A novel methodological framework for the optimisation of post-war social housing developments in the southeastern Mediterranean climate: Policy design and life-cycle cost impact analysis of retrofitting strategies

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Research paper

Abstract

This study analyses the development of modular building design elements to improve the thermal performance of base case post-war social housing development estates in the southeastern Mediterranean climate, which is subtropical (*Csa*) and partly semi-arid (*Bsh*), before different retrofits are undertaken to optimise each building's energy performance. This study's objective is to develop evidence-based passive cooling retrofit design strategies to improve occupants' thermal comfort and reduce the overheating risk. This empirical study employs the socio-technical systems approach to develop a bottom-up energy policy framework for the residential sector. Its mixed-methods design comprises a questionnaire survey, use of thermal imaging, environment monitoring and determining building optimisation. Furthermore, this study discusses the uncertain input parameters for the building energy simulations that quantitative modelling has adopted to calibrate dynamic thermal simulation findings in conjunction with occupants' socio-demographic characteristics, occupancy patterns, household size and recorded environmental conditions. The results reveal that in the non-retrofitted building, cooling and heating comprised the greatest proportion (73%) of total energy consumption. Applications for six passive cooling design strategies were analysed, and after the life-cycle cost assessment of each was considered, off-site modular building applications were developed. After building optimisation, approximately 81% of savings related to cooling consumption were achieved, which suggests that design, ventilation and servicing strategies combined with passive shading systems can improve energy efficiency and indoor air quality of residential buildings, as recommended by the Energy Performance of Buildings Directives.

Keywords: Building energy simulation; Energy efficiency; Energy use; Life-cycle cost assessment; Overheating risk; Thermal Comfort

Nomenclature	
Bsh	Semi-arid
°C	Celsius
Csa	Subtropical
Cv	Comfort vote
E	Energy (kWh/m^2)
EUI	Energy use intensity (MJ/ m^2 /year)
F	Fuel (MJ)
h	Equation parameter
h^{-1}	Air infiltration rate
M	Thermal conductivity coefficient (kJ/m^2K)
m^2	Square meter
m^3	Cubic meter
R	Heat absorptivity coefficient (m^2K/W)
Tmax	Maximum temperature
Top	Operative air temperature
Trm	Weighted mean of the daily mean outdoor air temperature
U	Heat loss coefficient (W/m^2K)
Q_{op}	Operative air infiltration threshold
W	Wind velocity (m^2s)
ΔT	Adaptive overheating limit
Abbreviations	
A/C	Air-Conditioning
AMY	Actual Meteorological Year
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BS	British Standards
CDD	Cooling-degree Days
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon dioxide
DBT	Dry Bulb temperature
DTS	Dynamic Thermal Simulation
EA	Electricity Authority
EEI	Energy Efficiency Implementation
EPBD	Energy Performance of Buildings Directives
EN	European Norm
EU	European Union
EUI	Energy Use Intensity
FLIR	Forward-looking infrared thermometer
GHG	Greenhouse gas
GIS	Geographic Information Systems
HDD	Heating-degree Days
HSI	Heat Stress Index
IES	Integrated Environmental Solutions

IHG	Internal heat gains
IR	Infrared radiometer
IRT	Infrared radiometer thermography
LCCA	Life cycle cost assessment
LCD	Low Carbon Design
MO	Multi-objective
MVHR	Mechanical Ventilation Heat Recovery Systems
nZEB	Nearly zero-energy buildings
OP1	Occupancy pattern 1 - low
OP2	Occupancy pattern 2 - moderate
OP3	Occupancy pattern 3 - high
OT	Operative temperature
PCRDS	Passive cooling retrofit design strategies
PPD	Predicted Percentage of Dissatisfied
PMD	Predicted Mean Vote
PV	Photovoltaic
RTB	Residential tower block
RH	Relative humidity
SA	Sensitivity analysis
SAR	Suggested acceptable range
SARS	Severe acute respiratory syndrome
SC	Self-consumption
SD	Standard deviation
SP	Set-point
SPSS	Statistical Package for the Social Sciences
SRC	Standardised Regression Coefficient
SRRC	Standardised Ranked Regression Coefficient
STS	Socio-Technical-Systems
TPV	Thermal preference votes
TRY	Test Reference Year
TRNSYS	Transient System Simulation Tool
TSV	Thermal sensation votes

1. Introduction

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 the Republic of Cyprus (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 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). Furthermore, 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 Cyprus 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. As such, the present study considers the Cypriot housing stock, which was not accurately demonstrated in the TABULA/EPISCOPE[1] 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 Cyprus 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 the RoC.

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.

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[1] The European EPISCOPE project provides a nationally representative online database to provide transparent, effective, energy-efficient retrofitting processes in the European housing sector: https://episcope.eu/welcome

The 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 socio-techncial-systems (STS) approach that simultaneously considers multiple factors is an effective means to address the EEG. In line with this objective, this 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. Figure 1 demonstrates the STS conceptual framework developed to address knowledge gap in energy efficiency and retrofitting of post-war social housing developments in the south-eastern Mediterranean climate.

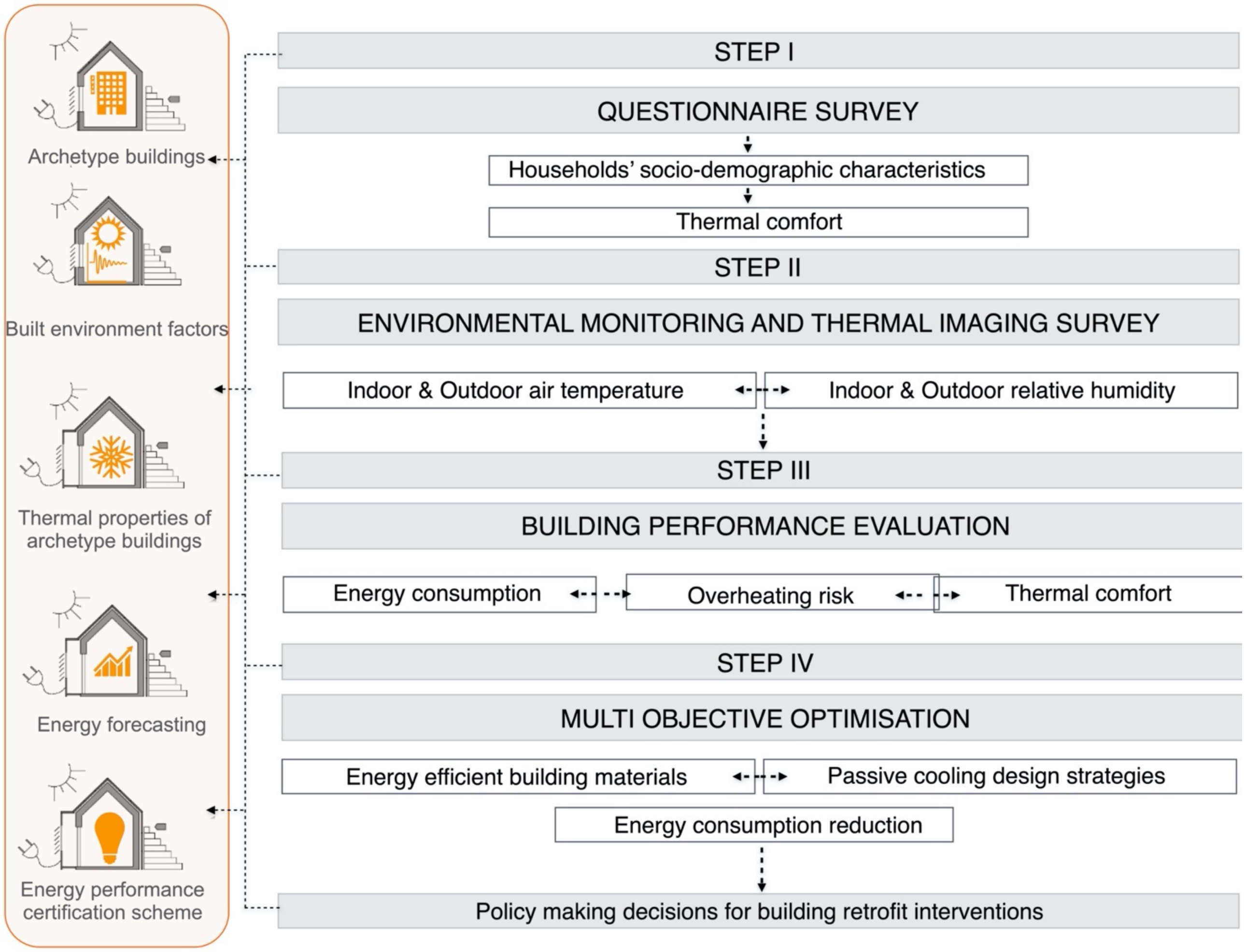


Fig.1. The conceptual framework of the study.

This paper discusses a novel methodological framework developed for optimisation of existing post-war social housing estate in the south-eastern Mediterranean climate, and application of six different passive-cooling design strategies were analysed. This paper will first present the motivations and the novelty of the study thereof, followed by a review of the literature related to the energy policy-making framework and the retrofitting of existing housing stock that addresses current thermal-comfort design methods, overheating risks and building energy optimisation. This is then followed by a description of the research methodology and the findings of the questionnaire survey, environmental monitoring, thermal imaging and energy modelling simulations that provided roadmap to identify the effectiveness of retrofitting interventions and analyse the life-cycle cost impact.

1.1. Aim and Motivation

The overall aim of the 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 Cypriot post-war social-housing estates.

Investigating current design methods while developing the STS design approach resulted in energy-policy frameworks and regulations that will enable the RoC and other EU member states to properly address the EEG. To achieve these targets, the 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 the RoC and EU countries when devising and implementing a universal energy-policy directive.

1.2. Novelty of Study and Implications for Energy Policy Design

The novelty of the study is the integration and development of an effective methodological research approach to create a roadmap of future household energy-consumption profiles that will optimise occupant thermal comfort by providing policy advice and government initiatives for stakeholders. It also contributes to efforts to improve occupants' health and wellbeing, reduce domestic-energy use and enhance the affordability, efficiency and effectiveness of retrofitting efforts for existing post-war social-housing stock in the South-eastern Mediterranean climate.

Importantly, this empirical study revealed the typical household awareness of energy use and a cultural assessment to develop a methodological framework for a building-energy-performance evaluation at the policy level. This novel benchmark criterion will radically change the manner in which calibration studies evaluate and optimise the energy efficiency of post-war social-housing developments and significantly increase the likelihood of implementing different strategies, which will then encourage early-stage designs and policy-decision-making related to domestic-energy use. This research provides the impetus to approach retrofitting efforts like a socio-technical process that must engage with different socio-cultural and material-technological contexts; this change will enable scholars to more fully comprehend the broader issue of how governance capacity is employed to manage complex social and material relationships.

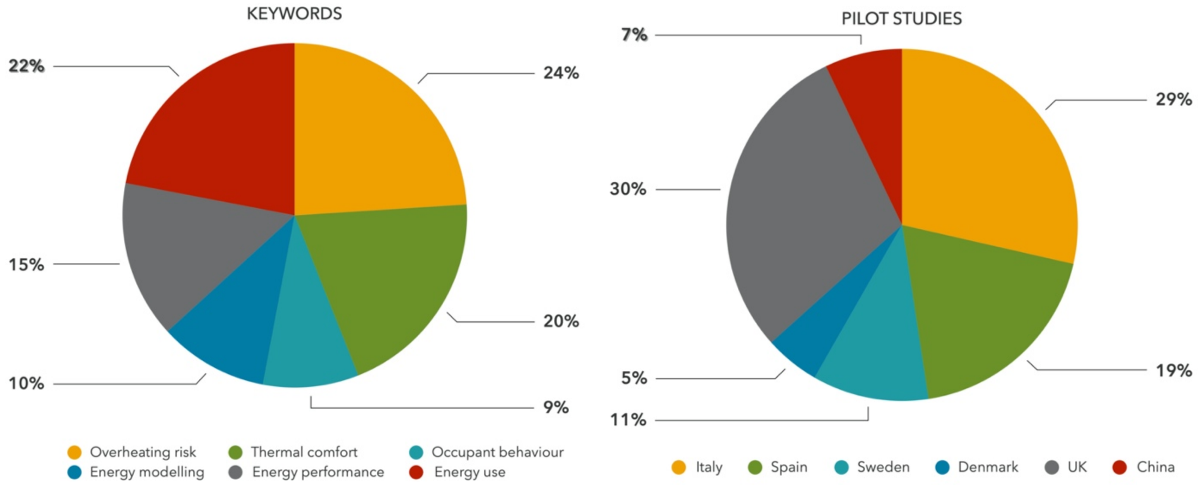
The outcome of the research was the development of an effective roadmap for EPC implementation, and by extension, the creation of a goal to design effective control mechanisms in the certification schemes thereof. As such, the findings were not limited to Cypriot households, but could be generalised for other EU countries, particularly in south-eastern Mediterranean EU nation states with similar climate characteristics, equivalent buildings codes and regulations and policy implications for energy use.

2. Systematic Literature Review

2.1. Knowledge Gap in Energy-Policy and Retrofitting Housing Stock: Assessment Criterion

The aim of this section 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. The focus of this review was to analyse empirical works that examined household home-energy performance in retrofitting schemes for social-housing stock that followed the EPBD mandates. To fill the EEG and address the RQs outlined for this empirical 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. The source of the systematic 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.

A search was conducted using the systematic review method; the Scopus platform was the main engine used for this search. The literature survey resulted in 184 documents, which included review articles, original research papers and conference proceedings that were collated between 1990 and 2021. 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 2(a) and (b) present an overview of the search results. To retrieve articles for the topic 'Building Performance', three title (TI) record files were created, as shown in Figure 2(a). The set results of the advanced searches were combined using the 'OR' Boolean operator to obtain original research papers and review articles from different countries to demonstrate a universal design approach for the development of STS conceptual framework, as shown in Figures 2(b).



(a) **(b)**

Fig. 2. **(a)** Keywords and percentage distribution related to appearance; **(b)** countries of pilot studies according to keyword selection criteria.

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 Sections 2.2 and 2.3.

2.2. Socio-Technical-Systems Conceptual Framework and Energy-Use Integrity

Research in the area of interaction—between dwellings, occupants and the environment—has primarily focused on occupants' interactions with a given type of heating control system used and the frequency with which these systems were used at home (d'Oca *et al.*, 2018; Serrano-Jimenez *et al.*, 2019). Several empirical studies have focused on occupant behaviour as it relates to the use of windows for thermal comfort, as well as the use of lighting and shading to ensure adequate daylighting in residential buildings. (Fabi *et al.*, 2012; Li & Yao, 2020; Page *et al.*, 2008). Although there is a paucity of evidence of occupant interactions with different types of cooling systems and the number of hours these systems were used in the home, these factors have been discussed in a few scholarly articles (Pesic *et al.*, 2018). Chai *et al.* (2020) and Lu *et al.* (2020) highlighted the fact that various models are available to calibrate occupant energy-use behaviour based on the quantitative data that are collected and analysed to validate the findings from other research instruments embedded in these processes.

According to Cali *et al.* (2016), another challenge of investigating occupancy patterns on energy use is energy consumption and other effects related to climate change that make it difficult to accurately calibrate the energy performance of multi-family houses (MFHs); this is partially due to energy and environmental regulations for these dwellings. Modelling in calibration studies is limited, which is why several studies concluded that a BES does not yield the same results as the actual operational outcomes of occupied dwellings (Barthelmes *et al.*, 2018; Naylor *et al.*, 2018; Santangelo *et al.*, 2018). In a methodological approach, however, several different methodologies can be employed to address this knowledge gap and validate data from a DTS analysis, as shown in Figure 3.

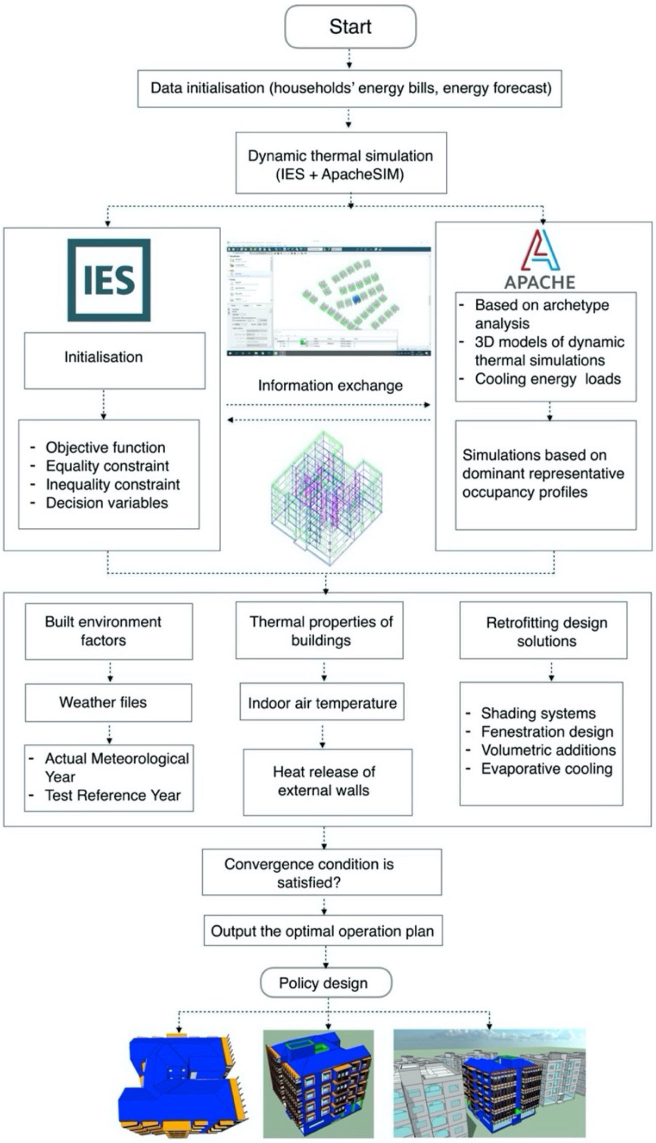


Fig. 3. Validation method flow diagram.

Research conducted by Erell *et al.* (2018) demonstrated that one of the breakthrough technical solutions proposed by Borgeson and Brager (2011) effectively models occupant behaviour by employing dynamic thermal simulations within the test reference year (TRY) weather files included into the analytical energy model; this methodological approach allows researchers to accurately predict the current energy performance of buildings within the context of climate-change projections. Many scholarly articles in this field have asserted that these energy models are deficient in a sense, due to the uncertainty posed by occupant behavioural aspects in the energy models. Tables 1(a) and (b) present a list of energy-calibration models developed by previous scholars to investigate correlations between occupant behaviour and energy use.

Table 1 (a) Longitudinal Field Studies That Explored Occupant Influence on Energy Use.

References	A. Study Location	B. Primary Aim of Model	C. Methodology	D. Main Findings
Kumareswaran *et al.* (2021)	Jaffna District, Sri Lanka	To explore the effect of energy poverty on occupant thermal comfort	- Indian social-housing schemes: Bungalow housing typology selected. - Random questionnaire survey conducted with 224 households under low-income housing rehabilitation schemes - Households selected according to their access to electricity and clean fuel for cooking; physical measurements recorded, including occupied room *in-situ* recordings; questionnaire survey distributed.	Actual mean thermal sensation of occupants was 0,86, which is a slightly warm sensation; mean thermal preference was -0,6; 64% of subjects preferred cooler indoor environment.
Rinaldi *et al.* (2018)	Bari, Italy	To investigate the influence of occupant behaviour on building energy performance	- Italian residential-building typologies were targeted. - Multivariate RA conducted; occupant behaviour and thermal-comfort preference questionnaire surveys conducted; online questionnaire undertaken with 450 participants; R software used for statistical analysis	Occupants used heating system for a greater number of hours with higher SP temperature values.
Erell *et al.* (2018)	Jerusalem and Nesher, Israel	To investigate the influence of occupant behaviour on the energy use of representative households in coastal Mediterranean and mountain temperate climate	Longitudinal field survey conducted with 120 middle-class urban households; socio-demographic characteristics recorded; BPE undertaken by DTS; multivariate RA conducted; computer simulations incorporating Israeli Standard 5282 for Energy Labelling of Residential Buildings completed	There was a weak correlation between simulated energy requirements for heating and cooling based on the floor plan and the thermal properties of the buildings.
Moeller *et al.* (2020)	Munich, Germany	To investigate the uncertainty surrounding the impact of occupant behaviour on heating energy consumption	- Occupant behaviour and physical building properties of several apartments investigated; six 3-storey apartment buildings selected for archetype analysis with sample size of 40 apartments - Indoor environmental conditions monitored; sensors positioned on window handles; multi-collinearity analysis conducted	On average, the predicted heating-energy demand differed from the thermal-insulation-certificate assessment by less than 5%.

Table 1 (b) Longitudinal Field Studies That Explored Occupant Influence on Energy Use. (Continued)

References	A. Study Location	B. Primary Aim of Model	C. Methodology	D. Main Findings
Zhang *et al.* (2020)	Beijing, China	To explore occupants' energy-related behaviour in residential buildings with empirical data	Online questionnaire survey conducted, which considered space-heating and -cooling, water heating, cooking, lighting, appliances and other equipment; 1003 valid responses recorded; statistical analysis employed to identify occupant-behavioural patterns.	Air conditioner used for space-heating and -cooling; this was critical because residents typically had A/C systems that were less energy-efficient.
Mitra *et al.* (2019)	United States	To develop typical occupancy schedules for a range of household types and occupants	Twelve years of U.S. 'Time Use Survey' data used; 'Residential Energy Consumption Survey' data also used; descriptive statistics and correlation analysis conducted; 'Reference Building' and 'Building America' simulation protocols adopted.	Approximately 42–44% of occupants under 55 years of age were absent from their homes for 8–12-hour periods.
Brewer (2020)	United States	To interpret reported choices of thermostat settings and examine the gender factor	Single-home occupants were selected for the sampling size; the U.S. Energy Information Administration Residential Energy Consumption Survey was examined and 494 single-occupant males and 786 single-occupant females were selected; and a linear RA was conducted.	Differences in mean reported thermostat settings between single-occupant males and females were small (i.e., < 0,3°C).
Kalluri *et al.* (2020)	Singapore	To assess the energy performance of state-of-the-art high-performance building design in the tropics	Longitudinal field-survey approach was adopted; post-occupancy building survey was conducted; smart sensors were installed to monitor luminosity, motion, ambient temperature and humidity; web-based dashboard platform was established; Building Management System was created via REST API software interface; and MATLAB was used to generate the datasets.	In the early occupancy stage, the projected energy-use intensity (EUI) was 77,0 kWh/m^2 per year; at the end of the first year; however, the measured EUI was 81,1 kWh/m^2 per year.
Chen *et al.* (2020)	China	To investigate appropriate integration of occupant-movement and energy-use-behaviour simulations	Description method established for energy-use behaviours; human dynamics and transient behavioural approaches adopted; sample of households selected; energy-use behaviours measured for one year; MATLAB and NETLOGO platforms used for energy calibration; stochastic energy-use behaviours established; BARABASI priority-queue model adopted for benchmark assessment method.	Sleeping and working outside of the home accounted for the highest proportion of respondents' daily schedule patterns: 38% in the simulation and 45% in the survey.

