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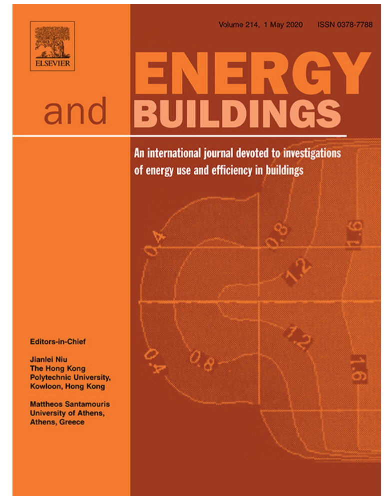

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B. Ozarisoy, H. Altan

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Bridging the energy performance gap of social housing stock in south-eastern Mediterranean Europe: Climate change and mitigation

Ozarisoy, B.[1,*], Altan, H.[2]

[1] PhD Researcher, Graduate School, School of Architecture, Computing & Engineering, University of East London (UEL), London, E16 2RD, United Kingdom
[2] Professor, Department of Architecture, Faculty of Design, Arkin University of Creative Arts and Design (ARUCAD), Kyrenia, 99300, Cyprus (via Mersin 10 Turkey)

*Corresponding author e-mail address: ozarisoybertug@gmail.com
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Abstract

Sustainable Development Goal #7 calls for "access to affordable, reliable, sustainable and modern energy for all." Scientific evidence is growing that greenhouse-gas emissions have a noticeable effect on the earth's climate. Many purpose-built post-war social housing estates in Europe that form high-density residential-tower blocks, however, do not meet current stringent energy-efficiency standards. As a result, many of these structures are under threat of overheating and require careful planning to implement holistic energy subsidisation schemes. This article presents a setup of building energy performance framework that was developed according to the *in-situ* measurements of building-fabric thermal structure to asset robust energy performance evaluation and certification schemes in the residential sector. This empirical study examines social householders' electricity reliability in accordance with assessing overheating risk of housing stock in South-eastern Europe where the weather is subtropical (*Csa*) and partly semi-arid (*Bsh*). It also investigates the gap between as-designed and as-built energy performances. The findings for thermal anomalies resulted from air infiltration through the building fabric, and a lack of natural ventilation through living spaces and excessive heat gains through sizeable and glazed areas. On a typical hot summer day, the internal temperatures of the simulated condominiums remained high throughout the day and night, ranging from a minimum 28.5°C to a maximum 36.5°C. Insights from this empirical study improve the national energy network and subsidisation schemes in Europe. The energy policy and regulations would benefit from conceptual level analysis and planning prioritisation in accordance with the climate characteristics of each EU-27-member state.

Keywords: Building performance evaluation; Climate change; Energy efficiency; Energy use; Energy modelling; South-eastern Mediterranean

Nomenclature	
Csa	Subtropical
E	Energy (kWh/m^2)
EUI	Energy use intensity ($MJ/ m^2 /year$)
h	Equation parameter
h^{-1}	Air infiltration rate
M	Thermal conductivity coefficient (kJ/m^2K)
R	Heat absorptivity coefficient (m^2K/W)
Tmax	Maximum temperature
Top	Operative air temperature
Trm	Weighted mean of the daily mean outdoor air temperature
Tupp	Upper limit of threshold temperature
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
ASTM	American Society for Testing and Materials
BS	British Standards
BES	Building energy simulations
CIBSE	Chartered Institution of Building Services Engineers
CEN	Comité Européen de Normalisation
DBT	Dry Bulb temperature
DTS	Dynamic Thermal Simulation
EA	Electricity Authority
EEI	Energy Efficiency Implementation
EEM	Energy-efficiency measures
EPBD	Energy Performance of Buildings Directives
EN	European Norm
EU	European Union
EUI	Energy Use Intensity
FLIR	Forward-looking infrared thermometer
IES	Integrated Environmental Solutions
IPCC	Intergovernmental Panel on Climate Change
IRT	Infrared radiometer thermography
IR	Infrared Radiometer
PCRD	Passive cooling retrofitting design strategies
PEM	Passive energy measures
PPD	Predicted Percentage of Dissatisfied
PMD	Predicted Mean Vote
RESNET	Residential Energy Services Network
RoC	Republic of Cyprus
RTB	Residential tower block
SAR	Suggested acceptable range
SD	Standard deviation
TPV	Thermal preference votes
TRY	Test Reference Year
TRNSYS	Transient System Simulation Tool
TSV	Thermal sensation votes
UHI	Urban heat island

1 Introduction

Efforts to retrofit existing residential buildings have gained increasing momentum in the last several years, especially after the European Union (EU) called for a zero carbon-emission target by 2050 [1]. The emerging issue of climate change and the increasing energy consumption in cities highlight the importance of optimising the thermal performance of buildings to avoid high winter energy bills [2]; the number of households has also increased by 46% since 1970, and it appears that this trend will accelerate in the coming decades [3]. Furthermore, heating and cooking in the domestic building sector are responsible for more than 15% of overall CO_2 emissions in the Republic of Cyprus (RoC), and this segment experienced a 3.6% increase in energy consumption from 2015 to 2016 [4].

The 2014 Intergovernmental Panel on Climate Change (IPCC) reported that, since 1900, urbanisation has led to a 0.006°C increase in temperatures each decade and that the global and ocean record has shown a 0.002°C increase over the same period [5]. Research into overheating experienced during the summer period as a consequence of climate change has found variations in average air temperatures (i.e., warming) and an increase in extreme temperature events that threaten people's health and well-being. Specifically, Giorgi claimed that the Mediterranean region is at risk of becoming one of the most prominent climate-response hotspots due to frequent long-term heatwaves that have been recorded in the last few decades [6]. A study by Kovats et al., which examined the effects of climate change in southern Europe, revealed that average temperatures in Europe have increased at different regional and seasonal warming rates, with a decadal average land-area temperature for 2002–2011 that was 1.3°C ± 0.11 higher than the 1850–1899 average [7]. These results were confirmed by data provided in the 2020 regionalised IPCC report for Europe.

To assess the effect of human activity on the climate, Ulbrich et al. compared Mediterranean climate variability by considering the atmospheric and ocean temperatures from 1951 to 2005 and found statistically significant increases in Mediterranean summer temperatures and a reduction in winter precipitation in densely populated cities and metropolitan regions [8]. The study also found that the Mediterranean Sea warmed by approximately 0.1°C per decade during 1951–2000, accompanied by a rapid increase in air temperature, with the fastest trend—up to 0.2°C per decade by mean summer temperature—occurring over the eastern Mediterranean and the western portion of North Africa [9].

An analysis and discussion of the subject by Kovats et al. noted that high-temperature extremes in Europe (i.e., hot days, tropical nights and heatwaves) have become more frequent since 1950 and that low-temperature extremes (i.e., cold spells and frosty days) have become less frequent on average during the same period [7, 10]. Similarly, an analysis by Barripedro et al. found that mega-heatwaves, such as those in 2003 and 2010, broke 500-year seasonal temperature records over nearly 50% of the European continent [11].

These climate change indicators have led many scholars to recognise multiple 'truths' and validate several different approaches, which has resulted in a proliferation of alternative ontological and epistemological positions to consolidating energy use and creating climate-resilient residential buildings in the future, and a wide range of possible emission scenarios to assess future climate change impacts have therefore been examined in scholarly studies in this field [12, 13]. A thorough review of these studies shows that differing climate models are in significant agreement regarding warming trends throughout Europe for all emissions scenarios; these studies have also found that vulnerable households living in post-war social housing estates experience significantly higher indoor air temperatures because of deficient building fabrics [14].

The study detailed a model that can be employed to investigate a range of building performance evaluation methods related to housing-energy consumption and to address issues associated with overheating risks experienced during the summer; as such, the research design and methodology of the study aims to enhance policymakers' understandings of the complex nature of energy consumption and occupant thermal comfort. The developed framework provides a scientific background that can be included in the BES platform to serve as a set of guidelines from the EPBD scientific committee for energy-policy design. The study findings can be extrapolated by current industry benchmarks or assessment criteria as a new European Norm that can be adopted by other EU countries.

This paper reviews an integration of infrared thermography and building-energy simulations (BES) that aims to develop a novel methodological framework for building diagnostics. This is the first research to assess the energy performance and thermal conductivity levels of buildings and the impact thereof on overheating risk assessments, and it offers a roadmap to upgrading the energy efficiency of social housing stock and demonstrates how EU objectives work to regulate the housing sector in order to improve policies and practices. The studies included in this paper suggest that enhanced energy efficiency might not be immediately implemented by the construction sector, contrary to what policymakers have anticipated. Previous scholarly research has also determined that overheating is linked to household occupancy and behavioural patterns, which has been corroborated by evaluating the building performance of case-study locations, as presented in Tables 1 (a) and (b).

Table 1a
Pilot studies that evaluated building-performance.

References	A. Location and Climate	B. Climate-Change Scenarios	C. Methodology	D. Housing and Occupant Characteristics
[15]	Adelaide, Australia (BSk): Mild temperate climate	Investigated current TMY climate and future TMY for 2070 CC scenario	Energy modelling (AccuRATE); best design based on minimum heating- and cooling-energy consumption	- Entire Australian population was targeted - Multi-family residences - Brick-veneer house (typical house design in Australia)
[16]	Brisbane, Australia (Cfa): Subtropical climate (hot and dry in the summer)	Reviewed data for heatwaves in 2004 and data related to air temperatures, air pollutants and health outcomes for period of 2001–2003	Energy modelling (AccuRATE); cooling and heating; base house and modifications with 2.5–7-star energy rating—utilised regression model to explore correlations between air temperatures and occupant health and wellbeing	- Detached brick-veneer residential house - Façades (U=0.75 W/m^{2}K) - Concrete roof tiles - Simple glazing - Holland blinds - Heating set points: 20°C in the living room and 18°C in the bedroom - Cooling set points vary from 23.0–26.5°C
[17]	Brisbane, Australia (Cfa): hot and dry Melbourne, Australia (Cfb): warm summer	Reviewed data for heatwaves in 2004	Energy modelling (AccuRATE); heatwave scenarios for Brisbane (2004) and Melbourne (2009)	Conventional single-family house without air conditioning. Steady-state analysis of standardised occupancy profiles
[18]	Adelaide, South Australia (BSk) – Subtropical cold and arid	Reviewed data for heatwaves in 2004	Online survey undertaken with representative sample ($N = 393$); Chi-square, Fisher's exact test and Fisher–Freeman–Halton exact test statistical analyses undertaken; Wilcoxon test performed	Vulnerable population living in energy poverty was targeted. - 90% dwellings with cooling systems (entire dwelling or a single room) - 25% rooms without shading - Most were without insulation and with light mass external walls
[19]	- Athens, Greece (Csa) - Lisboa, Portugal (Csa) - Rome, Italy (Csa) - Munich, Germany (Cfb) - London, England (Cfb) - Moscow, Russia (Dfb)	Reviewed climate-change projections for 2020, 2050 and 2080 (CCWorldWeatherGen)	Energy modelling; overheating (CIBSE). - Criterion 1: Hours of exceedance (3%) - Criterion 2: Daily weighted exceedance - Criterion 3: Upper-limit temperature	Mid-storey south- and east-facing flats - U-value (wall) = 0.18 W/m^{2}K - U-value (glass) = 1.4 W/m^{2}K - Pattern-of-use = 24 h^{-1} - Ventilation rate: 0.3–1.0 h^{-1} - Night ventilation - Interior blinds - Multi-family residents

Table 1b
Pilot studies that evaluated building-performance (Continued).

