed feeling thermally comfortable, and they indicated spending most of their time in the converted balcony and adjusting the windows according to their thermal-comfort preferences throughout the day. From the field survey observations, a retiree couple who were in the 55–65 age band was interviewed while sitting in their converted balcony space with only the windows opened; they stated that they felt thermally comfortable because they were able to control the prevailing winds coming into the enclosed balcony area.

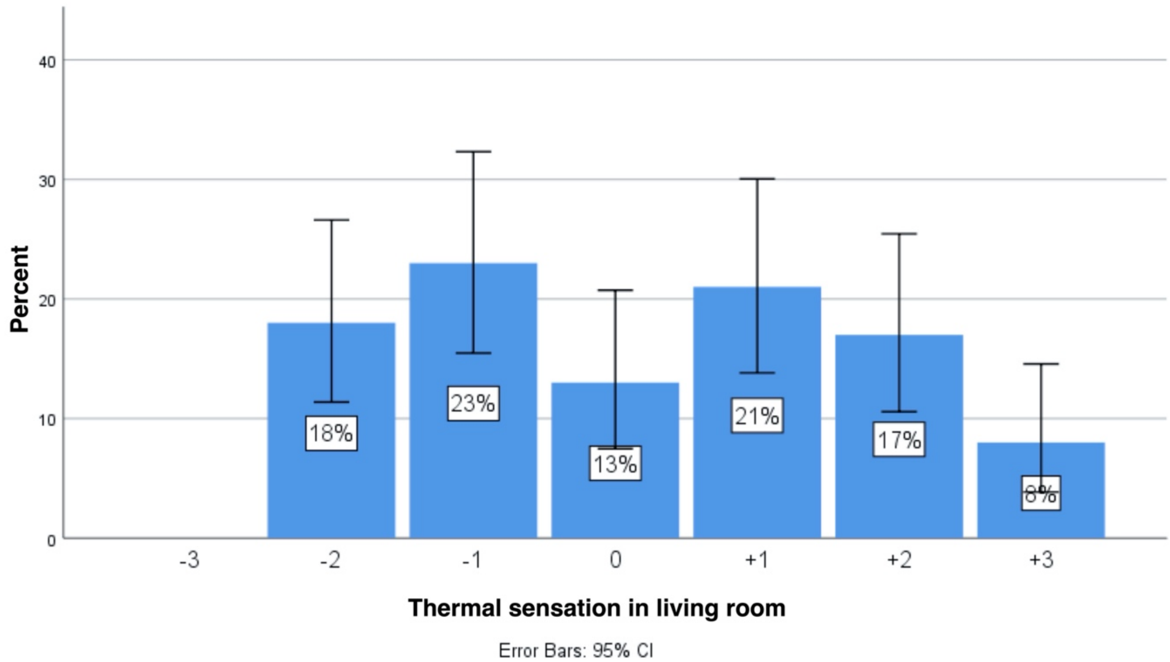
The results indicate that the RTB orientations play a crucial role in the occupants' TPVs. Therefore, the household size, occupancy patterns, and window-opening behaviour must be taken into account to assess the degree of thermal discomfort and identify adaptive thermal-comfort thresholds. The following section examines the occupants' TSVs for each occupied space in their properties to assess the risk of overheating and provide subsequent background information on building performance evaluation of base-case RTBs in Chapter 5.

4.2 Investigation of Occupant TSVs

Statistical analyses were therefore used to determine the factors that influence the occupants' TSVs in order to investigate the degree of overheating experienced in the summer. The analyses carried out in this research were explanatory in nature, and the objective was to determine the relationships amongst different variables (i.e., respondents' age, RTB orientation, different floor levels of the flats and indoor OT and outdoor-air temperatures). This section presents the findings of the relative influence and interaction amongst the variables and pave the way for an assessment of the occupants' thermal-comfort level for certain groups; this information is presented in Sub-Sections 4.2.1 and 4.2.2.

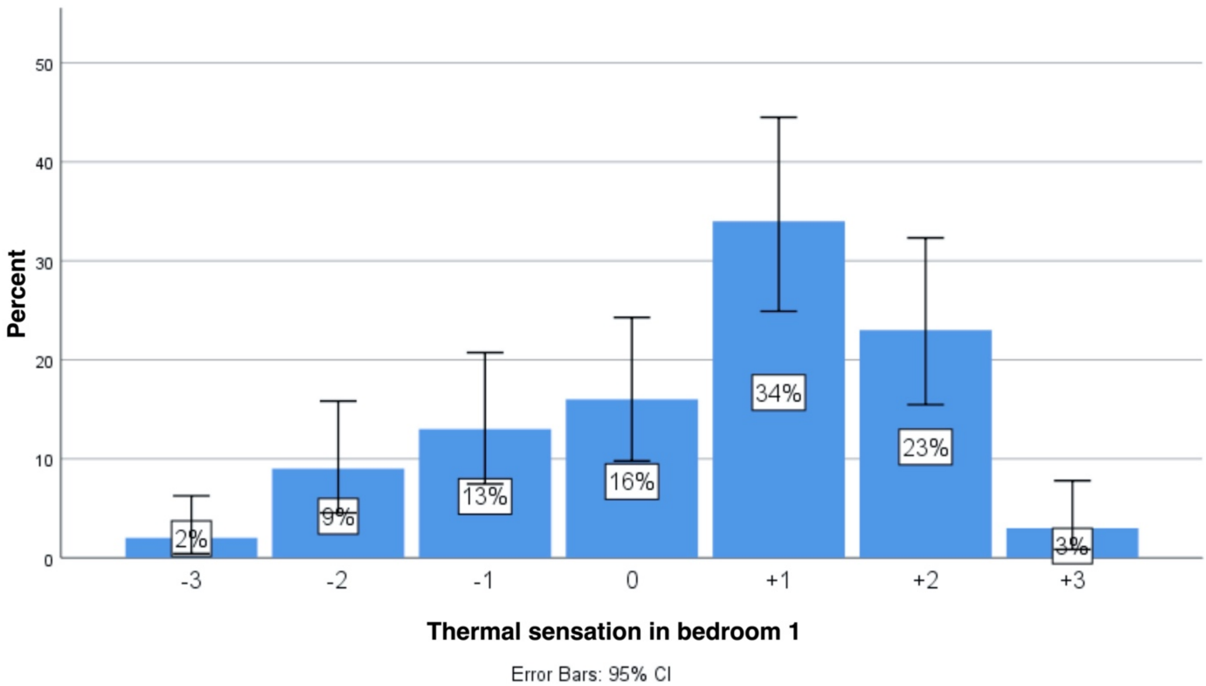
4.2.1 Descriptive Statistics

To fulfil the research objective, the study was 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 different floor levels of the flats (see **Appendix G** – Sample of Outliers Test). The TSVs were rated using the ASHRAE seven-point thermal-sensation scale[7]: 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 seven-point scale from −3 to +3 (Parkinson *et al.*, 2020). Figures 4.7(a) through (d) illustrate the findings of the occupants' TSVs in each occupied space across the surveyed sample size.



(a)

[7] The Likert scale is a measure of a person's attitudes, beliefs, or opinions about some object or event. Traditional Likert scales include the following features: declarative statements that express clearly positive or negative attitudes, seven ordered response options, particularly for the thermal comfort assessment (known as the response set), an equal number of positive and negative response options and numeric values assigned to each response option for analysis purposes.

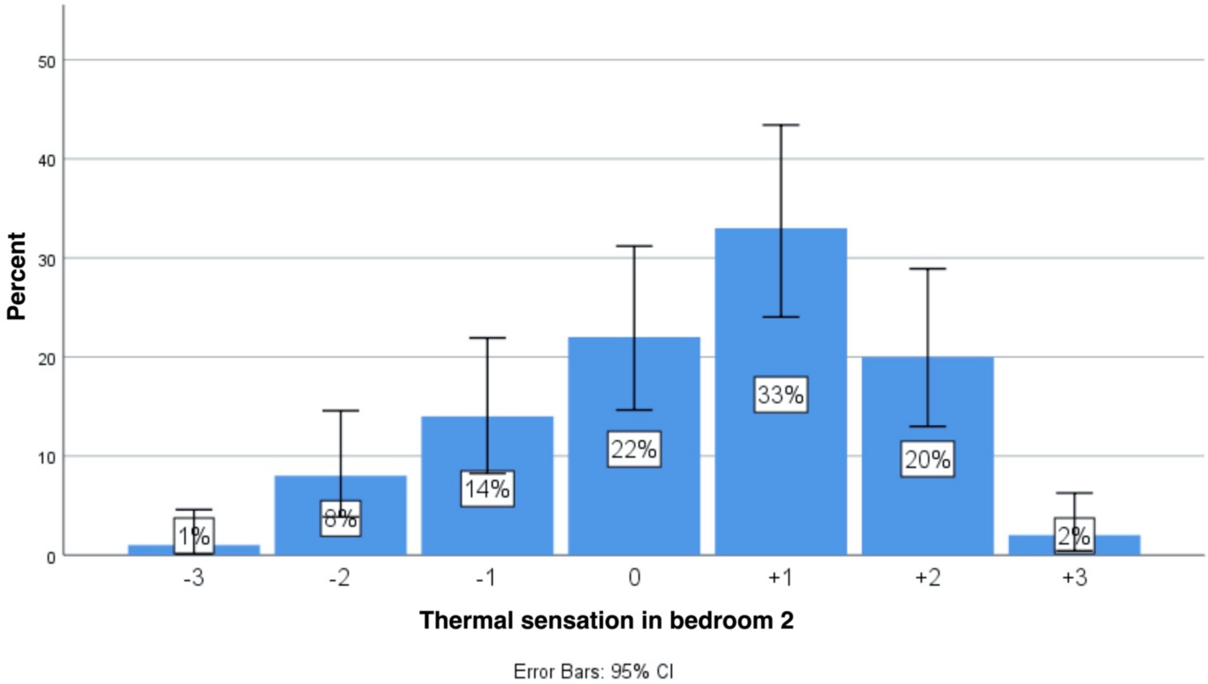


(b)

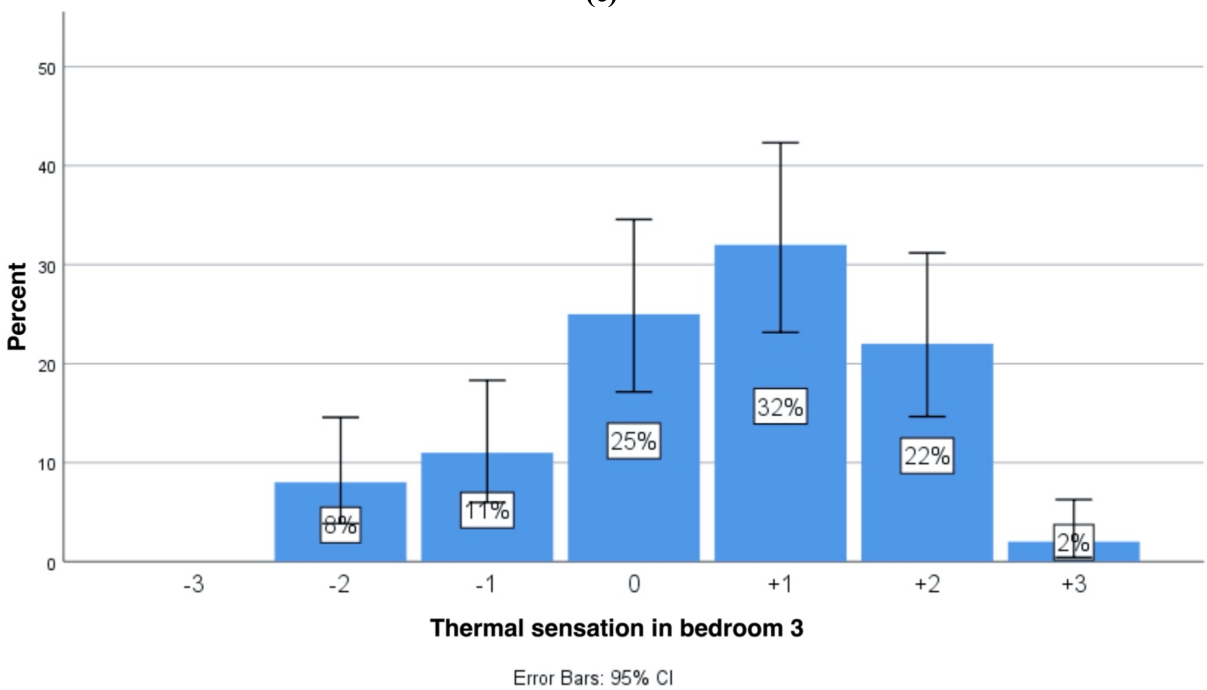
Figure 4.7: Percentage distribution of occupant TSVs in **(a)** living room and **(b)** bedroom 1.

As shown in Figure 4.7(a), 8% were of the respondents reported that they felt too warm in their living room in the summer, 17% felt too warm, 21% felt comfortably warm, 13% felt comfortable, 23% felt comfortably cool, and 18% felt too cool. 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 the summer due to the RTB orientations.

Figure 4.7(b) shows that 3% of the respondents felt too warm in their Bedroom 1 space in the summer, 23% felt too warm, 34% felt comfortably warm, 16% felt comfortable, 13% felt comfortably cool, 9% felt too cool, and 2% felt much too cool. Thus, approximately two-thirds (60%) of the participants voted that the space felt comfortably warm and much too warm.



(c)



(d)

Figure 4.7: Percentage distribution of occupant TSVs in **(c)** bedroom 2 and **(d)** bedroom 3.

According to Figure 4.7(c), 2% of the surveyed households reported that they felt much too warm in their Bedroom 2 space in the summer20% felt too warm, 33% felt comfortably warm, 22% felt comfortable, 14% felt comfortably cool, 8% felt too cool, and 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 different RTB orientations and floor levels.

The TSV results for the Bedroom 3 spaces more-or-less reflected the same patterns as the Bedroom 1 and Bedroom 2 spaces. According to Figure 4.7(d), 2% felt much too warm in their Bedroom 3 space, 22% felt too cool, 32% felt comfortably warm, 25% felt comfortable, 11% felt comfortably cool, and 8% felt too cool. As was previously mentioned, this could have been due to the RTB orientations and the different 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 RTBs' low-quality construction materials and high solar absorptivity, 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 poor window design and the absence of shading strategies to provide protection from the direct sun. This highlights the fact that the occupants' TSV ranking scale distribution included a lot of variation, thus indicating relatively thermally uncomfortable conditions in the summer.

4.2.2 Relationships for the Identification of Thermal Comfort

Crosstabulations[8] using Fisher's exact tests explored the reasons for thermal discomfort in respect to the household age, the orientation of the RTBs and the different floor levels in each occupied space based on the collected data from the respondents. This analysis was conducted because socio-demographic characteristics have been shown to be a significant factor in people's behaviour in any setting. Considering the age band in this crosstabulation analysis was necessary because nearly half (48%) of the households were in the 55–65 and 65-years-of-age and older age groups, it is important to consider the impact of age on thermal comfort in these measured flats.

[8] Crosstabulation was chosen to assess occupants' TSVs. This is the traditional way to identify a relationship, or association, between two categoric variables is to calculate percentages within categories of the independent variable and to compare these percentages across the categories of the independent variable.

In conjunction with households' socio-demographic analysis, the different RTB orientations and floor levels were taken into consideration. The results of feed-forward interviews highlight that 24% of the occupants complained about high humidity in the southwest-facing RTBs in the summer, and 17% complained about incoming sun. This indicated that the occupants may have experienced thermally uncomfortable conditions due to the high outdoor-air temperatures and humid conditions in this south-eastern Mediterranean climate. This became clear when the study determined that there were negative relationships between the occupants' reasons for thermal discomfort and the different floor levels for their respective flats, as shown in Table 4.3.

Table 4.3: Relationships Between Reasons for Thermal Discomfort and Household Age Band, RTB Orientation and Floor Level.

		Discomfort	Age Band	Orientation	Floor Level
Q 35: How would you best describe the source of this discomfort?	Cramer's V	1	0,203	0,405*	0,233*
	Significance	—	0,479	< 0,001	0,037
Age Band	Cramer's V	0,203	1	0,229	0,211
	Significance	0,479	—	0,165	0,380
Orientation	Cramer's V	0,405*	0,229	1	0,197
	Significance	< 0,001	0,165	—	0,188
Floor Level	Cramer's V	0,233*	0,211	0,197	1
	Significance	0,037	0,380	0,188	—

Household age band scale ran from 0 (20–25) to 5 (65 and over)
RTB orientation: 0 (north-east), 1 (south), 2 (north-west), 3 (south-west), and 4 (south-east)
Different floor levels: 0 (ground), 1 (first), 2 (second), 3 (third), 4 (fourth) and 5 (fifth)
Age band scale ran from 0 (20–25) to 5 (65 and over)
Reasons for thermal discomfort – Floor level, *Fisher's Exact* = 17,16, p = 0,037, *Cramer*'s V = 0,233
Reasons for thermal discomfort – Orientation, *Fisher's Exact* = 39,52, p < 0,001, *Cramer*'s V = 0,405
Reasons for thermal discomfort – Age bands, *Fisher's Exact* = 11,53, p = 0,479, *Cramer*'s V = 0,203
Age bands – Floor level, *Fisher's Exact* = 12,72, p = 0,380, *Cramer*'s V = 0,211
Age bands – Orientation, *Fisher's Exact* = 15,84, p = 0,165, *Cramer*'s V = 0,229
Orientation – Floor level, *Fisher's Exact* = 12,11, p = 0,188, *Cramer*'s V = 0,197

The results, shown in Table 4.3, indicate a moderate-strong relationship between orientation and reasons for thermal discomfort (*Fisher's Exact* = 39,52, p < 0,001, Cramer's V = 0,405). A greater proportion of participants living in South area felt thermal discomfort due to humidity than participants living in South-West. A greater proportion of participants living in South-West selected incoming sun as thermal discomfort reason than participants living in the other areas. Furthermore, floor level was moderately related to reasons for thermal discomfort (*Fisher's Exact* = 17,16, p = 0,037, Cramer's V = 0,233). A greater proportion of participants living at ground level felt thermal discomfort due to humidity than participants living at third-fourth levels; this was due to the poor window design in the RTBs, which prevented NV into the indoor occupied spaces. This led to a difference of 2–3°C between the ground and upper floor level flats due to a lack of NV and as a result of the upper floor receives the intense horizontal radiation on the roof surfaces. Thus, it appeared that the occupants' habitual adaptive behaviour in window-opening patterns also played a crucial role in their TSV decisions. Nevertheless, reasons for thermal discomfort were not significantly related to age and floor levels.

According to the survey findings, 55% of the respondents reported opening windows for more than eight hours in the summer, which highlighted the fact that most of the respondents preferred to open their windows to acclimatise their indoor-air temperatures. This possibly reflected a relationship between household socio-demographic characteristics and the RTBs' physical positions, partly because the occupants had experienced relatively uncomfortable indoor-air temperatures in their occupied spaces in the summer. From this analysis, it was determined that the different floor levels played a crucial role in the households' habitual adaptive behaviours in respect to thermal comfort.

In Questions 22–25, the occupants were asked to evaluate the overall quality of the indoor-air temperature in an open-ended question form. The question concerning the respondents' rating of the quality of their indoor-air environment was intended to assess the degree of thermal discomfort in the summer. Tables 4.4(a) and (b) illustrate the crosstabulations using Fisher's exact tests comparing thermal sensations with orientation and floor, and Pearson's correlations[9] comparing thermal sensations between the households' TSVs in the summer and

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[9] The Pearson correlation coefficient (also known as Pearson product-moment correlation coefficient) ***r*** is a measure to determine the relationship (instead of difference) between two quantitative variables (interval/ratio) and degree to which the two variables coincide with one another – that is, extent to which two variables are linearly related: changes in one variable correspond to changes in another variable. Pearson correlation coefficient (also referred to Pearson's r) is the most common measure of correlation and has been widely used in the sciences as a measure of the degree of linear dependence between two paired data.

the physical position of the RTBs and takes different RTB orientations into account (see **Appendix H** – Contingency Tables).

In Table 4.4 (a) Pearson's correlation analysis was undertaken to assess occupants' TSVs. To provide an accurate conventional method of design in thermal comfort studies households' TSVs [-3, +3] coding range represents [Cold to Hot] thermal sensation scale. Wang *et al.* (2018) recommended 7-point continuous thermal sensation scale which allows researchers to conduct Pearson's correlations at the time of identifying 'neutral' adaptive thermal comfort in longitudinal field studies.

In Table 4.4 (b) Cramer's V test was undertaken to demonstrate relationships between households' TSVs, orientation factor of each RTB in the post-war social housing estate and floor level differences of each apartment in the RTB. To provide an accurate conventional method of design in thermal comfort studies households' TSVs [0 to 6] coding range represents [-3, +3] thermal sensation scale band. Wang *et al.* (2018) recommended 7-point discrete thermal sensation scale could be applied to assess occupants' TSVs. This means that the variables related to occupants' TSVs could be used as ordinal variable to conduct the relevant Cramer's V test. It should be noted that in the questionnaire survey pro-forma, the survey was set 7-point Likert scale to assess occupants' TSVs.

In this respect, Cramer's V test was conducted to demonstrate the appropriateness of the chosen statistical analysis. Hence, according to adaptive thermal comfort theory which was developed by Haghighat and Donnini (1998) and Haldi and Robinsion (2008) recommended that [-3, +3] coding should be applied as continuous variable to conduct Pearson's correlations while interpretating the households' TSVs. These scholars highlighted that the interpretation of households' TSVs by selecting these variables which could not have significant effect on the outcome to identify 'neutral' adaptive thermal comfort thresholds in a field study.

In the present study, both Pearson's correlations and Cramer's V test were conducted and only the Pearson's correlation findings were reported according to the statistical convention. Additionally, Cramer's V findings were presented to respect the convention in statistics. In this present study, Fisher's exact test was applied before undertaking Cramer's V test to avoid any research bias and demonstrate the statistically representation of this method of design. However, in general many thermal comfort studies recommends Pearson's correlation outputs could provide a reliable guidance to the researchers to measure the effect of households' TSVs with the adaptive thermal comfort theory which was earlier recommended by Fanger in the 1970s and developed by de Dear in 1998 and 2001.

Table 4.4(a): Relationships Between Occupant TSVs for Each Occupied Space in the Summer: Living Room, Kitchen, Bedroom 1, Bedroom 2, Bedroom 3.

Thermal sensation votes (TSV) for each occupied space		**Living Room**	**Kitchen**	**Bedroom 1**	**Bedroom 2**	**Bedroom 3**
Living Room	Pearson's correlation	1	0,462**	0,302**	0,146	0,200*
	Significance	—	< 0,001	0,002	0,147	0,046
Kitchen	Pearson's correlation	0,462**	1	0,133	0,205*	0,220*
	Significance	< 0,001	—	0187	0,041	0,028
Bedroom 1	Pearson's correlation	0,302**	0,133	1	0,763**	0,724**
	Significance	0,002	0187	—	< 0,001	< 0,001
Bedroom 2	Pearson's correlation	0,146	0,205*	0,763**	1	0,829**
	Significance	0,147	0,041	< 0,001	—	< 0,001
Bedroom 3	Pearson's correlation	0,200*	0,220*	0,724**	0,829**	1
	Significance	0,046	0,028	< 0,001	< 0,001	—

** Correlation is significant at the 0,01 level (two-tailed)
*Correlation is significant at the 0,05 level (two-tailed)

Occupant TSVs for living room, kitchen and bedrooms 1, 2 and 3 in the summer: (−3) to (+3)
Note: To conduct the Pearson's correlations, the study adopted recommended TSV measurement criteria recommended by Wang *et al.* (2018) – see in Chapter 3, Sub-section 3.3.3, Figure 3.20(e)

As shown in Table 4.4(a), several strong and moderate positive correlations related to the occupants' decisions on TSVs in the summer were detected. TSVs in bedroom 1, bedroom 2, and bedroom 3 were strongly and positively correlated with each other (*r*s[10]= 0,724 - 0,829, *p*s[11] < 0,001). A moderate positive correlation was noted between the TSVs in the living room and kitchen spaces (r = 0,462, p < 0,001). TSVs in living room was significantly but weakly correlated with TSVs in bedroom 1 (r = 0,302, p = 0,002) and bedroom 3 (r = 0,200, p = 0,046). TSVs in kitchen was significantly but weakly related to TSVs in bedroom 2 (r = 0,205, p = 0,041) and bedroom 3 (r = 0,220, p = 0,028), which indicates that the position of the rooms in the flats should be taken into account to assess the occupants' thermal comfort and provide a basis for an ordinal logistic regression analysis; this is discussed in the following section. Table 4.4(b) demonstrates the Fisher's Exact tests if over 25% of cells had less than 5 expected counts that revealed relationships between occupant TSVs for each occupied space in the summer, orientation and floor level.

[10] Spearman's rank-order correlation coefficient (***ρ*** or ***rs***) is a statistical measure of the strength of a relationship between two variables. Spearman's correlation is a nonparametric variation of Pearson's product-moment correlation, used most commonly for a relatively short series of measurements that do not follow a normal distribution pattern.
[11] Pearson correlation coefficient is traditionally used in a referred to as the ***ps*** correlation that partials out the subject effect.

Table 4.4(b): Relationships Between Occupant TSVs for Each Occupied Space in the Summer: Living Room, Kitchen, Bedroom 1, Bedroom 2, Bedroom 3, RTB Orientation and Floor Level.

Thermal sensation votes (TSV) for each occupied space		**Orientation**	**Floor Level**
Living Room	Cramer's V	0,226	0,232
	Significance	0,379	0,220
Kitchen	Cramer's V	0,279	0,222
	Significance	0,118	0,384
Bedroom 1	Cramer's V	0,274	0,177
	Significance	0,176	0,952
Bedroom 2	Cramer's V	0,272	0,194
	Significance	0,121	0,891
Bedroom 3	Cramer's V	0,263	0,221
	Significance	0,094	0,489
Orientation	Cramer's V	1	0,197
	Significance	—	0,188
Floor Level	Cramer's V	0,197	1
	Significance	0,188	—

Living room TSV – Orientation, *Fisher's exact* = 15,40, p = 0,379, *Cramer*'s V = 0,226
Kitchen TSV – Orientation, *Fisher's exact* = 19,72, p = 0,118, *Cramer*'s V = 0,279
Bedroom 1 TSV – Orientation, *Fisher's exact* =20,81, p = 0,176, *Cramer*'s V = 0,274
Bedroom 2 TSV – Orientation, *Fisher's exact* = 22,54, p = 0,121, *Cramer*'s V = 0,272
Bedroom 3 TSV – Orientation, *Fisher's exact* = 20,19, p = 0,094, *Cramer*'s V = 0,263
Floor level - Orientation, *Fisher's exact* = 12,11, p = 0,188, *Cramer*'s V = 0,197

Living room TSV – Floor level, *Fisher's exact* = 18,15, p = 0,220, *Cramer*'s V = 0,232
Kitchen TSV – Floor level, *Fisher's exact* = 15.35, p = 0,384, *Cramer*'s V = 0,222
Bedroom 1 TSV – Floor level, *Fisher's exact* = 10,23, p = 0,952, *Cramer*'s V = 0,177
Bedroom 2 TSV – Floor level, *Fisher's exact* = 10,09, p = 0,891, *Cramer*'s V = 0,194
Bedroom 3 TSV – Floor level, *Fisher's exact* = 13,86, p = 0,489, *Cramer*'s V = 0,221

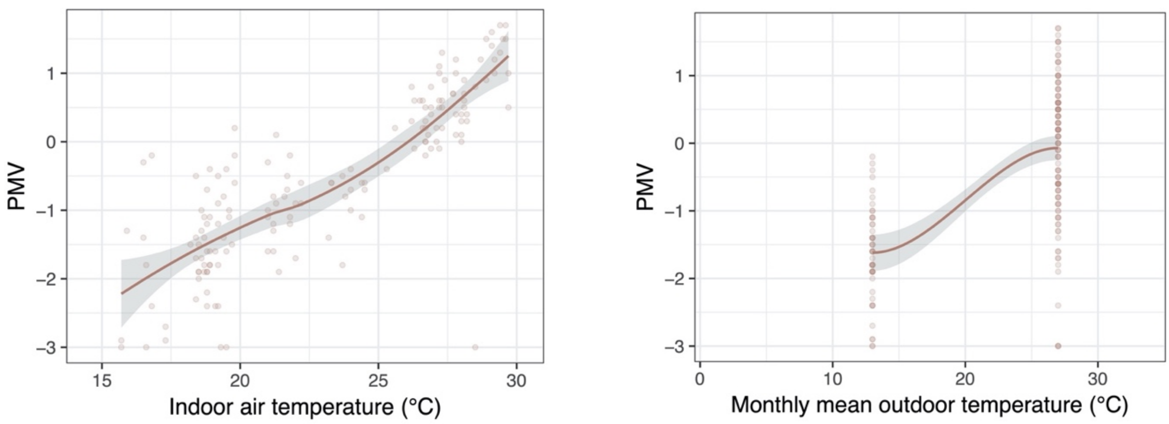
Occupant TSVs for living room, kitchen and bedrooms 1, 2 and 3 in the summer: (0) to (6)
RTB orientation: 0 (north-east), 1 (south), 2 (north-west), 3 (south-west) and 4 (south-east)
Different floor levels: 0 (ground), 1 (first), 2 (second), 3 (third), 4 (fourth) and 5 (fifth)
Note: To conduct the Pearson's correlations, the study adopted recommended TSV measurement criteria recommended by Wang *et al.* (2018) – see in Chapter 3, Sub-section 3.3.3, Figure 3.20(a)

The results revealed that orientation and floor level were not significantly related to any TSVs. 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.

4.3 Regression Forecasting Analysis

This section includes an analysis of Question 34, which concerned the occupants' overall thermal sensation for each occupied space in the summer. Furthermore, the results of household TSVs for each occupied space against indoor-air temperature recorded by undertaking *in-situ* measurements are also presented herein.

An ordinal logistic regression was conducted by calculating numerical values of the predicted mean vote (PMV) results to identify the neutral thermal-comfort benchmark level. When comparing the subject respondents' TSVs with the PMV predictor model, it must be emphasised that nearly all of the statistical tests revealed slightly warm conditions that ranged 10% outside the acceptable thermal environment for comfort ($-0,5 < \text{PMV} < 0,5$) (Földváry *et al.*, 2018). However, when the occupants' PMVs were normalised into a seven-point scale of TSVs (i.e., $-0,5 < \text{PMV} < 0,5$ set as 0 [neutral], $0,5 < \text{PMV} < 1,5$ set as +1 [slightly warm], etc.), 80% of the results produced by the heat-balance model were in the 'warmer-than-neutral' region (i.e., > +1) (BSI, 2007). Figures 4.8(a) and (b) demonstrate the development of an adaptive model to identify world global thermal-comfort benchmark criteria for multi-family houses (MFHs).



(a) **(b)**

Figure 4.8: Scatter-plot distribution of adaptive model of MFHs: **(a)** indoor-air temperature and **(b)** outdoor-air temperature. ***Source:*** ASHRAE Global Thermal Comfort Database II.[12]

[12] Graphs extracted from the thermal-comfort visualisation tool PMV-index interface, an open-access source: https://cbe-berkeley.shinyapps.io/comfortdatabase

Figure 4.8(a) shows that the PMV index ranged from 16–29°C in naturally ventilated buildings, which are included in the ASHRAE Global Thermal Comfort Database II. The PMV index ranged from 12–28°C when the outdoor environmental conditions were considered to identify the adaptive model, as is depicted in Figure 4.8(b). The satisfaction metric was selected to develop a baseline for a regression forecasting analysis. The occupants' TSVs were paired with indoor RH to explore the impact thereof on neutral sensation thresholds, and a regression coefficient analysis of the relationship between the respondents' TSVs for each occupied space and outdoor-air temperatures that were recorded by the weather station at the time the semi-structured interviews were conducted was undertaken at the same time.

The participants were asked, 'How would you rate the overall thermal satisfaction of indoor-air temperature for living room spaces?'; and their responses were evaluated according to the thermal-sensation scale to identify optimum indoor-air temperatures in the summer. An ordinal logistic regression[13] was performed, and the result revealed no significant relationship between occupant TSVs and living room OTs, *OR*[14] = 0,993 (95% *CI*[15] [0,816, 1,209]), p = 0,947, *Nagelkerke* R^2 [16]< 0,001, as shown in Table 4.5[17]. Figure 4.9 shows the respondents' TSVs plotted against operative air temperatures (OTs) recorded during the field-survey period.

Table 4.5: Summary of Ordinal Logistic Regression Predicting Living Room OTs from Occupant TSVs.

						95% CI of OR	
Predictor	**β**[18]	***SE***[19]	***Wald***[20]	***OR***	***p***	***Lower***	***Upper***
Occupant TSVs	-0,007	0,100	0,000	0,993	0,947	0,816	1,209

[13] Logistic regression provides an equation for circumstances in which the dependent variable is categorical, usually dichotomous (although there is a form of logistic regression for ordinal variables).
[14] The odds ratio can be interpreted as follows. ***(i)*** OR = 1: The variable does not affect the odds of the outcome; ***(ii)*** OR > 1: The variable is associated with higher odds of the outcome; ***(iii)*** OR < 1: The variable is associated with lower odds of the outcome.
[15] A confidence interval (***CI***) around the logistic regression coefficient ***bj*** provides important information for interpreting the coefficient. The confidence interval is formed using the regression coefficient plus or minus the product of a tabled critical value and standard error.
[16] *Nagelkerke* R^2 is an adjusted version of the Cox & Snell R-square that adjusts the scale of the statistic to cover the full range from 0 to 1.
[17] The R-squared analogue tests are considered pseudo-R-squared values or analogues to the R-squared value in ordinal logistic regression.
[18] The beta regression weights **β** (standardised coefficient) were used in ordinal linear regression to assess which predictor variables were the most important and contributed to the prediction of Y.
[19] Like the multiple linear regression, this is how much the unstandardised regression weight can vary by. It is similar to a standard deviation to a mean.
[20] The Wald chi-square test is computed as the logistic regression coefficient squared and divided by the square of the standard error (variance).

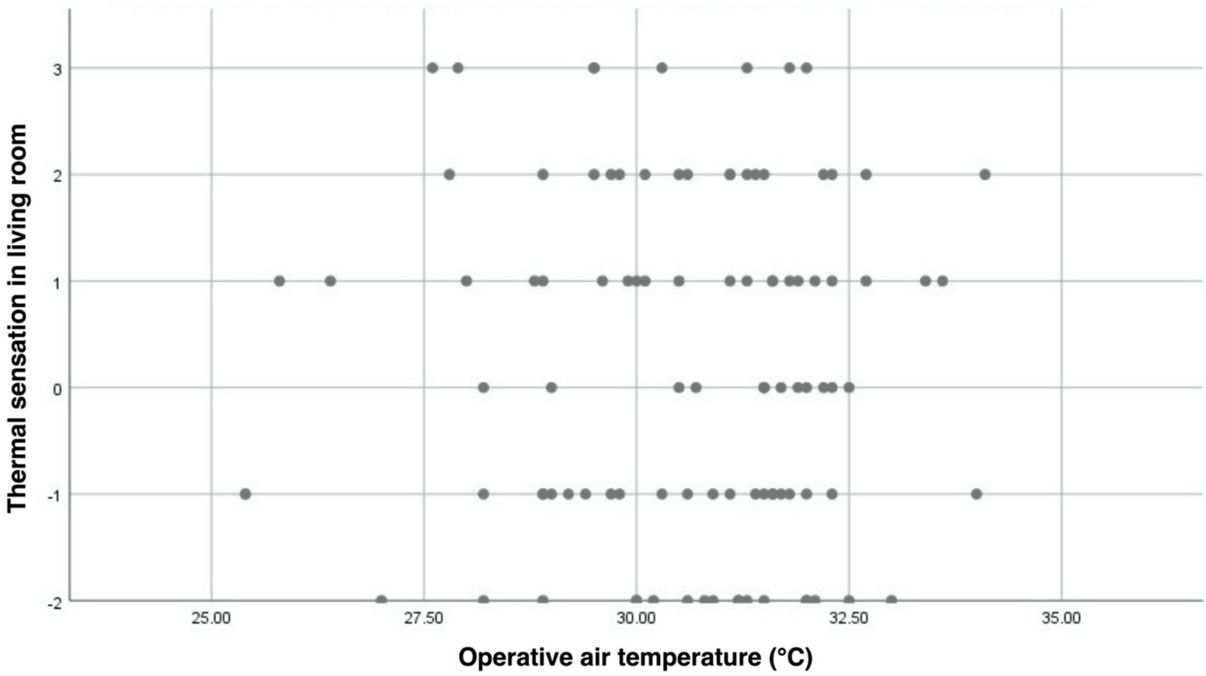


Figure 4.9: Relationship between occupant TSVs and living room OTs (a linear line was added at total).

The occupants' preferred temperatures for their living room spaces are shown in Figure 4.9. Research has shown that the occupants were slightly uncomfortable when indoor-air temperatures in their living room spaces ranged from 25–35°C. Of the respondents, 18% felt too warm (T_a 28–34°C, ±3°C and ±9°C); 23% felt comfortably warm (T_a 26–33°C, ±1°C and ±8°C); 13% felt comfortable (T_a 28,0–32,5°C, ±3°C and ±7,5°C); 21% felt comfortably cool (T_a 26–33°C, ±1°C and ±8°C); 17% felt too cool (T_a 27–33°C, ±2°C and ±8°C); and 8% felt much too cool (i.e., a similar pattern to that of the 'much too cool' thermal sensation). These results suggest that different thermal sensations significantly influence thermal comfort, and the also indicate that occupants feel uncomfortable at 32,5°C and very uncomfortable at 35°C (CIBSE, 2015).

The participants were asked, 'How would you rate the overall thermal satisfaction of the indoor-air temperature for the Bedroom 1 spaces in the summer?', and their responses were evaluated according to the thermal-sensation scale to assess their degree of thermal discomfort and predict acceptably comfortable summer temperatures. An ordinal logistic regression was performed, and the result revealed no significant relationship between occupant TSVs and bedroom 1 OTs, OR = 0,933 (95% CI [0,764, 1,139]), p =0,493, $Nagelkerke\ R^2$ = 0,005, as shown in Table 4.6. Figure 4.10 shows the TSVs plotted against OTs; to avoid discrepancies in the statistical data, the dataset was computed within each half-degree bin.

Table 4.6: Summary of Ordinal Logistic Regression Predicting Bedroom 1 OTs from Occupant TSVs.

						95% CI of OR	
Predictor	**β**	***SE***	***Wald***	***OR***	***p***	***Lower***	***Upper***
Occupant TSVs	-0,070	0,100	0,470	0,933	0,493	0,764	1,139

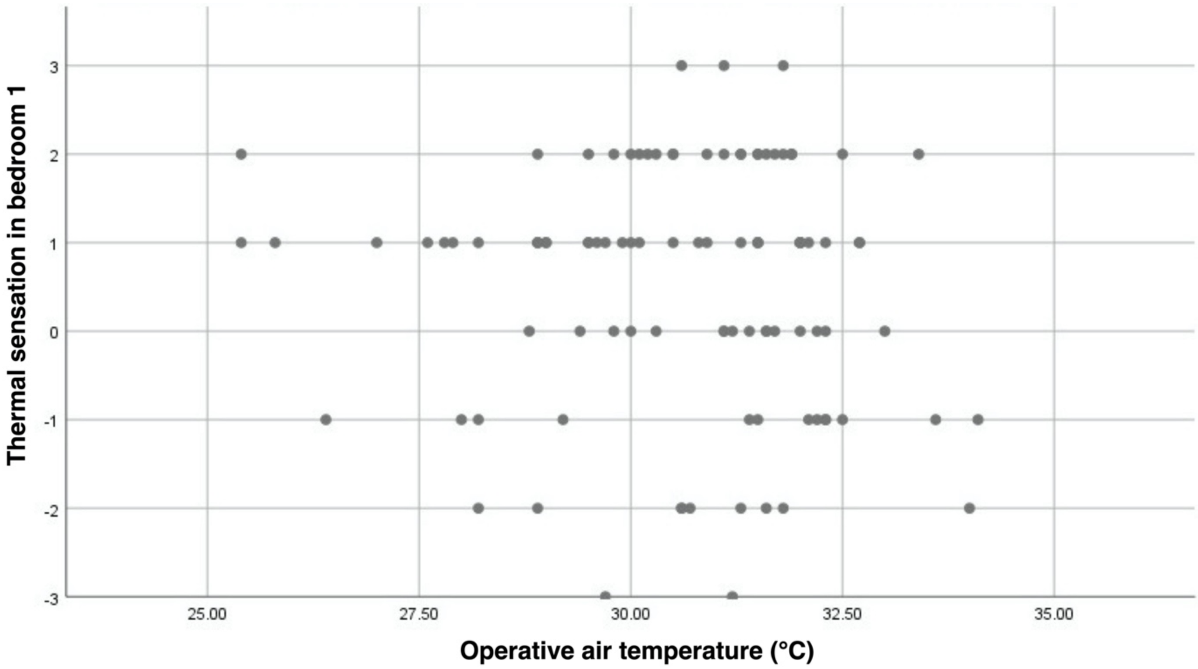


Figure 4.10: Relationship between occupant TSVs and Bedroom 1 OTs (a linear line was added at total).

Research has shown that of the respondents, 3% felt much too warm (*Ta* from 31–32°C, ±6°C and ±7°C); 9% felt too warm (*Ta* 26–33°C, ±1°C and ±8°C);13% felt comfortably warm (*Ta* 25,5–33°C, ±0.5°C and ±8°C); 16% felt comfortable (*Ta* 28–33°C, ±3°C and ±8°C); 23% felt too cool (*Ta* 28–34°C, ±3°C and ±9°C); and 3% felt much too cool (*Ta* 29–32°C, ±4°C and ±7°C); this indicates that the 90% percentile preference boundaries ranged from comfortable to comfortably warm. Thermally acceptable indoor-air temperatures ranged from 26–28°C, which was 1–3°C higher than the upper thermal-comfort threshold recommended in the *CIBSE Guide A* (CIBSE, 2013).

A quantitative scale ranking of data related to the occupants' TSVs towards was gathered to further explore the influences of the environmental parameters that were concurrently recorded as the questionnaire survey was being conducted when the participants were asked, 'How would you rate the overall thermal satisfaction of indoor-air temperature for the Bedroom 2 spaces in the summer?'

An ordinal logistic regression was performed, and the result revealed no significant relationship between occupant TSVs and bedroom 2 OTs, *OR* = 0,939 (95% *CI* [0,769, 1,146]), *p* = 0,536, *Nagelkerke* R^2 = 0,004, as shown in Table 4.7. Figure 4.11 shows the participants' TSVs plotted against OTs.

Table 4.7: Summary of Ordinal Logistic Regression Predicting Bedroom 2 OTs from Occupant TSVs.

						95% CI of OR	
Predictor	**β**	***SE***	***Wald***	***OR***	***p***	***Lower***	***Upper***
Occupant TSVs	-0,063	0,100	0,380	0,939	0.536	0,769	1,146

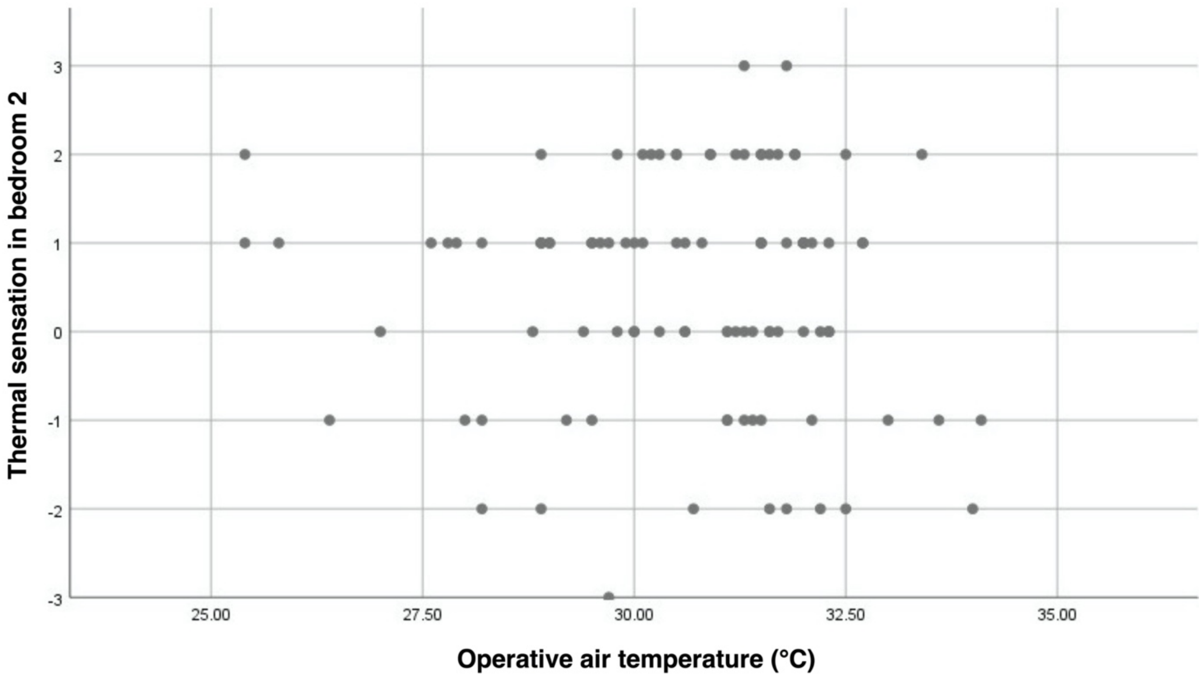


Figure 4.11: Relationship between occupant TSVs and Bedroom 2 OTs (a linear line was added at total).

The results revealed that of the respondents, 2% felt much too warm (*Ta* 31–32°C, ±6°C and ±7°C); 8% felt too warm (*Ta* 26–33°C, ±1°C and ±8°C); 14% felt comfortably warm (*Ta* 26–32,5°C, ±1°C and ±7,5°C); 22% felt comfortable (*Ta* 27–32°C, ±2°C and ±7°C); 32% felt comfortably cool (*Ta* 26–34°C, ±1°C and ±9°C); 20% felt too cool (*Ta* 28–33°C, ±3°C and ±8°C), and 1% felt much too cool (*Ta* 29°C, ±4°C). Based on the findings of ordinal logistic regression, it was concluded that in the 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 (CIBSE, 2015).

To determine the optimum thermal-comfort level in relation to a range of thermal sensations predicted by the PMVs, participants were asked, ‘How would you rate the overall thermal satisfaction of indoor-air environment for the Bedroom 3 spaces in the summer?’ An ordinal logistic regression was performed, and the result revealed no significant relationship between occupant TSVs and bedroom 3 OTs, *OR* = 0,908 (95% *CI* [0,743, 1,109]), *p* = 0,344, *Nagelkerke* R^2 = 0,009, as shown in Table 4.8. Figure 4.12 shows the participants’ TSVs plotted against OT. The thermal-sensation graphs were obtained by plotting the participants’ TSVs against the environmental parameters.

Table 4.8: Summary of Ordinal Logistic Regression Predicting Bedroom 3 OTs from Occupant TSVs.

						95% CI of OR	
Predictor	**β**	***SE***	***Wald***	***OR***	***p***	***Lower***	***Upper***
Occupant TSVs	-0,097	0,100	0,890	0,908	0,344	0,743	1,109

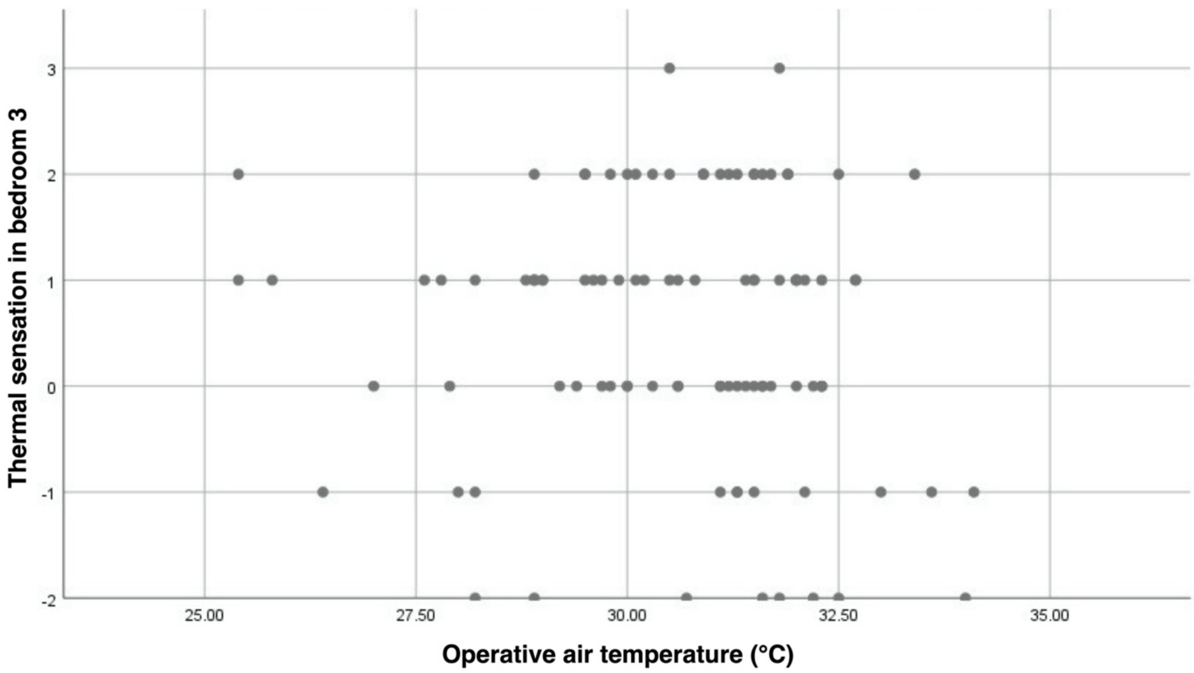


Figure 4.12: Relationship between occupant TSVs and Bedroom 3 OTs (a linear line was added at total).

As shown in Figure 4.12, 8% of respondents felt too warm (*Ta* 28–32,5°C, ±3°C and ±7,5°C), 11% felt comfortably warm (*Ta* 26–34°C, ±1°C and ±9°C), 25% felt comfortable (*Ta* 26–32°C, ±1°C and ±7°C), 32% felt comfortably cool (*Ta* 26–33°C, ±1°C and ±8°C); 22% felt too cool; and 2% felt much too cool (*Ta* 31–32°C, ±6°C and ±7°C).

According to the findings of ordinal regression analysis, thermally comfortable temperatures in the respondents' living room spaces ranged from 26–28°C during the summer (CIBSE, 2017). Considering that the influence of outdoor-air temperature on the occupants' thermal sensations in their living room spaces ranged from 23–35°C, these results indicate that even higher adaptation ranges occurred across the measured flats in the summer (Jeong *et al.*, 2016). Notably, the living rooms measurements that were concurrently gathered when the questionnaire survey was conducted also suggested that comfortable temperatures were well above the recommended international benchmark criteria for the spaces, with high values that indicated a strong relationship.

According to the respondents' TSVs related to their Bedroom 1 spaces, the indoor-air temperatures at which they stated that they felt thermally comfortable ranged from 26–28°C when outdoor-air temperatures were not in the 90% percentile range; this was partially due to the occupants' higher thermal-comfort preferences and the positions of the bedroom spaces in their flats. These results suggest that the occupants were better able to adapt to a thermal environment that was within a wide range of thermally comfortable threshold levels than to slightly warmer indoor-air temperatures.

Similar patterns were found among the occupants' thermal sensations associated with their Bedroom 2 spaces. On the ordinal regression plot, thermally comfortable TSVs were not scattered within the 90% percentile preference boundaries, which suggests that the occupants experienced overheating in their Bedroom 2 spaces. Thermally comfortable outdoor-air temperatures ranged from 33°C to above 35°C, however, when the outdoor temperatures peaked at 36°C, which suggests that the occupants preferred higher indoor-air temperature in their Bedroom 2 spaces in the summer (Teitelbaum *et al.*, 2020).

As it relates to the influence of indoor-air temperatures on the occupants' TSVs for their Bedroom 3 spaces, it was determined that thermally comfortable temperatures ranged from 26–28°C when outdoor-air temperatures ranged from 28–30°C (Ryu *et al.*, 2020). The analysis indicated that occupants preferred temperatures in the Bedroom 2 and Bedroom 3 spaces that were 2°C higher than in the Bedroom 1 spaces; the findings also revealed a significant difference of 5°C between preferred indoor and outdoor-air temperatures in all the bedroom spaces. Table 6.9 demonstrates the summary of ordinal logistic regression predicting summer temperature satisfaction from operative air temperature in order to understand the impact of RH on occupants' thermal comfort. Figure 4.13 shows the relationship between the occupants' overall TSVs in summer and the operative-air temperature of the interviewed flat units.

Table 4.9: Summary of Ordinal Logistic Regression Predicting Summer Temperature Satisfaction from Operative-air Temperature

						95% CI of OR	
Predictor	**β**	***SE***	***Wald***	***OR***	***p***	***Lower***	***Upper***
Indoor RH	-0,043	0,020	3,860	0,958	0,050	0,918	1,000

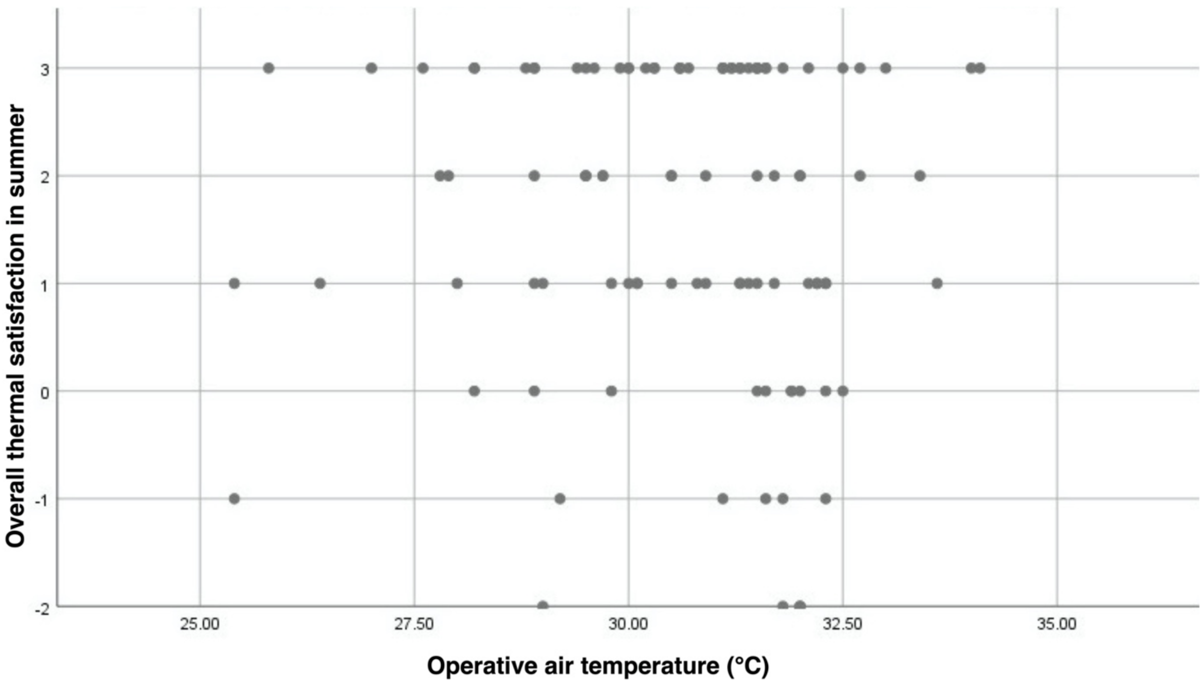
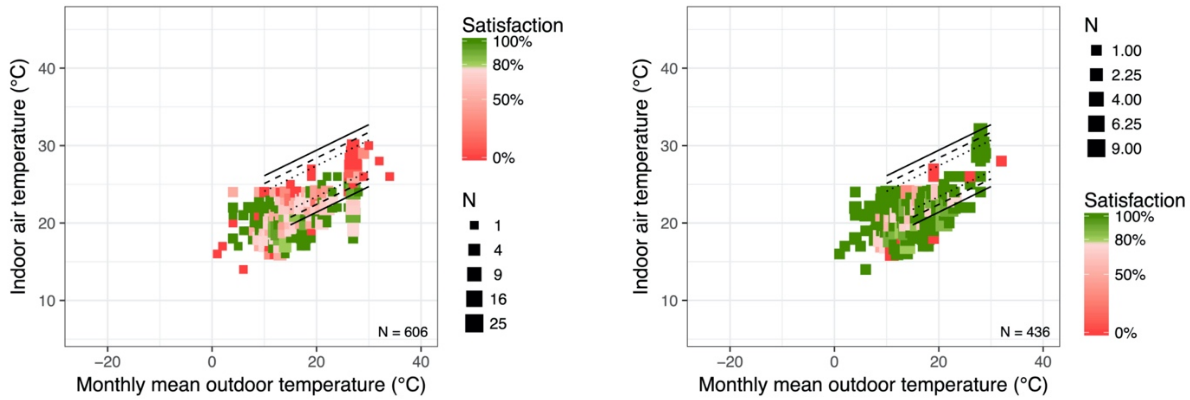


Figure 4.13: Relationship between occupant TSVs and operative-air temperature (a linear line was added at total).

As shown in Table 4.9, an ordinal logistic regression was performed, and the result revealed a marginally significant relationship between *in-situ* recorded operative-air temperature and summer temperature satisfaction, *OR* = 0,958 (95% *CI* [0,918, 1,000]), *p* = 0,050, *Nagelkerke* R^2 = 0,042. Research has shown that 18% of respondents felt 'too warm' (*Ta* from 28 °C to 34 °C ± 3 °C and ± 9 °C), 23% felt 'comfortably warm' (*Ta* from 28 °C to 35 °C ± 3 °C and ± 10 °C) and 13% felt 'comfortable' (*Ta* showed patterns similar to 'comfortable'), while 21% voted for feeling 'comfortably cool' (*Ta* fell from 23 °C to 35 °C ± 10°C), 17% felt 'too cool' (*Ta* fell from 28 °C to above 35 °C ± 3 °C and > ± 10 °C) and 8% felt 'much too cool' (*Ta* from 28 °C to 35 °C ± 3 °C and ± 10 °C). Further analysis revealed that, in summer, the relationship between thermal sensation in the living room spaces and the outdoor air temperature was considered 'comfortable' when the outdoor air temperature reaches 28 °C. The analysis indicates 'comfortable' for the indoor air temperature at 26 °C with a possibility for feeling 'comfortably cool' with an outdoor air temperature of 23 °C in summer, suggesting optimum comfortable temperatures with ±3 °C differences.

It was also noted that on average, the temperatures of the proposed model were 2°C higher than the temperatures that were recommended in the EN 15251 (2007) standards for naturally ventilated buildings. Notably, the TSVs that fell within the recommended benchmark parameters of the EN 15251 adaptive model were plotted against the 80% and 90% upper- and lower-acceptability limits; Figures 4.14(a) and (b) depict the acceptability of the thermal sensations that were available in the ASHRAE Global Thermal Comfort Database II.



(a) **(b)**

Figure 4.14: Scatter-plot distribution of thermal sensation by **(a)** building typology[21] and **(b)** climate type.[22] ***Source:*** ASHRAE Global Thermal Comfort Database II.[23]

Figure 4.14(a) shows that the participants' TSVs in naturally ventilated multi-family residential buildings ranged from 20–30% acceptability when the monthly mean outdoor temperatures were 25–30°C. To identify a baseline model and determine neutral adaptive thermal comfort levels for the present study, acceptable thermal-comfort levels in the hot summer Mediterranean climate included in the ASHRAE Global Thermal Comfort Database II were examined; as is shown in Figure 4.14(b), acceptable thermal sensations were felt between 19–33°C in subtropical (*Csa*) and partly semi-arid (*Bsh*) climates.

Importantly, significant proportions of the occupants' TSVs fell outside the upper and lower limits, which suggests that the occupants found a wider range of thermal-sensation conditions to be comfortable than was delineated in the adaptive model. It can therefore be concluded that the difference between the preferred temperatures and the neutral temperatures

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

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

[23] Graphs were extracted from an open-access thermal-comfort visualisation tool that utilised the satisfaction metric (i.e., Acceptability [TSV±2]), which is available at https://cbe-berkeley.shinyapps.io/comfortdatabase/

that were recorded from two different environmental conditions demonstrates the occurrence of thermal adaptation against to the hot and dry climate of Cyprus; when validating the questionnaire variables, comparing the neutral temperatures and the preferred temperatures served to highlight which group was better adapted to its thermal environment. According to these findings, the differences between neutral temperatures and preferred temperatures in the summer are ±0.4°C and ±9°C, respectively; this confirms that the study participants who reported the greatest differences between neutral temperatures and preferred temperatures had the best ability to adapt to their indoor thermal environments in the summer.

4.4 Discussions

Adaptive comfort is a subject worthy of investigation in purpose to reduce heating- and cooling-energy consumption. 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. As the majority of the residents/participants have been living in the social housing estate more than 10 years, it is expected that occupants can adapt to the environment and climate in the living spaces.

Brager and de Dear (1998) identified three thermal-adaptation types: Physiological, which is related to bodily reactions due to temperature change; psychological, which is related to the state of mind based on previous experience; and behaviour-related adaptation. Nicol and Roaf (2015) asserted that comfort can be reached if there are sufficient opportunities for people to adapt. Comfortable temperatures are changeable, rather than fixed. To capture the wider types of occupants and not create direct generalisation that have the potential to introduce a higher bias, a cluster analysis was conducted to validate the field investigation findings in thermal comfort.

The following discussion is structured according to the research question that guides the findings obtained through feed-forward interviews: (RQ-1) How environmental factors affect occupant thermal comfort to identify neutral adaptive thermal-comfort thresholds in this south-eastern Mediterranean climate.

4.4.1 Physiological Thermal Adaptation

Because the aim of this chapter is to test the factors that affected the occupants' thermal sensations, a statistical test was performed to determine the relationship between occupant TSVs and environmental parameters. An ordinal logistic regression was performed, and the result revealed no significant relationship between occupant TSVs and living room OTs, *OR* = 0,993 (95% *CI* [0,816, 1,209]), $p = 0{,}947$, *Nagelkerke* $R^2 < 0{,}001$. On the contrary, a marginally significant relationship between operative air temperature and households' overall summer temperature satisfaction, *OR* = 0,958 (95% *CI* [0,918, 1,000]), $p = 0{,}050$, *Nagelkerke* $R^2 = 0{,}042$. It should be noted that *p*-value is the probability of the null hypothesis.

In this case, the null hypothesis is that there is no relationship between operative air temperature and households' overall summer temperature satisfaction. When the *p*-value is less than or equal to 0,05[24], the probability of the null hypothesis is less than or equal to 5% (0,05), so reject the null hypothesis and there is a significant relationship between operative air temperature and households' overall summer temperature satisfaction. However, some papers consider less than 0,05 (not including 0,05) as the cutoff for significance (King, 2011; Schumacker, 2017). In this statistical analysis, marginal significance means the *p* values between 0,05 and 0,1, indicating that there is a trend relationship but did not reach a statistical significance.