As shown in Tables 1(a) and (b), developing a novel methodological approach that takes occupants' real-life energy-use experiences into consideration to accurately predict residential-building energy consumption is a matter of concern (Rinaldi *et al.*, 2018; Satre-Meloy, 2019). One reason for this is because in the scientific literature, an analysis of the thermal properties of buildings as it relates to the impact of energy consumption on the BPEs would fall within the spectrum of a systems-based methodological STS approach.

In summary, the portion of the literature review involving household home-energy performance draws attention to the integrity of the STS design approach in building-energy calibrations by delving into the issue of using the STS as a new BPE methodology and exploring the complex issue of occupancy patterns as it relates to domestic-energy use with the aim of filling the knowledge gap. This novel approach, which is capable of testing the energy effectiveness of retrofitting strategies to determine a roadmap of principles for policies and regulations in the housing sector, can eventually be proposed to policymakers.

2.3. Theoretical Framework Underpinning Household Energy Consumption

There is a plethora of theoretical adaptive frameworks within housing-energy studies that underpin deterministic variables and covariates of the socio-demographic characteristics of households (Hong et al., 2019; Roetzel, 2010; Sorgato et al., 2016; Sun et al., 2020). Natarajan et al. (2011) highlighted the limitations in disciplinary methods and acknowledged that occupancy patterns and occupants' habitual adaptive behaviour on window-opening patterns had an impact on the development of BES studies, which could result in technical constraints when assigning accurate occupancy profiles in a BES model for purposes of a DTS analysis.

By drawing on the concept of energy-calibration studies, Natarajan *et al.* (2011) were able to show that the limitations in disciplinary methods are largely dependent on discrepancies between predicted and actual energy consumption that were obtained from the DTS; there appears to be little consensus in the subject of building energy simulation as to the extent to which limitations in the disciplinary approach to energy-policy conceptualisation could be improved by upgrading the thermal properties of archetype buildings that were identified for an energy-forecasting analysis (Rochon-Lawrence *et al.*, 2021). A number of studies in the extant literature have advocated for an integrated framework that would promote a multi-disciplinary approach (Faiella & Lavecchia, 2021; Swan & Ugursal, 2009; Zhou *et al.*, 2020); since many household socio-demographic characteristics are directly correlated with energy use, an interdisciplinary approach would provide a theoretical framework that could capture the inter-relationships between scientific, technological, societal, economic and cultural factors in the context of an STS design approach.

The literature review revealed a lack of policy initiatives and implications related to understanding the importance of energy use. The research illustrated the applicability thereof to contribute to ongoing studies on overheating and to provide a new design method to the field of thermal comfort by taking into consideration household energy awareness and environmental conditions; the effect of these factors is still unclear, and further research is required.

3. Methods and Tools

3.1 Location and Climate Data

Cyprus is situated in the north-eastern area of the Mediterranean Sea between latitudes 34' 33" and 35' 41" north and longitudes 32' 15" and 34' 35" east (Makri, 2018). It is located approximately 40 miles north of Turkey, 60 miles east of Syria, 250 miles south of Egypt and 300 miles west of the Greek islands. The island has an area of 9.251 km^2 (Zittis *et al.*, 2020); it is the third largest island in the eastern portion of the Mediterranean Sea. This location has four distinct topographical characteristics—semi-mountainous (Zone 1), coastal (Zone 2), mountainous (Zone 3) and inland (Zone 4)—all of which gives rise to varied climate conditions. This study employed an exploratory case-study approach to conduct an energy-performance analysis of a base-case prototype post-war social-housing development estate in the South-eastern Mediterranean Island of Cyprus. The case-study location was in close proximity to the fenced-off Varosha territory in the south-west area of the city, the fortifications of the old walled city in the north-east and the densely built city centre in the north-east, as shown in Figure 4.

Fig.4. Location of base-case social-housing estate between old walled city and city centre in Cyprus.

According to the Köppen climate classification system[2], Cypriot climate characteristics are typical of the Mediterranean region. Köppen climate data show that the overall climate type for Cyprus is subtropical (*Csa*) and partly semi-arid (*Bsh*) in the northeast part of the island (Kottek *et al.*, 2006); this means that Cyprus is hot and dry during the summertime, as illustrated in Figure 5.

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[2] World Köppen climate classification data was reviewed; dataset is available to researchers.

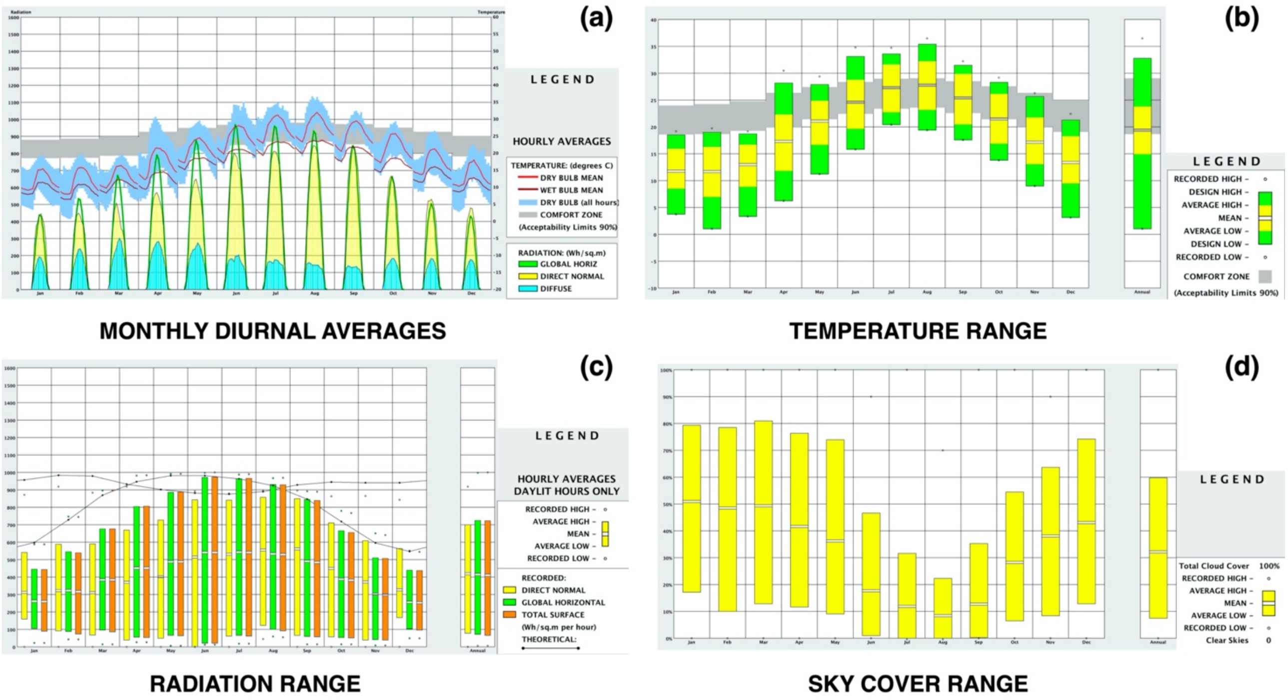


Fig. 5. Environmental conditions of the case-study location. ***Source:*** Extracted from Climate Consultant Version 6.0.13 (60.13); software suite developed in 2018 by the University of California.

Figure 5 illustrates the climate of Famagusta. The maximum Dry Bulb Temperature (DBT) can reach up to 28.1°C in the summertime, the hottest month of which occurs in August; and the minimum DBT can drop down to 10.6°C in the wintertime, the coldest month of which occurs in January. The mean-minimum DBT deviates between 6.8–22.3°C, while the mean-maximum DBT varies between 16.3–33.3°C. Hence, hot, dry summers and wet, moderate winters are the primary climate characteristics of the studied location and have a direct impact on the annual heating and cooling demands.

3.2 Archetype-Building Typology Selection

3.2.1 Selection Criteria

This empirical study was intended to identify the most dominant representative housing typology; this was determined to be medium-rise RTBs, which represent 56% of the housing stock. To generalise the findings and create a representative sample for the present study, an archetype-based method was adopted. Residential building-stock in Cyprus is comprised of approximately 6.646 representative buildings, which consist of 2.712 dwellings that were constructed in the 1984–1996 period under the governmental social-housing scheme, and 659 dwellings that were completed in collaboration with local cooperative establishments. An additional 3.275 dwellings were built between 2000 and 2005 by privately owned construction companies due to the absence of a social-housing scheme (SPO, 2018). According to the 2018 State Planning Organisation data, the most representative morphological building typologies were rectilinear block and H-shape, to which more than 30% of the total housing built belongs; approximately 40% are categorised in each typology (ibid). Table 2 lists the different building typologies that evolved between 1950–2018 in order to justify the selection of the post-war social housing estate: linear block (T1), H-shaped tower (T2) and rectangular-box-shaped tower (T3). Figure 6 illustrates the nationally representativeness of housing stock in Cyprus.

Table 2. Characteristics of the typologies and sub-typologies defined in this research context.

	Year of Construction	**Height**	**Dwellings per Floor**	**Area of Dwelling (m^2)**	**Orientation**
T1 Linear block					
T1.1 Grouped in quarter	1950–1973	< GF + 4	2	60–118	Double 180°
T1.2 Linear not grouped	1960–1972	< GF + 4	2	54–125	Double 180°
T1.3 Linear with 1 orientation	1950–1971	< GF + 4	4	59–94	Single
T1.4 Linear with minimum courtyard	1962–1973	< GF + 6	2	70–130	Double 180°
T2 H-shaped tower					
T2.1 H-tower with lateral courtyard	1985–1993	< GF + 5	2	55–107	Double 180°
T2.1 Without courtyard	1989–1993	< GF + 5	2	< 90	Double 90°
T3 Rectangular box-shaped tower					
T3.1 Block in Square	1995–2005	< GF + 8	4	55–107	Triple
T3.2 Block in Rectangle	2005–2018	< GF + 15	2–8	25–120	One-Triple
*** T = Tower block**					
**** GF = Gross floor area**					

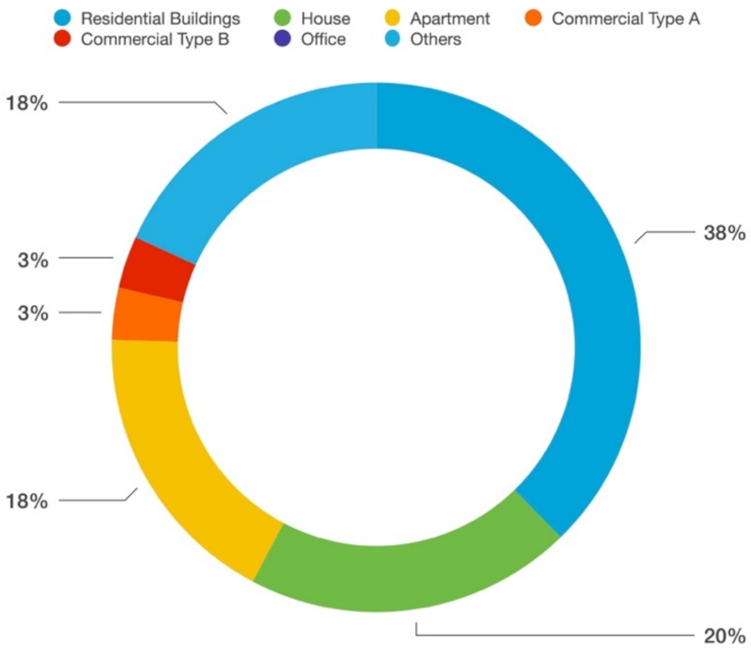


Fig.6. Proportional percentages of building types constructed in Famagusta between 2015–2019.

Figure 6 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 Cyprus (Ciftcioglu, 2017). There is currently an urgent need to undertake long-term holistic retrofitting schemes to upgrade the energy efficiency of post-war social-housing stock, but the Famagusta Municipality is not in an economic or political position to initiate a retrofitting agenda to improve the thermal resilience of the building fabric of these RTBs. 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.

3.2.2 General Building Description

As shown in Figure 7(a), the case-study social-housing development is a miniature city that was built in two phases. When it was constructed, the primary goal was to build a contiguous high-density urban neighbourhood that incorporated a combination of staggered volumes that moved forward and backward in relation to the main high street, as illustrated in Figure 7(b). Medium-rise RTBs 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; the blocks are 15 m × 15 m and 4–5 storeys high, as shown in Figures 7(c) and (d). 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^2K for the external walls, 1,23 W/m^2K for the internal walls, 1,2 W/m^2K for the roof and 2.10 W/m^2K for the doors and windows (see **Appendix A**).

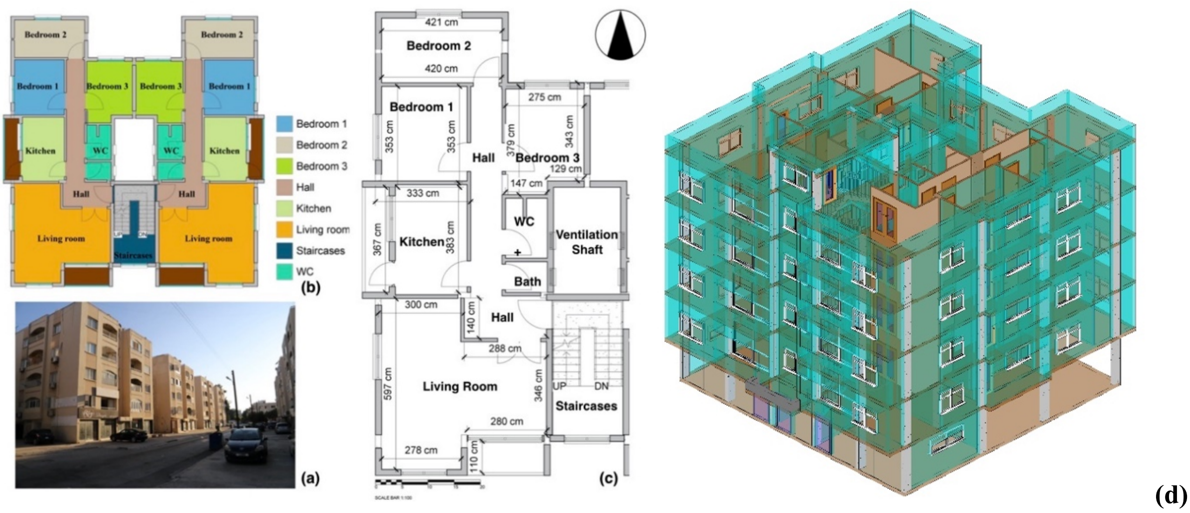


Fig.7. **(a)** Base-case medium rise residential-tower development built in the 1990s; **(b)** 3D urban-block model of social-housing estate; **(c)** floor-plan layout details and **(d)** analytical 3D model of RTB. ***Source:*** Floor plans and 3D model produced with Autodesk® Revit® Version 2020.1.0.

To understand the thermal vulnerability of the housing stock, medium-rise RTBs that were built as part of the governmental social-housing scheme were selected as case-study buildings. The building-taxonomy analysis determined that the most representative construction type of the investigated RTBs was the single-leaf brick façade, where neither cavity-wall insulation nor any type of insulation material were implemented to reduce energy consumption and optimise thermal comfort. To provide a generalisation of the findings, the case studies were selected according to the building typology and urban morphology characteristics, which had been identified by the State Planning Organisation and Famagusta Municipality as cases of interest in future energy-retrofitting plans. Figures 8(a) through (e) demonstrate the typical physical deterioration of the building envelopes (see **Appendix B**).

Fig.8. (a) through (e): Major decay observed on building envelopes and cracks in wall junctions of all base-case RTBs

Many of these RTBs have not undergone any architectural or energy-related upgrades since they were constructed. Due to a lack of maintenance mechanisms over the course of three decades, a change in the physical quality of all 36 RTBs in the social-housing estate was observed, with aesthetically mismatched building envelopes that were articulated by the occupants in the 2000s and dilapidated units with visibly damaged façades and construction junction details. It is important to note that heating systems were not installed in these dwellings; the district heating infrastructure was not constructed due to a lack of regulatory bodies and EU mandates in the case-study location.

3.3 Methodological Framework

To determine the input parameters for the simulation set, this empirical 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 9. A bottom-up approach was integrated into the comprehensive methodology in the conceptual framework of the study to achieve the objectives of the building-performance evaluation and the optimisation of existing housing stock that was not previously conducted to inform policymaking decisions related to energy use.

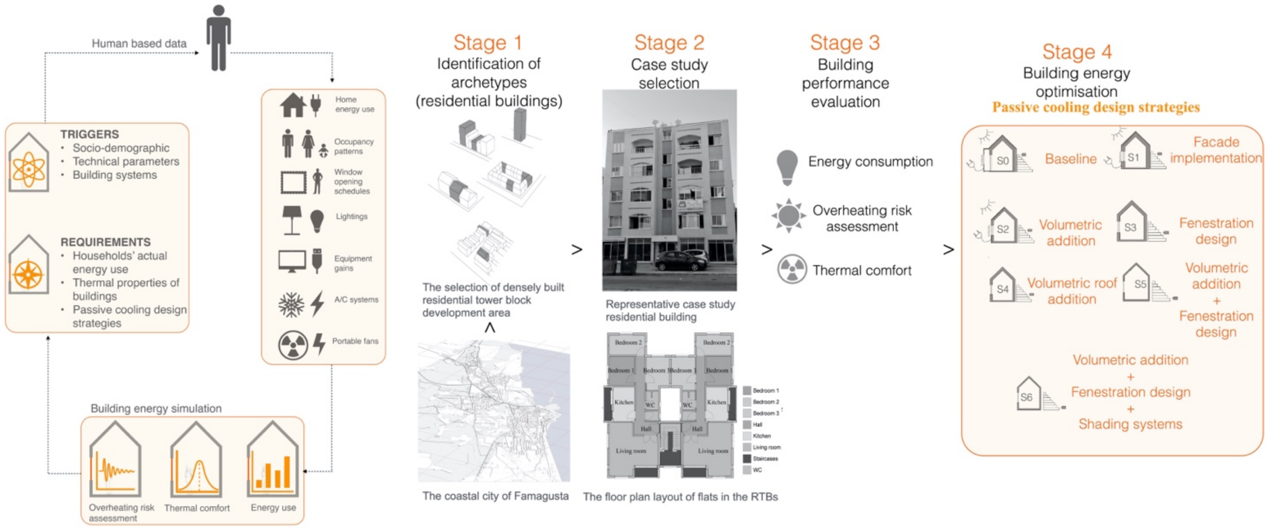


Fig.9. Flow diagram demonstrating novelty of STS approach.

The relative influence of stochastic variations was evaluated in order to calibrate building energy consumption for the purpose of improving building energy efficiency and reducing energy consumption. Table 3 summarises the list of input parameters utilised to calibrate the validity of the simulation results. Figure 10 presents the step-by-step development of multi-objective optimisation approach for decision making criterion in retrofit energy policy design.

Table 3. Parameters entailed in the simulation model for sensitivity analysis.

Dependent variables	**Input data**	
Air temperature	**Thermal zone**	**Direct sources**
Minimum zone air temperature	Roof thermal transmittance	In situ measurements Indoor air temperature Outdoor air temperature
Maximum zone air temperature	Wall thermal transmittance	Household survey Room occupancy schedules Window-opening schedules
Zone cooling degree hour	Intermediate floor thermal transmittance	Indirect sources
	Roof thermal specific capacitance	Technical sheet of materials
	Wall thermal specific capacitance	Standard sources
	Floor thermal specific capacitance	Technical standards
		Standard guidelines
		•BS EN 15251 •CIBSE TM 52 •CIBSE TM 59
	Output Data	
	Weather data for model calibration	
Suburban	**Urban (agglomeration)**	**Urban (city centre)**
	The worst-performing prototype RTB	
	Multi-objective optimisation	

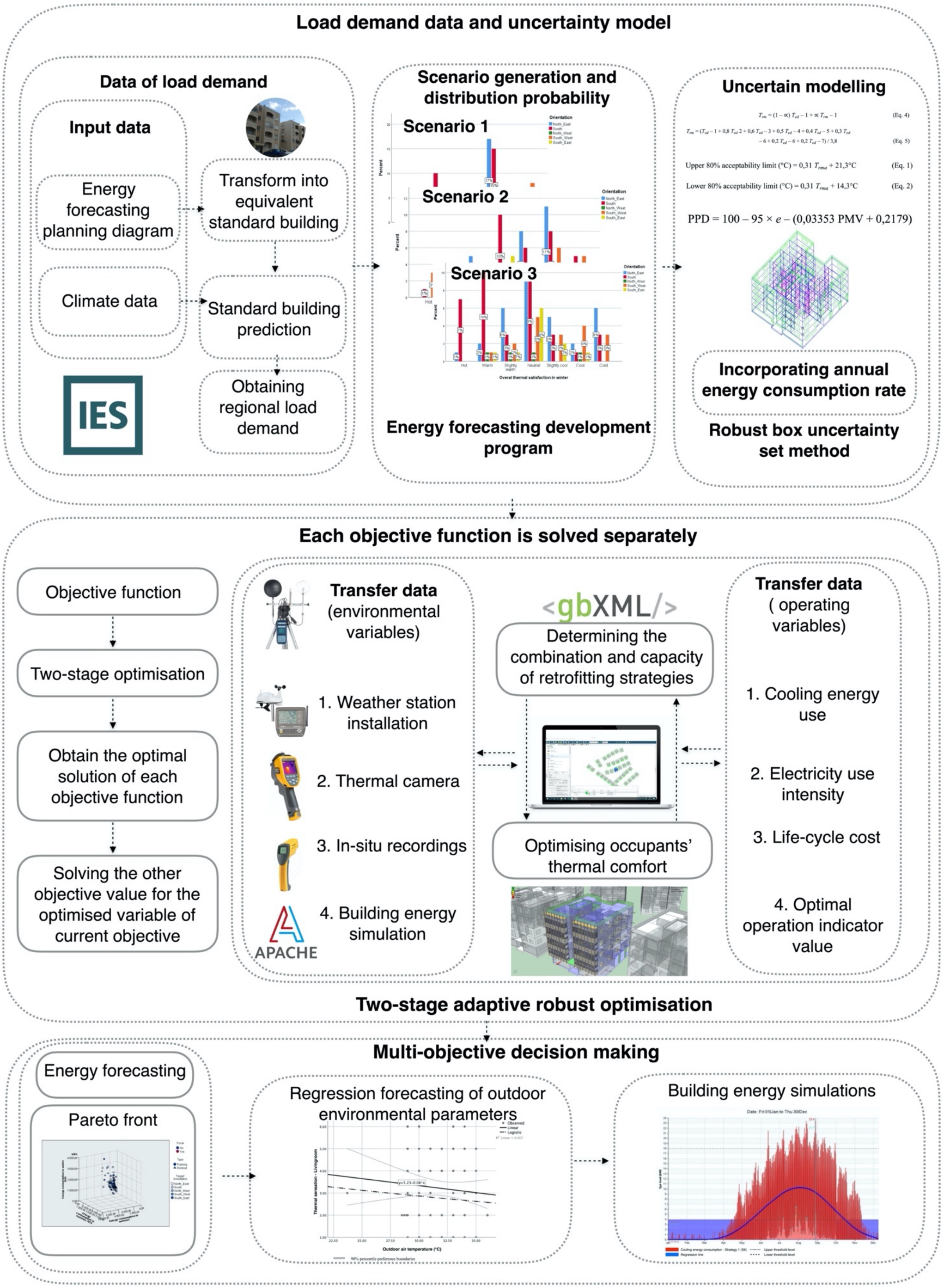


Fig.10. The workflow for the building optimisation study and identification of uncertainty parameters.