References	A. Location and Climate	B. Climate Change Scenarios	C. Methodology	D. Housing and Occupant Characteristics
[20]	Adelaide, Australia (*BSk*): Mild temperate climate	Investigated current and future typical meteorological year (TMY) climate TMY for 2070 CC scenario	Energy modelling (AccuRATE); best design based on minimum heating- and cooling-energy consumption	- Entire Australian population was targeted - Multi-family houses (MFHs) - Brick-veneer house (typical house design in Australia)
[21]	Brisbane, Australia (*Cfa*): Subtropical climate (hot and dry in the summer)	Reviewed data for heatwaves in 2004 and data related to air temperatures, air pollutants and health outcomes for period of 2001–2003	Energy modelling (AccuRATE); cooling and heating; base house and modifications with 2,5–7-star energy rating—utilised regression model to explore correlations between air temperatures and occupant health and wellbeing	- Detached brick-veneer residential houses - Façades (U = 0.75 W/m^{2}K) - Concrete roof tiles - Simple glazing - Holland blinds - Heating set points (SPs): 20°C in the living room and 18°C in the bedroom - Cooling SPs vary from 23.0–26.5°C
[22]	Brisbane, Australia (*Cfa*): hot and dry Melbourne, Australia (*Cfb*): warm summer	Reviewed data for heatwaves in 2004	Energy modelling (AccuRATE); heatwave scenarios for Brisbane (2004) and Melbourne (2009)	Conventional single-family houses (SFHs) without air conditioning (A/C) systems. Steady-state analysis of standardised occupancy profiles
[23]	Adelaide, South Australia (*BSk*): Subtropical cold and arid	Reviewed data for heatwaves in 2004	Online survey undertaken with representative sample (N = 393); Chi-square, Fisher's exact test and Fisher–Freeman–Halton exact test statistical analyses undertaken; Wilcoxon test performed	Vulnerable population living in energy poverty was targeted. - 90% dwellings with cooling systems (entire dwelling or a single room) - 25% rooms without shading - Most were without insulation and with light mass external walls
[24]	- Athens, Greece (*Csa*) - Lisboa, Portugal (*Csa*) - Rome, Italy (*Csa*) - Munich, Germany (*Cfb*) - London, England (*Cfb*) - Moscow, Russia (*Dfb*)	Reviewed climate-change projections for 2020, 2050 and 2080 (CCWorldWeatherGen)	Energy modelling; overheating (CIBSE). - Criterion 1: Hours of exceedance (3%) - Criterion 2: Daily weighted exceedance - Criterion 3: Upper-limit temperature	Mid-storey south- and east-facing flats - U-value (wall) = 0.18 W/m^{2}K - U-value (glass) = 1.4 W/m^{2}K - Pattern-of-use = 24 h^{-1} - Ventilation rate: 0.3 – 1.0 h^{-1} - Night ventilation - Interior blinds - MFHs

Source: Adapted from [25]

Several studies have revealed a correlation between energy use and building thermal properties [26-28]; several other studies have linked variations in indoor-air temperature to occupant health and wellbeing, particularly during long-term heatwaves [29,30]. Studies have investigated hazardous effects of summer temperatures on occupant thermal-comfort, including indoor-air temperature and relative humidity (RH) monitoring studies [31]; building-physics modelling studies [32-35]; and epidemiological studies of heat-wave mortalities [36]. Previous studies also determined that overheating is linked to household occupancy and behavioural patterns, which has been corroborated to evaluate the building performance of case-study locations [31,32]. Figure 1 delineates the key contributions of this empirical study.

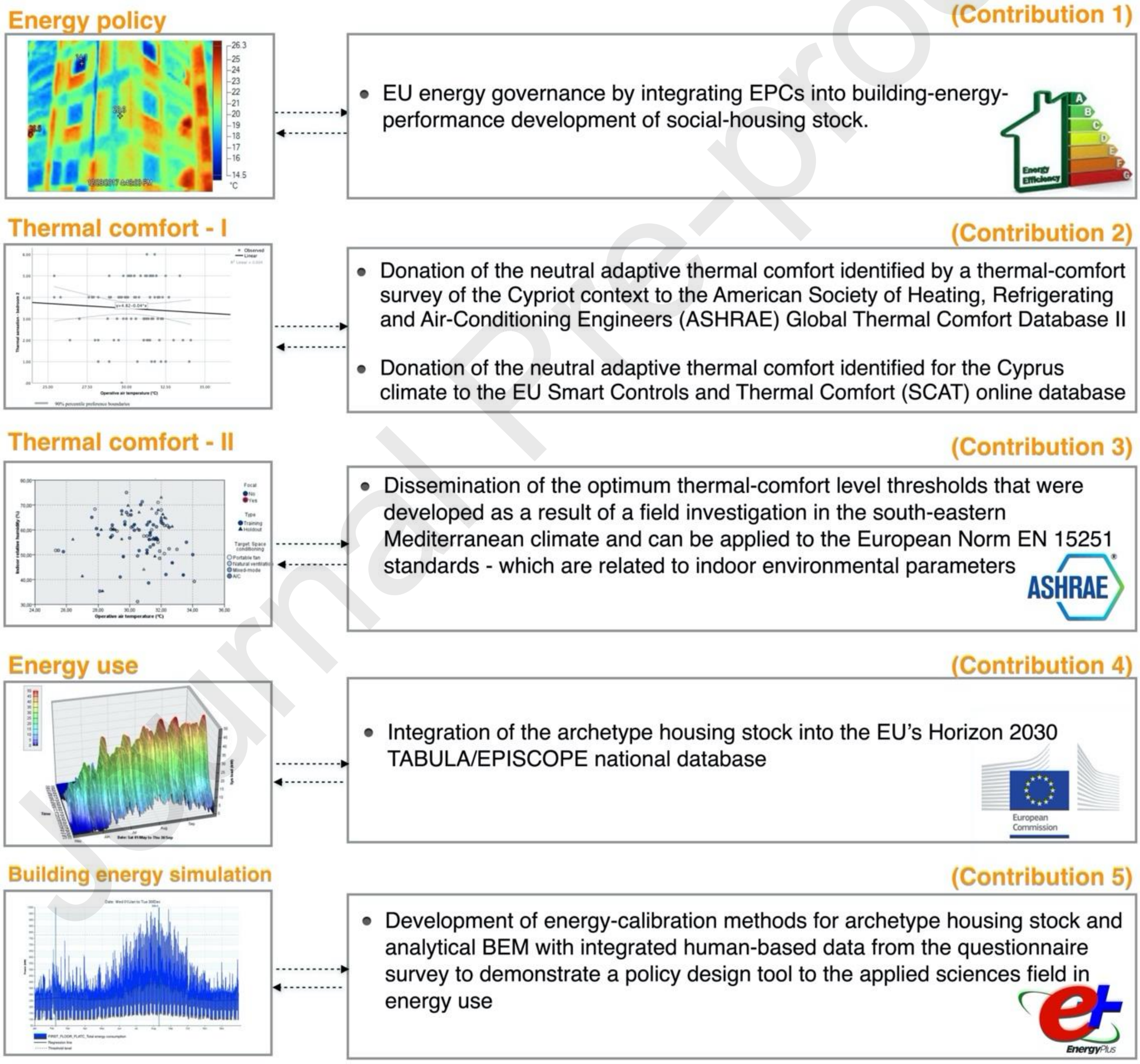


Fig. 1. Key research areas and step-by-step development of contribution to the knowledge.

Together, these in-depth literature reviews develop an understanding of retrofitting as a socio-technical process that must engage with different socio-cultural and material-technological contexts, which will then enable us to better comprehend the broader issue of how governance capacity is instituted to manage complex social and material relationships.

The novelty herein is to demonstrate a novel methodological workflow to diagnose the energy–thermal performance of RTBs in the south-eastern Mediterranean climate, where the summer climate is hot and dry (see **Graphical Abstract**). In Cyprus, there are no stringent buildings directives to reinforce regulations associated with energy-efficiency upgrades for the existing housing stock or any policy-design programmes intended to implement the Energy Performance of Buildings Directives (EPBD) [37, 38]. For this reason, there is an urgent need to develop performance diagnosis frameworks and approaches for accurate BEM simulations to develop energy-conscious retrofitting design solutions to improve existing buildings performances and bring them closer to current energy-efficiency measures (EEMs) in Europe [39, 40].

The findings of this study may impact the manner in which longitudinal field studies intended to detect heat losses in building envelopes are conducted, specifically with the use of *in-situ* measurements and an analysis of household energy bills. This step-by-step methodological workflow will demonstrate the manner in which the BES is undertaken to minimise the risk of discrepancies between actual and predicted energy use through a comprehensive illustration of a thermal-imaging survey.

This paper is structured as follows: The knowledge contribution and novelty of this study is presented in Section 1; followed by an in-depth literature review on the warming climate measures and the impact thereof on domestic energy use, and a thermal-comfort assessment and building-performance evaluation criteria in Section 2. Section 3 presents a comprehensive description of the methodological framework that was developed to provide background of effective retrofit delivery in high-density residential buildings. Findings and discussions are offered in Sections 4 and 5, and Section 6 includes the conclusion and further recommendations for energy policy design.

2 Systematic Literature Review

This section discusses the literature review that was conducted to identify the knowledge gap related to the implementation of EPBD directives; to address climate change and the detrimental impact thereof on the overheating risk of buildings, the thermal comfort of occupants and the energy use of households; and to explore the novelty of BES that is integrated with an energy audit and thermal imaging, an area where little research has been undertaken. To fulfil research aims and objectives, this section highlights the significance of building regulations that should be put into place here in the RoC to reduce cooling-energy consumption and make existing building stock resilient to warming climate conditions; this is a research gap that has not been previously addressed in similar studies.

2.1 Energy performance building directives implementation in residential buildings

Globally, many government initiatives have attempted to formulate effective solutions to problems associated with household energy consumption and carbon emissions, specifically those of vulnerable residents in all spheres of the economy [41]. Due to long-term heatwaves that have occurred more frequently in recent decades as a consequence of rapid climate changes in cities around the world, these are seen as being increasingly important [42]. A seminal report from the United Nations Department of Economic and Social Affairs was published in 2010, 'Buildings and construction as tools for promoting more sustainable patterns of consumption and production', which asserted that climate-change effects related to carbon emissions could cause an increase in global temperatures of up to 6°C [43]. If this were to happen, it would result in extreme weather conditions and would affect household energy consumption [44].

In order to address the impact of climate change, the EPBD must be implemented in buildings to assess the energy performance thereof and develop more stringent building regulations that will take climate characteristics and housing typologies for the 27 EU member states into account [45]. These efforts will indicate which buildings are energy efficient and ways to improve the efficiency of residential buildings, optimise the thermal comfort of residents and reduce energy bills.

More importantly, it is essential to thoroughly specify information requirements and exchange procedures during the EPBD legislative process related to building energy-efficiency upgrades. Research has shown that energy has become a significant issue in the EU. The study by Gupta et al. revealed that in 2018, European buildings consumed 40% of total energy usage, and approximately 55% of EU electricity consumption [46]; in their review of the importance of energy-consumption classification across different sectors in the EU, the building sector was found to consume the highest amount of energy, compared to the transportation (32%), industrial (26%) and agricultural (2%) sectors [47].

It can therefore be assumed that approximately two-thirds of the building sector's energy consumption is associated with the residential sector [48]. These findings support the idea that energy consumption has assumed a priority status in terms of the urgency thereof as a problem and action plans that reflect and highlight this importance due to a lack of stringent policy implications in residential sectors in EU-27 countries. To tackle the issues of a high energy demand for heating and cooling, emergency plans that are currently in place are directed at entire households and demonstrate the importance of energy-efficiency upgrades across Europe [49].

Several studies have highlighted the need for control mechanisms in retrofitting processes to help identify appropriate building materials based on the thermal properties of buildings that have undergone holistic systemic retrofitting efforts [50, 51]. To achieve this change, contemporary work progress must be re-examined and re-engineered. For this reason, the 2011 Energy Efficiency Plan increased understanding of the implementation of energy-efficiency policies and attendant measures for thoroughly implementing retrofitting interventions [52]. At the same time, this targeted plan covered the entire energy supply chain in the EU to provide an actual database for the pre- and post-retrofitting phases of pilot study projects [53]. This holistic approach has the potential to produce high-performance residential buildings that are both cost-effective and sustainable, which will also mitigate risks to optimise thermally comfortable indoor environments by taking current and future climate change projections into consideration [54, 55].

2.2 Overheating risk of European residential buildings

Several researchers have investigated passive measures and interventions in retrofitting efforts that were targeted to consider the thermal comfort of occupants by optimising indoor temperatures on a broad scale and reducing energy consumption with the aim of lessening the overheating risk in residential buildings [56, 57]. Furthermore, a significant amount of research and several surveys have concluded that improving the physical quality of buildings has a direct impact on the adaptive thermal comfort of residents [58, 59].

Only more recent studies, however, have provided a better understanding of the importance of implementing passive cooling retrofitting design strategies (PCRDs) as baseline scenarios in their simulation set input parameters. Mahdavi emphasised that the implementation of passive design systems increases the environmental socio-economic value of a building [60]. Additional evidence that supports this assertion has demonstrated that incorporating passive measures when retrofitting residential building systems reduces the overheating risks therein, decreases energy costs and increases societal awareness of effective adaptations during the retrofitting process [61]. As such, it has become evident that the potential benefits of a greater reduction in energy consumption and the value of the built-asset have increased [62–64].

One of the main goals of this empirical study was to encourage social-housing occupants to assess and adopt principles of retrofitting design policies to improve the extant mass-housing stock and bring them into effect. This approach will investigate buildings that were built under the governmental social-housing scheme, which have not yet undergone any refurbishments to make the structures more energy efficient and adaptable to the local environment. This endeavour was prompted by an understanding that the current planning policies have been ineffective when taking the energy consumption of the existing housing stock, including that of mass-housing estates built during the property boom in Cyprus, into consideration. The study revealed an urgent need for governmental bodies to devise effective policies for the mass-housing sector so the construction industry will apply necessary retrofitting strategies on a rapid and large-scale basis to reduce energy consumption.

Recognition of the limitations and inherent contradictions of this research has led a few studies to attempt to properly understand overheating and the impact thereof on the thermal comfort of occupants in residential buildings, particularly in Famagusta, Cyprus [65]; in fact, this issue remains unaddressed [66]. Despite the fact that these factors can have a significant impact, it is not important to evaluate the energy performance of existing residential buildings and assess the thermal satisfaction of the occupants thereof, because this can have a significant impact on the cooling energy use [67]. Even though energy-efficient building materials and passive cooling design measures were proposed by Ozarisoy and Altan, only one of these measures was implemented in a building simulation program to assess the validity of the assumptions for the subsequent research phase, as shown in Table 2. The preliminary results highlight that an acceptable reduction in cooling-energy consumption was demonstrated in the representative flats during the summer, but additional studies are needed for a better comprehension of the implications of passive energy measures (PEMs) in retrofitting efforts of residential buildings [68, 69].