It was found that the TSVs indicated that the minimum threshold for adaptive indoor-air temperature was 28,5°C, and the upper threshold was 31,5°C. The statistical value of *r*-squared ($R^2 = 0{,}042$) was extrapolated by the slightly weak regression coefficient factor to optimise indoor-air temperature, which was strongly correlated with the TSVs.

A multinominal logistic regression was conducted[25] predicting space conditioning/length of residency from operative air temperature, outdoor air temperature, overall thermal satisfaction in winter, thermal preference and type of cooling system. The results revealed that both of these two overall models were not significant, $\chi2(18) = 46.162$, *p*[26] = 0,120, Nagelkerke $R^2 = 0{,}393$, as shown in Tables 4.10(a) and (b).

[24] See the further details at https://en.wikipedia.org/wiki/P-value (accessed on 12/12/2021)
[25] Multinominal logistic regression is a statistical analysis procedure that expands linear regression by including more than one independent variable in an equation to understand their association with a dependent variable. Typically, the data used for multiple regression are made up of continuous variables (e.g., interval-level measurements such as Likert scales or amounts of observable behaviour), but it is also possible to use categorical data (e.g., demographic information such as gender or ethnicity). To use categorical data in multiple regression, one must employ a technique called dummy coding. Unlike correlation, which shows the co-occurrence of variables (e.g., perceptions of liking), regression can be used for prediction and casual inference.
[26] The ***p*** value refers to the probability for the observed empirical result or more extreme results to occur under the assumption that the null hypothesis is true.

Table 4.10(a): Summary of Multinominal Regression Predicting Space Conditioning.

							95% CI	
	Predictors	**B**	***SE***	***Wald***	***OR***	***p***	***Lower***	***Upper***
Natural ventilation[a]	Operative air temperature (°C)	-0,015	0,292	0,003	0,985	0,959	0,555	1,747
	Outdoor air temperature (°C)	-0,646	0,247	6,867	0,524	0,009	0,323	0,850
	Overall thermal satisfaction in winter	-0,515	0,307	2,823	0,597	0,093	0,327	1,090
	Thermal preference: Cold[b]	3,268	1,458	5,023	26,259	0,025	1,507	457,599
	Thermal preference: Cool[b]	1,246	1,067	1,363	3,477	0,243	0,429	28,156
	Thermal preference: Slightly cool[b]	-20,555	0,000	0,000	0,000	1,000	0,000	0,000
	Type of cooling system: A/C split unit[c]	0,848	1,258	0,454	2,334	0,500	0,198	27,461
	Type of cooling system: A/C inverter split unit and ceiling mounted fan[c]	0,207	1,424	0,021	1,230	0,885	0,075	20,049
	Type of cooling system: Portable fan[c]	0,741	1,128	0,431	2,097	0,512	0,230	19,150
Mixed-mode[a]	Operative air temperature (°C)	-0,353	0,233	2,300	0,703	0,129	0,445	1,109
	Outdoor air temperature (°C)	-0,349	0,223	2,446	0,705	0,118	0,456	1,092
	Overall thermal satisfaction in winter	-0,189	0,289	0,427	0,828	0,513	0,470	1,458
	Thermal preference: Cold[b]	3,286	1,461	5,055	26,728	0,025	1,524	468,766
	Thermal preference: Cool[b]	2,301	1,071	4,612	9,981	0,032	1,223	81,481
	Thermal preference: Slightly cool[b]	0,673	1,182	0,324	1,961	0,569	0,193	19,887
	Type of cooling system: A/C split unit[c]	0,221	1,238	0,032	1,247	0,859	0,110	14,117
	Type of cooling system: A/C inverter split unit and ceiling mounted fan[c]	1,340	1,203	1,241	3,819	0,265	0,361	40,367
	Type of cooling system: Portable fan[c]	0,961	1,046	0,845	2,616	0,358	0,337	20,321
Air-Conditioning (A/C)[a]	Operative air temperature (°C)	-0,397	0,228	3,029	0,673	0,082	0,430	1,051
	Outdoor air temperature (°C)	-0,431	0,218	3,913	0,650	0,048	0,424	0,996
	Overall thermal satisfaction in winter	-0,352	0,273	1,656	0,704	0,198	0,412	1,202
	Thermal preference: Cold[b]	2,812	1,392	4,081	16,637	0,043	1,087	254,537

Table 4.10(b): Summary of Multinominal Regression Predicting Space Conditioning. (Continued)

							95% CI	
	Predictors	**B**	***SE***	***Wald***	***OR***	***p***	***Lower***	***Upper***
Air-Conditioning (A/C)[a]	Thermal preference: Slightly cool[b]	0,011	1,075	0,000	1,011	0,992	0,123	8,319
	Type of cooling system: A/C split unit[c]	1,143	1,082	1,117	3,136	0,291	0,377	26,125
	Type of cooling system: A/C inverter split unit and ceiling mounted fan[c]	0,494	1,227	0,162	1,639	0,687	0,148	18,148
	Type of cooling system: Portable fan[c]	1,163	0,991	1,375	3,198	0,241	0,458	22,326
Portable fan/Air-Conditioning[a]	Operative air temperature (°C)	-0,100	0,264	0,143	0,905	0,705	0,540	1,517
	Outdoor air temperature (°C)	-0,422	0,236	3,193	0,656	0,074	0,413	1,042
	Overall thermal satisfaction in winter	-0,518	0,287	3,263	0,596	0,071	0,340	1,045
	Thermal preference: Cold[b]	0,835	1,653	0,255	2,304	0,614	0,090	58,777
	Thermal preference: Cool[b]	1,144	0,975	1,377	3,139	0,241	0,465	21,203
	Thermal preference: Slightly cool[b]	-0,451	1,110	0,165	0,637	0,685	0,072	5,609
	Type of cooling system: A/C split unit[c]	0,822	1,127	0,532	2,275	0,466	0,250	20,717
	Type of cooling system: A/C inverter split unit and ceiling mounted fan[c]	0,044	1,260	<0,001	1,045	0,972	0,088	12,342
	Type of cooling system: Portable fan[c]	-0,279	1,081	0,066	0,757	0,797	0,091	6,301

***Note*:** $\chi 2$ (36) = 46,162, p = 0,120, Nagelkerke R^2 = 0,393, [a]Compared to Portable fan. [b]Compared to Neutral/slightly warm. [c]Compared to A/C split unit and portable fans.

An ordinal regression using the logit link[27] function was conducted on perception of length of residency from operative air temperature, outdoor air temperature, overall thermal satisfaction in winter, thermal preference and type of cooling system. The results revealed that overall models were not significant, $\chi2(9) = 14.523$, $p = 0{,}105$, Nagelkerke $R^2 = 0{,}178$, as shown in Table 4.11.

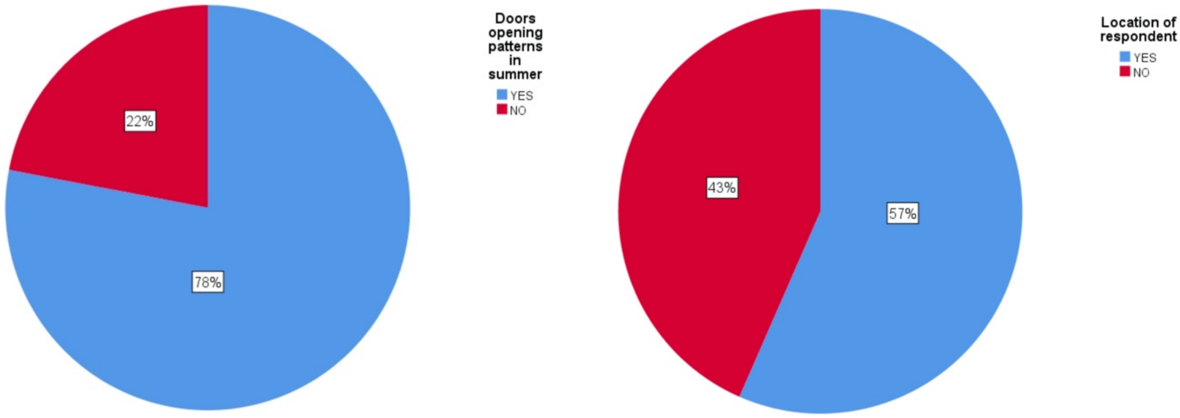
Table 4.11: Summary of Ordinal Regression Predicting Length of Residency.

						95% CI of OR	
Predictor	**β**	***SE***	***Wald***	***OR***	***p***	***Lower***	***Upper***
Operative air temperature (°C)	-0,010	0,137	0,005	0,990	0,944	0,757	1,296
Outdoor air temperature (°C)	-0,055	0,118	0,215	0,946	0,643	0,751	1,194
Overall thermal satisfaction in winter	-0,012	0,167	0,006	0,988	0,940	0,712	1,369
Thermal preference: Cold[a]	1,309	0,888	2,174	3,702	0,140	0,650	21,115
Thermal preference: Cool[a]	0,156	0,612	0,065	1,169	0,798	0,352	3,881
Thermal preference: Slightly cool[a]	-0,490	0,753	0,423	0,613	0,515	0,140	2,680
Type of cooling system: A/C split unit[b]	0,012	0,698	<0,001	1,012	0,986	0,258	3,971
Type of cooling system: A/C inverter split unit and ceiling mounted fan[b]	-1,373	0,703	3,821	0,253	0,051	0,064	1,004
Type of cooling system: Portable fan[b]	1,105	0,757	2,127	3,019	0,145	0,684	13,316

Note: $\chi2\ (9) = 14{,}523$, p = 0,105, *Nagelkerke* $R^2 = 0{,}178$. [a]Compared to Neutral/slightly warm. [b]Compared to A/C split unit and portable fans.

In this study, *in-situ* indoor-air temperature measurements were recorded, because indoor-air movement will significantly influence neutral thermal sensations and can make occupants feel comfortable despite relatively high indoor temperatures. In Question 19, the occupants were asked to report their door-opening habits when their air conditioning (A/C) system was not in use, as illustrated in Figure 4.15(a). Additionally, in the *pro-forma* questionnaire, the physical conditions and respondent locations within their living rooms were recorded to assess the occupants' thermal discomfort and identify neutral adaptive thermal comfort. The respondents' locations are illustrated in Figure 4.15(b).

[27] The process of logistic regression provides the generation of an equation in order to provide an improved means of prediction that extends beyond an individual variable.



(a) **(b)**

Figure 4.15: (a) Distribution of household internal door-opening patterns in summer; **(b)** participant location in living rooms during survey.

Figure 4.15(a) shows that 78% of the respondents kept internal doors closed when using their A/C system, 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 A/C 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. Figure 4.15(b) shows that 57% of respondents were surveyed 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 environmental conditions and the thermal properties of their flats. Figure 6.16 illustrates the percentage distribution of the respondents' room conditions to show the effect of this information on the occupants' *in-vivo* experiences associated with their thermal comfort.

4.4.2 Psychological Thermal Adaptation

The *in-situ* measurements and *on-site* environmental monitoring findings from the field study depicted in the graph were recorded from the *in-vivo* experiences of the households' TSVs, and a determination of the influence thereof on the identification of neutral adaptive thermal comfort levels took the participants' habitual adaptive behaviours into account. Of the respondents, 41% preferred to use all types of domestic cooling appliances, and 25% of the surveyed households also used all types of space conditioning systems to acclimatise their indoor-air environments; this indicates that the household TSVs are strongly correlated with observed indoor environmental conditions (i.e., type of space conditioning used, *in-situ* measurements and *on-site* environmental monitoring).

According to the findings of the present study, when the indoor-air temperatures ranged from 25–27,5°C, the participants' TSVs all fell within an acceptable comfort zone, and the occupants indicated that they were mostly satisfied with their indoor-air temperatures. Notably, 6% of participants reported feeling thermally uncomfortable and 94% of participants reported feeling thermally comfortable in the 27,5–30°C temperature range. When indoor operative air temperatures increased by 2,5°C to slightly above the neutral temperature range of 30–32,5°C, the respondents' predicted percentage dissatisfied (PPD) with their indoor-air temperatures rose to 23%; the occupants' PMVs increased to 41% when temperatures ranged from 32,5–35°C, and no participants felt thermally comfortable when outdoor-air temperatures exceeded 35°C.

The participants reported that they used both their A/C systems and mixed-mode (MM) ventilation when temperatures ranged from 28–36°C; A/C systems were utilised when temperatures ranged from 34–36°C; one participant used a portable fan when the outdoor temperature was 24°C, which is 1°C below the thermally acceptable comfort level; and MM ventilation was used to optimise indoor-air temperatures between 32–34°C, which was the most notable pattern. These findings demonstrate that the building thermal properties and poor window design were the reason that high indoor-air temperatures were reported when outdoor-air temperatures were thermally acceptable.

Figures 4.16(a) through (h) illustrate the climate characteristics of the cities in Cyprus to represent the generalisation of applied thermal comfort threshold levels as identified through regression forecasting analysis.

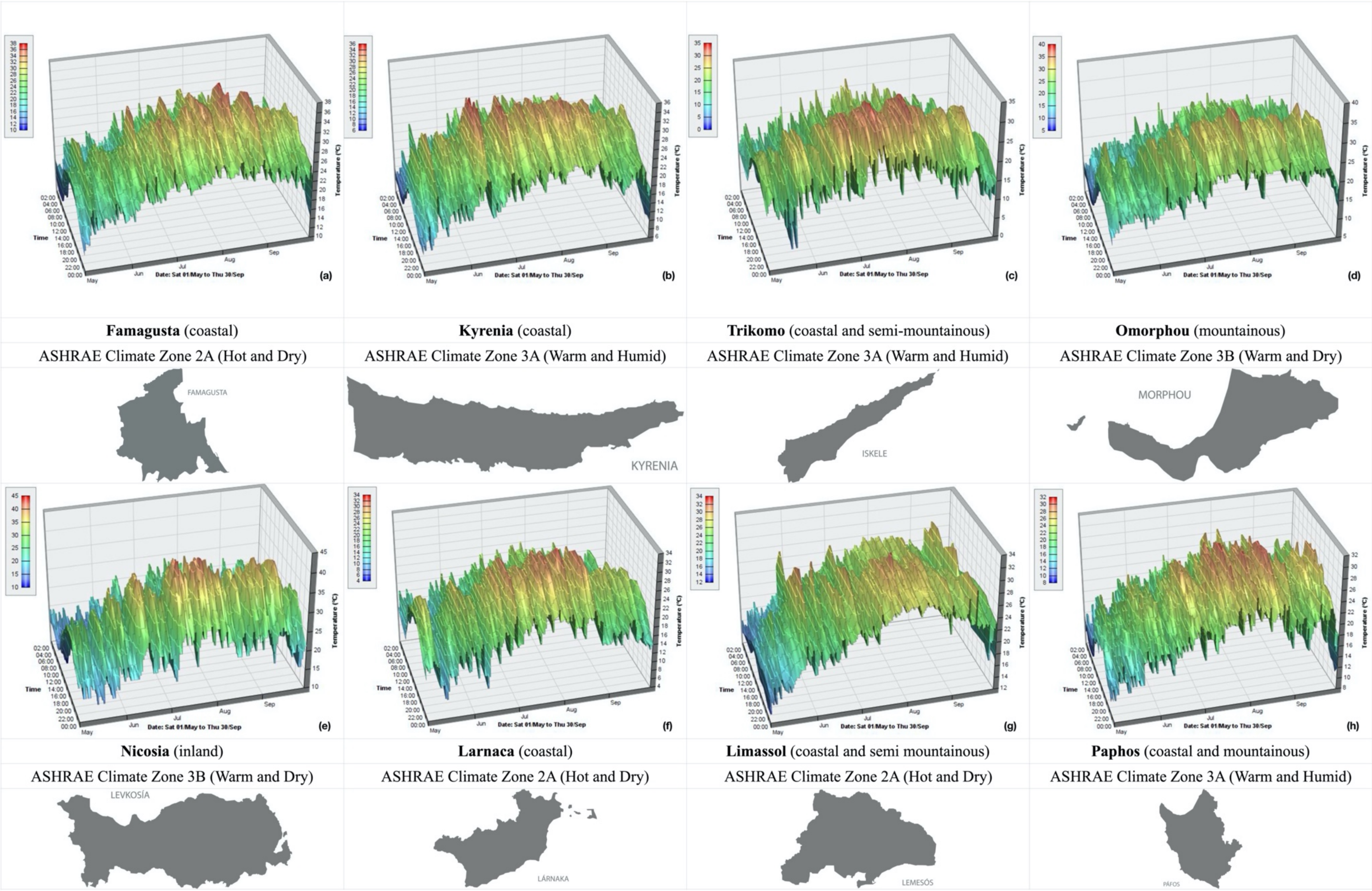


Figure 4.16:(a) through (h): Mapping of climate variations of eight cities in Cyprus.

The present study investigates the effects of local climate conditions on the psychological adaptation of human thermal comfort. The pilot case study was conducted in the coastal city of Famagusta; this city was selected as a baseline model to represent all major cities in the same climate conditions. One of the primary reasons this study was not conducted in the laboratory environment of a climatic chamber was so the experiment parameters could be properly identified and consequently be widely applied to the climate zone of the south-eastern Mediterranean basin.

To test the validity of the field-study investigation in post-war social-housing estates in Cyprus, the climate datasets of eight Cypriot cities were extracted from EnergyPlus as an EPW weather file; this information was then assigned into the IES software weather datasets. Dynamic thermal simulations were conducted to generate the climate patterns of each city, with the intention of assessing the results derived from building energy-simulation platform to validate the field-study findings.

The results revealed a discrepancy between the *in-situ* physical measurements and the building energy simulation predictions. The field-study findings demonstrate that the neutral adaptive thermal comfort threshold was found to be 28,5–31,5°C in the case study location. On the contrary, the building energy simulation results indicate that the climate shows variations around 10–15°C among the eight representative cities in Cyprus.

According to Figure 4.16(a), the air temperature in Famagusta from May to September, which is the cooling period for 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, at which time temperatures peaked at 38°C, then decreased and hovered between 28–32°C until the end of September. The climate-pattern variations were within the acceptable neutral adaptive thermal-comfort thresholds developed through this empirical study investigation in the baseline scenario; the benchmark criteria for thermally comfortable MFHs in Cyprus range between 28,5–31,5°C, and slightly warmer temperature fluctuations between 32–38°C were observed.

To understand the representativeness of the neutral adaptive thermal comfort threshold level, the climate characteristics of seven other cities were then examined to prove the general applicability of the benchmarking criterion and determine whether it can be applied to the whole of Cyprus.

Figure 4.16(b) illustrates the air temperature in Kyrenia, which showed temperature variations between 24–28°C, which peaked at 36°C in the middle of June, then steadily decreased to 25°C throughout the month. Air temperatures rose to 35°C at the end of the first week of July and fluctuated between 28–32°C until the end of August; thermally comfortable temperatures between 22–28°C were predicted throughout the month of September. The neutral adaptive thermal-comfort threshold level fell within the benchmark threshold, and climate patterns observed in the simulation prediction also fell within 30% of the recommended upper thermal-comfort limit in the ASHRAE Global Thermal Comfort Database II.

Figure 4.16(c) illustrates the air-temperature patterns in Trikomo, which fluctuated between during the peak cooling period between July and August 30–35°C; a difference of ±3,5°C was identified when the neutral adaptive thermal-comfort threshold was selected as a benchmark criterion. As shown in the graph, steady, continuous warm air temperature was observed through most of the summer months; notably, the air temperature in the third week of September peaked at 30 °C, which is the upper thermal-comfort limit according to the ASHRAE Global Thermal Comfort Database II criteria.

Figure 4.16(d) depicts pleasant air-temperature patterns in Omorphou, which steadily fluctuated between 20–25°C from the beginning of May to the first week of June, at which time temperatures increased to 32°C, fluctuated between 25–28°C until the first week of August, then peaked at 40°C; temperature variations between 28–32°C were then observed until the end of September. Air temperatures exhibited a ±8,5°C difference from the upper neutral adaptive thermal-comfort threshold for the Cypriot climate.

Figure 4.16(e) demonstrates the slightly cool environment conditions of Nicosia: Air temperatures varied between 10–25°C from the beginning of May to the end of first week of June, rose to 35°C early in the second week of June and remained consistent through the third week, then steadily decreased to 30°C from the last week of June through the second week of July. Air temperatures peaked at 45°C in the second week of July and stayed in this range until the middle of August, at which time air temperatures slightly decreased to 36°C and fluctuated between 36–42°C until the third week of September, then steadily decreased to 34°C through the end of September.

The results revealed that there was a significant ±15°C variation difference between day and night temperatures due to the inland geographical location of Nicosia and the city’s location between two high altitude mountains that block effective summer breezes from the coastline regions; this also caused the urban heat island (UHI) effect, which led to thermally uncomfortable indoor-air environments. In the graph, the upper thermal-comfort limit was above 35°C from the first week of July through the third week of September; the simulation prediction was ±3,5°C higher than the 31,5°C upper neutral adaptive thermal-comfort threshold, which suggests that a higher adaptive thermal-comfort limit is needed for multi-family houses (MFHs) in Nicosia.

Figure 4.16(f) delineates the thermally acceptable (i.e., neutral) temperatures in Larnaca, which hovered between 22–24°C in the first week of May, then fluctuated between 10–16°C until the third week of May; air temperatures oscillated between 24–34°C from the third week of June through the first week of September. Pleasant air temperatures were predicted between 20–26°C until the end of September; notably, the peak air temperatures were observed on several occasions. From the middle of July through the first week of September, the upper thermal-comfort limit was found to be in the range of 30–32°C; this threshold fell within the 28,5–31,5°C neutral adaptive thermal-comfort benchmark criterion developed in the course of the field study.

Continuous warm-air fluctuations that were above the upper thermal-comfort limit recommended in the ASHRAE Global Thermal Comfort Database II, were observed for a prolonged period of time; these climate patterns fell within the thermally acceptable air-temperature range of 30–33°C that is recommended for Mediterranean countries with hot, dry summer climate characteristics.

Figure 4.16(g) details the pleasant weather fluctuations in Limassol, which ranged between 8–23°C from the beginning of May to the first week of June; at this time, air temperatures peaked at 32°C, then decreased to 30°C in the second week of the same month. The curvilinear weather patterns depicted in the graph fluctuated between 25–32°C from the middle of June through the end of August, then peaked at 34°C in the second week of September and steadily decreased to 22°C by the end of September; peak air temperature ranged between 26–30°C, which fell within the neutral adaptive thermal-comfort threshold developed for the present study.

Figure 4.16(h) shows the reasonably comfortable air temperatures in Paphos, which fluctuated between 12–22°C from the beginning of May through the final week of June. Temperatures peaked at 29°C in the first week of July, fluctuated between 30–32°C from mid-July through mid-September, peaked again at 32°C in the second week of August; notable variations in air temperatures that ranged between 18–30°C were observed until the end of September.

Predicted air temperatures fell within the neutral adaptive thermal-comfort threshold developed for the baseline coastal city of Famagusta. Notably, the significant difference in air temperatures between Paphos and the baseline city is due to its geographical location on the south-western corner of the island, which benefits from effective summer breezes from the eastern Mediterranean Sea; this demonstrates that the high frequency of outdoor air movement is a determinant environmental factor that ensures pleasant thermal conditions, even during the peak cooling period. The results suggest that the lower neutral adaptive thermal-comfort threshold is needed for this part of the island.

It should be noted that the neutral adaptive thermal-comfort threshold developed through the longitudinal field study represents 80% of the Cypriot climate zones, which encompass 56% of the low-, medium- and high-rise RTBs in the country. The matrix presented in Figures 4.16(a) through (g) demonstrates the natural representativeness of housing stock by exploring the neutral adaptive thermal comfort in the designated areas, and the results can be extrapolated to other south-eastern Mediterranean cities with similar climate characteristics to those of Cyprus. This figure can be applied to different climate zones in Cyprus and provide a roadmap of the methodological workflow developed as an outcome of this empirical study; this workflow is not limited to exploring the thermal comfort of MFHs in social-housing estates, but can also be generalised to other housing typologies in areas in the Mediterranean basin that experience hot, dry summer climate characteristics.

4.5 Summary

The present study sought to draw conclusions related to the optimisation of occupants' thermal-comfort levels to fully explore the influences of various environmental parameters that were monitored and/or measured in a post-war social housing development in Famagusta, Cyprus, where the climate is subtropical (*Csa*) and partly semi-arid (*Bsh*) (i.e., hot and dry in the summer). Numerous field studies have determined that occupants' thermal comfort levels vary according to the climate conditions; as such, there is no generally recommended acceptable comfort range for MFHs, nor are there specific adaptive thermal-comfort prediction methods.

The findings of this study enhanced the overall understanding of the complex interrelationships between household socio-demographic characteristics, building thermal properties and occupants' habitual adaptive behaviour related to thermal comfort in heat-vulnerable MFHs. It was found that TSVs in living room was significantly but weakly correlated with TSVs in bedroom 1 ($r = 0{,}302$, $p = 0{,}002$) and bedroom 3 ($r = 0{,}200$, $p = 0{,}046$). TSVs in kitchen was significantly but weakly related to TSVs in bedroom 2 ($r = 0{,}205$, $p = 0{,}041$) and bedroom 3 ($r = 0{,}220$, $p = 0{,}028$). An ordinal logistic regression was performed, and the result revealed no significant relationship between occupant TSVs and living room OTs, $OR = 0{,}993$ (95% CI [0,816, 1,209]), $p = 0{,}947$, $Nagelkerke\ R^2 < 0{,}001$. On the contrary, a marginally significant relationship between operative air temperature and overall summer temperature satisfaction, $OR = 0{,}958$ (95% CI [0,918, 1,000]), $p = 0{,}050$, $Nagelkerke\ R^2 = 0{,}042$. Marginal significance means the p values between 0,05 and 0,1, indicating that there is a trend relationship but did not reach a statistical significance. The occupants' TSVs 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 occupants in hot and dry climates where thermally uncomfortable indoor environments occur are able to tolerate warmer conditions than residents of other high and medium altitudes.

Data related to the occupants' adaptation to slightly warmer indoor-environment conditions and outdoor-air temperatures could be seen as a significant contribution to the ASHRAE Global Thermal Comfort Database II in terms of the delineation of a specific method to conduct a longitudinal field survey in this particular south-eastern Mediterranean climate and the prediction of neutral adaptive thermal comfort levels with the use of an ordinal logistic regression analysis. The present study also provides a roadmap to the EN 15251 thermal-comfort assessment criteria in the event that industry-based temperature design criteria are unable to comply with the ASHRAE Global Thermal Comfort Database II because they conflict with the occupants' adaptive comfort temperatures.

Chapter 5

Results and Discussions: Building-Performance Evaluation and Overheating Risk Assessment

Introduction

This chapter describes the set-up of the building-energy-performance framework that was developed according to *in-situ* measurements of the building-fabric thermal structure to assess robust energy performance evaluation and certification schemes recommended by the Energy Performance Building Directives (EPBD); a discussion of the reliability of social-housing residents' electricity as it relates to assessing the overheating risk of the 36 archetype residential tower blocks (RTBs) in the social-housing estate is also presented. This chapter illustrates the quantitative and qualitative findings of the infrared radiometer thermography (IRT) survey and building-energy simulation (BES) studies to develop an evidence-based building-energy-performance evaluation for the south-eastern Mediterranean climate of Cyprus.

In the following sections, the results of the IRT survey and an analysis of data collected from *on-site* monitoring, *in-situ* physical measurements, household energy bills and building-energy modelling (BEM) are detailed to implement an evidence-based framework in domestic energy use policy. Finally, the energy-model procedure is delineated to provide subsequent information related to the BEM and retrofitting design strategies that are presented in Chapter 6.

5.1 Building-Fabric Thermal Performance

This section examines the significance of the orientation factor of the 36 base-case representative RTBs and the impact thereof on the building-fabric thermal performance of the surveyed flats, while also taking different floor levels into consideration. The aim of this section is to investigate the overheating risk experienced in each occupied space in the representative flats against the acceptable adaptive thermal-comfort limits and industry benchmark of the *CIBSE TM59: Design Methodology for the Assessment of Overheating Risk in Homes*.

The thermal performance of the archetype buildings is then validated by conducting a solar-exposure analysis in an energy-simulation platform to develop a reliable energy-use assessment for space conditioning and optimise occupants' thermal comfort. This section presents the major benchmarking criteria being adopted to investigate the overheating risk in archetype post-war social housing. Figure 5.1 illustrates the parameters which were set out to undertake building performance evaluation for developing an evidence-based energy policy design.

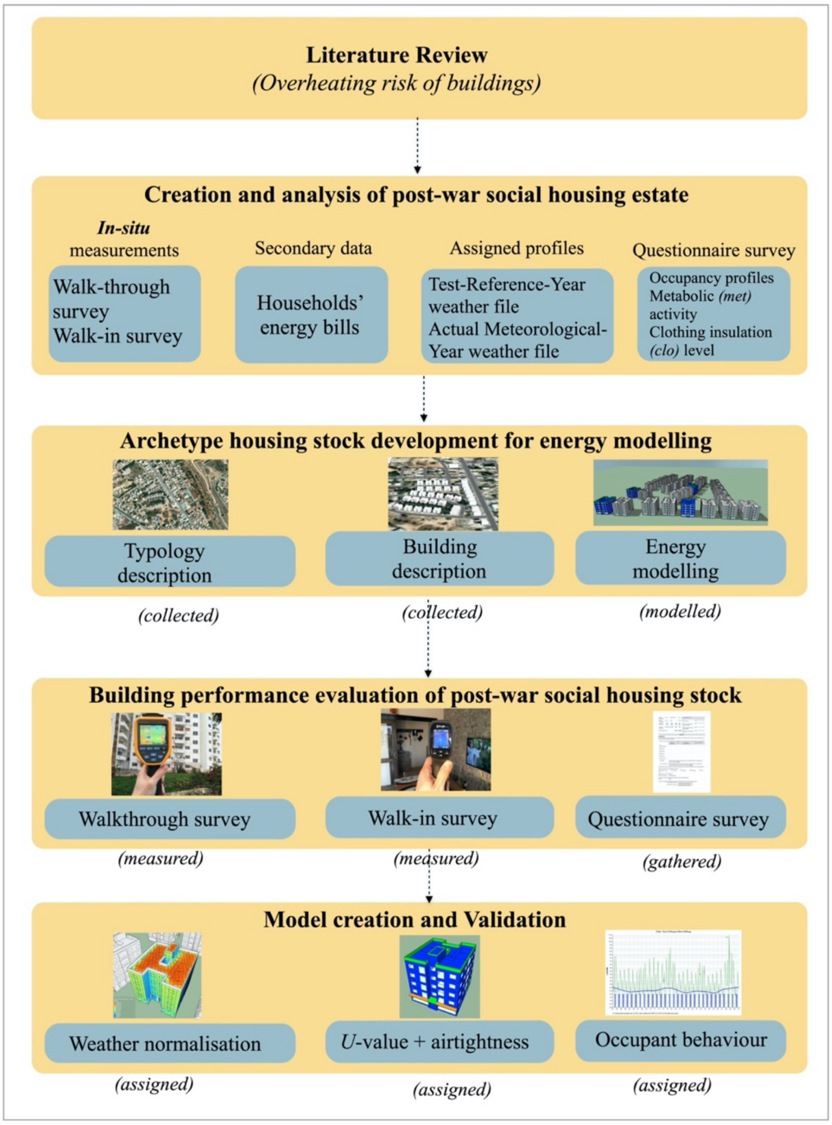


Figure 5.1: Conceptualisation stages for the representation of reported parameters in this study.

5.1.1 Thermal Imaging: Walk-Through Survey

This section presents the findings of a walk-through thermal-imaging survey that was conducted in the winter prior to the *on-site* questionnaire survey, *in-situ* physical indoor-environment measurements and *on-site* environmental monitoring that were performed in August of 2018, as shown in Figure 5.2. These results were also validated by the SunCast application of the IES software suite, which sought to analyse the importance of the solar-irradiance factor onto building envelopes in Section 5.4.2. A total of 36 case-study RTBs were surveyed, and IRT imaging was conducted with a Fluke TiS20 thermal camera twice each day during the winter period—in the early morning and late evening—to avoid possible errors caused by direct solar radiation. A thermal-imaging survey was carried out beforehand to diagnose the building, and after these data were taken into account, they were used to determine feasible retrofitting strategies for policymakers.

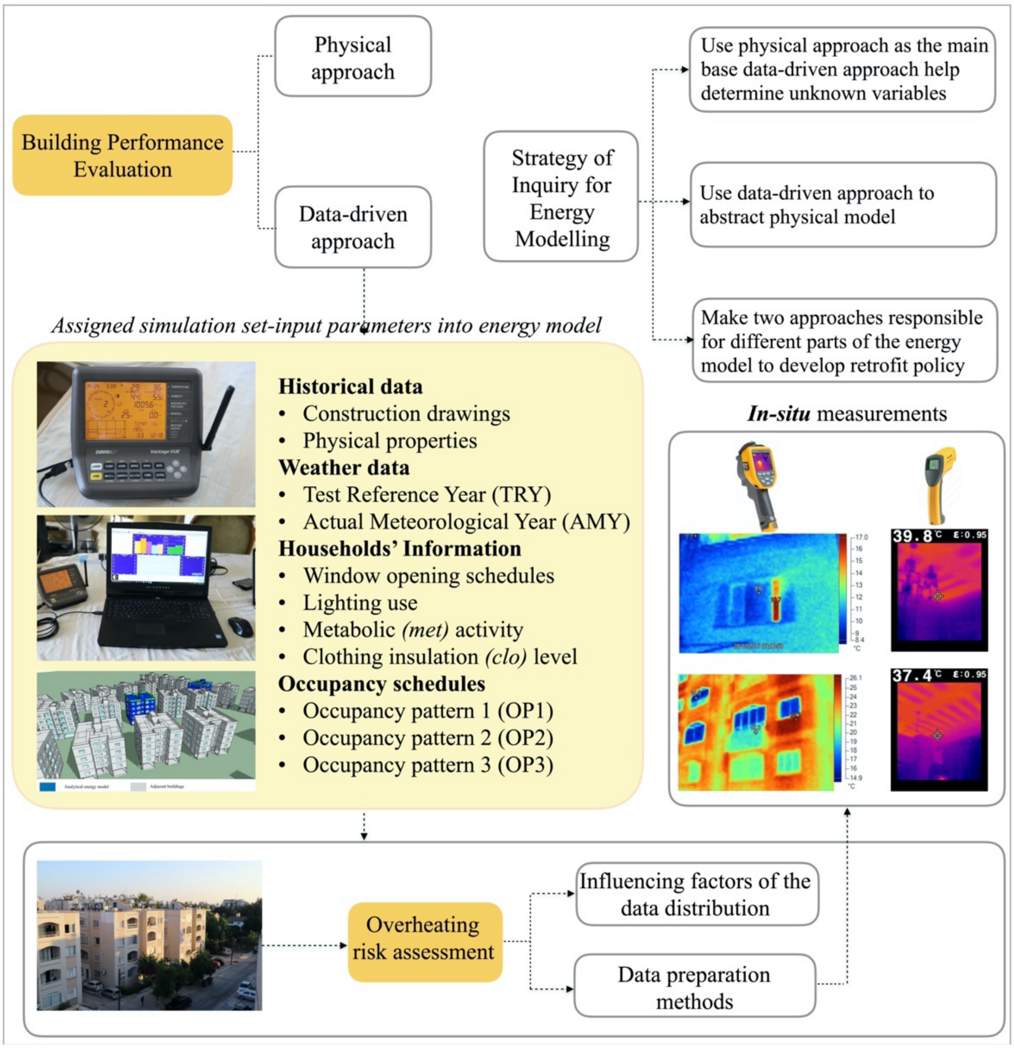


Figure 5.2: Representation of measured, monitored and assigned parameters to undertake building performance evaluation.

Table 5.1 demonstrates the timeline for the thermal-imaging investigations related to heat loss and overheating-risk assessment that was conducted between December 26, 2017 and January 12, 2018, and Figure 5.3 illustrates the mapping of the thermal vulnerability of the archetype buildings in the social-housing estate.

Table 5.1: Timeline of Base-Case Representative RTBs Surveyed in December 2017 and January 2018.

Date	**Time**	**Weather Conditions Observed at Time of Walk-Through Survey**	**Outdoor Temperature Mean (°C)** (*In-situ*)	**Outdoor Temperature Min (°C)** (*In-situ*)	**Outdoor Temperature Max (°C)** (Ercan Airport)
December 26, 2017	06:30–07:45	Sunny/clear cloudy; slightly cold	13,4	9,0	19,1
December 26, 2017	16:00–16:45	Sunny/clear cloudy; slightly cold	13,4	9,0	19,1
December 28, 2017	06:30–07:45	Sunny/clear cloudy; warm	17,4	11,6	20,5
December 28, 2017	16:00–17:00	Sunny/clear cloudy; warm	17,4	11,6	20,5
December 29, 2017	06:30–07:45	Sunny/clear cloudy; warm	15,0	9,3	18,8
December 29, 2017	16:00–17:00	Sunny/clear cloudy; warm	15,0	9,3	18,8
January 2, 2018	16:00–17:00	Sunny/clear cloudy; slightly cold	15,6	11,9	19,6
January 3, 2018	06:30–08:15	Cloudy/scattered rain; no wind; warm	15,6	11,6	19,1
January 3, 2018	16:00–17:15	Cloudy; torrential rain; slightly windy; warm	15,6	11,6	19,1
January 4, 2018	16:00–17:15	Rainfall AM; cloudy; mild weather	14,8	13,2	17,1
January 6, 2018	06:30–07:45	Cloudy; no wind	15,0	10,1	17,2
January 6, 2018	16:00–17:30	Cloudy/sunny; slightly cold	15,0	10,1	17,2
January 8, 2018	06:30–08:15	Clear sky; cold	13,7	9,4	18,9
January 8, 2018	16:00–17:30	Sunny/clear sky; warm	13,7	9,4	18,9
January 9, 2018	06:30–08:15	Sunny/clear sky; warm	14,1	10,0	18,2
January 11, 2018	15:35–17:30	Sunny/cloudy; warm	16,9	11,9	19,6
January 12, 2018	16:00–17:30	Sunny/cloudy; warm	14,6	9,9	19,5

Note: Max outdoor temperature collected by Meteorological Office of Northern Cyprus in September of 2018; data retrieved from Ercan Airport in Nicosia, which is approximately 50km away from case-study location.

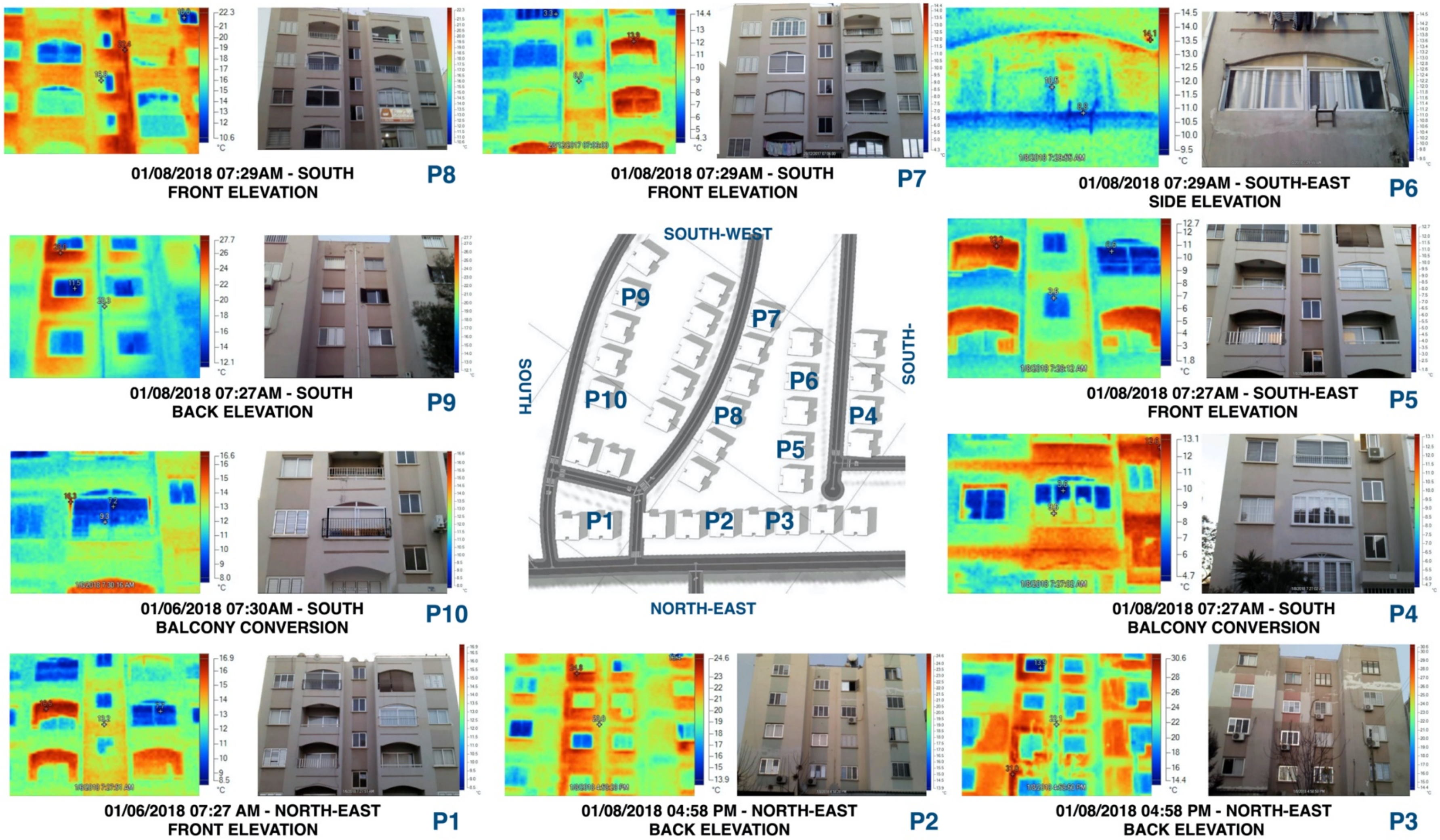


Figure 5.3: Point-by-point mapping of walk-through thermal-imaging survey conducted in winter 2017–2018, taking RTB orientations and impact of different time of day on overheating risk assessment into account.

Figure 5.3 presents overall observations to demonstrate the heat vulnerability of the base-case RTBs. Temperature readings from approximately 2830 images were analysed using the forward-looking infrared radiometer (FLIR) analysis tool to diagnose the thermal performance of all 36 prototype RTBs for the worst-case scenario development that is presented in Chapter 6. These assessments were performed during the 2017–2018 winter months, and all of the survey data were used to model the base-case building and validate the building-energy-simulation findings (Bayomi *et al.*, 2021); the field-observation *on-site* thermal images and photographic documentation and the quantitative temperature recordings of the building-fabric systems also validated the findings related to the development of adaptive thermal-comfort thresholds, which are presented in Chapter 4. This documentation indicates that the identification of ‘neutral’ adaptive thermal comfort is not only limited by local climate conditions; building-fabric thermal performance should also be taken consideration when developing a robust thermal-adaptive threshold benchmark for the Mediterranean region. Figures 5.4(a) and (b) illustrate the built-environment parameters that had a direct impact on the thermal-imaging results.

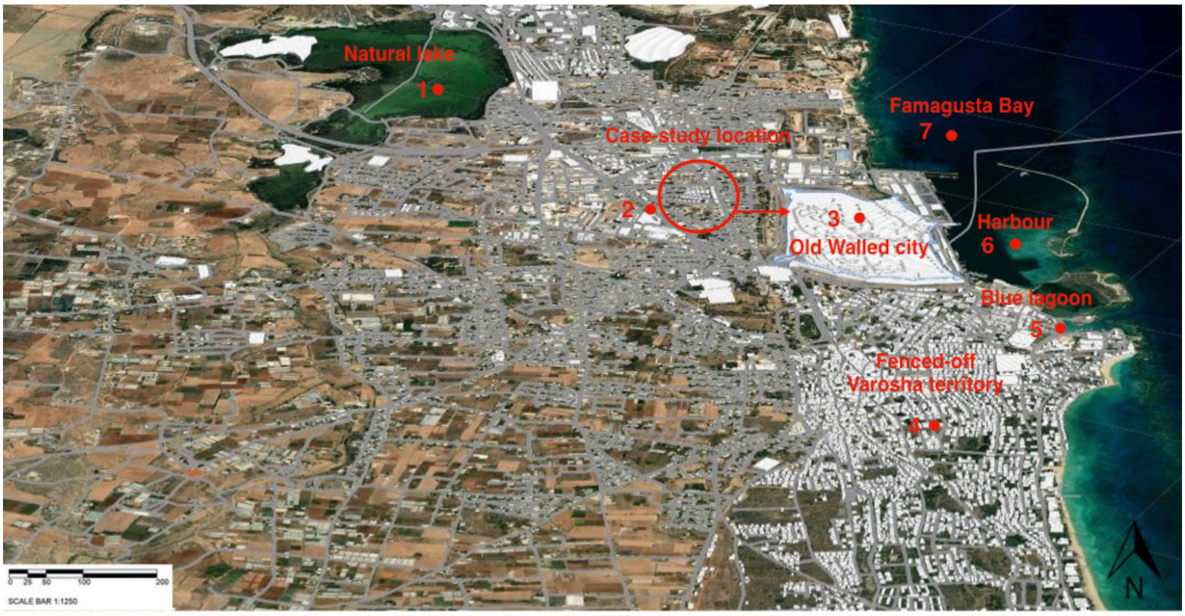


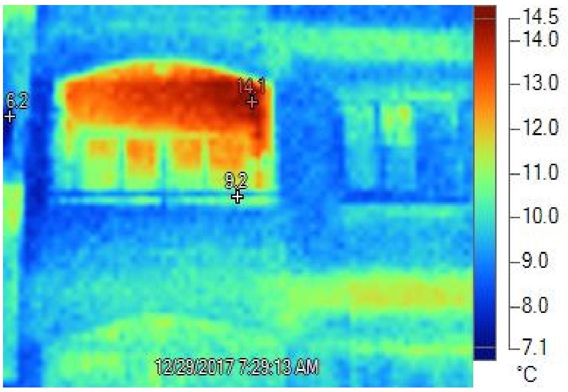
Figure 5.4(a): Location of urban-built social-housing estate and proximity to Old Walled city.

Figure 5.4(a) shows the location of the archetype buildings, which represent 38% of the housing stock in Northern Cyprus (NC). The social-housing estate is located 900 m away from the fortifications of the Old Walled city, which is surrounded by 18-metre walls and several historic towers with heights up to 32,5 metres; this urban-fabric feature provides constraints in terms of minimising the penetration of prevailing winds and direct summer breezes from the Mediterranean Sea. It should be emphasised that the built-environment features also impact occupants' thermal comfort, which has previously been explored by scholars (Dartevelle *et al.*, 2021; Gao *et al.*, 2021; Yang *et al.*, 2021).

Anecdotally, in the questionnaire survey, one interviewee who lived in a first-floor northeast-facing RTB commented that there was insufficient natural ventilation due to the close proximity of these urban blocks and that the height of the city walls caused an overheating risk. Another interviewee in a fourth-floor northeast-facing RTB indicated that they were very satisfied with the effectiveness of the natural ventilation to acclimatise their indoor-air environment in the summer, because they received good-quality summer breezes from the sea; this participant reported that they relied on their wall mounted air conditioning (A/C) system and a gas cylinder to heat their rooms in the winter. Figure 5.4(b) presents a map of the social-housing estate to aid in the discussion of the thermal-imaging survey findings in which the different RTB orientations were taken into account.

Figure 5.4(b): Locations of participating RTBs for street-by-street thermal-imaging survey to diagnose thermal anomalies in building-fabric elements.

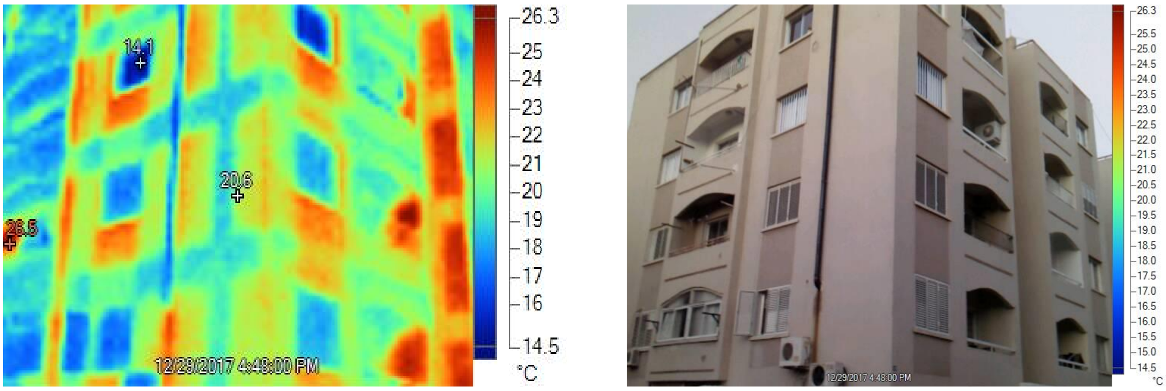
The walk-through thermal-imaging analysis examined temperature differences and variations across each RTB building envelope and potential thermal anomalies. This process validated the thermal performance of the buildings, overheating risk assessment and domestic-energy use by triangulating the research methods with the energy bills of each household and the BES analysis that was previously recommended by scholars who researched energy and thermal comfort (Defruyt *et al.*, 2013; Mahmoud *et al.*, 2019). To examine the building-energy performance gap caused by household modifications to the building envelope, a series of images from the living room and kitchen balcony were recorded to document the various refurbishment activities. Figures 5.5(a) through (k) provide details of thermographs of the base-case representative buildings that were conducted.



(a) **(b)**

Figure 5.5: (a) Heat acclimatisation on southeast-facing RTB balcony area (P2-B23); **(b)** photograph of large glazed windows of converted balcony area with closed internal blind.

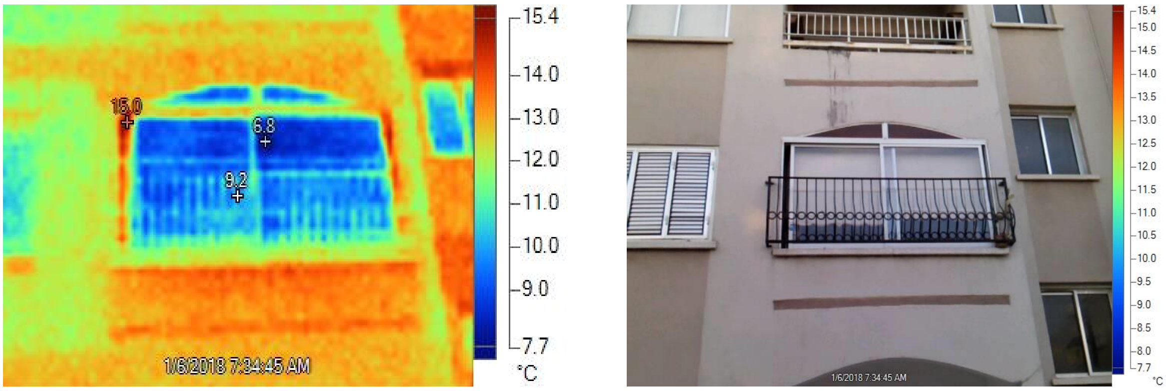
Building-envelope surface temperatures of the southeast-oriented RTB shown in Figure 5.5(a) ranged between 7,1–14,5°C, and these units experienced heat loss through the external wall, possibly due to the absence of insulation material; the thermograph image was taken on December 29, 2017 between 06:30–07:30, when the outdoor temperature was recorded at 10°C. Occupants in these units installed large, glazed windows and an aluminium external-shutter system to avoid incoming solar radiation; a photograph of these modifications is shown in Figure 5.5(b). Throughout the *on-site* observations, it was noted that this was the most common refurbishment effort that occupants implemented to avoid incoming sun, acclimatise indoor-air temperatures and lessen noise pollution.



(c) **(d)**

Figure 5.5: (c) Heat loss of concrete-made southeast-facing RTB due to absence of insulation materials and various structural issues (P1-B6); **(d)** photograph of wood-burning stove service shaft installed by first-floor occupants.

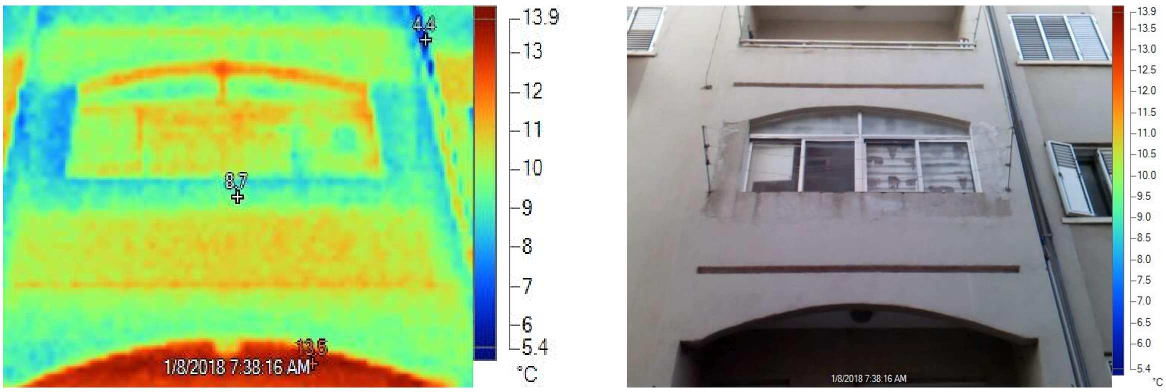
Building-envelope surface temperatures of the northeast-oriented RTB shown in Figure 5.5(c) ranged from 14,5–26,3°C, and this building exhibited significant heat loss through the windows, wall-junction details and cracks on the building surface; the thermograph image was taken on December 29, 2017 between 16:30–17:00, when the outdoor-air temperature was recorded at 10°C. Figure 5.5(d) is a photograph of the wood-burning stove and heating system installed by occupants, because these units did not have a central-heating system due to the absence of a natural gas system infrastructure in Cyprus; this led to significant heat loss, which suggests that this type of housing stock is susceptible to overheating in the summer. In addition, these households installed mechanical ventilation shafts for their wood-burning stoves, but failed to consider the health implications, and the close proximity of these shafts to the A/C compressor damaged the building envelope and resulted in significant heat loss.



(e) **(f)**

Figure 5.5: (e) Heat loss through large glazed windows of converted balcony space in southwest-facing RTB (P2-B20); **(f)** photograph of refurbishment articulated by second-floor occupants.

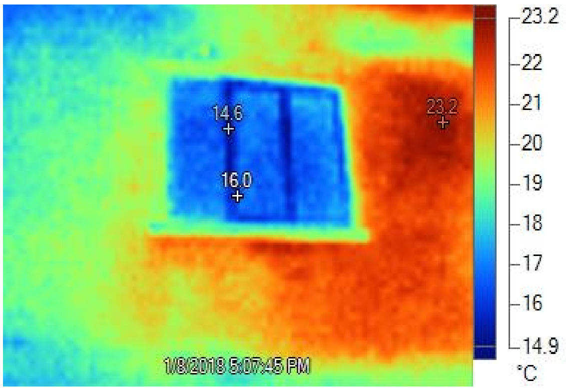
Building-envelope surface temperatures of the southwest-oriented RTB shown in Figure 5.5(e) ranged between 7,7–15,4°C, and this structure demonstrated heat loss through the external wall and the windows; the thermographic image was taken on January 6, 2018 between 06:30–07:45, when the outdoor-air temperature was recorded at 10°C. Most of these households installed operable double-glazed window systems that covered the balcony areas to adjust the frequency and effectiveness of natural ventilation and increase the living room floor area. The Figure 5.5(f) photograph shows this refurbishment, and that these occupants also utilised internal roller blinds in the summer to minimise sun exposure.



(g) **(h)**

Figure 5.5: (g) Heat loss of southwest-facing RTB kitchen extension (P2-B18); **(h)** photograph of refurbishment activity articulated by third-floor occupants.

Building-envelope surface temperatures in the southwest-orientated RTB shown in Figure 5.5(g) ranged between 5,4–13,9°C, and this structure exhibited heat loss through the external wall; the thermographic image was taken on January 8, 2018 between 06:30–07:54, when the air-temperature was recorded at 9,4°C. The detected thermal anomalies were possibly due to the small kitchens in these units; motivated by limited floor area and inadequate meal-preparation, most of the surveyed households had refurbished balcony areas of their kitchen spaces, and these modifications led to significant heat loss through the wall surfaces. The Figure 5.5(h) photograph shows occupant refurbishments to the kitchen space at balcony enclosure with large glazed window openings.



(j)

(k)

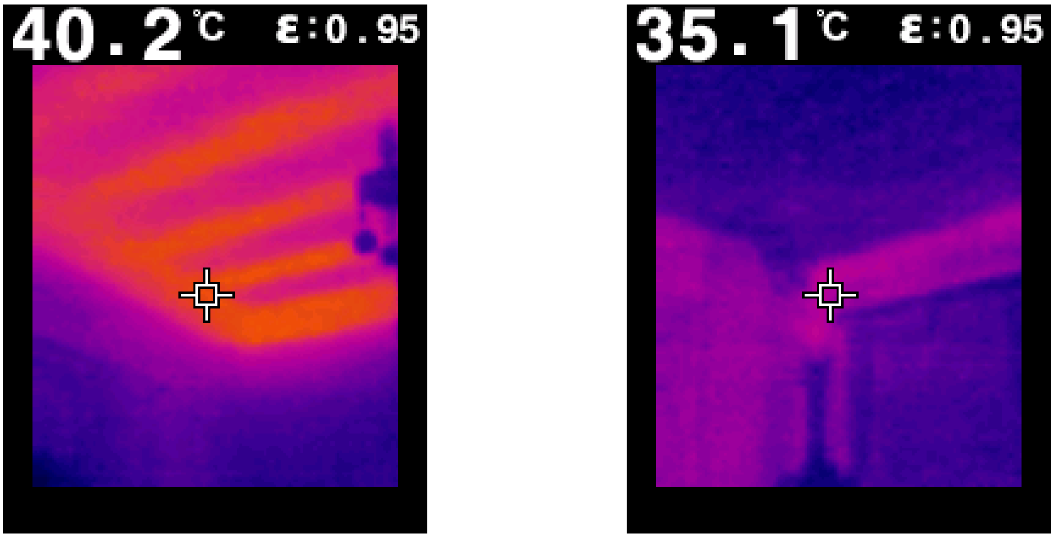
Figure 5.5: (i) Heat absorptivity of south-facing corner block (P2-B13); **(j)** aluminium-framed shutters installed on first-floor flat.

Building-envelope surface temperatures of the south-facing RTBs shown in Figure 5.5(j) ranged between 14,9–23,2°C, and these units experienced heat loss through external wall; the thermographic image was taken on December 28, 2017 between 17:00–17:34, when the outdoor-air temperature was recorded at 10°C. The recorded heat loss was possibly due to a crack in the wall surface. The Figure 5.5(k) photograph shows aluminium-framed window shutters that were installed in the southeast-facing buildings. This was a popular refurbishment which has caused high absorptivity of solar radiation both in winter and summer.

The survey results for the base-case RTB buildings demonstrated that most heat loss resulted from air infiltration, primarily through uninsulated exterior walls and windows, which necessitated a high annual energy demand for heating and cooling purposes across the surveyed RTBs. Notably, this section only discussed a small selection of the experiment images; the full findings were tabulated into spreadsheets to assess the overheating risk of each RTB while evaluating building-energy performance and are presented in **Appendices C.1** through **C.9.**

5.1.2 In-Situ Measurements: Walk-In Survey

To validate the BES findings, which revealed the overheating risk of different indoor occupied spaces, thermography measurements were taken with a FLIR thermographic camera to assess the thermal behaviour of the construction materials for the base-case RTBs. This method validated the IRT survey that was conducted between July 28, 2018 and September 3 of the same year, which concurrently investigated the degree of thermal discomfort when the *on-site* questionnaire survey was administered; a total of 118 flats were inspected with this technology. Figures 5.6(a) through (f) illustrate the recorded temperature readings and demonstrate the detected thermal anomalies of the different building envelopes.



(a) **(b)**

Figure 5.6: (a) High solar transmittance of ceiling surface of top-floor flat (measurement recorded when all windows were closed); **(b)** heat acclimatisation of third-floor living room space (measurement recorded when balcony door and two side windows were open).

Figure 5.6(a) shows the thermal performance of the living room ceiling surface of a top-floor southwest-facing flat, which was measured at 40,2°C; this image was taken on August 10, 2018 at 17:35, when the outdoor-air temperature was recorded at 36°C, and confirms that these roof surfaces absorbed a high level of solar radiation due to a lack of insulation on the building envelopes. Figure 5.6(b), which was taken at the same time as the thermal image reading in the previous figure, illustrates the thermal performance of the kitchen side-wall surface of the same flat, which was measured at 35,1°C. These images reveal the overheating risk for the living room and kitchen due to high transmittance of building properties and local climate conditions; notably, the windows in the living room and kitchen spaces were kept open 6–8 hours every day in the summer.

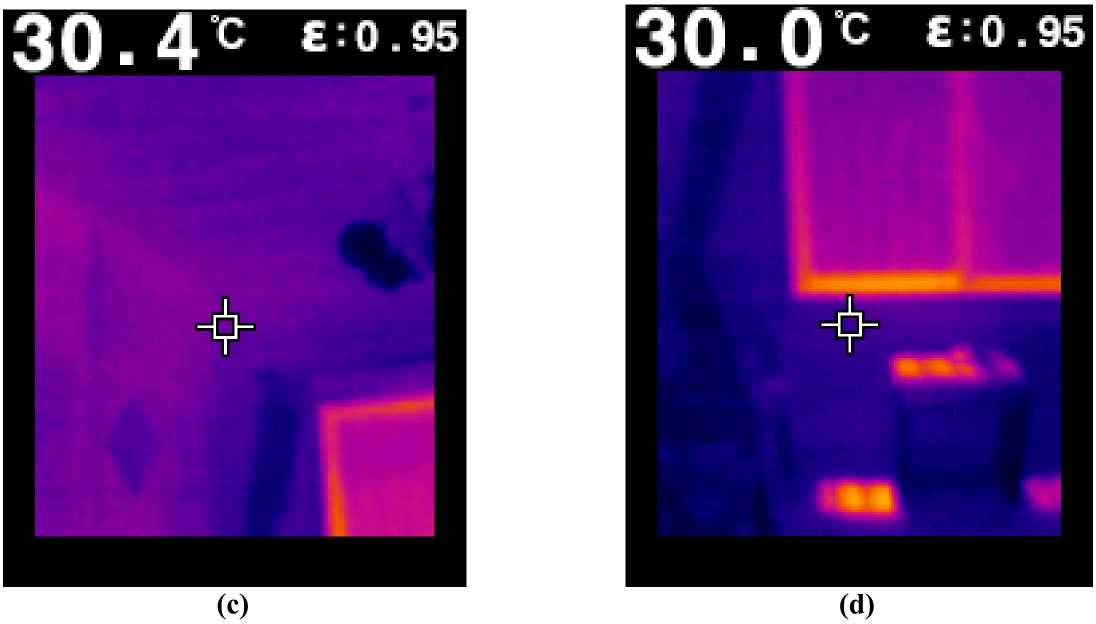
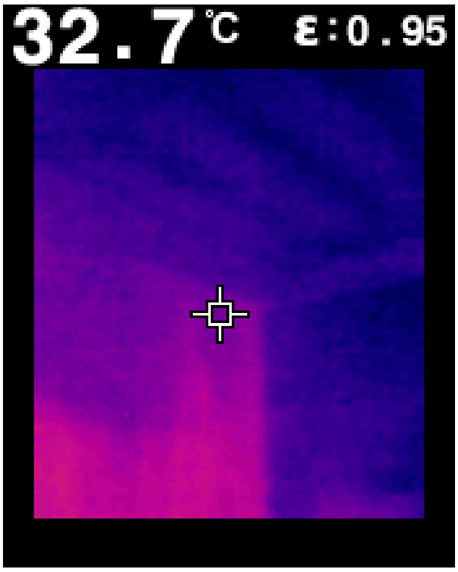
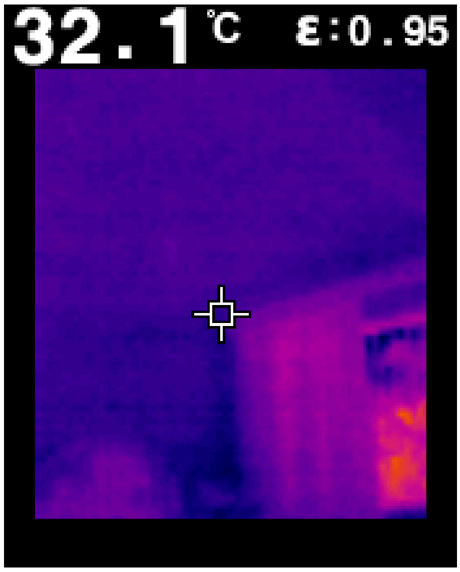


Figure 5.6: (c) Heat acclimatisation of living room air environment when wall-mounted A/C system in use; **(d)** high transmittance of aluminium single-glazed windows.