As shown in Figure 10, model calibration is an iterative process that aims to reduce discrepancies between simulated and actual building energy consumption, through refinement of the model parameters. In order to ensure the reproducibility of the calibration process and to reduce the uncertainties of model predictions, a reference procedure must be established that defines the operative methodologies and the evaluation criteria of building properties. Particularly for this study, the multi-objective optimisation (MO) approach is the most applicable to obtain total uncertainty factors between dependent and independent variables. It focuses on the effects of uncertain inputs distributed over the gamut of input parameters in line with using internal standards for benchmarking criteria. It enables investigating the effects of several input parameters at once (Abela *et al.*, 2016). The global MO method is regarded as more reliable, but this calibration method requires more computing time compared to the local sensitivity analysis (SA) approach (Tian, 2009), as illustrated in Figure 11.

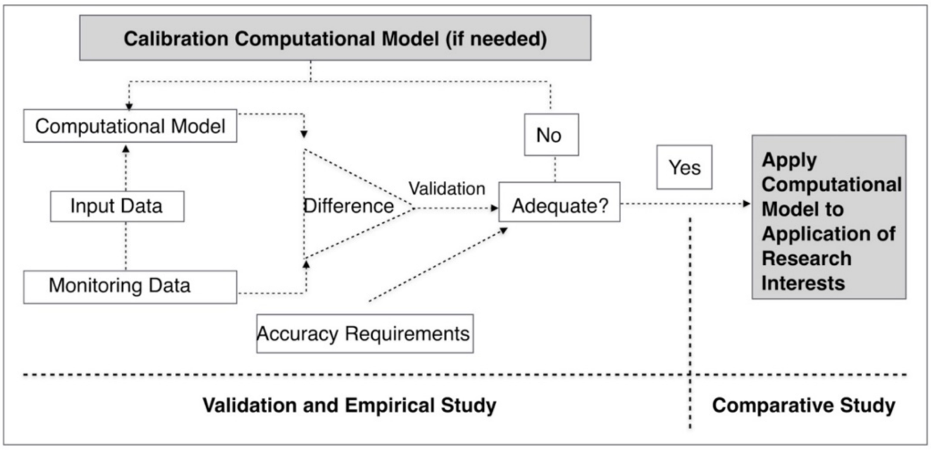


Fig. 11. Validation method flow diagram.

To validate the findings from the dynamic thermal simulations in the Integrated Environmental Solutions (IES) software, the regression method was implemented to carry out a global MO. It is the most widely used MO method for building energy simulation. Aside from that, the Standardised Regression Coefficient (SRC) and Standardised Ranked Regression Coefficient (SRRC) are indicators that show sensitivity levels with the embedding regression method (Tian, 2009). The coefficients mentioned above standardise input and output variables by subtracting the sample mean from the real values and dividing by standard deviation (Abrahamse & Steg, 2011). For this purpose, a regression-based global MO was conducted to investigate the effects of input parameters on energy use and thermal comfort indicators.

3.4 Overheating Risk-Assessment Criteria

The building-performance evaluation considered in the present study can be calculated in the following manner:

$$T_{max} = 0{,}33\ T_{rm} + 18{,}8°\mathrm{C} + \mathrm{SAR}$$

where T_{rm} is the exponentially weighted running mean of the daily mean outdoor-air temperature, and the suggested acceptable range (SAR) is 4°C; notably, the maximum benchmark range suggested by the CIBSE as a performance expectation is lower for the context of this study (CIBSE, 2017).

An additional method was suggested in CIBSE Guide A: BS EN 13779 (CIBSE, 2017), which asserts that building ventilation is an applicable performance requirement for ventilation and A/C systems. The chosen criteria for the thermal-comfort analyses in the present study were as follows:

- Criterion 1: Percentage of hours above 33°C
- Criterion 2: Percentage of hours above 35°C
- Criterion 3: Percentage of hours below 18°C

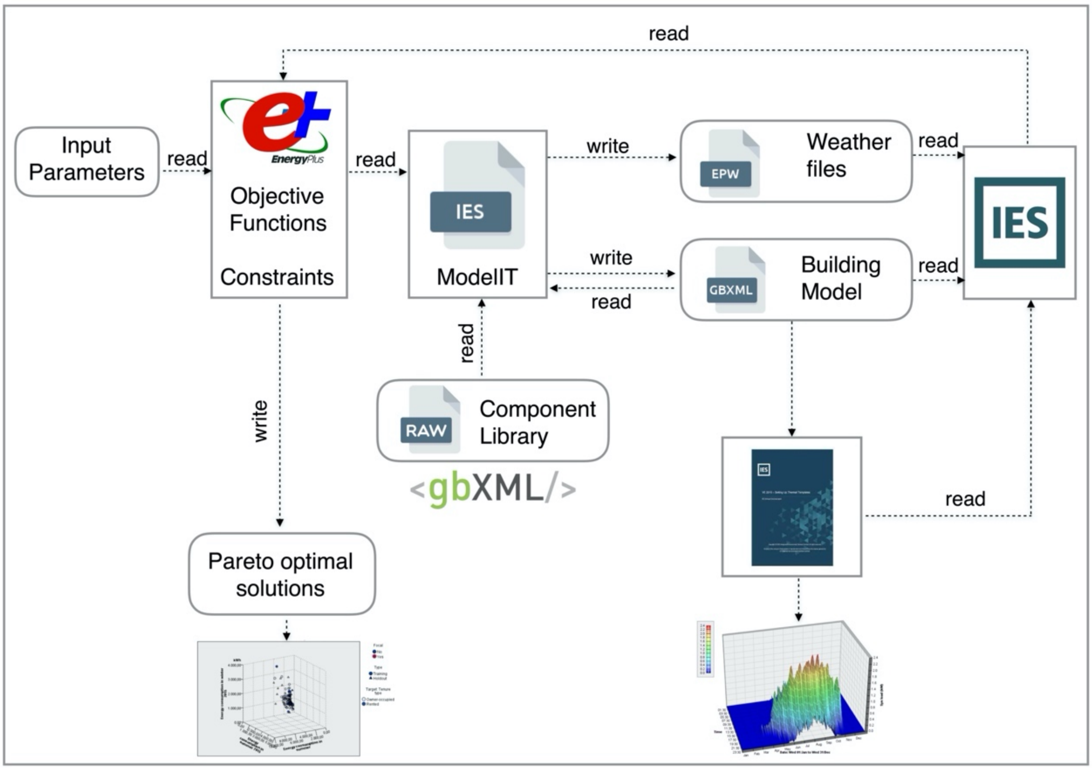


Fig.12. The simulation set input parameters for the building optimisation study.

As shown in Figure 12, to properly take the contextual features and simulation benchmarks of the representative RTBs into account, all three criteria use indoor dry-resultant temperatures. Percentages of hours were calculated as the percentage of hours out of the total hours in a year (CIBSE, 2017). It is important to note that these assessment criteria do not only refer to the occupied hours in each building, since exact information related to occupancy patterns was difficult to find (Cuerda *et al.*, 2020; Deb & Schlueter, 2021); this knowledge gap initiated the development of certain building-energy-simulation models within the dominant representative occupancy patterns in the RTBs that were gathered from the findings of the questionnaire survey (Salata *et al.*, 2020). This resulted in the inclusion of the most accurate data in the simulation model and minimised discrepancies between predicted household energy use and actual energy consumption (Ding *et al.*, 2021; Zhang *et al.*, 2020).

3.5 Data Collection Procedures and Research Instruments

3.5.1 Questionnaire Survey

The study methodology included questionnaire surveys distributed in RTBs with different orientations, in order to investigate whether floor-level differences had a significant impact on the energy usage of households. A thorough review of the STS conceptual framework was conducted, including several instances of feedback obtained during the pilot study. The methodology was then calibrated to verify the accuracy and reliability of the results obtained through semi-structured interviews conducted in the form of both close-ended and open-ended discussions with household members of 36 RTBs in this social housing development estate (see **Supplementary Material A**).

The survey of the members of 118 households was conducted between July 28, 2018 and September 3, 2018. The questionnaire included 28 questions, which included a combination of open-ended, partially closed-ended and predominantly closed-ended questions (see **Data set A**); the raw data of the statistical data set was designed in the Statistical Analysis in Social Science (SPSS) Version 25.0 and included spv. files for further research. The survey was designed to obtain quantitative feedback from respondents and used quota sampling to generate a nationally representative sample of households in Cyprus by reflecting the demographic make-up of the households in which the interviews were given.

3.5.2 Environmental Monitoring

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 interviewed flats across 36 RTBs in the social housing estate. Outdoor thermal conditions, including the outdoor air temperature, RH levels and the heat-stress index, were monitored with a Wireless Vantage Pro weather station. As shown in Figures 13 (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 9 (b), the weather station was mounted on a pole approximately 17 meters aboveground. It was equipped with a set of thermocouples that were continuously monitored, which recorded temperature variations throughout the questionnaire survey period, as shown in Figures 13 (c) and (d).

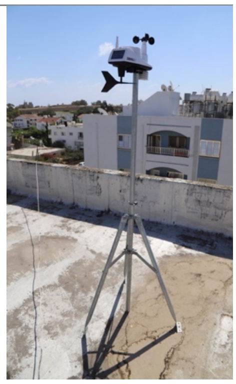
(a) (b)

(b) (d)

Fig.13. **(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. 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 4.

Table 4. 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 4, 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.

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

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

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:

$$Cv = T_{op} + h \qquad \text{(Eq. 3)}$$

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.

3.5.3 On-site Walk-Through Survey Thermal Imaging

This empirical study investigated the usefulness of infrared radiometer thermography (IRT) as a quick diagnostic tool to judge the building-fabric thermal performance of the base-case representative RTBs. IRT is a potent technique that allows a quick determination of the thermal conditions of existing buildings and structures (Tejedor *et al.*, 2017). For this reason, it was utilised as a primary diagnostic tool to identify the worst-performing representative RTB in a worst-case scenario for the energy-audit and -calibration analyses. A thermal-imaging survey was conducted between December 25, 2017 and January 12, 2018. The details of the instrumentation utilised in the field studies are summarised in Table 5.

Table 5. 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	
	Fluke 63 Infrared Thermometer	−25°C to 85°C	±0,5°C for 0–40°C	Minimum: ±0,5°C Ideal: ±0,2°C	

*Per the 2015 CIBSE Guide A benchmarks

It is worth mentioning that in warm climates similar to that of Cyprus, thermographic inspections are often undertaken during the cooler months (i.e., November through March) and at the time of the day when temperatures are at the coolest level to provide an accurate baseline measurement for the surveyed buildings (Bayomi *et al.*, 2020). However, the field-investigation time to conduct these inquiries was restricted by a timeframe to gain access to the flats, which limited the field inspections to socially acceptable hours in the morning and in the evening. Therefore, the 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; BRE Global, 2014).

3.5.4 Walk-Through Survey In-Situ Measurements

Building thermography is a qualitative testing method that utilises an infrared radiometer (IR) camera to detect surface temperature variations to visualise irregular thermal patterns that correspond to defects in the building envelope, such as thermal bridging or air leakage (Borelli *et al.*, 2020). In conjunction with the thermal-imaging survey that this field investigation was completed in the winter of 2017–2018, an internal thermography was performed in the summer of 2018 to measure heat gains coming through the high transmittance of building envelopes at the time of the survey, which was conducted between July 28, 2018 and September 3, 2018. A total of 118 flats were inspected with this technology. The internal thermography survey was concurrently undertaken with the survey during the late morning, afternoon and early evening between 10:00–20:45. Figures 14(a) through (c) illustrate the setups for the weather station and indoor air temperature measurement instrument.

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

Fig. 14. (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.

In addition to *on-site* environmental monitoring throughout the survey period and outdoor environment measurements that were recorded on the peak day of the heatwave, the ambient temperatures of the living room spaces of the surveyed flats were also measured using the IR camera; these measurements were taken early in the morning and late in the evening to avoid direct sunlight. The aims of the study were to ascertain an accurate ambient air temperature and to detect problems that arose from building envelopes in the base-case representative flats selected for the base case scenario development.

3.6 Building Energy Simulations

3.6.1 Black-box Energy Model

The Integrated Environmental Solutions (IES) Version IES 2020.1.0.0 software was used throughout this study (Integrated Environmental Solutions, 2020). The scope of the simulations was based on the indoor air temperature in relation to the thermal comfort temperature of each selected occupied space in the representative apartment units. In this study, the software tools used to illustrate building energy, the thermal performance of each building property and the impact thereof on indoor air environment quality simulations were, respectively, the ApacheSIM, MacroFlow and IES software suite applications (Patlakas *et al*., 2014). The modular interface structure of IES software makes it a flexible tool that can be used for building-optimisation studies (Altan *et al*., 2015); which requires that these modular functions develop surrogate energy models to inform effective energy-use policy-making decisions. The dynamic thermal modelling approach was employed to assess the current energy performance of the specified households. A south-facing RTB was selected as the base-case representative building to reduce the timely process of performing dynamic thermal simulations and numeric calculations in the IES software suite, as shown in Figures 15 (a)–(d).

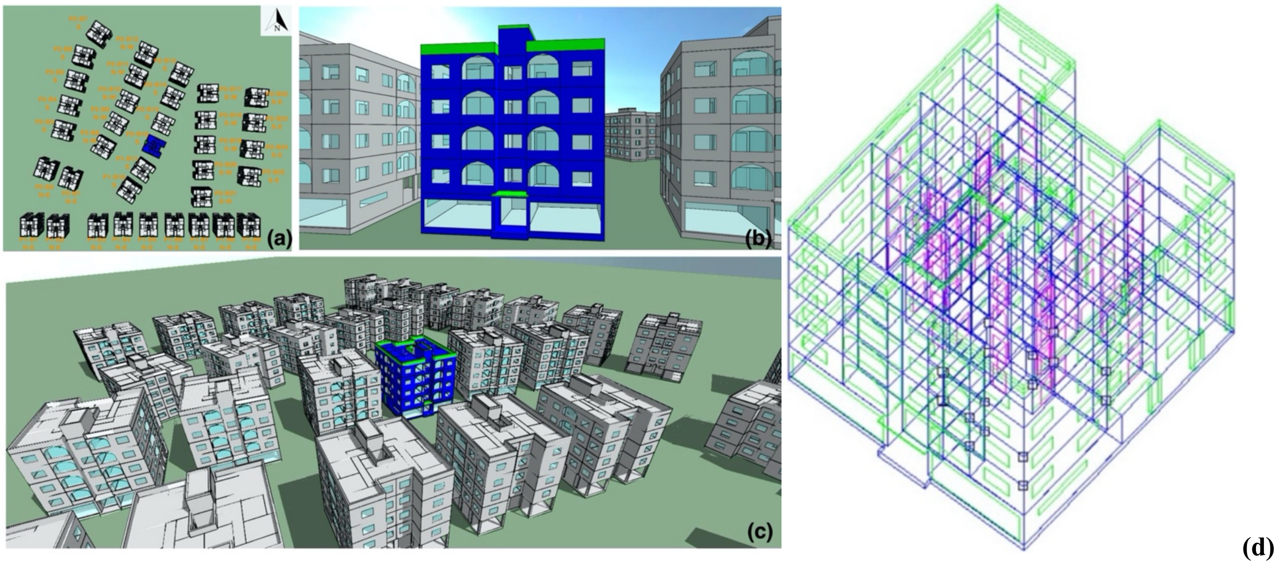


Fig 15. (a) Location map of the RTBs constructed in the ModelIT in the IES software suite. **(b)** Base-case representative model of south-facing RTB within adjacent buildings. **(c)** Analytical energy model of representative RTBs in the social housing development estate viewed from the main road. **(d)** Black-box energy model of the RTB. ***Source:*** Analytical energy model created with Integrated Environmental Solutions Version IES 2020.1.0.0 software suite.

The IES software can be easily coupled with the Energy Plus, DesignBuilder and Revit Green Building software suites to acquire building geometry and location information from the Test Reference Year (TRY) data available in the Energy Plus databases (Brembilla *et al*., 2020). IES offers users the ability to convert analytical energy models into gbxml. files to provide an interpolation of the analytical model within other energy software suites, such as the EDSL TAS and the Transient System Simulation Tool. IES can also interpret the dynamic-thermal simulation results within the recommended CIBSE TM59 benchmarks to assess the risk of overheating and the ASHRAE Standard 90.1-2019 benchmark criteria to assess indoor air environment quality of buildings (Hellwig *et al*., 2019). It should be emphasised that the IES software suite was chosen for this study because it has been shown to provide the most accurate results and recommendations to validate the findings from the questionnaire survey, the thermal imaging and the environmental monitoring (see **Data set B**); raw data from the analytical energy model was constructed in the IES, which included a gbxml. file for further research.

3.6.2 Weather Files Assigned in Simulation Model

Using the Integrated Environmental Solutions (IES) energy-simulation tool, building-energy modelling and a dynamic thermal simulation (DTS) were conducted to validate the field-survey findings and determine the energy-use reliability of the surveyed households. The aim of this section is to develop a viable model that can be adopted for the building-performance evaluation and for future retrofitting design strategies.

The base-case model in the present study was simulated by using a weather file that was defined with data obtained between May and September of 2018 from the closest weather station[3]; this was

[3] Weather data obtained from Larnaca Airport, which is approximately 60 km away from case-study location.

located in Paralimni[4] in the Famagusta district[5] (i.e., *Ammochostos* in Greek), which is in the ASHRAE Climate Zone 2A, as shown in Figure 16. The dynamic thermal-simulation output was then compared to the actual household energy bills collected in 2015–2016 to accurately assess the cooling demand of each occupied space by determining the deviations and the relevant uncertainty parameters in the simulation model (Carnieletto *et al.*, 2021).

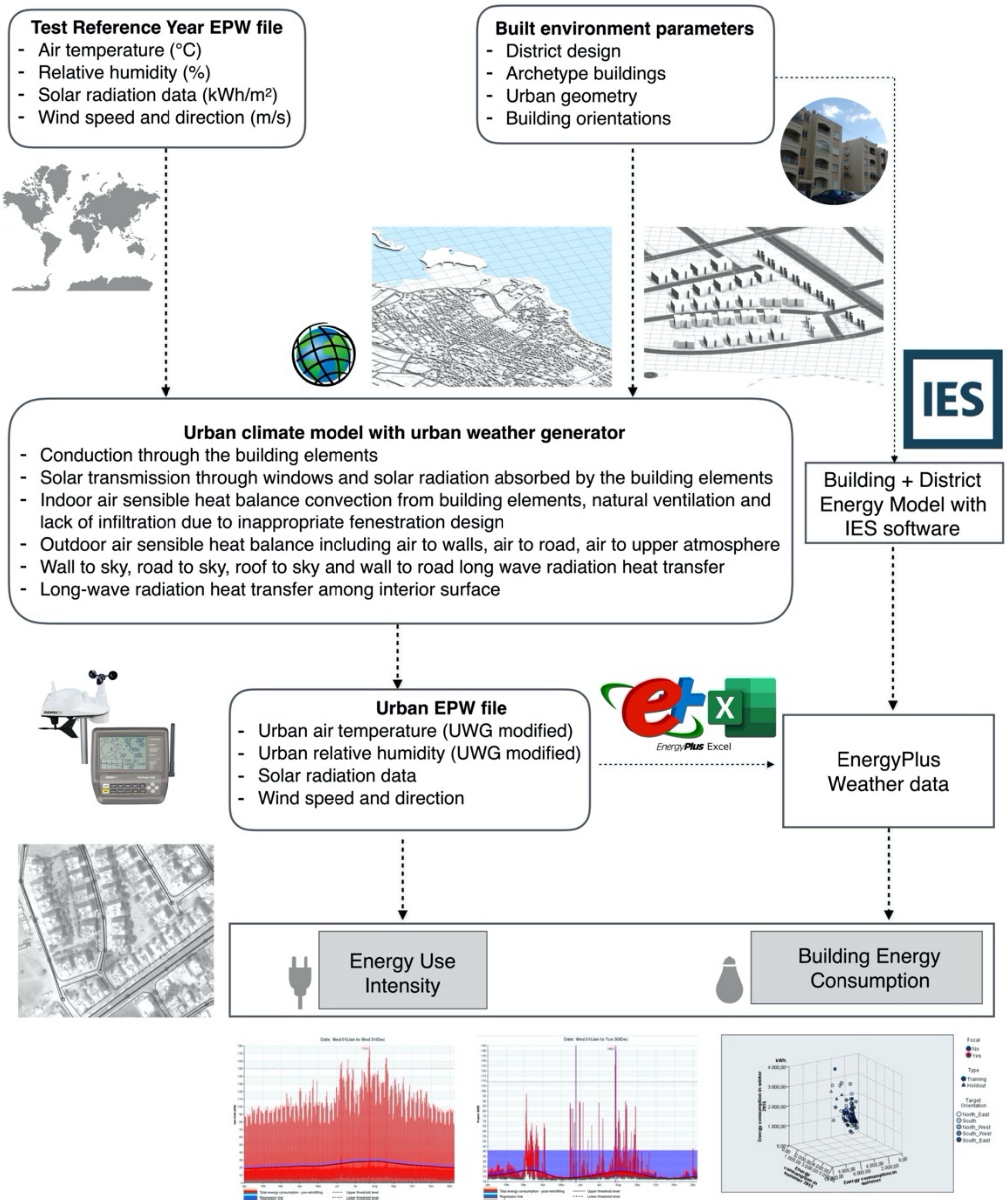


Fig.16. The set-up of the weather files assigned into building energy model for the dynamic thermal simulations.

[4] Paralimni is located on the Famagusta Bay shoreline, which is approximately 20 km away from case-study location; this area has typical eastern Mediterranean coastal climate characteristics.

[5] Due to the geopolitical situation of Cyprus, the Famagusta district is divided into two entities, the RoC and NC; data was collected from Larnaca Airport, which is located in the RoC, and Ercan Airport, which is located in the NC. A mobile weather station was installed at the case-study location at the time of the survey to monitor the *on-site* environmental conditions. The weather datasets were extrapolated together to avoid discrepancies in weather files assigned to the building-energy-simulation model. Open-source *.epw* files were generated from the EnergyPlus databases to identify accurate information for DTS analysis.

Test reference year (TRY) weather files for the one-year period of January through December of 2018 were utilised to conduct the DTS. Several modifications were made during the calibration phase to minimise data loss when the actual meteorological weather files were generated (Hosseini *et al.*, 2021; Liu *et al.*, 2021); these modifications were primarily related to the inner load and occupancy schedules, which were updated with information provided in the questionnaire survey. The TRY and actual meteorological year (AMY) weather files were comprehensively analysed to avoid discrepancies; in addition to the customised weather files utilised in the simulation program, the present study also used weather files constructed according to meteorological data gathered from EnergyPlus weather datasets (Sakiyama *et al.*, 2021). To adjust these weather files, constructed weather profiles, which included heating-degree days (HDDs) and cooling-degree days (CDDs), were compared with weather files assigned to weather profiles in the IES building-energy modelling platform.

3.6.3 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 6. 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):

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

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

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 ∝ constant between 0 and 1 (0,8 is recommended).

Table 6. 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 this empirical 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 2,778 l/m^2s, which corresponded to 1,408 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).