Table 2
Description of various validation techniques for an overheating risk assessment and a model-calibration analysis.

Techniques	Description	Application
Comparison to other models	Various validated simulation-model results are compared to the results of other valid models.	Applied to validate simulation model
Worst-case scenario development	Analytical energy-model structures and outputs for extreme and unlikely factor-level combinations in the system should be plausible.	Comparative study for worst-case scenario, such as implementation of CIBSE TM59 overheating-assessment criteria and EN 15251 thermal adaptive theory to assess overheating risk and occupants' thermal comfort
Face validation	Asking individuals who are knowledgeable about the system (i.e., practitioners and energy consultants) if the model and/or its behaviour are reasonable.	Applied to validate model input data
Historic data validation	If historical data exists, or if data are collected on a system to build or test a model, some data are used to build the model; and the remainder are used to determine (i.e., test) if the model behaves like the system.	Applied to validate simulation model
Historic methods (i.e., rationalism, empiricism and positive economics)	Only the empirical method was used to develop the validation technique for this study. Empiricism requires every assumption and outcome to be empirically validated.	Applied to validate simulation model
Multi-stage validation	1. Developing the model's assumption on theory, observations and general knowledge. 2. Validating the model's assumptions where possible by empirically testing them. 3. Comparing (testing) the input–output relationship of the model to the real system.	Applied to validate simulation model

An exemplar study that addressed summertime overheating was that of Nicol et al. [70], in which the overheating risk was introduced, and methods to assess the likelihood of overheating on a base-case representative-building typology during long-term heatwave peaks experienced in the summer period were delineated. In addition to this study, Roccotelli et al. proposed an index to predict the summer overheating risks caused by the charge and discharge of heat-stress-index factors that influenced the thermal comfort of occupants [71]. Table 3 (a) through (c) demonstrate the systematic literature review undertaken to fulfil the knowledge gap on infrared radiometer thermography for the energy audit of buildings which identifies the key instruments and innovative aspects for bridging energy performance gap according to main aim and objectives of this empirical study.

Table 3a
Pilot studies that evaluated on the literature on infrared thermography for the energy audit of buildings.

References	A. Study Location	B. Building Type	C. Primary Aim of Model	C. Methodology	D. Main Findings
[72]	Italy, all the regions including the Mediterranean island of Sicily	Buildings (i.e., residential, offices)	- To propose a critical review on the employment of the quantitative IRT survey for the assessment of the U-value of the building envelope. - To demonstrate a novel methodological framework for the IRT technique and its impact on building performance evaluation studies. - To highlight the necessity for specialized thermographs who deal with an evolving methodology.	- A systematic literature review was conducted. - Laboratory test, in-situ measurements and infrared radiometer thermography approaches were selected main keyword for the bibliographic analysis. - Common approaches to the U-value assessment were discussed as follows; (i) analogies with coeval buildings; (ii) calculation method; (iii) heat flow meter measurements; (iv) laboratory testing; (v) IRT survey.	- The U-value can be calculated by using IRT. - Further research is required between simulation and experimental data in order to provide reliable results for the development of new techniques based on IRT. - Experimental field-testing studies demonstrate more reliable findings than steady-state analysis of U-values of building envelopes. - Sensitivity analysis is required to validate discrepancies between the effects of radiations and boundary conditions.
[73]	Worldwide	Buildings (i.e., residential, offices)	- To provide an analytical framework for energy auditors and thermographers. - To present a critical review of the use of the IRT survey in the building energy audit.	- Bibliographic analysis was conducted. - Current energy audit approaches in energy audit were conducted. - Both passive and active thermography measures and its implications on building performance evaluation were conducted.	- Passive approach was found to be the most common driver to detect thermally significant defects. - Significance of integration of different non-destructive testing of building envelopes could contribute to the IRT survey development framework. - Further research is required to represent archetype housing stock analysis for the development of benchmarking criterion in residential sector.
[74]	San Siro – Milan, Italy	Social housing stock	To identify an innovative and up-to-date methodological didactic approach for defining the most appropriate solutions for the refurbishment of a social housing stock.	Exploratory case study approach was conducted. Design driven approach was adopted with employing the historical research and survey, on-site visit, hands-on-training and on-site exposition.	To improve the awareness of the students on the possibilities of building renovation and design applications for social housing stock.

Table 3b
Pilot studies that evaluated on the literature on infrared thermography for the energy audit of buildings (Continued).

References	A. Study Location	B. Building Type	C. Primary Aim of Model	C. Methodology	D. Main Findings
[75]	Worldwide	Buildings (i.e., residential, offices)	To present a methodological framework for evaluating energy and environmental performance of building stock by the use of non-invasive techniques.	A review of instrumental analysis was conducted as follows (i) visual testing; (ii) thermographic inspection; (iii) thermal comfort; (iv) post-occupancy evaluation.	Only the use of coring showed the presence of moisture and water percolation on thermal insulation. Sonic trial proved the presence of some mechanical anomalies revealed by different velocities of the sound propagation in the masonry.
[76]	Victoria, Canada	On-site experimental structure	- To develop an external IRT method to determine clear wall U-values. - To determine the viability of an external thermographic survey technique for use in energy audits.	- The IRT measures were conducted on a conditioned at-scale insulated wood-frame wall structure. FLIR A65 IR camera was used. - A 3D thermal modelling the Nx software package was used to validate IRT survey findings.	- U-value measurement with IRT in the best-case scenario deviated between 6.25%-25.00%. - The U-value results with IRT were validated and ranged between 11.53% - %10.00 in the best-case scenario.
[77]	Porto, Portugal	On-site experimental structure	- To develop a thermographic 2D U-value map for the characterization of heavy walls in stationary regime. - To assess the temperature distribution of each transition phase between each defect and its undisturbed surroundings.	- Measurements were conducted in a walk-in climatic chamber – FITOCLIMA 1000. 2D U-value map is created. 2D colour map was developed to identify the distribution of the thermal transmittance of the walls. - In-situ QIRT test was conducted.	- Optimisation of a TWALL mesh comprised of 1600 elements of 8 x 6 pixels. - Image quality losses were estimated at 6.65%. - 2D correlation coefficient, R was equal to 0.287 which means that only 8.23% of the processed thermal image can be attributed to the original thermogram.
[78]	Brescia, Italy	Residential Tower Block	- To verify the applicability of the energy rating system which was newly drawn up by the Green Building Council in Italy. - To design a methodological framework for low-energy design and retrofitting.	- On-site building diagnostic method was used. EnergyPlus software suite was used to undertake dynamic thermal simulations. - IRT survey was carried out. The PAN software used to process the IRT survey findings.	The rock wool insulation under the ventilated façade with a density of 70 kg/m^3 and a thickness of 12 cm which is highly breathable allows surface temperatures of over 18° C to be reached and guarantees good hygrometric behaviour.

Table 3c
Pilot studies that evaluated on the literature on infrared thermography for the energy audit of buildings (Continued).

References	A. Study Location	B. Building Type	C. Primary Aim of Model	C. Methodology	D. Main Findings
[79]	Nottingham, United Kingdom	19th century detached house (renovated cottage house)	- To develop a novel methodological framework where infrared thermography of a deep retrofitted building is combined with deep learning neural networks. - To predict the future effectiveness and economic viability of wall insulation in terms of energy savings.	- Exploratory case study approach was adopted. - A mathematical model was developed to predict the accuracy of life-long monitoring of buildings. - Infrared thermography and temperature sensors were used to assess building fabric thermal performance. FLIR E25 thermal camera was used as building diagnostic tool. The Matlab was used to validate temperature recordings.	- High accuracy of predicting the actual energy savings with success rate of about 82% when compared with the calculated values. - The Artificial Neural Networks (ANN) predicted heat losses are slightly higher than the calculated ones in 14 out 21 cases for each wall type. - The range of error for the insulated wall is -13% to +15% and for the uninsulated wall is -14% to +17.5%.
[80]	Mestre-Venice, Northern Italy	20th century multi-family medium-rise apartment building	- To assess the current condition and propose cost effective and energy-efficient retrofit design interventions. - To develop a methodological workflow to provide a guidance on the development of retrofit interventions in order to improve structural resistance of existing housing stock.	- The housing typology classification was conducted to identify nationally representative housing type for archetype analysis. - IRT survey was conducted. - 3D analytical model was developed to perform structural seismic analysis. The 3Muri software suite was used to perform overall seismic behaviour of building.	- In respect to out-of-plane mechanisms, the weakest panel was n.1 in wall 15 in the north wing and n. 1 in the west wing. - Building fabric thermal performance analysis confirmed that low temperatures on internal surfaces (10-14° C) close to the dew point temperatures, especially in the junctions between floor slabs and walls and between the roof and the walls.
[81]	The city of York – England, United Kingdom	Low-energy dwellings which were built according to Passivhaus standard	- To present the methodology and results of in-situ testing of building fabric thermal performance to calibrate as-built energy models.	Integrated Environmental Solutions (IES) software suite was used. The in-situ tests included repeat testing of air permeability integrated with thermal imaging survey and heat flux measurements of the building fabric elements.	Calibration of the model by altering the wall U-value to 0.26 W/ m^2 K made sense as this brought the external wall U-values closer to the BRUKL limiting parameter of 0.30 W/ m^2 K.

Tables 3 (a) through (c) present a list of previously undertaken pilot BPEs, which was retrieved from the collection of research articles in the Clarivate Analytics database. A large body of research has been undertaken on the overheating risks of different building variants that could potentially be used to support retrofitting and design decisions (i.e., housing typology, household socio-demographic characteristics, etc.). As can be seen, several scholars have conducted building-energy modelling (BEM) and environmental monitoring to calibrate the overheating risk of these residential buildings, and an exploratory case-study approach was applied to these methodologies to properly understand the building performance of existing housing stock [82-84].

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

In a variety of field-assessment procedures, there is a growing recognition that the overheating phenomenon could be deployed in different experimental studies to corroborate the thermal properties of buildings, occupant behaviour and the physical environment in the development of national adaptive thermal comfort indices for the European Survey of Thermal Comfort database. In this endeavour, Diaz et al. adopted the 'Percentage Outside Range' methodological approach, which is based on the European adaptive-comfort model, to reduce the impact of overheating that is created by an increase in thermal mass [85]. This study outlines the development of previous studies' thermal comfort indices' outcomes for assessing occupants' thermal comfort with considering overheating risk and domestic energy use of social households.

2.3 Thermal-comfort assessment and building-performance evaluation criteria

Many field studies have been conducted in various climates across the world, which demonstrated that comfortable temperatures are closely linked to local climate [86–90]. By following a similar approach, the adaptive thermal comfort theory explains this phenomenon as it related to occupants' active engagement with their indoor environments [91]. According to a study by Nicol et al., an alternative approach to defining comfortable temperatures is the adaptive approach, which stems from the results of a wide range of field studies [92]; this study found that the thermal expectations of occupants are related on a variable basis to outdoor climate conditions.

It is important to note, however, that there is little information related to night-time thermal comfort [93]. Studies have shown that sleep deprivation due to overheating during the night is a major motivation for buying domestic cooling appliances; moreover, apart from the most energy-efficient building systems and applications, conventional passive-cooling strategies involve shading transparent elements of the building envelope and effectively ventilating spaces during the night [94].

Ferrari and Zanaotto's studies emphasised the possible implementation of a night-time cooling strategy during the summer season that would have a significant impact on cooling demand when performing a dynamic analysis; these studies have also shown that lower air temperature is associated with a high daily air-change rate in the monthly average of wind speed frequency recorded in Mediterranean countries [95]. Ferrari and Zanaotto's simulation studies also found that the substitution of a standard set-point with the daily air-change rate resulted in a decreased discomfort degree-hours calculation [95]. Although these studies, in order to show the relevance of energy efficiency of retrofitting options, other exemplar pilot case studies provided useful references regarding the role of programmed natural ventilation that can reduce the risk of overheating experienced in RTBs in London [96].

In addition to these findings, based on these base-case studies, cooling demand in the south-eastern Mediterranean climate varies between 10% and 50%, depending on the building orientation and the level of implementation of various passive cooling strategies [97]. These studies present evidence that increased energy consumption related to the active cooling of a building poses a serious environmental danger, which demonstrates why it is important to increase the number of residential buildings or to at least partially rely on passive cooling strategies [98]. It should be emphasised, however, that adaptive comfort standards are an important measure that can be adopted in retrofitting strategies [99]. This trend is especially problematic in the urban context, where there is less air movement and urban heat island (UHI) effects are more noticeable after dusk [100–102].

Consequently, the adoption of globalised housing design standards and inadequate standards for thermal comfort assessment in RTB development projects in urban areas of Famagusta means that affordable RTBs are being planned and designed without climate considerations, resulting in relatively high indoor air temperatures and diminished thermal comfort. Gupta and Gregg drew on an extensive range of sources to assess the overheating risks in residential buildings, and they concluded that the thermal properties of buildings are complex and there are several interdependencies and multi-causal relationships involved in occupant thermal-comfort optimisation efforts [103]; interestingly, when attempting to assess overheating risks and optimise occupant thermal comfort, these variables relate to changes in occupant behaviour in a nonlinear manner, especially in vulnerable households, as shown in Figure 2.