Figure 5.6(c) depicts the thermal performance of the living room ceiling surface of the southeast-oriented intermediate-floor flat, which was measured at 30,4°C; this image was taken on August 1, 2018 at 10:05, when the recorded outdoor temperature was 29°C. At the time of the thermography survey, the wall-mounted A/C system was set at 19°C and had been in use for approximately two hours. Thermal anomalies of regular shapes and clearly identified boundaries were associated with the underlying structure, and temperature-distribution within this pattern was demonstrated; this image reveals an area of the ceiling from the flat that was located above this unit, which had high *U*-values. Figure 5.6(d), which was taken at the same time as the thermal image reading in the previous figure, reveals the thermal performance of the living room side wall of the same flat, which was measured at 30°C. Significant heat gains through the aluminium-framed single-glazed windows were recorded. Furthermore, air leakage caused thermal anomalies with irregular shapes, and large temperature variations that formed characteristic 'streaks' or 'ray' patterns were detected.



(e)



(f)

Figure 5.6: (e) Heat acclimatisation of living room space in first-floor flat; **(f)** heat absorptivity of corner junction details of ground-floor flat.

Figure 5.6(e) illustrates the thermal performance of the living room ceiling surface of a south-facing first-floor flat, which was measured at 32,7°C; this image was taken on August 16, 2018 at 09:25, when the outdoor-air temperature was recorded at 29,7°C. The living room windows were open for natural ventilation at the time of the thermography survey. Similar anomalies to those in Figure 5.6(c) that were caused by construction flaws were detected on the ceiling surfaces, and the thermography survey also captured heat gains through the large glazed opaque window surfaces in the enclosed balcony space; it was concluded that this structural modification led to a 2–3°C increase in indoor-air temperatures. Figure 5.6(f) shows the thermal performance of the living room ceiling surface of a southeast-oriented ground-floor flat, which was recorded at 32,1°C; this image was taken on August 1, 2018 at 11:25, when the outdoor-air temperature was recorded at 30,1°C. At the time of the thermography survey, a portable fan was in use and the windows were open; a significant thermal anomaly was detected on the aluminium-framed single-glazed window structure.

The indoor walk-through thermography surveys determined that all 36 participating RTBs and 118 flats exhibited signs of thermal anomalies, which were characterised as either air leakages or heat conductivity. Figure 5.7 illustrates the overheating-risk mapping of the selected flats to provide an overall understanding of the thermal vulnerability of social-housing stock.

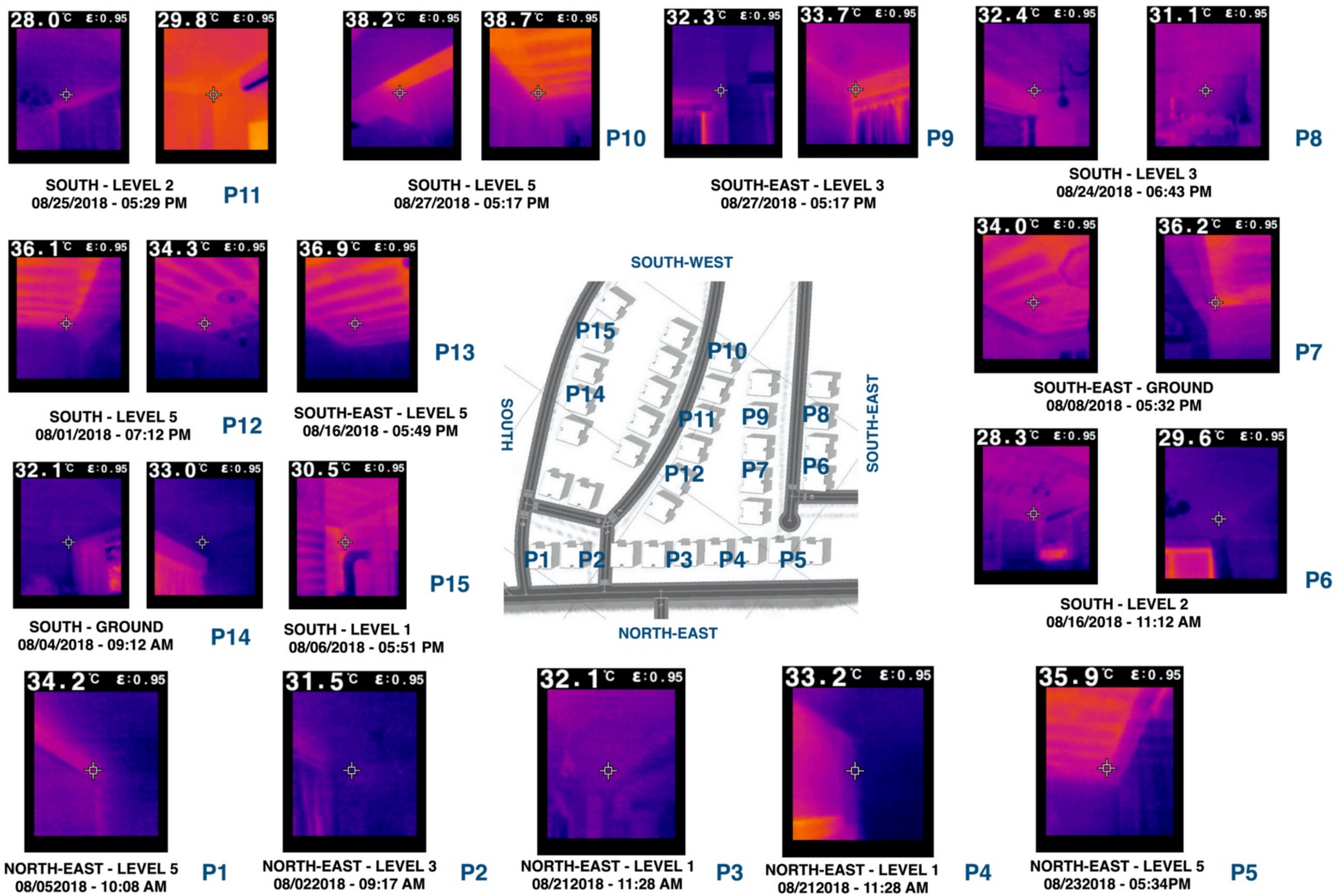


Figure 5.7: Point-by-point mapping of indoor walk-through thermal-imaging survey conducted while questionnaire survey was administered, taking different floor levels and impact of different time of day on overheating risk assessment into account.

In-situ measurements of the indoor-air environments were conducted to understand the impact of the building thermal properties on overheating risks and the occupants' thermal comfort; the results are shown in Figure 5.7. It should be noted that the use of a solar-mask form of adaptation to the physical environment, which directly influenced the occupants' psychology when their thermal sensation votes (TSVs) were assessed with the *on-site* environmental monitoring through the questionnaire survey (Lassen *et al.*, 2021). The solar radiation readings of the building envelopes and the time-of-day factor were also examined to avoid research bias related to the generated results that are presented in Chapter 6, and the results are shown in Figure 5.8.

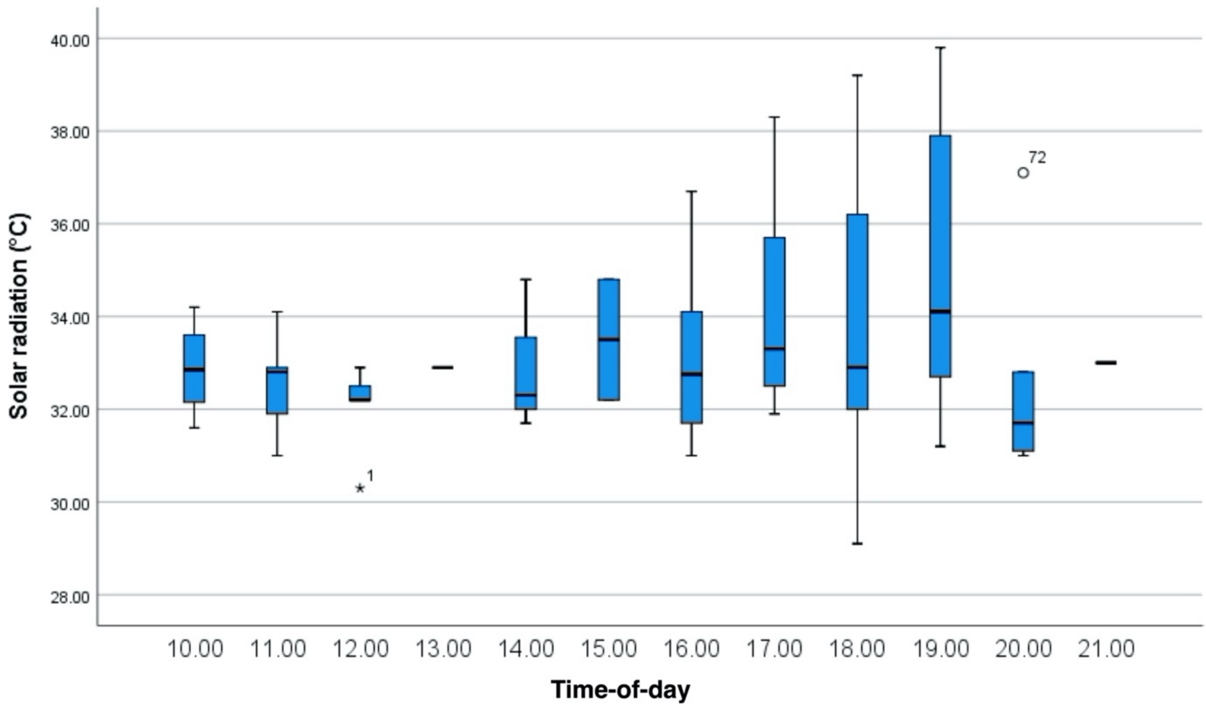


Figure 5.8: Distribution of associations between solar radiation *(measured)* and time-of-day *(measured)*.

The building-envelope temperatures shown in Figure 5.8 ranged between 29.1–39.8°C; these were recorded on July 27, 2018 and September 3 of the same year between 10:00–21:00, when the *on-site* questionnaire survey was conducted. Most of the scatter dot lines are positioned between 17:00–20:00, because 73% of the households were recruited in the afternoon; this was intentionally done to increase the sample size. Even though the ASHRAE 55 standards (2017) recommend an optimum thermal-comfort temperature of 25°C, according to the *in-situ* measurements findings, indoor-air temperatures during the survey period were never below 29,1°C; it should be noted that 27% of the flats were surveyed late in the morning, when indoor-air temperatures fluctuated between 29,1–34,1°C. These results revealed that the building-envelope *U*-values were a determinant factor of the heat vulnerability of the recruited RTBs.

Indoor walk-through surveys of the base-case representative flats were conducted to identify potential defects and provide a basis for information that would be needed for the BES studies – as shown in Figure 5.9; when the survey results were compared, few differences that were recorded in the walk-through inspections were attributable to the orientations or floor levels of the flats.

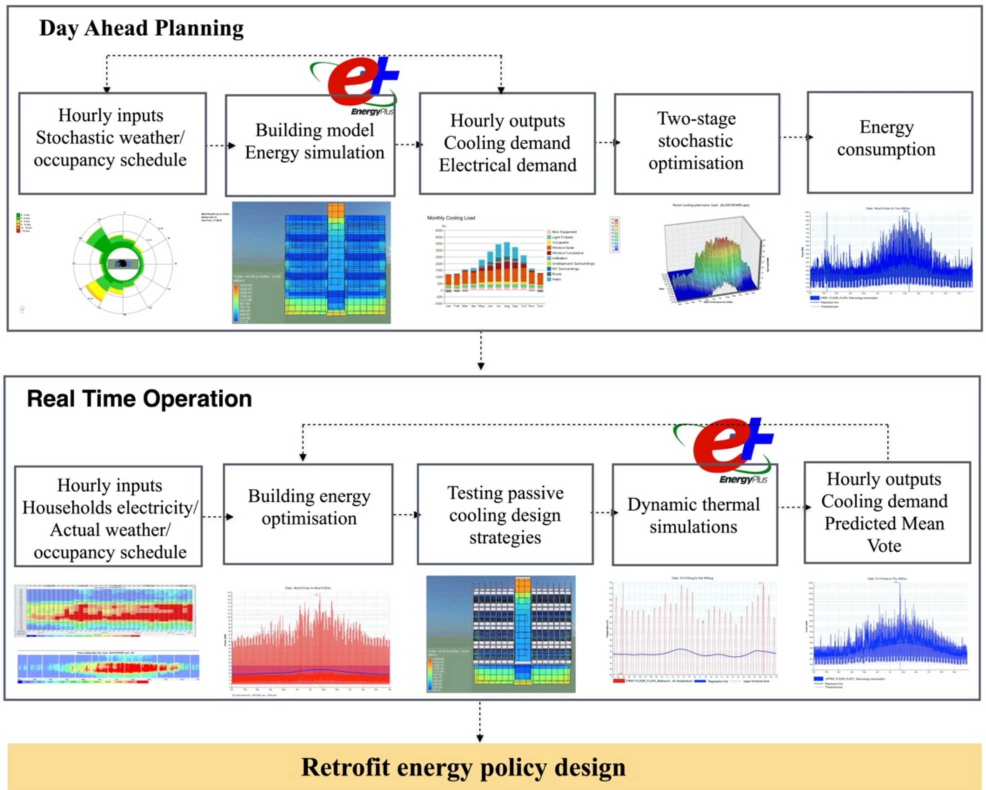


Figure 5.9: Aggregated data to develop set-input parameters for the building energy simulation stage of this study.

Notably, no moisture-related anomalies or service faults were detected. Further observations revealed that only a few of the surveyed flats experienced structural draughts and that a majority of ventilation defects were because of windows; this could be due to the thermal conductivity of the aluminium-framed single-glazed windows, compared to that of the doors, and a flawed seal between the windows and window frames that was documented. Similarly, conductivity heat loss was the most common building defect observed across the sample; significant heat loss was likely due to uninsulated roof surfaces, and additional heat loss was recorded through the walls, windows and doors.

5.2 Building-Performance Evaluation

The SunCast software interface tool was implemented in the building-modelling simulation to assess the amount of solar radiation that was absorbed by any given external surface of the prototype RTB, based on the orientation thereof and the effects from adjacent buildings, as shown in Figure 5.10. The SunCast simulation module was used to validate the qualitative and quantitative analyses of the survey findings that were obtained from the thermal-imaging survey. *on-site* observations and *in-situ* physical measurements before the DTS studies were conducted for the purpose of black-box model development.

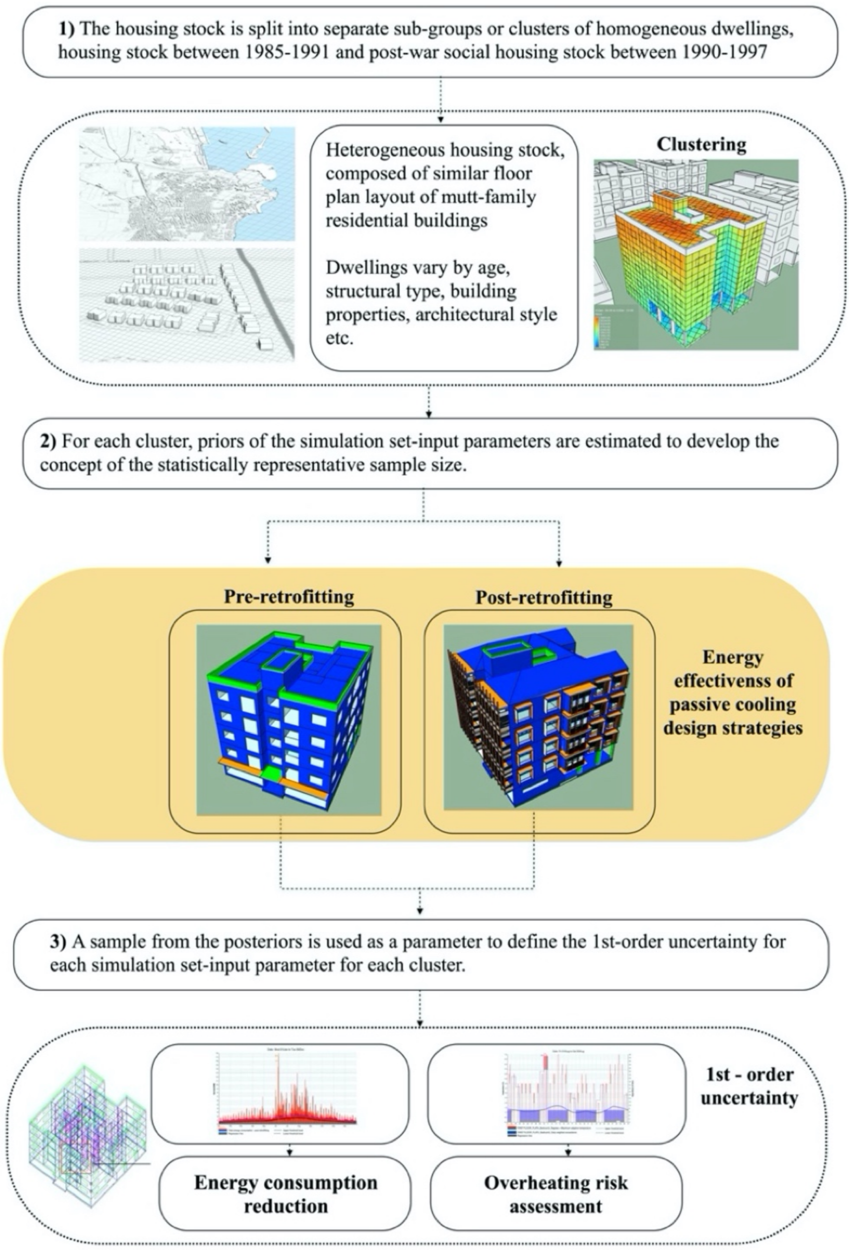
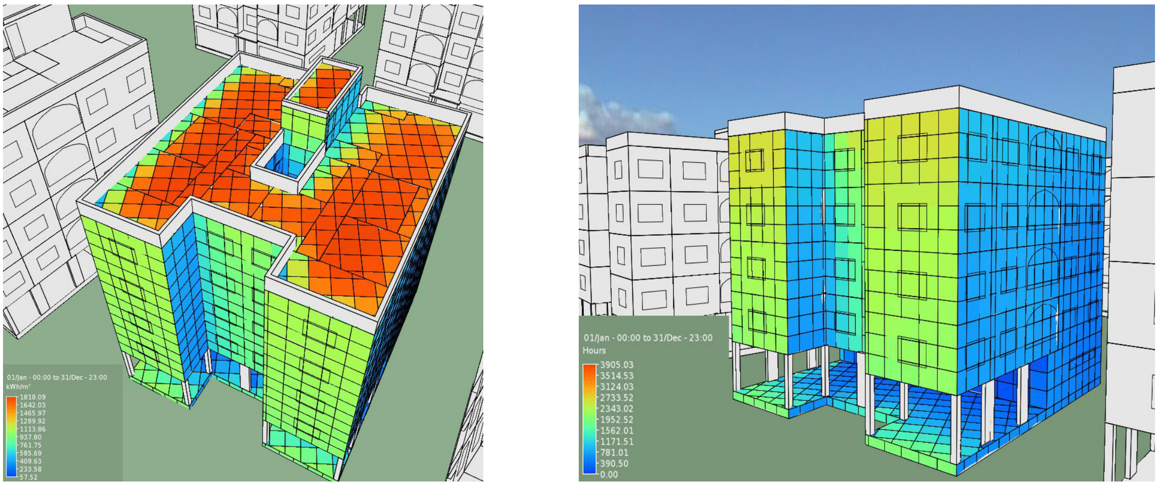


Figure 5.10: The selection of national representative post-war social housing stock, archetype RTBs' retrofitting stages and its outcomes on domestic energy use and building performance evaluation.

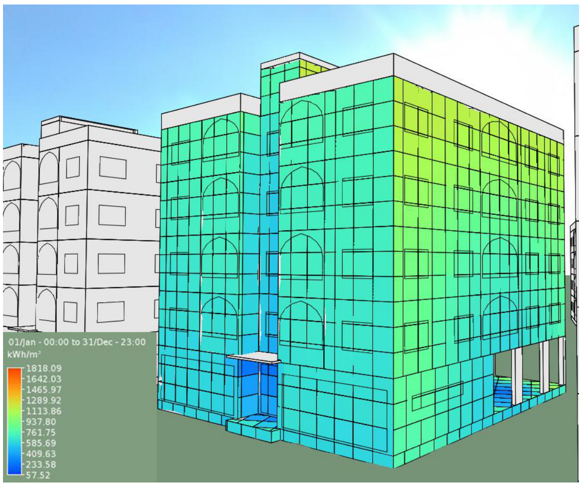
The solar-exposure analyses were divided into three stages to fully understand the impact of the building envelope on the overall energy performance of the social-housing stock. The first stage was carried out for the entire building simulation between January and December of 2018; the second phase was undertaken between May and September of 2018, which is the cooling period that was recommended by the CIBSE TM59 standards to assess the overheating risks in residential buildings; and the final phase focused on the peak cooling month of August of 2018 to provide a basis to compare the simulation results with the survey findings. Figures 5.11(a) through (f) show the maximum solar radiation and mean values of the three analyses that were adopted for the worst-case scenario of the south-facing RTB.



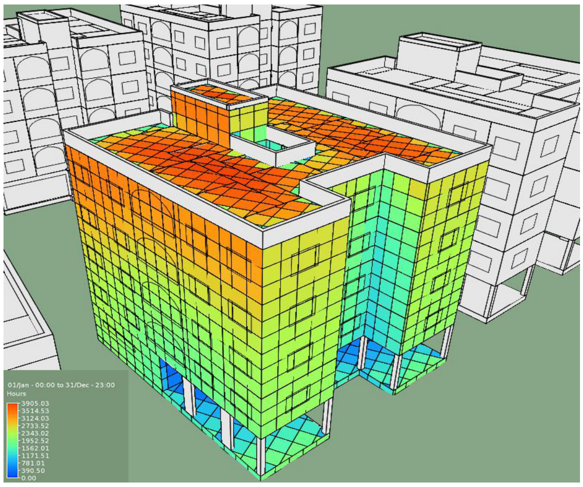
(a) **(b)**

Figure 5.11: Step-by-step solar-exposure analysis of south-facing prototype RTB for worst-case scenario: **(a)** High solar radiation absorbed on uninsulated roof surface; **(b)** mutual-shading-impact factor from adjacent RTBs that minimised direct sunlight on building.

The SunCast simulation analysis in Figure 5.11(a), which shows the positions of Bedroom 2 and Bedroom 3 in the southeast-oriented RTBs, revealed that between January and December of 2018, annual maximum-conduction gains due to higher absorptivity were characterised by a high-transmittance roof construction with a *U*-value of 1.20 W/m^{2}K; and the deficient building surfaces absorbed 1.818,09 kWh/m^{2}K. The southeast- and southwest-oriented façades shown in Figure 5.11(b) experienced 3.905,03 hours of solar-radiation exposure between January and December of 2018, and the mutual shading factor from the adjacent building significantly affected the southwest-oriented building façade.



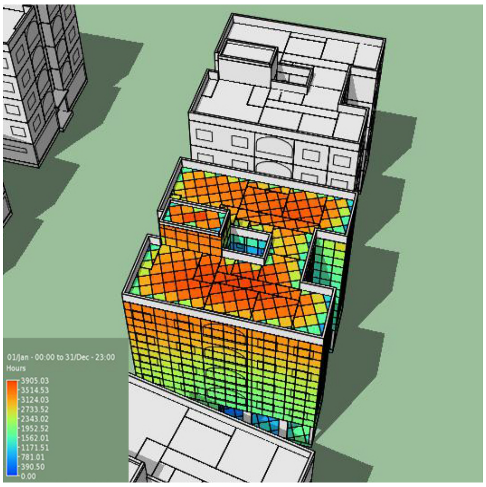
(c)



(d)

Figure 5.11: (c) Mutual-shading-impact factor of adjacent RTBs; **(d)** high absorption of solar radiation, due to RTB orientation and lack of insulation materials and water-proofing system.

According to Figure 5.11(c)—which shows where the living room spaces are positioned in RTBs with a south-oriented front façade, and where the living room, kitchen, Bedroom 1 and Bedroom 2 spaces were positioned in southeast-oriented flats—annual maximum conduction gains due to higher absorptivity were characterised by high-transmittance external wall construction with a *U*-value of 3.47 W/m^{2}K, and the high transmittance *U*-values of the building surfaces absorbed 1.818,09 kWh/m^{2}K between January and December of 2018. The southeast-oriented façades shown in Figure 5.11(d) experienced 3.905,03 hours of solar-radiation exposure between January and December of 2018; it is evident from these figures that the upper floor of the southeast-oriented unit absorbed a particularly high level of solar radiation throughout the year.



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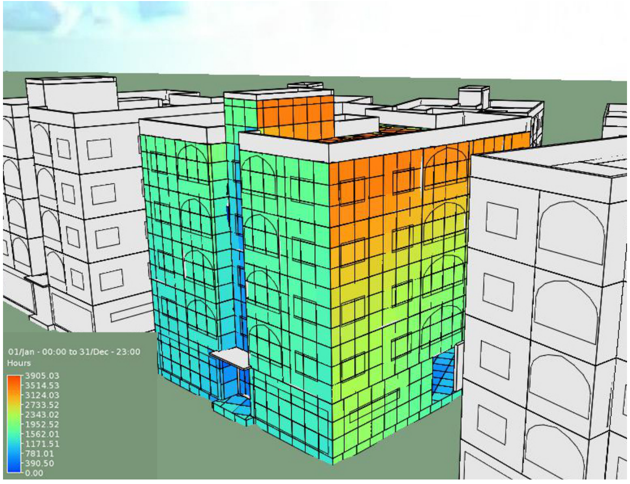


(f)

Figure 5.11: (e) High solar transmittance of roof surfaces and southeast-facing building envelopes; **(f)** graphic showing susceptibility of upper-floor flats to high risk of overheating in the summer.

Between January and December of 2018, the south- and southeast-facing exposed surfaces shown in Figure 5.11(e) absorbed high levels of solar radiation due to the high transmittance of the building *U*-values, and occupants in the upper-floor flats of these RTBs experienced thermally uncomfortable indoor-environment conditions; the SunCast simulation for the building analysis validated the results of the thermography walk-through survey in the winter and the *in-situ* measurements that were recorded in the summer to prove overheating risk of RTBs' building envelopes. The southeast-facing façade depicted in Figure 5.11(f) experienced 3.905,02 hours of solar-radiation exposure between January and December of 2018; this figure reveals the significant effect of orientation and distance from adjacent buildings on home-energy performance.

Only three external surfaces were exposed in Figures 5.11(a) through (f), and all three exhibited different heat gains throughout the year due to poor insulation in the exposed wall, with noted exacerbations in the summer, which created overheating risks. Upper-floor flats demonstrated the greatest risk of overheating due to the impact of the *U*-values of the building envelopes and the solar panels for the hot-water tanks that were placed on top of the original surface; for this reason, all bedroom spaces in the upper- and intermediate-floor flats experienced a greater likelihood to overheat, compared to the CIBSE TM59 overheating criteria (CIBSE, 2017). It was determined that the living rooms of these flats were also susceptible to overheating, but this was because of different factors: The rooms had significant window-opening ratios with no shading, and the spaces all faced either south or south-east and were therefore exposed to high-intensity sunlight throughout most of the day; the external walls, which were constructed from brick and exterior rendering without insulation, were also exposed to high solar-heat gains. A combination of these factors led to overheating issues and significant occupant discomfort, especially in the summer.

The field-survey findings revealed that most of the south-facing RTBs and upper-floor flats experienced high indoor-air temperature ranges that were above the 28°C upper threshold comfort limit (CIBSE, 2017); notably, participants were recruited at different times of the day, which directly influenced their TSVs and thermal preference votes (TPVs). This determinant factor was taken into consideration to identify the most accurate findings for the building-performance evaluation that was conducted in the present study (Weinberger & Mosfegh, 2021). The findings of the building-energy simulations were developed based on this technical detail, which was neglected by previous scholarly work related to thermal comfort (Lei *et al.*, 2021; Pungercar *et al.*, 2021). A statistical analysis was undertaken between the time of day and the *on-site* environmental monitoring conditions to concurrently validate the overheating risk and the occupants' TSVs that were gathered through the questionnaire survey that is described in Chapter 4. The impact of outdoor environmental conditions on the overheating risk of buildings is shown in Figure 5.12.

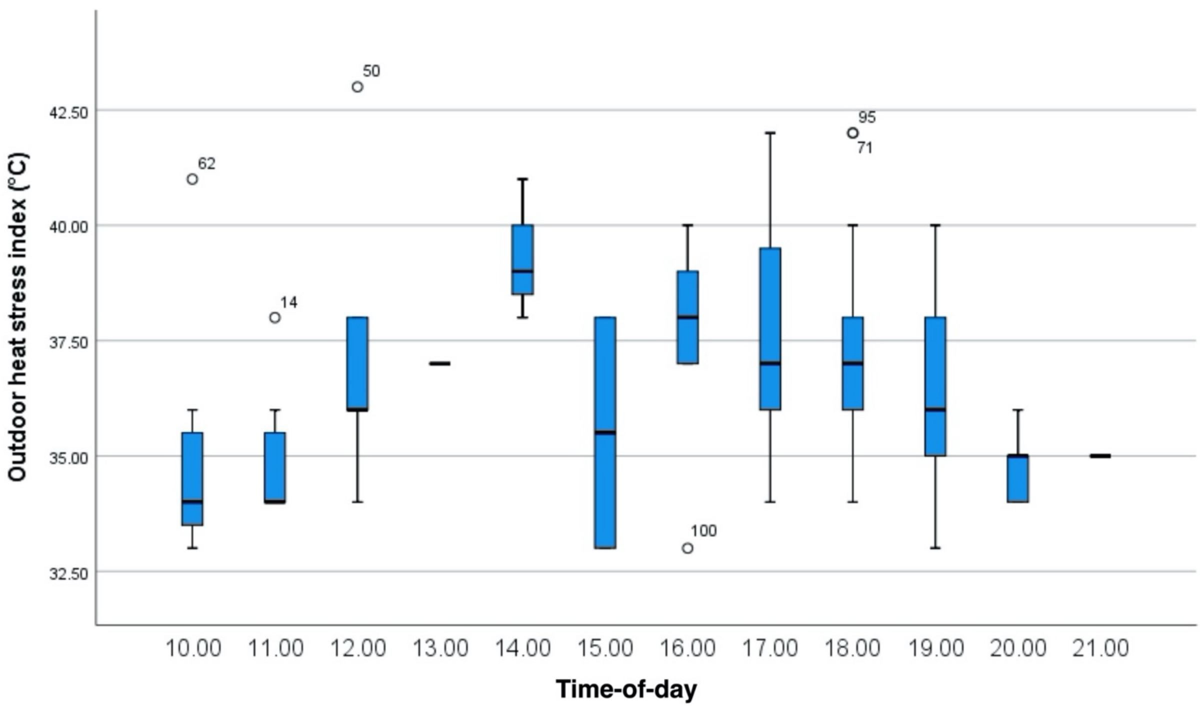


Figure 5.12: Associations between heat stress index factor *(monitored)* and time-of-day *(measured)*.

Figure 5.12 illustrates the monitoring period for the case-study location, where thermal comfort should be between 23–25°C; on the first day that data were recorded, the outdoor heat-stress index reached 30°C, which demonstrates that local climate conditions are determinant factors for the indoor-air environment (Maggiotto *et al.*, 2021). This high temperature trend fluctuated with high and low peaks, but it was always above Criterion 1 (i.e., percentage of hours above 33°C) (CIBSE, 2017). This reveals a pattern that is similar to outdoor-air temperature fluctuations, even though the outdoor temperatures were much higher; this is due to the long-lasting heatwave period that enveloped the European continent in the summer of 2018 (Khan *et al.*, 2021).

The highest thermally uncomfortable heat-stress factor of 39°C was recorded between 16:45–18:45, while the highest overall heat-stress index temperature of 42°C was recorded between 17:45–18:15. The lowest heat-stress temperature of 33°C, which showed no sign of overheating risk, was recorded between 10:15–19:45. Notably, the occupants' TSVs indicated that the 'neutral' temperature was 28,5°C, and the upper limit of the comfort range for warm indoor-air temperature conditions was 31,5°C. These results suggest that the subject participants were able to tolerate high-temperature environmental conditions (Abokersh *et al.*, 2021).

In Figure 5.12, the outdoor heat stress index *on-site* measured environmental parameters are presented by considering the time-of-day factor to assess the overheating risk of buildings. To provide an accurate analysis method for interpretation, the results were presented using a quartile division of time; this allows presentation of actual environmental conditions monitored. In the representation on the bar chart, however, the integer time factor was presented to keep consistency within the presented findings.

5.3 Discussions

This section provides a discussion of the findings of the present study to identify the knowledge gap related to the implementation of EPBD directives; to address climate change and the detrimental impact thereof on the overheating risk of buildings, the occupants' thermal comfort and the energy use of households; and to explore the novelty of a BES study that is integrated with an energy audit and thermal imaging, which is an area in which little research has been undertaken, as shown in Figure 5.13. Further benchmarking indicators are presented in **Appendix K**. The following discussion is structured according to the research question that guided the findings obtained through the field survey—specifically, (RQ-2) 'How this empirical study will contribute to and inform the design of net-zero energy buildings in the EU countries?'—to develop a universally acceptable energy-policy framework for the south-eastern Mediterranean Cypriot climate.

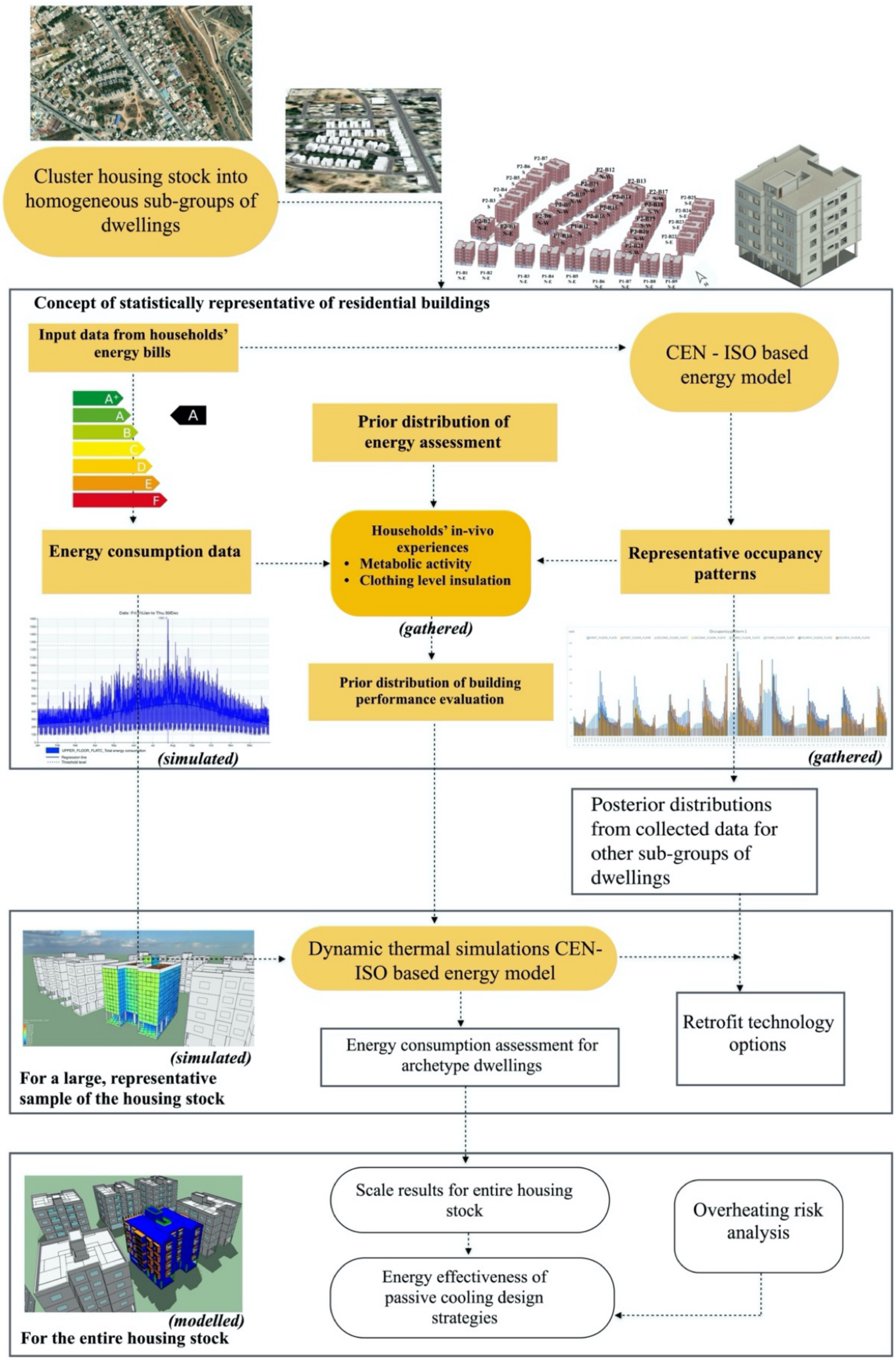


Figure 5.13: Identification of parameters measured and simulated to develop building energy simulation base-case model for the study.

The overheating risk within the living room spaces was evaluated using the static CIBSE TM59 overheating risk criterion and Fanger's dynamic adaptive thermal-comfort equation. Alterations were made to the base models to simulate the current building-fabric thermal performance and overheating that was experienced, and the corresponding changes that can be utilised to develop accurate black-box energy model set-up are discussed in Sub-Sections 5.3.1 and 5.3.2.

5.3.1 Impact of Building-Fabric Thermal Properties on Overheating Risk

This section presents the *in-situ* measurements of the building-fabric elements to validate the overheating risk of buildings and the degree of the occupants' thermal discomfort. To demonstrate the thermal performance of the RTBs, Figures 5.14(a) through (d) illustrate the heat loss of the different building envelopes.

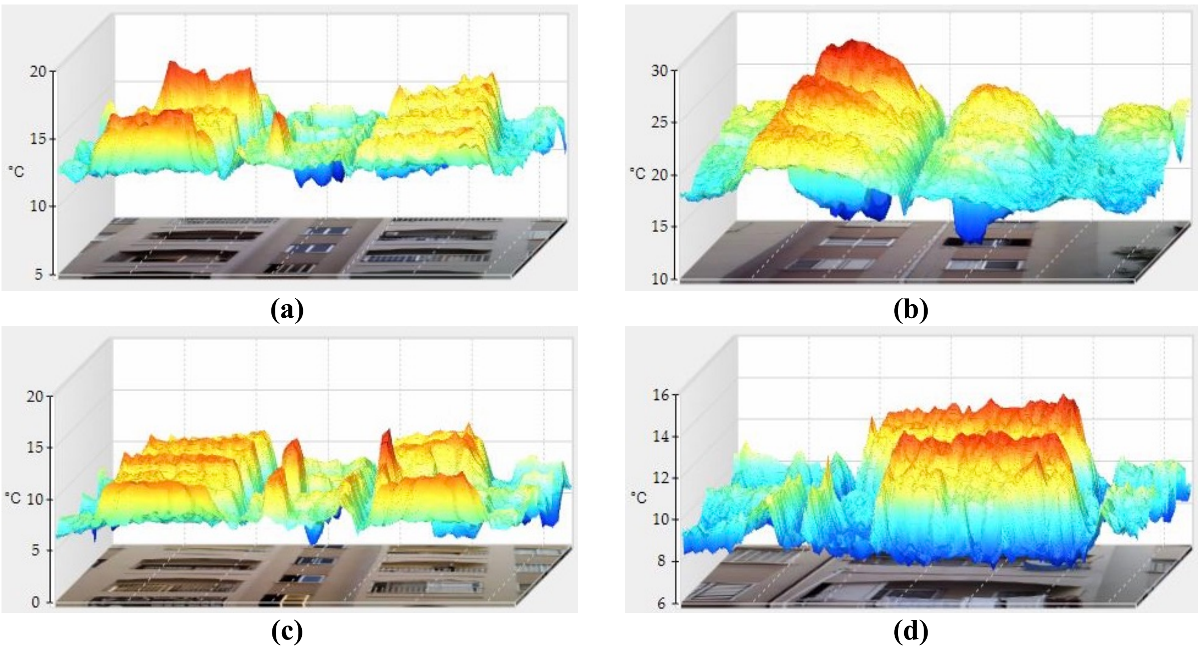


Figure 5.14(a) through (d): Sample of winter thermal-imaging analysis *(measured)*.

Figure 5.14(a) reveals that the living room balcony spaces of the southwest-facing RTBs accumulated heat with a maximum recorded temperature of 18°C at 06:45 on December 29, 2017; a maximum temperature of 32°C was recorded on the upper-level flat at 16:45 on the same day, as presented in Figure 5.14(b). Notably, warm winter weather conditions were observed at the time the thermal-imaging survey was conducted, which is why relatively high temperature readings were recorded, compared to typical Cypriot winter conditions.

According to Figure 5.14(c), heat accumulation in the living room balcony areas resulted in a maximum recorded temperature of 16°C at 06:55 on January 6, 2018. Figure 5.14(d) illustrates the side view of the southwest-facing RTB; the enclosed balcony spaces caused accumulated heat throughout the structure, which is why the enclosed balcony areas were susceptible to overheating in the summer. Furthermore, significant heat loss was observed through the external walls, which lacked any type of insulation material.

Results from the thermal-imaging analysis indicated three types of anomalies in the RTBs that were examined: thermal bridges, degradation of the building-envelope material and structural failure of the concrete-and-steel skeleton system. In the present study, the areas with the greatest heat loss were located at the connections between the junction details, especially the penetrations that were formed when doors and windows interrupted the façade. Damaged structural connections were observed at the corners of the RTBs where the walls met the floor, especially on the ground-floor flats and on the roof surfaces of the upper-floor flats.

Notably, significant heat loss was detected where the front façades (i.e., the living room spaces) of the south-, southeast- and southwest-facing RTBs met the corner of the construction junction. Most of the south-oriented flats showed signs of significant thermal loss in the winter, and it appeared as if these RTBs also demonstrated a greater risk of overheating in the summer. The *on-site*-measurement method allowed the worst-performing RTB to be identified so further energy-performance studies could be conducted in the building-modelling phase of the present study, which is described and discussed in Chapter 6.

The thermal transmittance of building-fabric elements, such as external walls, doors and windows and roofs, were considered in the present study to confirm that the local climate characteristics and the types of construction materials of buildings are vital components of energy consumption. These findings are supported by information related to the occupants' energy-use variations, which provided useful insights that will aid in the development of evidence-based retrofitting design interventions and increase the life-cycle span of buildings, as shown in Figure 5.15.

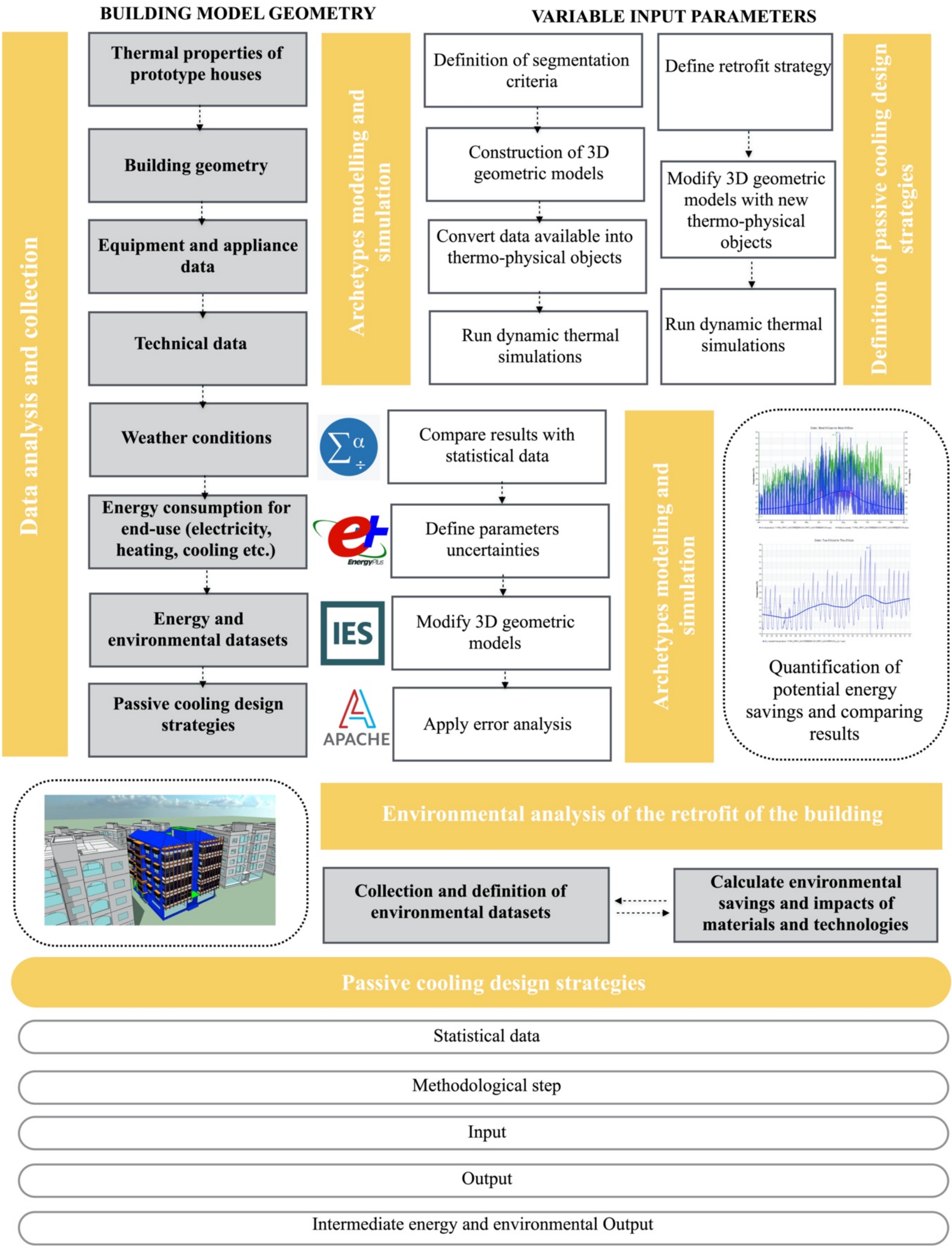


Figure 5.15: Building energy simulation parameters were developed as an outcome of building performance evaluation study.

5.3.2 Impact of Local Climate Conditions on Overheating Risk

This section presents the OTs of the living room spaces in the measured flats, which highlighted the significance of the different RTB orientations and floor levels on the occupants' TPVs and TSVs. Figures 5.16(a) and (b) illustrate the *in-situ* measurements of the surveyed flats, taking these factors into consideration.

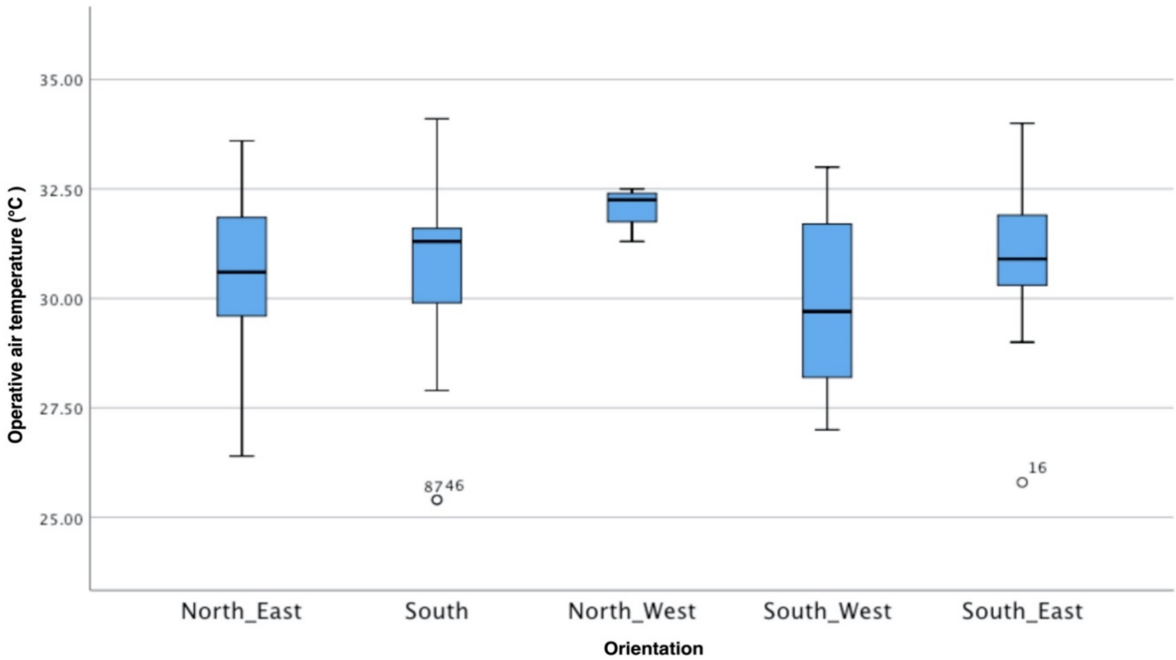


Figure 5.16(a): Distributions of measured OTs, taking different RTB orientations into account.

According to Figure 5.16(a), indoor-air temperatures during the summertime survey in the northeast-facing RTBs ranged between 26–33°C; temperatures in the south-facing RTBs ranged from 28–34°C; temperatures in the northwest-facing RTBs ranged between 31–32,5°C; temperatures in the southwest-facing RTBs ranged from 25–33°C; and temperatures in the southeast-facing RTBs ranged between 28–34°C.

The static method criteria outlined in *CIBSE Guide A* (2006) state that overheating is likely when the temperature in a room exceeds a threshold temperature for more than 1% of the occupied hours (i.e., bedroom threshold temperature is 26°C and living room threshold temperature is 28°C). The occupied hours of the inspected living room spaces were based on the questionnaire-survey findings to ensure that the accuracy of overheating risk measures was in line with the *on-site* monitoring of actual weather conditions (Mukhopadhyay *et al.*, 2021). Table 5.2 delineates the recorded operative-air temperature according to the different RTB orientations.

Table 5.2: *In-Situ* Recordings of Indoor-Environment Conditions of Representative RTBs.

		Percentiles		
	Orientation	**25th**	**50th**	**75th**
Weighted Average Operative Air Temperature (°C) *(measured)*	North-east	29,50	30,60	31,90
	South	29,85	31,30	31,60
	North-west	31,52	32,25	32,45
	South-west	28,20	29,70	31,72
	South-east	30,10	30,90	32,30

According to Table 5.2, the northwest- and northeast-facing RTBs experienced the highest levels of overheating within the 75th-percentile cluster group; this is likely due to the position of the RTBs and the properties of the buildings during the summer months. These findings were not limited to the local climate conditions; the occupants' habitual adaptive behaviour related to window opening and their occupancy patterns were also considered (Beckmann *et al.*, 2021; Etxebarria-Mallea *et al.*, 2021).

In the present study, 26% of the respondents used wall-mounted A/C systems, 28% used portable fans and 39% used a combination of the above cooling systems. Furthermore, 78% of the respondents closed their internal doors and windows when their wall-mounted A/C system was in use, and 20% kept their internal doors open and their windows closed when their A/C systems were in use. These variations provided a wide range of acceptable thermal sensations that influence an assessment of the impact of building-fabric thermal performance on overheating risk (Verbruggen *et al.*, 2019). Notably, occupants in the south-facing RTBs comprised the highest percentage (36%) of the total sample size; these prototype buildings were chosen to represent the overall thermal performance of the prototype RTBs and provide accurate information while assessing the overheating risk against the industry CIBSE TM59 industry benchmarks.

An adaptive approach is currently implemented in the EN 15251 international standard concerning thermal comfort, but it is usually considered to be an assessment method for the summer performances of naturally ventilated multi-family residential buildings (Dracou *et al.*, 2017; Piselli *et al.*, 2020). As such, inclusion of human-based approach has been neglected by previous thermal-comfort studies (Castaño-Rosa *et al.*, 2021). The findings of the present study will contribute to the development of adaptive thermal-comfort models on hot summer days in the Mediterranean region. To provide subsequent background information for the BES studies, the associations between operative-air temperatures and the different floor levels were also explored and are shown in Figure 5.16(b).

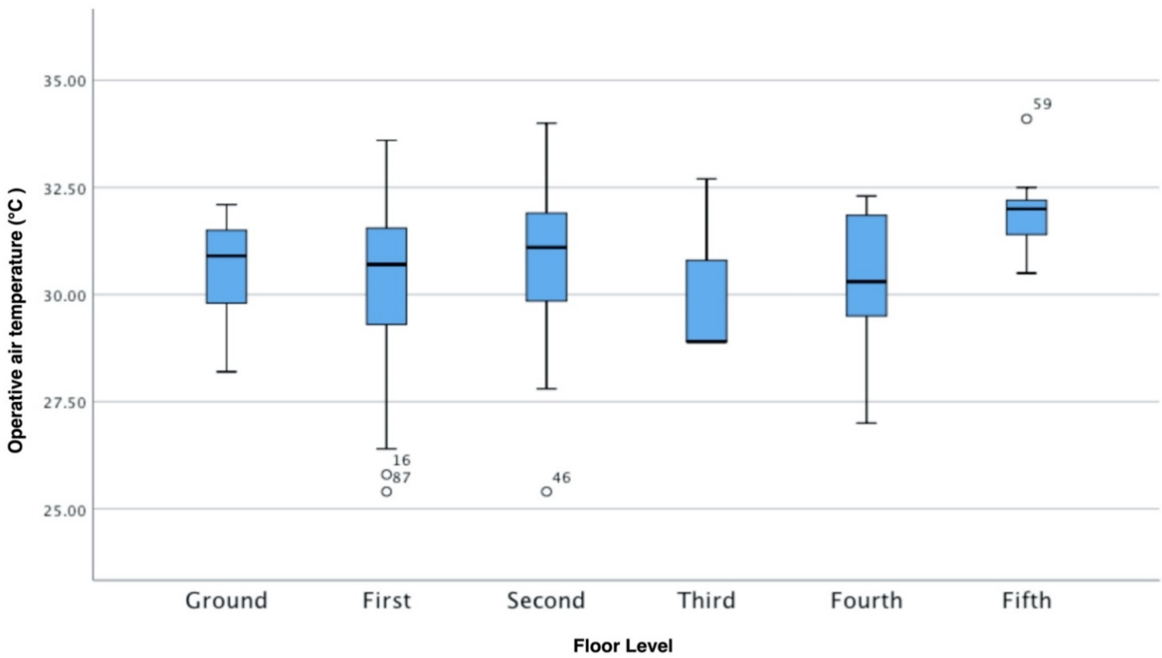


Figure 5.16(b): Distributions of measured indoor-air temperatures, taking different floor levels into account.

According to Figure 5.16(b), indoor-air temperatures in the ground-floor flats ranged from 28–32°C; temperatures in the first-floor flats ranged between 26–33°C; temperatures in the second-floor flats ranged from 28–34°C; temperatures in the third-floor flats ranged between 28–33°C; temperatures in the fourth-floor flats ranged from 26–32°C; and temperatures in the fifth-floor flats ranged between 31–32,5°C. Indoor-air temperatures recorded in the living room spaces of these units during the *on-site* environmental monitoring period exceeded the 28°C overheating threshold; and according to the *in-situ* physical measurements, the 25°C upper thermal-comfort threshold was regularly exceeded. It should be noted that similar indoor-environment conditions were also observed at a later time, when cooling systems were likely to have been switched on.

According to the questionnaire survey, 21% of the respondents turned on their cooling systems for 0–4 hours, 38% for 5–9 hours, 34% for 10–12 hours and 7% for more than 12 hours on weekdays. On the weekends, 20% of the respondents used their cooling systems for 0–4 hours, 24% for 5–9 hours, 34% for 10–12 hours and 22% for more than 12 hours. Table 5.3 presents the OTs that were recorded for each floor level.

Table 5.3: *In-Situ* Recordings of Indoor-Environment Conditions of Representative RTBs.

		Percentiles		
	Floor Level	**25th**	**50th**	**75th**
Weighted Average Operative Air Temperature (°C) *(measured)*	Ground	30,00	32,00	33,00
	First	30,25	32,00	33,00
	Second	30,00	33,00	34,00
	Third	28,90	32,00	—
	Fourth	30,00	32,00	34,00
	Fifth	31,00	33,00	34,00

According to Table 5.3 the indoor-air temperature of 75th-percentile cluster group was well above the CIBSE TM59 Criterion I overheating threshold for the entire field-survey period. The results presented above indicate that the interviewed flats are prone to overheating during a period of hot weather under the current climate if the static threshold approach is adopted, which does not factor in heat acclimatisation and other adaptation actions the residents may take (de la Flor *et al.*, 2021; Gupta & Gregg, 2018). Figure 5.17 demonstrates the step-by-step development of building energy model developed to assess energy performance of archetypes.

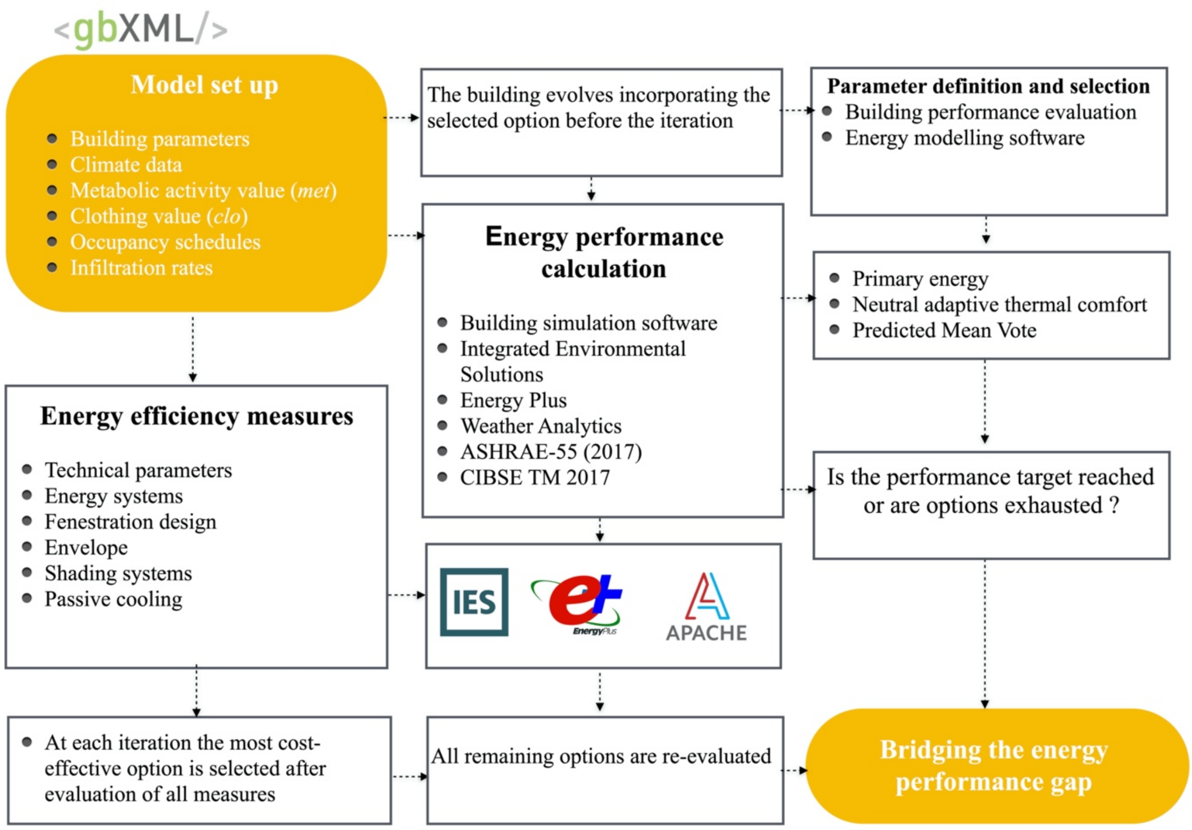


Figure 5.17: Distributions of building energy simulation parameters for benchmarking in retrofitting.

Considering that the adaptive capacity of most vulnerable individuals residing in social-housing units is likely to be fairly limited, this finding indicates that attention should be paid to the thermal properties of the buildings and occupancy patterns to thoroughly assess the overheating risk of archetype RTBs were selected (Abbas *et al.*, 2021; Ahmed & Asif, 2021). However, when the EN 15251 adaptive approach was used, the risk of overheating appears significantly lower than under the environmental conditions measured at the time of survey. This could relate to a wide range of acceptable thermal-adaptive thresholds limits that were found to influence the occupants' TPVs and TSVs, taking the physiological thermal-comfort approach into account (Liao & Laverge, 2019; Shin *et al.*, 2021).

During the data processing, it was observed that the PPD in all of the flats was observed to be above the maximum limit of 15% set by ISO 7730 for a Category C thermal environment, which is the least-strict category indicated for naturally ventilated residential buildings (EN ISO 7730, 2008). It is worth mentioning that the manner in which the PPD assessment criterion defines adaptive comfort according to votes outside of the indicated benchmark categories are questionable; earlier research determined that some participants may find the thermal environment acceptable, even if the occupants voted outside of these categories (Laverge *et al.*, 2013; Tsang *et al.*, 2021). To capture a wider variety of occupants and not create a direct generalisation, the time-of-day factor was also considered; this is shown in Figures 5.18(a) and (b).