3.6.4 Occupancy-Pattern Variations

An energy-consumption assessment that utilised representative occupancy profiles was compared to the standard assessment protocols recommended by the EN 15251 and CIBSE TM59 standards to evaluate overheating risk and investigate each household's degree of thermal discomfort (Sun *et al.*, 2020; Uddin *et al.*, 2021). The primary focus of the BES studies was to use the dominant occupancy and energy-use patterns to determine the impact of different occupancy schedules on the building-energy performance evaluation (see **Supplementary Material B**). Table 7 delineates the cooling-energy-use schedules and occupancy patterns for the representative flats according to three different occupancy profiles, which were later implemented in the IES simulation tool.

Table 7. Low, Moderate and High Occupancy Patterns Assigned to Representative Flats A, B and C in BES Model

Spaces		OP1*	OP2**	OP3***
Living Room	**Cooling**	13:00–18:00	11:30–18:00	09:00–19:00
	Occupancy	Two people: 07:00–22:00 every day	Four people: 07:30–18:00 weekdays Two people: 18:00–22:00 every day	Two people: 09:00–16:00 every day Three people: 16:00–17:00 weekdays Four people: 17:00–23:00 weekdays
Bedroom 1	**Cooling**	22:00–07:00	11:30–18:00 22:00–03:00 03:00–06:00	23:00–06:00
	Occupancy	Two people: 22:00–07:00 every day	Four people: 07:30–18:00 weekdays Two people: 22:00–06:00 every day	Two people: 23:00–06:00 every day
Bedroom 2	**Cooling**	Off	Off	23:00–06:00
	Occupancy	None	None	Two people: 23:00–06:00 every day
Bedroom 3	**Cooling**	Off	Off	17:30–07:00
	Occupancy	None	None	One person: 17:30–07:00 weekdays
Kitchen	**Cooling**	Off	Off	17:30–19:30
	Occupancy	Usually one person: 07:00–08:00, 11:30–13:00 and 17:00–19:30 weekdays	Usually four people: 07:00–08:00 and 11:30–13:00 weekdays Usually two people: 19:00–20:00 every day	Three people: 06:00–06:45 weekdays Five people: 18:00–19:00 weekdays Five people: 10:00–11:30 weekends Five people: 17:00–18:00 weekends

*OP1: Occupancy pattern 1 (low)
**OP2: Occupancy pattern 2 (moderate)
***OP3: Occupancy pattern 3 (high)

According to Table 7, Flat A was located on the first floor and was occupied by a retired couple who used a portable fan in the living room between13:00–18:00 and in the bedroom between 22:00–07:00. The respondents also indicated that their living room and bedroom windows were open during occupancy hours every day of the week; the window and door in their kitchen space were opened during meal preparation between 11:30–14:00.

Flat B, which was located on the intermediate floor, was occupied by an elderly couple and their two grandchildren, who typically used their wall-mounted A/C system in the living room and Bedroom 1 between 11:30–18:00. All windows were kept closed when their grandchildren were present in the home, but the respondents stated that they kept their windows open from 18:00–07:00 to dissipate stale air. The occupants reported that they used their A/C system between 22:00–03:00 with all of their windows closed, and they used a portable fan in Bedroom 2 from 03:00–06:00 with all their windows open; the kitchen window and door were open 24 hours a day. The A/C system in the living room and bedroom spaces was set to 21°C.

Flat C was located on the upper floor and was occupied by a family of two adults and three children who turned their A/C system on in the living room between 09:00–19:00. Two adults predominantly used a portable fan in Bedroom 1 between 23:00–06:00. The A/C system was used in Bedroom 2, which was occupied by two children who were 8 and 14 years of age, from 23:00–08:00, and their windows were closed. The A/C system was used in Bedroom 3, which was occupied by one 16-year-old youth, between 17:00–08:00, and their windows were closed. The A/C system was set to 18°C in the living room, 21°C in Bedroom 2, and 16°C in Bedroom 3.

3.6.5 Building Energy Optimisation Input Parameters

This study presents an analysis of the PCRDS development framework to demonstrate an evidence-based integrated design approach for energy use (see **Graphical Abstract**). The multi-objective optimisation of the building assessment provides information related to the energy effectiveness of retrofitting interventions by determining the LCCA for policymakers in the residential sector.

The building optimisation studies attempted to gain an understanding of the most effective ventilation and shading strategies in terms of corresponding percentages of time of comfortable temperatures in order to design a building envelope that is resilient in the ever-changing outdoor temperatures, since the current building envelope presented a lack of air ventilation in the occupied spaces of the RTBs.

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, which were considered to be the baseline designs. The second retrofit design strategy also included the energy performance of a combination of passive design measures, which was comprised of 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 operable external shading systems. The fourth, fifth and sixth strategies included adaptable passive designs to evaluate the improvement according to the percentage of hours of thermal discomfort. These strategies, including the analysis methods and the descriptions thereof, are listed in Table 8.

Table 8. 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 3	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 aim was to develop an evidence-based methodologically planned framework to increase the energy efficiency of the existing housing stock and improve the indoor air quality of the RTBs. S1, S2, S3, S4, S5 and S6 were initially applied separately, then the obtained results were all applied together to test the effectiveness of these design strategies as a whole (see **Appendix C**).

The proposed solution for passive-design retrofitting of the building envelope was the instalment of a thick, thermal-insulated clay-tile external-facing system, the replacement of windows and door glazing (from single- to double-Low-E glazing) and the use of timber-framed shading elements. The presented scenarios were reviewed and studied globally, including the use of energy efficient building systems and local construction codes, and these evaluations yielded improvement models that were especially suitable for the specific region. Table 9 illustrates the assigned construction properties of the base-case and the six strategies that were applied in the simulation.

Table 9. 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

It should be emphasised at this point that the dominant representative occupancy profiles that were recommended by the CIBSE TM59 criteria were adapted into the simulation model at the time of the energy-effectiveness evaluation of the assigned thermal properties and the ventilation infiltration rates. Notably, the starting point in this study was the human-based data, which enabled us to triangulate the findings from the primary data sources discussed in Section 4.

4. Results

4.1. Questionnaire Survey

4.1.1. Assessing Energy-Saving Awareness and Participant Opinions on Energy Conservation

The participants' awareness of the energy use and energy conservation in their dwellings was sought in order to ascertain how this knowledge affected their energy usage and their level of awareness of energy-consumption reduction. This section included an analysis of Questions 4–7 (see **Data set C**), which assessed the awareness of each household of their energy use. This part of the survey investigated whether the occupants had been given sufficient information related to energy conservation from local authorities, energy suppliers or other resources during the period of residency in their dwellings. Figures 17(a) through (d) demonstrates the findings of questionnaire survey to provide subsequent information on tenure type and energy-saving awareness.

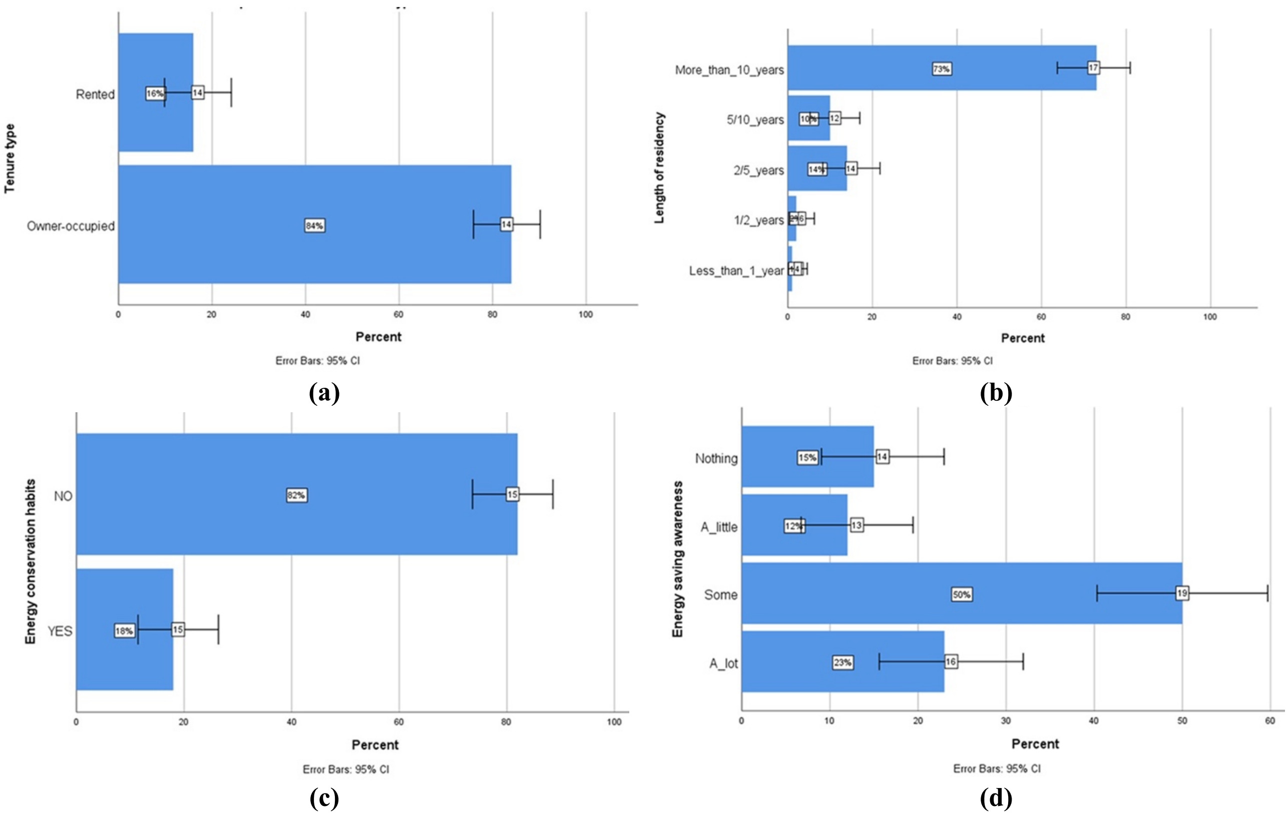


Fig. 17. (a) Percentage distribution of household energy consumption rates. **(b)** Percentage distribution of households that received energy advice. **(c)** Percentage distribution of household habits of frequent electricity meter-reading. **(d)** Percentage distribution of household awareness of energy saving.

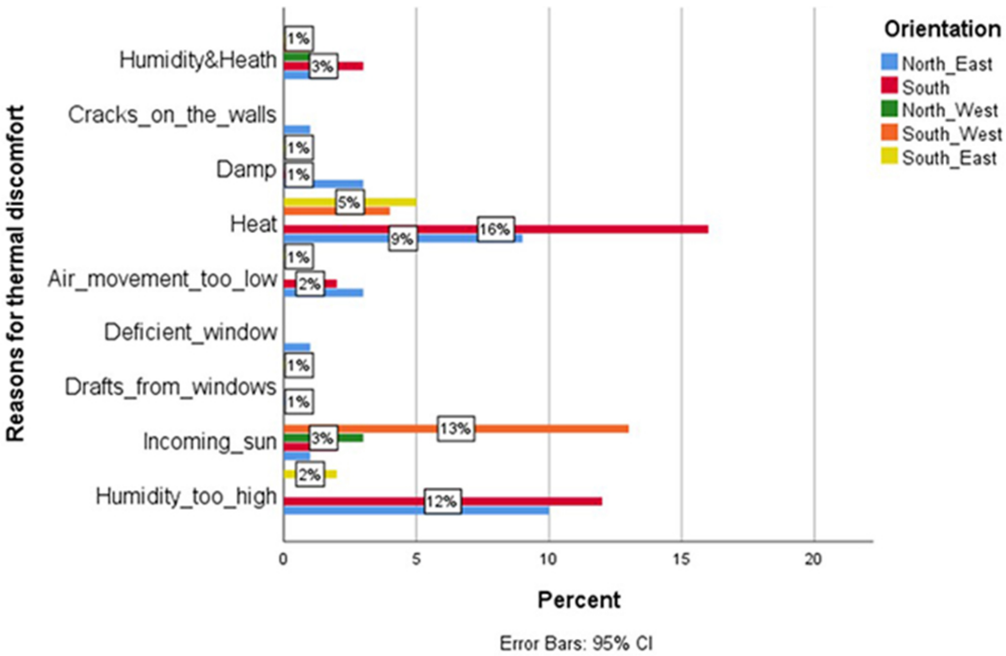
Figure 17(a) shows that 69% of the respondents paid their monthly energy bills at a higher rate, while 31% of the respondents paid at a lower rate. These results can be correlated with the household income levels and the number of family members living in each flat. The sources of energy advice received are indicated in Figure 17(b). Among the respondents who received energy advice, 12% received this advice from the Famagusta municipality, and 15% received this advice from the Electricity Authority in Cyprus; an additional 6% received energy advice from other resources, such as television commercials, or they received energy-conservation training from other local authorities or institutions. Of the respondents, 67% stated that they had not previously received advice from any type of local institution. It was determined that there was a general lack of awareness related to energy use across the interviewed households. This resulted in the residents paying monthly energy bills at higher rates. The survey further illustrated that both the Famagusta municipality and the Electricity Authority in Cyprus had not undertaken any serious efforts to inform and educate households in this social housing development. Households may over-consume energy due to a lack of knowledge and in an attempt to achieve a more comfortable living environment. Households were asked in a closed-ended question if they frequently checked their home electricity meters. Of the respondents, 82% indicated they had never checked their home electricity meter to regulate their energy usage throughout the year, while 18% reported they checked their home's electricity meter on a regular basis to ensure that they were able to manage their energy bills, as illustrated in Figure 17(c).

Figure 17(d) illustrates the household awareness of energy use. Each household was asked if they had ever been informed about any type of energy-saving measures through Likert-scale questions. When asked about their awareness of energy-saving methods, 23% of the respondents said they always considered any type of energy saving measures; 50% sometimes considered them, 12% considered them quite a few times, and 1% never considered them even though smart meters were installed in their dwelling. It is important to note that the smart meter systems were installed in these flats in 2016, but the households did not receive any type of training to understand the benefits of installing these systems in their properties. It can be concluded that household expenditures on energy bills were high throughout the RTBs. The findings indicate that the environmental monitoring of these units was essential to assess indoor air quality and the impact of the buildings' thermal properties on the occupants' thermal comfort before undertaking any type of retrofitting.

4.1.2. Reasons for Thermal Discomfort

This section comprises the analysis of question 35 concerning occupants' complaints about thermal discomfort in summer (see **Data set D**). The reason for this was to enable us to understand the overheating risk of their indoor occupied spaces, taking into account the RTBs' orientations.

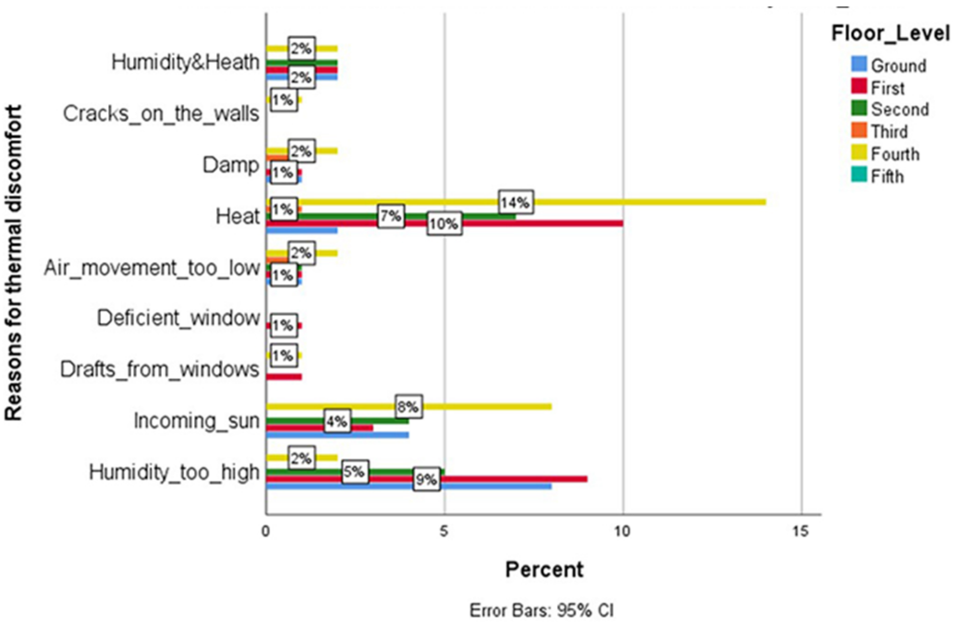
As shown in Figure 18(a), the results showed that with the south-facing RTBs, 12% of the respondents complained about high humidity, and in northeast-facing RTBs, 10% reported that the high humidity was one of the main reasons for their thermal discomfort. In addition, in the southeast-facing RTBs, 2% complained that high humidity contributed to a thermally uncomfortable indoor environment in summer. It was also noted that during the period of the thermal comfort surveys, external temperatures ranged from 25.3 °C to 38.7 °C, with a mean of 28.7 °C. The RH ranged from 53.5% to 87.1%, with a mean of 67.7%, an indication of the relatively hot and dry climate conditions experienced at the time.



(a)

Fig.18. (a) Percentage distribution of the reasons for thermal discomfort, taking into consideration the RTBs' orientation

Figure 18(a) depicts that in the southwest-facing RTBs, 13% of the households complained about incoming sun while in the northwest-facing RTBs, only 3% complained that incoming sun caused the indoor air temperature to increase in their occupied spaces, and in the south- and northeast-facing RTBs, only 1% complained of incoming sun. In the southeast- and northeast-facing RTBs, only 1% of the households complained about a draught from the single-glazed aluminium-framed windows. Furthermore, in the northeast-facing RTBs, 3% of the households complained that air movement was too low in their indoor occupied spaces due the small window openings.



(b)

Fig.18. (b) Percentage distribution of the reasons for thermal discomfort, taking into consideration the flats' different floor levels

As can be seen in Figure 18(b), from the flats located on the ground floor, 8% of the respondents complained of high humidity, 4% mentioned incoming morning sun, 2% mentioned heat, and only 1% mentioned damp due to the defective building foundations. Lastly, 2% of the respondents mentioned both humidity and extreme heat. In the first-floor flats, 10% of respondents complained of extreme heat, 9% mentioned high humidity, 3% mentioned incoming sun, and 2% complained about both humidity and extreme heat. In the second-floor flats, 7% of the respondents complained of extreme heat, 5% mentioned high humidity, 4% mentioned incoming sun, and 2% mentioned both of these factors. For the third floor, only 1% of respondents complained about extreme heat. This is due to the occupant living in block number 18 in phase two, where the angle of the sun comes directly onto the building envelope. On the fourth floor, 8% of the respondents complained of extreme heat, 8% said incoming sun, 2% said high humidity, and 2% complained about both extreme heat and incoming sun. Finally, on the fifth floor, 6% of the respondents complained about extreme heat, 1% said there were draughts from the deficient window frames, and only 1% complained about cracks in the walls; additionally, 1% of the households complained of dampness issues on the wall surfaces in the home.

4.2. Thermal-Comfort Assessment Indicators

4.2.1. Metabolic Activity

This section discusses how and why thermal-comfort results were calibrated in the simulation outputs according to the occupants' metabolic rates and clothing-insulation levels and included in the building-performance evaluation. During the questionnaire survey, participants were asked to record their activity level for the previous 20 minutes, and their metabolic rates were calculated to validate the findings discussed in Sub-section 4.5.2. The mean average metabolic rate of the participants was 3,22 *met* (*SD* = 1,931), as shown in Figure 19.

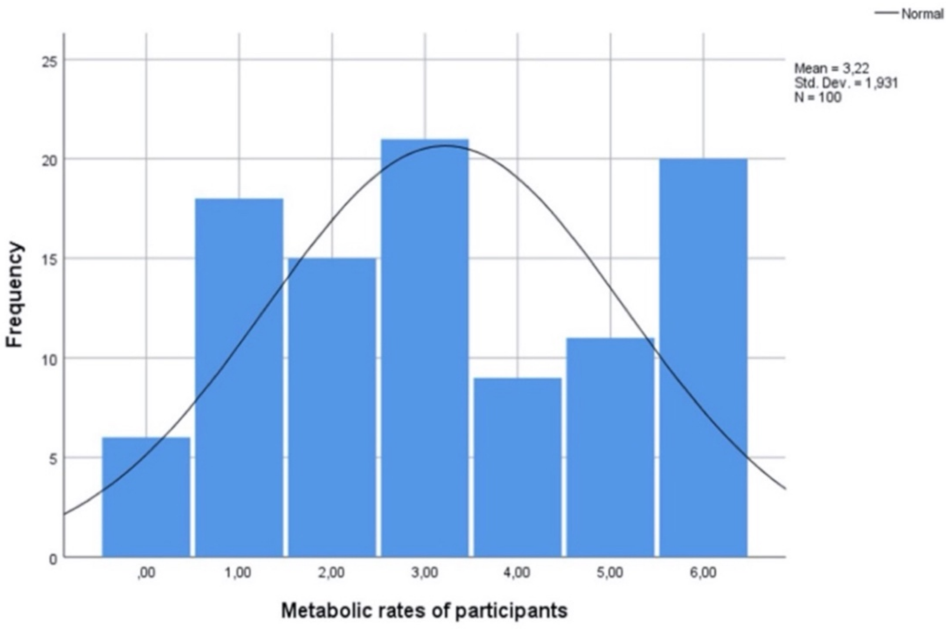


Fig.19. Average participant metabolic rates.

These results were compiled using the metabolic-rate range included in the ASHRAE 55 adaptive thermal-comfort standards (2017). Notably, the ASHRAE adaptive-comfort model is applicable to spaces in which occupants are engaged in near-sedentary physical activities with metabolic rates that range from 0,8–2,10 *met* (ASHRAE, 2017).[6] According to the frequency statistics for this survey, the overall average metabolic rate was 1,93 *met*, and the most frequent metabolic rate was 0,3 *met*; it was determined that the activities in which the residents had engaged during the 20-minute period prior to the survey were largely sedentary in nature. Figure 20 illustrates the variations in participant metabolic rates, taking gender into account.

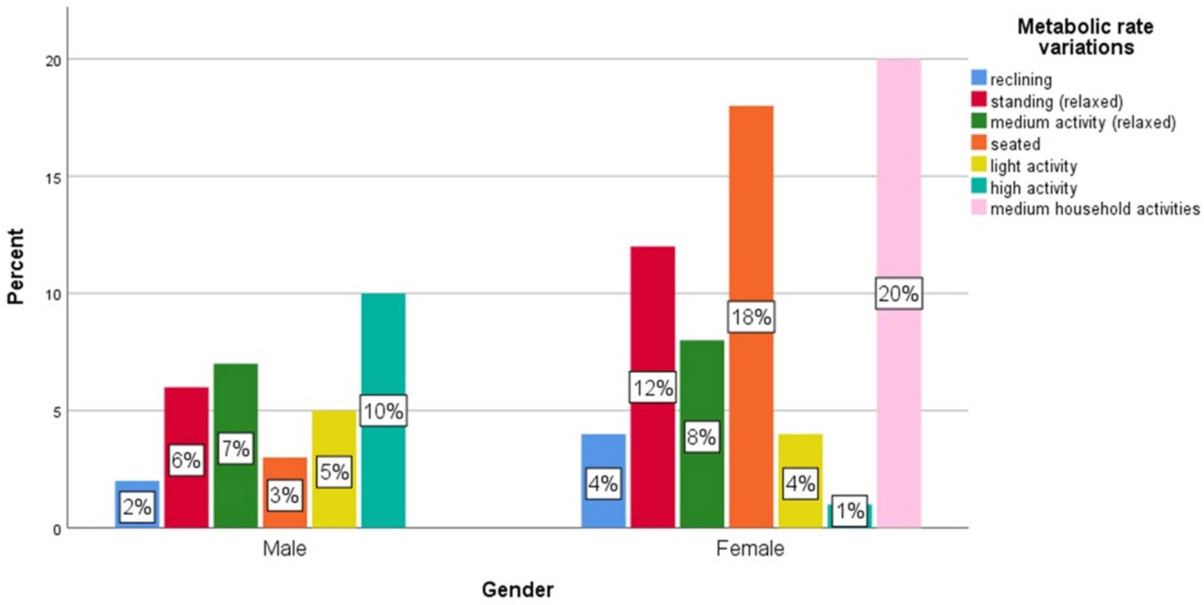


Fig.20. Percentage distribution of participant metabolic rates, taking gender into account.