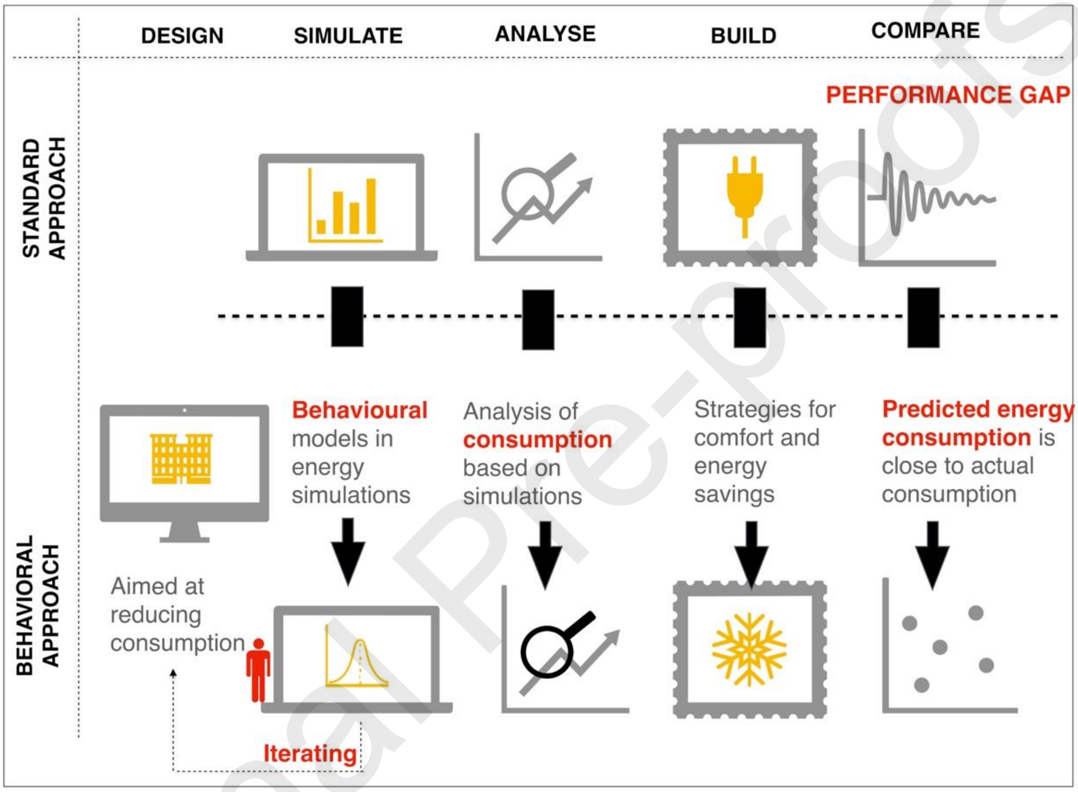


Fig. 2. Comparison of standard and behavioural approaches.

The adaptive approach concerning thermal comfort is currently used in international standards [104, 105]. The Chartered Institution of Buildings Services Engineers (CIBSE) Overheating Task Force decided that a new approach to overheating is necessary, however, especially in residential buildings without mechanical cooling; this new technique follows the methodology and recommendations of BS EN 15251 to determine whether an existing occupied building or a proposed building will be at risk of overheating [106]. Studies by local energy assessors in 2019 have shown that many RTBs within Famagusta and the urban agglomerations thereof struggle with overheating and that this trend will only become worse with continuing climate change [67].

According to the literature review, assessing heat losses of building envelopes with the use of infrared radiometer thermography (IRT) is feasible and can offer practical building diagnostic solutions during the pre-retrofitting phase [107, 108]. However, IRT is a qualitative approach to foresee anomalies detected throughout this stage [109]; as such, this remains an issue that requires attention from the scientific community. A number of studies have advocated for an integrated framework that would promote a multi-disciplinary approach [110-112]; since many socio-demographic characteristics are correlated with energy use, an interdisciplinary approach would provide a theoretical framework that could capture inter-relationships between scientific, technological, societal, economic and cultural factors within the context of an STS design approach, as shown in Figure 3.

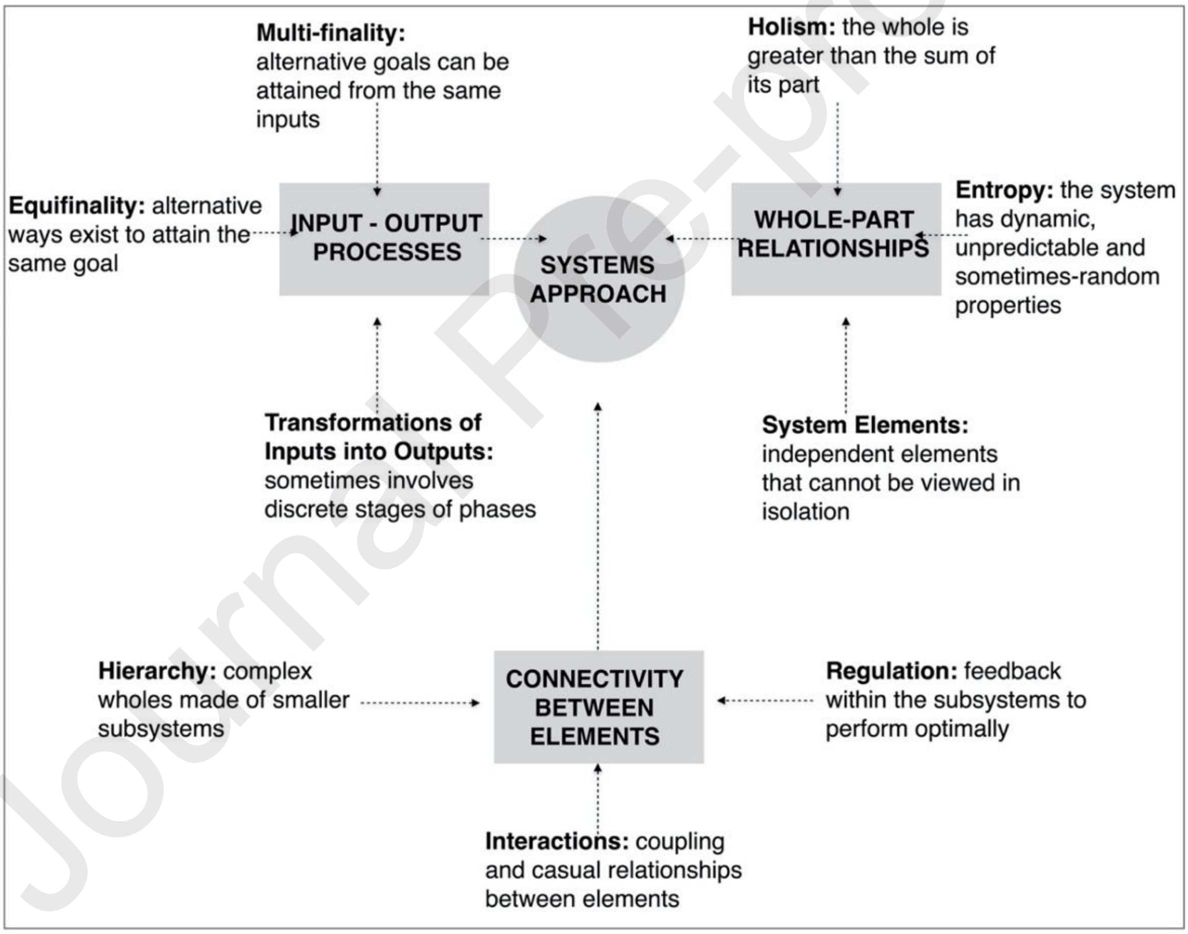


Fig. 3. Components and characteristics of socio-technical-systems approach.

To address the knowledge gap of current building diagnostic design methods, this paper delineates the development of a novel methodological framework based on an empirical case study approach that utilises a field survey, IRT and numerical experimentations to calibrate BES. This empirical study outlines the development of previous studies' thermal comfort indices' outcomes for assessing occupants' thermal comfort with considering overheating risk and domestic energy use of social households. The input parameters required for energy modelling include the building geometry and properties of the different construction materials, specifications of the building components and the local climate conditions of the built environment and occupants' energy consumption will be further discussed in Section 3.

3 Method and Tools

3.1 Climate data: South-eastern Mediterranean Europe

Cyprus is the third largest Mediterranean island, after Sicily and Sardinia [113]. It is located at latitude 35° North and longitude 33° in the south-eastern portion of the Mediterranean Sea [19]. According to the Köppen–Geiger climate classification category Csa, Cyprus has typical Mediterranean climate characteristics [114]: hot, dry summers and moderate, wet winters, which leads to problems related to energy-consumption demands due to the need for both summer cooling and winter heating [115]. This local climate condition also highlights the fact that the prevailing south-western winds are able to change the relative humidity rate along the southern coastline by as much as 90% in the summertime, particularly during the evening hours, as illustrated in Figure 4 (a); it is reasonable to assert that the cooling effect of the prevailing winds affects the thermal-comfort conditions of buildings and significantly decreases the demand for space cooling.

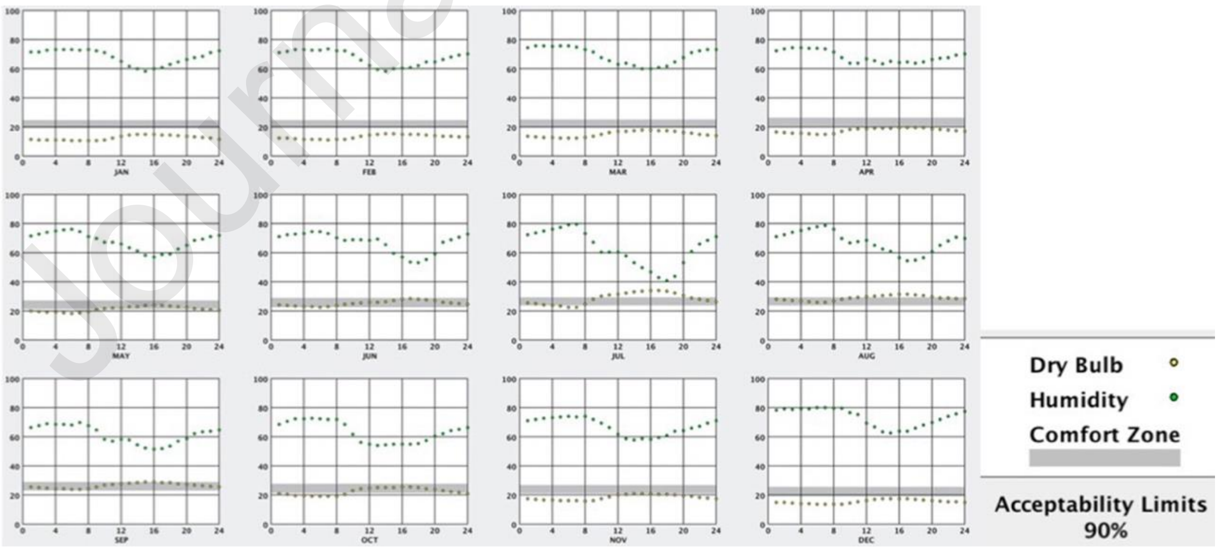
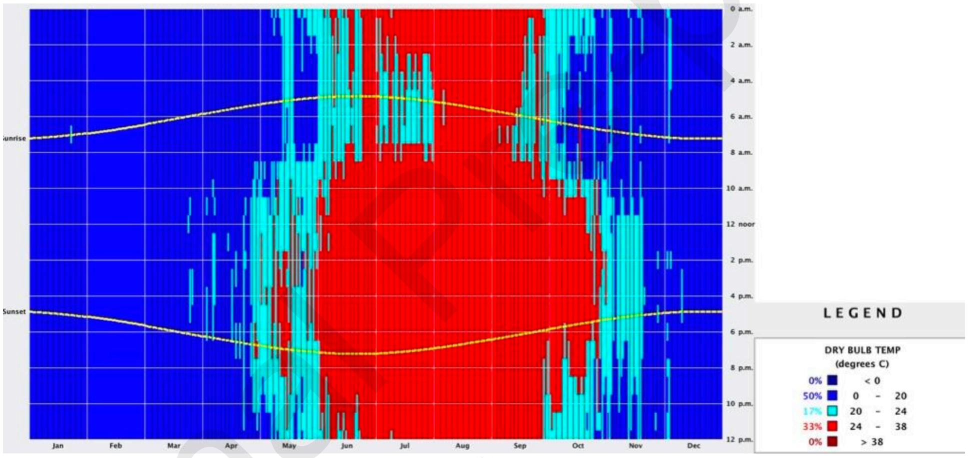
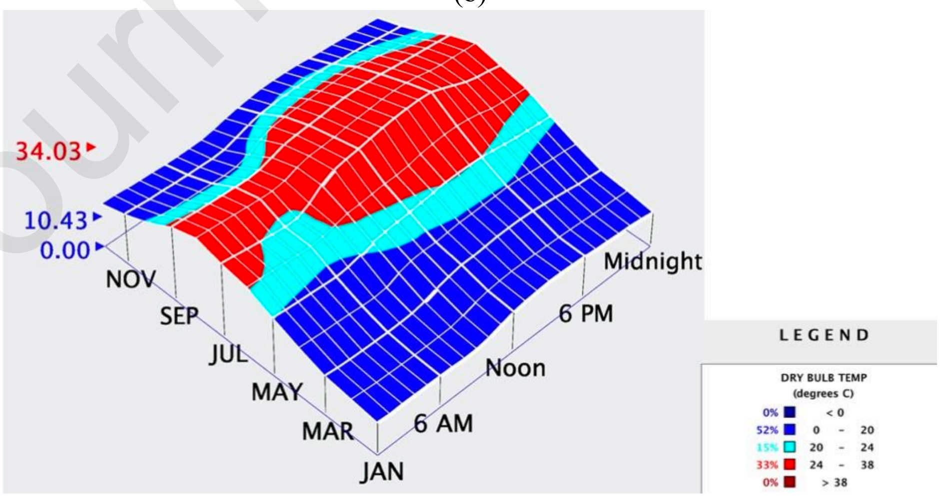


Fig. 4. (a) Monthly relative-humidity and dry-bulb temperature fluctuations. ***Source:*** Diagram extracted from the Climate Consultant Version 6.0.13 (60.13), which was developed in 2018 by the University of California (US).