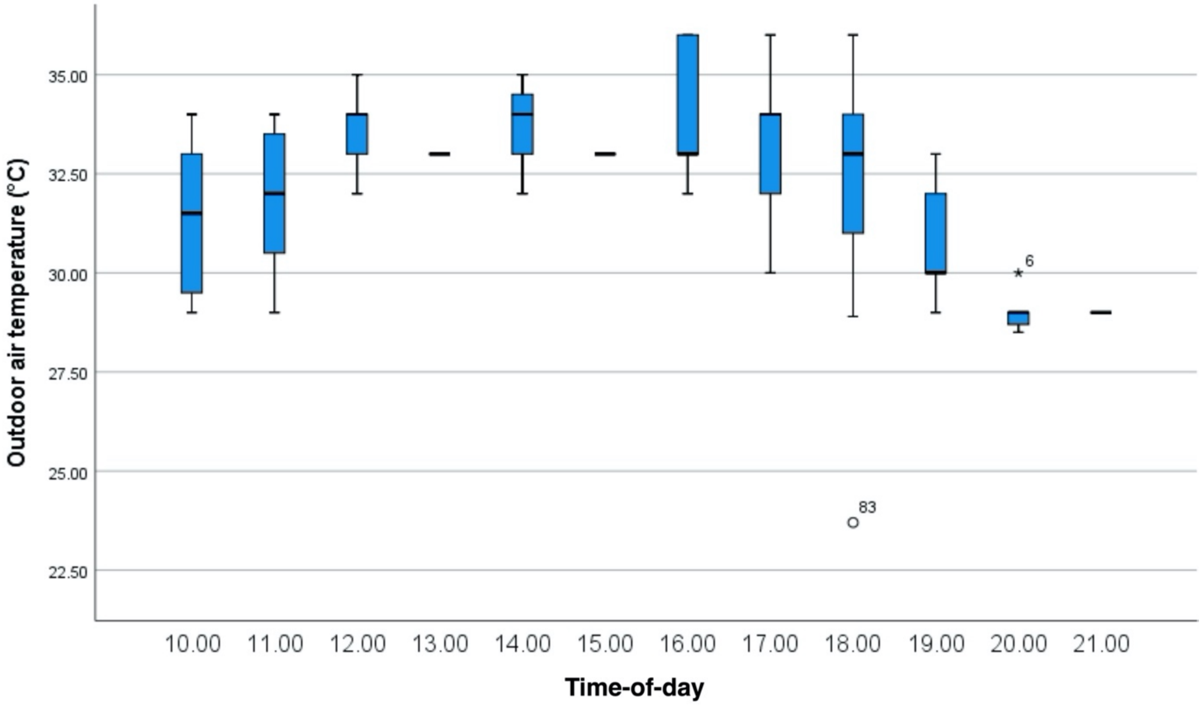


Figure 5.18(a): Associations between outdoor-air temperature *(monitored)* and time-of-day *(measured)*.

Outdoor-air temperatures were recorded between 10:05–17:35 on July 28, 2018 and at the end of September of the same year and are shown in Figure 5.18(a); acceptable temperature-fluctuation levels ranged between 30–31°C. Most of the flats were recruited between 10:05–20:00, when the recorded temperature was 29°C; this is why a wide range of acceptable thermal sensations were observed. The *on-site* monitoring results indicated that the highest peak outdoor-air temperature of 36°C was recorded on August 16, 2018; this was +5°C higher than the 28°C upper thermal-comfort limit recommended by the CIBSE TM59 overheating risk-assessment guidelines. These findings confirm that in addition to the *U*-values of the RTB thermal properties, the time-of-day factor had a direct impact on the participants' TSVs.

Only the outdoor-air movement was recorded in the present study, because indoor-air movement has been shown to affect the likelihood of achieving neutral thermal sensations by causing occupants to feel comfortable in relatively high indoor-air temperatures (Lu & Warsinger, 2020). To properly consider behaviour-related adaption that was developed in 1998 by Brager and de Dear, tests-of-associations between the time-of-day and OTs were conducted; the results are presented in Figure 5.18(b).

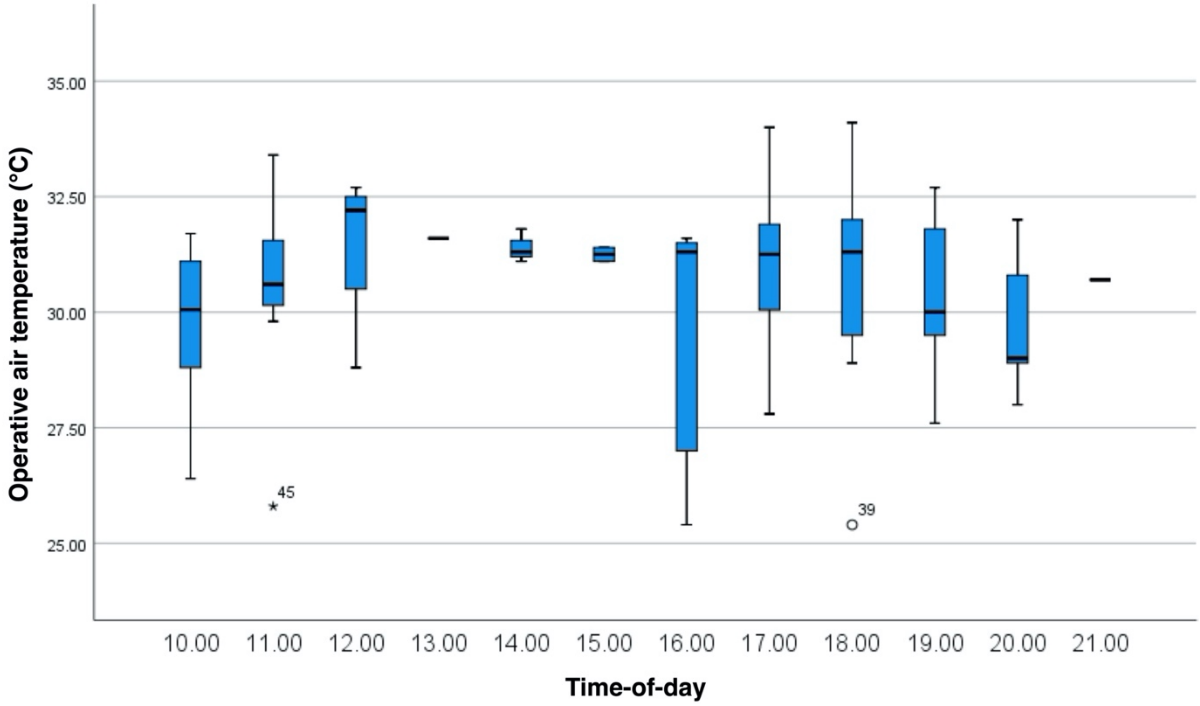


Figure 5.18(b): Associations between OT *(measured)* and time-of-day *(measured)*.

According to Figure 5.18(b), the indoor-air temperature of the occupied spaces between 16:30–18:00 was 25,4°C. Relatively high indoor-air temperatures were observed late in the morning: the recorded temperature at 10:05 was 29,7°C. The subject participants were interviewed between 17:45–20:45, and scattered patterns were detected in the range of 28.2–34.0°C. *In-situ* measurements that were collected during the field survey showed that the indoor-air temperature in all the flats was above 25°C, which confirms the risk of overheating during the summer. Notably, the maximum outdoor-air temperature recorded during this period was 36°C, and the highest and lowest temperatures in the living room spaces were 34,10°C and 25,40°C, respectively; these variations require further investigation to better understand adaptive household behaviours and attitudes that could improve the existing energy performance of the worst-performing base-case prototype RTB, which is described and discussed in Chapter 6.

5.4 Summary

A quantitative research methodology based on *in-situ* measurements was employed. These measurements included recorded household indoor-air temperatures that were integrated with thermal-imaging surveys and *on-site* heat-flux measurements of the building-fabric elements, in addition to concurrently monitored environmental conditions and a review of household energy bills to accurately determine actual energy use.

The thermal-imaging readings demonstrated that the primary reasons for thermal anomalies were air infiltration through the building fabric, a lack of NV through living spaces and excessive heat gains through sizable glazed windows. The findings suggest that the percentage of hours that fell into Category 1 of the CIBSE TM59 overheating criterion directly influenced the solar-irradiance factor and the thermal absorptivity levels of the building envelopes. During the field-survey period, outdoor-air temperatures ranged from 25,3–38,7°C with a mean temperature of 28,7°C, which indicates hot-and-dry weather conditions at the time. Moreover, the recorded indoor-air temperatures ranged between 25,0–35,0°C with an average temperature of 27,8°C and an *SD* of 1,8°C; global temperatures at this same time ranged between 24,5–37,0°C with an average temperature of 28°C and an *SD* of 1,9°C. It was determined that occupants felt thermally comfortable indoors when the mean temperature was 29°C with an *SD* of 1,1 and maximum and minimum mean temperatures of 31,5°C and 28,5°C, respectively; the recruited sample size was thermally comfortable at higher indoor-air temperatures than those recommended by such international standards as ISO EN 7730:2005.

The IRT survey, which integrated the *in-situ* measurements, led to a better understanding of the thermal behaviour of building *U*-values and facilitated the development of an assessment methodology for the implementation of the energy-performance certificates. The findings suggest that the building thermal characteristics included in the overheating risk assessment for the base-case representative RTBs clarified the difference between the expected and actual energy-consumption rates, and the longitudinal survey for the present study revealed a strong correlation between building fabric and local climate conditions in the summer and winter. This conclusion highlights the need for future energy-performance development studies to conduct BES analyses; the thermal lag of the building envelopes, which had a significant impact on energy consumption, should also be further studied.

Chapter 6

Results and Discussions: Building Energy Simulation and Retrofitting Strategies

Introduction

This chapter presents an assessment of the thermal behaviour of the base-case representative flats, taking the occupants' real-life energy-use experiences into consideration. Data obtained from the questionnaire survey were used to validate the simulation model to attempt to anticipate effects and modify some of the early design stages to implement passive-cooling design strategies that will reduce energy consumption and optimise occupants' thermal comfort. It concludes with a presentation of the findings of retrofitting design interventions that were developed in the present study, the implications thereof and the manner in which everything related to the prevailing literature.

6.1 Energy Use

In the dynamic thermal simulation (DTS) analysis, the energy consumption of the base-case representative flats was assessed by conducting a full one-year simulation between January and December 2018. The aim of this research strategy was to predict the energy consumption of these flats, and the conclusions are presented in Sections 6.1.1 and 6.1.2.

6.1.1 Overall Electricity-Consumption Assessment

This section examines the overall electricity consumption for the base-case representative flats for the purpose of a building-performance evaluation that will take the different floor levels of the flats into consideration. Three occupancy patterns were identified from the field-survey findings to represent the interviewed sample: low (i.e., OP1), moderate (i.e., OP2) and high (i.e., OP3) occupancy. Once these were established, they were compared to the occupants' actual energy bills to validate the data. Figures 6.1 (a) through (c) delineate the overall energy consumption of the first-, intermediate- and upper-level base-case representative flats.

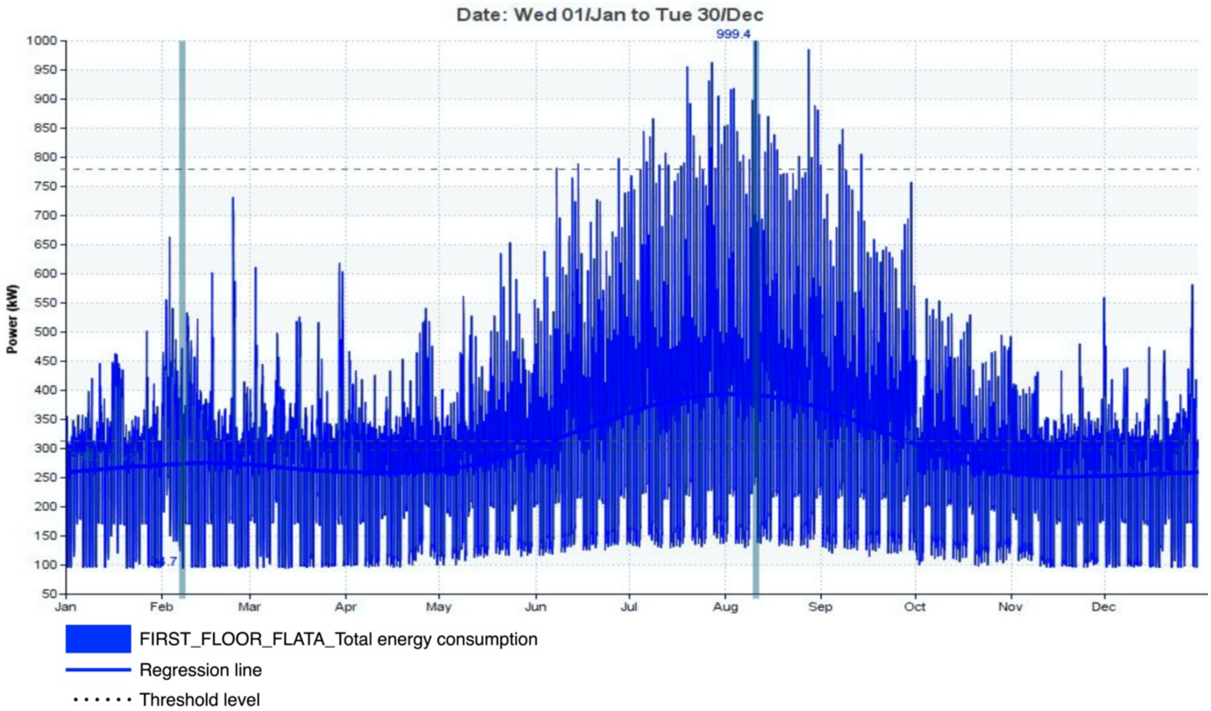


Figure 6.1(a): Maximum monthly energy consumption of worst-performing south- and southwest-facing first-floor flats in August was 999,4 kWh.

The results of the energy-consumption simulation for the south- and southwest-facing first-floor flats is shown in Figure 6.1(a). The dashed line at 780 kWh indicates the recommended upper limit for average energy consumption, and the margin line at 310 kWh delineates the lower limit of acceptable energy consumption range; energy-consumption fluctuations throughout the year fell between these two levels, and excessive energy demand was generally greater than 780 kWh.

Energy consumption for Flat A fluctuated between 350–450 kWh in January and February and peaked at 650 kWh in the first week of February; after this spike, energy consumption decreased to 350 kWh, peaked above 740 kWh in the first week of March, then dropped to 400 kWh in the second week of March. From the second week of March to mid-July, consumption fluctuated between 520–800 kWh; from mid-July until September, usage wavered between 740–950 kWh, which is above the upper limit, and peaked at 999,4 kWh in the first week of August. Energy consumption then steadily decreased from 740 kWh to 550 kWh throughout September and October, and usage hovered around 500 kWh from the first week of October until November. Consumption continued to follow this trend until reaching the lowest-recorded level of 310 kWh in the first week of December, after which usage increased and peaked at 580 kWh in the final week of the month.

It should be noted that the upper recommended limit for energy consumption in this case-study flat was 780 kWh, which was significantly surpassed in the first week of August. According to the energy-bill analysis, however, actual mean energy consumption was calculated to be 540,7 kWh, which means that at its peak, the energy consumption of this flat was just below the level delineated in the relevant criterion.

According to the simulation predictions, overall energy consumption between January and December was predicted to be 27.405 kWh. Notably, the occupants' actual energy-consumption between January and December of 2016 was calculated to be 3.079 kWh. It can therefore be concluded that in the peak cooling summer month of August, the average energy-consumption level for this flat was above the benchmark level for what the occupants needed for cooling purposes; this was also validated by an analysis of the actual energy bills, which concluded that peak energy consumption in the first week of August was actually 910 kWh.

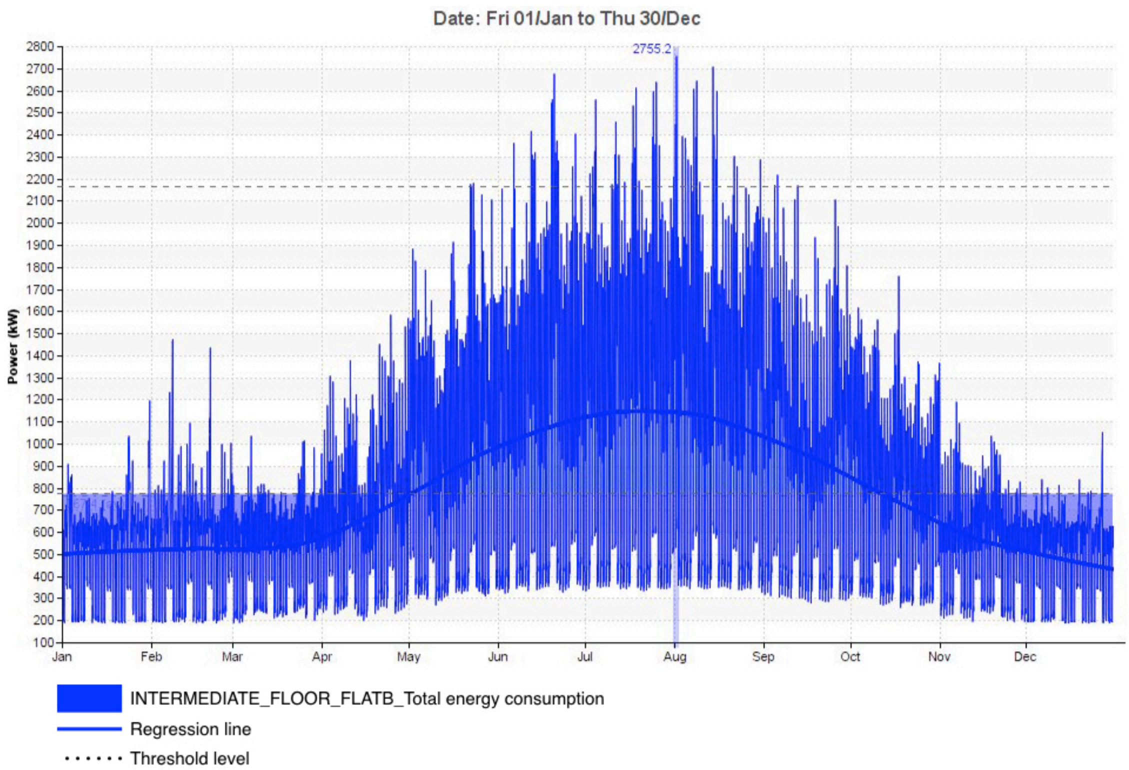


Figure 6.1(b): Maximum monthly energy consumption of worst-performing south- and southeast-facing intermediate-floor flat in August was 2.755,2 kWh.

The energy-consumption fluctuations of the south- and southeast-oriented intermediate-floor Flat B in August of 2016 are shown in Figure 6.1(b). The lower energy-consumption margin was 300 kWh, and the upper margin was 2.200 kWh, which was higher than that of the first-floor flats due to internal heat gains from appliances and different floor levels and building-envelope orientations. Energy consumption in January was 780 kWh, and this fluctuated between 520–910 kWh until the second week of February, when it peaked at 1.500 kWh. These variations continued through the end of February, when usage reached 1.400 kWh; at this time, usage dropped to 700 kWh and hovered around this level until the end of March, then steadily increased from 800 kWh to 2.200 kWh between April and mid-June. Energy consumption remained near or above the upper margin from mid-July through September and peaked at 2.755,2 kWh in the beginning of August. From September through November, energy usage decreased to 1.100 kWh and fluctuated around this level, then continued to decrease until December; energy consumption peaked at 1.000 kWh in the final week of December.

The regression line stayed well above the lower 300 kWh recommended limit for average energy consumption throughout the year and peaked above the lower margin at 1.100 kWh in August. It can be concluded that although there was a potential risk for overheating, overall consumption was well above the recommended energy consumption benchmark because of the occupants' heavy reliance on cooling systems in the summer.

It should be noted that the heating temperature for the energy simulations was set to 21,0°C in the ApacheSIM module construction profiles (Salvati *et al.,* 2020); this was because the occupants predominantly used gas-cylinder heating systems in the winter, which was why energy consumption fluctuated around 780 kWh between December and February. It is also notable that energy consumption increased in February and March and varied from 780–1.450 kWh, which strongly indicates that portable domestic heating systems were used in the winter when children were present in the flat.

According to the simulation predictions, overall energy consumption between January and December was predicted to be 4.440,5 kWh; actual energy consumption for the year, however, was 5.259 kWh. It can therefore be concluded that in the peak cooling summer month of August, the average energy-consumption of the case-study flat was above the benchmark level for what the occupants needed for cooling purposes (Gulotta *et al.,* 2020). This was validated by an analysis of the actual energy bills, which revealed that peak energy consumption in the first week of August was recorded at 2.453 kWh, even though the energy-consumption benchmark for Flat B was 2.200 kWh; this is because the Type 2 occupancy pattern was assigned to represent the continuous day- and night-time presence of retiree couples who engaged in high energy consumption. These results can be extrapolated to represent the energy-use intensity of the surveyed households, which is presented in Sub-Section 6.2.2.

Interestingly, based on these simulation measurements; it can be concluded that the energy consumption of this base-case unit consistently remained above the recommended benchmark. The energy-bill analysis determined, however, average energy consumption for Flat B was 1.999,7 kWh; and energy consumption in the peak cooling month of August was 2.755,2 kWh. According to these data, there was a contradictory finding related to actual energy consumption, because the CIBSE TM59 guidelines were intended to assess the overheating risk of existing residential buildings in the U.K., yet the research context of the present study was in a different geographic domain (i.e., the south-eastern Mediterranean area).

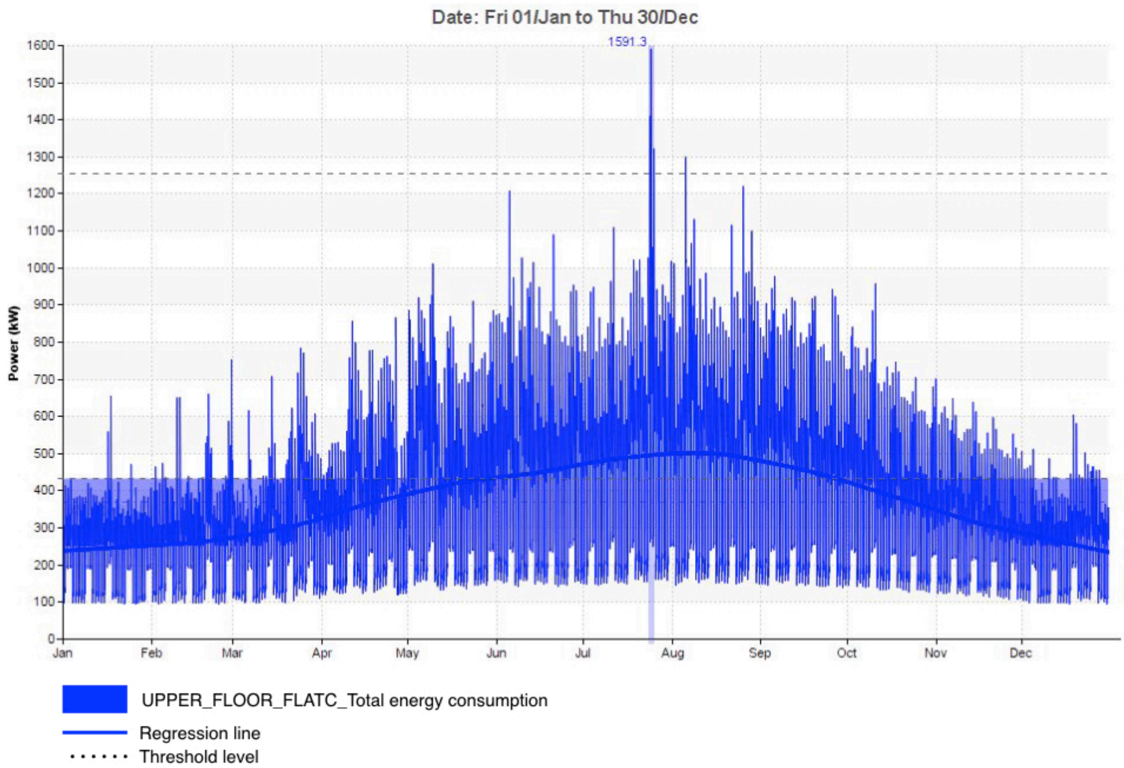


Figure 6.1(c): Maximum monthly energy consumption of worst-performing south- and southwest-facing upper-floor flat in August was 1.591,3 kWh.

The energy-consumption simulation for the south- and southwest-facing upper-floor Flat C is delineated in Figure 6.1(c). The line at 1.250 kWh indicates the recommended upper limit for average energy consumption, and the margin line at 410 kWh is the lower limit for average energy consumption; the acceptable range for energy consumption is between these margins, and usage above the 1.250 kWh margin indicates high energy consumption. Energy consumption for this flat remained below the recommended 1.250 kWh usage benchmark throughout most of the year and only surpassed the upper limit at the end of July, when 1.591,3 kWh of energy was utilised. Energy consumption for Flat C was 420 kWh in the beginning of January, and usage fluctuated between 450–800 kWh until the first week of May, then increased to 1.000 kWh in the second week of May. Consumption then decreased to 800 kWh and hovered around this level until the final week of July, at which time usage peaked at 1.591,3 kWh, then plummeted to 750 kWh. From August until mid-October, energy consumption continued to decrease from 750 kWh to 600 kWh, then sharply decreased from 600 kWh to 400 kWh between mid-October and December and fluctuated at this level until the end of December.

The regression line was initially well below the lower margin for average energy consumption. From January to April, it fluctuated around 220 kWh, then steadily increased to 500 kWh; peak energy consumption peaked at 1.591,3 kWh in the final week of July, then decreased and fluctuated around 210 kWh, which was below the lower margin. Notably. the generated benchmark for Flat C was 1.250 kWh. Overall electricity consumption decreased below the lower limit for average energy consumption in the final week of July, but usage was still well above the upper limit; moreover, even though relatively high energy consumption that was in line with both the simulation predictions and actual energy consumption was observed, overall energy consumption was well below the upper limit for the recommended average usage. The findings related to energy consumption during the peak cooling period were therefore validated.

6.1.2 Validation Study Results Based on Occupant Energy Bills

Validation for the simulation model was performed using the occupants' annual energy bills. To fulfil the aim and objectives of the present study, a cooling-energy consumption assessment between the predicted and actual energy consumption with a target error of 10% was conducted (Pasichnyi *et al.,* 2019). It is worth noting at this point those internal temperatures were iteratively adjusted during the model-development process until the simulated annual energy-consumption totals converged with the actual energy-usage totals with values that were less than the target error. Table 6.1 summarises the validation-study results[28].

[28] The value of difference has been obtained by using an open-source software of the HOT2000 version 11.10. The HOT2000 is an energy modelling software developed and maintained by Natural Resources Canada to support the EnerGuide Rating system to support residential energy efficiency initiatives for energy-policy making decisions. The present study was undertaken in the South-eastern Mediterranean climate which was aimed to design universal design approach. This is the reason that this software tool was used to calculate differences between the predicted and actual energy use in order to make generalisation of the study findings.

Table 6.1: Comparative Results of Overall Occupant Energy Consumption Between DTS and Analysis of Actual Energy Bills.

Flat Information	Occupancy-Pattern Type	Simulation Prediction (kWh)	Actual Consumption (kWh)	Difference (%)
FIRST_FLOOR_FLATA	OP1	999,4	3.079,0	20.8
INTERMEDIATE_FLOOR_FLATB	OP2	2.755,0	5.259,0	25.04
UPPER_FLOOR_FLATC	OP3	1.591,0	10.004,0	84.13

OP1: Low occupancy
OP2: Moderate occupancy
OP3: High occupancy

Validation of the simulation predictions with the actual household energy bills is delineated in Table 6.1. The first-floor flat, which had a Type 1 (i.e., low) occupancy pattern, was predicted to consume 2.740,5 kWh of energy during the summer, and actual energy consumption was 3.079,0 kWh; the position of the RTB in the social-housing estate and local climate conditions caused variations in the predicted model, which suggests that the TRY weather files that were assigned in the black-box model require further modification to accurately represent the actual conditions of the built environment. Flats on the intermediate-level floors were predicted to consume 4.450,5 kWh of energy, but their actual bills data revealed 5.259,0 kWh of energy use. The upper-floor flats were predicted to consume 9.689,6 kWh of energy, but actual energy use for these units was 10.004,0 kWh. In the present study, it was found that actual energy consumption was higher than predicted energy use in all the base-case representative flats.

Table 6.1 validates the actual energy-consumption data for most of the base-case representative flats. With the exception of Flat C on the upper-floor, all results fell within the acceptable percentage difference; longer occupancy hours led to increased energy consumption, which is why there was a −2,4% difference between the simulation prediction and actual consumption for Flat C. For this reason, the simulation prediction required a 5% deduction from the initial prediction to align with the actual occupancy patterns; after this deduction rate was taken into consideration, the simulation prediction was 10.468,8 kWh, and the simulation prediction was 3%, a difference that was within the acceptable range. As such, the Flat C simulation model can also be confirmed as a valid model.

6.2 Retrofitting Design Strategies

This study presents an analysis of the passive-cooling design strategy (PCDS) development framework to demonstrate an evidence-based integrated design approach for energy use. The multiple objectives of the building assessment provided information related to the energy effectiveness of retrofitting interventions by determining the life-cycle cost assessment (LCCA) for policymakers in the residential sector. Further retrofitting design strategies are presented in **Appendix E**.

6.2.1 Implications for Energy Use

This section examines the impact and applicability of passive-cooling design strategies to retrofit base-case buildings, optimise the thermal comfort of occupants and reduce overheating risks in the summer.

This analysis was divided into six strategies, each of which consisted of a set of dynamic building energy simulations that were intended to assess the current energy performance of the representative flat units. The first strategy was considered the balcony space addition on the front elevation. The second strategy considered the energy performance of a combination of passive design measures, which included appropriate shading systems, external wall insulation on the roof and the more-exposed walls and natural ventilation. The third strategy was a newly proposed architectural intervention for RTBs that included a new fenestration design and the addition of an operable external shading system. The fourth, fifth and sixth strategies utilised adaptable passive designs to evaluate an improvement in energy use according to the percentage of hours of thermal discomfort. These strategies, including the analysis methods and descriptions thereof, are detailed in Table 6.2.

Table 6.2: Structure of Step-by-Step Applicable Retrofitting Strategies and Those of Existing Base Case

Strategy: Base Case	**Description: Base-Case Design**	**Analysis Method: Thermal Performance**	**Dynamic Thermal Simulations: Currently Assigned Construction Materials for Building-Performance Evaluation**
Strategy 1 (S1)	Proposed design	Thermal performance of living room	Base-case design + volumetric sunspace addition
			Base-case design + operable pine wood external shutters
Strategy 2 (S2)	Natural-ventilation analysis	Thermal performance of living room and kitchen	Base-case design + volumetric sunspace addition
			Base-case design + operable external venetian blinds
Strategy 3 (S3)	Natural-ventilation analysis	Thermal performance of Bedrooms 1 and 2 and kitchen	Base-case design + window opening projections
			Base-case design + overhanging window canopy
			Base-case design + horizontal external pine-wood louvres
Strategy 4 (S4)	Natural-ventilation analysis	Thermal performance of Bedroom 1	Base-case design + volumetric window opening projection
			Base-case design + folded window system
			Base-case design + overhanging window canopy
			Base-case design + operable pine wood external shutters
Strategy 5 (S5)	Natural-ventilation analysis	Thermal performance of Bedroom 2	Base-case design + fixed overhanging solar-shading systems
Strategy 6 (S6)	All-proposed designs	Thermal performance	Base-case design + S1 + S2 + S3 + S4 + S5 in combination

The six retrofitting design strategies, which are illustrated in Figure 6.2, were initially applied separately, then the obtained results were applied together to test the effectiveness of these design strategies as a whole.

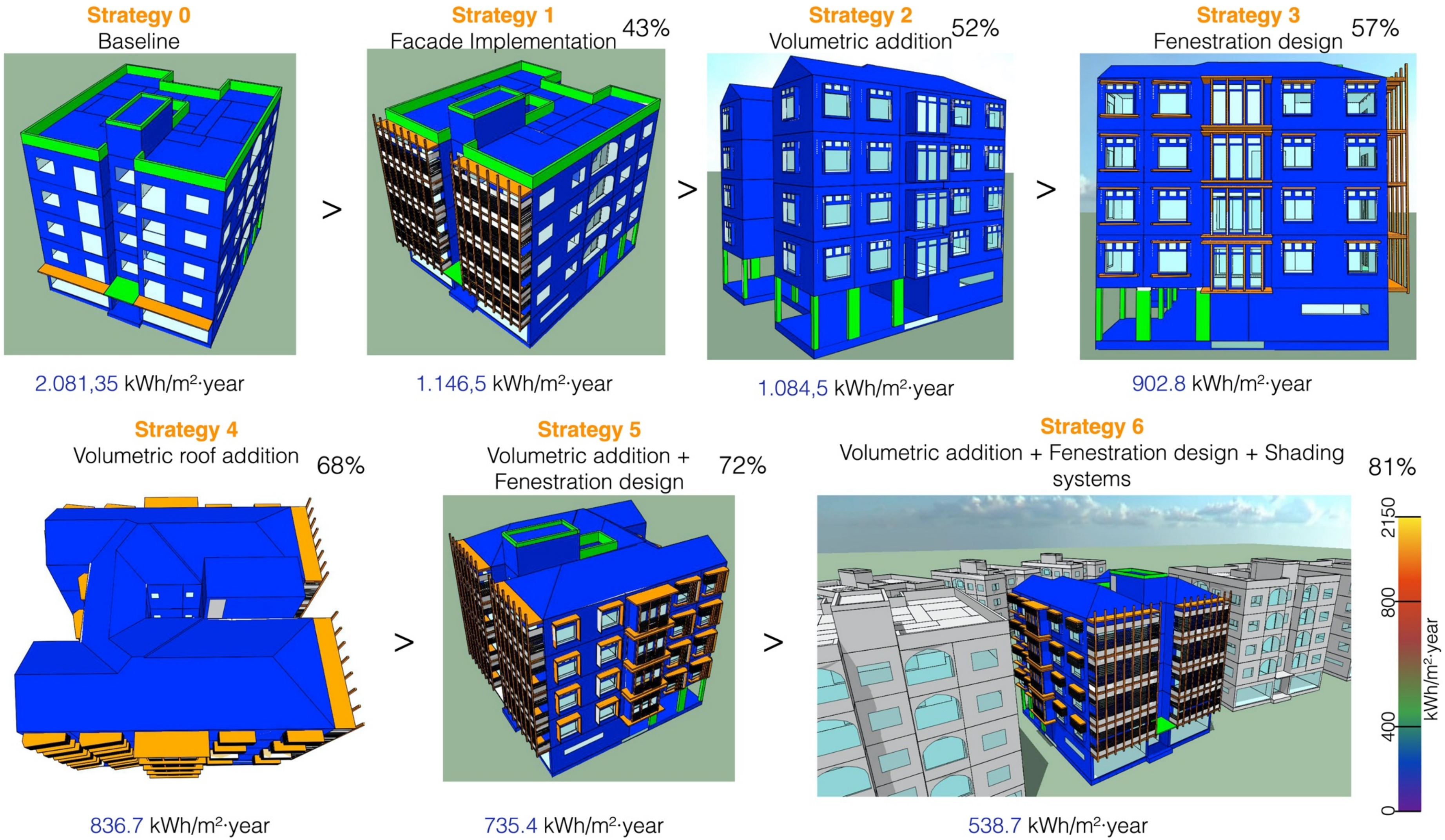
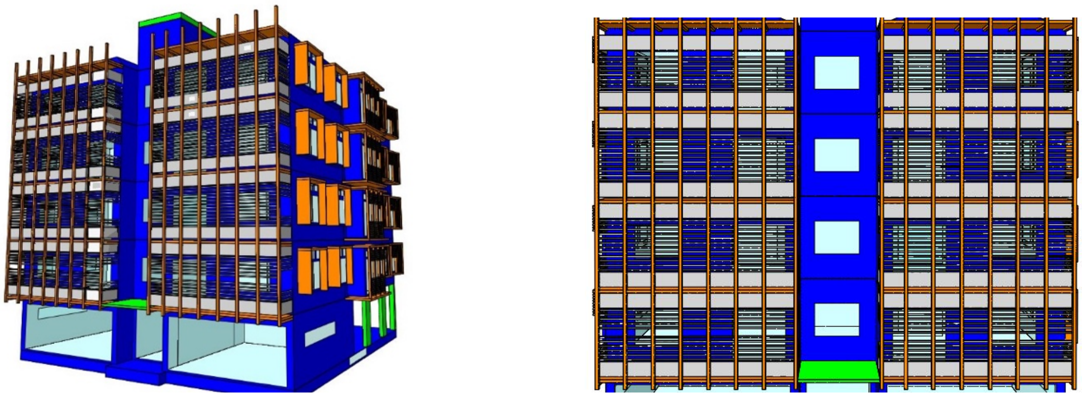


Figure 6.2: Schematic illustration of six strategies implemented to test design-strategy effectiveness.

Table 6.3 delineates the construction properties of the base-case RTBs and the six strategies that were applied in the simulation.

Table 6.3: Specifications of State-of-the-Art Retrofitting Strategies and Those of Existing Base-Case.

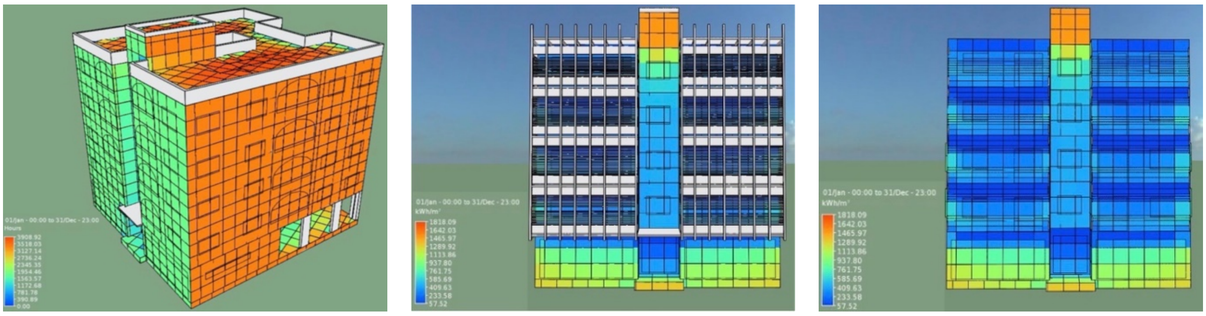
Strategy	Element Details	*U*-value (W/m^2K)	*R*-value (m^2K/W)	Thickness (mm)	Mass (kg/m^2)	Thermal mass (kJ/m^2K)
Base-Case	Common brick: HF-C4 + brickwork (inner leaf) + clear-float 4 mm	4,05	0,076	28,0	56,17	11,16
S1	Clay tile: HF-C1 + vermiculite insulating brick + thermalite-high strength + thermo-clear 8 mm polycarbonate cliffing + clear-float 4 mm	0,95	0,88	110,5	83,32	34,6
S2	Asphalt mastic roofing + particleboard: High density + roof insulation + thermo-clear 8 mm polycarbonate cliffing + clear-float 4 mm + insulation board – HF-B2 + timber solar shield with adjustable blinds (500 mm)	0,80	1,10	285,5	511,65	240,0
S3	Combination of S1 + S2 envelope rehabilitation with shading and 0,63h^{-1} ventilation rate	0,80	1,10	285,5	511,65	240,0
S4	Combination of S1 + S2 envelope rehabilitation with shading and 0,4h^{-1} ventilation rate	0,80	1,10	285,5	511,65	240,0
S5	Combination of S1 + S2 envelope rehabilitation with shading without passive night-time ventilation in summer and 0,4h^{-1} ventilation rate	0,80	1,10	285,5	511,65	240,0
S6	Common brick: HF-C4 + brickwork (inner leaf) + clear-float 4 mm + combination of S1 +S2 envelope rehabilitation with shading and 0,4h^{-1} ventilation rate	1,30	0,5	61,5	38,75	21,39



(a) (b)

Figure 6.3: (a) Volumetric sun-space addition installed on southwest-facing deck area of prototype RTB in Strategy 1; **(b)** modification provided additional space and allowed more NV in occupied space.

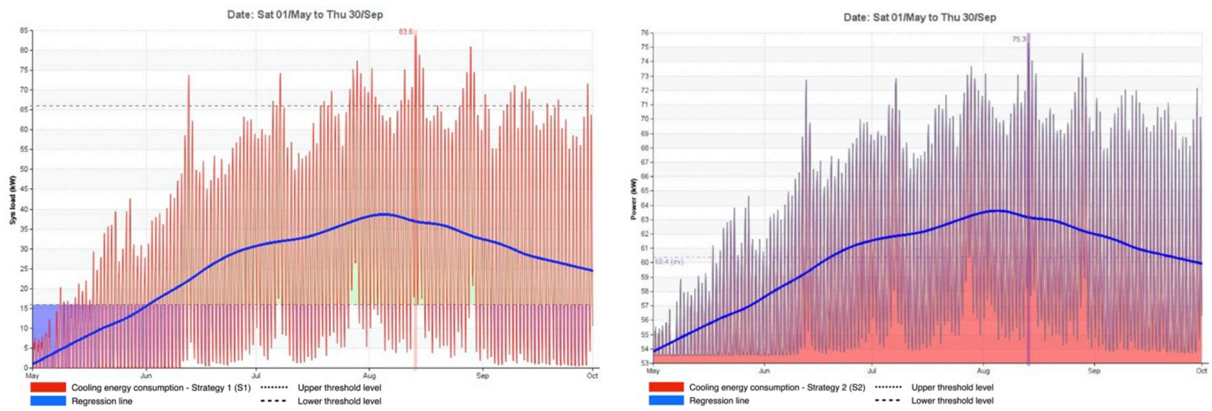
Strategy 1, which is shown in Figures 6.3(a) and (b), was a volumetric space addition with a sunscreen blade affixed to the southeast-facing building envelope in the living room area. This modification was in the form of a room extension with a slanted overhanging roof that measured 1,8m (length) × 2,1m (height); the external walls were made of operable double-glazed windows with 50% opening ratios. The living room was chosen because, according to various findings, this was the worst-performing room that was under the greatest threat of overheating in the summer; the aim of this strategy was to determine to what extent this passive application could diminish the overheating risk in this room. The simulation resulted in a significant decrease in the living room energy-consumption patterns, while at the same time, indoor-air temperature was decreased due to an optimised, effective infiltration rate on the building envelope.



(a) **(b)** **(c)**

Figure 6.4: Solar exposure analysis: **(a)** degree of solar radiation absorbed on side façade; **(b)** integration of overhanging balcony with tinted shading systems; **(c)** decreased solar absorptivity of building envelopes after implementation of S1.

Figures 6.4(a) through (c) illustrates the Strategy 1 retrofitting design, the primary aim of which was to provide solar protection to the living room. The solar-exposure analysis demonstrated that prior to the retrofitting, annual solar radiation for this room peaked at 8.908,92 hours; solar radiation was reduced to a maximum of 1.818,09 hours as a result of this endeavour, which means that implementing these passive shading elements led to a 50% improvement in energy effectiveness. To reduce the thermal vulnerability of the building envelopes, S1 was implemented to predict the effect of this retrofitting design interventions; this is shown in Figures 6.5(a) and (b).



(a) (b)

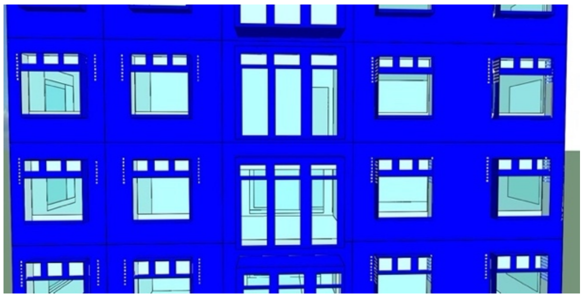
Figure 6.5: (a) Monthly cooling load of living room in worst-performing south-facing RTB in August reached maximum 83,6 kWh after implementing S1; **(b)** monthly cooling load of living room in south-facing RTB in August peaked at 75,3 kWh after implementation of S2.[29]

Figures 6.5(a) and (b) represent the monthly cooling-energy consumption during the cooling period that extends from May to October after the implementation of the first two strategies. It should be noted that the energy-consumption data representing the actual energy use of 100 households was included in the statistical data. As such, the BES demonstrated data obtained from three representative flats (i.e., first-, intermediate- and upper-level floors) to provide representative sampling criteria and test the energy effectiveness of the PCDS implemented onto building envelopes (Kotireddy *et al.,* 2019).

Following the implementation of Strategy 1, which is shown in Figure 6.5(a), peak cooling-energy consumption was reduced to 83,6 kWh; the upper threshold was determined to be 66,0 kWh, and the lower threshold was 16,0 kWh. Notably, household energy bills revealed that energy consumption between June and September of 2016 was 291,0 kWh, and energy consumption in August specifically was 33,0 kWh. Figure 6.5(b) shows that after Strategy 2 was implemented, energy consumption was reduced to 75,3 kWh; the upper threshold was 60,0 kWh, and the lower threshold was 55 kWh. The results confirm that Strategy 2 increased natural ventilation and acclimatised the indoor-air environment and thereby significantly reduced cooling-energy consumption. Unfortunately, the strategy was ineffective against solar radiation, which caused overheating risk, so Strategies 3 and 4 were developed to provide a solution that will affect climate conditions.

[29] Graph only demonstrates cooling-energy consumption generated from the BES; the comparative analysis was conducted using actual household-energy use of domestic heating water (DHW) electricity.

(a)

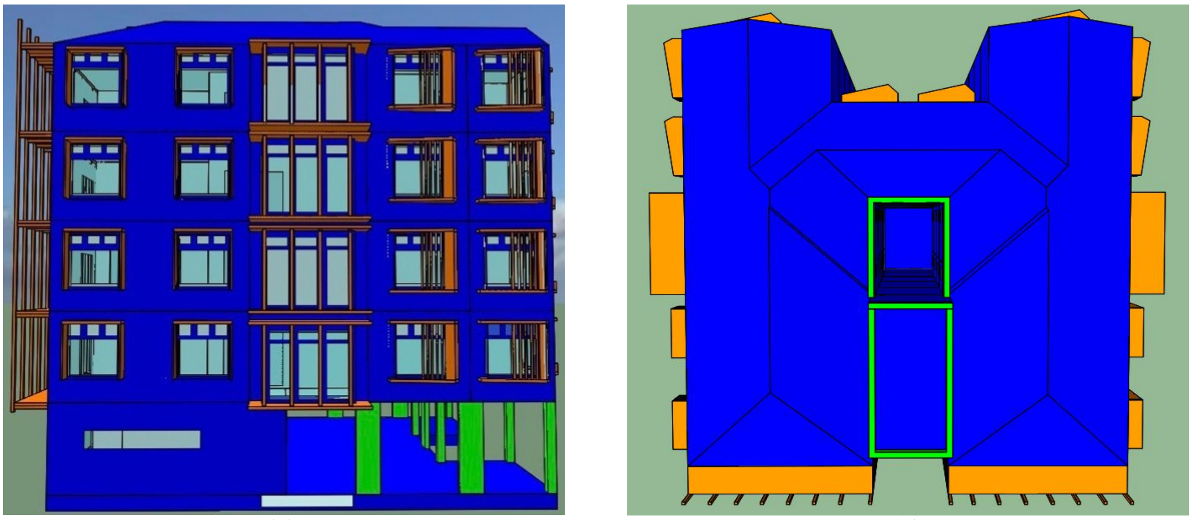


(b)

Figure 6.6: (a) Overhanging window projections installed in customised window openings on external wall surfaces within operable top-window openings: Window dimensions 1,10m (length) ×1,20m (height), top-window opening dimensions 0,30m (length) × 0,30m (height); **(b)** 3D rendering of overhanging kitchen addition and modular window frame integration.

In Strategy 2, which is shown in Figure 6.6(a), a volumetric space addition was installed on the southwest- and southeast-facing kitchen spaces within the area of the existing balcony areas; this addition created more liveable space and provided additional NV for every kitchen in the RTB. Three operable vertical-windows and three top-window openings were installed on this modular system to provide effective NV, as shown in Figure 6.6(b). Implementing the horizontal louvre window openings proposed in Strategy 2 led to a 20% decrease in cooling-energy consumption, because the Venetian louvres offered a simple, cost-effective method to improve indoor-air quality and regulated indoor-air temperatures to enhance the occupants' thermal comfort and decrease their energy costs (Mukhamet *et al.,* 2020).

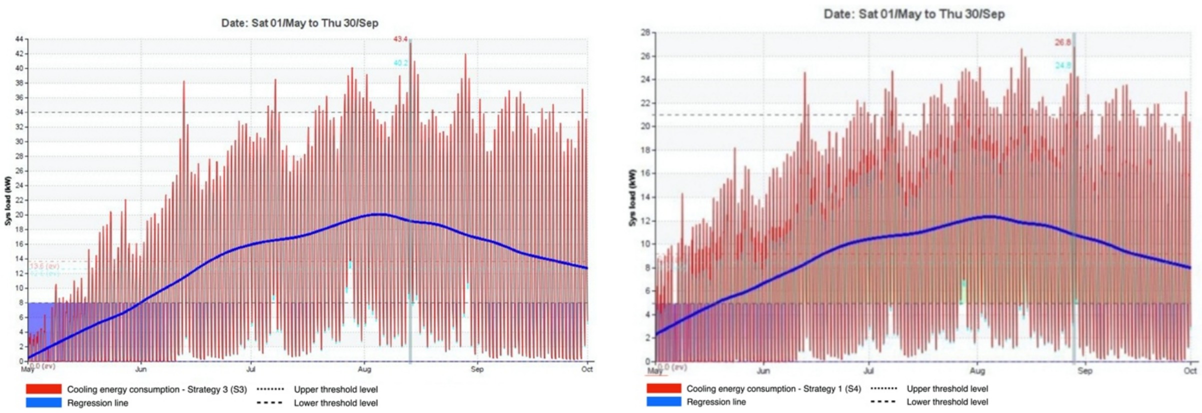
Strategy 3 was implemented to address the overheating risk for all occupied spaces in the worst-performing prototype RTB and to test the efficiency of the passive ventilation system in the building. In this strategy, which is shown in Figures 6.7(a) and (b), a traditional overhanging volumetric space-addition was applied to the building envelope; this was in the form of a rectangular wedge that projected 2,2m (length) × 0,6m (width) × 2,8m (height) from the external wall surface. The three exposed wall surfaces of this volumetric space-addition design were constructed out of double-glazed glass with 50% opening ratios, and horizontal pine-wood louvres were affixed to the exterior of these windows for the purpose of shading.



(a) (b)

Figure 6.7: (a) Horizontal planar elements installed on bottom and top portion of volumetric space to provide shading and protection from rainfall in winter, and vertical secondary structural elements installed between these surfaces with fixed louvre systems for shading purposes; **(b)** bird's-eye view of volumetric overhanging roof addition.

The aim of Strategy 3 and Strategy 4 was to provide sufficient natural ventilation to indoor spaces, which would then create an 'air-buoyancy-driven' natural ventilation effect whereby the accumulated indoor heat would be circulated into the outside environment, resulting in lower indoor-air temperatures. This was tested on the representative base-case RTB and led to reduced overheating risks and decreased electricity consumption during high cooling-demand periods, and the occupants' thermal comfort was optimised; the results are shown in Figures 6.8(a) and (b).

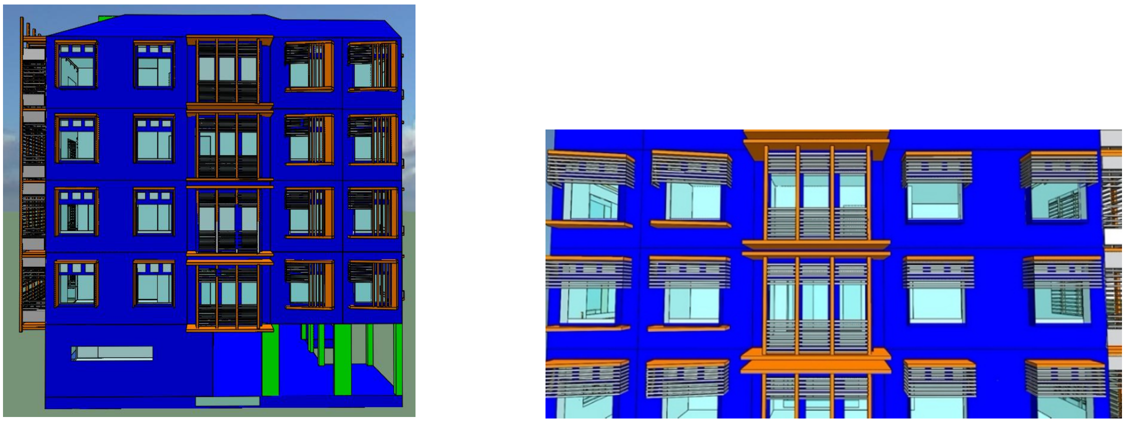


(a) (b)

Figure 6.8: Monthly cooling load of Bedroom 1 in worst-performing south-facing RTB in August peaked at **(a)** 43,4 kWh after implementation of S3 and **(b)** 26,8 kWh after implementation of S4.

As shown in Figure 6.8(a), peak energy consumption after Strategy 3 was implemented was reduced to 43,4 kWh; the upper energy-consumption threshold was 34 kWh, and the lower threshold was 8 kWh. Notably, actual household energy use in August of 2016 was 63,0 kWh, and there was a 68% reduction in overall energy consumption. It is important to highlight that the thermal comfort of all treated indoor spaces after this intervention was within the acceptable limits defined by the CIBSE TM59 standards, even though the indoor-air temperatures in the living room and Bedroom 2 remained slightly higher than the acceptable thermal-comfort threshold.

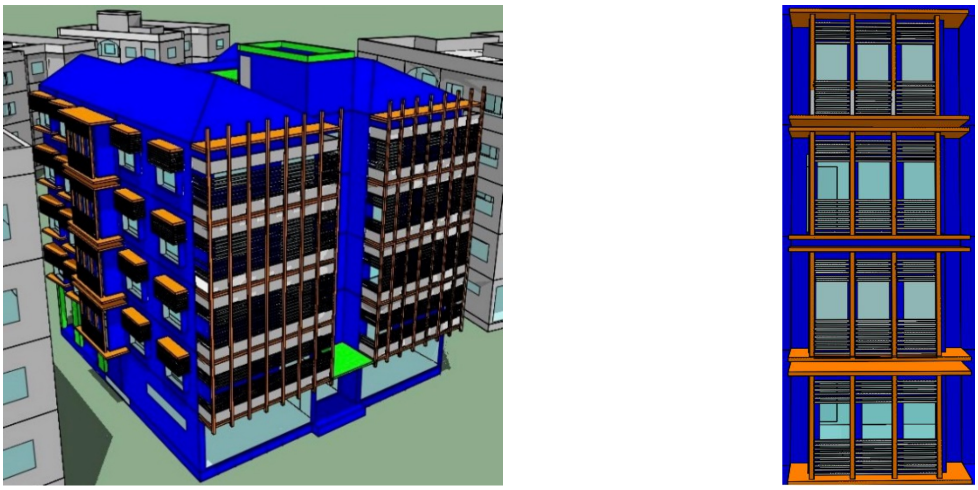
A 57% reduction in energy consumption was achieved after Strategy 1, Strategy 2 and Strategy 3 were implemented, but a significant overheating risk remained for the upper-floor flats due to the absence of roof-top insulation material. To reduce high solar radiation on the flat roof surfaces, the volumetric overhanging roof in Strategy 4 was designed to provide solar protection to the occupied spaces in the upper-floor flats; ventilation openings were positioned on the overhang to improve natural air flow and avoid heat accumulation in the summer. Peak energy consumption, which is shown in Figure 6.8(b), was reduced to 26,8 kWh; the upper energy-consumption threshold was 21 kWh, and the lower threshold was 5 kWh. It can be concluded that implementation of Strategy 4 had a significant overall impact on the thermal performance of the base-case RTBs.



(a) (b)

Figure 6.9: (a) Horizontal sunscreen shading systems in exposed surfaces of southwest-facing living room installed on overhanging window projections (systems can be applied to all southwest-facing exposed surfaces without minor or major modifications on windows opening applications); **(b)** solar shield for outdoor use with adjustable and packable blinds (packing of blinds allows very compact folded element; typology can be applied to screen balconies other than windows to avoid high solar radiation in late afternoon).

In Strategy 5, angular pine-wood vertical louvres were affixed midway down the length of the windows, as shown in Figures 6.9(a) and (b). This type of shading system absorbs the wind from different angles and promotes NV in indoor spaces. Moreover, this strategy reduces excessive incoming solar radiation.

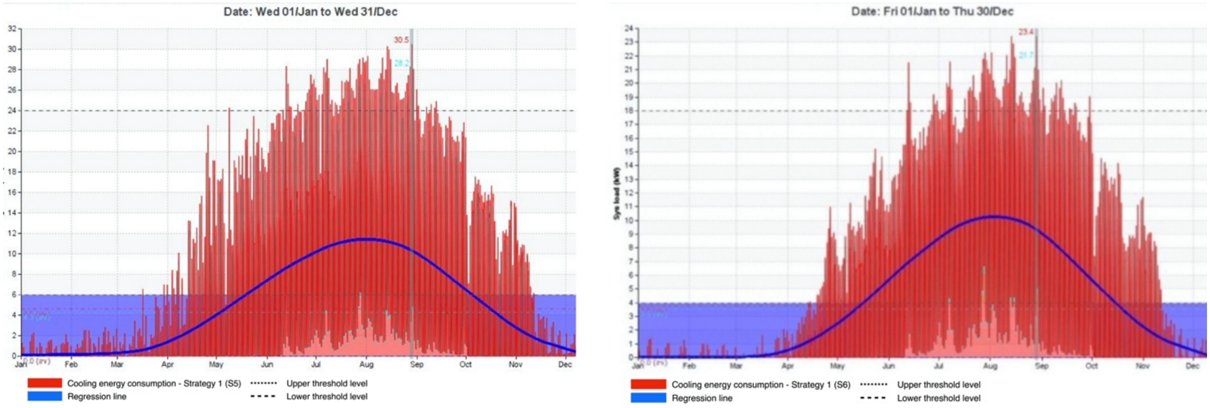


(a) (b)

Figure 6.10: (a) Horizontal brise-soleil louvre systems installed on horizontal planar balcony projections (fixed shading systems on top and bottom balcony projections to avoid excessive sun rays in occupied living room spaces); **(b)** operable oak-timber horizontal louvre systems installed between fixed elements (flexible design systems allow NV and sun according to occupant thermal comfort preferences).

In Strategy 6, which is shown in Figures 6.10(a) and (b), the living room was retrofitted with balcony projections within a fenestration design that was fitted onto the building envelope to allow NV to penetrate into the occupied spaces. This solution was constructed by removing the two existing glazed windows, opening up the space between them and lowering the opening to the floor. The new window openings were then covered with double-glazed glass and folding window panels, which were divided into upper and lower sections; the top portion had small windows that opened to the outside, and the lower portion had long windows that also opened. The aim of this strategy was to improve NV at night, and the extended window opening yielded a large surface area that provided NV that cooled the room and lowered the indoor-air temperature a noticeable amount. Unfortunately, this solution also allowed direct solar radiation into the main southeast-oriented living room area, which already received direct sunlight throughout the day, thereby leading to an overheating risk for this space in the summer; the use of vertical sunscreen-building systems only resulted in a 32% reduction.

Overall, an 81% reduction in cooling-energy consumption was achieved after the implementation of all six strategies. To fully understand the effect of PCDS on home-energy performance—specifically, to determine the impact of PCDS on heating consumption patterns and demonstrate that these strategies would not lead to increased heating-energy consumption in the winter—a one-year DTS analysis was conducted (Rouleau *et al.,* 2019). It should be emphasised that even though this study investigated the energy effectiveness of all the proposed PCDS to assess cooling-energy consumption, the effect of Strategy 5 and Strategy 6 on household heating needs was also considered, and the results are shown in Figures 6.11(a) and (b).



(a) **(b)**

Figure 6.11: (a) Monthly cooling load in worst-performing south-facing RTB in August peaked at 30,5 kWh after implementation of S5; **(b)** monthly cooling load in south-facing RTB in August peaked at 23,4 kWh after implementation of S6.

According to Figure 6.11(a), peak cooling consumption after Strategy 5 was implemented was 30,5 kWh; the upper energy-consumption threshold was 24 kWh, and the lower threshold was 6 kWh. Figure 6.11(b) demonstrates that after Strategy 6 was implemented, peak cooling consumption was reduced to 23,4 kWh, the upper threshold was 18 kWh, and the lower threshold was 4 kWh. Notably, these strategies did not have a negative effect on heating-energy consumption, and a significant reduction in cooling-energy consumption was observed.

Table 6.4 delineates the overheating risks for each criterion using the adaptive-comfort method. Based on the recorded design and construction parameters, overheating was not a problem after the proposed passive-design cooling systems were implemented, even though the living room in the upper-floor flat still demonstrated an overheating risk.

It should be noted that all living rooms in the development had large, double-glazed windows that absorbed direct solar radiation, instead of the aluminium-framed single-glazed window with 50% window-opening ratios in Bedroom 1 and Bedroom 2. It should also be noted that Bedroom 1 faced south-west and overheated to a slightly greater degree than Bedroom 2. Importantly, no signs of overheating were observed when the above-tested strategies were input into the building-model simulation, but the living room and Bedroom 1 still displayed overheating, albeit to a lesser degree.

Table 6.4: Effects of Six Strategies on Summer Overheating.

Room Name and Location	Occupied Days (%)	Criterion 1 (% of Hrs Top $T_{max} \geq 1K$	Criterion 2 (Max. Daily Deg. Hrs)	Criterion 3 (Max. ΔT)	Failing Criteria
FIRST_Livingroom	100	0,8	4,5	2	—
FIRST_Bedroom1	100	1,4	4,5	2	—
FIRST_Bedroom2	100	0,7	5,5	3	—
FIRST_Bedroom3	100	1,4	4,5	2	—
INTERMEDIATE_Livingroom	100	1,8	5,5	3	—
INTERMEDIATE_Bedroom1	100	0,7	4,5	2	—
INTERMEDIATE_Bedroom2	100	0,5	4,0	3	—
INTERMEDIATE_Bedroom3	100	1,4	4,5	2	—
UPPER_Livingroom	100	1,5	4,5	3	—
UPPER_Bedroom1	100	1,4	4,5	3	—
UPPER_Bedroom2	100	0,5	5,5	3	—
UPPER_Bedroom3	100	0,8	5,5	2	—

The efficiency of the analysed and tested passive-design measures was evaluated for the south-facing RTB prototype. According to the results, the Venetian (i.e., a brise-soleil) louvre system proposed in Strategy 1 was the most efficient in the summer when the blind apparatus was completely controlled by the occupants; specifically, tilting the blinds to a 60° angle was shown to be the most effective. To ensure these benefits, combining this shading strategy with an automated system that manages the window opening in a dynamic manner might prove to be very useful.

The addition of the shading system proposed in Strategy 3 to an existing balcony or the addition of a volumetric space onto the existing building structure also yielded noteworthy results, especially when these strategies were combined with horizontal blinds that were tilted to a 30° angle; notably, the depth of the balcony in this passive-design strategy was 0,8–1,2 m, which affected the results to a limited extent.