Prior to being surveyed, 10% of the males were involved in high-intensity activity, 2% were reclining, 6% were standing (relaxed), 7% were engaged in medium-intensity activity, 3% were seated, 5% were involved in light activity (standing), and 10% were engaged in high-intensity activity. Before the female respondents were surveyed, 4% were reclining, 12% were standing (relaxed), 8% engaged in light activity, 18% were seated, 4% engaged in light activity (standing), 1% engaged in high-intensity activity, and 20% were involved in medium-intensity activity.

The male participants who reported high-intensity activities were repairing indoor wall surfaces or damaged building components in their properties to avoid heat losses through the building envelopes, and the male participants who reported medium-intensity activity were either standing up and were involved in household activities. Of the female respondents who were engaged in medium-intensity household activities, 20% were busy with meal preparation in the kitchen; in this regard, it is important to consider the additional internal heat-gain factor from domestic kitchen appliances, which was found to have a significant impact on the TSVs.

[6] The ASHRAE 55 standards (2017) recommend the following thermal-comfort assessment criterion for subject participants: 1 *met* = 58,2 W/m^2

4.2.2. *Clothing Insulation*

This section is comprised of an analysis of Question 31, which concerned the participants' clothing (see **Supplementary Material A**). The level-of-insulation of the clothing that the respondents were wearing at the time of the questionnaire survey was observed and recorded in the questionnaire checklist, and the impact of the respective clothing-insulation levels on the occupants' thermal-preference votes (TPVs) was evaluated; this was then converted into a numerical clothing value (clo), according to the ASHRAE 55 standards (2017) to assess the occupants' thermal comfort in naturally ventilated residential buildings.

Clothing-level adjustment is an important adaptation process that maintains comfort at different temperatures (Verbruggen *et al.*, 2019). The occupants estimated the statistical summaries of their clothing-insulation values from the clothing-insulation list. Due to the chair-insulation effect, the insulation of a chair in the present study was assumed to be 0,35 *clo*, because the participants were all sitting on fabric sofas during the survey (de Dear & Brager, 1998). Figure 21 shows the clothing-insulation value frequencies; the occupants' mean clothing insulation in the cooling season was 2,66 *clo* (*SD* = 2,19).

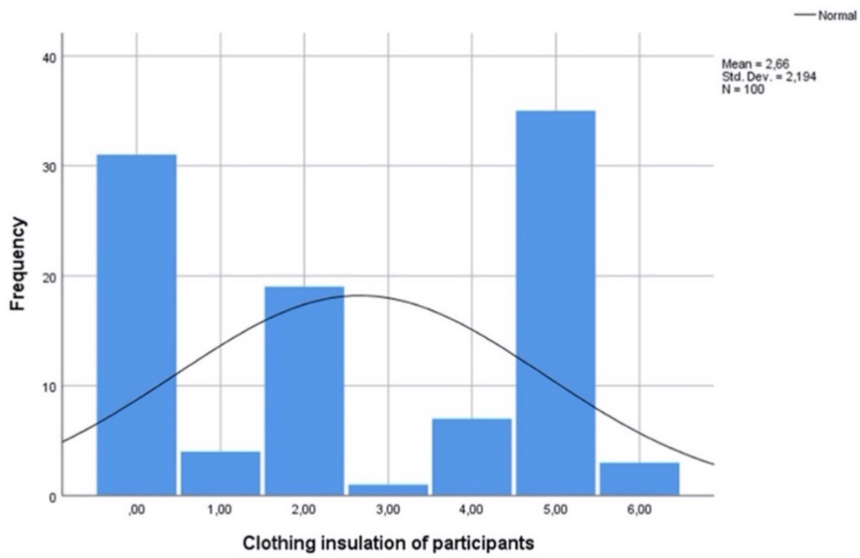


Fig.21. Distribution of household clothing-insulation values.

Previous scholarly work related to the identification of adaptive thermal comfort determined that there are three types of thermal adaptation: physiological, which is related to the body reaction due to the temperature change; psychological, which is derived from the state of mind of previous experiences; and adaptations related to behaviour (Brager & de Dear, 1998). According to Nicol *et al.* (2009) comfort can be achieved if there are sufficient opportunities for people to adapt. Comfortable temperatures are changeable, rather than fixed.; as such, clothing is a behavioural adjustment that directly affects heat balance, and it is a key thermal-adaptive response (de Dear & Brager, 1997). Figure 22 illustrates the various garments worn by respondents, taking gender into account.

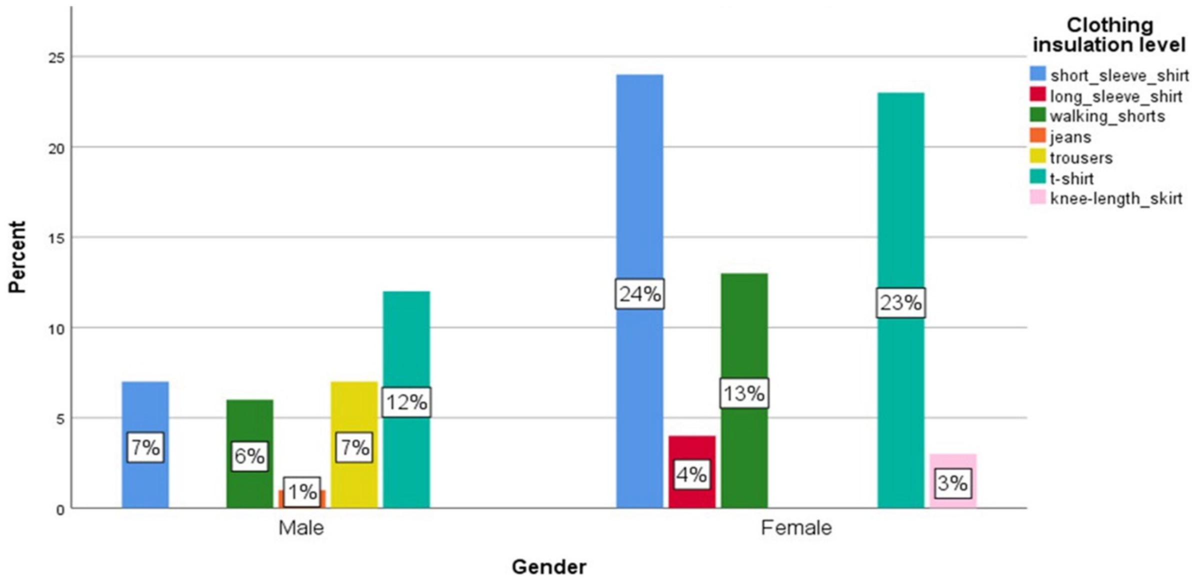


Fig.22. Percentage distribution of participant clothing levels, taking gender into account.

Figure 22 demonstrates the summer period classification of clothing types worn by the participants: Of the male respondents, 7% wore a short-sleeve shirt, 12% wore a T-shirt, 6% wore walking shorts, 1% wore jeans, and 7% wore trousers; this correlates with the NC cultural domain, where most men prefer to wear long trousers when they have guests in their home out of respect for the cultural and religious norms of the research context. Of the female respondents, 24% wore a short-sleeve shirt, 23% wore a T-shirt, 13% wore walking shorts, and 3% wore a knee-length skirt; in the cool season, 4% of the elderly women wore long-sleeve shirts and straight, thin trousers, because of the cultural domain of these female respondents, most of whom were religious.

Notably, it is important to consider the occupants' physiological characteristics to optimise their thermal comfort, which correlated with the occupants' real-life energy-use experiences (Yan *et al.*, 2020). When the BES study was conducted, the households' *in-vivo* experiences related through their TPVs and TSVs were shown to be significant determinant factors. The base-case representative flats were selected for this reason, and the predicted percentage of dissatisfied (PPD) was retrieved from the simulation results that are presented in Sub-section 4.5.2.

4.2.3. Clothing Insulation

To calculate the impact of occupancy patterns on the occupants' thermal comfort, the household metabolic activity and clothing-insulation levels were used to adjust the equation formula for the calibration analysis. Table 10 demonstrates the summary of household metabolic rates and clothing-insulation levels used in the calibration analysis.

Table 10. Evidence-Based Input Parameters Gathered Through Questionnaire Survey.

Statistical Features		Participants' Metabolic Rates (*met*)	Participants' Clothing Insulation (*clo*)
***N* (Sampling Size)**	**Valid**	100	100
	Missing	0	0
Mean		3,2200	2,6600
Std. Error of Mean		0,1931	0,21937
Median		3,0333[a]	2,5500[a]
Mode		3,00	5,00
Std. Deviation		1,93103	2,19375
Variance		3,729	4,813
Skewness		0,102	−0,029
Std. Error of Skewness		0,241	0,241
Kurtosis		−1,222	−1,688
Std. Error of Kurtosis		0,478	0,478
	25th	1,6061[b]	0,5429[b]
Percentiles	**50th**	3,0333	2,5500
	75th	5,0323	4,7857

[a] Median total calculated from grouped data
[b] Percentiles calculated from grouped data

According to Fanger (1973), a given environment could be considered comfortable ±1°C corresponding to a PPD of 20%; when it is above ±2°C, however, the environment is considered to be too hot or too cold. To develop a set-up for the identification of adaptive thermal thresholds, Fanger's equation model was utilised to calibrate simulation data collected from the survey findings; PPD is computed with the predicted mean vote (PMV) as follows:

$$PPD = 100 - 95 \times e - (0{,}03353\ PMV + 0{,}2179)$$

This equation is notable because it has a minimum PPD of 5% for thermally acceptable (i.e., neutral) votes; it provides an evidence-based method to calculate the manner in which the occupants' TPVs and TSVs will be utilised in the BES study. The step-by-step development of a calibration analysis demonstrates how thermal comfort can be concurrently improved while the retrofitting design strategies delineated in Section 4.6 are implemented.

Table 11. Simulation Input Parameters for Thermal-Comfort Assessment.

Representative Room-Design Settings	Comfort Parameters
Nominal design air speed	0,15 m/s
Activity level	1,93
Clothing level	2,19
Summer elevated air speed	0,80 m/s

Category I for existing buildings was selected in line with CIBSE TM59 overheating risk assessment criteria.
Note: Indicator parameters identified through questionnaire survey.

Table 11 demonstrates the thermal-comfort parameters that were assigned in the IES simulation platform. Notably, the representative room-design settings widened due to the adjustability of comfort parameters in the ApacheSim module. After the DTS analyses were completed according to the defined occupancy patterns, thermal comfort was evaluated in the IES software as a post-simulation process; post-simulation processing occurred within the VistaPro application of the IES software suite. The ASHRAE 55 (2017) adaptive-comfort criteria were chosen to evaluate the occupants' thermal comfort; this ensured constant metabolic-activity rates and clothing-insulation levels in the black-box model that was developed for the BES.

4.3. Environmental Monitoring and Household Thermal Sensation Votes

This section presents the significance of physical factors and the influence thereof on occupants' thermal comfort, and an explanation of the methods that were used to deal with subjective sensations of thermal comfort by interpretating the data with environmental monitoring findings is offered. During the questionnaire survey, participants were asked, 'How would you prefer feeling at this precise moment?' Participants recorded their thermal sensation on the Likert scale, which demonstrated a determinant factor similar to the ASHRAE-2017 point-scale for the evaluation of occupants' thermal comfort, as can be seen in Table 12 (ASHRAE, 2017).

Table 12. Data of indoor Climatic arameters in representative first-, intermediate- and upper-floor flats.

Floor Level	Descriptive Statistic	Air Temperature (°C)	Global Temperature (°C)	Relative Humidity (%)
First	Min	24,4	24,5	53,0
	Mean	27,8	28,0	66,9
	Max	30,8	31,0	81,0
	SD	1,8	1,9	8,1
Intermediate	Min	24,4	24,5	53,0
	Mean	27,8	28,0	66,9
	Max	30,8	31,0	81,0
	SD	1,8	1,9	8,1
Upper	Min	28,0	28,0	55,0
	Mean	32,3	32,2	65,7
	Max	34,7	34,8	83,0
	SD	1,7	1,7	8,0

In the upper-floor flat, the measured indoor air temperatures fell between 28–34,7°C, with an average of 32,3°C and a standard deviation (SD) of 1,7°C. The global temperatures were between 28–34.8°C, with an average of 32,2°C and an SD of 1,7°C. The air and global temperatures tended to be identical in the southeast and northeast orientations. This was a reflection of the minor variations in outdoor temperatures in a hot, dry climate, such as that of the coastal city of Famagusta, and of minor differences between the indoor temperatures of the flats and the outdoor temperatures of the adjacent building.

Notably, the indoor RH ranged between 55–83%, with an average of 65,7% and an SD of 8% for the upper-floor flat. Subjects' thermal sensation votes (TSVs) were distributed in such a way that out of 100 respondents, 28 (9,2%) were neutral, 68 (85,8%) voted on the warm and hot side and only 4 (5%) were on the cool side. The mean vote was 1.5, which means that on average, subjects felt uncomfortably warm. Table 12 illustrates the measured living room space's environmental conditions, taking into account the floor-level differences of the RTBs under investigation.

On the first floor, the measured indoor air temperatures were between 24,4–30,8°C, with an average of 27,8°C and an SD of 1,8°C. The global temperatures were between 24,5–31,0°C, with an average of 28°C and an SD of 1,9°C. The indoor RH ranged between 53–81%, with an average of 66,9% and an SD of 8,1%. Subject TSVs were distributed in such a way that 28 respondents (13,5%) were neutral, 37 (66,2%) voted on the warm and hot side, and only 35 (20,3%) were on the cool side. The mean vote was 0,7, which means that on average, subjects felt slightly warm.

It should be noted that the intermediate-floor flat also displayed similar findings to those of the first floor, due to its orientation and the corresponding window ratios. At the same time, the occupancy patterns showed similar TSV rates; hence, the building model simulation findings produced the same results as the occupants' thermal sensation votes described in Section 5.3. The findings of this field survey validated the simulation results, thereby proving the risk of overheating and the thermally uncomfortable indoor environment conditions in the summer in these representative flats.

4.4. *On-site Thermal Imaging Survey and In-Situ Measurements*

This section presents the *on-site* 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 23 (a) through (d) illustrate the heat loss of the different building envelopes.

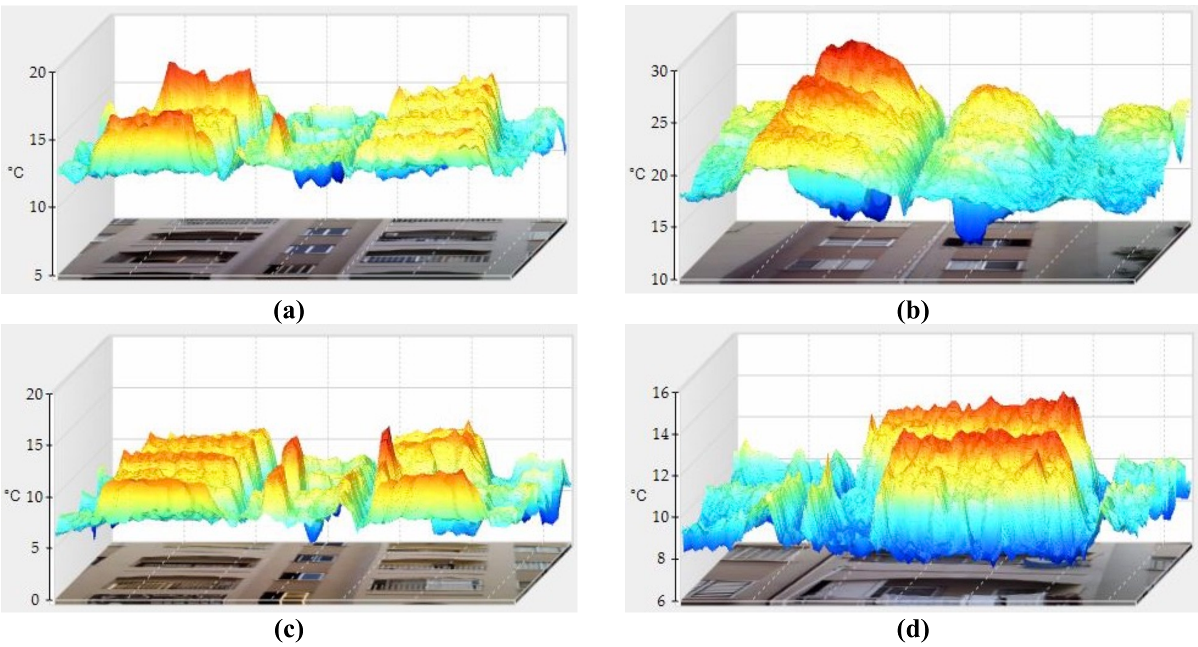


Fig.23. (a) through (d): Sample of winter thermal-imaging analysis.

Figure 23(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 23(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 23(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 23(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 calibration studies could be conducted in the building-modelling phase of the study, which is described and discussed in Sub-sections 4.6.1 and 4.6.2.

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. 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 24 illustrates the mapping of the thermal vulnerability of the archetype buildings in the social-housing estate.

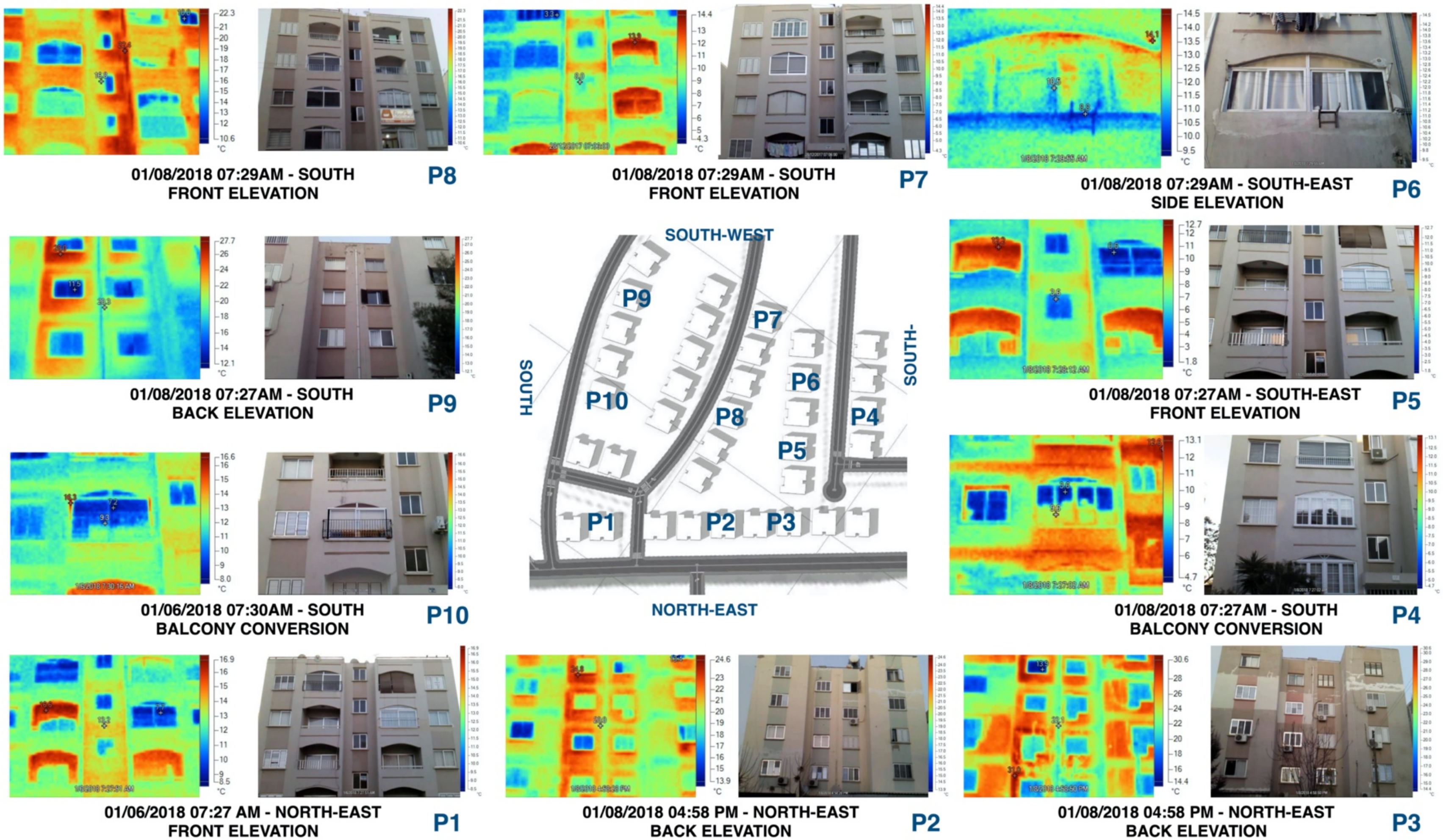
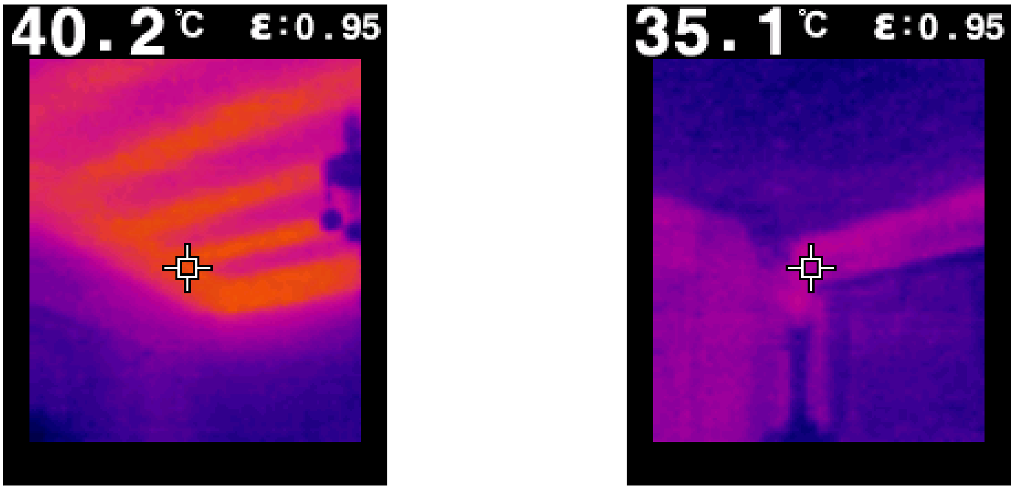


Fig.24. Point-by-point mapping of walk-through thermal-imaging survey conducted in winter 2017–2018, taking RTB orientations and impact of different time of day on overheating risk assessment into account.