Famagusta demonstrates mild Mediterranean climate characteristics [116]. Maximum Dry-Bulb Temperature (DBT) can reach as high as 42°C in the summer, the hottest month of which is August; and minimum DBT can drop down to –6°C in winter, the coldest month of which is January. Mean minimum DBT varies between 6.8–22.3°C, and mean maximum DBT varies between 16.3–33.3°C. Even though prevailing winds come from the north-east, the most consistent wind directions are to the south-west and west. Hot, dry summers and moderate, wet winters are the primary climate characteristics and have direct impact on annual heating and cooling demands due to the need for both summer cooling and winter heating. Figures 4 (b) and (c) illustrate the time-plot series of dry-bulb temperature data and a 3D representational chart thereof to demonstrate the significance of high temperatures on the building-envelope absorptivity levels; this was used as a reference source when conducting infrared thermography survey in the summer and winter.



(b)

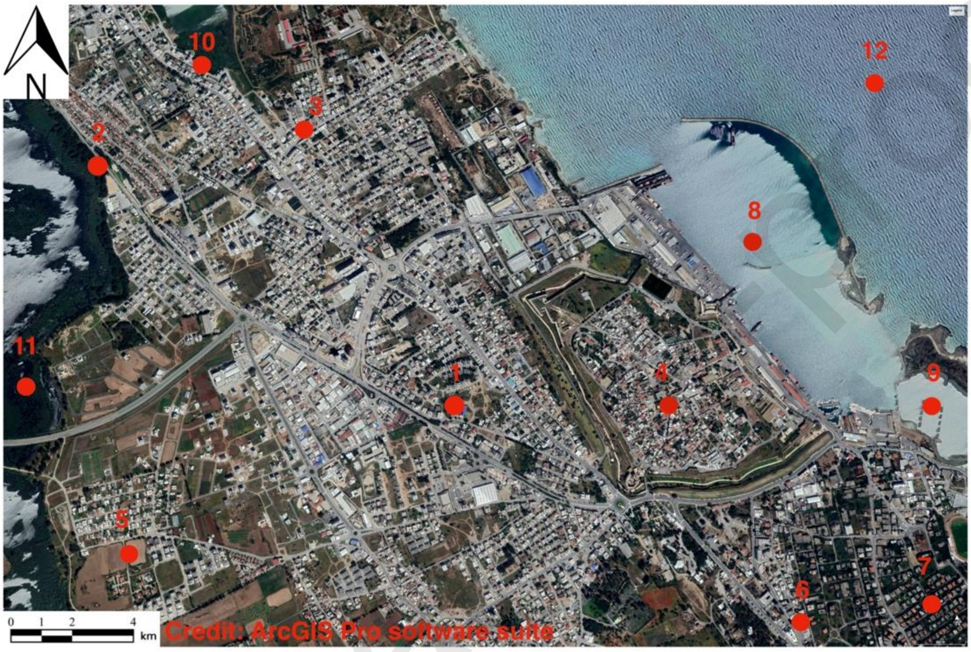


(c)

Fig. 4. (b) The time plot series of monthly dry bulb temperature; **(c)** The 3D representational of DBT fluctuations. ***Source:*** The diagram extracted from the Climate Consultant Version 6.0.13 (60.13); software suite was developed in 2018 by the University of California (US).

3.2 Location: South-eastern Mediterranean Island of Cyprus

This study employed an exploratory case-study approach to carry out an analysis of a base-case prototype high-density post-war social-housing development estate in Famagusta, Cyprus. The case study was in close proximity to the fenced-off Varosha territory in the southwest area of the city, the fortifications of the old walled city in the northeast and the densely built city centre in the northeast, as shown in Figure 5. The intention was to identify the most dominant representative housing typology; this was determined to be medium-rise RTBs, which represents 38% of housing stock in Cyprus.



1. Base-case prototype post-war social-housing development estate
2. Terraced house-type post war social housing
3. Newly built high-rise residential tower-blocks
4. Old walled city of Famagusta
5. Urban agglomeration region
6. Mid-town Varosha territory
7. Fenced-off Varosha territory
8. Famagusta Harbour
9. Blue Lagoon waterfront development area
10. Newly built medium-rise residential-tower blocks
11. Famagusta Lake
12. Famagusta Bay

Fig. 5. Map of residential building stock and post-war social-housing development estates in the city centre of Famagusta retrieved from the Geographic Information System (GIS) database, and statistical information provided by the 2018 Housing Demand Survey. ***Source:*** Maps were extracted from the ArcGIS Pro Version 2019.01 software suite, which was developed by Esri (UK).

The selected housing typology was the first of its kind to be built as a governmental social-housing scheme to address the housing shortage in the mid-1980s and early 1990s [117]. This explanatory case-study approach provided a good representation of the common drivers in the property market with different levels of retrofitting strategies and representative samples from the construction era between 1985–1997 with respect to housing typology, age of the structure, floor-plan design layout and construction materials. The RTBs were chosen from privately owned construction companies that specialised in mass-housing development projects, specifically owner-occupied dwellings. The buildings that were constructed under the government's social-housing scheme can be described by three newly defined variables: energy-consumption patterns of the occupants, thermal performance of the buildings and thermal-comfort level of occupants. The input parameters required for energy modelling include the building geometry and properties of the different construction materials, specifications of the building components and the outdoor air temperature of the built environment and occupants' energy consumption will be further discussed in Section 4.

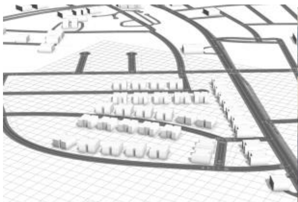
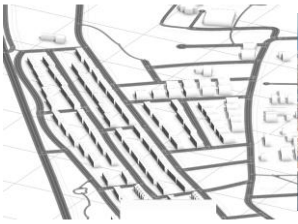
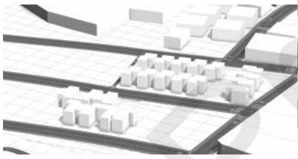
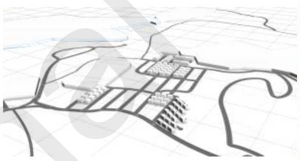
3.3 Archetype selection of vulnerable urban neighbourhood

This section discusses the issue of the thermal vulnerability of medium-rise residential tower blocks constructed in Famagusta, Cyprus in the mid-1980s and early 1990s, after the Civil War of the 1970s, as a frontier example of the first regulations derived from government initiatives and planning agendas for large-scale social-housing developments [118]. In Europe, a similar construction practice occurred after World War II to address housing demand; due to housing shortages and the speed of the construction processes, a significant proportion the European housing stock was built with low-quality thermal envelopes [119]. The purpose of this section is to present the location and climate characteristics of the base-case prototype RTB for this study. The case study is presented and discussed, and the selection criteria for the archetype post-war social housing development estates is explained and illustrated by *on-site* photographic documentations and field observations in order to address the research problem and indicate the urgent need for holistic retrofitting schemes that are implemented by policymakers in Famagusta, Cyprus.

A comprehensive study of the development of social-housing estates demonstrated that these residential buildings were constructed in the deprived cores of the city centres on regenerated vacant land and offered poor liveable accommodations to residents at the time of the initial implementation of social-housing policies. These building typologies and the thermal characteristics thereof are similar to the buildings in social neighbourhoods, however, partly due to the bespoke architecture of the structures, and also because of the lack of common design principles and processes. In the ensuing years, these building typologies eventually became the blueprint for commonly built medium-rise residential-tower block developments by privately owned construction companies [120].

Due to climate changes in recent decades, these households also suffer from high energy expenditures in the summer, as well [121]. As was previously discussed, many estates were built in urban and suburban city areas, which led to the creation of distinctive neighbourhoods that cause two significant problems: the ongoing deterioration of building envelopes and of urban settings, and changes in the socio-demographic characteristics of households due to the age and activity levels of the first owners of the apartment units in these social-housing developments, as shown in Table 4.

Table 4
Taxonomy of social-housing estates in Cyprus.

Location and Typology	3D Model	Historic Image: 1986–1997	Current Outlook: 2021
Famagusta Urban Residential Tower Block			
Famagusta Urban Terraced House			
Lefke Suburban Residential Tower Block			
Lefke Suburban Terraced House			

Historic images were authorised in 2016 by the State Planning Organisation. ***Source:*** Maps were extracted from the ArcGIS Pro Version 2019.01 software suite, which was developed by Esri in the UK.

After conducting a thorough review and an in-depth investigation of social-housing developments, we identified cases in which households were at risk of suffering energy poverty, which were then divided into three categories: resource shortages; high energy costs (i.e., electricity, heating, cooling, etc.) due to deficient thermal-envelope characteristics; or an absence of heating or wall-mounted air-conditioning systems or portable fans for cooling.

We felt, however, that the best starting point would be to fully understand the significant reliance on cooling measures in warmer summertime climate conditions. Consequently, our analysis was conducted at the social neighbourhood and/or city level with representative residential building types and the contributions thereof to energy demand, in accordance with such energy risk factors as the year of construction, structural features of the thermal envelope, building orientation and type of heating and cooling devices used, in addition to the socio-demographics of each household (i.e., family structure, occupants' ages, income, health conditions, occupations, etc.), all of which proved to be useful tools to detect specific energy-related social vulnerabilities in this specific research context.

This convergence of research objectives led to the development of significant energy-efficiency measures that aided in a proper understanding of the applicability of various retrofitting interventions while also considering the occupants' real-life energy use. This indicates that there is strong correlation between residential energy use and the social characteristics of households, which made this a key element in residential sector policy-making [122]. For policymakers, therefore, social mapping and longitudinal surveys on thermal comfort with concurrent on-site monitoring of environmental conditions in a vulnerable social-housing development facilitates the making of realistic decisions and solutions with correspond governmental institutions and research establishments for future development of feasible and effective retrofit solutions in a holistic manner [123].

3.4 Archetype residential buildings as base-case scenario

The case study for this research was a post-war social-housing development estate for which the early proposals were developed in 1984 and mass construction projects were completed in two phases between 1990–1997 [51]. This high-density residential complex is comprised of 36 RTBs and was located at a random orientation without considering local climate characteristics or any type of environmental design principles in the architecture. The complex originally contained 288 housing units with similar layouts and construction characteristics, as shown in Figures 6 (a)–(e). There were two types of RTBs that were constructed: four-storey structures without communal amenities and five-storey structures with commercial premises located beneath the flats. There were no available lifts, mechanical services or ventilation shafts due to the reduced construction costs, and no central-heating systems or infrastructure were available for residential use.

(a) (b) (c)

Fig. 6. (a) High-density medium-rise post-war social-housing development estate; **(b)** current condition of prototype residential tower block development and southwest-facing tower block; **(c)** building façade, which was designed without considering climate characteristics of case-study buildings under investigation.

(d) (e)

Fig. 6. (d) Location map of RTBs in social-housing development: * P1-B1-11: Phase 1–11, ** P2-B1-25, *** N-E: northeast, N-W: northwest, S-W: southwest, S-E: southeast, S: south; **(e)** representative floor plan of multi-family housing at the southwest-facing RTB.

Notably, this project was the paradigm for building a collective living environment that was based on the relationship between each housing unit and on the whole 36 RTB structures at the social housing estate [66]. Before an in-depth analysis of thermal performance of buildings, it should be emphasised that in the early years of 21st century, the garden-city model became very popular in some European countries as a response to overcrowding in the inner city [67]. It was soon realised by the government initiatives, however, that this model required most of the derelict spaces to be transformed into high-density medium-rise structures. There were no architectural design principles that considered effective natural ventilation in the occupied spaces, nor were any sun-path organisation measures implemented. This is why most of the RTBs are vulnerable to the overheating in the summer. This lack of a decision-making process for these purpose-built estates related to land-use planning, architectural design features and environmental design principles were a motivation for this study.

3.5 Nationally representativeness of housing stock

The housing typology classification reveals that these RTBs were built without informed decision-making related to land use and planning. All of these RTBs lacked planning for a social-housing structure scheme, which led to poor air quality and high thermal conductivity in the summer and caused an overheating risk and thermally uncomfortable indoor environments. Table 5 demonstrates the number of dwellings were constructed under the government's social housing scheme between 1984-1996.