The shading system proposed in Strategy 4 and the opaque horizontal overhang exhibit proposed in Strategy 5 both resulted in a 50% decrease in solar radiation exposure. Furthermore, the effectiveness of the analysed sunscreens for the RTBs with south-west orientations was confirmed; specifically, the external Venetian blind systems proposed in Strategy 1 that included the balcony and integrated shield, the sunshade proposed in Strategy 4 that was constructed perpendicular to the façade with horizontal blinds and the horizontal overhang proposed in Strategy 5 were all shown to be highly efficient.

After running the simulations to determine the overheating risks and thermal comfort for each strategy, several conclusions can be drawn. Even though all six strategies reduced overheating risk and optimised the occupants' thermal comfort in the summer, Strategy 5 and Strategy 6 addressed the three criteria related to overheating most effectively. Another important factor that emerged from the analyses was associated with the indoor-air temperature in occupied spaces: Combining Strategy 5 and Strategy 6 was shown to improve indoor thermal comfort by reducing the indoor-air temperature in the living room of the upper-floor flat from 36,4°C to 28,1°C. Furthermore, these results demonstrated the impact of all six implemented strategies on the PPD, which the CIBSE TM59 standards determined should not exceed 15%; PPD was reduced from 100% in the base-case scenario to 30,5% with the combination of Strategy 5 and Strategy 6, but this is still considered unacceptable and underscores the need for additional building-performance optimisation interventions (Rinaldi *et al.,* 2018).

The neutral adaptive thermal-comfort thresholds of the households involved in this portion of the present study ranged between 28,5–31,5°C, which demonstrates that the occupants' thermal acceptability was within the range that was obtained from the longitudinal field survey. This suggests that a significant proportion of respondents wanted drier air and decreased humidity; implementing the six strategies led to a decrease in RHI, which in turn increased the occupants' thermal acceptability.

Table 6.5 presents the implementation of all retrofitting design interventions that were undertaken after the local climate characteristics, locally available building materials and passive design strategies that evolved during the construction of vernacular buildings in Cyprus were all taken into consideration.

Table 6.5: Synthesis of Achievable Results of Each Strategy and Those of Base Case.

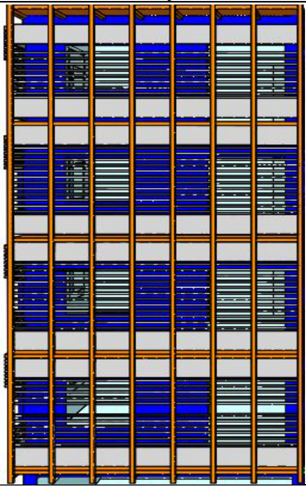
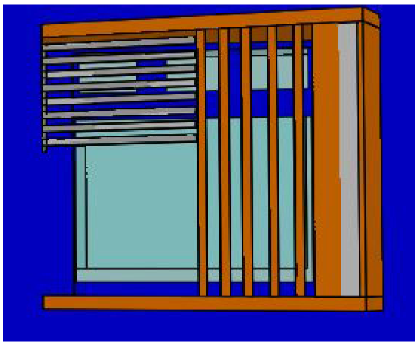
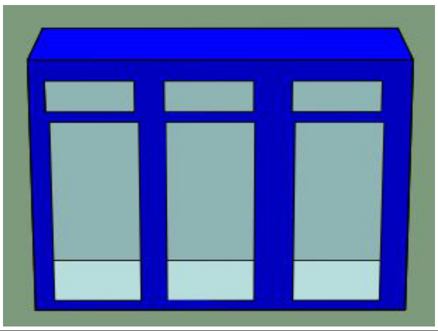
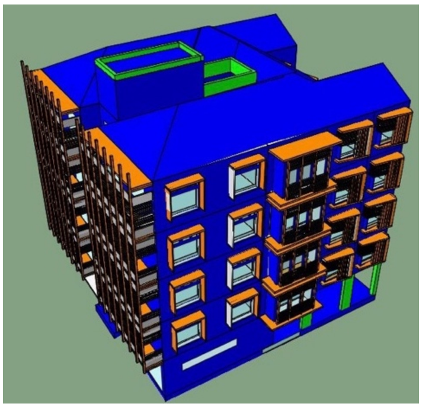
	**Strategy 1 (S1): Fixed-blade sunscreen façade implementation** **Description:** Outdoor solar shading; most effective for RTBs with south and west orientations; more frequently applied to residential buildings. Pre-oriented blades affixed to the façade; can also be applied to balconies. Blades can be vertical. **Energy-performance total** 1.146,5 kWh/m^2 **Savings** 43% **Strengths** Lower cost; single interventions are allowed; reduced construction time **Weaknesses** Less effective; thermal bridges are not avoided
	**Strategy 2 (S2): Venetian blinds or brise-soleil louvres volumetric addition** **Description:** Outdoor solar shield with adjustable, packable blinds; can also be applied to screen balconies. Blinds can be rolled up and compact when not in use. **Energy performance total** 1.084,5 kWh/m^2 **Savings** 52% **Strengths** Effective **Weaknesses** Longer construction time; greater cost; comprehensive intervention is required
	**Strategy 3 (S3): Overhanging fenestration design** **Description:** Fixed opaque overhang made of different materials; consists of horizontal and vertical elements in a grate pattern. **Energy performance total** 902,8 kWh/m^2 **Savings** 57% **Strengths** Effective; single interventions are allowed; reduced construction time **Weaknesses** Complex design

Table 6.5: Synthesis of Achievable Results of Each Strategy and Those of Base Case. (Continued)

<table>
<tr><td rowspan="5"></td><td colspan="4">Strategy 4 (S4): Venetian or roller blinds volumetric roof addition
Description:
Double-glazed, integrated into interior chamber; stored in a sealed package with desiccants to ensure humidity and condensation control.</td></tr>
<tr><td>Energy performance total</td><td>836,7 kWh/m²</td><td>Savings</td><td>68%</td></tr>
<tr><td>Strengths</td><td colspan="3">Effective; single interventions are allowed; reduced construction time; increases usable floor area</td></tr>
<tr><td>Weaknesses</td><td colspan="3">Complex design; higher construction costs</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td rowspan="4"></td><td colspan="4">Strategy 5 (S5): Fixed overhang
Description:
Fixed vertical, opaque overhang made of different materials; structurally integrated or anchored to the wall; most effective for RTBs with east and west orientations. Shields may also have a vertical arrangement perpendicular to the façade.</td></tr>
<tr><td>Energy performance total</td><td>735,4 kWh/m²</td><td>Savings</td><td>72%</td></tr>
<tr><td>Strengths</td><td colspan="3">Reduced cooling-energy consumption; optimised thermal comfort; effective; flexible interventions are allowed</td></tr>
<tr><td>Weaknesses</td><td colspan="3">Longer construction time and higher costs; comprehensive intervention is required</td></tr>
<tr><td colspan="5">*Base-case energy consumption in the peak cooling month of August was 2.081,35 kWh/m²</td></tr>
</table>

6.2.2 Implications for Energy-Policy Design

An LCCA, which referred to the net usable area, was required and a reference optimisation criterion needed to be defined to compare the energy investment with the energy demand that is needed to operate of each passive-cooling design system after implementation. The amount of embodied energy was therefore spread throughout the net-floor area, and the obtained value was converted from MJ/m^2 to kWh/m^2. The presented scenarios were studied globally, and sustainable energy-efficiency implementation measures, local construction practices and models of improvement that were suitable for the present research context were created. Table 6.6 shows the typical assumptions related to energy consumption and CO_2 emissions of the building that formed energy-optimisation measures during the pre- and post-retrofitting phases.

Table 6.6: Energy-Consumption Reduction Measures Pre- and Post-Retrofitting.

Base Case Energy, Carbon and Cost Summary		**Retrofitting Interventions Estimated Energy and Cost Summary**	
Annual Energy Cost	$4.254	**Annual Energy Cost**	$2.643
Lifecycle Cost	$60.937	**Lifecycle Cost**	$44.456
Annual Energy			
EUI*	1.218 MJ/m^2/year	**EUI**	1.214 MJ/m^2/year
Electricity	30.674 kWh	**Electricity**	22.349 kWh
Fuel	10.309 MJ	**Fuel**	8.966 MJ
Annual Peak Demand	103 kW	**Annual Peak Demand**	2,4 kW
Lifecycle Energy			
Electricity	913.423 kW	**Electricity**	640.437 kW
Fuel	218.054 MJ	**Fuel**	128.870 MJ

*EUI: Energy-use intensity

The LCCA, the aim of which was to assess the overall effect of applying all six retrofitting strategies to devise effective energy-policies, was developed in the following manner: The LCCA study-period had 30-year lifespan, and the hours-of-operation were input in the life-cycle-cost application on the IES platform as a 1,00 stipend. The Turkish Lira was not an available currency in the application, so the U.S. dollar was chosen for the LCCA analysis to ensure a globally recognised calculation rate. The data presented in Table 8.6 demonstrates energy consumption before and after the retrofitting solutions were implemented.

Annual household energy expenditures were $4.254 prior to the retrofitting, and this rate decreased to $2.643 after implementation of the PCDS. The LCCA for each RTB prototype was $60.937 in the pre-retrofitting phase; this was reduced to $44.456 post-retrofitting, which is still relatively high. The proposed PCDS will initially be introduced to the construction industry as retrofitting solutions that will require high-quality workmanship, and trained, qualified energy assessors will monitor the long-term impact of these modifications.

Implementing these passive-cooling design strategies resulted in 43–81% energy savings. Annual peak demand was reduced from 103,0 kWh to 2,4 kWh; this confirms that the households became independent of their reliance on domestic cooling appliances in the summer, which is a good indicator of energy effectiveness. Even though energy consumption was reduced from 30.674 kWh to 22.349 kWh, the energy-consumption threshold was still relatively high due to discrepancies between the actual and predicted energy use of the three occupancy patterns in the black-box energy model developed for this empirical study; extrapolating three different weather profiles to minimise discrepancies did not resolve the DTS constraints in the IES software platform.

Extensive ventilation is crucial in the summer to prevent shaded terraces from generating additional heat due to unregulated natural-ventilation systems and under-ventilated apartments. The discounted rate is a key variable for the LCCA; the energy-use intensity and the life-cycle energy use and costs of the retrofitting strategies are presented in Table 6.7. It should be noted that these costs were independently calculated in the life cycle assessment module of the IES software suite, which can be used to determine benchmarks in retrofitting efforts (Mostavi *et al.,* 2017).

Table 6.7: Energy-Use Intensity and Life-Cycle Energy Use of Base-Case RTB Costs.

Energy-Use Intensity		Life-Cycle Energy Use and Cost	
Electricity EUI*	240 kWh/m^2/year	**Life-Cycle Electricity Use**	630.570 kWh
Fuel EUI	406 MJ/m^2/year	**Life-Cycle Fuel Use**	812.600 MJ
Total EUI	1.444 MJ/m^2/year	**Life-Cycle Energy Cost**	$46.396

*EUI: Energy-use efficiency

Implementation of all six strategies decreased the amount of electricity that was required to maintain the occupants' thermal comfort for a full year; while the baseline model of energy was 2.081,35 kWh/m^2, annual energy-use intensity with these strategies was 240,0 kWh/m^2, which is a significant reduction in energy consumption. Due to the condition of the thermal-conductivity parameters, the energy-use intensity of heating- and cooling-energy demand in relation to optimum cost was approximately 630.570,0 kWh/m^2 per year. Figures 6.12(a) through (f) detail the energy use and carbon footprint of the PCDS that were implemented.

Energy Efficient Implementation Measures **Low Carbon Design Measures**

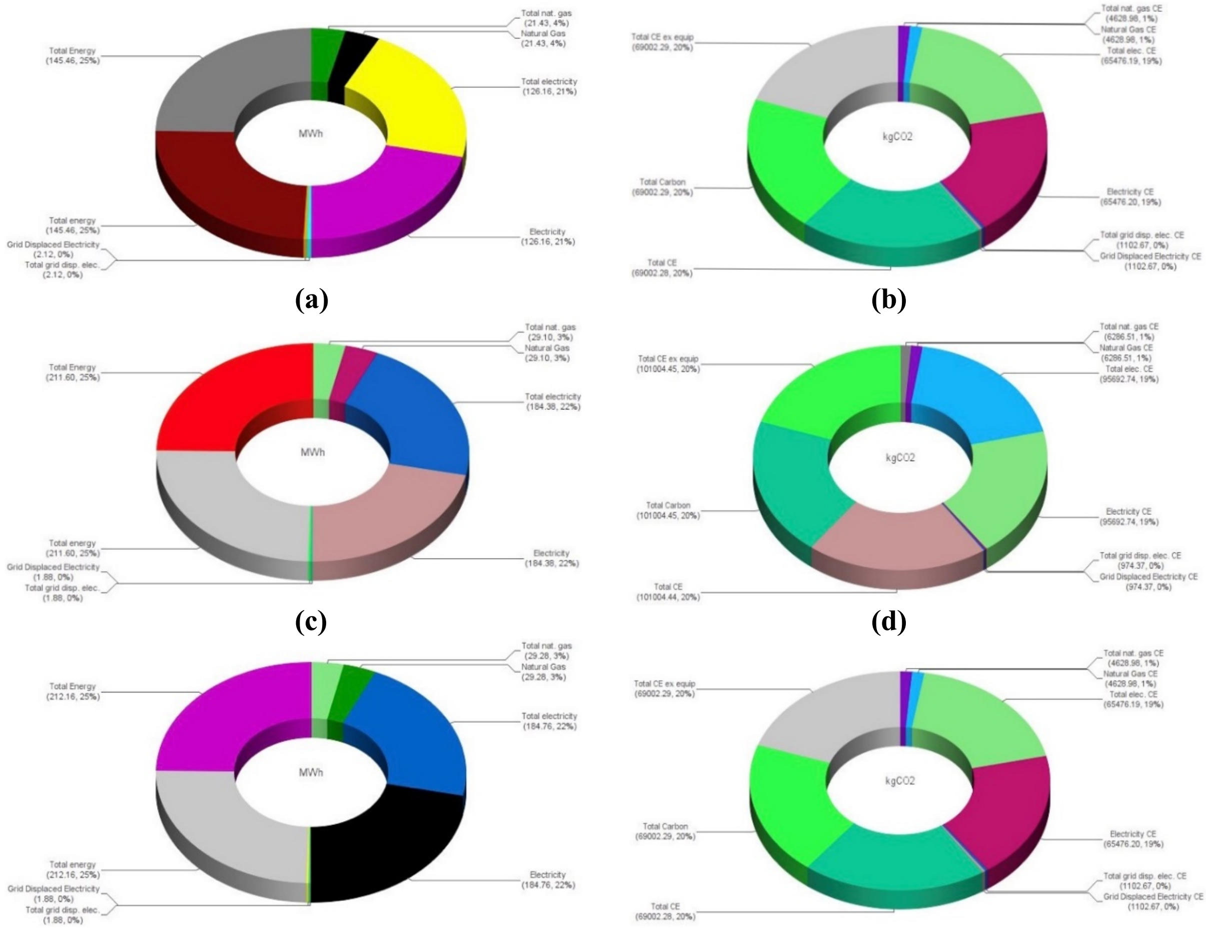


Figure 6.12: (a) Monthly electricity consumption of representative flat with low-occupancy profile (i.e., OP1); **(b)** overall first-floor CO_2 emissions; **(c)** monthly electricity use of intermediate-floor flat with medium-occupancy profile (i.e., OP2); **(d)** overall intermediate-floor CO_2 emissions; **(e)** monthly electricity use of upper-floor flat with high-occupancy profile (i.e., OP3); **(f)** overall upper-floor CO_2 emissions.

The total energy consumption for the representative first-floor flat, which is shown in Figure 6.12(a), was 145,46 kWh, total electricity usage was 126,16 kWh, actual household energy consumption peaked at 1.223 kWh, mean energy consumption was 374,58 kWh, and the standard deviation (*SD*) was 262.500,0 kWh. The BES analysis determined that energy-consumption in August peaked at 999,4 kWh before the retrofittings, and energy consumption after the retrofittings was below the mean energy-consumption levels; the significant reduction in energy use also had a direct impact on the CO_2 emissions, which is shown in Figure 6.12(b).

Total energy consumption in the intermediate-floor flat after implementation of all six PCDS, which is shown in Figure 6.12(c), was 211,6 kWh, total electricity usage was 184,38 kWh, actual household energy consumption peaked at 1.233,0 kWh, mean energy consumption was 374,58 kWh and the *SD* was 262,5 kWh; the simulation prediction demonstrated that total energy consumption on a hot summer day peaked at 2.755,2 kWh. The intermediate-floor flats consumed relatively high levels of energy due to additional heat gains from the flats located above and below these units. Notably, flats with the Type 2 occupancy pattern (i.e., moderate) also had this effect. These were mostly occupied by retired couples who were 65-years-of-age and older and looked after their grandchildren from 08:00–17:00 while they were on school holiday; these residents kept their windows opened for natural ventilation and to dissipate dirty air. Moreover, CO_2 emissions, which are shown in Figure 6.12(d), were reduced to 101.004,45 ppm.

Total energy consumption of the upper-floor flat, which is shown in Figure 6.12(e), was 212,6 kWh actual household energy peaked at 1.223,0 kWh, and peak electricity consumption was 1.591,3 kWh; the simulation predictions were slightly higher than actual energy consumption because of the dominant representative occupancy type (i.e., OP3) that was assigned in the black-box model for this study (Bamdad *et al.,* 2020). Energy consumption post-retrofitting was reduced from 1.591,3 kWh to 212,6 kWh; this significant reduction confirms the energy effectiveness of the PCDS, which also reduced CO_2 emissions, as shown in Figure 6.12(f).

These findings demonstrate that input parameters (i.e., benchmarks), such as life-cycle data and the discount rate of the price of energy, should be carefully planned for. Furthermore, energy-efficiency measures can improve indoor-air quality and reduce overheating risks throughout the building (Harputlugil & de Wilde, 2021). In addition to directly impacting energy consumption, household energy bills will also be significantly reduced (Gupta & Gregg, 2018).

When the PCDS were applied to the other prototype RTBs, economic and energy-performance analyses were performed to determine the feasibility of these retrofitting scenarios. These assessments confirmed that based on the significant energy-cost savings, decreased energy usage and lower CO_2 emissions, the proposed retrofitting interventions should be considered so the existing housing stock in Cyprus can be renovated in a systematic manner to achieve significant energy savings.

6.3 Discussions

The present study elucidated the potential applicability of passive-cooling design strategies in various retrofitting interventions to improve the energy efficiency of existing residential buildings. Based on this study, passive-cooling design principles resulted in significant reductions in energy consumption and optimised thermally comfortable indoor air for occupants, as shown in Figure 6.13. This important finding needs to be further explored by robust energy performance certification schemes, which will provide a wider domain to assess and optimise the risk of overheating and better understand occupants' thermal comfort when seeking to enhance 'night cooling' effects in RTBs in the south-eastern Mediterranean climate.

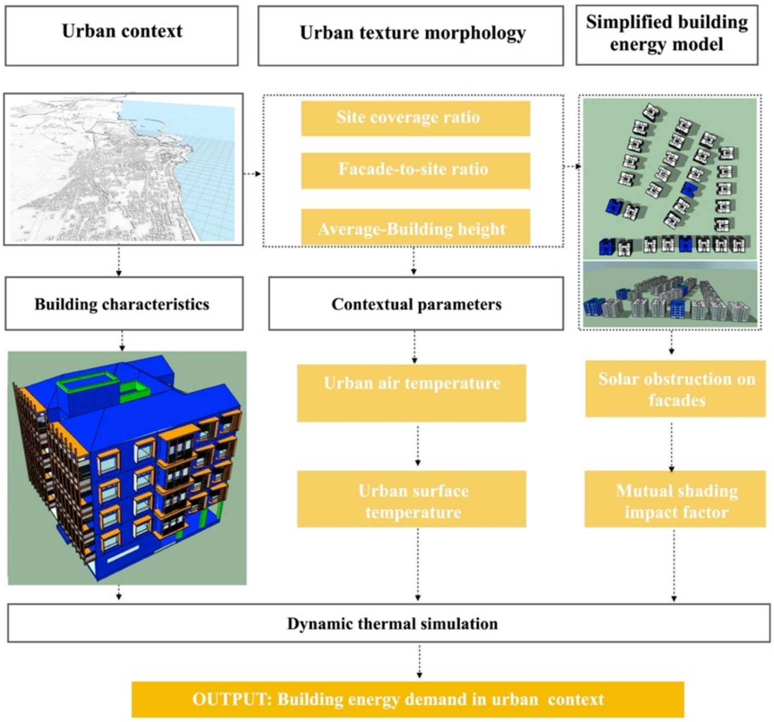
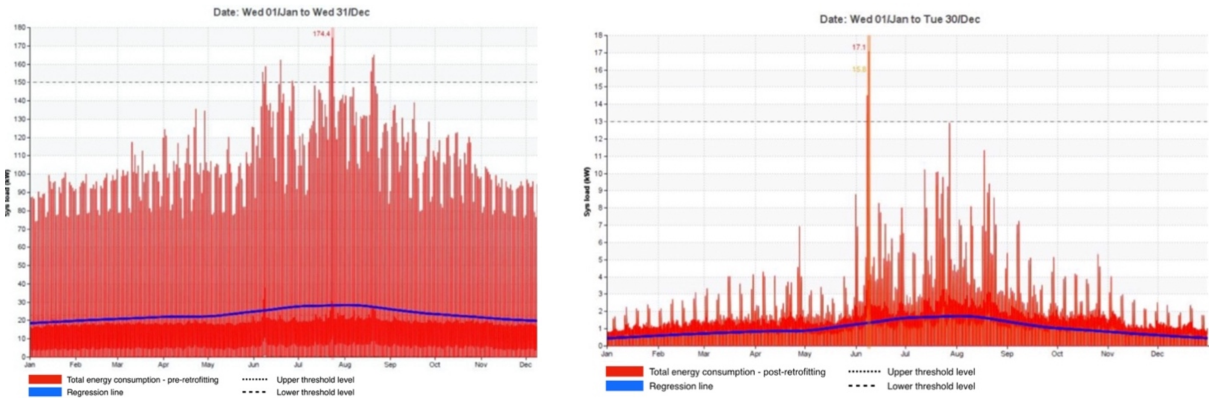


Figure 6.13: Development stages of building energy modelling and its impact on the built environment.

Implementation of the EPCs at the household- and building-level is seen by stakeholders and government initiatives as a decisive factor for the successful transition of the EPBD objectives; yet one that has thus far not been fully realised (Dell'Anna, 2020). Uptake by an evidence-based STS approach will be key for the adoption of energy-conscious retrofitting technologies that will grow from this void (Bolwig *et al.,* 2020). The following discussion is structured according to the research question that guided the building energy modelling of this study—(RQ-3): What are the determinants of energy use in archetype RTBs, and to what extent do retrofitting options have the potential to achieve optimum indoor comfort conditions?

6.3.1 Energy Performance

The simulation results were analysed to better understand existing energy-use conditions and to calibrate energy-consumption patterns, especially those related to the cooling demands of the representative first-, intermediate- and upper-floor flats. When examining energy consumption as it relates to specific heat loss, the prototype flats consumed 237,1 kW of energy during the pre-retrofitting phase and 140,2 kW during the post-retrofitting phase due to implementation of PCRDS onto the existing building envelope. Figures 6.14(a) and (b) detail the overall energy performance of the three representative flats for the base-case scenario development.



(a) (b)

Figure 6.14: Total electricity consumption of representative base-case RTBs; **(a)** before retrofitting and **(b)** after retrofitting.

Energy consumption prior to the retrofittings, which is shown in Figure 6.14(a), was 174,4 kWh, mean energy consumption fluctuated within the range of 20–25 kWh with an upper energy-consumption limit of 150 kWh, and mean actual energy consumption was 374,58 kWh. Actual household energy consumption, which was higher than the simulation prediction, was determined by the energy-bill data for 100 flats; as was previously explained, discrepancies between predicted and actual energy use were due to the three different occupancy patterns (i.e., OP1, OP2 and OP3) that were assigned in the black-box model for the DTS analysis.

According to peak cooling-energy consumption post-retrofitting, which is shown in Figure 6.14(b), was 17,1 kWh, mean energy consumption fluctuated between 0,8–1,5 kWh with an upper energy-consumption limit of 13,0 kWh, and peak energy-consumption between June and September of 2016 fluctuated between 2,5–11,5 kWh. Implementing these passive-cooling strategies resulted in an 81% reduction in energy consumption during peak summer-cooling demand, which confirms that the differences in energy use before and after the retrofittings can be correlated with energy management; this suggests that the energy-usage ranges obtained from the BES analysis can be applied as a benchmark to confirm the energy effectiveness of PCDS for future energy-policy decisions.

The adaptive comfort temperatures in the present study represented an acclimatisation system set-point of 21°C, which was autonomously managed by the occupants according to external climate conditions. During the peak cooling summer season, the occupied spaces displayed significant differences from the adaptive temperature set-point for heavy construction materials, especially for the base-case model, according to the occupants' energy-use patterns and comfort levels in different seasons (Hellwig *et al.,* 2020). Figures 6.15(a) through (d) depict the mean cooling-energy sensible load of the representative flats in the pre- and post-retrofitting phases between May and September, taking the time-of-day factor into account.

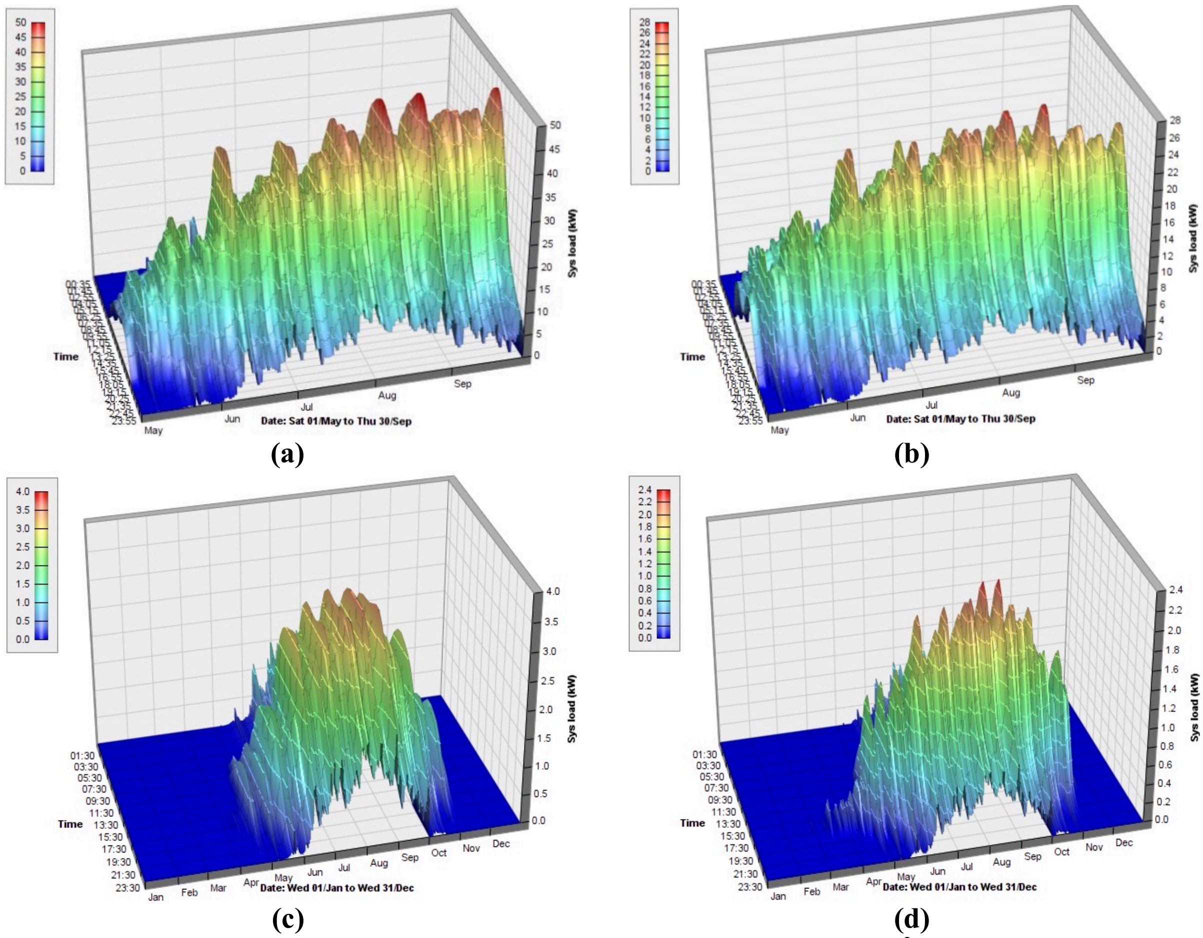


Figure 6.15: **(a)** Room-electricity plant-sensible loads reached 50 W/m^{2}K between May 1 and September 30 during pre-retrofitting phase; **(b)** decreased to 28 W/m^{2}K in August; **(c)** reached 4,0 W/m^{2}K during peak cooling season; and **(d)** decreased to 2,4 W/m^{2}K in August. ***Note:*** Statistical graphs demonstrate energy-fluctuation time series on typical day between May 1 and September 30.

As shown in Figure 6.15(a), the mean peak cooling sensible load decreased from 50 kWh to 28 kWh during the cooling period; these results revealed that a 43% cooling-energy consumption reduction was achieved after the retrofitting interventions were applied. These graphs depict the time-of-day factor as it relates to cooling sensible load-fluctuations to demonstrate the highest peak of mean energy consumption in the summer; prior to retrofitting, peak cooling was required in the middle of August between 11:05–13:25, when the peak reached 50 kWh, but this decreased to a median peak of 28 kWh post-retrofitting.

Figures 6.15(b) and (c) demonstrate the mean cooling-energy sensible load of the representative flats between January and December in the pre- and post-retrofitting phases. According to these results, when all six strategies were implemented onto the building envelope, the cooling-sensible load between May and September decreased from 4,0 kWh to 2,4 kWh.

Notably, the cooling-consumption pattern that is depicted in Figure 6.15(d) reveals that there were variations after all six strategies were implemented; starting at the beginning of April of 2018, cooling-energy consumption was 0,5 kWh, and it was 1,8 kWh in the first week of November. The results suggest that even though substantial overall energy-consumption reduction was achieved, occupants will still need to use some type of domestic cooling appliances to optimise their thermal comfort; his is due to the occupants' socio-demographic characteristics and occupancy patterns, which directly influence thermal adaptability, in addition to physical conditions that are determinant factors on cooling-energy use. Notably, the occupants' cultural assets that were gathered through the regression forecasting analysis, such as their neutral adaptive thermal-comfort threshold 28,5–31,5°C, are among the important factors that affects their adaptability in any physical environment.

It should be highlighted that the small proportion of cooling-energy use shown in Figure 6.15(d) that was still needed after the six strategies were implemented suggests that PCDS would not make the prototype RTB completely independent of mechanical cooling. Further research is required to assess the energy effectiveness of PCDS in the south-eastern Mediterranean climate.

One of the significant findings of this study was that cooling-energy consumption decreased by 81% after all six passive design strategies were implemented. These conclusions will create the prerequisites and the background information that is needed for the development of a novel methodological framework and a ground-breaking epistemological design approach in the area of development and design, energy-related policymaking, the drafting of subsidisation schemes and targeted actions to improve the energy efficiency of existing housing stock.

The novelty of this study could mean, however, that the retrofitting interventions developed herein may not be economically feasible with current energy-efficiency policy targets, even though the applicability of the research context and the recommended EPBD objectives from the EU may lead to an increased demand for domestic-cooling options. As such, it can be asserted that the economic and environmental benefits of these strategies are mutually supportive of one another and addressing current methods of design related to thermal comfort, overheating risk and building optimisation will eventually lead to a win–win situation.

6.3.2 RoadMap to EU Energy-Policy Framework

Importantly, the present study reveals typical household awareness of energy use and provides a cultural assessment to develop a methodological framework for building optimisation at the policy level. This novel benchmark criterion could radically change the manner in which energy development studies evaluate and optimise the energy efficiency of residential buildings in post-war social-housing developments and would significantly increase the likelihood of implementing different strategies, which would in turn encourage early-stage designs and policy decision-making related to domestic energy use.

These findings suggest that EPCs do not correlate with the actual thermal performance of dwellings when energy-efficient retrofitting interventions are implemented during the decision-making process (Arcipowska *et al.,* 2016; Niskanen & Rohracher, 2020). This has led to current energy-consumption estimates and savings potentials that do not accurately reflect what actually happens in practice during retrofitting efforts (Dascalaki *et al.,* 2016; Levi, 2021). For this reason, policymakers will need to review prominent methodological approach to implement effective retrofitting solutions that will take local contextual factors, including a socio-technical evaluation of a given society, into account (Galvin & Sunikka-Blank, 2014; Nematchoua *et al.,* 2021). The present study recommends that an emphasis should be placed on conducting longitudinal and transverse surveys with households to avoid underestimating the impact of retrofitting interventions due to the technical challenges of implementing any type of holistic retrofitting intervention.

The scope to conduct a building energy simulation in this study was limited to input parameters that were obtained from longitudinal field surveys, the archetype building analysis and the results that demonstrated that the differences in energy use between the existing state of a building and one that has been retrofitted were correlated with the degree of energy management after cost-effective energy-efficient systems were implemented; this study limitation will, however, provide future opportunities for additional research.

6.4 Summary

In the present empirical study, the thermal performance of building elements in a base-case post-war social-housing estate in Famagusta, Cyprus was analysed, and different retrofitting efforts were undertaken to optimise the energy performance of each structure. The objective of this study was to develop evidence-based passive-cooling retrofitting design strategies to improve the occupants' thermal comfort and reduce the overheating risks in the base-case RTBs. This study employed a socio-technical-systems (STS) approach to develop a bottom-up energy-policy framework for the residential sector.

The results indicate that indoor-air temperatures in Famagusta, Cyprus follow a consistent pattern throughout the month of August. Indoor-air temperatures in the sample units range from 28,5–36,5°C throughout the day and night; this lack of diurnal temperature variation suggests that internal operative air temperatures (OTs) remain relatively high and do not induce cooling at night. Furthermore, the external building fabric, uninsulated roof and three exposed wall surfaces were found to be key determinant factors due to the high *U*-value of the building properties, the surface area and the amount of solar-gain exposure, all of which resulted in high heat transmittance into and out of the upper-floor flats and had a significant effect on the OTs of all the flats.

In the non-retrofitted buildings, 73% of the total energy consumption was for cooling and heating. Six different passive-cooling design strategies were analysed, and after the LCCA of each was considered, off-site modular building applications were developed and implemented. After the buildings were retrofitted, cooling consumption was reduced by approximately 81%; this confirms that considering design, ventilation and servicing strategies and implementing passive shading systems, which was previously recommended by the EPBD objectives, will improve the energy efficiency and indoor-air quality of residential buildings. Furthermore, energy models that were calibrated via temperature monitoring resulted in less-extreme energy-performance gaps than model validation that simply replaced the design values with the simulation results.

Insights from this study will enhance the national energy network for Cyprus and improve subsidisation schemes throughout Europe. Moreover, energy policies and regulations will benefit from a conceptual-level analysis of the climate characteristics of each EU member state, as this will allow more accurate planning.

Chapter 7

Conclusions

A number of significant advances were made in the present study to provide a comprehensive understanding of the thermal performance of archetype residential buildings and occupant thermal-comfort levels; the findings allow direct comparison, where applicable, against the objectives of this thesis (see Section 1.1 in Chapter 1).

A literature review was undertaken to fill the existing knowledge gap in four key areas: building overheating risks, thermal comfort, occupant behaviour and energy modelling. Occupancy patterns and habitual household adaptive behaviours were already known to be significant determinant factors related to home-energy performance, but occupant thermal comfort in relation to the development of a socio-technical-systems (STS) conceptual framework had not been addressed, and existing available data on the neutral adaptive thermal comfort of social housing residents were not found in the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) Global Thermal Comfort Database II. It was therefore determined that a quantitative assessment of the thermal performance of the building fabric of representative residential tower blocks (RTBs) in a post-war social housing estate in the subtropical (*Csa*) and partly semi-arid (*Bsh*) South-eastern Mediterranean climate, along with a quantitative assessment of social housing occupants' thermal-preference votes (TPVs) and thermal-satisfaction votes (TSVs), would provide valuable input for the global database.

Accordingly, the present empirical study introduced selection criteria for housing stock and developed evidence-based retrofitting design interventions by conducting an *on-site* questionnaire survey and recording *in-situ* physical measurements for a variety of building envelopes to assess the overheating risk assessment of the base-case RTBs. This study utilised an exemplar energy policy design strategy whereby data was collected through a comprehensive methodology that was then applied to the RTB prototypes; this will contribute to the limited number of published reviews related to retrofitting efforts for high-density residential buildings in Europe. The present study explored the reason the building-energy-performance evaluation method was chosen, utilised a standardised assessment procedure to investigate actual energy use and assessed the study findings against existing international thermal-comfort benchmark criteria.

A comprehensive methodological framework to develop energy-performance certificate (EPC) schemes in Northern Cyprus (NC) was presented in this thesis. The primary research question (RQ) that was addressed was: What is the most effective and universally applicable energy policy framework to implement the EPBD mandates recommended by the EU and improve the energy efficiency of existing housing stock in NC? This research question set out to contribute to the body of knowledge an integration of the human-based approach in modelling; it emphasises the importance of an STS conceptual framework to investigate housing-energy use and CO_2-emission reductions with the aim of improving the overall understanding of the complex issue of occupancy patterns as they relate to energy use. Even though scholars have previously conducted building energy modelling and *on-site* environmental monitoring to assess the overheating risk of residential buildings, the present study applied these methodologies to fully explore the existing building performance of the case-study RTBs by understanding the *in-vivo* experiences of social housing residents related to their home-energy performance and occupancy patterns. This is a novel approach for testing the effectiveness of different retrofitted design strategies as part of the development and integration of EPBD mandates in the housing sector.

The following research outcome is structured according to the RQs that guided the findings obtained through subject respondents' thermal-sensation votes and the findings of both *on-site* environmental monitoring and *in-situ* physical measurements of households' indoor occupied spaces. These methods were adopted in response to RQ-1: How do environmental factors affect occupant thermal comfort and how can neutral adaptive thermal-comfort thresholds be identified in this South-eastern Mediterranean climate?

Other variants that were considered in the present study included the physical features of the built environment (i.e., site layout plans and different building orientations and floor levels). When the occupants' reasons for thermal comfort were included as a dependent variable, a moderate-strong relationship was found between orientation and reasons for thermal discomfort (*Fisher's Exact* = 39,52, p < 0,001, Cramer's V = 0,405). Individual levels of thermal comfort were not limited to household socio-demographic characteristics, however; environmental factors were also determinants in the development of adaptive thermal-comfort theory. Furthermore, floor level was moderately related to reasons for thermal discomfort (*Fisher's Exact* = 17,16, p = 0,037, Cramer's V = 0,233). A greater proportion of participants living at ground level felt thermal discomfort due to humidity than participants living at third-fourth levels. An ordinal logistic regression was performed, and the result revealed a marginally significant relationship between operative air temperature and households' overall summer temperature satisfaction, OR = 0,958 (95% CI [0,918, 1,000]), p = 0,050, *Nagelkerke* R^2 = 0,042. Marginal significance means the p values between 0,05 and 0,1, indicating that there is a trend relationship but did not reach a statistical significance. The occupants' TSVs indicated that in a South-eastern Mediterranean climate, 28,5 °C is considered a neutral temperature, and the upper limit of the indoor-air thermal-comfort range is 31,5 °C.

According to the ASHRAE Global Thermal Comfort Database II, occupants' thermal acceptability in the South-eastern Mediterranean climate ranges from 25 to 30 °C on hot summer days; the thermal acceptability of households in multi-family social housing RTBs was +1,5 °C higher than that of the sampling size included in the ASHRAE database. The comparable sample in the database was developed in 2005 by Bouden and Ghrab and represents a small sample population in Tunisia. Notably, there was not a sampling population available in the ASHRAE Global Thermal Comfort Database II that represented the South-eastern Mediterranean climate in Europe; due to the limited sampling size, the 28,5–31,5 °C neutral adaptive thermal-comfort threshold proposed in the present study could not be effectively compared with Fanger's predicted mean vote method for thermal comfort. This is an important outcome of the methodological framework developed in this study – it contributes to current adaptive thermal-comfort studies. The ASHRAE Global Thermal Comfort Database II is the result of a project led by an international team of experts to collate field measurements of thermal comfort for public use. The dataset of this present PhD thesis is a valuable contribution to the ASHRAE Global Thermal Comfort Database II. The field study in the South-eastern Mediterranean climate of Cyprus is a unique context and a noteworthy addition to this public source.

This is the first study to undertake a longitudinal analysis of a field investigation on the development of the adaptive thermal comfort of households in the South-eastern Mediterranean climate. The present study provided an important opportunity to advance the current knowledge of adaptive thermal-comfort theory in the Cypriot context in the following ways: *(i)* it questioned existing adaptive thermal-comfort models for naturally ventilated residential buildings; *(ii)* it developed a novel framework that combined an assessment methodology with existing benchmark criteria for thermal comfort; and *(iii)* it demonstrated *in-vivo* experiences of subject respondents' thermal-sensation votes to analyse individual aspects of adaptive thermal comfort and influences on the validity of feed-forward interviews gathered through a questionnaire survey.

The present study makes a major contribution to research on the development of a thermal-comfort assessment benchmark criteria as the present study was used to systematically evaluate the results obtained from the questionnaire survey and environmental monitoring. The primary data demonstrates the actual numeric experimentation of a 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 Bedford in 1946 and Fanger in 1970 and a scientific conceptual framework developed by Nicol and Humphreys in 2002.

The following research outcome is structured according to the RQs that guided the findings through the thermal-imaging survey and building performance evaluation of representative archetype buildings by developing a universally acceptable energy policy framework for the South-eastern Mediterranean Cypriot climate. Specifically, this outcome addresses RQ-2: ‘How will this empirical study contribute to and inform the design of net-zero energy buildings in EU countries?’

The empirical model that was created for this study addressed the development of an evidence-based STS conceptual framework that could explore the influence of building thermal properties on occupant thermal comfort; the results revealed relatively warm global temperatures ranging from 24,5 to 37,0 °C. According to the CIBSE TM59 Criterion 1, the upper thermal-comfort limit for this region is 33 °C, yet the *on-site* monitoring in this study recorded a maximum outdoor temperature of 38,7 °C, and the *in-situ* measurements revealed indoor-air temperatures that ranged from 25 to 35 °C, which is well above the acceptable threshold limits.

The building performance evaluation studies revealed that there were significant signs of overheating risks, and these indoor-air temperatures negatively affected the occupants’ physiological thermal adaptation to their environments; elevated temperatures fluctuated with high and low peaks, but always rose above the recommended 25 °C upper thermal-comfort threshold. Notably, the highest indoor-air temperatures were predicted August 14–16, and they reached 37,3 °C on August 28; a peak outside temperature of 43,2 °C was recorded on August 16 at 14:55 by the weather station that was installed on the site.

Even though the recommended overheating threshold is 28 °C, the indoor- and outdoor-air temperatures followed a pattern of overheating. Peak indoor-air temperatures were recorded +5,3 °C above the comfort-level zone, and the regression line fluctuated between 25 and 27 °C, which is near or above the upper comfort-threshold margin. These fluctuating temperatures could be perceived as acceptable thermal-comfort levels, however, due to the psychological adaptation of the occupants to their local climate. Taken together, these results suggest an association between the *U*-values of building properties and the occupants' thermal comfort. The daily variation ΔT exceeded a 6,2 °C increase-per-hour on several occasions over the simulation period in August, which highlights the importance of considering *on-site* environmental monitoring data when assessing overheating risks and developing neutral adaptive thermal-comfort thresholds.

Owner-occupier residents reported that they felt thermally comfortable in warmer indoor-air temperatures than those recommended by international standards such as *ISO EN 7730:2005* and *EN 15251:2007*. Previous scholarly work that focused on the South-eastern Mediterranean climate found that occupants felt thermally comfortable within the 19–33 °C range; these different threshold limits were because the associated studies were conducted in a climatic chamber with control variables to represent optimal thermal-comfort conditions. However, the empirical model for the present study was based on a case study and application of a longitudinal field survey; as such, the findings of this study represent actual scenarios for the development of accurate neutral adaptive thermal-comfort measures in Cyprus.

The following research outcome is structured according to the RQs that guided the findings of a novel methodological framework for the optimisation of post-war social housing developments in the South-eastern Mediterranean climate. RQ-3: What are the main determinants of energy use in archetype RTBs, and to what extent do retrofitting options have the potential to achieve optimum indoor comfort conditions?

Building energy simulations were conducted to confirm the validity of the neutral adaptive thermal-comfort thresholds. The results indicated a lack of diurnal temperature variations within the sample flats, which suggests that internal operative temperatures remained relatively high throughout the day and night; indoor-air temperature ranged from 28,5 to 36,5 °C, and there was a difference of +5 °C between the actual and the simulated-and-predicted operative-air temperatures. The 36,5 °C upper thermal-comfort threshold identified in the building-energy-simulation analysis was +3,5 °C higher than the recommended thermally acceptable threshold for hot Mediterranean climates in the summer.

The study findings can be extrapolated by current industry benchmarks or assessment criteria as a new European Norm (EN) that can be adopted by other EU countries. The present study is the first to follow the recommended methodology laid out in *EN 15251*. To date, no other studies have focused on the development of this particular *EN 15251* standard; as such, the present study developed an STS conceptual framework to provide a significant contribution to the body of knowledge related to a novel methodological framework for BPEs.

Insights from this study will enhance the national energy network for Cyprus and improve subsidisation schemes throughout Europe. Moreover, energy policies and regulations will benefit from a conceptual-level analysis of the climate characteristics of each EU member state, as this will allow for more accurate planning. The application of passive cooling design strategies from an archetype post-war social housing estate to the regional scale retrofitting of high-density residential buildings will result in the effective development of EPC schemes for occupants and policymakers alike. In addition to this, the present study attempts to fulfil EEG to contribute to the EU Horizon 2030 framework and retrofitting initiatives among the EU member states that currently implement similar energy policies, most specifically the other southern EU member states that have similar building regulations. The impact of implementing evidence-based retrofitting strategies will be beneficial for society, as these strategies will result in the development of effective and engaged local communities for whom energy efficiency–awareness improvement involves the social, economic and natural ecologies of their contextual sites.

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Appendix A: National Representativeness of Housing Stock

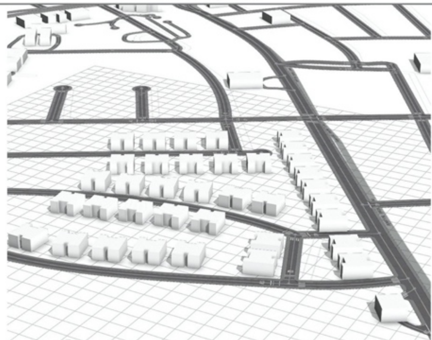
Mapping of the post-war social housing development estates in the South-eastern Mediterranean island of Cyprus - M.1						
Location	**Climate Zone -Type**	**Housing Type**	**Built Year**	**Google Map ArcGIS Online Database**	**3D Render Model ArcGISPro Database**	**Image**
Famagusta City centre	**Coastal ASHRAE - 2A**	**RTB Urban - City Centre**	**1987-1996**			
Famagusta Agios Loukas	**Coastal ASHRAE - 2A**	**Terraced House Urban - Natural lake region**	**1986-1990**			
Famagusta UN Military Camp Zone	**Coastal ASHRAE - 2A**	**RTB Urban - City Centre**	**1993-1996**			

Figure A.1: Taxonomy of high-density post-war social-housing developments including location, climate zone, land-use planning and RTB orientations in coastal city Famagusta located on eastern side of island.

Appendix A: National Representativeness of Housing Stock

Mapping of the post-war social housing development estates in the South-eastern Mediterranean island of Cyprus - M.2

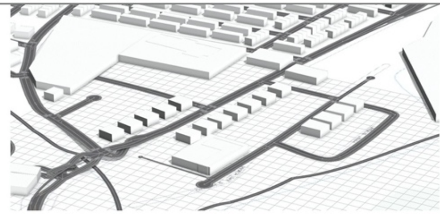
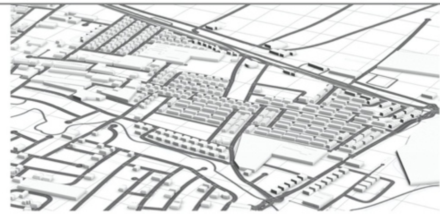
Location	Climate Zone -Type	Housing Type	Built Year	Google Map ArcGIS Online Database	3D Render Model ArcGISPro Database	Image
Nicosia Metehan Agios Dometios	**Inland ASHRAE - 3A**	**Terraced house - Urban agglomeration**	**1993-1997**			
Nicosia Taskinkoy	**Inland ASHRAE - 3A**	**RTB - City centre**	**1993-1997**			
Nicosia Gocmenkoy	**Inland ASHRAE - 3A**	**Terraced house - City Centre**	**1986-1991**			

Figure A.2: Taxonomy of high-density post-war social-housing developments including location, climate zone, land-use planning and RTB orientations in capital city Nicosia, located on southern side of island.

Appendix A: National Representativeness of Housing Stock

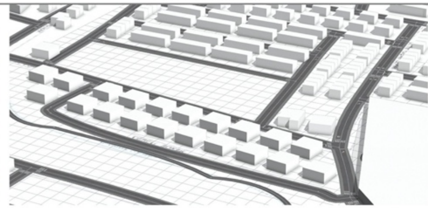
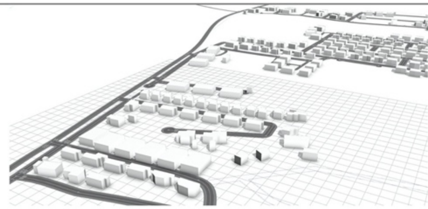
Mapping of the post-war social housing development estates in the South-eastern Mediterranean island of Cyprus - M.3						
Location	**Climate Zone -Type**	**Housing Type**	**Built Year**	**Google Map ArcGIS Online Database**	**3D Render Model ArcGISPro Database**	**Image**
Nicosia Taskinkoy	**Inland ASHRAE - 3A**	**RTB Urban - City Centre**	**1990 - 1993**			
Nicosia Kucuk Kaymakli Omorfita	**Inland ASHRAE - 3A**	**RTB Urban - City Centre**	**1993-1996**			
Kyrenia Bogaz Police Houses	**Inland ASHRAE - 3A**	**RTB Urban agglomerat ion**	**1993-1996**			

Figure A.3: Taxonomy of high-density post-war social-housing developments including location, climate zone, land-use planning and RTB orientations of in capital city Nicosia and urban agglomerations thereof, located on south-western side of island.

Appendix A: National Representativeness of Housing Stock

Mapping of the post-war social housing development estates in the South-eastern Mediterranean island of Cyprus - M.4

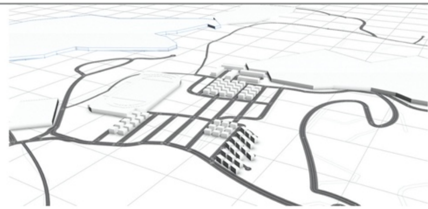
Location	Climate Zone - Type	Housing Type	Built Year	Google Map ArcGIS Online Database	3D Render Model ArcGISPro Database	Image
Kyrenia	**Coastal - Mountainous - ASHRAE 4A**	**RTB Urban - City Centre**	**1990 - 1993**			
Kyrenia	**Coastal - Mountainous - ASHRAE 4A**	**Terraced House Urban - City centre**	**1986 - 1990**			
Lefke	**Coastal - Semi-mountainous - ASHRAE 4A**	**RTB Urban - City Centre**	**1993 - 1996**			

Figure A.4: Taxonomy of high-density post-war social-housing developments including location, climate zone, land-use planning and RTB orientations of coastal cities Kyrenia, located on northern side of island, and Lefke, located on western side of island.

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Appendix B: Pro-Forma Questionnaire Survey

UEL
University of East London

Investigation of Household Heating- and Cooling-Energy-Consumption Patterns and Thermal Comfort Survey Questionnaire

This survey is part of a PhD research undertaken at the Graduate School - School of Architecture, Computing & Engineering, University of East London, to assess overheating risk and occupant thermal comfort in 36 residential tower blocks (RTBs) in a post-war social-housing estate development in Famagusta, Cyprus. The aim of this survey questionnaire is to evaluate and assess the indoor air environment of sample flat units to identify the worst-case RTB prototype. This study also intends to propose cost-effective retrofitting design strategies that would bring about significant energy savings in the residential sector. Your input is vital in collecting a large, representative sample of data.

Please take a few minutes to answer the questions and please note that the generated data will be retained and safely stored in accordance with the university's policy of academic integrity. Furthermore, the information you provide will be treated with the utmost confidentially and neither your name nor any detail that could reveal your identity will be recorded. The collected data will be analysed for purely statistical purposes. The data are secure, and your complete anonymity is guaranteed.

Please try to give the most complete and accurate information to the best of your knowledge. It is especially vital that energy-consumption figures, details of energy consumption and particulars regarding treated areas are provided as accurately as possible. Any further comments or explanations are welcome in the space provided at the end of the form. The form is filled out by the researcher in the course of the interview process itself. The form was designed to allow the researcher to complete and fill answers directly onto the survey form. This interview will probably last a maximum of 25 minutes.

Many thanks in advance for your kind contribution. If you have any questions at any point of the interview process, please do not hesitate to ask me

Sincerely,
Bertug Ozarisoy
PhD Researcher, Graduate School - School of Architecture, Computing & Engineering, University of East London
E-mail: u1542178@uel.ac.uk

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Figure B.1: Descriptive information related to survey aim and objectives.

Appendix B: 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

2

Figure B.2: Questions intended to record physical and environmental parameters and household socio-demographic characteristics.

Appendix B: 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.

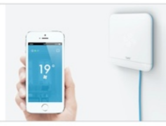
☐ Central cooling system ☐ A/C split unit ☐ A/C inverter split unit ☐ A/C portable unit____

☐ 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	

3

Figure B.3: Questions related to household occupancy patterns and types of cooling systems.

Appendix B: 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	

4

Figure B.4: Questions related to household cooling-energy-use patterns and types of heating systems.

Appendix B: 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);____________

5

Figure B.5: Questions related to household heating-energy-use patterns and habitual window-opening behaviour and schedules in summer.

Appendix B: 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); ________

6

Figure B.6: Questions related to built-environment factors that impacted household TSVs.

Appendix B: 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

7

Figure B.7: Questions related to household health and income.

Appendix B: 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	**Bottom**
☐ Short-sleeved shirt	☐ Trousers
☐ Long sleeved shirt	☐ Knee-length skirt
☐ Walking Shorts	☐ Suit vest
☐ Jeans	☐ T-shirt
☐ Athletic sweat pants.	☐ 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	☐ Seated
☐ Relaxed, standing	☐ Light activity, standing
☐ Medium activity, standing	☐ High activity
☐ Reclining	☐ Seated
☐ Cooking, standing	☐ Light activity standing
☐ Medium 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)	☐ Humidity too low (dry)	☐ N/A
☐ Air movement too high	☐ Air movement too low	
☐ Incoming sun	☐ Heat from home appliances	
☐ Drafts from windows	☐ Draft from vents	
☐ Thermostat is inaccessible.	☐ Thermostat is adjusted by other household members	

☐ 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:

8

Figure B.8: Thermal-comfort assessment.

Appendix C: Thermal-Imaging Survey

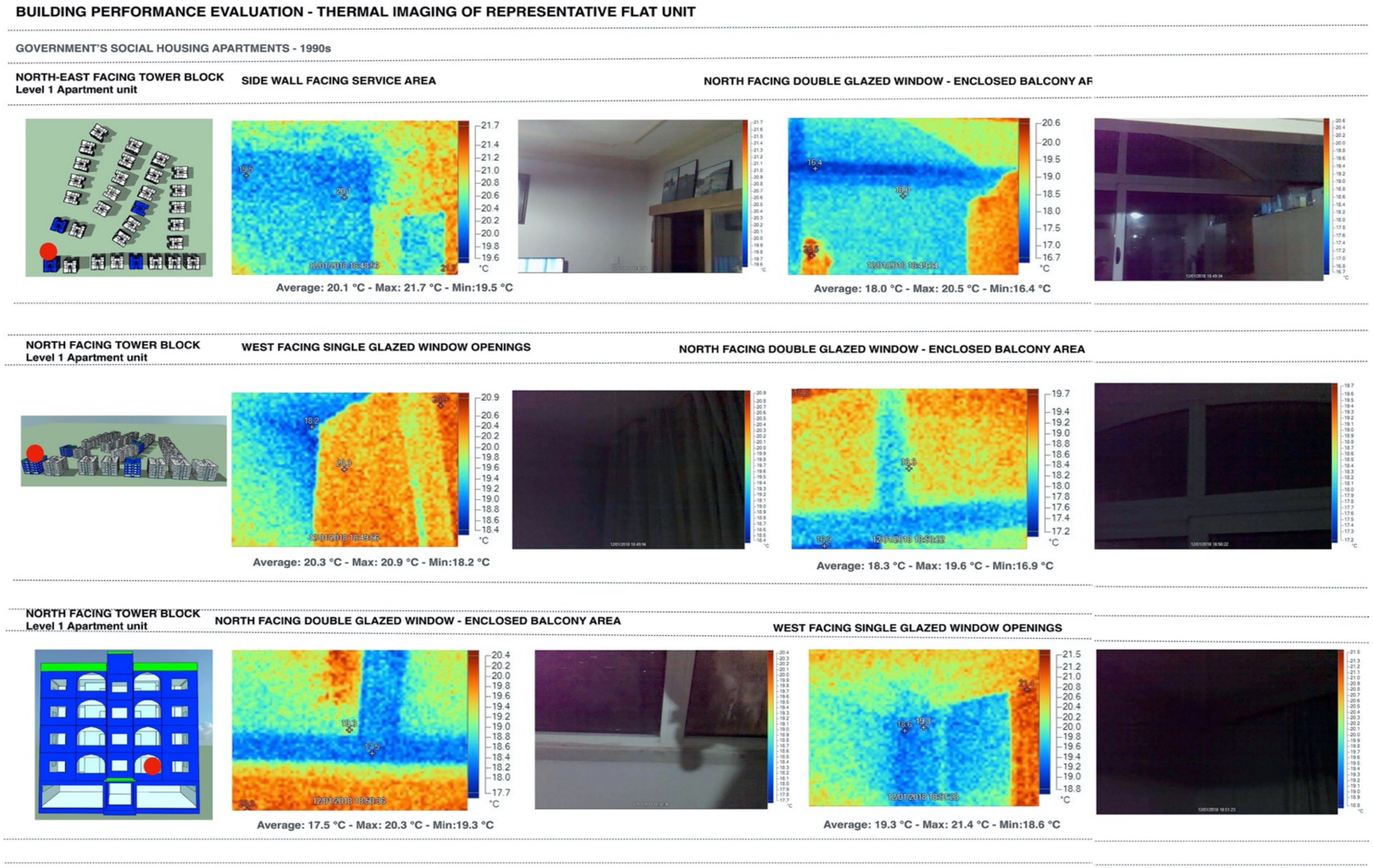


Figure C.1: Distribution of building component heat loss; household information collected when thermal imaging survey conducted in winter of 2018 to inform questionnaire survey prior to undertaking field study in August of 2018.

Appendix C: Thermal-Imaging Survey

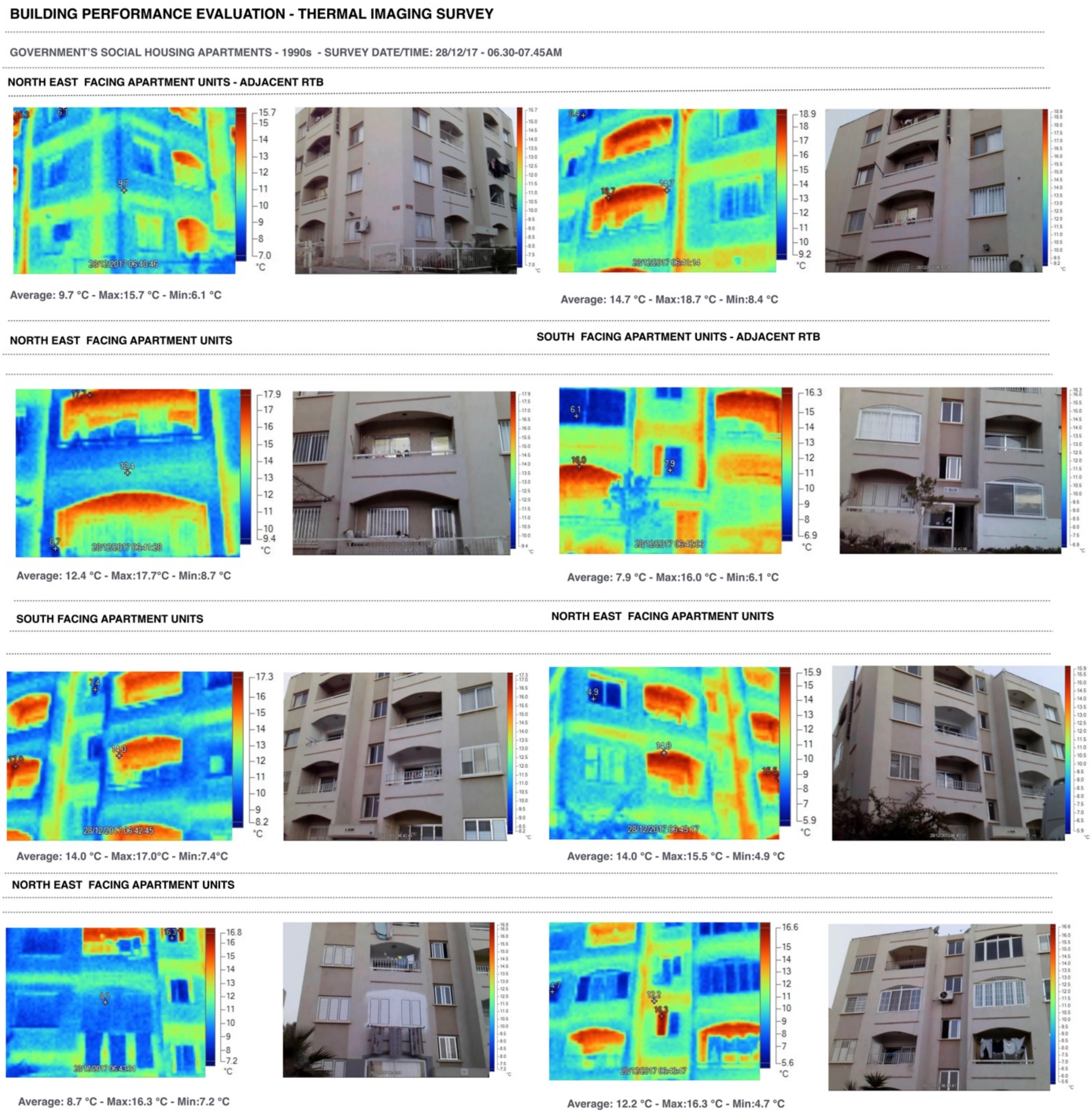


Figure C.2: Photographic documentation of physical condition of building envelopes. Thermal imaging survey was conducted on December 28, 2017 between 06:30–07:45; IRT survey conducted in early morning to understand degree of heat loss on building envelopes. Thermal readings demonstrate that concrete structural system was visible due to absence of insulation material on external walls.