(a) **(b)**

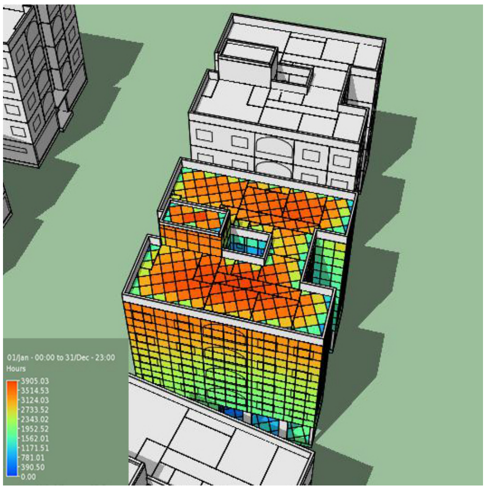
Fig.25. **(a)** High solar transmittance of ceiling surface of upper-floor flat (measurement recorded when all windows were closed); **(b)** heat acclimatisation of intermediate-floor living room space (measurement recorded when balcony door and two side windows were open).

Figure 25(a) shows the thermal performance of the living room ceiling surface of an upper-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 25(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. The results revealed that most south-oriented flats showed signs of significant thermal loss in the winter. It appeared that the RTBs inspected in the winter also demonstrated a greater risk of overheating in the summer. This walk-through site measurement method allowed us to identify the worst-performing RTB in order to conduct further calibration studies in the building-modelling phase of the study.

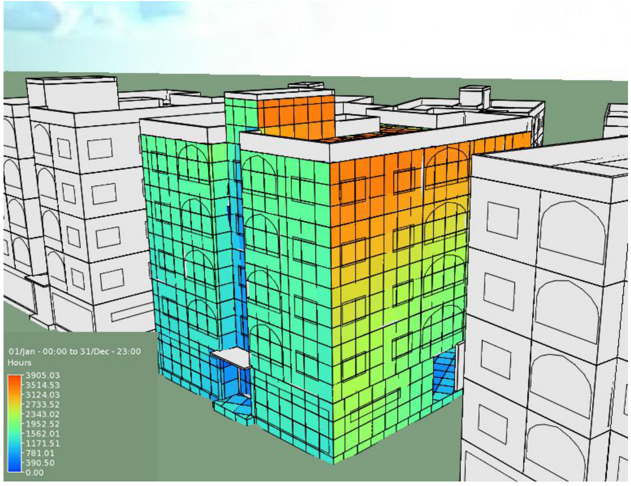
4.5. Building Performance Evaluation

4.5.1. Solar-Exposure Analysis

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. 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 model calibration. Figures 26(a) and (b) show the maximum solar radiation and mean values of the analyses that were adopted for the worst-case scenario of the south-facing RTB.



(a)



(b)

Fig.26. (a) High solar transmittance of roof surfaces and southeast-facing building envelopes; **(b)** 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 26(a) 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.

The southeast-facing façade depicted in Figure 26(b) 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 26(a) and (b), 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 (see **Video A**): 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.

4.5.2. Overheating Risk and Adaptive Thermal Comfort

The collated data is reported in this section, and an analysis and interpretation thereof are provided to explain the findings of the methodological approach that was developed to diagnose the thermal performance of existing housing stock by adopting the CIBSE TM59 international benchmarks to assess overheating risks. Indoor-environment conditions and the occupants' reported thermal comfort in the summer, which are delineated in Table 13, are analysed.

Table 13. Simulation-Based Thermal Comfort of Occupied Rooms in Baseline Model.

Occupied Spaces: Flat Location, Room Name	Temperature (°C)		RH (%)		PPD (%)	
	Max.	Min.	Max.	Min.	Max.	Min.
FIRST_FLOOR_Livingroom	36,2	23,0	100,0	26,6	100,0	13,1
FIRST_FLOOR_Bedroom1	35,2	23,0	100,0	25,9	95,6	11,7
FIRST_FLOOR_Bedroom2	36,2	23,0	100,0	24,6	98,9	10,9
FIRST_FLOOR_Bedroom3	35,2	23,0	100,0	26,0	93,5	11,3
INTERMEDIATE_FLOOR_Livingroom	35,2	23,0	100,0	25,8	97,6	12,5
INTERMEDIATE_FLOOR_Bedroom1	34,4	23,0	100,0	27,4	94,5	10,1
INTERMEDIATE_FLOOR_Bedroom2	35,4	23,0	100,0	25,6	98,9	10,1
INTERMEDIATE_FLOOR_Bedroom3	35,1	23,0	100,0	26,2	94,1	10,5
UPPER_FLOOR_Livingroom	36,4	23,0	100,0	26,2	100,0	12,8
UPPER_FLOOR_Bedroom1	35,3	23,0	100,0	25,7	98,0	11,7
UPPER_FLOOR_Bedroom2	36,1	22,3	100,0	24,7	99,1	7,6
UPPER_FLOOR_Bedroom3	35,6	23,0	100,0	25,4	96,4	11,1

*The PPD (i.e., percentage of people who found the room thermally uncomfortable) maximum limit value was 15%.

The performance of each occupied space on three different floor levels according to CIBSE TM59 benchmark Criteria 1 and 2 is delineated in Table 13. The upper-floor flat outperformed the flats on the other floor levels (see **Data set E**): It maintained indoor-air temperatures above 34,4°C in all rooms for the entire year and only exceeded this temperature when it reached 36,4°C, which was +1,4°C higher than temperatures recommended in Criterion 1. A 36,4°C peak temperature was observed in the upper-floor living room, while Bedroom 2 on the same floor experienced overheating with a recorded temperature of 36,1°C (see **Data set F**). Notably, all occupied spaces on all three floor levels exceeded the 33°C thermal-comfort benchmark temperature that is recommended for south-eastern Mediterranean countries (Bouden & Ghrab, 2005).

As it relates to Criterion 1, the representative flats exceeded the failure limits, with the upper-floor flat demonstrating the greatest signs of overheating; in this unit, the living room surpassed a 6°C increase-per-hour for a total of 115 days per year, and Bedroom 2 surpassed a 6°C increase-per-hour for a total of 77 days per year. Bedroom 1 in the first-floor flat exceeded a 4°C increase-per-hour for four and 11 hours each year, respectively, which indicates that this flat was thermally uncomfortable for a significant portion of the year. The results for the first and intermediate floors were similar with high predicted percent dissatisfied (PPD) levels for each occupied space.

It is important to highlight that in terms of Criterion 3, the bedrooms in each of the surveyed flats also exceeded a 4°C increase-per-hour during the simulated summer period. This can be attributed to the classification of bedrooms as 'night zones', since they are only occupied at night; in comparison, the living room was either partially or fully occupied at all times. When external temperatures rose above a certain point at night, the internal-heat gains were significant enough to increase the indoor-air temperature above $T_{upp.}$

4.6. Building Energy Optimisation

4.6.1. Passive Cooling Design Strategies

The model was set up to assess the performance of each dwelling in the south-facing case-study RTB under worst case scenario conditions. The profiles in this empirical study were set in the IES dynamic thermal-assessment platform as required for each zone to describe the temporal variations of the ventilation flow rates, cooling set-points, lighting usage and occupancy profiles. At the same time, the modular interface structure of the IES software makes it a flexible tool that can be employed for building-optimisation studies; which requires that these modular functions develop surrogate energy models to inform effective energy-use policymaking decisions. Utilising this software in combination with the DTS set input parameters such as the thermal-conductivity levels of different building materials, air-infiltration rates, internal heat gains (IHGs) and occupancy profiles assigned in the IES software, was found to be effective, as shown in Figure 27.

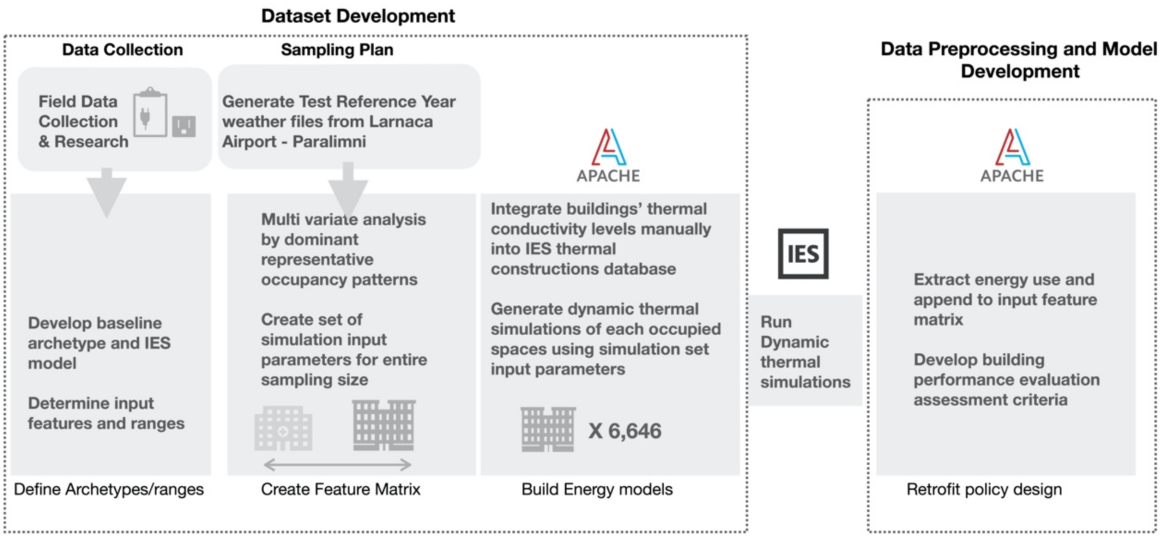


Fig.27. Inquiry strategy of DTS analysis using ApacheSIM software interface.

Simulating, investigating and optimising the energy performance of different building component structures revealed significant differences in cooling loads in the base-case RTBs (see **Data set G**). The results of the simulation of the existing performance for the representative units indicated that the largest share of heat loss came from air infiltration, uninsulated exterior walls and windows, which led to a high annual energy demand for cooling measures. The results of the simulations were analysed to better understand existing energy-use conditions and to calibrate the energy-consumption patterns, especially the cooling demands of the representative first-, intermediate- and upper-floor flats. The six retrofitting strategies, which are illustrated in Figure 28, were initially applied separately, then the obtained results were applied together to test the effectiveness of these strategies as a whole.

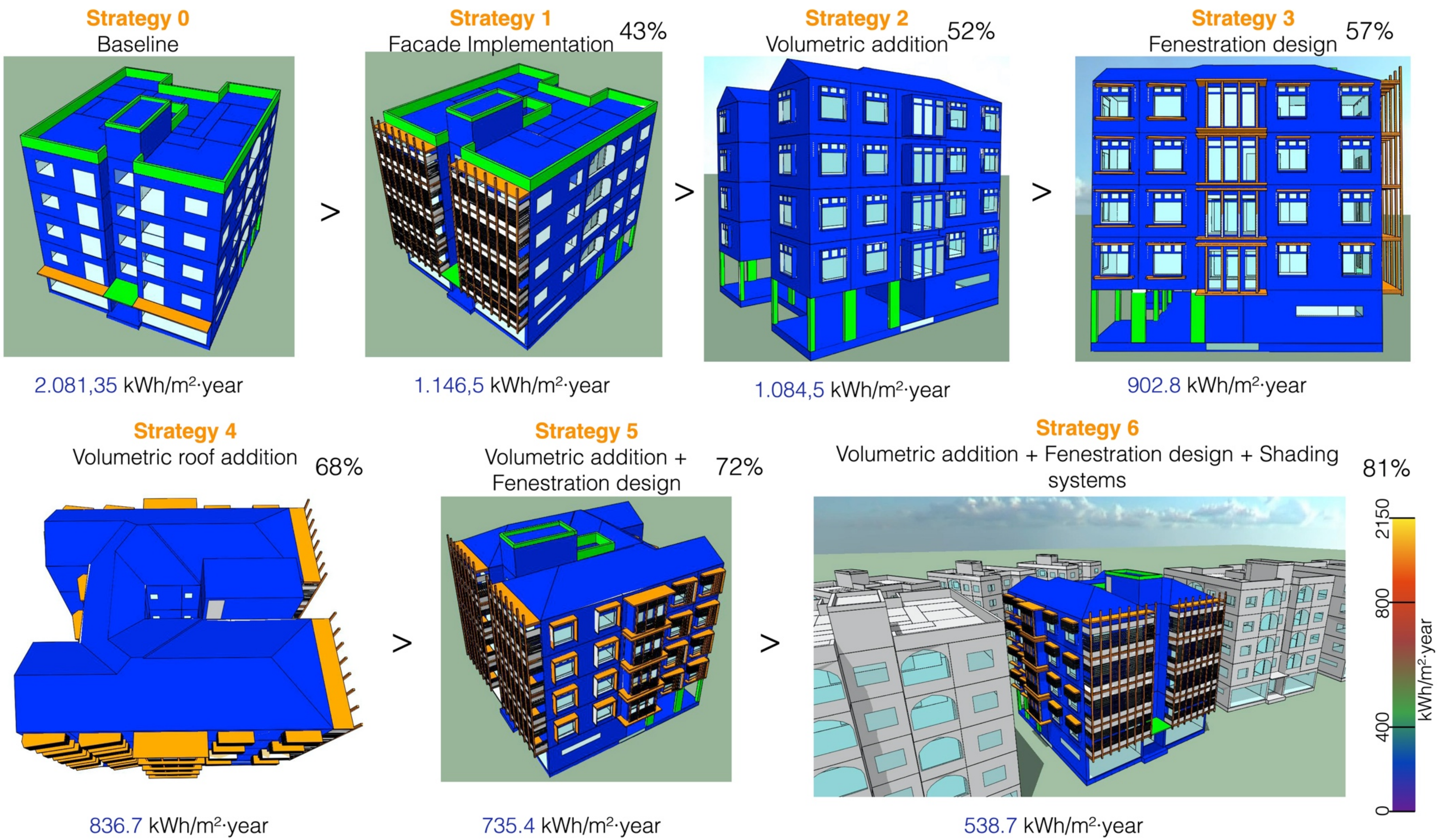
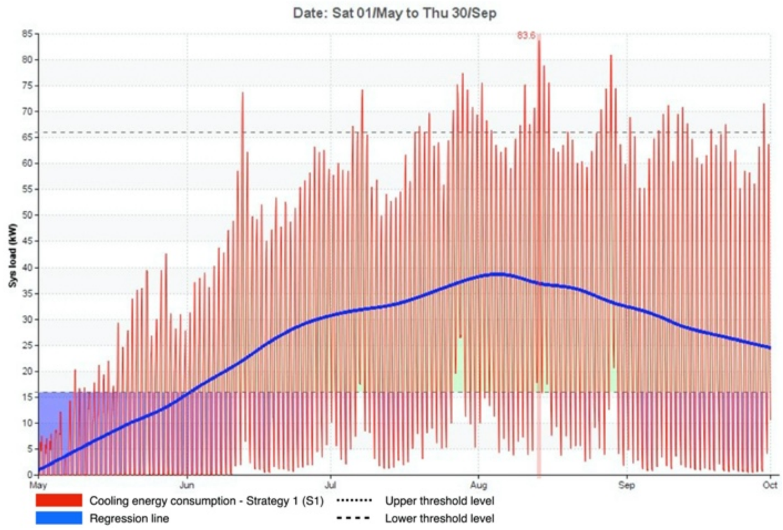


Fig.28. Schematic illustration of six strategies implemented to test design-strategy effectiveness.

4.6.2. *Energy Effectiveness of Retrofitting Strategies*

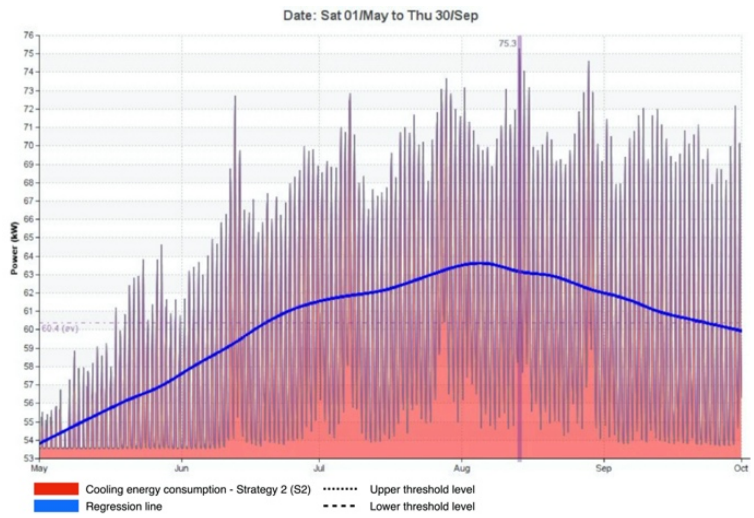
This section examines the impact and applicability of passive-cooling design strategies to retrofit base-case buildings, optimise the thermal comfort of occupants and reduce overheating risks in the summer. Figures 29(a) through (f) demonstrate the dynamic thermal simulation results for the energy effectiveness of PCDS.



(a)

Fig. 29. (a) Monthly cooling load of living room in worst-performing south-facing RTB in August reached maximum 83,6 kWh after implementing S1.

Following the implementation of Strategy 1 (see **Video B**), which is shown in Figure 29(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.

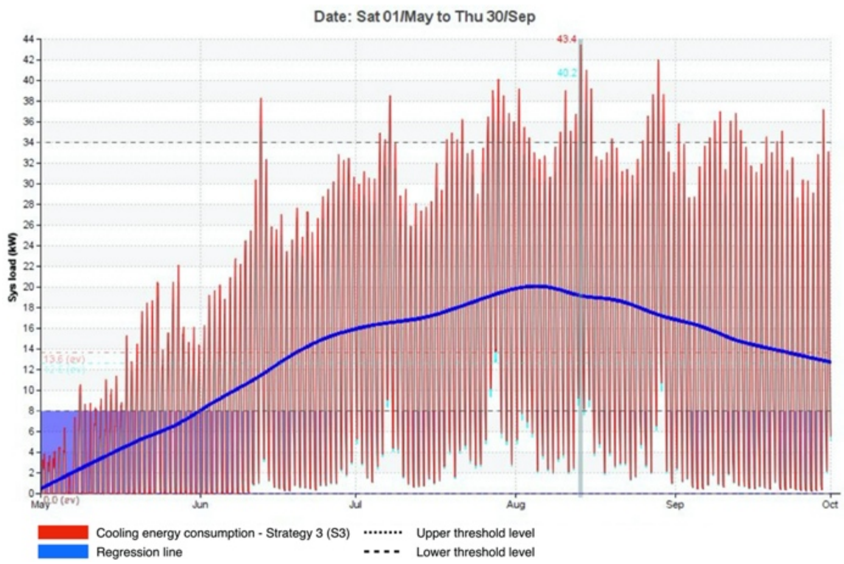


(b)

Fig. 29. (b) Monthly cooling load of living room in south-facing RTB in August peaked at 75,3 kWh after implementation of S2.

Figure 29(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. It should be noted that 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.

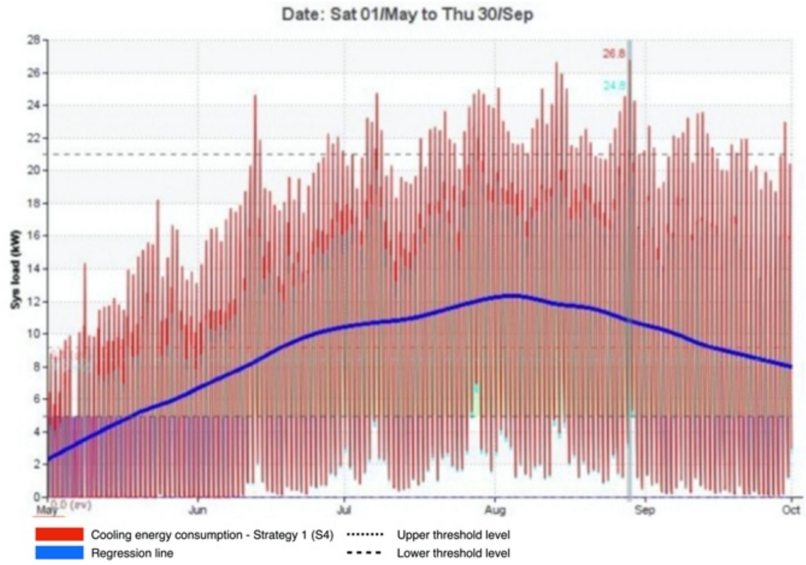
The aim of Strategy 3 and Strategy 4 was to provide sufficient natural ventilation to indoor spaces, which would then create an ‘air-buoyancy-driven’ natural ventilation effect whereby the accumulated indoor heat would be circulated into the outside environment, resulting in lower indoor-air temperatures. 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 29(c) and (d).



(c)

Fig. 29. (c) Monthly cooling load of Bedroom 1 in worst-performing south-facing RTB in August peaked at 43,4 kWh after implementation of S3.

As shown in Figure 29(c), 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.



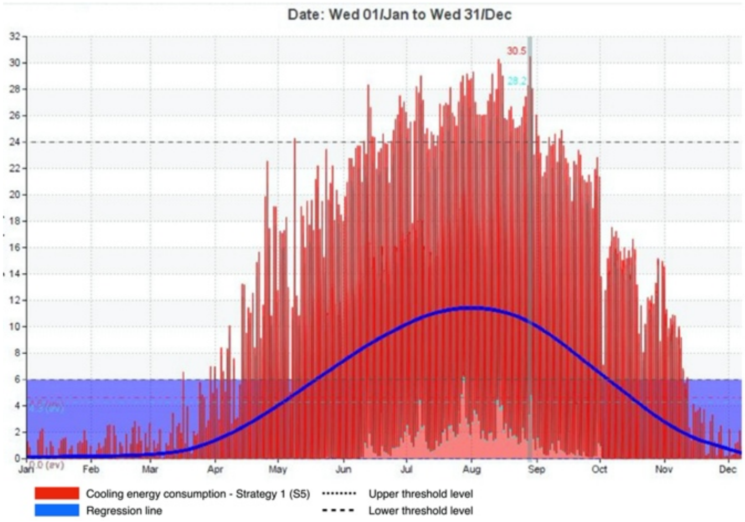
(d)

Fig.29. (d) Monthly cooling load of Bedroom 1 in worst-performing south-facing RTB in August peaked at 26,8 kWh after implementation of S4.

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 29(d), 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.

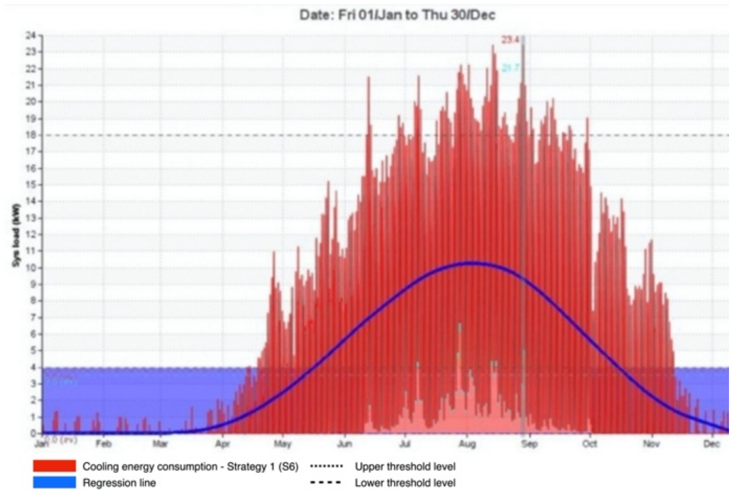
In Strategy 5, angular pine-wood vertical louvres were affixed midway down the length of the windows. This type of shading system absorbs the wind from different angles and promotes NV in indoor spaces. Moreover, this strategy reduces excessive incoming solar radiation. In Strategy 6, the living room 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 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.