Table 5
Government social-housing development projects in Cyprus.

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

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

Figure 7 shows the total number of construction projects in Famagusta that were completed between 2015–2019 [124]; the highest number of construction projects were recorded in residential buildings. According to the housing data, residential buildings that were completed in 2019 consisted of 154 housing units, followed by 148 condominiums in 2018; the second-most-dominant housing typology was self-built houses, which showed a steady increase between 2015–2017. A total of 149 house projects were completed by either building contractors or private construction companies (i.e., single-storey bungalows, two-storey detached or semi-detached houses). Between 2018–2019, there was a notable increase in the number of this type of housing projects as a consequence of uncertainty due to the implementation of new town-planning regulations and stringent measures related to the protection of rural villages and shorelines in Famagusta and Trikomo.

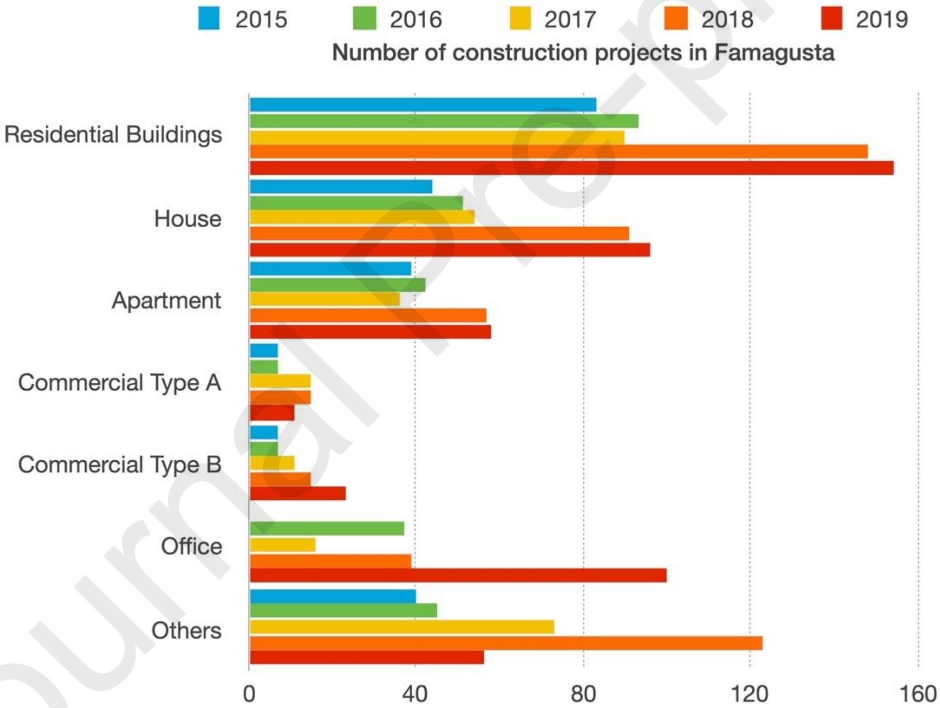


Fig. 7. Total number of buildings constructed in Famagusta between 2015-2019.

According to the Annual Report of Housing Census, 187 self-built houses were completed between 2018–2019. As it relates to apartment construction, 117 apartment buildings were completed between 2015–2017, then a slightly decrease in the number of built apartments can be observed between 2018–2019 [125], during which time 115 projects were completed; these apartment projects were 5–23-storey standalone buildings that were built on vacant land or wherever close-proximity to the shoreline to attract foreign second home buyers.

3.6 Thermal Imaging: Walk-through survey

This empirical study investigated the usefulness of IRT as a quick diagnostic tool to judge the 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 [126]. For this reason, it was utilised as a primary diagnostic tool to identify the most ill-performing representative RTBs in a worst-case scenario for the energy audit and analysis. A thermal-imaging survey was conducted between December 25, 2017 and January 12, 2018.

It is worth mentioning that in warm climates similar to that of the Mediterranean island 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 were at their coolest levels in order to provide an accurate baseline measurement for the surveyed multi-family residential buildings [127]. However, our time for conducting these inquiries was restricted by our need to gain access to the flats, thereby limiting our inspections to socially acceptable hours in the morning and in the evening. Therefore, we chose one particular methodology—the 'pass-by thermography' method—to speed up the inspection process, so we could investigate more buildings in each survey period.

3.7 In-Situ Measurements: Walk-in survey

Building thermography is a qualitative testing method that utilises an Infrared Radiometer (IR) camera to detect surface temperature variations in order to visualise irregular thermal patterns that correspond to defects in the building envelope, such as thermal bridging or air leakage [50]. In conjunction with the thermal-imaging survey that we completed in the winter of 2017–2018, an internal thermography was performed in the summer of 2018 to measure heat gains coming through deficient building envelopes at the time of our survey, which was conducted between July 28, 2018 and September 3, 2018. In total, 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.

3.8 Energy bills

In order to gather reliable data to assess the energy consumption of the occupants and to compare the results of the building-modelling simulation to the utility-bill analysis, this study evaluated the occupants' energy consumption in the winter of 2015-2016 and summer 2016.

These data served as the basis for a real-energy consumption dataset that could be used in the building-modelling simulation. These data also enabled us to evaluate the existing energy performance of the surveyed RTBs in order to assess the overheating issues experienced in each flat. The household electricity bills were obtained from the Electricity Authority's database with consent from the householders. Scholars have long debated integrating Forrester's dynamic approach to develop effective energy-policy designs and subsidisation schemes while delivering an assessment of EPCs that should be addressed [128-130], as shown in Figure 8.

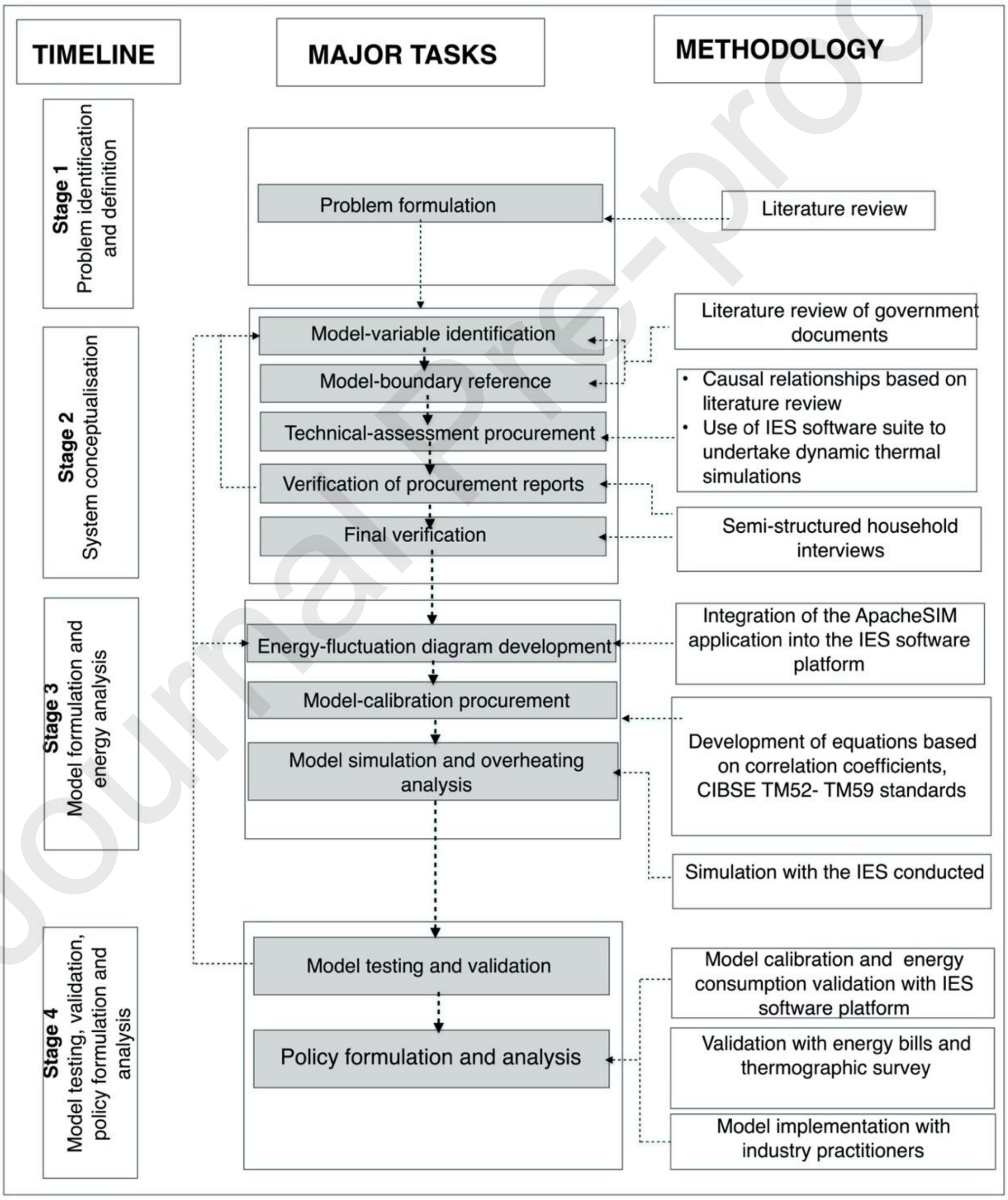


Fig. 8. Bottom-up modelling process developed for the study.

3.9 Building energy simulations: Model calibration

To provide a sufficient understanding and an analysis of the thermal performance of the case-study RTBs, it was necessary to use a dynamic thermal simulation (DTS) model. The Integrated Environmental Solutions (IES) software suite was selected as the most appropriate application for this purpose because it used the Test Reference Year (TRY) weather files of the research context to provide accurate results and simulate actual environmental conditions (see **Appendix A.1**) [131]; the IES software suite was known to meet a number of international standards, including *CIBSE TM59*, and it is also accredited for use according to the European standard *EN 15251* [132]. It also proved to be effective to use 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 and occupancy profiles assigned in the IES software, as shown in Figure 9.

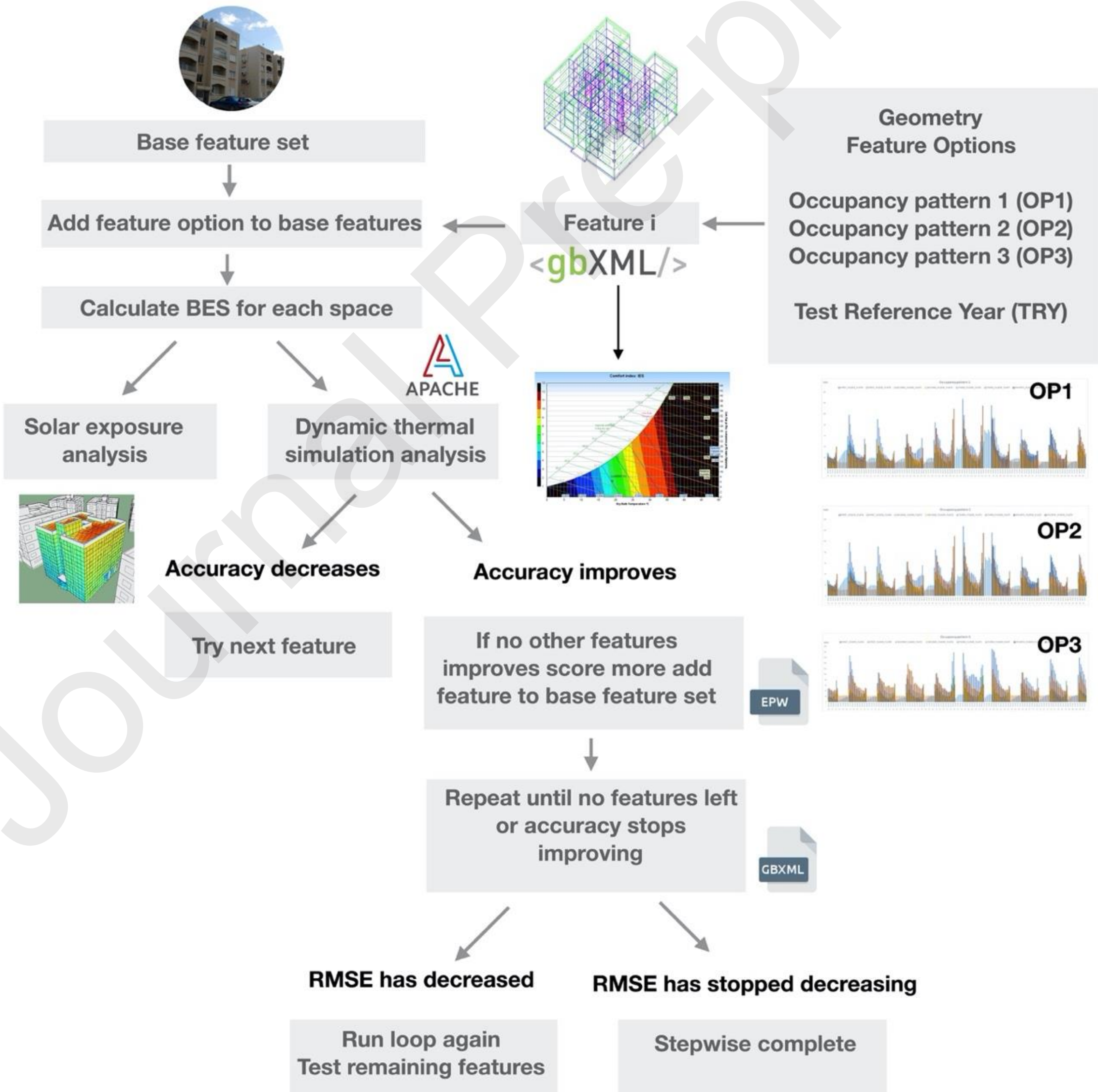


Fig. 9. Inquiry strategy of DTS analysis using the ApacheSIM software interface.