Appendix C: Thermal-Imaging Survey

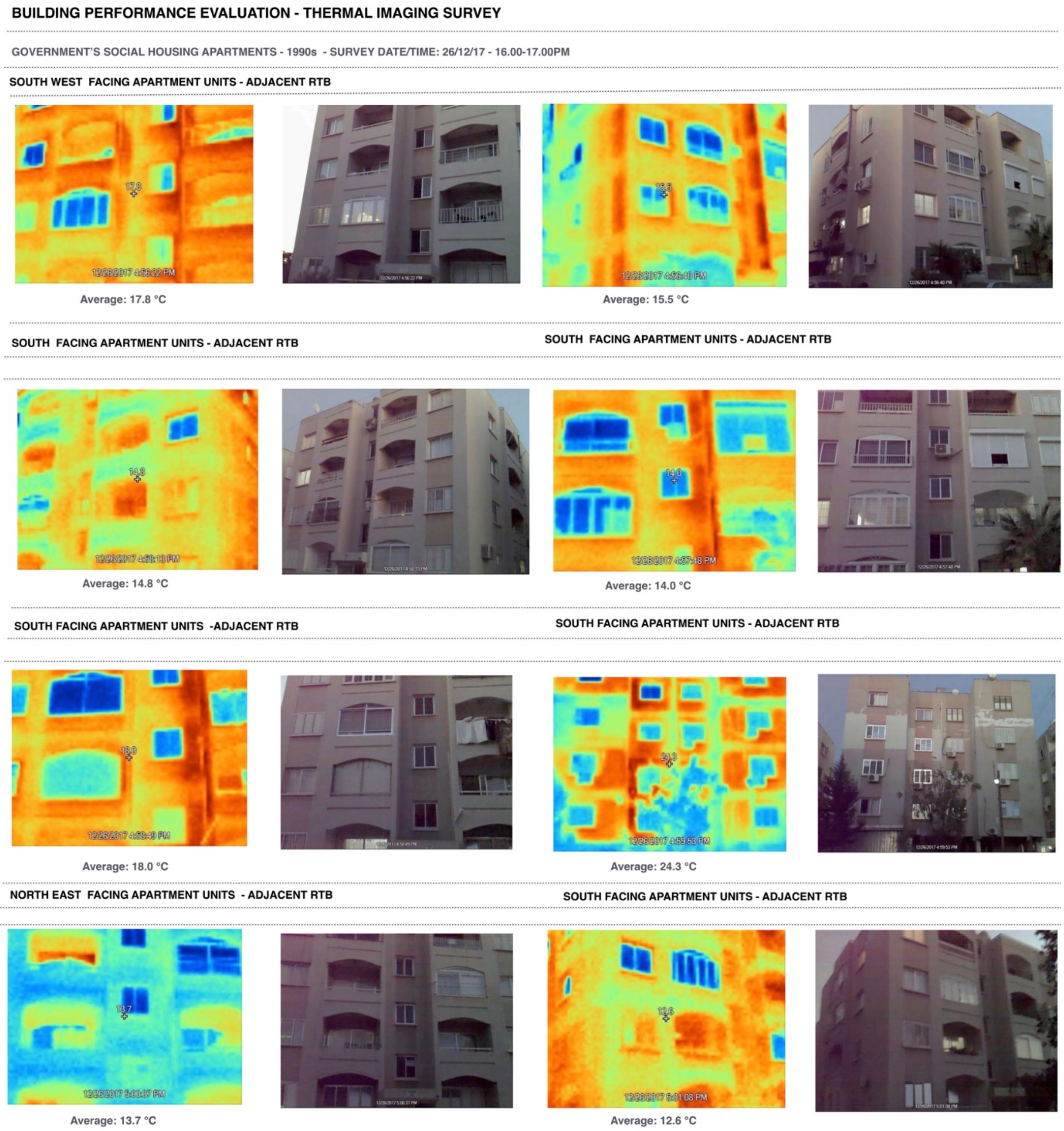


Figure C.3: Photographic documentation of physical conditions of building envelopes. Thermal imaging survey was conducted on December 28, 2017 between 16:00–17:00; IRT survey conducted in late afternoon to understand degree of heat absorptivity of building envelopes. Images demonstrate that households already articulated building components on their own accord: In south-facing RTB, one household painted their third-floor flat; thermal graph shows that painting external walls provided notable difference on building fabric thermal performance. (proportion of newly painted wall surfaces were green and other surfaces were orange, which demonstrates heat vulnerability of RTBs in summer).

Appendix C: Thermal-Imaging Survey

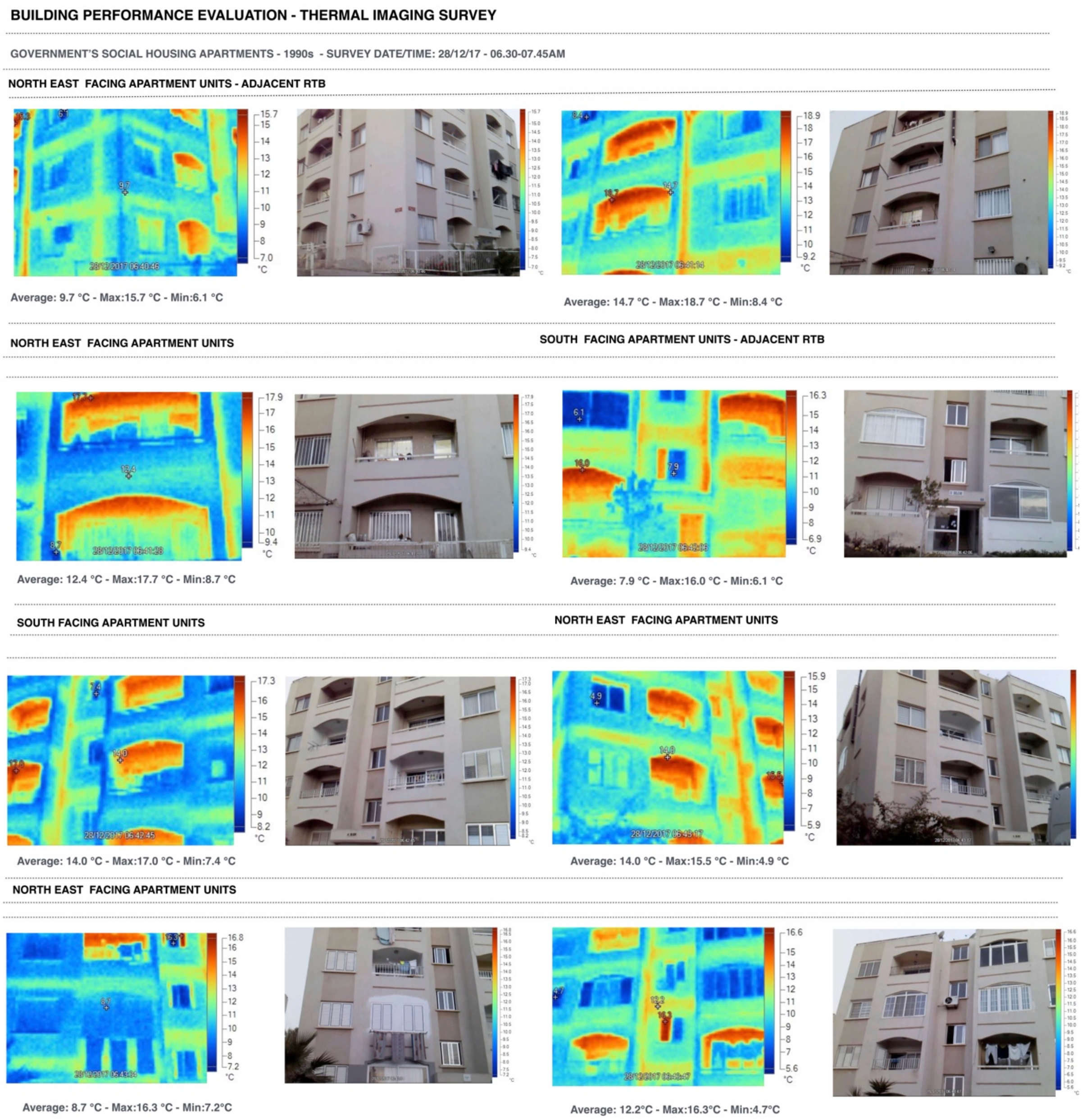


Figure C.4: Photographic documentation of physical conditions of building envelopes. Thermal imaging survey conducted on December 28, 2017 between 06:30–07:45. Image readings taken of front façade to understand overall performance of living environment; one reason for this is because questionnaire surveys were conducted in living room where occupants felt comfortable to answer questions, and *in-situ* physical measurements were recorded in living room when questionnaire survey was administered. Readings provide background information on home-energy performance before field-study investigation in August 2018. In northeast-facing RTB, households converted living room balcony space, and two windows with aluminium window shutters were installed. Walk-through thermal imaging revealed that building envelopes were main determinant factor for increased heating- and cooling-energy consumption.

Appendix C: Thermal-Imaging Survey

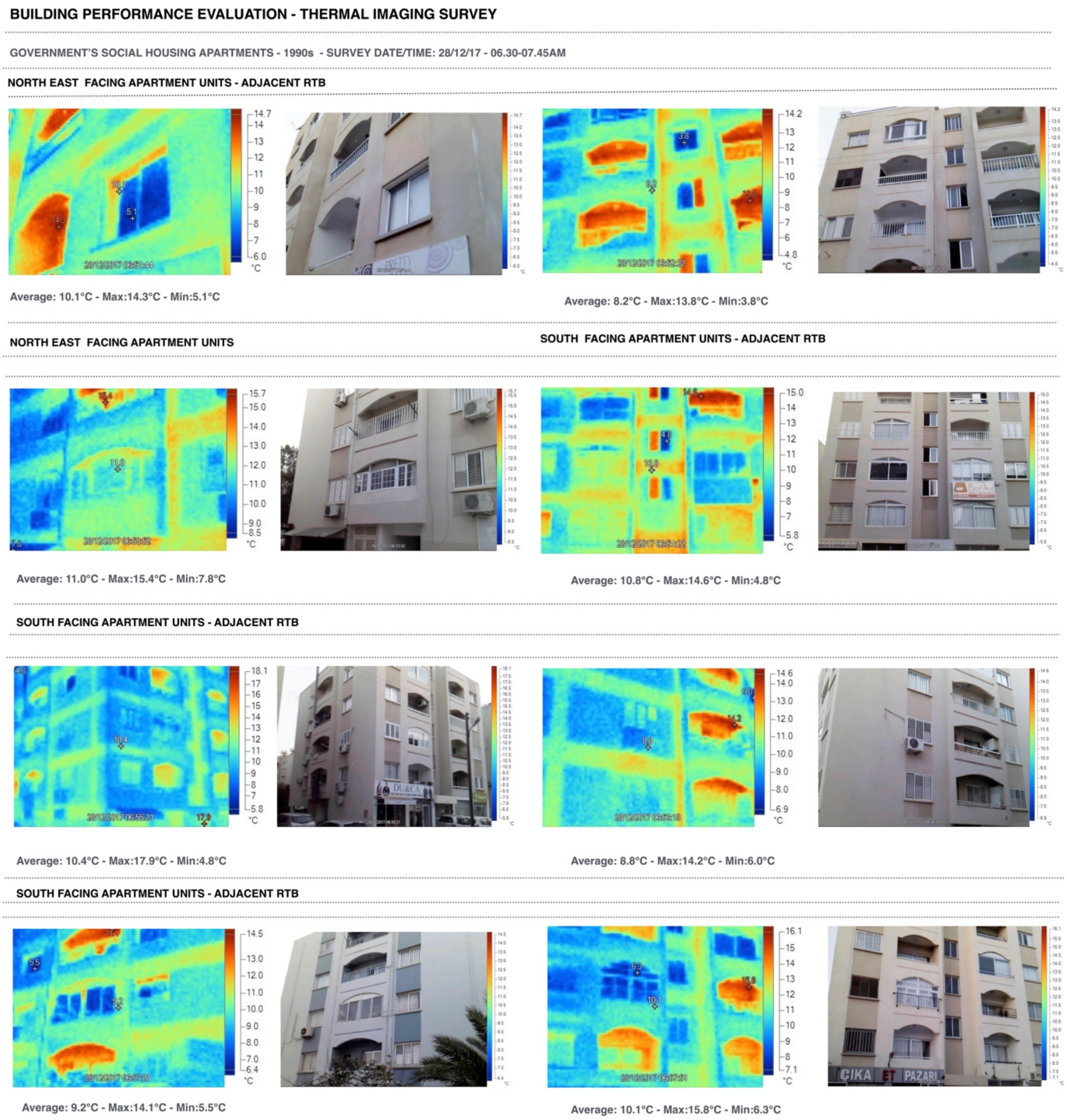


Figure C.5: Photographic documentation of physical conditions of building envelopes. Thermal-imaging survey conducted on December 28, 2017 between 06:30–07:45; thermographic recordings were taken to investigate thermal performance of side walls to understand mutual shading impact factor of RTBs. Results revealed that close proximity of RTBs caused cold bridges on side walls in winter. Wall-mounted A/C systems in northeast-facing RTBs randomly installed on external walls due to absence of centralised service shafts or systems to provide adequate infrastructure to allocate service pipes in RTBs, which led to significant heat loss on building envelopes.

Appendix C: Thermal-Imaging Survey

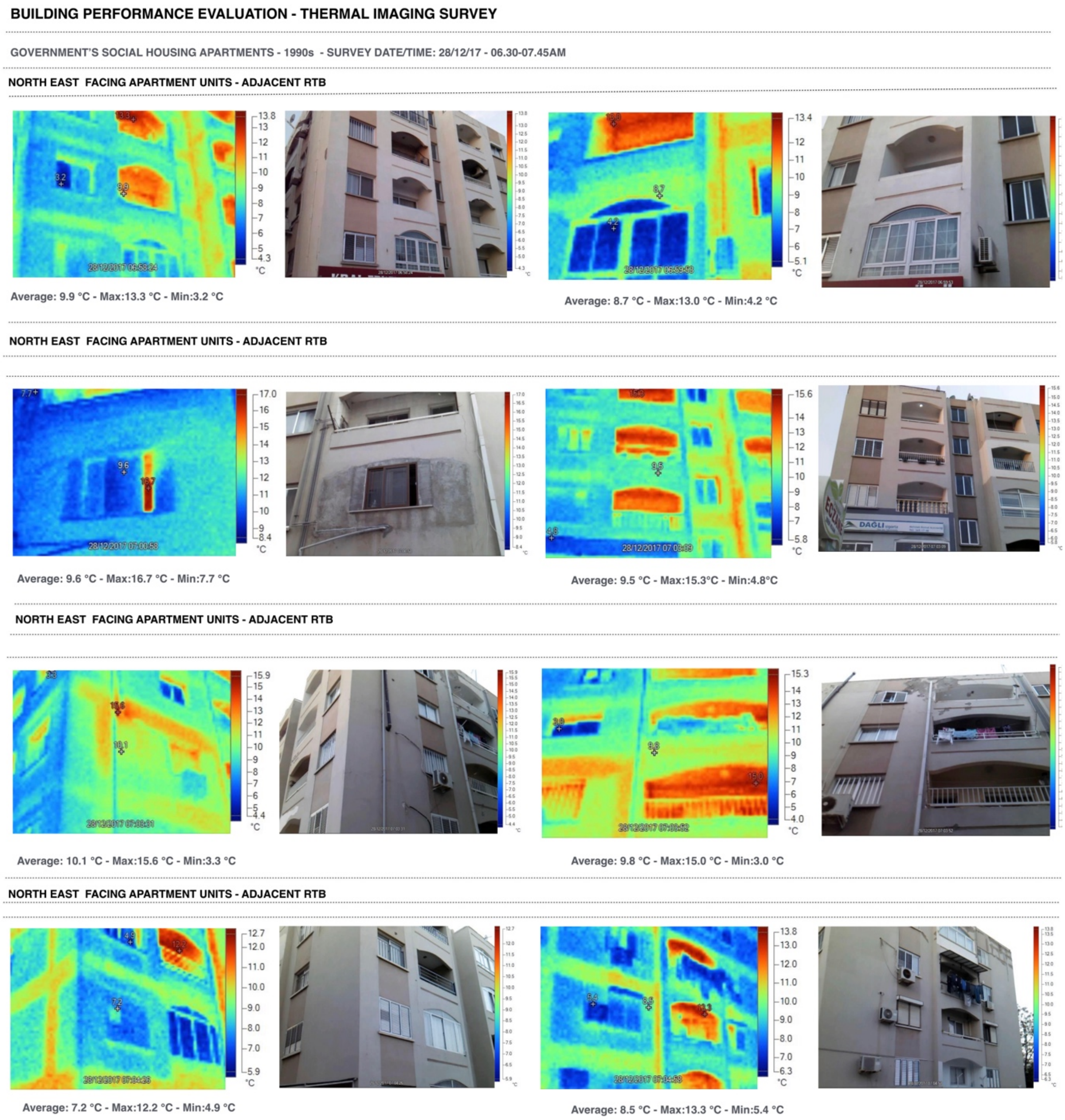


Figure C.6: Photographic documentation of physical conditions of building envelopes. Thermal imaging survey was conducted on December 28, 2017 between 06:30–07:45; thermography readings demonstrate that various refurbishments articulated by occupants had significant impact on home-energy performance. In northeast-facing apartment, kitchen balcony was converted with double-sided window; window was left open to dissipate dirty air at night, and notable heat-loss flow through the enclosure of balcony space was observed on RTB side elevation.

Appendix C: Thermal-Imaging Survey

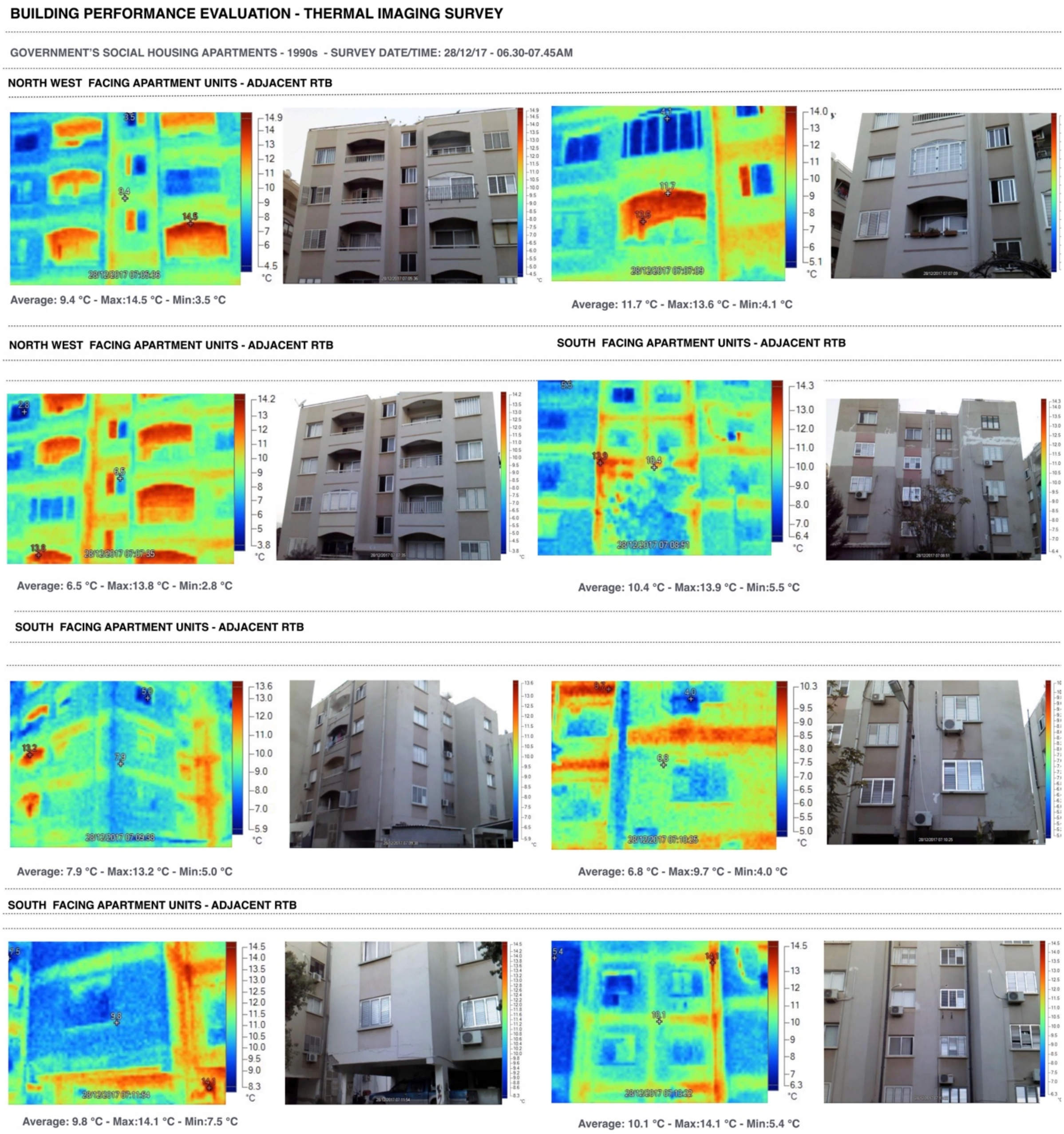


Figure C.7: Photographic documentation of physical conditions of building envelopes. Thermal imaging survey was conducted on December 28, 2017 between 06:30–07:45; thermal images recorded at RTB back elevation facing public space designed by residents. Bedroom 1 and Bedroom 2 located on back elevation, which absorbed fewer sunshine hours. Image readings demonstrated that building envelopes showed different degree of heat loss due to RTB orientation factor and location in social-housing estate.

Appendix C: Thermal-Imaging Survey

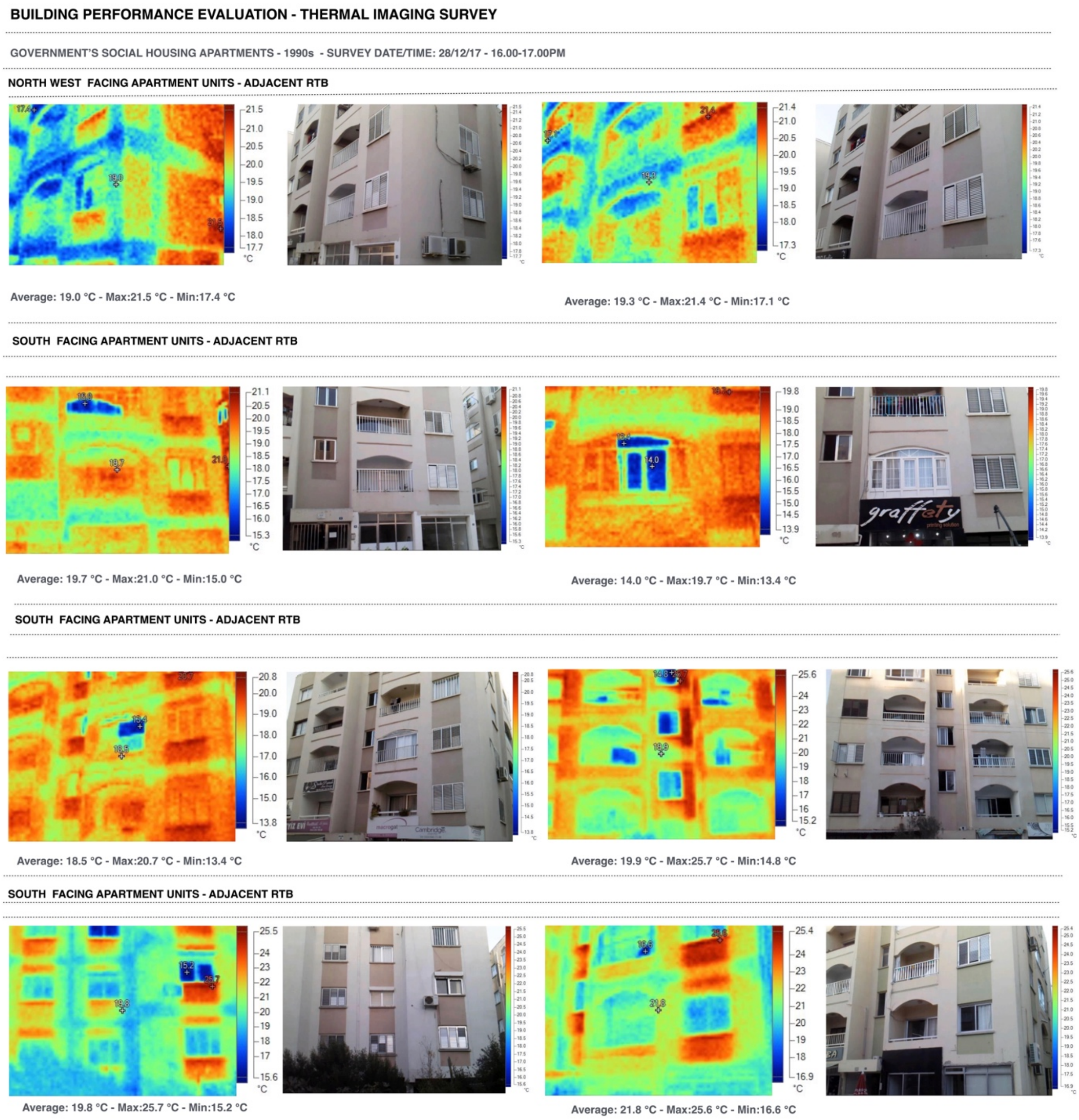


Figure C.8: Photographic documentation of physical conditions of building envelopes. Thermal-imaging survey conducted on December 28, 2017 between 16:00–17:00. IRT survey recordings taken on front façade of RTBs; results reveal that all living room spaces susceptible to overheating in summer due to low-quality construction materials used in 1990s and absence of insulation materials on building envelopes.

Appendix C: Thermal-Imaging Survey

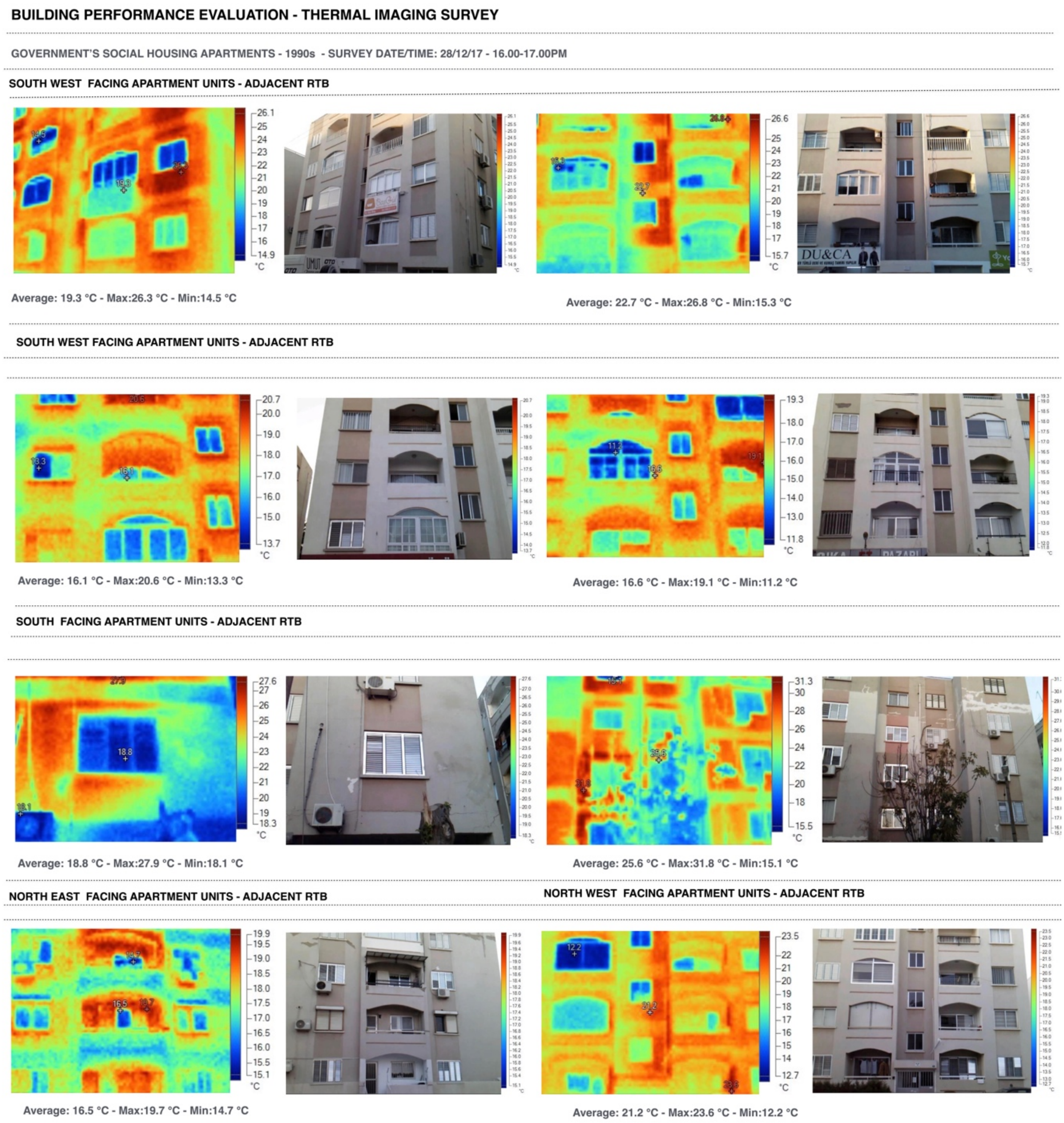


Figure C.9: Photographic documentation of physical conditions of building envelopes. Thermal imaging survey conducted on December 28, 2017 between 16:00–17:00; thermography readings revealed heat accumulations in junction details of window openings in living room spaces of all base-case RTBs due to absence of insulation materials in structural junction details.

Appendix D: Ethics Approval Letter

University of East London

Dear Bertug

Application ID: ETH1920-0063

Original application ID: UREC 1718 36

Project title: **Assessing the Domestic Energy Use and Thermal Comfort of Occupants in a Post-war Social Housing Development Estate in Famagusta, Northern Cyprus**

Lead researcher: Mr Bertug Ozarisoy

Your application to Arts and Creative Industries School Research Ethics Committee was considered on the 7th of November 2019.

The decision is: **Approved**

The Committee's response is based on the protocol described in the application form and supporting documentation.

Your project has received ethical approval for 2 years from the approval date.

If you have any questions regarding this application please contact your supervisor or the secretary for the Arts and Creative Industries School Research Ethics Committee.

Approval has been given for the submitted application only and the research must be conducted accordingly.

Should you wish to make any changes in connection with this research project you must complete 'An application for approval of an amendment to an existing application'.

Approval is given on the understanding that the UEL Code of Practice for Research and the Code of Practice for Research Ethics is adhered to.□□

Any adverse events or reactions that occur in connection with this research project should be reported using the University's form for Reporting an Adverse/Serious Adverse Event/Reaction.

The University will periodically audit a random sample of approved applications for ethical approval, to ensure that the research projects are conducted in compliance with the consent given by the Research Ethics Committee and to the highest standards of rigour and integrity.

Please note, it is your responsibility to retain this letter for your records.

With the Committee's best wishes for the success of the project

Yours sincerely

Fernanda Pereira Da Silva

Figure D.1: Ethics approval letter granted in 2019.

Appendix E: Retrofitting Design Strategies

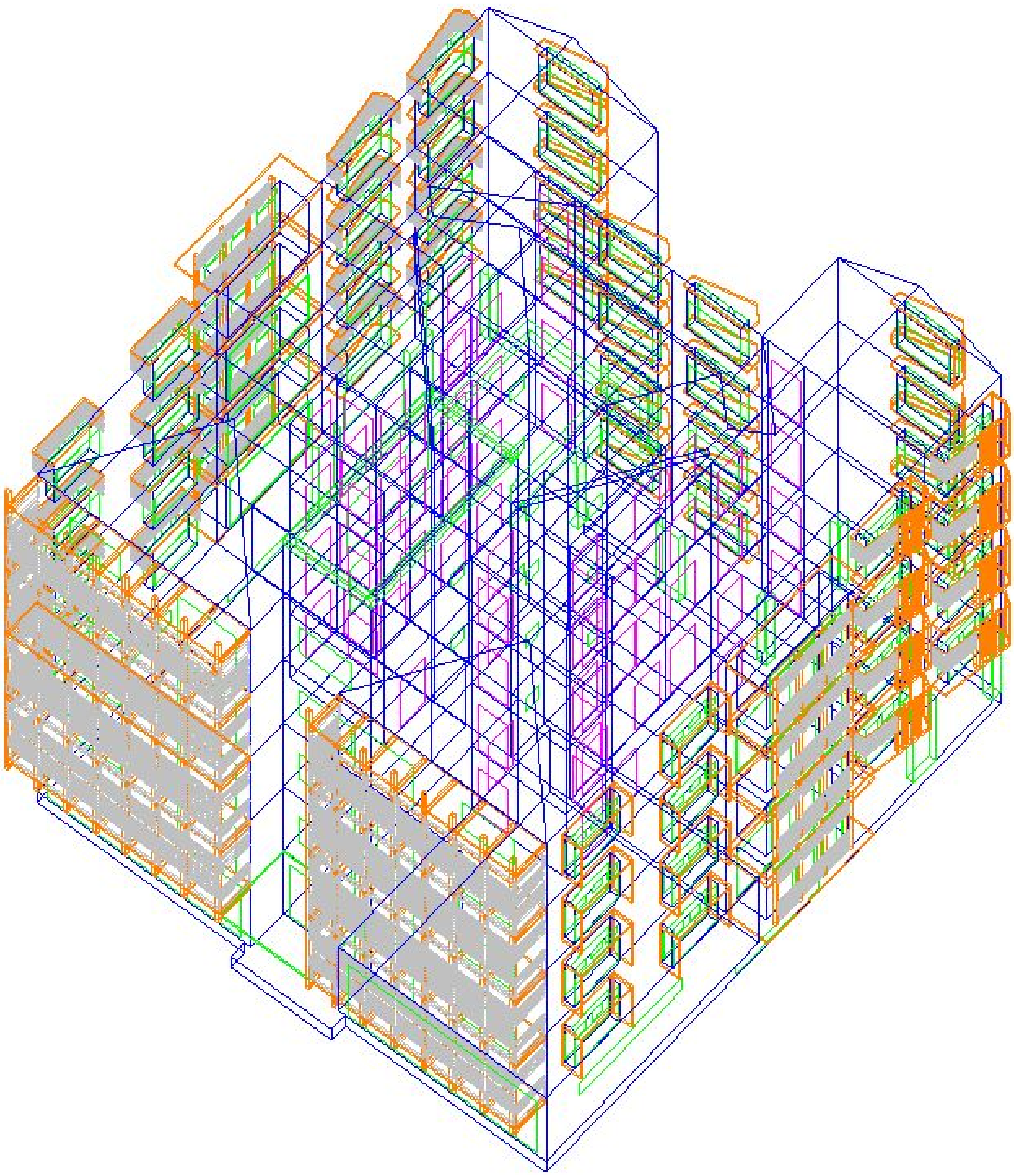


Figure E.1: 3D rendering of analytical-energy model. Black-box energy model developed to test energy effectiveness of passive-cooling design strategies implemented onto building envelopes; each occupied space created in individual zones to undertake dynamic thermal simulations in IES-software. Off-site modular construction systems provided affordable refurbishment solutions to occupants and government initiatives to improve energy efficiency of dwellings.

Appendix E: Retrofitting Design Strategies

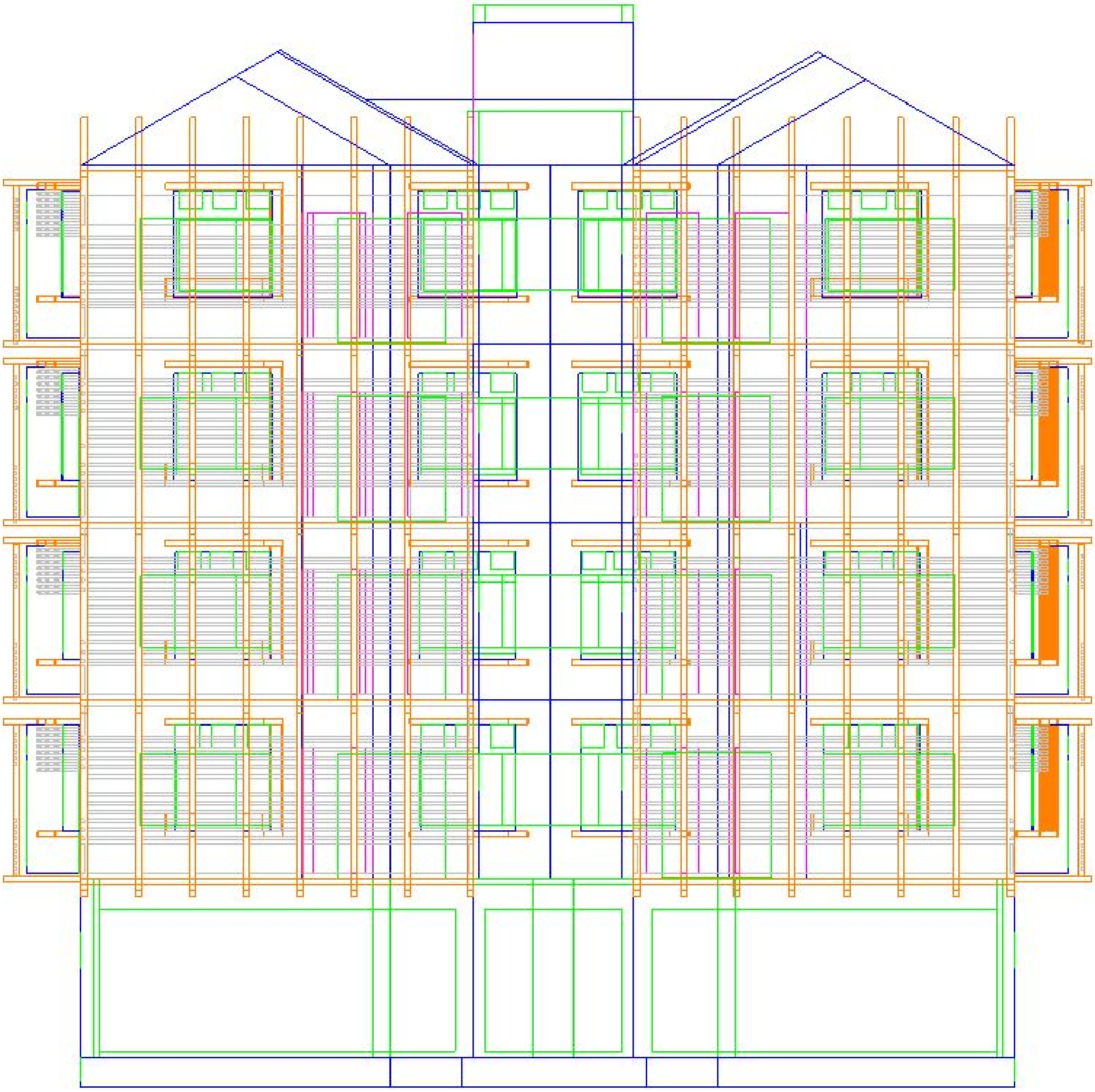


Figure E.2: Front elevation of RTB prototype after all six passive-cooling design strategies implemented. Volumetric balcony space addition with adjustable horizontal passive shading elements (i.e., brise soleil) improved architectural quality of building and brought RTBs up to European housing-standard criterion; varied according to building envelope orientation. Monitored environmental parameters and household feed-forward interviews demonstrated roadmap to develop evidence-based retrofitting strategy.

Appendix E: Retrofitting Design Strategies

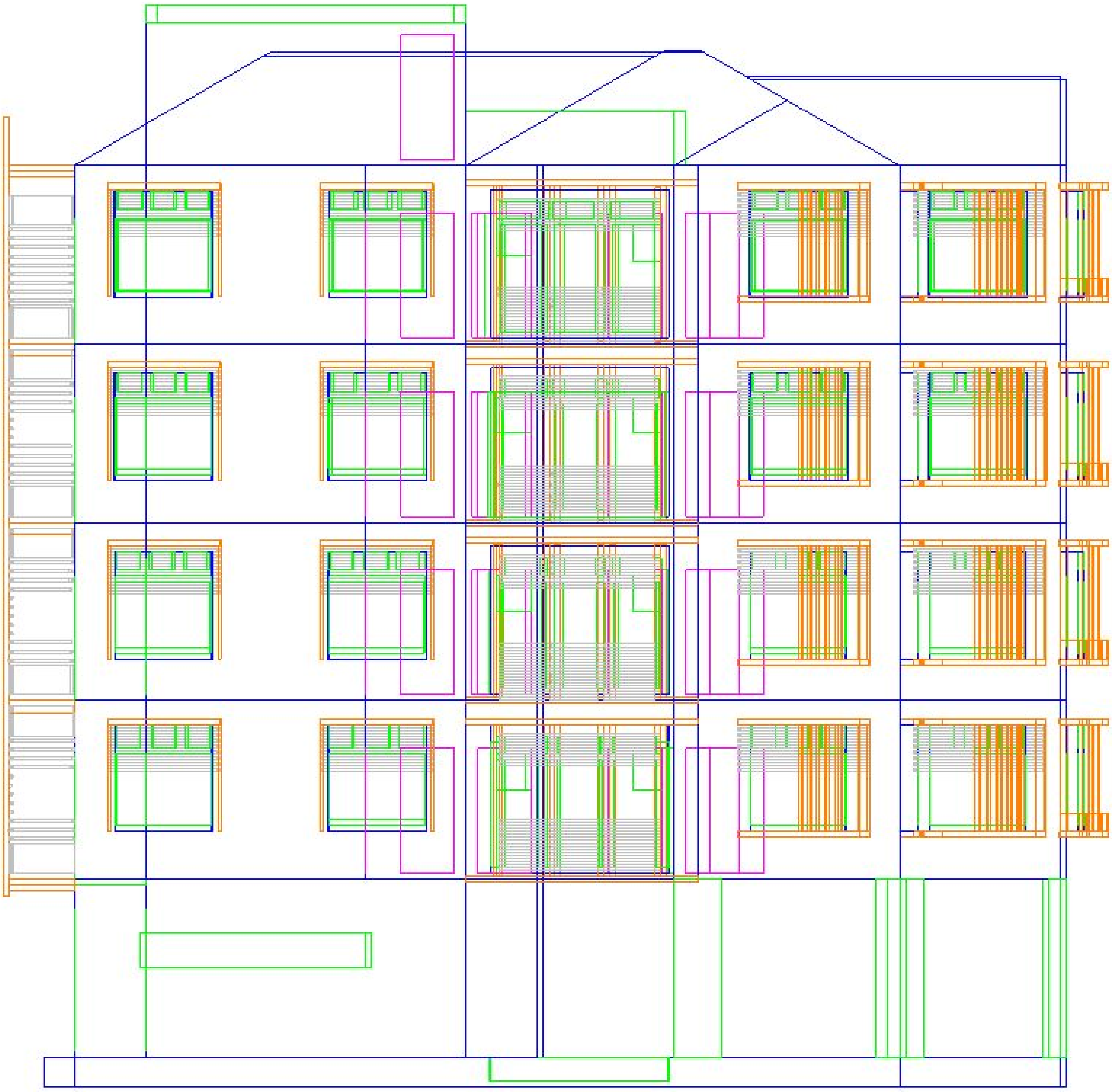


Figure E.3: Typical side elevation of RTB prototype after all six passive-cooling design strategies implemented. Overhanging kitchen addition designed to improve space quality in kitchen areas. Operable shading elements implemented to avoid direct solar radiation due to different RTB orientations; top-window openings positioned in each occupied space (i.e., living room, Bedroom 1, Bedroom 2 and Bedroom 3) to increase frequency of natural ventilation; appropriate shading systems proposed that took RTB orientations into consideration.

Appendix E: Retrofitting Design Strategies

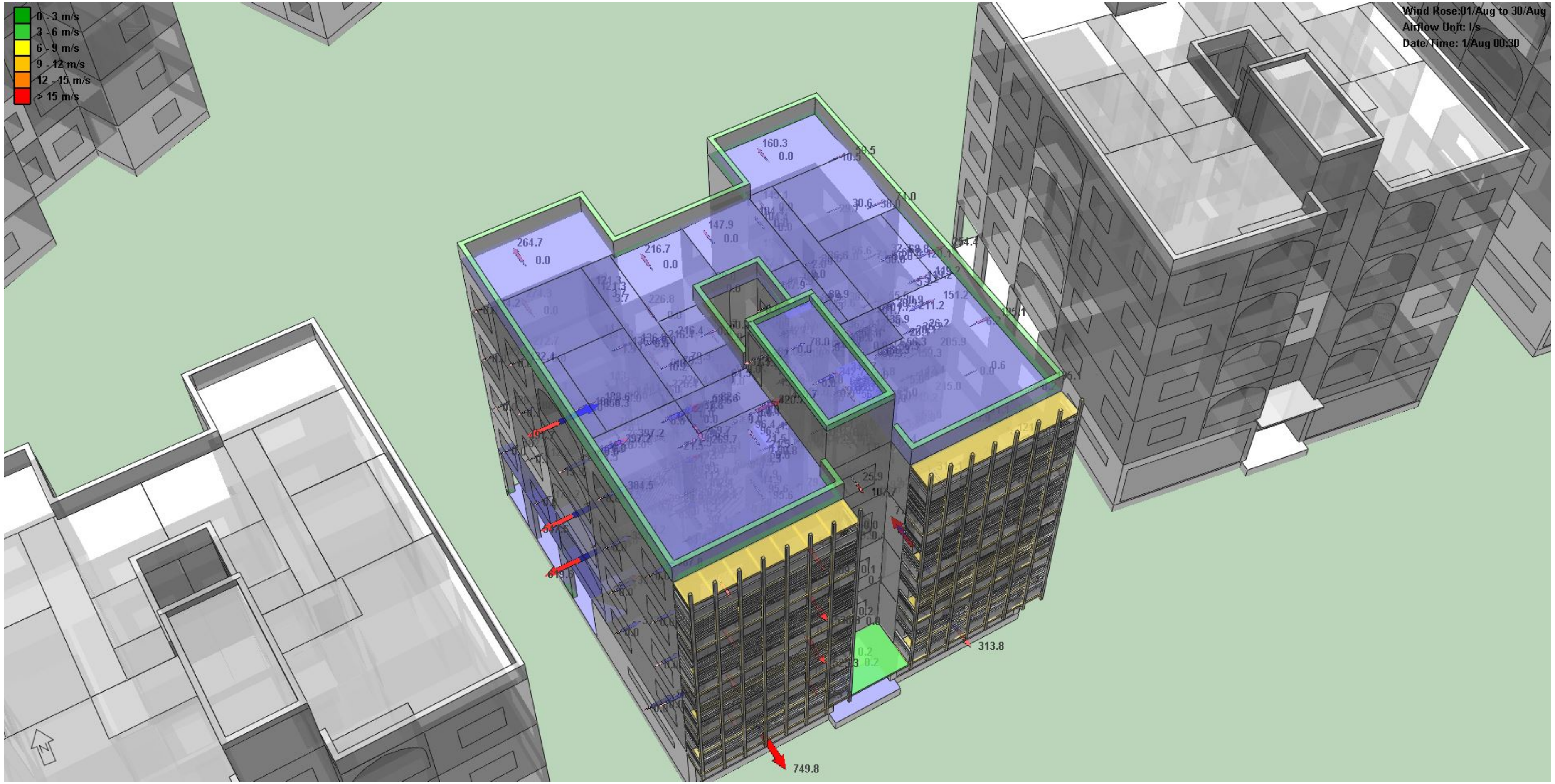


Figure E.4: 3D rendering of RTB prototype after Strategy 1 (i.e., volumetric balcony space addition with adjustable shading elements) implemented; image shows infiltration rates of each occupied space on different floor levels; results generated from MacroFlow application of IES software.

Appendix E: Retrofitting Design Strategies

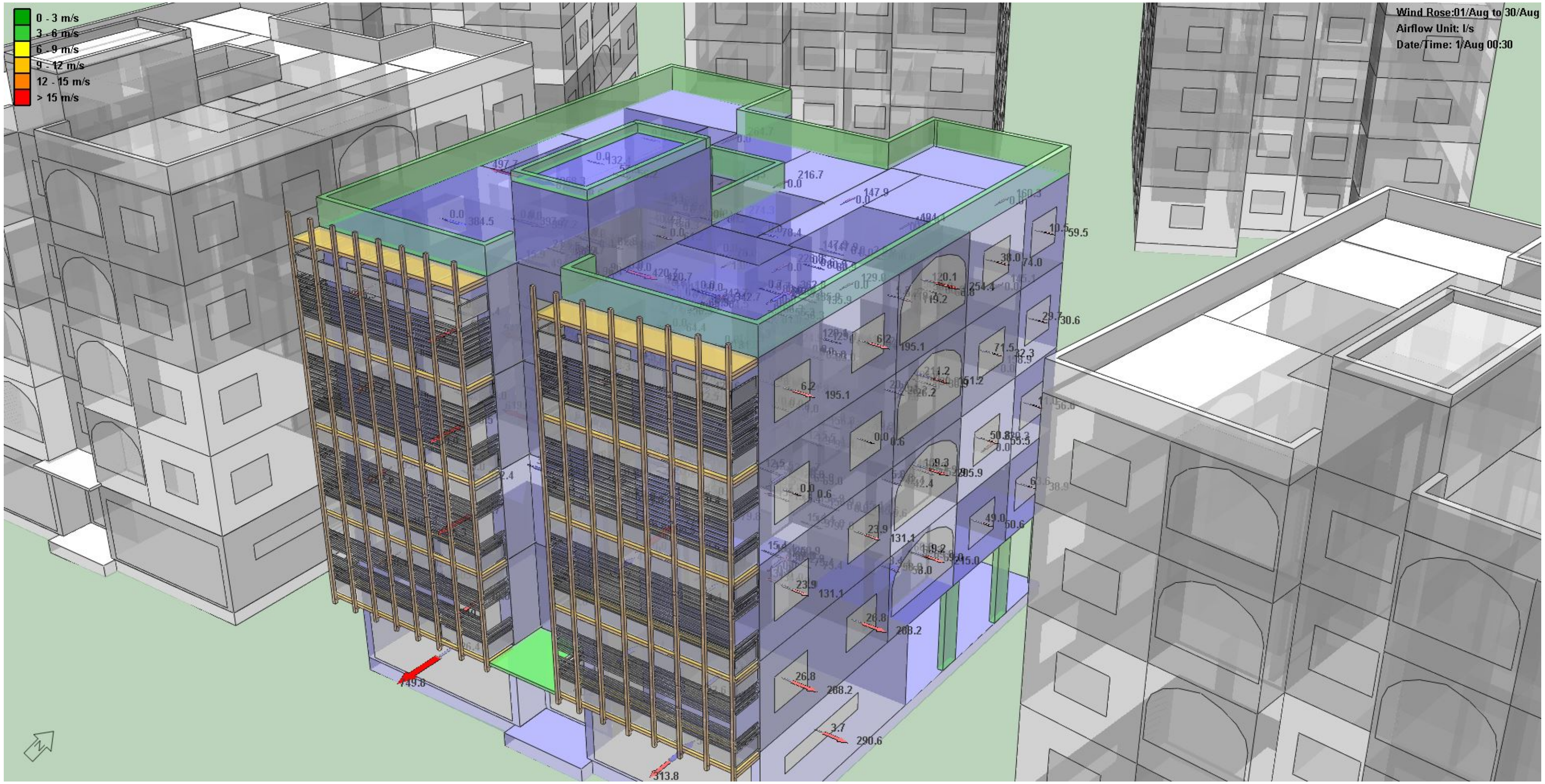


Figure E.5: 3D rendering of RTB prototype after Strategy 1 implemented; image shows infiltration rates of occupied spaces on side elevation. RTBs built in close proximity to one another, which caused poor natural ventilation; S1 was not intended to reduce overheating risk of each occupied space, but to provide optimised indoor-air quality for occupant thermal comfort.

Appendix E: Retrofitting Design Strategies

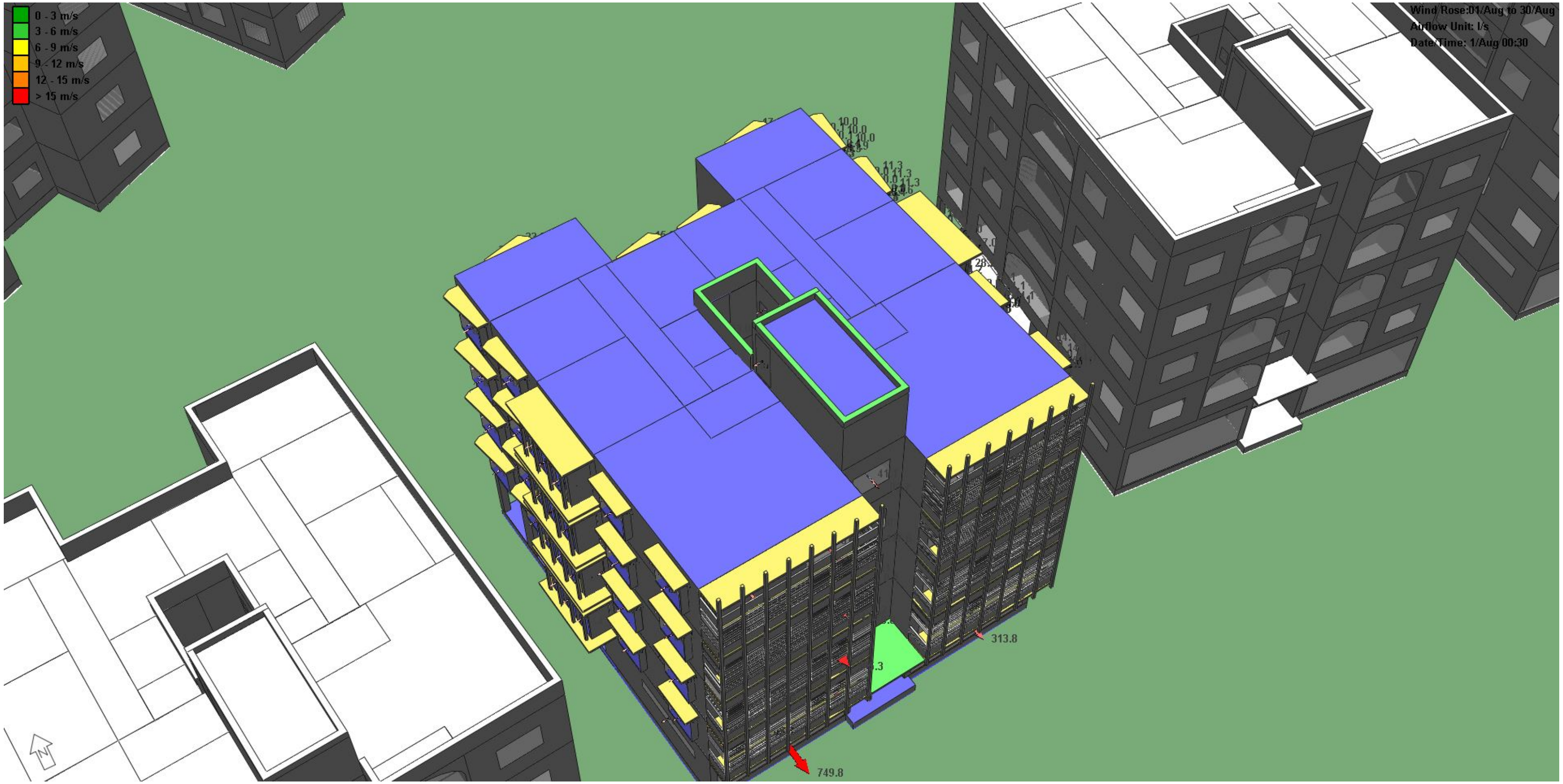


Figure E.6: 3D rendering of RTB prototype after all six passive-design strategies implemented; overhanging living room balcony with adjustable shading elements and kitchen balcony projection added significant value. Initial strategies intended to reduce effect of high solar radiation in summer so retrofitting efforts could achieve EU housing standards while considering real-life experiences related to home-energy performance.

Appendix E: Retrofitting Design Strategies

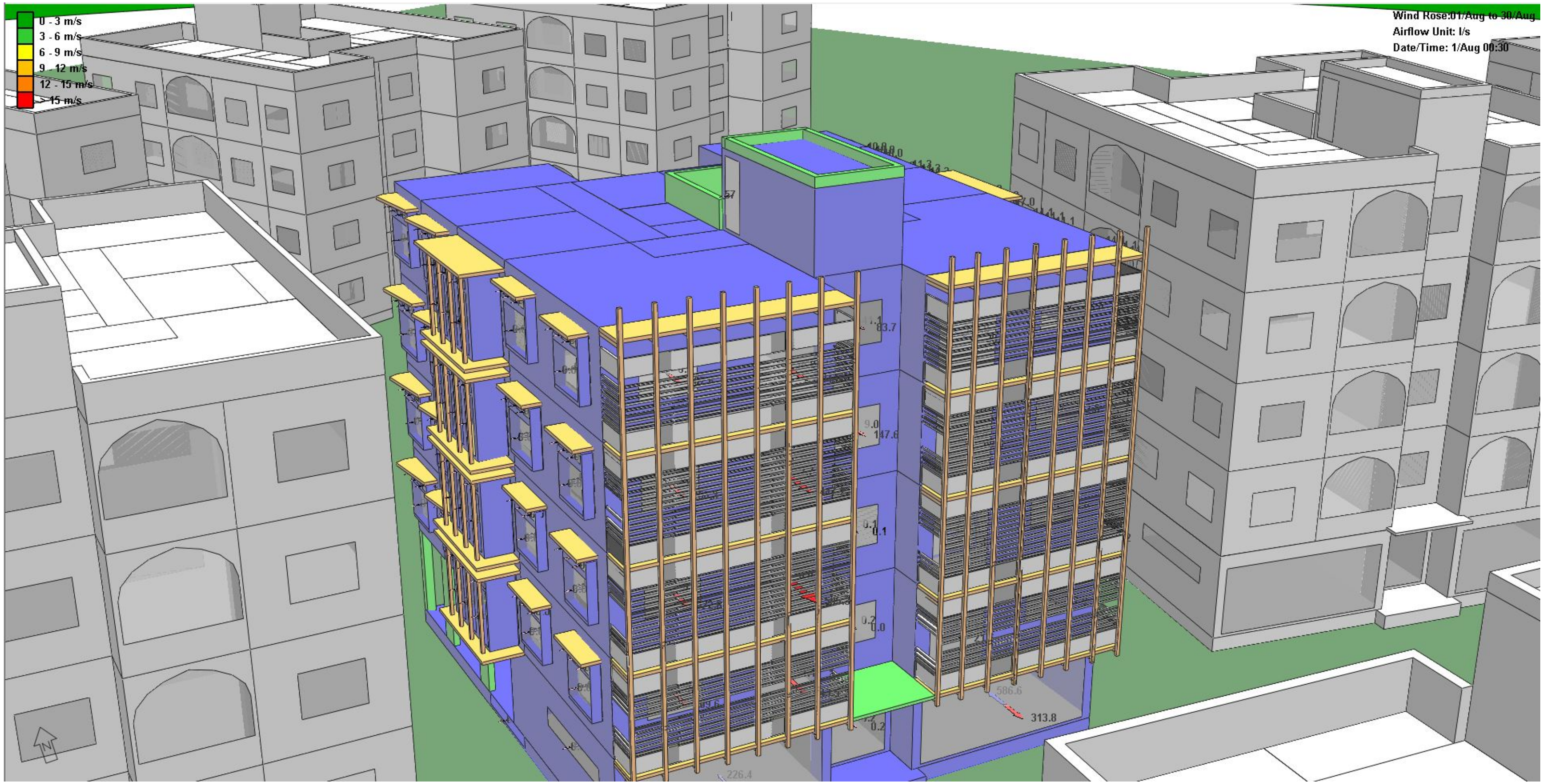


Figure E.7: 3D rendering of RTB prototype after all six passive-cooling design strategies implemented. Image shows volumetric balcony space addition with adjustable shading elements on front elevation; side elevation shows fenestration design of window openings designed taking RTB orientation into consideration.

Appendix E: Retrofitting Design Strategies

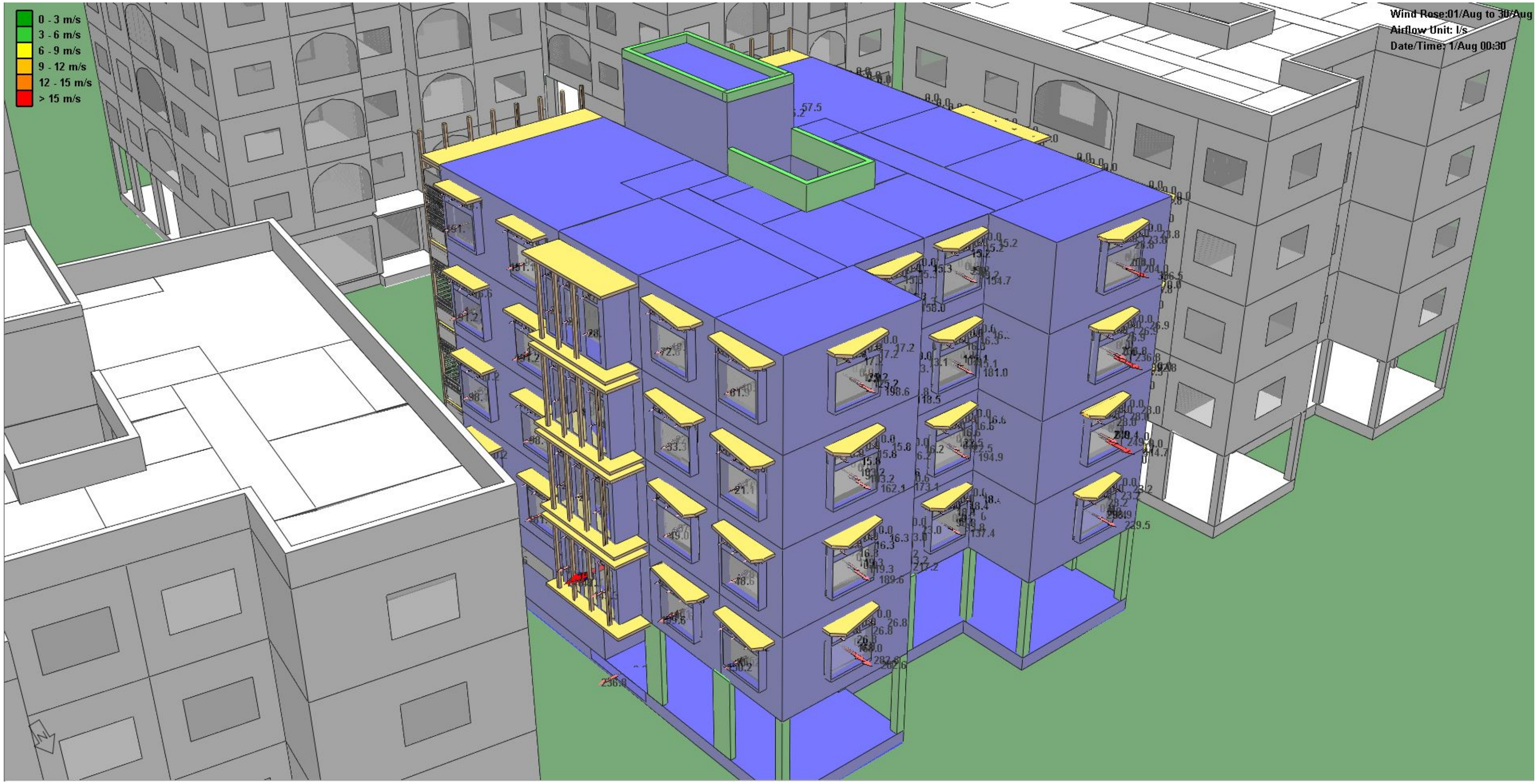


Figure E.8: 3D rendering of RTB prototype after all six passive-cooling design strategies implemented. Image shows back elevation, where Bedroom 1 and Bedroom 2 are located; fenestration design was intended to accommodate three top window openings to increase air infiltration rate at night.