Overall, an 81% reduction in cooling-energy consumption was achieved after the implementation of all six strategies (see **Video C**). 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.,* 2018). 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 29(e) and (f).



(e)

Fig.29. (e) Monthly cooling load in worst-performing south-facing RTB in August peaked at 30,5 kWh after implementation of S5.



(f)

Fig.29. (f) Monthly cooling load in worst-performing south-facing RTB in August peaked at 23.4 kWh after implementation of S6.

According to Figure 29(e), 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 29(f) 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.

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 (see **Data set H**)

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.

4.6.3. Life Cycle Cost Assessment of Retrofitting Strategies

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 14 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 14. 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

As shown in Table 14, 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. 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 15.

Table 15. 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.

5. Discussions

5.1. Implications for Energy-Policy Design

The study elucidated the potential applicability of passive-cooling design strategies in various retrofitting interventions to improve the energy efficiency of existing residential buildings (see **Supplementary Material C**). Figures 30(a) through (f) detail the energy use and carbon footprint of the PCDS that were implemented.

Energy Efficient Implementation Measures **Low Carbon Design Measures**

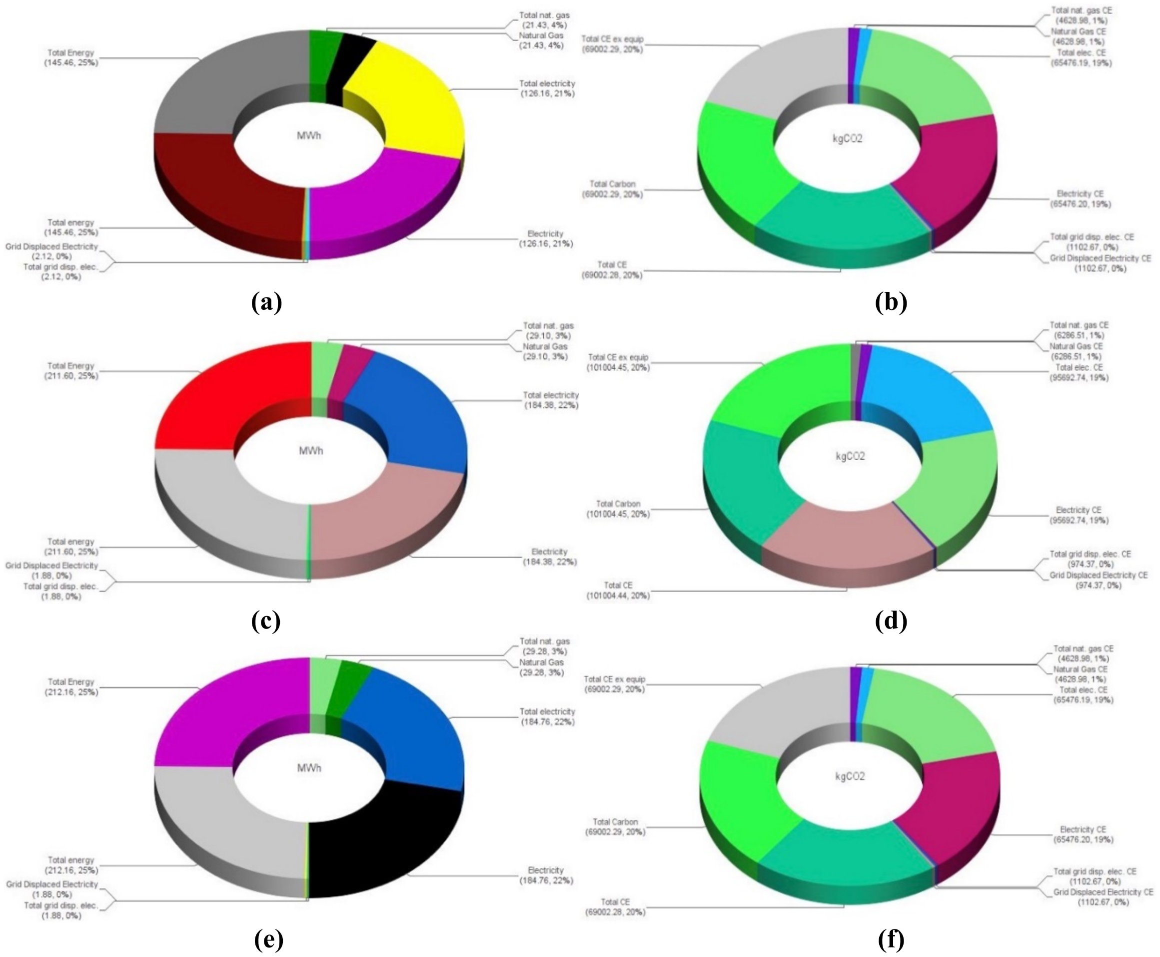


Fig.30. (a) Monthly electricity consumption of representative flat with low-occupancy profile (i.e., OP1); **(b)** overall first-floor CO_2 emissions; **(c)** monthly electricity use of intermediate-floor flat with medium-occupancy profile (i.e., OP2); **(d)** overall intermediate-floor CO_2 emissions; **(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 30(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 30(b).

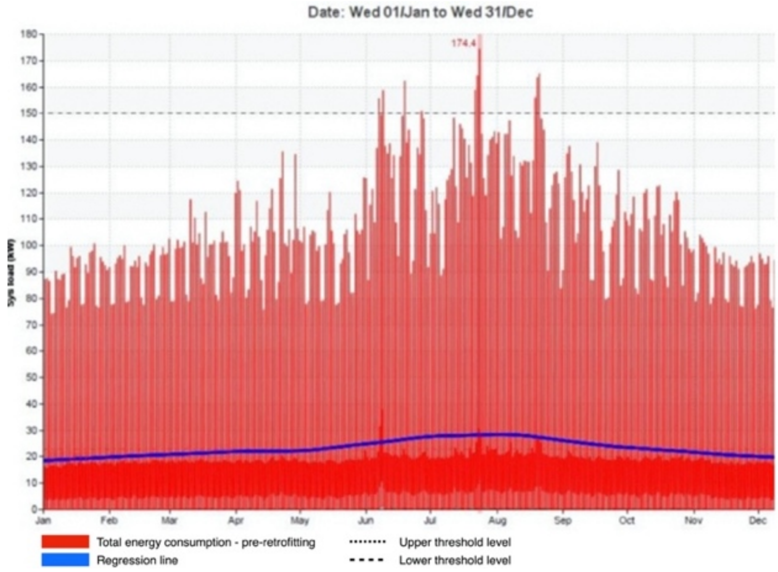
Total energy consumption in the intermediate-floor flat after implementation of all six PCDS, which is shown in Figure 30(c), was 211,6 kWh, total electricity usage was 184,38 kWh, actual household energy consumption peaked at 1.233,0 kWh, mean energy consumption was 374,58 kWh and the *SD* was 262,5 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 30(d), were reduced to 101.004,45 ppm.

Total energy consumption of the upper-floor flat, which is shown in Figure 30(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 30(f).

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.

5.2. Energy Performance

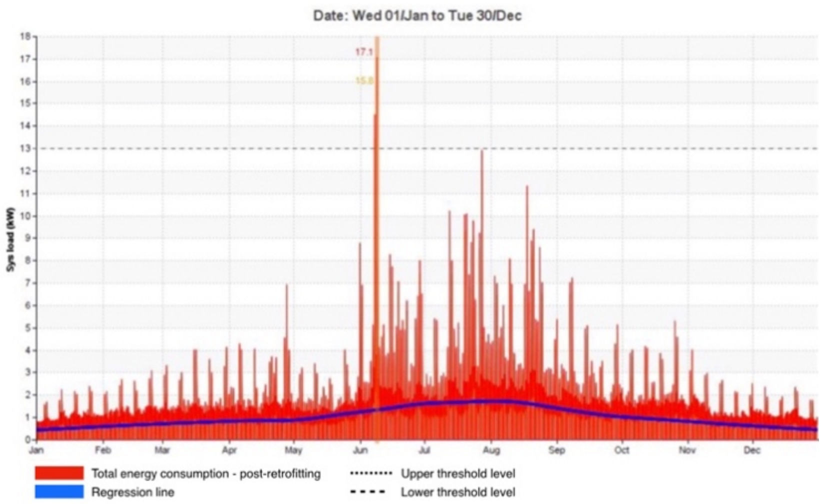
The simulation results were analysed to better understand existing energy-use conditions and to calibrate energy-consumption patterns, especially those related to the cooling demands of the representative first-, intermediate- and upper-floor flats. When examining energy consumption as it relates to 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 31(a) and (b) detail the overall energy performance of the three representative flats for the base-case scenario development.



(a)

Fig.31. (a) Total electricity consumption of representative base-case RTBs before retrofitting.

Energy consumption prior to the retrofittings, which is shown in Figure 31(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.



(b)

Fig.31. (b) Total electricity consumption of representative base-case RTBs after retrofitting.

According to peak cooling-energy consumption post-retrofitting, which is shown in Figure 31(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. Figures 32(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.

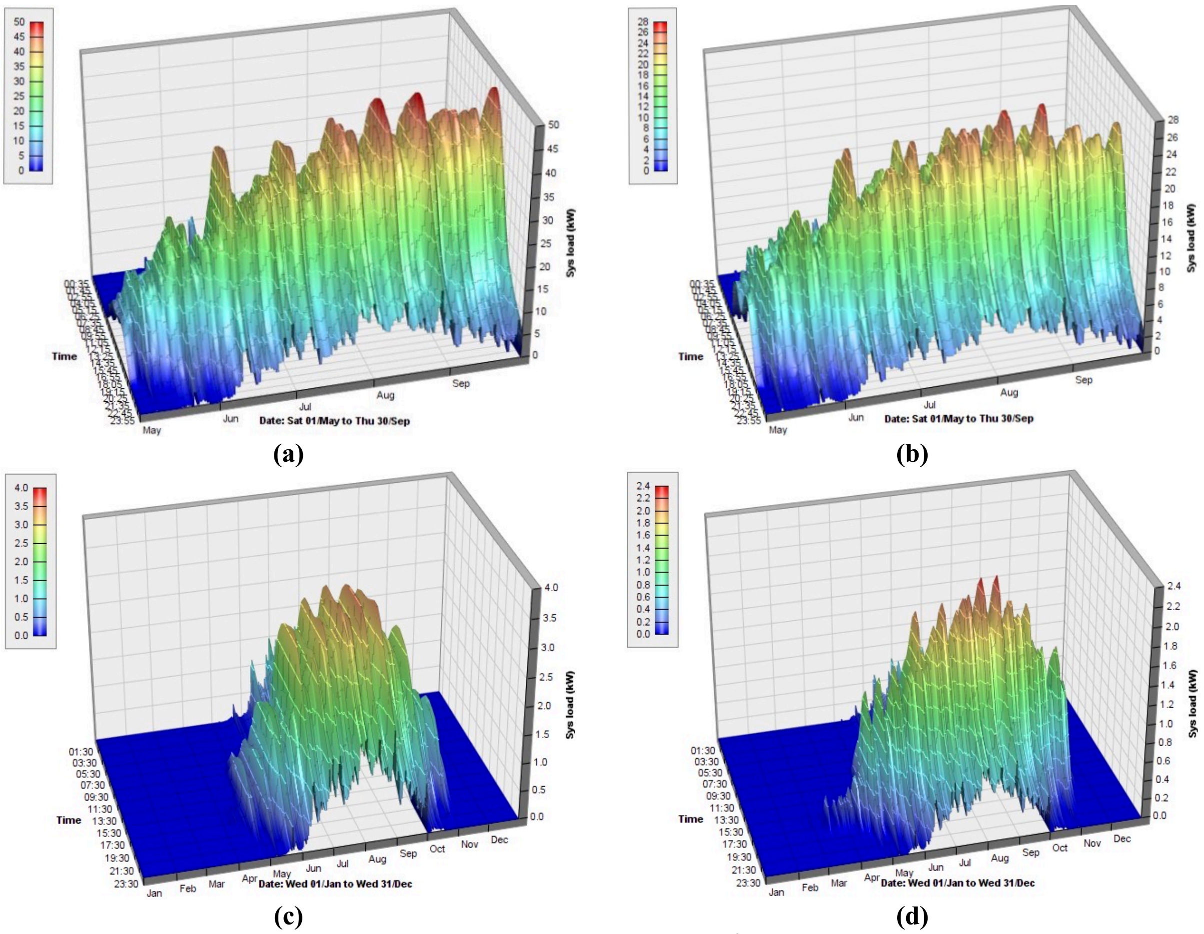


Fig.32. **(a)** Room-electricity plant-sensible loads reached 50 W/m^{2}K between May 1 and September 30 during pre-retrofitting phase; **(b)** decreased to 28 W/m^{2}K in August; **(c)** reached 4,0 W/m^{2}K during peak cooling season; and **(d)** decreased to 2,4 W/m^{2}K in August. ***Note:*** Statistical graphs demonstrate energy-fluctuation time series on typical day between May 1 and September 30.

As shown in Figure 32(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.

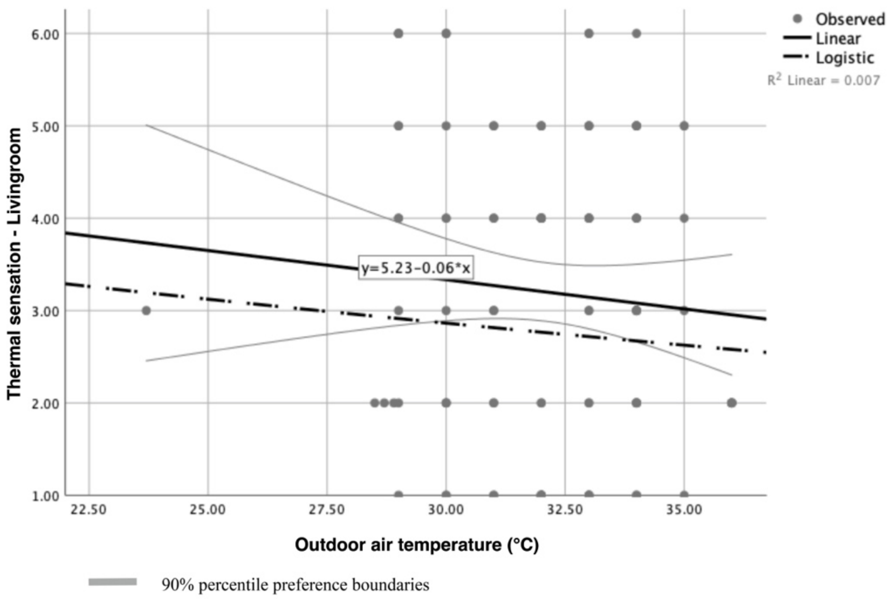
Figures 32(b) and (c) demonstrate the mean cooling-energy sensible load of the representative flats between January and December in the pre- and post-retrofitting phases. According to these results, when all six strategies were implemented onto the building envelope, the cooling-sensible load between May and September decreased from 4,0 kWh to 2,4 kWh.

Notably, the cooling-consumption pattern that is depicted in Figure 32(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 32(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.

5.3. Regression Forecasting of Outdoor Environmental Parameters

This section presents the results of households' TSVs plotted against the outdoor air temperature monitored concurrently with *in-situ* measurements across one hundred households recruited for the study. Figure 33(a) shows the mean TSVs plotted against operative temperature within each half-degree bin to find the thermal comfort zone in summer.



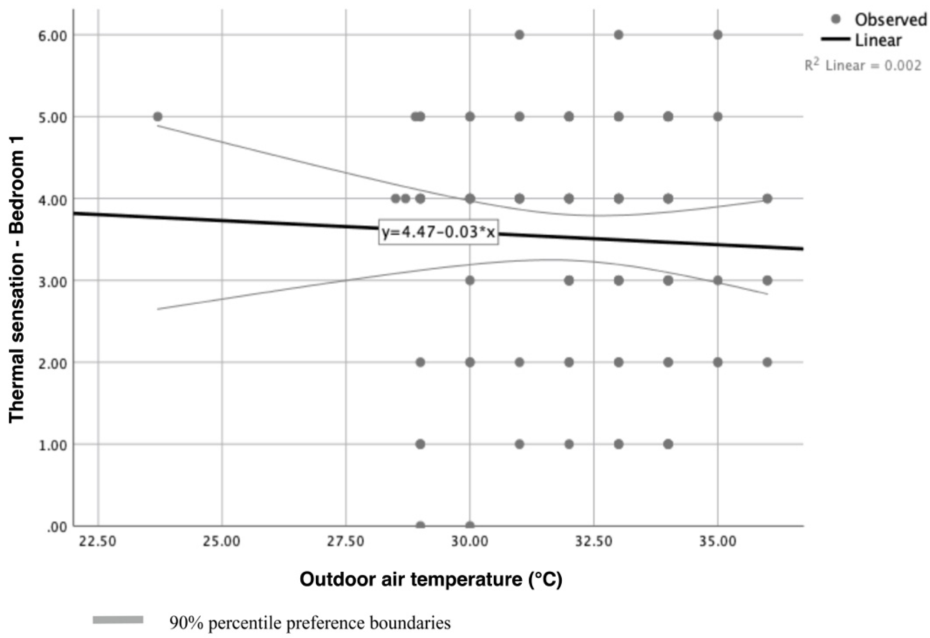
(a)

Fig. 33. (a) Relationship between occupants' thermal sensation in living room spaces and outdoor air temperature.

Figure 33 (a) shows the occupants' thermal comfort preferences calculated for their votes against the outdoor air temperature. The resulting regression line suggests a strong negative correlation between the thermal comfort preference votes and outdoor air temperature ($R^2 = 0.007$, $p < 0.001$), as the comfort preference temperatures showed significant variation amongst the occupants for the same outdoor running mean. However, the narrow 90% confidence intervals suggest that the slope of the line can be considered reliable (slope: y = 4.21 + 4.74E – 3*x). The regression line of the calculated Tcomf data was approximately +2 °C higher than the results of the adaptive comfort equation underlying the EN 15251 existing building category equations.

As can be seen in Figure 33 (a), 18% of respondents felt ‘too warm’ (To from 28 °C to 34 °C ± 3 °C and ± 9 °C), 23% felt ‘comfortably warm’ (To from 28 °C to 35 °C ± 3 °C and ± 10 °C) and 13% felt ‘comfortable’ (To showed patterns similar to ‘comfortable’), while 21% voted for feeling ‘comfortably cool’ (To fell from 23 °C to 35 °C ± 10°C), 17% felt ‘too cool’ (To fell from 28 °C to above 35 °C ± 3 °C and > ± 10 °C) and 8% felt ‘much too cool’ (To 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.

In the questionnaire, participants were asked, ‘How would you rate the overall quality of indoor environment for the bedroom 1 spaces in summer?’. Their responses were evaluated on the thermal sensation scale to assess their degree of thermal discomfort and predict acceptable comfort temperatures in summer. Figure 33 (b) shows the mean TSVs plotted against operative temperature within each half-degree bin in summer.



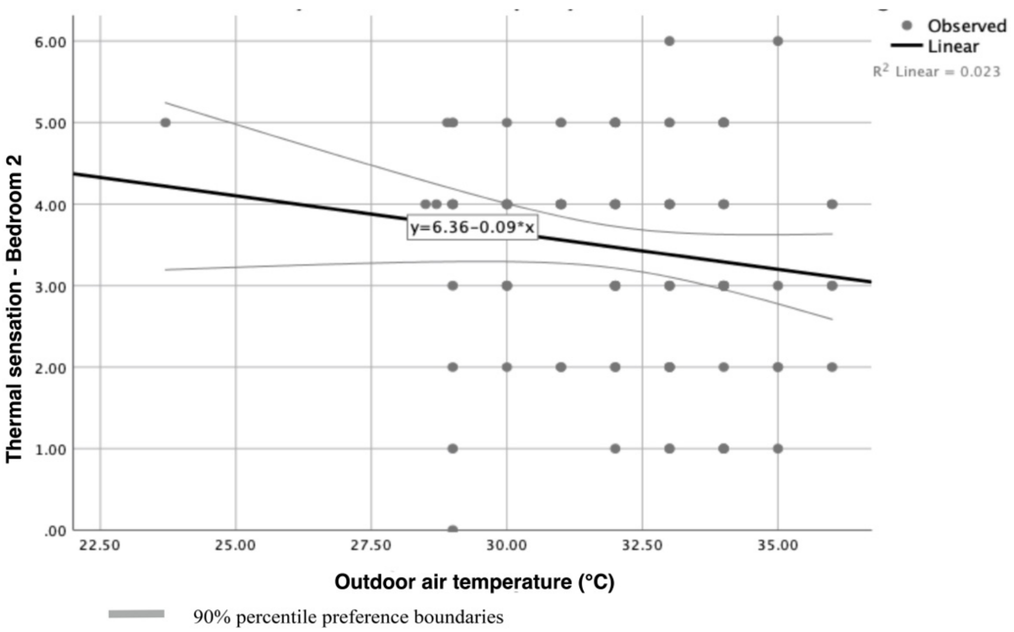
(b)

Fig. 33. (b) Relationship between occupants’ thermal sensation and the indoor air temperature in the bedroom 1 spaces.

A significant negative regression coefficient appeared between occupants’ thermal sensation and outdoor air temperature ($R^2 = 0.002$, $p < 0.001$). As shown in Figure 33 (b), 3% of respondents felt ‘much too warm’ (To from 31 °C to 35 °C ± 6 and ± 10), 9% felt ‘too warm’ (To from 28 °C to 35

°C ± 3 °C and ± 10 °C), 13% felt 'comfortably warm' (To from 28 °C to above 35 °C ± 3 °C and > ± 10 °C), 16% voted for feeling 'comfortable' (To from 30 °C to above 35 °C ± 5 °C and > ± 10 °C), 23% voted for feeling 'too cool' (Ta fell from 28 °C to 34 °C ± 3 °C and ± 9 °C) and 3% voted for feeling 'much too cool' (To from 28 °C to 30 °C ± 3 °C and ± 10 °C0. According to the linear regression equation, the thermally 'comfortable' indoor air temperatures in summer were from 26 °C to 28 °C when TSV regression equalled 4, and the thermally 'comfortably cool' outdoor air temperatures ranged from 23 °C to 35 °C. It is worth noting that the range was widened due to the adjustability of clothes in summer.

A quantitative scale ranking of data was collected on the participants' sensation towards their thermal environment by asking them, 'How would you rate the overall quality of indoor air environment for the bedroom 2 spaces in summer?' Fig. 33 (c) shows the mean TSVs plotted against operative temperature within each half-degree bin in summer.