As it relates to the energy-calibration analysis, the version of the IES software used throughout this study was IES 2020.1.0.0. Specifically, the Thermal Comfort Analytical energy-simulation platform of the IES software suite was determined to be the application that would best be able to measure the 'adaptive comfort' of the prototype RTBs. To properly conceptualise the analytical-energy model that was developed for the study, commonly used BES packages reviewed globally, as shown in Table 6.

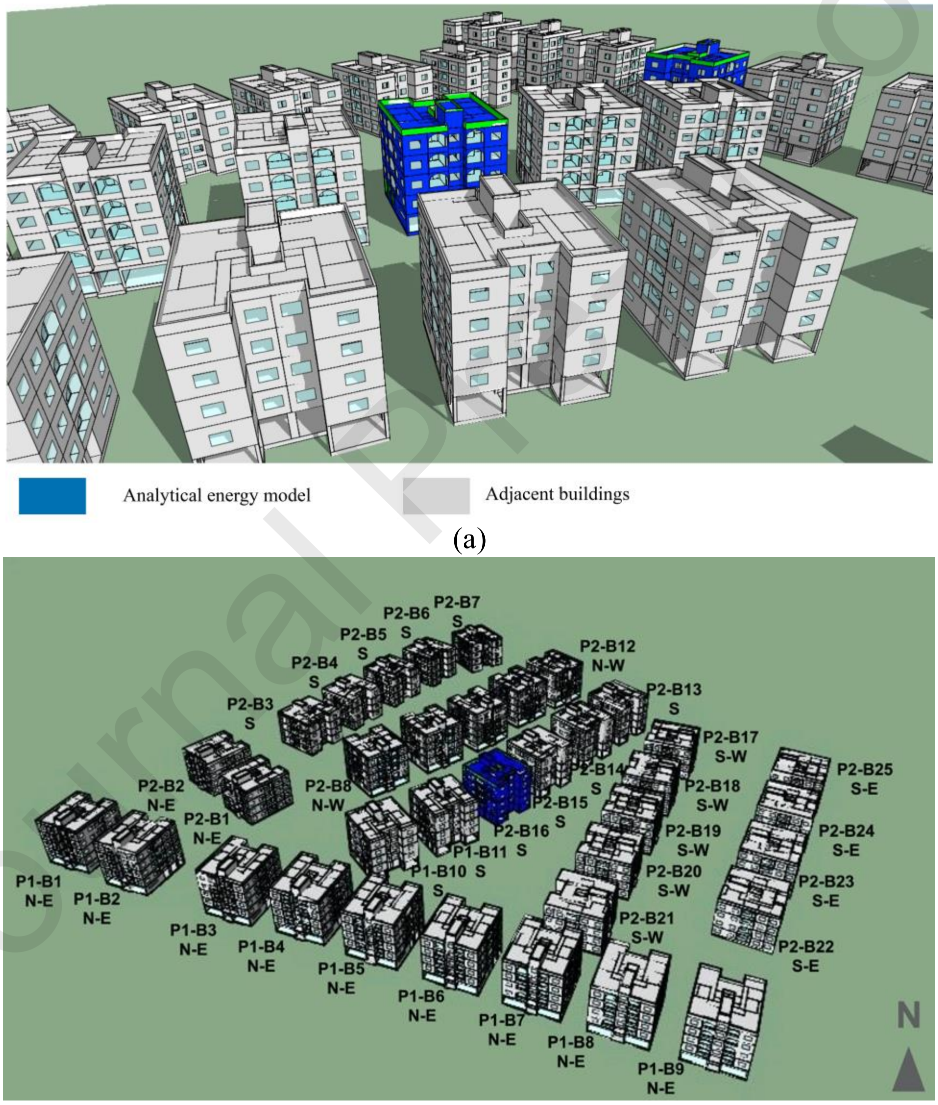
Table 6
Summary of data-processing capabilities of BES software and plug-ins.

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

Table 6 presents a list of BES software suites and plug-in components that were utilised to calculate numeric experiments. The platform provides effective tools to construct an actual building geometry and assign building thermal properties, occupancy profiles, ventilation schedules for each room to undertake various of numeric experiment targeted for BPE studies [133]. The IES computational platform provided the most accurate data related to solar-exposure analyses of buildings; this is because large-scale weather files can demonstrate the solar-diffusion frequency of building thermal properties for the initial overheating risk analysis, which are discussed in Section 4.4.2.

3.9.1 Construction of the black-box model

The building-performance evaluation tool of the IES software using the Apache-Sim assessment application for DTS was employed to assess the overheating risk from May to September of 2018. In this empirical case study, cooling-load calculations were made using the IES Apache-Constructions database and Apache-Loads in the IES software suite in order to calibrate the current energy performance of the prototype base-case building (see **Dataset A**). Figure 10 (a) and (b) illustrate the analytical energy model of the base-case prototype buildings (see **Video A**).

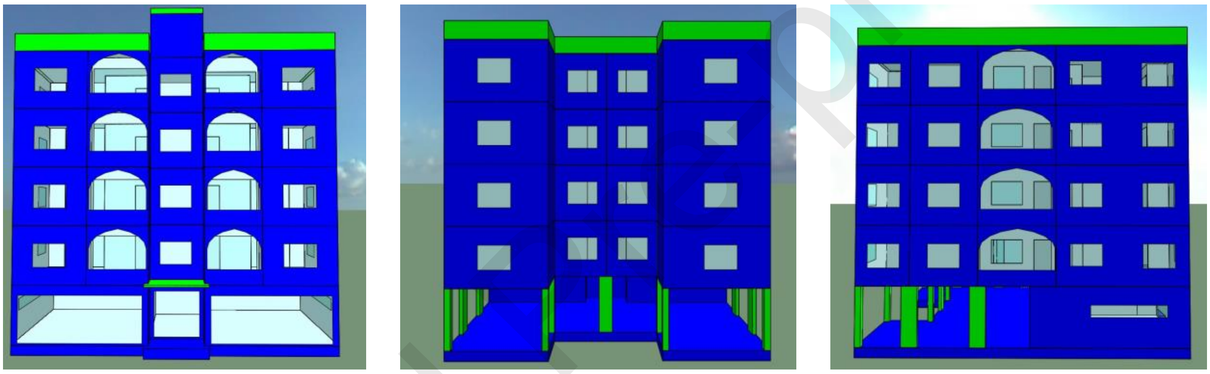


(b)

Fig. 10. (a) Orientation of the base-case RTB within the social-housing development estate; **(b)** Analytical energy model of the RTB within its surroundings.

The base-case representative building was modelled with a simple rectilinear form. In the modelling phase, only one form was considered to be the average 'urban' geometry factor, which was determined by the database analysis described in Section 3.5. To determine the technical parameters of the IES, the selection of archetypes permitted other factors—such as the number of floors, floor height, the width and length of the building and the distances and heights of the adjacent buildings—to be derived. Staircase spaces were allowed in each form and included within the total floor area, since these were observed in all the base-case buildings (see **Video A**).

In this study, the geometries of the existing RTBs were constructed directly in the IES ModelIT module, usually by tracing over the respective computer-aided design survey plans. In order to validate the data from the first phase, representative first-, intermediate- and upper-floor flats were modelled using ModelIT in the IES software, as illustrated in Figures 11 (a), (b) and (c).



(a) (b) (c)

Fig. 11. Analytical energy-simulation model of the analysed residential tower block; **(a)** south elevation view; **(b)** north elevation view; **(c)** representative west- and east-side elevation views.

For the base-case representative flats, floor heights were determined by site measurements; glazing heights were also either obtained by site measurements or based on external images. Notably, the outline geometries of the adjacent buildings considered to have potential shading effects were included for each building. In the development of this base-case scenario, a suitable holistic retrofitting scheme for the medium-rise social-housing typology was designed, and a replicable research-design approach was proposed by concurrently combining the experimental and analytical methods. Figures 12 (a) and (b) demonstrate the black-box model that was developed to calibrate BES in order to validate the findings from the IRT survey.

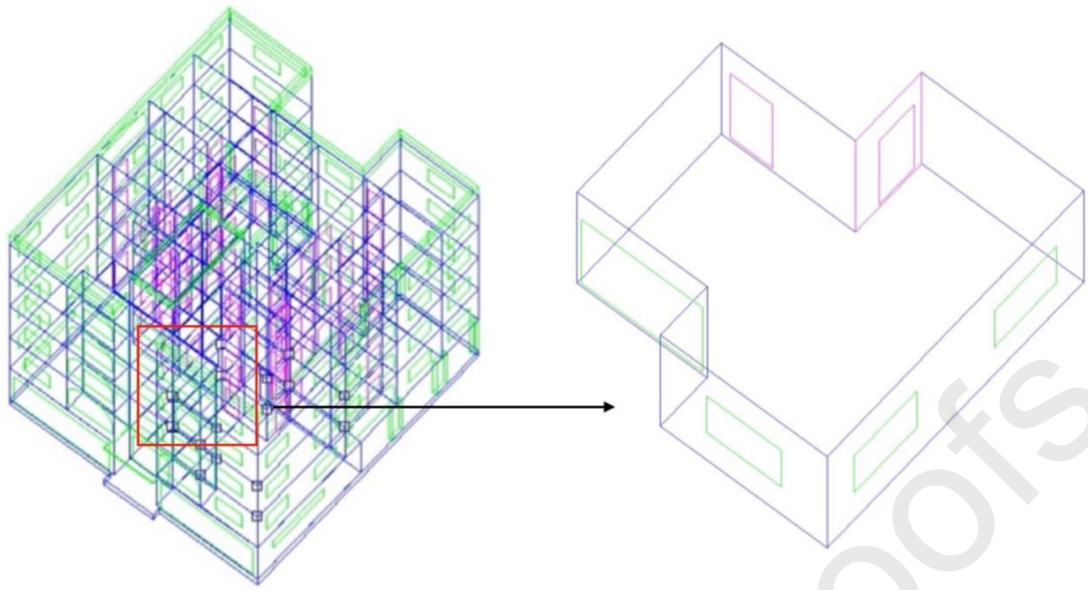


Fig. 12. (a) Analytical model of the representative RTB, which was built in the IES ModelIT interface; **(b)** black-box model of the living room of the sample units in the RTBs for the DTS analysis.

To calibrate energy-use measures, a room survey was employed to determine a standard room schedule and to record the characteristics of every room in each flat; this schedule included the principal characteristics that are listed in Table 7.

Table 7
Principal characteristics incorporated into the building-model simulation.

Room occupancy	Peak occupancy hours between 17:00 - 06:00
Materials	Glazing type, ceiling finish, floor finish, partitions, doors
Lighting	Source, lighting type, number of light bulbs
Space conditioning	Heating type, ventilation type, cooling type, space control method
Appliances	Personal computers [to include laptops and gaming stations], televisions/music systems, irons, washer/dryers [if these flats would have them in their individual homes], refrigerators, etc. – as the major heat producers/energy consumers.

An equipment inventory survey was completed in each room to obtain an accurate assessment of the total energy use in the occupied room spaces through simulation studies. Notably, a tally was maintained to evaluate the internal heat gain of each occupied space. Other equipment was recorded on the inventory checklist, which included a variety of domestic equipment—such as personal desktops, laptops, tablets and the like—and kitchen appliances. Table 8 demonstrates the simulation set input parameters assigned to the black-box model that was developed for the BES.

Table 8
Assigned profiles in the BES Model for calibration analysis.

Building Energy Performance Factors	
Location	35°.166015625,33.8896446228027
Weather Station	1253311
Outdoor Temperature	Max: 40 °C /Min:1 °C
Internal gross floor area	90 m^2
Number of floors	4 or 5 storey medium-rise RTBs
Area-to-volume ratio [m^{-1}]	0.33
Floor surface of a typical tested room	42.5 (m^2)
Room volume of a typical tested room	102.7 (m^3)
Window size	1.5 x 1.2 (m^2) per window pane
Exterior Window Ratio	0.21
Number of the subjects involved	1 male/1 female (parents), 2 girls and 1 son in-law
Age of the subjects	Between 23 and 57
Internal heat gains in the simulation	
Occuppants: 3W/m^2	Usage rate: 0.6 (15.8 kWh/m^2-year)
Appliances equipment: 3W/m^2	Usage rate: 0.6 (15.8 kWh/m^2-year)
Lighting: 8W/m^2	Usage rate: 0.1 (7.0 kWh/m^2-year)
Mechanical ventilation	No

Simulations of the energy use of the buildings can provide insights into how energy-efficient retrofitting efforts and operational changes can influence the total and temporal energy use of a building [134]. Before those models can be used to generate recommendations, however, it is important to understand how accurately the simulations are able to predict actual energy use [135]. This study sought to determine model accuracy by employing the black-box model to calculate the boundary conditions of each space into the analytical energy model [136]. The thermal characteristics of all considered constructions are summarised in Table 9.