Appendix E: Retrofitting Design Strategies

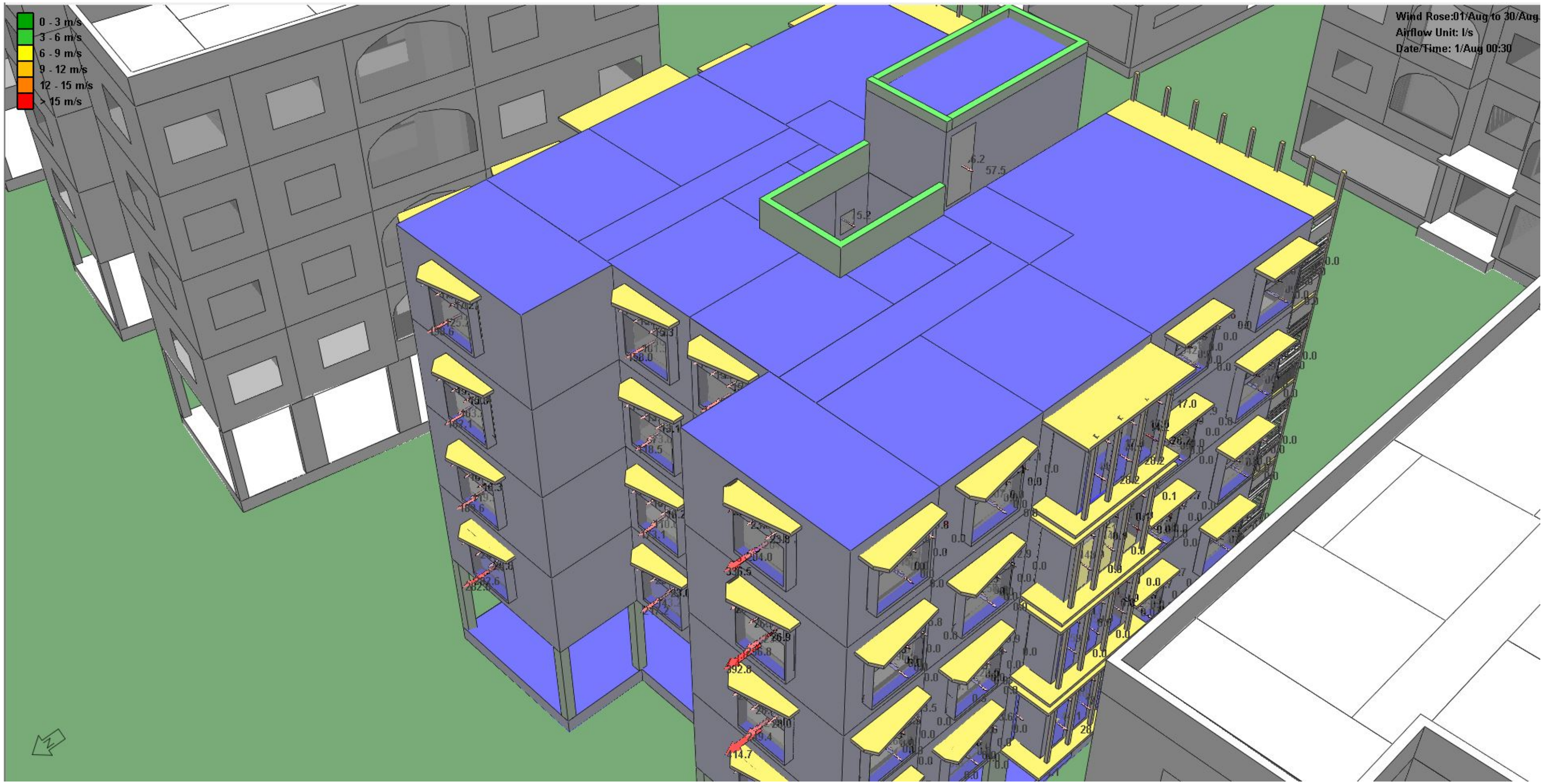


Figure E.9: 3D rendering of RTB prototype after all six passive-cooling design strategies implemented. Bird's-eye view shows that shading systems designed with fenestration strategies to acclimatise indoor-air environment; balcony projections show that spatial layout of each flat was re-configured to increase liveability in condominiums.

Appendix E: Retrofitting Design Strategies

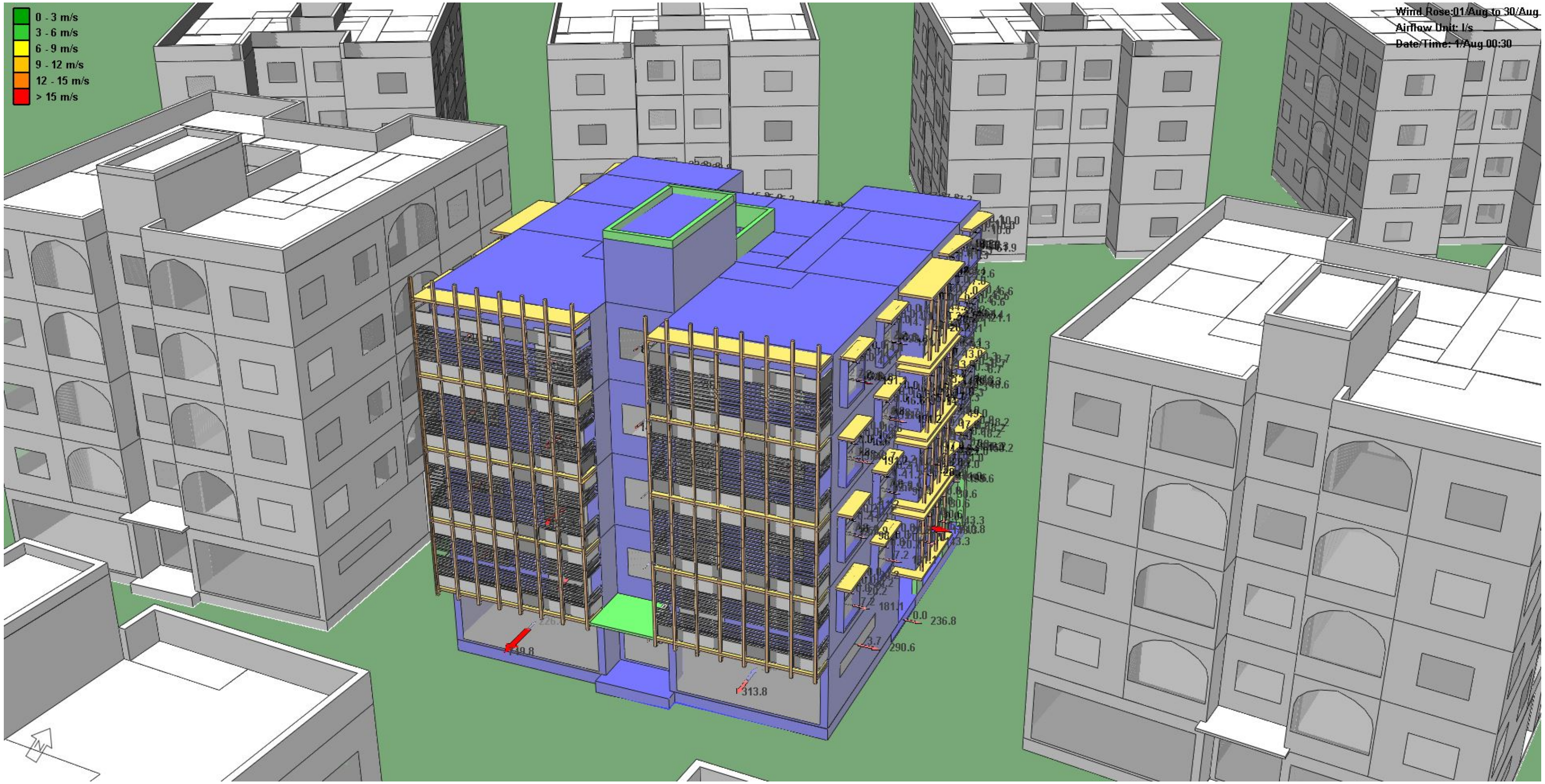
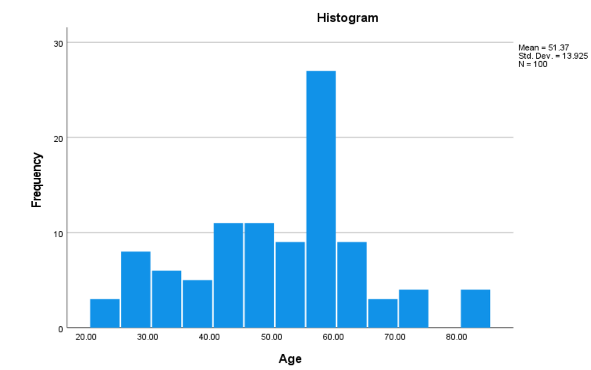


Figure E.10: 3D rendering of street view of RTB prototype and psychological cognition of all six passive design strategies. These strategies not limited to reducing overheating risks and optimising occupant thermal comfort; existing housing could also be treated to achieve EU housing quality standar

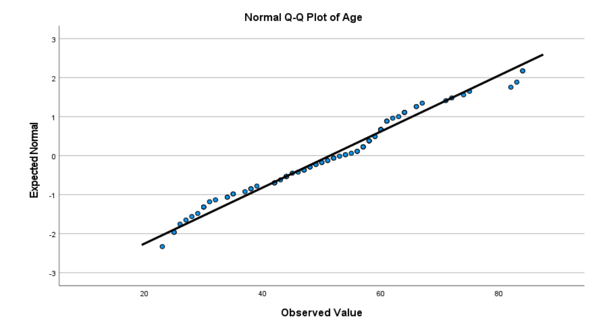
Appendix F: Sample of Validation Results for the Statistical Analyses

Statistics			
Age			
N	Valid	100	
	Missing	0	
Mean		51.37	
Median		53.5	
Std. Deviation		13.92524	
Skewness		-0.007	-0.0290456
Std. Error of Skewness		0.241	
Kurtosis		-0.221	-0.4623431
Std. Error of Kurtosis		0.478	
Minimum		23	
Maximum		84	

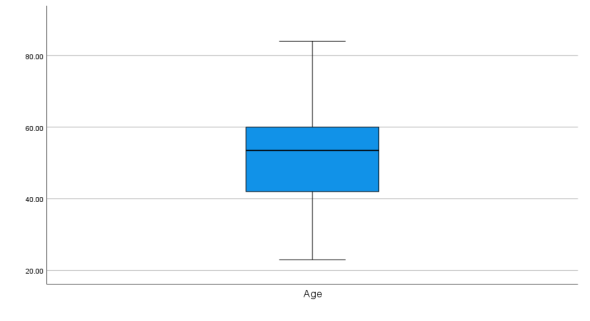
(a)



(b)



(c)

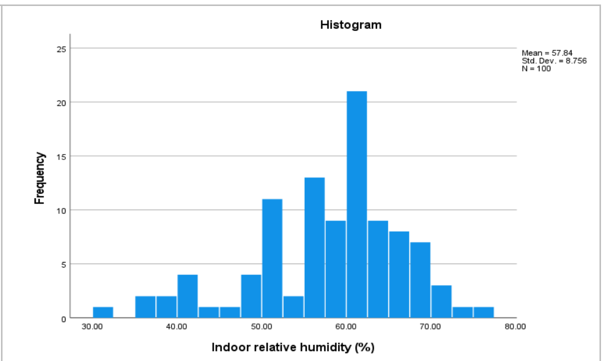


(d)

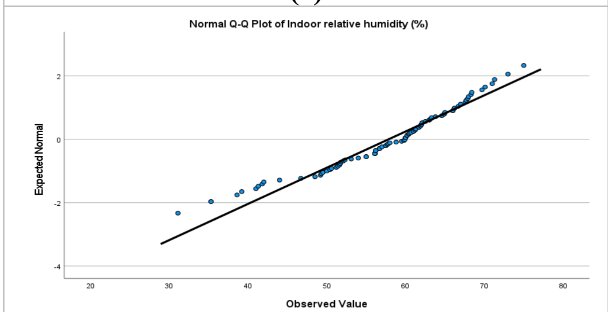
Figure F.1: (a) Skeweness and Kurtosis of the age sampling; **(b)** Histogram of age of the households; **(c)** Normality analysis for an age variable; **(d)** Whisker graph of age distribution of households.

Statistics			
Indoor relative humidity (%)			
N	Valid	100	
	Missing	0	
Mean		57.838	
Median		59.95	
Std. Deviation		8.75611	
Skewness		-0.805	-3.340249
Std. Error of Skewness		0.241	
Kurtosis		0.616	1.28870293
Std. Error of Kurtosis		0.478	
Minimum		31.1	
Maximum		75	

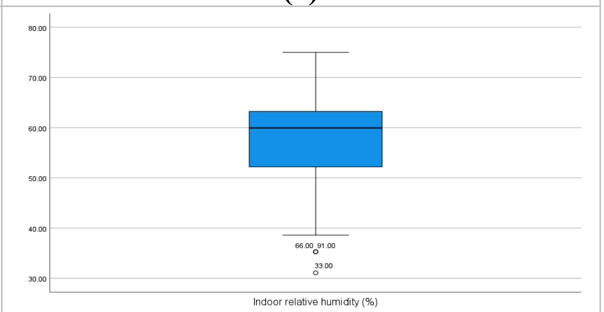
(a)



(b)



(c)



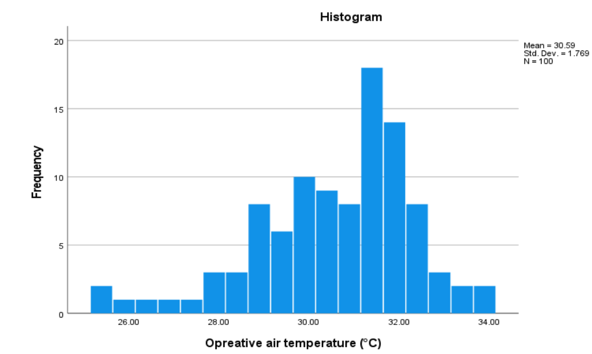
(d)

Figure F.2: (a) Skeweness and Kurtosis of the *in-situ* recorded indoor relative humidity (RH); **(b)** Histogram of indoor RH; **(c)** Normality analysis of indoor RH; **(d)** Whisker graph of indoor RH

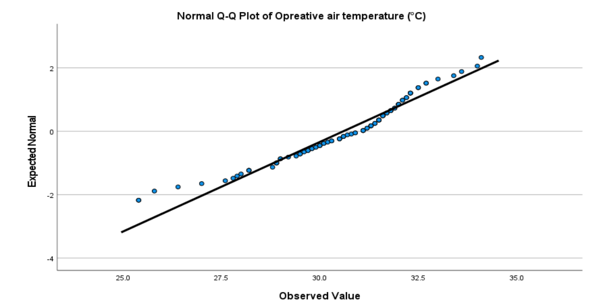
Appendix F: Sample of Validation Results for the Statistical Analyses

Statistics			
Opreative air temperature (°C)			
N	Valid	100	
	Missing	0	
Mean		30.595	
Median		31.1	
Std. Deviation		1.7686	
Skewness		-0.816	-3.3858921
Std. Error of Skewness		0.241	
Kurtosis		0.756	1.58158996
Std. Error of Kurtosis		0.478	
Minimum		25.4	
Maximum		34.1	

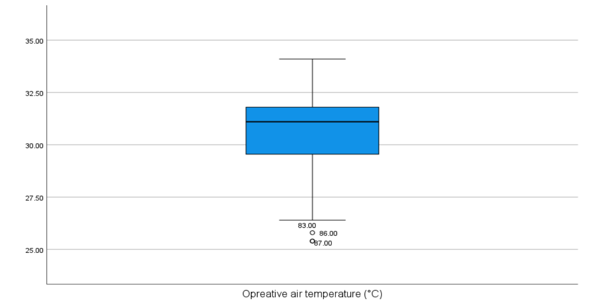
(a)



(b)



(c)

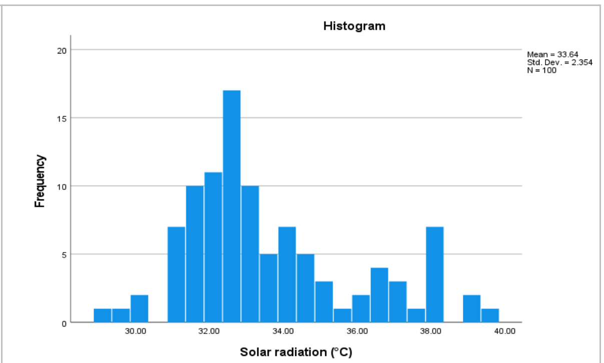


(d)

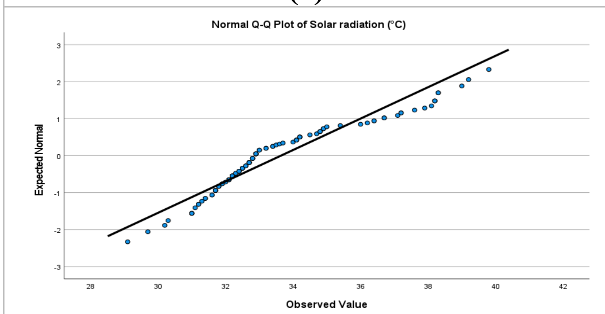
Figure F.3: (a) Skeweness and Kurtosis of the *in-situ* recorded operative air temperature; **(b)** Histogram of operative air temperature; **(c)** Normality analysis of operative air temperature; **(d)** Whisker graph of operative air temperature.

Statistics			
Solar radiation (°C)			
N	Valid	100	
	Missing	0	
Mean		33.641	
Median		32.9	
Std. Deviation		2.35445	
Skewness		0.84	3.48547718
Std. Error of Skewness		0.241	
Kurtosis		-0.036	-0.0753138
Std. Error of Kurtosis		0.478	
Minimum		29.1	
Maximum		39.8	

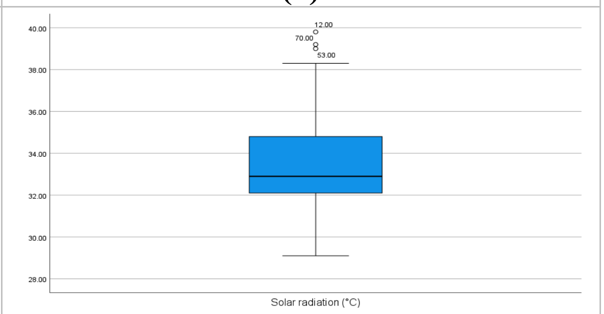
(a)



(b)



(c)

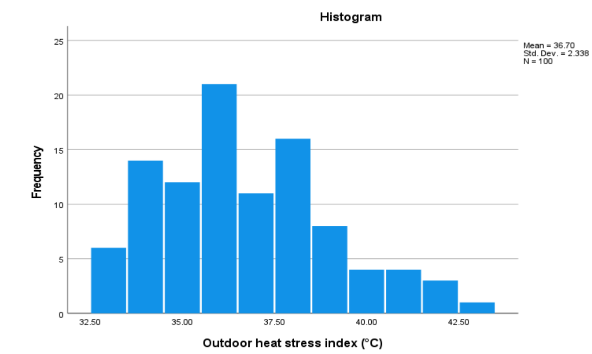


(d)

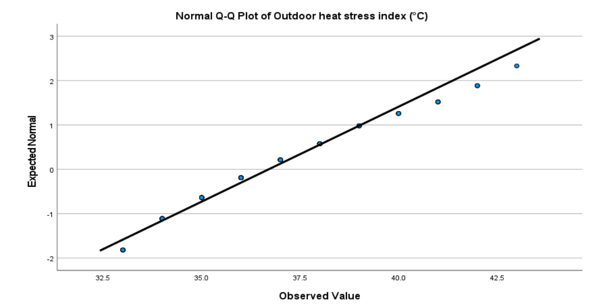
Figure F.4: (a) Skeweness and Kurtosis of the *in-situ* recorded solar radiation of RTBs building envelopes; **(b)** Histogram of solar radation factor; **(c)** Normality analysis of solar radiation factor; **(d)** Whisker graph of solar radiation factor.

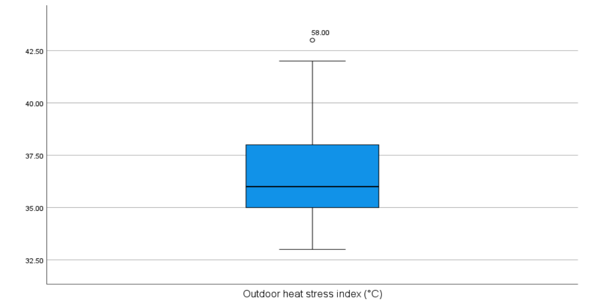
Appendix F: Sample of Validation Results for the Statistical Analyses

Statistics			
Outdoor heat stress index (°C)			
N	Valid	100	
	Missing	0	
Mean		36.7	
Median		36	
Std. Deviation		2.33766	
Skewness		0.521	2.16182573
Std. Error of Skewness		0.241	
Kurtosis		-0.208	-0.4351464
Std. Error of Kurtosis		0.478	
Minimum		33	
Maximum		43	



(a) **(b)**

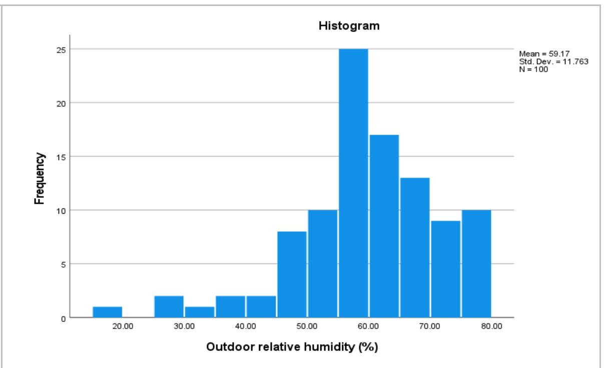




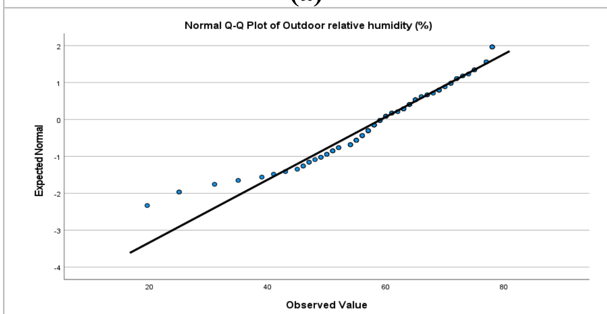
(c) **(d)**

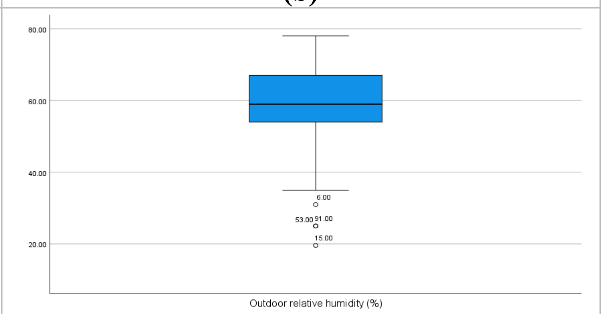
Figure F.5: (a) Skeweness and Kurtosis of the *on-site* recorded outdoor heat-stress index factor; **(b)** Histogram of the outdoor heat-stress index factor; **(c)** Normality analysis of the outdoor heat-stress index factor; **(d)** Whisker graph of the heat-stress index factor.

Statistics			
Outdoor relative humidity (%)			
N	Valid	100	
	Missing	0	
Mean		59.166	
Median		59	
Std. Deviation		11.76264	
Skewness		-0.853	-3.5394191
Std. Error of Skewness		0.241	
Kurtosis		1.39	2.90794979
Std. Error of Kurtosis		0.478	
Minimum		19.6	
Maximum		78	



(a) **(b)**





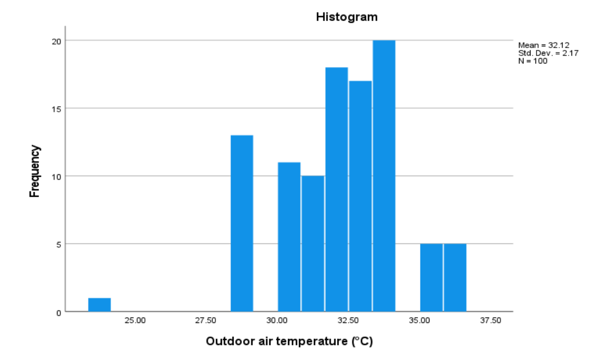
(c) **(d)**

Figure F.6: (a) Skeweness and Kurtosis of the *on-site* recorded outdoor relative humidity (RH); **(b)** Histogram of the outdoor RH; **(c)** Normality analysis of the outdoor RH; **(d)** Whisker graph of the outdoor RH.

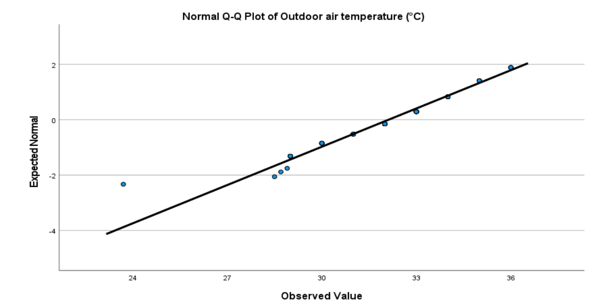
Appendix F: Sample of Validation Results for the Statistical Analyses

Statistics			
Outdoor air temperature (°C)			
N	Valid	100	
	Missing	0	
Mean		32.118	
Median		32	
Std. Deviation		2.17015	
Skewness		-0.587	-2.4356846
Std. Error of Skewness		0.241	
Kurtosis		0.952	1.9916318
Std. Error of Kurtosis		0.478	
Minimum		23.7	
Maximum		36	

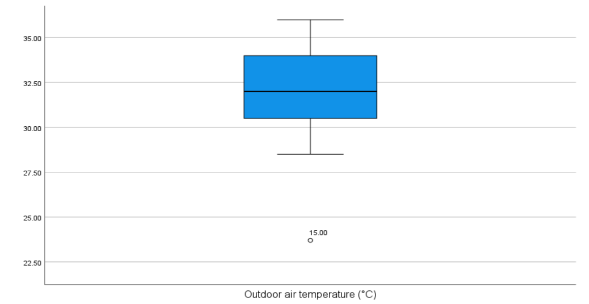
(a)



(b)



(c)



(d)

Figure F.7: (a) Skeweness and Kurtosis of the *on-site* recorded outdoor air temperature; **(b)** Histogram of the outdoor air temperature; **(c)** Normality analysis of the outdoor air temperature; **(d)** Whisker graph of the outdoor air temperature.

Appendix G: Sample of Outliers Test

Table G.1: Outliers test of households' thermal sensation votes (TSVs) in bedroom 1

Thermal sensation in bedroom 1 (recoded)		Extreme Values	Case Number	Value
	Highest	1	22	3.00
		2	58	3.00
		3	68	3.00
		4	16	2.00
		5	23	2g
	Lowest	1	82	-3.00
		2	11	-3.00
		3	71	-2.00
		4	60	-2.00
		5	38	-2h

g Only a partial list of cases with the value 2 are shown in the table of upper extremes.

h Only a partial list of cases with the value -2 are shown in the table of lower extremes.

```
Thermal sensation in bedroom 1
(recoded) Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

    10.00 Extremes    (=<-2.0)
     9.00       -1 .  000000000
      .00       -0 .
      .00       -0 .
    12.00        0 .  000000000000
      .00        0 .
    29.00        1 .
00000000000000000000000000000
      .00        1 .
    16.00        2 .  0000000000000000
     3.00 Extremes    (>=3.0)

 Stem width:         1
 Each leaf:        1 case(s)
```

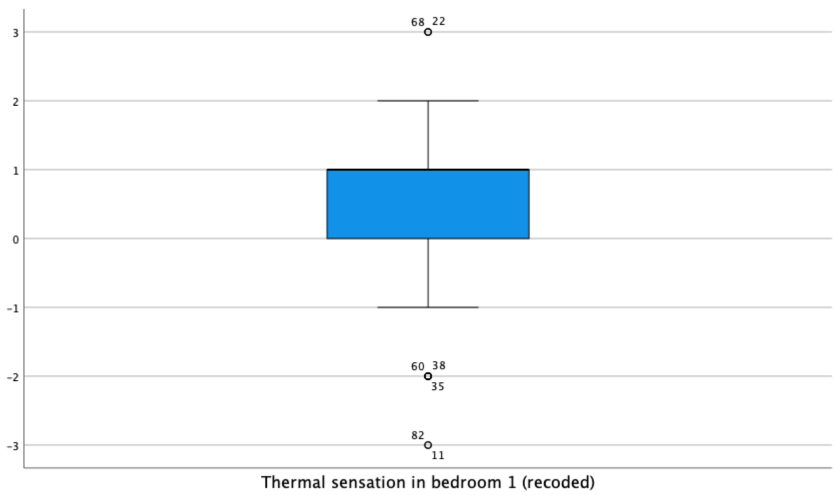


Figure G.1: Box plot distribution of households' thermal sensation in bedroom 1.

Appendix G: Sample of Outliers Test

Table G.2: Outliers test of households' thermal sensation votes (TSVs) in bedroom 2

Thermal sensation in bedroom 2 (recoded)		Extreme Values	Case Number	Value
	Highest	1	22	3.00
		2	48	3.00
		3	16	2.00
		4	23	2.00
		5	25	2g
	Lowest	1	11	-3.00
		2	75	-2.00
		3	60	-2.00
		4	38	-2.00
		5	35	-2h

g Only a partial list of cases with the value 2 are shown in the table of upper extremes.
h Only a partial list of cases with the value -2 are shown in the table of lower extremes.

```
   Thermal sensation in bedroom 2 (recoded) Stem-and-Leaf Plot

    Frequency    Stem &  Leaf

        8.00 Extremes    (=<-2.0)
        9.00       -1 .  000000000
         .00       -0 .
         .00       -0 .
       17.00        0 .  00000000000000000
         .00        0 .
       28.00        1 .  0000000000000000000000000000
         .00        1 .
       15.00        2 .  000000000000000
        2.00 Extremes    (>=3.0)

    Stem width:         1
    Each leaf:        1 case(s)
```

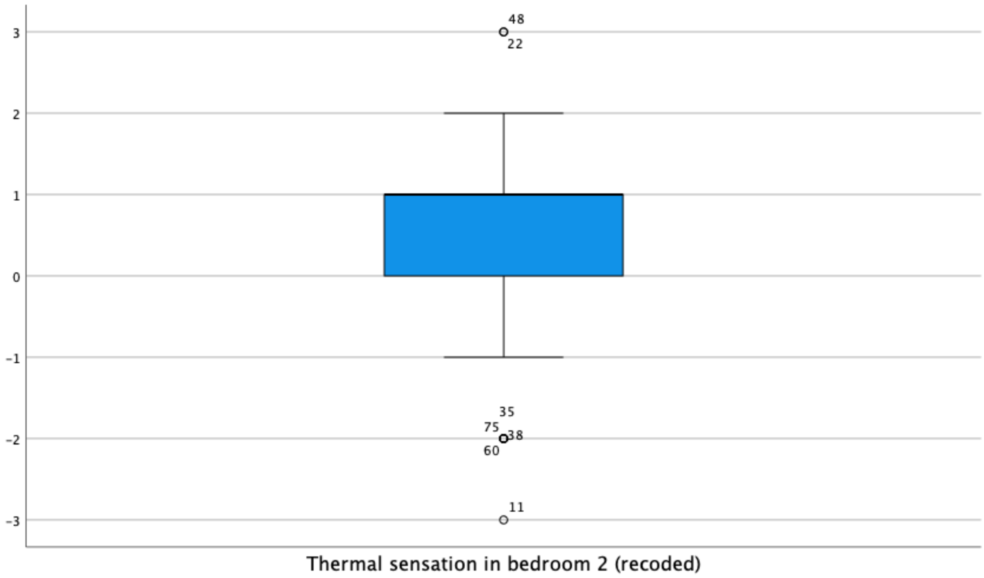


Figure G.2: Box plot distribution of households' thermal sensation in bedroom 2.

Appendix G: Sample of Outliers Test

Table G.3: Outliers test of households' thermal sensation votes (TSVs) in bedroom 3

Thermal sensation in bedroom 3 (recoded)		Extreme Values	Case Number	Value
	Highest	1	22	3.00
		2	70	3.00
		3	4	2.00
		4	16	2.00
		5	23	2g
	Lowest	1	75	-2.00
		2	60	-2.00
		3	38	-2.00
		4	35	-2.00
		5	24	-2h

g Only a partial list of cases with the value 2 are shown in the table of upper extremes.

h Only a partial list of cases with the value -2 are shown in the table of lower extremes.

```
Thermal sensation in bedroom 3 (recoded) Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

     7.00 Extremes    (=<-2.0)
     9.00       -1 .  000000000
      .00       -0 .
      .00       -0 .
    19.00        0 .  0000000000000000000
      .00        0 .
    26.00        1 .  00000000000000000000000000
      .00        1 .
    16.00        2 .  0000000000000000
     2.00 Extremes    (>=3.0)

 Stem width:         1
 Each leaf:        1 case(s)
```

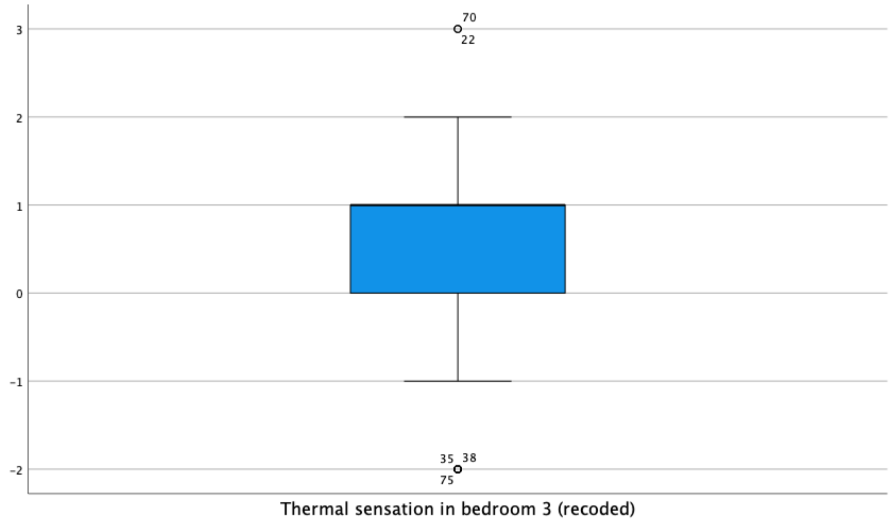


Figure G.3: Box plot distribution of households' thermal sensation in bedroom 3.

Appendix G: Sample of Outliers Test

Table G.4: Outliers test of households' thermal sensation votes (TSVs) in livingroom

Thermal sensation in livingroom (recoded)		Extreme Values	Case Number	Value
	Highest	1	5	3.00
		2	32	3.00
		3	48	3.00
		4	55	3.00
		5	66	3d
	Lowest	1	82	-2.00
		2	71	-2.00
		3	67	-2.00
		4	64	-2.00
		5	63	-2h

d Only a partial list of cases with the value 3 are shown in the table of upper extremes.

h Only a partial list of cases with the value -2 are shown in the table of lower extremes.

```
Thermal sensation in livingroom (recoded) Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

    14.00       -2 .  00000000000000
      .00       -1 .
    19.00       -1 .  0000000000000000000
      .00       -0 .
      .00       -0 .
    10.00        0 .  0000000000
      .00        0 .
    15.00        1 .  000000000000000
      .00        1 .
    14.00        2 .  00000000000000
      .00        2 .
     7.00        3 .  0000000

 Stem width:          1
 Each leaf:        1 case(s)
```

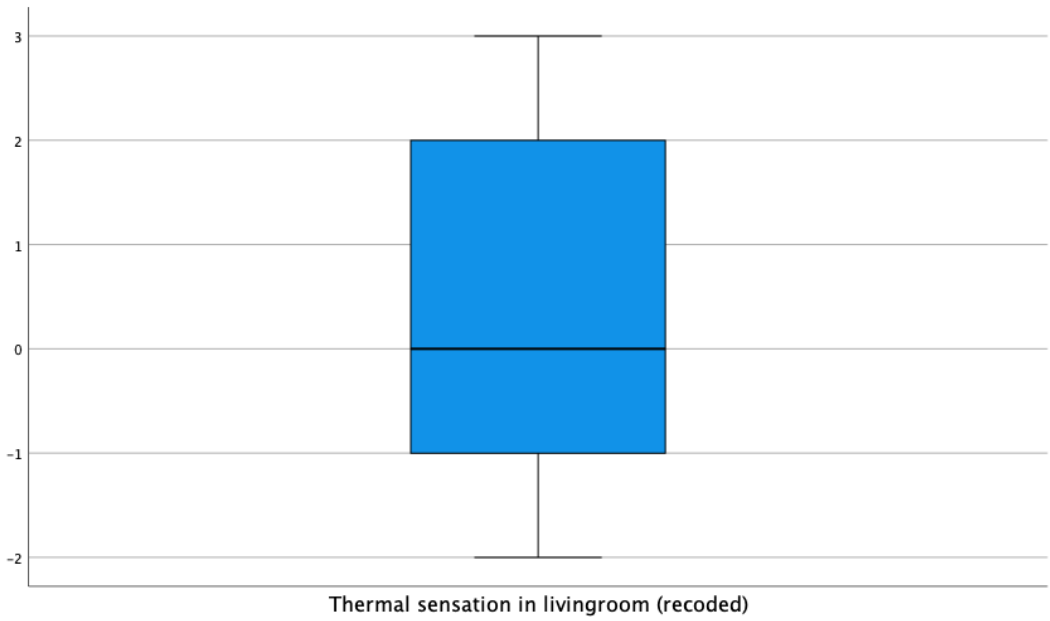


Figure G.4: Box plot distribution of households' thermal sensation in living-room.

Appendix G: Sample of Outliers Test

Table G.5: Outliers test of households' cooling energy use in summer of August 2015

Cooling energy consumption in summer of August 2015 (4 groups)		Extreme Values	Case Number	Value
	Highest	1	1	3.00
		2	2	3.00
		3	4	3.00
		4	6	3.00
		5	8	3.00d
	Lowest	1	100	0.00
		2	99	0.00
		3	98	0.00
		4	97	0.00
		5	96	.00e

d Only a partial list of cases with the value 3 are shown in the table of upper extremes.

e Only a partial list of cases with the value 0 are shown in the table of lower extremes.

```
Cooling energy consumption in summer of 2015 (5 groups) Stem-
and-Leaf Plot

 Frequency    Stem &  Leaf

    10.00 Extremes    (=<.0)
     5.00        1 .  00000
      .00        1 .
      .00        1 .
      .00        1 .
      .00        1 .
    26.00        2 .  00000000000000000000000000
      .00        2 .
      .00        2 .
      .00        2 .
      .00        2 .
    27.00        3 .  000000000000000000000000000
      .00        3 .
      .00        3 .
      .00        3 .
      .00        3 .
    11.00        4 .  00000000000

 Stem width:      1.00
 Each leaf:         1 case(s)
```

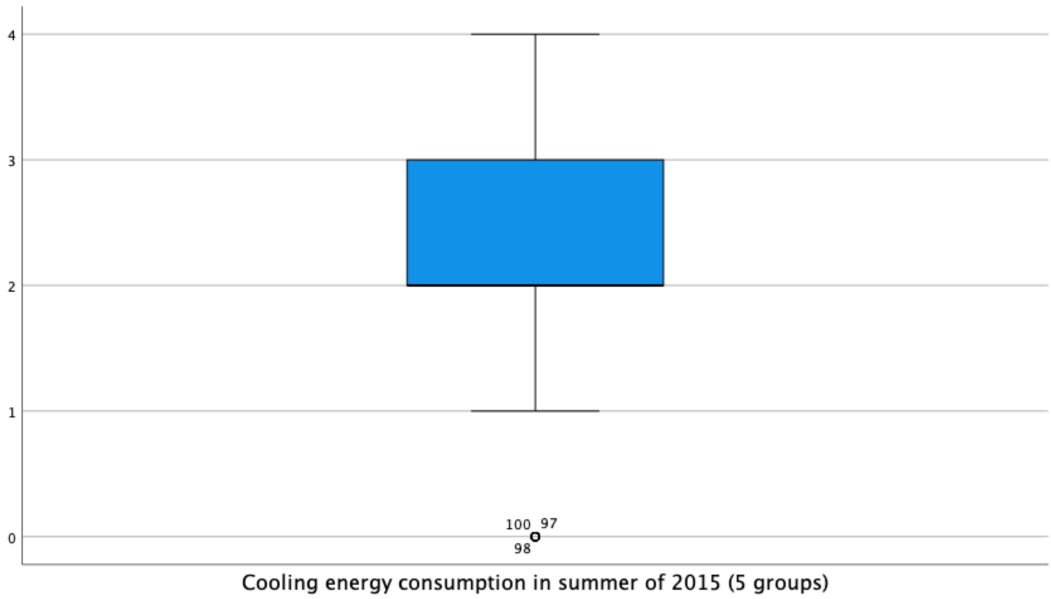


Figure G.5: Box plot distribution of households' cooling energy use in summer of August 2015.

Appendix G: Sample of Outliers Test

Table G.6: Outliers test of *in-situ* recorded DEW point temperature

Indoor DEW (°C)		Extreme Values	Case Number	Value
	Highest	1	83	32.40
		2	82	32.10
		3	63	25.10
		4	73	25.00
		5	75	24.80
	Lowest	1	38	11.40
		2	8	11.40
		3	18	12.00
		4	34	12.70
		5	39	14.40[1]

1 Only a partial list of cases with the value 14.40 are shown in the table of lower extremes.

```
Indoor DEW (°C) Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

     8.00 Extremes    (=<14.9)
     1.00       17 .  8
     2.00       18 .  22
     1.00       18 .  9
     3.00       19 .  144
     3.00       19 .  667
     7.00       20 .  0022234
     5.00       20 .  66999
     3.00       21 .  000
    10.00       21 .  5667889999
    11.00       22 .  00111133344
     3.00       22 .  689
     5.00       23 .  00134
     5.00       23 .  55677
     4.00       24 .  0013
     4.00       24 .  5668
     2.00       25 .  01
     2.00 Extremes    (>=32.1)

 Stem width:      1.00
 Each leaf:        1 case(s)
```

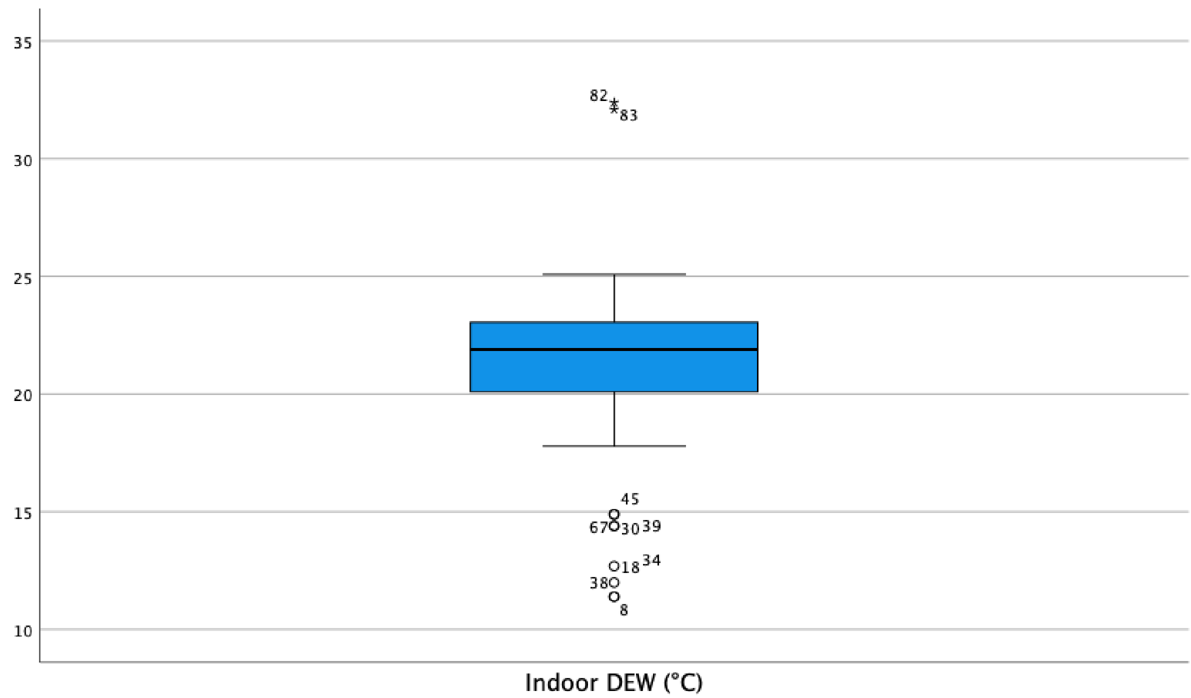


Figure G.6: Box plot distribution of *in-situ* recorded DEW point temperature.

Appendix G: Sample of Outliers Test

Table G.7: Outliers test of *in-situ* recorded indoor relative humidity

Indoor relative humidity (%)		Extreme Values	Case Number	Value
	Highest	1	62	75.00
		2	63	71.30
		3	9	71.00
		4	24	70.10
		5	76	68.30
	Lowest	1	70	31.10
		2	38	35.30
		3	8	35.30
		4	67	38.60
		5	41	39.20

```
Indoor relative humidity (%) Stem-and-Leaf Plot

 Frequency     Stem &  Leaf

     3.00 Extremes    (=<35)
     2.00        3 .  89
     5.00        4 .  11124
     4.00        4 .  6899
    10.00        5 .  0011111234
    16.00        5 .  5566666666777889
    26.00        6 .  00000000011111122222333444
     9.00        6 .  566667778
     3.00        7 .  011
     1.00        7 .  5

 Stem width:      10.00
 Each leaf:         1 case(s)
```

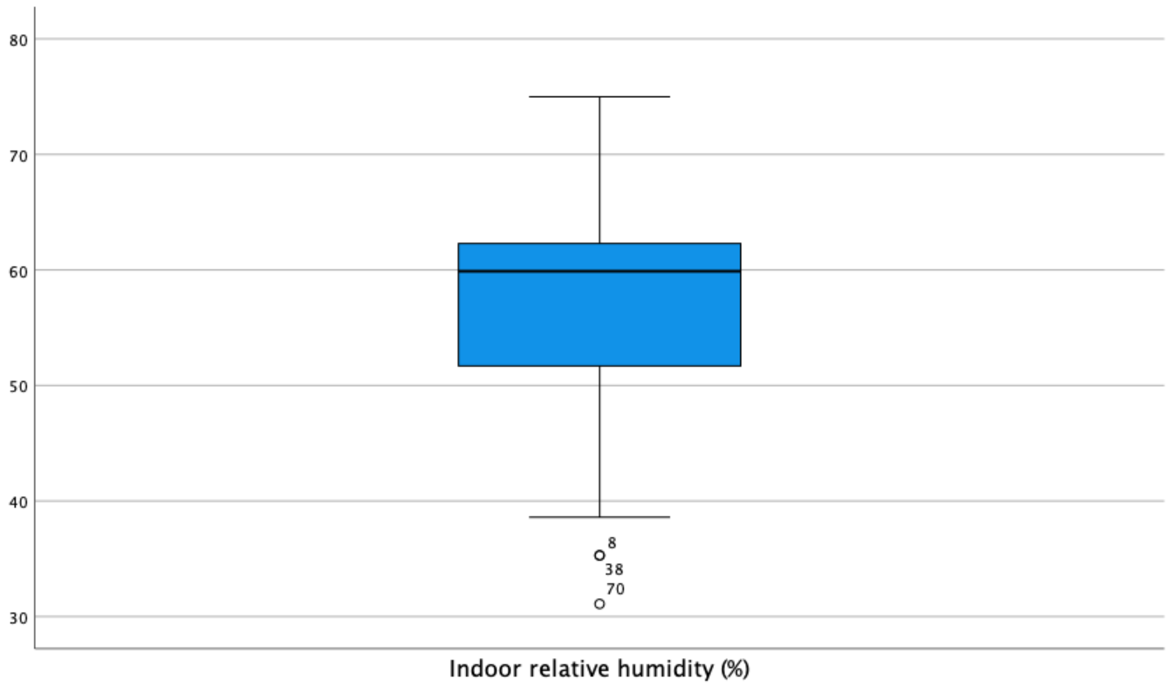


Figure G.7: Box plot distribution of *in-situ* recorded indoor relative humidity.

Appendix G: Sample of Outliers Test

Table G.8: Outliers test of *on-site* recorded operative air temperature

Operative air temperature (°C)		Extreme Values	Case Number	Value
	Highest	1	41	34.10
		2	35	34.00
		3	79	33.60
		4	56	33.40
		5	64	33.00
	Lowest	1	39	25.40
		2	30	25.40
		3	45	25.80
		4	34	27.00
		5	5	27.60

```
Operative air temperature (°C) Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

     3.00 Extremes    (=<25.8)
     1.00       27 .  0
     3.00       27 .  689
     4.00       28 .  0222
     6.00       28 .  899999
     3.00       29 .  004
     7.00       29 .  5556778
     7.00       30 .  0001123
     9.00       30 .  555666789
     8.00       31 .  11122334
    13.00       31 .  5555556678899
     9.00       32 .  001123333
     1.00       32 .  7
     2.00       33 .  04
     1.00       33 .  6
     2.00       34 .  01

 Stem width:      1.00
 Each leaf:        1 case(s)
```

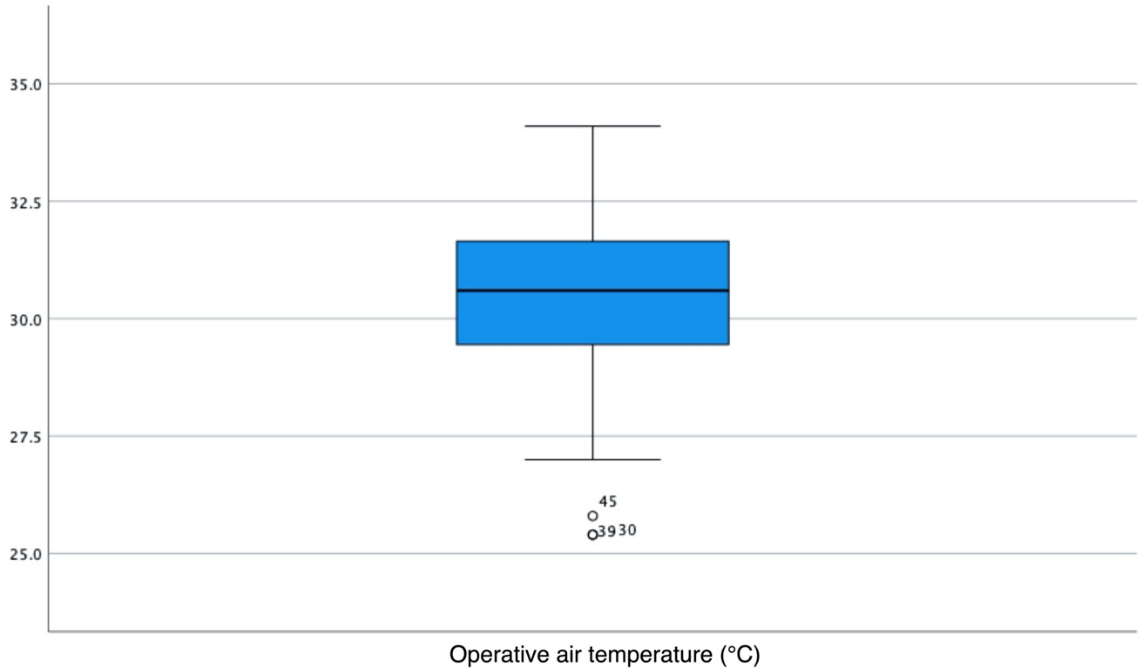


Figure G.8: Box plot distribution of *on-site* recorded operative air temperature.

Appendix G: Sample of Outliers Test

Table G.9: Outliers test of *in-situ* recorded solar radiation factor on building envelopes

Solar radiation (°C)		Extreme Values	Case Number	Value
	Highest	1	47	39.80
		2	41	39.20
		3	18	39.00
		4	17	38.30
		5	8	38.20m
	Lowest	1	60	29.70
		2	4	30.20
		3	1	30.30
		4	28	31.00
		5	27	31.00n

m Only a partial list of cases with the value 38.20 are shown in the table of upper extremes.

n Only a partial list of cases with the value 31.00 are shown in the table of lower extremes.

```
Solar radiation (°C) Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

     1.00       29 .  7
     2.00       30 .  23
    17.00       31 .  00012244677778899
    24.00       32 .  011122244556677777889999
     9.00       33 .  002244567
    10.00       34 .  0125788899
     2.00       35 .  04
     3.00       36 .  077
     3.00       37 .  269
     5.00       38 .  12223
     1.00       39 .  0
     2.00 Extremes    (>=39.2)

 Stem width:      1.00
 Each leaf:        1 case(s)
```

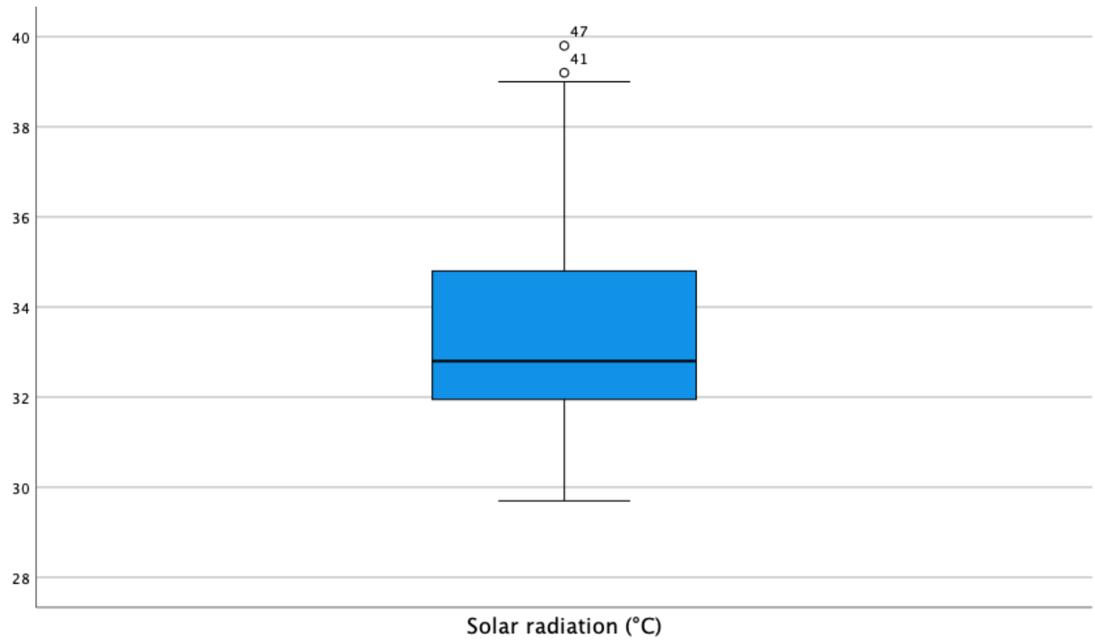


Figure G.9: Box plot distribution of *in-situ* recorded solar radiation factor on building envelopes.

Appendix G: Sample of Outliers Test

Table G.10: Outliers test of *in-situ* recorded indoor wet bulb ground temperature

Indoor wet bulb ground temperature (°C)		Extreme Values	Case Number	Value
	Highest	1	70	30.70
		2	73	28.60
		3	75	28.50
		4	9	28.40
		5	51	28.40
	Lowest	1	10	21.00
		2	39	21.20
		3	30	21.20
		4	45	21.40
		5	34	21.40

```
Indoor wet bulb ground temperature (°C) Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

     6.00 Extremes    (=<21.5)
     3.00       21 .  888
      .00       22 .
     1.00       22 .  9
      .00       23 .
      .00       23 .
     3.00       24 .  144
     2.00       24 .  77
    11.00       25 .  00000000134
     2.00       25 .  77
    10.00       26 .  0001123344
    18.00       26 .  555666777788888888
     6.00       27 .  000334
     5.00       27 .  56688
     9.00       28 .  012222344
     2.00       28 .  56
     1.00 Extremes    (>=30.7)

 Stem width:      1.00
 Each leaf:        1 case(s)
```

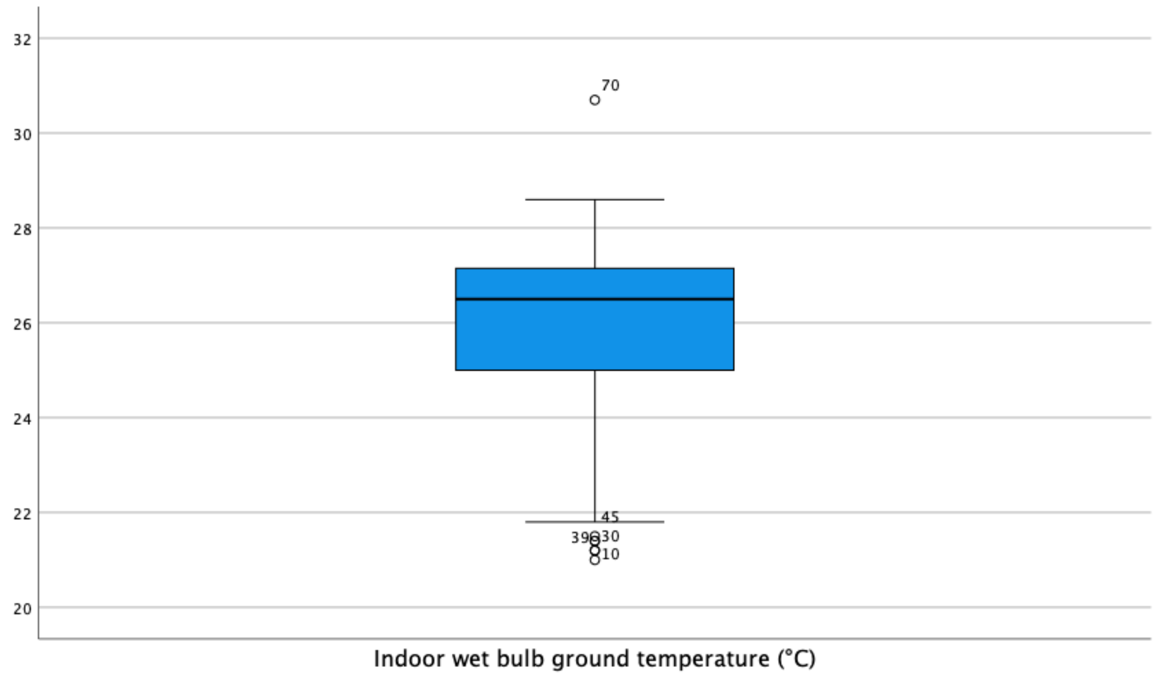


Figure G.10: Box plot distribution of *in-situ* recorded indoor wet bulb ground temperature.