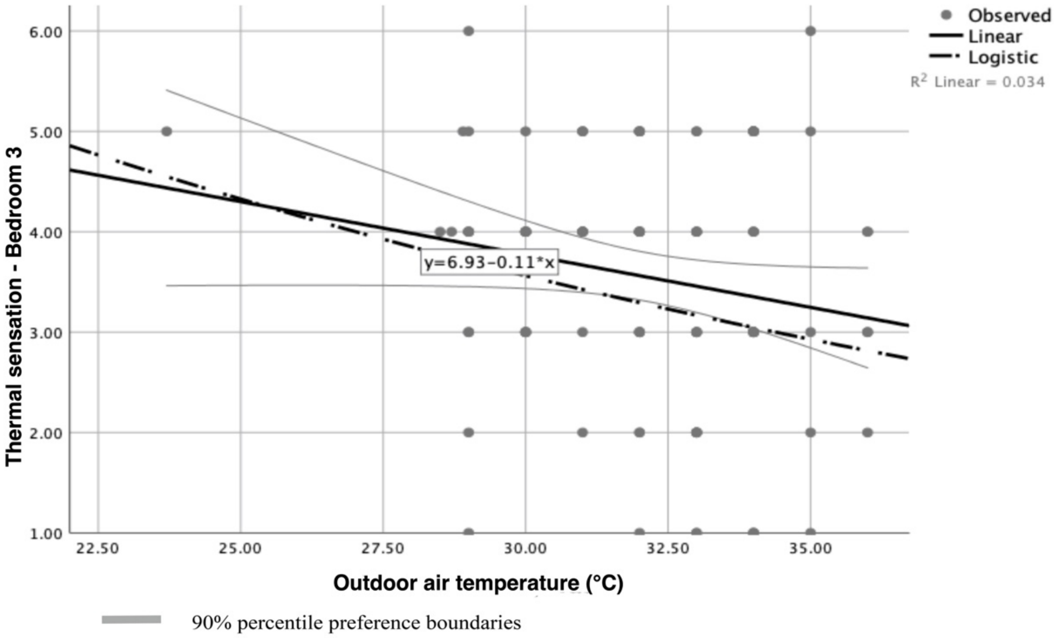


(c)

Fig. 33. (c) Relationship between occupants' thermal sensation and outdoor air temperature in bedroom 2 spaces.

Another negative and remarkably high regression coefficient appeared between occupants' thermal sensation and outdoor air temperature ($R^2 = 0.023$, $p < 0.001$). As shown in Figure 33 (c), 2% of respondents felt 'much too warm' (To from 33 °C to 35 °C ± 8 °C and ± 10 °C), 8% felt 'too warm' (To from 23 °C to 33 °C ± 8 °C), 14% felt 'comfortably warm' (To from 28 °C to above 35 °C ± 3 °C and > ± 10 °C), 22% felt 'comfortable' (To from 28 °C to above 35 °C ± 3°C and ± 10 °C), 32% voted for feeling 'comfortably cool' (similar to the pattern for the 'comfortable' sensation), 20% voted for feeling 'too cool' (To from 28 °C and 35 °C ± 3 °C and ± 10 °C) and just 1% voted for feeling 'much too cool' (To at 28 °C ± 3 °C).

In order to determine the optimum thermal comfort level in relation to a range of thermal sensations predicted by the PMV, participants were asked, 'How would you rate the overall quality of indoor air environment for the bedroom 3 spaces in summer?'. Figure 33 (d) shows the mean TSVs plotted against operative temperature within each half-degree bin in summer. The thermal sensation graphs were obtained by plotting participants' TSVs against the environmental parameters. The grouping was done so that it reflected a wide range of thermal sensations experienced by respondents rather than an arbitrary number.



(d)

Fig. 33. (d) Relationship between occupants' thermal sensation and outdoor air temperature in bedroom 3 spaces.

Another negative and strong coefficient was noted between occupants' thermal sensation and outdoor air temperature ($R^2 = 0.034$, $p < 0.001$). As shown in Figure 33 (d), 8% of respondents voted for feeling 'too warm' (To from 29 °C to 35 °C ± 4 °C and ± 10 °C), 11% voted for feeling 'comfortably warm' (To from 29 °C to above 35 °C ± 4 °C and > ± 10 °C), 25% voted for feeling 'comfortable' (similar to patterns for the 'comfortably warm' sensation'), 32% voted for feeling 'comfortably cool' (To from 28 °C to above 35 °C ± 3 °C and > ± 10 °C), 22% voted for feeling 'too cool' (To from 23 °C to 35 °C ± 10 °C) and 2% voted for feeling 'much too cool' (To from 28 °C to 35 °C ± 3 °C and ± 10 °C).

The study concluded that the proportion of people who wanted a drier indoor-air environment was expected to decrease with diminishing sensations of humidity, which indicates that relative humidity is a significant source of thermal discomfort in the summer. According to the Köppen climate classification system, the weather in Cyprus is subtropical (*Csa*) and partly semi-arid (*Bsh*), but the field study findings contradicted these world climate data due to the geological and topographical characteristics of the eastern Mediterranean Cyprus peninsula of Cyprus that served as the research context for this study.

The results reveal that a methodological approach can play a decisive role in the calibration of building energy performance. As such, this study predominantly lies within the STS approach, which highlights the importance of utilising an innovative methodology to upgrade the energy efficiency of buildings and implementing effective retrofitting interventions that are influenced by human actions. The energy-consumption reduction measures for social-housing estates developed in the course of this study will further benefit from a conceptual-level analysis and prioritisation in accordance with the climate characteristics of the regional context.

5.4. Roadmap to EU Energy-Policy Framework

Energy security has received increasing attention in EU academic and governmental circles due to shrinking fossil-fuel reserves in the North Sea, the closure of several power stations and increasingly frequent long-term heatwaves across the continental Europe in the past decade (Shariq & Hughes, 2020). Many of the current strategies that address energy security in the EU are directed at the provision side of the energy chain at the community scale or the local energy peak load reduction targets at building scale (Pallonetto *et al.*, 2020); measures and policies aimed at quickly reducing energy use through behavioural changes have been discussed to a lesser extent (D'Oca *et al.*, 2018). EU countries agree that the residential sector could significantly reduce GHG emissions in cost-effective ways (Annibaldi *et al.*, 2019). The potential for retrofitting existing housing stock is due to steadily improving technological innovations in this field, and the EPBD directives introduced guidelines that attempted to enhance energy efficiency and to develop energy-efficient technologies (Cornelis, 2019; Cunha *et al.*, 2020; Li *et al.*, 2019).

In Europe, there are currently a variety of statutory and non-statutory subsidisation schemes to upgrade the energy efficiency of existing housing stock and develop a methodologically planned framework to conduct building-performance evaluations (BPEs) at the conceptual and policy levels during the decision-making process (Bergman & Foxton, 2020; Fokaides *et al.*, 2016; Serghides *et al.*, 2016; van Middelkoop *et al.*, 2017). As it relates to energy efficiency in the residential sector, the European Commission and Parliament Delegated Regulation 244/2012 recommends supplementation of EPBD standards with an effective energy-policy framework to calculate a cost analysis of the minimum energy-performance requirements for buildings and building services (EPISCOPE, 2016). The most important energy-related legislative tasks to emerge from the EU were the EPBD mandates, which improved household energy efficiency and reduced CO_2 emissions (Betto *et al.*, 2020; Franke & Nadler, 2019); this directive requires that all EU countries implement effective plans and feasible scenarios to update their building regulations and introduce EPCs.

The 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. This novel benchmark criterion could radically change the manner in which calibration 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, as shown in Figure 34.

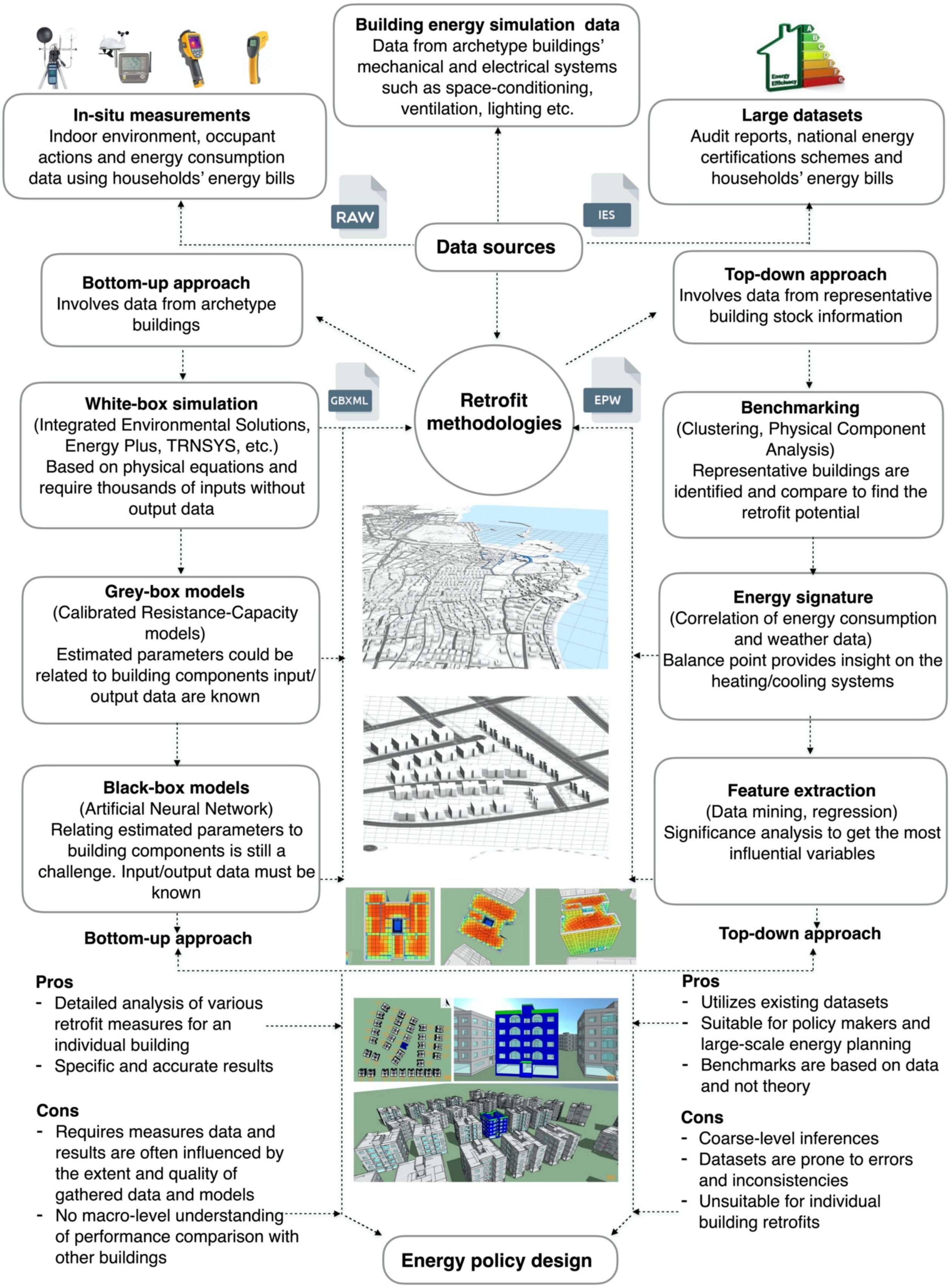


Fig.34. The developed STS conceptual framework for the retrofit energy policy design.

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. Conclusions

In this 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.

Accordingly, this 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 were collected through a comprehensive methodology, which was then applied to the RTB prototypes, which will contribute to the limited number of published reviews related to retrofitting efforts for high-density residential buildings in Europe. The study explored the reason the building-energy-performance evaluation method was chosen, utilised a standardised assessment procedure to calibrate actual energy use and assessed the study findings against existing international thermal-comfort benchmark criteria.

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 top-floor flats and had a significant effect on the OTs of all the flats.

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 between 24,5–37,0°C. According to the CIBSE TM59 Criterion 1, the upper thermal-comfort limit for this region is 33°C, yet the *on-site* monitoring recorded a maximum outdoor temperature of 38,7°C, and the *in-situ* measurements revealed indoor-air temperatures that ranged between 25–35,0°C, which is well above the acceptable threshold limits.

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 28,5–36,5°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.

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 calibrations 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

Declaration of Competing interest

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

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CRediT authorship contribution statement

Bertug Ozarisoy: Writing – original draft, Conceptualisation, Methodology, Investigation, Writing – review & editing. **Bertug Ozarisoy** conducted the field surveys, computational analysis, analysis of the numerical experiments and the designing of retrofit strategies; and **Bertug Ozarisoy** provided sources (e.g. illustrations, tables, datasets and videos), comments, and major edits to the paper. **Prof. Hasim Altan** involved in the development of Methodology for the paper. He checked the technical merits and accuracy of data interpreted in Results and Discussions (sections 4 and 5). **Prof. Hasim Altan** checked the raw data set and simulation set input parameters of dynamic thermal simulations due to his expertise on the simulation software suite used for the study. He also provided necessary advice and guidance for the architectural design interventions developed as an outcome for the study. **Prof. Hasim Altan** wrote the Conclusions (section 6).

Graphical Abstract

Graphical abstract to this article can be found online at –The Graphical abstract illustrates the adopted and developed comprehensive methodological design approach for the study.

Video

Video A - It demonstrates the outdoor heat temperature fluctuations on the performance of building fabric before implementing energy conscious retrofit interventions for building optimization.

Video B - It shows the implementation of external wooden shutter systems on those opaque window surfaces to reduce impact of solar radiation throughout the year.

Video C - It illustrates all strategies applied on building envelopes without changing the existing state of the building.

Supplementary Material

Supplementary data to this article can be found online at –

Supplementary Material A – The questionnaire survey proforma **-** An investigation of cooling energy consumption patterns of households and Thermal comfort.

Supplementary Material B – Occupancy profiles.

Supplementary Material C – Retrofitting design strategies

Data set

Data Brief to this article can be found online at –

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

Data set B: The raw data of analytical energy model was constructed in the IES, including gbxml. file for other scholars' further research work.

Dataset set C: Questionnaire survey – script.

Dataset set D: Reasons for thermal discomfort – script.

Data set E: The results of overheating risk assessment of each flats in the RTBs.

Data set F: The results of indoor air temperature of each occupied space from the DTS analysis.

Dataset set G: The results of cooling energy use of each flats in the RTB.

Data set H: The results of percentage of people dissatisfied.

Appendix A.1

Table A.1. Construction Materials Assigned Into Simulation Model.

Construction type	Element details	U-value W/m^2K	R-value m^2K/W	Thickness mm	Mass kg/m^2	Thermal mass kJ/m^2K
External walls	External rendering + plasterboard + stucco + common brick	3.47	0.11	25	41.13	23.5
Internal walls	Plasterboard + brickwork	3.18	0.07	25	30.0	17.0
Roof	Asphalt mastic roofing + concrete deck	3.40	0.13	200	472.5	240.0
Floor	Reinforced concrete + chipboard flooring	2.82	0.19	120.0	240.0	108.0
Window	Outer pane + cavity + clear float 10 mm	5.20	0.82	-	-	-
Ceiling	Chipboard flooring + reinforced concrete	2.31	0.19	120.0	240.0	138.0

*Window – inner pane net U-value (including frame) 5.20 W/m^2 K, net R-value 0.18 m^2 K/W, U-value (glass only) 5.27 W/m^2 K, g-value 0.82 m^2 K/W

Appendix A.2

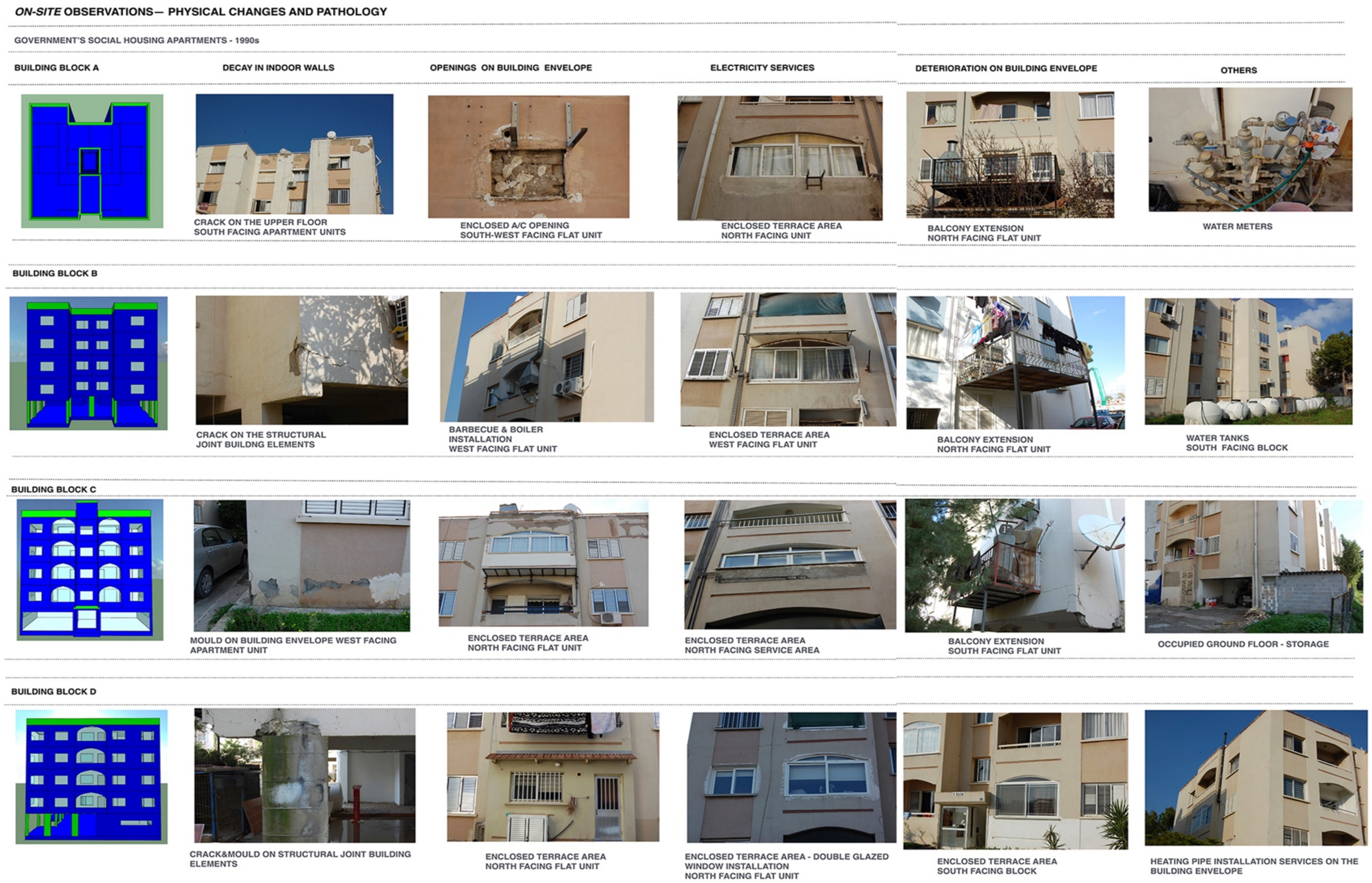


Figure A.1. Building deteriorations observed in base-case RTBs.

Appendix A.3

Table A.2. Synthesis of Achievable Results of Each Strategy and Those of Base Case.

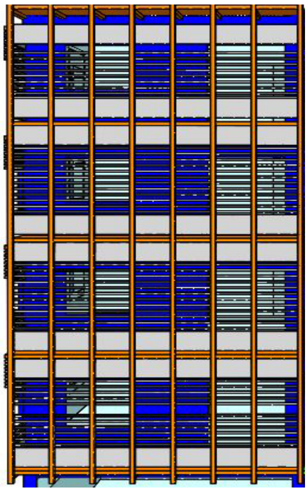
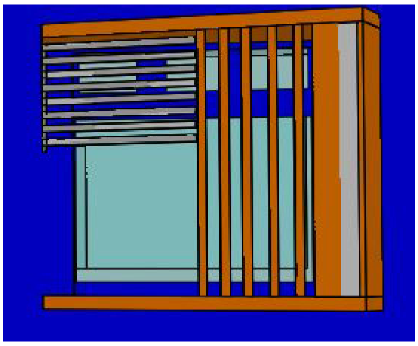
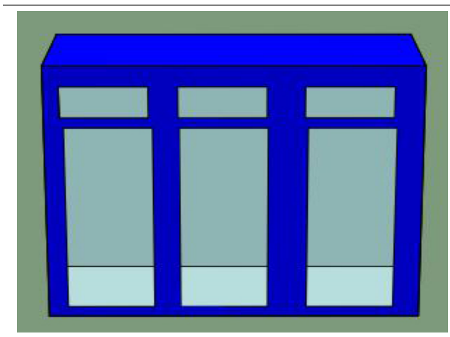
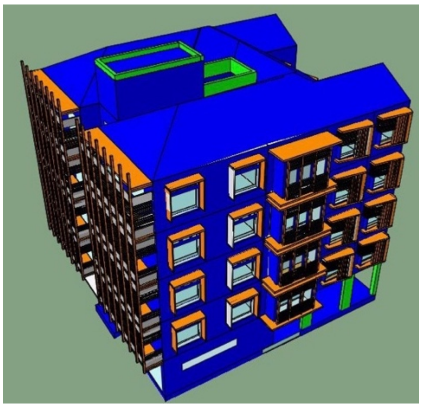
<table>
<tr><td rowspan="5"></td><td colspan="4">Strategy 1 (S1): Fixed-blade sunscreen façade implementation</td></tr>
<tr><td colspan="4">Description:
Outdoor solar shading; most effective for RTBs with south and west orientations; more frequently applied to residential buildings. Pre-oriented blades affixed to the façade; can also be applied to balconies. Blades can be vertical.</td></tr>
<tr><td>Energy-performance total</td><td>1.146,5 kWh/m^2</td><td>Savings</td><td>43%</td></tr>
<tr><td>Strengths</td><td colspan="3">Lower cost; single interventions are allowed; reduced construction time</td></tr>
<tr><td>Weaknesses</td><td colspan="3">Less effective; thermal bridges are not avoided</td></tr>
<tr><td rowspan="5"></td><td colspan="4">Strategy 2 (S2): Venetian blinds or brise-soleil louvres volumetric addition</td></tr>
<tr><td colspan="4">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.</td></tr>
<tr><td>Energy performance total</td><td>1.084,5 kWh/m^2</td><td>Savings</td><td>52%</td></tr>
<tr><td>Strengths</td><td colspan="3">Effective</td></tr>
<tr><td>Weaknesses</td><td colspan="3">Longer construction time; greater cost; comprehensive intervention is required</td></tr>
<tr><td rowspan="5"></td><td colspan="4">Strategy 3 (S3): Overhanging fenestration design</td></tr>
<tr><td colspan="4">Description:
Fixed opaque overhang made of different materials; consists of horizontal and vertical elements in a grate pattern.</td></tr>
<tr><td>Energy performance total</td><td>902,8 kWh/m^2</td><td>Savings</td><td>57%</td></tr>
<tr><td>Strengths</td><td colspan="3">Effective; single interventions are allowed; reduced construction time</td></tr>
<tr><td>Weaknesses</td><td colspan="3">Complex design</td></tr>
</table>

Table A.2. Synthesis of Achievable Results of Each Strategy and Those of Base Case (Continued)

	**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.			
	Energy performance total	836,7 kWh/m^2	**Savings**	68%
	Strengths	Effective; single interventions are allowed; reduced construction time; increases usable floor area		
	Weaknesses	Complex design; higher construction costs		
	**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.			
	Energy performance total	735,4 kWh/m^2	**Savings**	72%
	Strength	Reduced cooling-energy consumption; optimised thermal comfort; effective; flexible interventions are allowed		
	Weakness	Longer construction time and higher costs; comprehensive intervention is required		

*Base-case energy consumption in the peak cooling month of August was 2.081,35 kWh/m^2

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Declaration of interests

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

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

To the readers' information:

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

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