Appendix G: Sample of Outliers Test

Table G.11: Outliers test of *on-site* recorded outdoor relative humidity

Outdoor relative humidity (%)		Extreme Values	Case Number	Value
	Highest	1	24	78.00
		2	63	78.00
		3	66	78.00
		4	27	77.00
		5	70	77.00
	Lowest	1	83	19.60
		2	18	25.00
		3	8	25.00
		4	99	31.00
		5	67	35.00

```
Outdoor relative humidity (%) Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

     5.00 Extremes    (=<35)
     1.00        3 .  9
     2.00        4 .  13
     6.00        4 .  566789
     7.00        5 .  0111244
    21.00        5 .  555566677777888889999
    13.00        6 .  0000012333444
    10.00        6 .  5555778999
     6.00        7 .  011224
     8.00        7 .  55577888

 Stem width:     10.00
 Each leaf:        1 case(s)
```

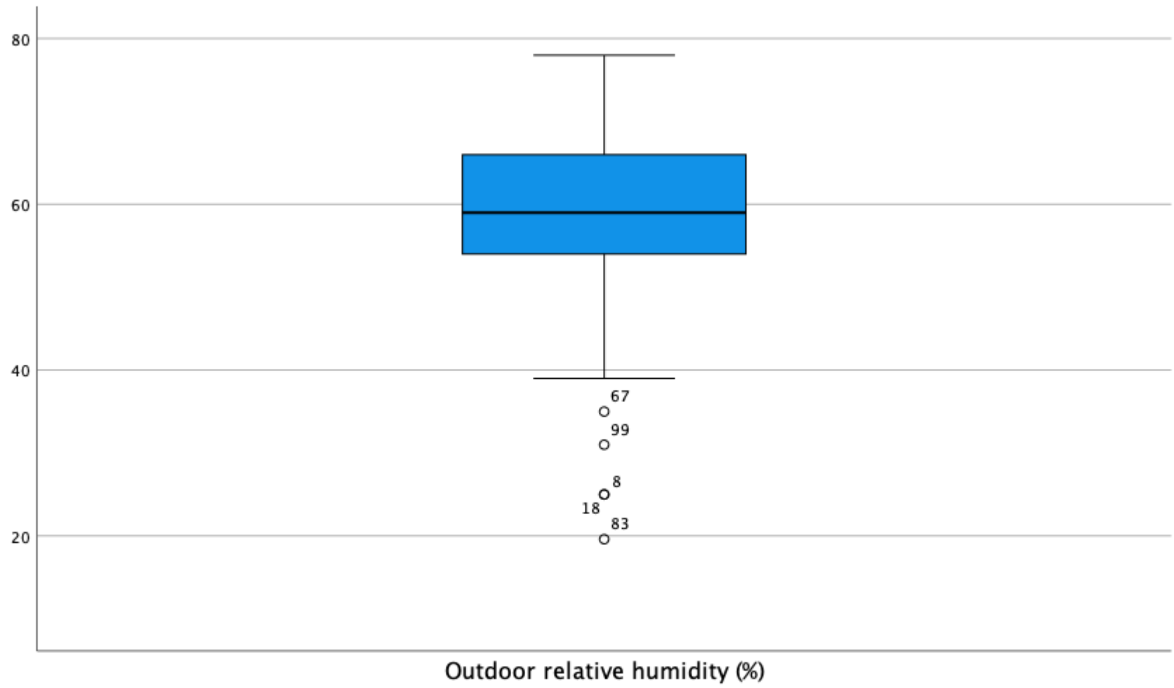


Figure G.11: Box plot distribution of *on-site* recorded outdoor relative humidity

Appendix G: Sample of Outliers Test

Table G.12: Outliers test of *on-site* recorded outdoor air temperature

Outdoor air temperature (°C)		Extreme Values	Case Number	Value
	Highest	1	8	36.00
		2	18	36.00
		3	30	36.00
		4	52	36.00
		5	99	36.00
	Lowest	1	83	23.70
		2	37	28.70
		3	91	28.90
		4	70	29.00
		5	66	29.00p

p Only a partial list of cases with the value 29.00 are shown in the table of lower extremes.

```
Outdoor air temperature (°C) Stem-and-Leaf Plot

 Frequency    Stem &  Leaf

     1.00 Extremes    (=<23.7)
     2.00       28 .  79
     9.00       29 .  000000000
      .00       29 .
     9.00       30 .  000000000
      .00       30 .
     7.00       31 .  0000000
      .00       31 .
    14.00       32 .  00000000000000
      .00       32 .
    13.00       33 .  0000000000000
      .00       33 .
    16.00       34 .  0000000000000000
      .00       34 .
     3.00       35 .  000
      .00       35 .
     5.00       36 .  00000

 Stem width:      1.00
 Each leaf:        1 case(s)
```

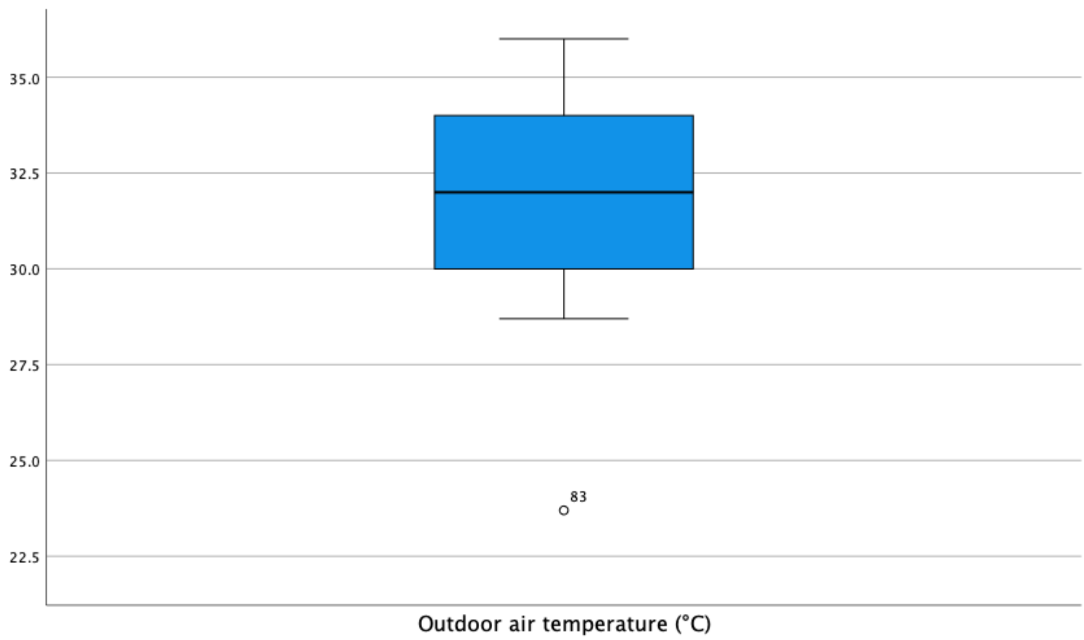


Figure G.12: Box plot distribution of *on-site* recorded outdoor air temperature.

Appendix H: Contingency Tables

Information on the Presentation of Contingency Tables

In this study, whilst correlations are indicative of association, there is scope with the data to perform hypothesis testing of significant differences between variables that would add weight to the results. To provide a clear representation of the study findings and report research outcomes in accordance with the research questions, which were set out to develop a novel methodological framework for the universal applicability of the Energy Performance of Buildings Directives (EPBD) in the residential sector, the relevant concepts of statistical convention were presented in Chapter 3 Subsection 3.3.1 (The Concept of Statistical Representativeness), Subsection 3.3.2 (References to the Works of Other Scholars on Representativeness) and Subsection 3.3.3 (Sample Size Calculation Criteria).

This appendix presents the contingency tables that support the findings of the statistical analysis presented in Tables 4.3 and 4.4(a) and (b) in Chapter 4. These findings are presented in the appendix to provide guidance on the applied statistical method in order to comply with the convention of supporting research outcomes. It should be noted that Chapter 4 presents the identification of a “neutral” adaptive thermal comfort threshold by conducting statistical analysis with *in-situ* measurements, *on-site* environmental monitoring, and a thermal comfort assessment questionnaire survey to develop benchmarking criteria for the South-eastern Mediterranean climate of Cyprus. These contingency tables are presented in the appendix because, according to the conventions of thermal comfort studies, representation of households’ thermal sensation by using descriptive statistics, frequencies, Cramér’s V test, Pearson’s correlations and further ordinal logistic regression analysis methods could provide a valid background for the development of reliable thermal comfort thresholds. In Chapter 4, the convention of the thermal comfort assessment method was applied in accordance with the concept of a statistically representative sampling size, which was achieved by undertaking a longitudinal field survey. This field study enables researchers to present households’ *in-vivo* experiences on thermal satisfaction.

In this appendix, the researcher decided to demonstrate the below-listed contingency tables because they are noteworthy contributions to the building and environment field where researchers could apply and adopt the statistical conventions presented in Chapter 4. At the same time, in Chapter 3, Subsections 3.3.1 and 3.3.2, scholars in the literature review recommend that reliable representativeness of sampling size within the variables identified to develop the concept of statistical convention plays an important role at the time of developing an evidence-based energy policy design. This is the reason that contingency tables for thermal comfort studies are not the primary factor used for identifying "neutral" adaptive thermal comfort thresholds, but the contingency tables are still presented. In this present study, Chapter 4 aims to demonstrate the longitudinal field survey findings with occupants' TSVs and, because of this, contingency tables are not presented in Chapter 4 but instead in the appendix to provide useful guidance for future scholars.

Important note about Tables 4.4(b-1)–(b-5): These are the contingency tables that support the statistical analysis in Table 4.3 in Chapter 4. In this statistical analysis, occupants' TSVs were identified as ordinal variables to conduct the Cramér's *V* test accurately. In the contingency tables presented in this appendix, it can be seen that household thermal sensation is represented by the terminology of "thermal feeling" indicators to provide a clear understanding to readers about household thermal sensation. It must be stressed that, in the dataset, the TSV code was set to [0 to 6] which represents the [-3, +3] thermal sensation band according to thermal comfort convention. Hence, the researcher decided to report the findings by using the terminology of each thermal feeling at the time of undertaking the statistical analysis for the contingency tables (Tables 4.4(b-1)–(b-5)).

Appendix H: Contingency Tables

Table H.1 [4.3-(1)]: Relationships Between Reasons for Thermal Discomfort and Household Age Band, RTB Orientation and Floor Level – Floor Level Variable.

Floor	Ground		First		Second		Third-Fourth		Fisher's Exact	p	Cramer's V
	n	%	n	%	n	%	n	%			
Age bands									12,72	0,380	0,211
Less than 35	1	5,6 [a]	3	10,7 [a]	4	21,1 [a]	8	22,9 [a]			
35–45	2	11,1 [a]	3	10,7 [a]	5	26,3 [a]	6	17,1 [a]			
45–55	2	11,1 [a]	7	25,0 [a]	3	15,8 [a]	8	22,9 [a]			
55–65	10	55,6 [a]	9	32,1 [a]	3	15,8 [a]	10	28,6 [a]			
65 or over	3	16,7	6	21,4	4	21,1	3	8,6			
Orientation									12,11	0,188	0,197
South	6	33,3 [a]	9	32,1 [a]	7	36,8 [a]	14	40,0 [a]			
North East or North West	3	16,7 [a]	13	46,4 [a]	7	36,8 [a]	12	34,3 [a]			
South West	6	33,3 [a]	2	7,1 [a]	2	10,5 [a]	8	22,9 [a]			
South East	3	16,7 [a]	4	14,3 [a]	3	15,8 [a]	1	2,9 [a]			
Reasons for thermal discomfort									39,52	<0,001	0,405
Humidity related	10	55,6 [a]	11	39,3 [a, b]	7	36,8 [a, b]	4	11,4 [b]			
Incoming sun	4	22,2 [a]	3	10,7 [a]	4	21,1 [a]	8	22,9 [a]			
Other reasons	2	11,1 [a]	4	14,3 [a]	1	5,3 [a]	8	22,9 [a]			
Heat	2	11,1 [a]	10	35,7 [a]	7	36,8 [a]	15	42,9 [a]			

Note. For each row category, pairs of column proportions with different superscripts differed significantly, $p < 0,05$.

Appendix H: Contingency Tables

Table H.2 [4.3-(2)]: Relationships Between Reasons for Thermal Discomfort and Household Age Band, RTB Orientation and Floor Level – Orientation Variable.

Orientation	South		North East or North		South West		South East		Fisher's Exact	*p*	Cramer's *V*
	n	%	*n*	%	*n*	%	*n*	%			
Age bands									15,84	0,165	0,229
Less than 35	6	16,7 [a]	9	25,7 [a]	0	0,0 [a]	1	9,1 [a]			
35–45	8	22,2 [a]	4	11,4 [a]	2	11,1 [a]	2	18,2 [a]			
45–55	9	25,0 [a]	4	11,4 [a]	4	22,2 [a]	3	27,3 [a]			
55–65	6	16,7 [a]	12	34,3 [a, b]	10	55,6 [b]	4	36,4 [a, b]			
65 or over	7	19,4 [a]	6	17,1 [a]	2	11,1 [a]	1	9,1 [a]			
Reasons for thermal discomfort									39,52	<0,001	0,405
Humidity related	15	41,7 [a]	13	37,1 [a, b]	1	5,6 [b]	3	27,3 [a, b]			
Incoming sun	2	5,6 [a]	4	11,4 [a]	13	72,2 [b]	0	0,0 [a]			
Other reasons	3	8,3 [a]	9	25,7 [a]	0	0,0 [a]	3	27,3 [a]			
Heat	16	44,4 [a]	9	25,7 [a]	4	22,2 [a]	5	45,5 [a]			

Note. For each row category, pairs of column proportions with different superscripts differed significantly, $p < 0,05$.

Appendix H: Contingency Tables

Table H.3 [4.3-(3)]: Relationships Between Reasons for Thermal Discomfort and Household Age Band, RTB Orientation and Floor Level – Age Band Variable.

Age bands	Less than 35		35−45		45−55		55−65		55−65				
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	Fisher's Exact	*p*	Cramer's *V*
Reasons for thermal disco											11,53	0,479	0,203
Humidity related	6	37,5 [a]	4	25,0 [a]	5	25,0 [a]	9	28,1 [a]	8	50,0 [a]			
Incoming sun	1	6,3 [a]	1	6,3 [a]	5	25,0 [a]	10	31,3 [a]	2	12,5 [a]			
Other reasons	4	25,0 [a]	3	18,8 [a]	2	10,0 [a]	4	12,5 [a]	2	12,5 [a]			
Heat	5	31,3 [a]	8	50,0 [a]	8	40,0 [a]	9	28,1 [a]	4	25,0 [a]			

Note. For each row category, pairs of column proportions with different superscripts differed significantly, $p < 0,05$.

Appendix H: Contingency Tables

Table H.4 [4.4-(b-1)]: Relationships Between Occupant TSVs for Each Occuppied Space in the Summer: Living room, Kitchen, Bedroom 1, Bedroom 2, Bedroom 3, RTB Orienttion and Floor Level – RTB Orientation.

Orientation	South		North East or North		South West		South East		Fisher's Exact	p	Cramer's V
	n	%	n	%	n	%	n	%			
Thermal sensation in livingroom									15,40	0,379	0,226
Cool	6	16,7 [a]	4	11,4 [a]	6	33,3 [a]	2	18,2 [a]			
Slightly cool	8	22,2 [a]	5	14,3 [a]	8	44,4 [a]	2	18,2 [a]			
Comfortable	5	13,9 [a]	5	14,3 [a]	1	5,6 [a]	2	18,2 [a]			
Slightly warm	8	22,2 [a]	9	25,7 [a]	2	11,1 [a]	2	18,2 [a]			
Warm	7	19,4 [a]	8	22,9 [a]	0	0,0 [a]	2	18,2 [a]			
Hot	2	5,6 [a]	4	11,4 [a]	1	5,6 [a]	1	9,1 [a]			
Thermal sensation in kitchen									19,72	0,118	0,279
Cool	11	30,6 [a, b]	5	14,3 [b]	10	55,6 [a]	2	18,2 [a, b]			
Slightly cool	12	33,3 [a]	9	25,7 [a]	4	22,2 [a]	3	27,3 [a]			
Comfortable	7	19,4 [a]	7	20,0 [a]	1	5,6 [a]	1	9,1 [a]			
Slightly warm	4	11,1 [a]	5	14,3 [a]	2	11,1 [a]	3	27,3 [a]			
Warm	1	2,8 [a]	3	8,6 [a]	1	5,6 [a]	2	18,2 [a]			
Hot	1	2,8 [a]	6	17,1 [a]	0	0,0 [a]	0	0,0 [a]			

Note. For each row category, pairs of column proportions with different superscripts differed significantly, $p < 0,05$.

Appendix H: Contingency Tables

Table H.5 [4.4-(b-2)]: Relationships Between Occupant TSVs for Each Occuppied Space in the Summer: Living room, Kitchen, Bedroom 1, Bedroom 2, Bedroom 3, RTB Orienttion and Floor Level – RTB Orientation (Continued).

Orientation	South		North East or North		South West		South East		Fisher's Exact	*p*	Cramer's *V*
	n	%	*n*	%	*n*	%	*n*	%			
Thermal sensation in bedroom 1									20,81	0,176	0,274
Cold	2	5,6 [a, b]	0	0,0 [a]	0	0,0 [a]	0	0,0 [a]			
Cool	3	8,3 [a]	2	5,7 [a]	2	11,1 [a]	2	18,2 [a]			
Slightly cool	5	13,9 [a]	4	11,4 [a]	3	16,7 [a]	1	9,1 [a]			
Comfortable	7	19,4 [a]	3	8,6 [a]	5	27,8 [a]	1	9,1 [a]			
Slightly warm	15	41,7 [a]	9	25,7 [a]	6	33,3 [a]	4	36,4 [a]			
Warm	3	8,3 [a]	15	42,9 [b]	2	11,1 [a, b]	3	27,3 [a, b]			
Hot	1	2,8	2	5,7 [a]	0	0,0 [a]	0	0,0 [a]			
Thermal sensation in bedroom 2									22,54	0,121	0,272
Cold	1	2,8 [a]	0	0,0 [a]	0	0,0 [a]	0	0,0 [a]			
Cool	2	5,6 [a]	3	8,6 [a]	2	11,1 [a]	1	9,1 [a]			
Slightly cool	6	16,7 [a]	4	11,4 [a]	4	22,2 [a]	0	0,0 [a]			
Comfortable	10	27,8 [a]	4	11,4 [a]	5	27,8 [a]	3	27,3 [a]			
Slightly warm	14	38,9 [a]	10	28,6 [a]	6	33,3 [a]	3	27,3 [a]			
Warm	3	8,3 [a]	13	37,1 [b]	1	5,6 [a, b]	3	27,3 [a, b]			
Hot	0	0,0 [a]	1	2,9 [a]	0	0,0 [a]	1	9,1 [a]			
Thermal sensation in bedroom 3									20,19	0,094	0,263
Cool	2	5,6 [a, b]	3	8,6 [a]	2	11,1 [a]	1	9,1 [a]			
Slightly cool	4	11,1 [a]	2	5,7 [a]	4	22,2 [a]	1	9,1 [a]			
Comfortable	14	38,9 [a]	3	8,6 [b]	5	27,8 [a, b]	3	27,3 [a, b]			
Slightly warm	12	33,3 [a]	12	34,3 [a]	5	27,8 [a]	3	27,3 [a]			
Warm	4	11,1 [a]	13	37,1 [a]	2	11,1 [a]	3	27,3 [a]			
Hot	0	0,0 [a]	2	5,7 [a]	0	0,0 [a]	0	0,0 [a]			

Note. For each row category, pairs of column proportions with different superscripts differed significantly, $p < 0,05$.

Appendix H: Contingency Tables

Table H.6 [4.4-(b-3)]: Relationships Between Occupant TSVs for Each Occuppied Space in the Summer: Living room, Kitchen, Bedroom 1, Bedroom 2, Bedroom 3, RTB Orienttion and Floor Level – Floor Level.

Floor	Ground		First		Second		Third-Fourth		Fisher's Exact	*p*	Cramer's *V*
	n	%	*n*	%	*n*	%	*n*	%			
Thermal sensation in livingroom									18,15	0,220	0,232
Cool	2	11,1 [a]	6	21,4 [a]	3	15,8 [a]	7	20,0 [a]			
Slightly cool	4	22,2 [a]	4	14,3 [a]	5	26,3 [a]	10	28,6 [a]			
Comfortable	3	16,7 [a]	3	10,7 [a]	2	10,5 [a]	5	14,3 [a]			
Slightly warm	6	33,3 [a]	9	32,1 [a]	5	26,3 [a, b]	1	2,9 [b]			
Warm	1	5,6 [a]	4	14,3 [a]	4	21,1 [a]	8	22,9 [a]			
Hot	2	11,1 [a]	2	7,1 [a]	0	0,0 [a]	4	11,4 [a]			
Thermal sensation in kitchen									15,35	0,384	0,222
Cool	5	27,8 [a]	5	17,9 [a]	4	21,1 [a]	14	40,0 [a]			
Slightly cool	4	22,2 [a]	9	32,1 [a]	4	21,1 [a]	11	31,4 [a]			
Comfortable	4	22,2 [a]	4	14,3 [a]	4	21,1 [a]	4	11,4 [a]			
Slightly warm	2	11,1 [a]	7	25,0 [a]	4	21,1 [a]	1	2,9 [a]			
Warm	2	11,1 [a]	2	7,1 [a]	2	10,5 [a]	1	2,9 [a]			
Hot	1	5,6 [a]	1	3,6 [a]	1	5,3 [a]	4	11,4 [a]			

Note. For each row category, pairs of column proportions with different superscripts differed significantly, $p < 0,05$.

Appendix H: Contingency Tables

Table H.7 [4.4-(b-4)]: Relationships Between Occupant TSVs for Each Occuppied Space in the Summer: Living room, Kitchen, Bedroom 1, Bedroom 2, Bedroom 3, RTB Orienttion and Floor Level – Floor Level (Continued).

Floor	Ground		First		Second		Third-Fourth				
	n	%	*n*	%	*n*	%	*n*	%	Fisher's Exact	*p*	Cramer's *V*
Thermal sensation in bedroom 1									10,23	0,952	0,177
Cold	0	0,0 [a]	0	0,0 [a]	1	5,3 [a]	1	2,9 [a]			
Cool	2	11,1 [a]	3	10,7 [a]	2	10,5 [a]	2	5,7 [a]			
Slightly cool	2	11,1 [a]	4	14,3 [a]	1	5,3 [a]	6	17,1 [a]			
Comfortable	2	11,1 [a]	2	7,1 [a]	5	26,3 [a]	7	20,0 [a]			
Slightly warm	7	38,9 [a]	11	39,3 [a]	5	26,3 [a]	11	31,4 [a]			
Warm	4	22,2 [a]	7	25,0 [a]	5	26,3 [a]	7	20,0 [a]			
Hot	1	5,6 [a]	1	3,6 [a]	0	0,0 [a]	1	2,9 [a]			
Thermal sensation in bedroom 2									12,09	0,891	0,194
Cold	0	0,0 [a]	0	0,0 [a]	0	0,0 [a]	1	2,9 [a]			
Cool	2	11,1 [a]	1	3,6 [a]	2	10,5 [a]	3	8,6 [a]			
Slightly cool	2	11,1 [a]	5	17,9 [a]	2	10,5 [a]	5	14,3 [a]			
Comfortable	3	16,7 [a]	4	14,3 [a]	5	26,3 [a]	10	28,6 [a]			
Slightly warm	7	38,9 [a]	11	39,3 [a]	4	21,1 [a]	11	31,4 [a]			
Warm	3	16,7 [a]	6	21,4 [a]	6	31,6 [a]	5	14,3 [a]			
Hot	1	5,6 [a]	1	3,6 [a]	0	0,0 [a]	0	0,0 [a]			

Note. For each row category, pairs of column proportions with different superscripts differed significantly, $p < 0,05$.

Appendix H: Contingency Tables

Table H.8 [4.4-(b-5)]: Relationships Between Occupant TSVs for Each Occuppied Space in the Summer: Living room, Kitchen, Bedroom 1, Bedroom 2, Bedroom 3, RTB Orienttion and Floor Level – Floor Level (Continued).

Floor	Ground		First		Second		Third-Fourth		Fisher's Exact	*p*	Cramer's *V*
	n	%	*n*	%	*n*	%	*n*	%			
Thermal sensation in bedroom 3									13,86	0,489	0,221
Cool	2	11,1 [a]	1	3,6 [a]	2	10,5 [a]	3	8,6 [a]			
Slightly cool	2	11,1 [a]	6	21,4 [a]	1	5,3 [a]	2	5,7 [a]			
Comfortable	3	16,7 [a]	5	17,9 [a]	4	21,1 [a]	13	37,1 [a]			
Slightly warm	6	33,3 [a]	11	39,3 [a]	5	26,3 [a]	10	28,6 [a]			
Warm	4	22,2 [a]	4	14,3 [a]	7	36,8 [a]	7	20,0 [a]			
Hot	1	5,6 [a]	1	3,6 [a]	0	0,0 [a]	0	0,0 [a]			
Orientation									12,11	0,188	0,197
South	6	33,3 [a]	9	32,1 [a]	7	36,8 [a]	14	40,0 [a]			
North East or North West	3	16,7 [a]	13	46,4 [a]	7	36,8 [a]	12	34,3 [a]			
South West	6	33,3 [a]	2	7,1 [a]	2	10,5 [a]	8	22,9 [a]			
South East	3	16,7 [a]	4	14,3 [a]	3	15,8 [a]	1	2,9 [a]			

Note. For each row category, pairs of column proportions with different superscripts differed significantly, $p < 0,05$.

Appendix I: Development Stages of the Statistical Analysis – Part 1

```
*Table 4.1 (in-situ measurements and on-site environmental monitoring data).
FREQUENCIES VARIABLES=In_TA In_RH Out_TA Out_RH Out_Heat_Index
  /FORMAT=NOTABLE
  /STATISTICS=STDDEV MINIMUM MAXIMUM MEAN
  /ORDER=ANALYSIS.

*Table 4.2 (in-situ measurements data).
FREQUENCIES VARIABLES=In_Temperature In_WET_rec In_DEW
  /FORMAT=NOTABLE
  /NTILES=4
  /STATISTICS=STDDEV MINIMUM MAXIMUM SEMEAN MEAN MEDIAN SKEWNESS SESKEW KURTOSIS SEKURT
  /ORDER=ANALYSIS.

*Figure 4.4 (in-situ measurements and on-site environmental monitoring data).
EXAMINE VARIABLES=In_TA Out_TA In_RH Out_RH
  /PLOT BOXPLOT HISTOGRAM NPPLOT
  /COMPARE GROUPS
  /STATISTICS NONE
  /CINTERVAL 95
  /MISSING LISTWISE
  /NOTOTAL.

*Figure 4.6 (data gathered from the questionnaire survey - occupants' TSVs [0 to 6] represents [-3, +3] as discrete parameter for the representation of thermal feeling terminology between [Hot to Cold]).
CROSSTABS
  /TABLES=Summer_temperature_satisfaction_Q33_rec by Orientation_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).

*Figure 4.7 (a) through (d). (data gathered from the questionnaire survey - occupants' TSVs represents [-3, +3] represents [Hot to Cold] as continuous parameter for the representation of thermal sensation between [-3, +3].
FREQUENCIES VARIABLES=Summer_thermal_sensation_bedroom1_Q22_rec  Summer_thermal_sensation_livingroom_Q22_rec
  /ORDER=ANALYSIS.

FREQUENCIES VARIABLES=Summer_thermal_sensation_bedroom2_Q22_rec Summer_thermal_sensation_bedroom3_Q22_rec
  /ORDER=ANALYSIS.

*Table 4.3 (data gathered from the questionnaire survey - Age band represents 1 = Less than 5; 2 = 35-45; 3 = 45-55; 4 = 55-65; 5 = 65 or over).
CROSSTABS
  /TABLES=Reason_for_thermal_discomfort_4grps  Age_bands_6grps  Orientation_4grps BY Floor_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).
CROSSTABS
  /TABLES=Reason_for_thermal_discomfort_4grps  Age_bands_6grps BY Orientation_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).
CROSSTABS
  /TABLES=Reason_for_thermal_discomfort_4grps BY Age_bands_6grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).

*Table 4.4 (a) and (b) - Pearson's correlations Occupant TSVs for living room, kitchen and bedrooms 1,2 and 3 in the summer (-3) to (+3) - Fisher's exact test - Occupant TSVs for living room, kitchen and bedrooms 1,2 and
```

Figure I.1: Codebook of series of statistical analysis was presented in Chapter 4.

Appendix I: Development Stages of the Statistical Analysis – Part 1

```
*Table 4.4 (a) and (b) - Pearson's correlations Occupant TSVs for living room, kitchen and bedrooms 1,2 and 3 in the summer (-3) to (+3) - Fisher's exact test - Occupant TSVs for living room, kitchen and bedrooms 1,2 and 3 in the summer (0) to (6).
CROSSTABS
  /TABLES=Summer_thermal_sensation_livingroom_Q22_rec  Summer_thermal_sensation_kitchen_Q22_rec Summer_thermal_sensation_bedroom1_Q22_rec Summer_thermal_sensation_bedroom2_Q22_rec
  Summer_thermal_sensation_bedroom3_Q22_rec Orientation_4grps BY  Floor_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).
CROSSTABS
  /TABLES=Summer_thermal_sensation_livingroom_Q22_rec  Summer_thermal_sensation_kitchen_Q22_rec Summer_thermal_sensation_bedroom1_Q22_rec Summer_thermal_sensation_bedroom2_Q22_rec
  Summer_thermal_sensation_bedroom3_Q22_rec BY Orientation_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).
CROSSTABS
  /TABLES=Summer_thermal_sensation_livingroom_Q22_rec  Summer_thermal_sensation_kitchen_Q22_rec Summer_thermal_sensation_bedroom1_Q22_rec Summer_thermal_sensation_bedroom2_Q22_rec BY
  Summer_thermal_sensation_bedroom3_Q22_rec
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).
CROSSTABS
  /TABLES=Summer_thermal_sensation_livingroom_Q22_rec  Summer_thermal_sensation_kitchen_Q22_rec Summer_thermal_sensation_bedroom1_Q22_rec BY Summer_thermal_sensation_bedroom2_Q22_rec
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).
CROSSTABS
  /TABLES=Summer_thermal_sensation_livingroom_Q22_rec  Summer_thermal_sensation_kitchen_Q22_rec BY Summer_thermal_sensation_bedroom1_Q22_rec
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).
CROSSTABS
  /TABLES=Summer_thermal_sensation_livingroom_Q22_rec  BY Summer_thermal_sensation_kitchen_Q22_rec
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).

*Figure 4.9 (data gathered from the questionnaire survey and in-situ measurements).
PLUM Summer_thermal_sensation_livingroom_Q22_rec WITH In_TA
  /CRITERIA=CIN(95) DELTA(0) LCONVERGE(0) MXITER(100) MXSTEP(5) PCONVERGE(1.0E-6) SINGULAR(1.0E-8)
  /LINK=LOGIT
  /PRINT=FIT PARAMETER SUMMARY.

*Figure 4.10 (data gathered from the questionnaire survey and in-situ measurements).
PLUM  Summer_thermal_sensation_bedroom1_Q22_rec WITH In_TA
  /CRITERIA=CIN(95) DELTA(0) LCONVERGE(0) MXITER(100) MXSTEP(5) PCONVERGE(1.0E-6) SINGULAR(1.0E-8)
  /LINK=LOGIT
  /PRINT=FIT PARAMETER SUMMARY.

*Figure 4.11 (data gathered from the questionnaire survey and in-situ measurements).
PLUM Summer_thermal_sensation_bedroom2_Q22_rec WITH In_TA
```

Figure I.2: Codebook of series of statistical analysis was presented in Chapter 4.

Appendix I: Development Stages of the Statistical Analysis – Part 1

```
*Figure 4.11 (data gathered from the questionnaire survey and in-situ measurements).
PLUM Summer_thermal_sensation_bedroom2_Q22_rec WITH In_TA
  /CRITERIA=CIN(95) DELTA(0) LCONVERGE(0) MXITER(100) MXSTEP(5) PCONVERGE(1.0E-6) SINGULAR(1.0E-8)
  /LINK=LOGIT
  /PRINT=FIT PARAMETER SUMMARY.

*Figure 4.12 (data gathered from the questionnaire survey and in-situ measurements).
PLUM Summer_thermal_sensation_bedroom3_Q22_rec WITH In_TA
  /CRITERIA=CIN(95) DELTA(0) LCONVERGE(0) MXITER(100) MXSTEP(5) PCONVERGE(1.0E-6) SINGULAR(1.0E-8)
  /LINK=LOGIT
  /PRINT=FIT PARAMETER SUMMARY.

*Figure 4.13 (data gathered from the questionnaire survey and in-situ measurements).
PLUM Summer_temperature_satisfaction_Q33_rec WITH In_RH
  /CRITERIA=CIN(95) DELTA(0) LCONVERGE(0) MXITER(100) MXSTEP(5) PCONVERGE(1.0E-6) SINGULAR(1.0E-8)
  /LINK=LOGIT
  /PRINT=FIT PARAMETER SUMMARY.

*Figure 4.15 (a) (data gathered from the questionnaire survey).
FREQUENCIES VARIABLES=Summertime_doors_opening_preference_Q19_rec  Location_of_respondent
  /ORDER=ANALYSIS.

*Figure 4.15 (b) (data gathered from the questionnaire survey).
CROSSTABS
  /TABLES=Location_of_respondent by Gender_Q1.1
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
    /METHOD=EXACT TIMER(5).

*



*Figure 5.8 (in-situ measurements data).
EXAMINE VARIABLES=Time_of_day BY In_Temperature
  /PLOT BOXPLOT
  /COMPARE GROUPS
  /STATISTICS NONE
  /CINTERVAL 95
  /MISSING LISTWISE
  /NOTOTAL.

*

*Figure 5.12 (on-site environmental monitoring data).
EXAMINE VARIABLES=Time_of_day BY Out_Heat_Index
  /PLOT BOXPLOT
  /COMPARE GROUPS
  /STATISTICS NONE
  /CINTERVAL 95
  /MISSING LISTWISE
  /NOTOTAL.

*Figure 5.16 (a) (in-situ measurements data and data gathered from the questionnaire survey).
EXAMINE VARIABLES=In_TA BY Orientation_4grps
  /PLOT BOXPLOT
  /COMPARE GROUPS
  /STATISTICS NONE
  /CINTERVAL 95
  /MISSING LISTWISE
```

Figure I.3: Codebook of series of statistical analysis was presented in Chapters 4 and 5.

Appendix I: Development Stages of the Statistical Analysis – Part 1

```
  /MISSING LISTWISE
  /NOTOTAL.

*Figure 5.16 (a) (in-situ measurements data and data gathered from the questionnaire survey).
EXAMINE VARIABLES=In_TA BY Orientation_4grps
  /PLOT BOXPLOT
  /COMPARE GROUPS
  /STATISTICS NONE
  /CINTERVAL 95
  /MISSING LISTWISE
  /NOTOTAL.

*Table 5.2 (in-situ measurements data and data gathered from the questionnaire survey).
SORT CASES  BY Orientation.
SPLIT FILE LAYERED BY Orientation.

FREQUENCIES VARIABLES=In_TA
  /NTILES=4
  /ORDER=ANALYSIS.

SPLIT FILE OFF.

*Figure 5.16 (b) (in-situ measurements data and data gathered from the questionnaire survey).
EXAMINE VARIABLES=In_TA BY Floor_4grps
  /PLOT BOXPLOT
  /COMPARE GROUPS
  /STATISTICS NONE
  /CINTERVAL 95
  /MISSING LISTWISE
  /NOTOTAL.

*Table 5.3 (in-situ measurements and data gathered from the questionnaire survey).
SORT CASES  BY Floor_4grps.
SPLIT FILE LAYERED BY Floor_4grps.

FREQUENCIES VARIABLES=In_TA
  /NTILES=4
  /ORDER=ANALYSIS.

SPLIT FILE OFF.

*Figure 5.18 (a) (on-site environmental monitoring data).
EXAMINE VARIABLES=Time_of_day by Out_TA
  /PLOT BOXPLOT
  /COMPARE GROUPS
  /STATISTICS NONE
  /CINTERVAL 95
  /MISSING LISTWISE
  /NOTOTAL.

*Figure 5.18 (b) (in-situ measurements data).
EXAMINE VARIABLES=Time_of_day by In_TA
  /PLOT BOXPLOT
  /COMPARE GROUPS
  /STATISTICS NONE
  /CINTERVAL 95
  /MISSING LISTWISE
  /NOTOTAL.
```

Figure I.4: Codebook of series of statistical analysis was presented in Chapters 4 and 5.

Appendix I: Development Stages of the Statistical Analysis – Part 2

```
* Encoding: UTF-8.
****************************************************
***************Check Supplementary - Material 2 - Descriptive Analysis and Material 3 - Type of Measures for each Variable************
****************************************************


* Encoding: UTF-8.
*Table S.2.1 - Descriptive analysis of the variable related to identification of 'neutral' adaptive thermal comfort thresholds for benchmarking (data gathered from the questionnaire survey).
FREQUENCIES VARIABLES=Summer_temperature_satisfaction_Q33_rec Summer_temperature_satisfaction_5grps
   Summer_thermal_sensation_bedroom1_Q22_rec Summer_thermal_sensation_bedroom2_Q22_rec
   Summer_thermal_sensation_bedroom3_Q22_rec Summer_thermal_sensation_kitchen_Q22_rec
   Summer_thermal_sensation_livingroom_Q22_rec Winter_temperature_satisfaction_Q34
   Summer_thermal_sensation_bedroom1_5grps Summer_thermal_sensation_bedroom2_5grps
   Summer_thermal_sensation_bedroom3_5grps Summer_thermal_sensation_kitchen_5grps
   Reason_for_thermal_discomfort_4grps Feeling_preference_rec_4grps
  /ORDER=ANALYSIS.

*Table S.2.2 - Descriptive analysis of the variables related to hosueholds' socio-demographic characteristics (data gathered from the questionnaire survey).
FREQUENCIES VARIABLES=Age_Q1.2 Age_bands_6grps Awareness_in_energy_saving_Q6_rec
   Electricity_meter_reading_Q4_rec education_4grps Clothing_insulation_4grps Residency_3grps
   Floor_4grps Ethnicity_2grps Orientation_4grps Interviewed_room_condition_5grps Health_4grps
   Household_density_4grps Income_4grps Metabolic_activity_7grps Energy_consumption_Q5 Gender_Q1.1
   Occupation_4grps Occupation_Q1.3 Tenure_type_Q3
  /ORDER=ANALYSIS.

*Table S.2.3 - Descriptive analysis of the variables related to households' habitual adaptive behaviour on home energy use (data gathered from the questionnaire survey).
FREQUENCIES VARIABLES=Summertime_doors_opening_preference_Q19_rec
   Wintertime_doors_opening_preference_Q24_rec Cooling_control_4grps Cooling_patterns_weekdays_3grps
   Cooling_patterns_weekends_Q13 E2015_SUMMER_AUGUST_4grps E2015_SUMMER_OVERALL_5grps
   E2016_SUMMER_AUGUST_4grps E2016_SUMMER_OVERALL_5grps Health_4grps Heating_patterns_weekdays_3grps
   Heating_patterns_weekends_3grps Windows_opening_reason_2grps E2015_WINTER_OVERALL_4grps
   E2016_WINTER_OVERALL_4grps Type_of_heating_system_4grps Type_of_cooling_system_4grps
   Windows_closing_reason_5grps
  /ORDER=ANALYSIS.

*Table S.2.4 - Descriptive analysis of the variables realted to both on-site monitored and in-situ recorded environmental parameters (data gathered from the research instruments - on-site weather station, infrared radiometer camera).
FREQUENCIES VARIABLES=In_DEW In_RH In_TA In_Temperature In_WET_rec In_WBGT Out_Heat_Index Out_RH
   Out_TA Out_DEW In_TG
  /ORDER=ANALYSIS.


****************************************************
************ Supplementary Material 6 - Cramer's V tests by using Fisher's Exact tests  ***************
****************************************************


*Table S.6.1 (data gathered from the questionnaire survey).
*Floor by orientation in crosstabs.
CROSSTABS
  /TABLES=Floor_4grps BY Orientation_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
     /METHOD=EXACT TIMER(5).

*Table S.6.2 (data gathered from the questionnaire survey).
CROSSTABS
  /TABLES=Age_bands_6grps Occupation_Q1.3 education_4grps Occupation_4grps Income_4grps BY Health_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
```

Figure I.5: Codebook of series of statistical analysis was presented.

Appendix I: Development Stages of the Statistical Analysis – Part 2

```
*Table S.6.2 (data gathered from the questionnaire survey).
CROSSTABS
  /TABLES=Age_bands_6grps Occupation_Q1.3 education_4grps Occupation_4grps Income_4grps BY Health_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
    /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES=Age_bands_6grps Occupation_Q1.3 education_4grps Occupation_4grps BY Income_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
      /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES=Age_bands_6grps Occupation_Q1.3 education_4grps BY Occupation_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
      /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES=Age_bands_6grps Occupation_Q1.3 BY education_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
      /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES=Age_bands_6grps BY Occupation_Q1.3
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
      /METHOD=EXACT TIMER(5).

*Table S.6.3 (data gathered from the questionnaire survey).
CROSSTABS
  /TABLES=Age_bands_6grps Tenure_type_Q3 BY Residency_3grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES=Age_bands_6grps BY Tenure_type_Q3
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).

*Table S.6.4 (data gathered from the questionnaire survey)..
CROSSTABS
  /TABLES= Energy_advise_Q7 Awareness_in_energy_saving_Q6_rec Income_4grps Energy_consumption_Q5 BY Elec
```

Figure I.6: Codebook of series of statistical analysis was presented. (Continued)

Appendix I: Development Stages of the Statistical Analysis – Part 2

```
*Table S.6.4 (data gathered from the questionnaire survey)..
CROSSTABS
  /TABLES=  Energy_advise_Q7 Awareness_in_energy_saving_Q6_rec  Income_4grps  Energy_consumption_Q5 BY Electricity_meter_reading_Q4_rec
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES=  Energy_advise_Q7 Awareness_in_energy_saving_Q6_rec  Income_4grps  BY Energy_consumption_Q5
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES=  Energy_advise_Q7 Awareness_in_energy_saving_Q6_rec BY Income_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).
CROSSTABS
  /TABLES=  Energy_advise_Q7 BY Awareness_in_energy_saving_Q6_rec
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).



*Tables S.6.5(a) and (b) - (data gathered from the questionnaire survey).
CROSSTABS
  /TABLES=  Occupation_4grps Cooling_patterns_weekdays_3grps Cooling_patterns_weekends_Q13  Heating_patterns_weekdays_3grps BY Heating_patterns_weekends_3grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES=  Occupation_4grps Cooling_patterns_weekdays_3grps Cooling_patterns_weekends_Q13 BY  Heating_patterns_weekdays_3grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES=  Occupation_4grps Cooling_patterns_weekdays_3grps BY Cooling_patterns_weekends_Q13
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).
```

Figure I.7: Codebook of series of statistical analysis was presented (Continued).

Appendix I: Development Stages of the Statistical Analysis – Part 2

```
CROSSTABS
  /TABLES=  Occupation_4grps BY Cooling_patterns_weekdays_3grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).

*Tables S.6.6(a) and (b) - (data gathered from the questionnaire survey).
*Relationships between occupation, open window in winter, open window in summer, and heating control.
CROSSTABS
  /TABLES= Occupation_4grps Windows_opening_patterns_Winter_4grps Windows_opening_patterns_Summer_3grps Heating_control_5grps BY Summertime_doors_opening_preference_Q19_rec
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES= Occupation_4grps Windows_opening_patterns_Winter_4grps Heating_control_5grps BY Windows_opening_patterns_Summer_3grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES= Occupation_4grps Heating_control_5grps BY Windows_opening_patterns_Winter_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICTAS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES= Occupation_4grps BY Heating_control_5grps
  /FORMAT=AVALUE TABLES
  /STATISTICTAS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).

CROSSTABS
  /TABLES= Occupation_4grps Windows_opening_patterns_Winter_4grps Windows_opening_patterns_Summer_3grps Summertime_doors_opening_preference_Q19_rec Heating_control_5grps BY
 Wintertime_doors_opening_preference_Q24_rec Windows_opening_reason_2grps Windows_closing_reason_5grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).



*Table 4.3  (data gathered from the questionnaire survey - Age band represents 1 = Less than 5; 2 = 35-45; 3 = 45-55; 4 = 55-65; 5 = 65 or over) .
CROSSTABS
  /TABLES=Reason_for_thermal_discomfort_4grps  Age_bands_6grps  Orientation_4grps BY Floor_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
```

Figure I.8: Codebook of series of statistical analysis was presented. (Continued)

Appendix I: Development Stages of the Statistical Analysis – Part 2

```
*Table 4.3  (data gathered from the questionnaire survey - Age band represents 1 = Less than 5; 2 = 35-45; 3 = 45-55; 4 = 55-65; 5 = 65 or over) .
CROSSTABS
  /TABLES=Reason_for_thermal_discomfort_4grps  Age_bands_6grps  Orientation_4grps BY Floor_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).
CROSSTABS
  /TABLES=Reason_for_thermal_discomfort_4grps  Age_bands_6grps BY Orientation_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).
CROSSTABS
  /TABLES=Reason_for_thermal_discomfort_4grps BY Age_bands_6grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).

*Table 4.4 (a) and (b) - Pearson's correlations Occupant TSVs for living room, kitchen and bedrooms 1,2 and 3 in the summer (-3) to (+3) - Fisher's exact test - Occupant TSVs for living room, kitchen and bedrooms 1,2 and 3 in the summer (0) to (6) .
CROSSTABS
  /TABLES=Summer_thermal_sensation_livingroom_Q22_rec  Summer_thermal_sensation_kitchen_Q22_rec Summer_thermal_sensation_bedroom1_Q22_rec Summer_thermal_sensation_bedroom2_Q22_rec
  Summer_thermal_sensation_bedroom3_Q22_rec BY Orientation_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
 /METHOD=EXACT TIMER(5).


CROSSTABS
  /TABLES=Summer_thermal_sensation_livingroom_Q22_rec  Summer_thermal_sensation_kitchen_Q22_rec Summer_thermal_sensation_bedroom1_Q22_rec Summer_thermal_sensation_bedroom2_Q22_rec
  Summer_thermal_sensation_bedroom3_Q22_rec Orientation_4grps BY  Floor_4grps
  /FORMAT=AVALUE TABLES
  /STATISTICS=CHISQ PHI
  /CELLS=COUNT COLUMN BPROP
  /COUNT ROUND CELL
   /METHOD=EXACT TIMER(5).


CORRELATIONS
  /VARIABLES=Summer_thermal_sensation_livingroom_Q22_rec  Summer_thermal_sensation_kitchen_Q22_rec Summer_thermal_sensation_bedroom1_Q22_rec Summer_thermal_sensation_bedroom2_Q22_rec
  Summer_thermal_sensation_bedroom3_Q22_rec
  /PRINT=TWOTAIL NOSIG
  /MISSING=PAIRWISE.


*Figure 5.12 (on-site environmental monitoring data).


COMPUTE Time_of_day_rc = xdate.hours(Time_of_day).
EXECUTE.


EXAMINE VARIABLES=Out_Heat_Index BY  Time_of_day_rc
  /PLOT BOXPLOT
```

Figure I.9: Codebook of series of statistical analysis was presented in Chapters 4 and 5.

Appendix I: Development Stages of the Statistical Analysis – Part 2

```
CROSSTABS
 /TABLES=Summer_thermal_sensation_livingroom_Q22_rec  Summer_thermal_sensation_kitchen_Q22_rec Summer_thermal_sensation_bedroom1_Q22_rec Summer_thermal_sensation_bedroom2_Q22_rec
 Summer_thermal_sensation_bedroom3_Q22_rec Orientation_4grps BY  Floor_4grps
 /FORMAT=AVALUE TABLES
 /STATISTICS=CHISQ PHI
 /CELLS=COUNT COLUMN BPROP
 /COUNT ROUND CELL
  /METHOD=EXACT TIMER(5).


CORRELATIONS
 /VARIABLES=Summer_thermal_sensation_livingroom_Q22_rec  Summer_thermal_sensation_kitchen_Q22_rec Summer_thermal_sensation_bedroom1_Q22_rec Summer_thermal_sensation_bedroom2_Q22_rec
 Summer_thermal_sensation_bedroom3_Q22_rec
 /PRINT=TWOTAIL NOSIG
 /MISSING=PAIRWISE.


*Figure 5.12 (on-site environmental monitoring data).


COMPUTE Time_of_day_rc = xdate.hours(Time_of_day).
EXECUTE.


EXAMINE VARIABLES=Out_Heat_Index BY  Time_of_day_rc
 /PLOT BOXPLOT
 /COMPARE GROUPS
 /STATISTICS NONE
 /CINTERVAL 95
 /MISSING LISTWISE
 /NOTOTAL.

*Figure 5.8 (in-situ measurements data).
EXAMINE VARIABLES=In_Temperature BY Time_of_day_rc
 /PLOT BOXPLOT
 /COMPARE GROUPS
 /STATISTICS NONE
 /CINTERVAL 95
 /MISSING LISTWISE
 /NOTOTAL.

*Figure 5.16 (a) (in-situ measurements data and data gathered from the questionnaire survey).
EXAMINE VARIABLES=Out_TA by Time_of_day_rc
 /PLOT BOXPLOT
 /COMPARE GROUPS
 /STATISTICS NONE
 /CINTERVAL 95
 /MISSING LISTWISE
 /NOTOTAL.

*Figure 5.16 (b) (in-situ measurements data and data gathered from the questionnaire survey).
EXAMINE VARIABLES=In_TA by Time_of_day_rc
 /PLOT BOXPLOT
 /COMPARE GROUPS
 /STATISTICS NONE
 /CINTERVAL 95
 /MISSING LISTWISE
 /NOTOTAL.
```

Figure I.10: Codebook of series of statistical analysis was presented in Chapter 5.

Appendix I: Development Stages of the Statistical Analysis – Part 3

```
* Encoding: UTF-8.
*Figure 4.9 (data gathered from the questionnaire survey and in-situ measurements).

DATASET ACTIVATE DataSet1.
* Chart Builder.
GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=In_TA Summer_thermal_sensation_livingroom_Q22_rec
    MISSING=LISTWISE REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE
  /FITLINE TOTAL=NO SUBGROUP=NO.
BEGIN GPL
  SOURCE: s=userSource(id("graphdataset"))
  DATA: In_TA=col(source(s), name("In_TA"))
  DATA: Summer_thermal_sensation_livingroom_Q22_rec=col(source(s),
    name("Summer_thermal_sensation_livingroom_Q22_rec"))
  GUIDE: axis(dim(1), label("Opreative air temperature (°C)"))
  GUIDE: axis(dim(2), label("Thermal sensation in livingroom (recoded)"))
  GUIDE: text.title(label("Scatter Plot of Thermal sensation in livingroom (recoded) by ",
    "Operative air temperature (°C)"))
  ELEMENT: point(position(In_TA*Summer_thermal_sensation_livingroom_Q22_rec))
END GPL.


*Figure 4.10 (data gathered from the questionnaire survey and in-situ measurements).

* Chart Builder.
GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=In_TA Summer_thermal_sensation_bedroom1_Q22_rec
    MISSING=LISTWISE REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE
  /FITLINE TOTAL=NO SUBGROUP=NO.
BEGIN GPL
  SOURCE: s=userSource(id("graphdataset"))
  DATA: In_TA=col(source(s), name("In_TA"))
  DATA: Summer_thermal_sensation_bedroom1_Q22_rec=col(source(s),
    name("Summer_thermal_sensation_bedroom1_Q22_rec"))
  GUIDE: axis(dim(1), label("Opreative air temperature (°C)"))
  GUIDE: axis(dim(2), label("Thermal sensation in bedroom1 (recoded)"))
  GUIDE: text.title(label("Scatter Plot of Thermal sensation in bedroom1 (recoded) by ",
    "Operative air temperature (°C)"))
  ELEMENT: point(position(In_TA*Summer_thermal_sensation_bedroom1_Q22_rec))
END GPL.

*Figure 4.11 (data gathered from the questionnaire survey and in-situ measurements).

* Chart Builder.
GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=In_TA Summer_thermal_sensation_bedroom2_Q22_rec
    MISSING=LISTWISE REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE
  /FITLINE TOTAL=NO SUBGROUP=NO.
BEGIN GPL
  SOURCE: s=userSource(id("graphdataset"))
  DATA: In_TA=col(source(s), name("In_TA"))
  DATA: Summer_thermal_sensation_bedroom2_Q22_rec=col(source(s),
    name("Summer_thermal_sensation_bedroom2_Q22_rec"))
  GUIDE: axis(dim(1), label("Opreative air temperature (°C)"))
  GUIDE: axis(dim(2), label("Thermal sensation in bedroom2 (recoded)"))
  GUIDE: text.title(label("Scatter Plot of Thermal sensation in bedroom2 (recoded) by ",
    "Operative air temperature (°C)"))
  ELEMENT: point(position(In_TA*Summer_thermal_sensation_bedroom2_Q22_rec))
END GPL
```

Figure I.11: Codebook of series of statistical analysis was presented in Chapter 4.

Appendix I: Development Stages of the Statistical Analysis – Part 3

```
END GPL.

*Figure 4.11 (data gathered from the questionnaire survey and in-situ measurements).

* Chart Builder.
GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=In_TA Summer_thermal_sensation_bedroom2_Q22_rec
    MISSING=LISTWISE REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE
  /FITLINE TOTAL=NO SUBGROUP=NO.
BEGIN GPL
  SOURCE: s=userSource(id("graphdataset"))
  DATA: In_TA=col(source(s), name("In_TA"))
  DATA: Summer_thermal_sensation_bedroom2_Q22_rec=col(source(s),
    name("Summer_thermal_sensation_bedroom2_Q22_rec"))
  GUIDE: axis(dim(1), label("Opreative air temperature (°C)"))
  GUIDE: axis(dim(2), label("Thermal sensation in bedroom2 (recoded)"))
  GUIDE: text.title(label("Scatter Plot of Thermal sensation in bedroom2 (recoded) by ",
    "Operative air temperature (°C)"))
  ELEMENT: point(position(In_TA*Summer_thermal_sensation_bedroom2_Q22_rec))
END GPL.

*Figure 4.12 (data gathered from the questionnaire survey and in-situ measurements).


GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=In_TA Summer_thermal_sensation_bedroom3_Q22_rec
    MISSING=LISTWISE REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE
  /FITLINE TOTAL=NO SUBGROUP=NO.
BEGIN GPL
  SOURCE: s=userSource(id("graphdataset"))
  DATA: In_TA=col(source(s), name("In_TA"))
  DATA: Summer_thermal_sensation_bedroom3_Q22_rec=col(source(s),
    name("Summer_thermal_sensation_bedroom3_Q22_rec"))
  GUIDE: axis(dim(1), label("Opreative air temperature (°C)"))
  GUIDE: axis(dim(2), label("Thermal sensation in bedroom3 (recoded)"))
  GUIDE: text.title(label("Scatter Plot of Thermal sensation in bedroom3 (recoded) by ",
    "Operative air temperature (°C)"))
  ELEMENT: point(position(In_TA*Summer_thermal_sensation_bedroom3_Q22_rec))
END GPL.

*Figure 4.13 (data gathered from the questionnaire survey and in-situ measurements).


GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=In_TA Summer_temperature_satisfaction_Q33_rec
    MISSING=LISTWISE REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE
  /FITLINE TOTAL=NO SUBGROUP=NO.
BEGIN GPL
  SOURCE: s=userSource(id("graphdataset"))
  DATA: In_TA=col(source(s), name("In_TA"))
  DATA: Summer_temperature_satisfaction_Q33_rec=col(source(s),
    name("Summer_temperature_satisfaction_Q33_rec"))
  GUIDE: axis(dim(1), label("Opreative air temperature (°C)"))
GUIDE: axis(dim(2), label("Summer temperature satisfaction (recoded)"))
  GUIDE: text.title(label("Scatter Plot of Summer temperature satisfaction (recoded) by ",
    "Operative air temperature (°C)"))
  ELEMENT: point(position(In_TA*Summer_temperature_satisfaction_Q33_rec))
END GPL.
```

Figure I.12: Codebook of series of statistical analysis was presented in Chapter 4.

Appendix I: Development Stages of the Statistical Analysis – Part 3

```
* Encoding: UTF-8.
*Table 4.5.
PLUM Summer_thermal_sensation_livingroom_Q22_rec WITH In_TA
  /CRITERIA=CIN(95) DELTA(0) LCONVERGE(0) MXITER(100) MXSTEP(5) PCONVERGE(1.0E-6) SINGULAR(1.0E-8)
  /LINK=LOGIT
  /PRINT=FIT PARAMETER SUMMARY.



*Table 4.6.
PLUM  Summer_thermal_sensation_bedroom1_Q22_rec WITH In_TA
  /CRITERIA=CIN(95) DELTA(0) LCONVERGE(0) MXITER(100) MXSTEP(5) PCONVERGE(1.0E-6) SINGULAR(1.0E-8)
  /LINK=LOGIT
  /PRINT=FIT PARAMETER SUMMARY.



*Table 4.7.
PLUM Summer_thermal_sensation_bedroom2_Q22_rec WITH In_TA
  /CRITERIA=CIN(95) DELTA(0) LCONVERGE(0) MXITER(100) MXSTEP(5) PCONVERGE(1.0E-6) SINGULAR(1.0E-8)
  /LINK=LOGIT
  /PRINT=FIT PARAMETER SUMMARY.



*Table 4.8.
PLUM Summer_thermal_sensation_bedroom3_Q22_rec WITH In_TA
  /CRITERIA=CIN(95) DELTA(0) LCONVERGE(0) MXITER(100) MXSTEP(5) PCONVERGE(1.0E-6) SINGULAR(1.0E-8)
  /LINK=LOGIT
  /PRINT=FIT PARAMETER SUMMARY.



*Table 4.9.
PLUM Summer_temperature_satisfaction_Q33_rec WITH In_RH
  /CRITERIA=CIN(95) DELTA(0) LCONVERGE(0) MXITER(100) MXSTEP(5) PCONVERGE(1.0E-6) SINGULAR(1.0E-8)
  /LINK=LOGIT
  /PRINT=FIT PARAMETER SUMMARY.


* Encoding: UTF-8.
* Table 4.10(a)and (b)

NOMREG Space_conditioning (BASE=FIRST ORDER=ASCENDING) BY Feeling_preference_rec_4grps
    Type_of_cooling_system_4grps WITH In_TA Out_TA Winter_temperature_satisfaction_Q34_rec
  /CRITERIA CIN(95) DELTA(0) MXITER(100) MXSTEP(5) CHKSEP(20) LCONVERGE(0) PCONVERGE(0.000001)
    SINGULAR(0.00000001)
  /MODEL
  /STEPWISE=PIN(.05) POUT(0.1) MINEFFECT(0) RULE(SINGLE) ENTRYMETHOD(LR) REMOVALMETHOD(LR)
  /INTERCEPT=INCLUDE
  /PRINT=PARAMETER SUMMARY LRT CPS STEP MFI.


* Table 4.11.
PLUM Residency_3grps BY Feeling_preference_rec_4grps
    Type_of_cooling_system_4grps WITH In_TA Out_TA Winter_temperature_satisfaction_Q34_rec
  /CRITERIA=CIN(95) DELTA(0) LCONVERGE(0) MXITER(100) MXSTEP(5) PCONVERGE(1.0E-6) SINGULAR(1.0E-8)
  /LINK=LOGIT
  /PRINT=FIT PARAMETER SUMMARY.
```

Figure I.13: Codebook of ordinal logistic regression analysis was presented in Chapter 4.

Appendix J: Contribution to the ASHRAE Global Thermal Comfort Database II

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September 13th, 2021

Prof. Dr. Haşim Altan
Department of Architecture, Faculty of Design
Director of Research Centre (ARUCAD)
Arkin University of Creative Art and Design
Girne, Cyprus

Dear Hasim,

This letter confirms the donation of a field measurement dataset to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Global Thermal Comfort Database II. This is an important outcome of the methodological framework developed to contribute to the adaptive thermal comfort studies as part of the PhD study undertaken by Mr. Bertug Ozarisoy at the Graduate School, School of Architecture, Computing & Engineering (ACE), University of East London (UEL), London, United Kingdom.

I received the associated dataset from the PhD thesis entitled 'Assessing the Domestic Energy Use and Thermal Comfort of Occupants in a Post-war Social Housing Development Estate in Famagusta, Northern Cyprus' on 10th May 2021. The dataset has been processed via the project web tool for quality assurance before being published in the open access ASHRAE Global Thermal Comfort Database II. The database is the result of a project led by an international team of experts to collate field measurements of thermal comfort for public use.

The dataset of this PhD thesis is a valuable contribution to the ASHRAE Global Thermal Comfort Database II. The field study in the South-eastern Mediterranean climate of Cyprus is a unique context and a noteworthy addition to this public resource.

Sincerely,

Thomas Parkinson, PhD
Assistant Professional Researcher
Center for the Built Environment, College of Environmental Design
University of California, Berkeley
tom.parkinson@berkeley.edu

Figure J.1: Confirmation letter to the contribution to the ASHRAE Global Thermal Comfort database II.

Appendix K: Benchmarking Indicators – Part 1 (Measured/Collected)

Table K.1: Conceptualisation of the Variables in the Dataset.

Contribution to Key research area(s)	***In-situ* measurements** *(measured)*	***On-site* environmental monitoring** *(recorded)*	**Secondary data** *(collected from the authorities)*	**Primary data I – Questionnaire survey** *(gathered)*	**Primary data II – Thermal comfort survey** *(gathered)*
Thermal Comfort + Overheating Risk	Indoor DEW (°C)	Outdoor heat stress index (°C)	Cooling energy consumption in summer of August 2015	Age	Location of subject respondent
Thermal Comfort + Overheating Risk	Indoor relative humidity (%)	Outdoor relative humidity (%)	Cooling energy consumption in summer of 2015	Age bands	Thermal preference [0 to 6]
Thermal Comfort + Energy Modelling	Operative air temperature (°C)	Outdoor air temperature (°C)	Cooling energy consumption in summer of August 2016	Energy efficiency awareness	Overall thermal satisfaction [-3, +3]
Overheating Risk + Energy Modelling	Solar radiation (°C)	Outdoor DEW (°C)	Cooling energy consumption in summer of 2016	Energy conservation	Thermal sensation in living room [-3, +3]
Thermal Comfort + Energy Modelling	Indoor WET (°C)	-	Heating energy consumption in winter of 2015	Doors opening patterns in summer	Thermal sensation in kitchen [-3, +3]
Energy Modelling	Time-of-day	-	Heating energy consumption in winter of 2016	Doors opening patterns in winter	Thermal sensation in bedroom 1 [-3, +3]
Thermal Comfort + Energy Modelling	Indoor temperature ground (°C)	-	Energy consumption in April of 2015	Type of heating control at home	Thermal sensation in bedroom 2 [-3, +3]
Thermal Comfort + Energy Modelling	-	-	Energy consumption in August of 2015	Type of cooling control at home	Thermal sensation in bedroom 3 [-3, +3]
Thermal Comfort + Energy Modelling	-	-	Energy consumption in December of 2015	Length of residency	Clothing insulation level of participants
Thermal Comfort	-	-	Energy consumption in February of 2015	Floor level	Reasons for thermal discomfort
Thermal Comfort	-	-	Energy consumption in January of 2015	Orientation	Interviewed room condition
Thermal Comfort	-	-	Energy consumption in July of 2015	Cooling consumption patterns on weekdays	Metabolic rates of participants
Energy Modelling	-	-	Energy consumption in June of 2015	Cooling consumption patterns on the weekend	-
Energy Policy	-	-	-	Health condition	-
Energy Modelling	-	-	-	Household density	-
Energy Policy	-	-	-	Income	-
Energy Policy	-	-	-	Energy advice	-
Energy Policy	-	-	-	Energy consumption	-
Abbreviations:	**TC:** Thermal Comfort; **OR:** Overheating Risk; **EM:** Energy Modelling; **EP:** Energy Policy				

Appendix K: Benchmarking Indicators – Part 2 (Measured/Collected)

Table K.2: Conceptualisation of the Variables in the Dataset. (Continued)

Contribution to Key research area(s)	***In-situ* measurements** *(measured)*	***On-site* environmental monitoring** *(recorded)*	**Secondary data** *(collected from the authorities)*	**Primary data I – Questionnaire survey** *(gathered)*	Primary data II **– Thermal comfort survey *(gathered)***
Thermal Comfort + Energy Modelling	-	-	Energy consumption in March of 2015	Heating consumption patterns on weekdays	Overall thermal satisfaction [0 to 6]
Thermal Comfort + Energy Modelling	-	-	Energy consumption in May of 2015	Heating consumption patterns on the weekend	Thermal sensation in living room [0 to 6]
Thermal Comfort + Energy Modelling	-	-	Energy consumption in November of 2015	Windows opening reasons	Thermal sensation in kitchen [0 to 6]
Thermal Comfort + Energy Modelling	-	-	Energy consumption in October of 2015	Economic statues	Thermal sensation in bedroom 1 [0 to 6]
Thermal Comfort + Energy Modelling	-	-	Energy consumption in September of 2015	Occupation	Thermal sensation in bedroom 2 [0 to 6]
Thermal Comfort + Energy Modelling	-	-	Energy consumption in April of 2016	Space conditioning	Thermal sensation in bedroom 3 [0 to 6]
Thermal Comfort + Energy Policy	-	-	Energy consumption in August of 2016	Tenure type	-
Overheating Risk + Thermal Comfort	-	-	Energy consumption in December of 2016	Type of heating system	-
Overheating Risk + Thermal Comfort	-	-	Energy consumption in February of 2016	Type of cooling system	-
Thermal Comfort + Energy Modelling	-	-	Energy consumption in January of 2016	Windows closing reasons	-
Thermal Comfort + Energy Modelling	-	-	Energy consumption in July of 2016	Windows opening patterns in winter	-
Thermal Comfort + Energy Modelling	-	-	Energy consumption in June of 2016	Windows opening patterns in summer	-
Energy Modelling	-	-	Energy consumption in March of 2016	-	-
Energy Modelling	-	-	Energy consumption in May of 2016	-	-
Energy Modelling	-	-	Energy consumption in October of 2016	-	-
Energy Modelling	-	-	Energy consumption in September of 2016	-	-
Abbreviations:	**TC:** Thermal Comfort; **OR:** Overheating Risk; **EM:** Energy Modelling				