Table 9
Thermal characteristics of the construction elements of the prototype RTB.

	S[cm]	**U [W/(m^2K)]**	**M [kg/m2]**	**C [kJ/(m^2K)]**
Vertical walls	35.00	0.3.479	305	264
Roof	36.00	1.20	317	302
Floor	28.50	1.66	303	258
Windows	-	2.91	-	-
Internal floors	28.50	1.63	298	256
Internal walls	11.0	1.57	92	84

To provide a novel methodological flow for the energy-calibration analysis, the development of the black-box model demonstrated the impact of the adaptation of some energy-efficiency technologies in a real-life context and allowed us to better understand the uncertainty between the predicted and actual energy use in the residential sector [137]. For this reason, detailed energy models were developed to measure the impact of space volume and the thermal properties of the building envelopes while documenting occupancy profiles and window-opening schedules into the ApacheSIM interface of the IES model.

3.9.2 Weather files assigned in simulation model

In this empirical study, the base-case model was simulated by using the weather file that was defined with data that was obtained between May and September of 2018 from the closest weather station, which was located in Paralimni in the Famagusta district (*Ammochostos* in Greek): the ASHRAE Climate Zone 2A. The output of the dynamic-thermal simulations was then compared to the households' actual energy bills collected between 2015-2016, to discern the cooling demand for each occupied space by determining the deviations and the relevant uncertainty parameters in the simulation model [138].

The test reference year (TRY) weather files were used to conduct the DTS for a period of one year between January and December 2018. It is worth mentioning that several modifications were made during the calibration phase in order to avoid any risk of data loss while generating actual meteorological weather files to assess the overheating risk of each occupied space in the RTBs. These modifications were primarily related to the inner load and occupancy schedules that were updated with information provided by the building-occupancy survey. To avoid discrepancies on both TRY and actual meteorological year (AMY) weather files were comprehensively analysed, and apart from the weather files customised in the simulation program, this study used weather files constructed after gathering meteorological data from the EnergyPlus weather datasets [139]. In order to adjust weather files, the constructed weather profiles, including both heating degree days (HDDs) and cooling degree days (CDDs) were compared with the weather files assigned to the weather profiles in the IES building energy modelling platform [140].

It should be noted that energy calibration model was developed to provide subsequent basis information in order to establish the simulation set input parameters for the DTS analysis [141]. This means that the base model was simulated with input weather files created from data that was available for the generated weather files from the closest station for the same year, or with weather files of the typical reference year that were conducted according to the algorithm that was recommended by the EN ISO 15927-4: 2005 standard, which was related to the thermal performance of buildings [142]. In this study, the available datasets were generated into IES weather-file extensions by using the Weather Analytics software suite in order to assess the overheating period that extended from May to September 2018.

3.9.3 Rationale for the selection of weather files for the energy modelling

In this study, the effect of the thermal transmittance of the U-value of each building was simulated according to an adaptive thermal-comfort approach, which was in line with the relevant European BS EN 15251 standard [143]. The case-study location was the coastal city of Famagusta, which is located along the eastern periphery of Cyprus, a local climate characteristic that is known for its hot, humid summers. This is why the 2018 CIBSE weather files were adopted by IES and used to produce the psychometric chart, which served as a climate analysis interface tool for the IES software that automatically interpreted the climate variables for the typical meteorological-year data for this location, as shown in Figure 13.

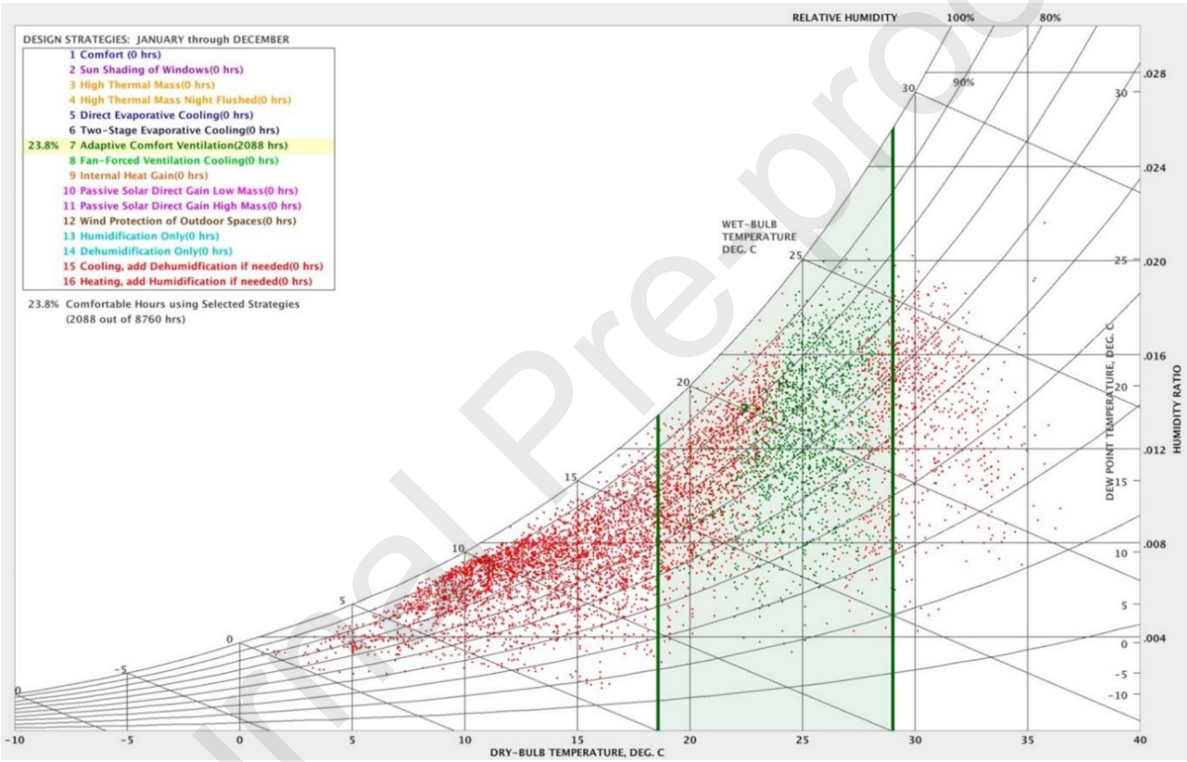


Fig. 13. Psychometric chart for Famagusta and the amount of solar radiation of the prototype residential tower block. ***Source:*** Diagram was extracted from the Climate Consultant Version 6.0.13 (60.13); software suite was developed in 2018 by the University of California (US).

As shown in Figure 13, the software that produced the psychometric chart can be utilised to plot the temperature and relative humidity that occurred over a period of 3.865 hours in accordance with the generated weather climate data of the year from the CIBSE's database. Different design specifications and comfort-index parameters were represented by specific zones on the psychometric chart [144].

3.9.4 Shading, night ventilation and indoor set-point temperature

The shading strategy was modelled to consider the likely activation of different appliances by the occupants. For this reason, the condition for the application thereof in the simulation software was the amount of solar radiation that arrived on the large glazed surfaces, which was set at 100 W/(m^{2}K) in order to take into account the issue of overheating. The shading devices that were applied to every flat were external Venetian blinds. Within the simulation software, the shading type needed to be represented with a decreasing factor of solar-heat gains through the windows and with the position thereof both internally and externally, which served to calibrate the related thermal performance (see **Video B**).

Indoor environmental input parameters for the design and assessment of building energy performance addressed the indoor air quality, thermal environment and lighting benchmark; night ventilation was modelled between 23:00–07:00 during the cooling season, specifically when the indoor operative temperature exceeded the cooling set-point, with an increase in the air-change rate of 0.5 h^{-1}, which was recommended as a value that was low-but-consistent with ventilation rates that were naturally achievable through single-sided openings (see **Video C**).

The comfort requirements from the EN 15251 international standards were expressed in terms of an operative temperature, and the prototype case-study RTB set-point regulation was performed according to this value [145]. As such, T_{op} values of 26°C for cooling, as delineated in EN 15251 for a normal level of comfort, were set for the energy-need analysis of the prototype RTB [146]. In this regard, since the CEN adaptive method provided in EN 15251 was valid for an outdoor reference temperature that was as high as 30°C, only the running mean temperature equation thereof was considered for this study, which applied up to 33.5°C and was therefore more applicable for the Mediterranean climatic context [147].

4 Analysis and Results

In this section, simulations and calibration studies have been examined according to the recommended international benchmarks and criteria to assess overheating risks and the thermal comfort of the occupants, and the thermal transmittance of building properties have been taken into consideration. In the calibration analysis, the southwest-facing RTBs were chosen as the base-case representative buildings in order to investigate the existing energy performance of the representative flats for further energy simulations. To further to validate the findings, the indoor air temperatures have been calibrated during the DTS of the indoor occupied spaces and have been discussed in Sections 4.4.1 and 4.4.2.

4.1 Thermal imaging: walk-through survey

The case study RTBs were surveyed, and IRT imaging was conducted twice each day during the winter period with a Fluke TiS20 thermal camera—in the late evening and early morning hours to avoid possible errors caused by direct solar radiation (see **Appendix A.2** and **A.3**). To achieve the objective of the present empirical study, a socio-technical-systems (STS) conceptual framework was implemented to assess the influence of thermal transmittance of building properties. To accomplish this, the calculation method was classified or divided into two main sections, which are shown in Figure 14.

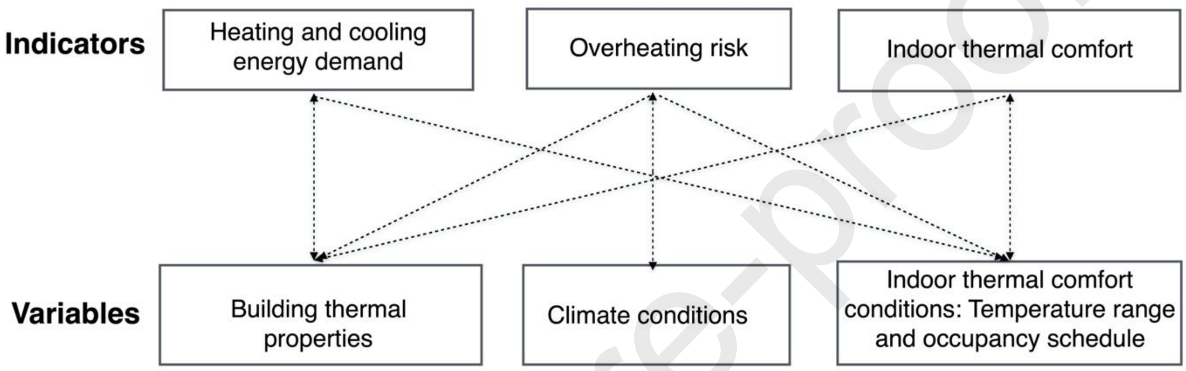


Fig. 14. Calculation-methodology scheme.

This section presents the findings of a walk-through thermal-imaging survey that was conducted in the winter prior to the *on-site* questionnaire survey, *in-situ* physical indoor-environment measurements and *on-site* environmental monitoring that were performed in August of 2018. These results were also validated by the SunCast application of the IES software suite, which sought to analyse the importance of the solar-irradiance factor onto building envelopes. Temperature readings from approximately 2830 images were analysed using the forward-looking infrared radiometer (FLIR) analysis tool to diagnose the thermal performance of all 36 prototype RTBs for bridging the energy performance gap of social housing stock. These assessments were performed during the 2017–2018 winter months, and all of the survey data were used to model the base-case building and validate the building-energy-simulation findings. Table 10 demonstrates the timeline for the thermal-imaging investigations related to heat loss and overheating-risk assessment that was conducted between December 26, 2017 and January 12, 2018.

Table 10
Timeline of base-case representative RTBs surveyed in December 2017 and January 2018.

Date	Time	Weather Conditions Observed at Time of Walk-Through Survey	Outdoor Temperature Mean (°C) (*In-situ*)	Outdoor Temperature Min (°C) (*In-situ*)	Outdoor Temperature Max (°C) (Ercan Airport)
December 26, 2017	06:30–07:45	Sunny/clear cloudy; slightly cold	13.4	9.0	19.1
December 26, 2017	16:00–16:45	Sunny/clear cloudy; slightly cold	13.4	9.0	19.1
December 28, 2017	06:30–07:45	Sunny/clear cloudy; warm	17.4	11.6	20.5
December 28, 2017	16:00–17:00	Sunny/clear cloudy; warm	17.4	11.6	20.5
December 29, 2017	06:30–07:45	Sunny/clear cloudy; warm	15.0	9.3	18.8
December 29, 2017	16:00–17:00	Sunny/clear cloudy; warm	15.0	9.3	18.8
January 2, 2018	16:00–17:00	Sunny/clear cloudy; slightly cold	15.6	11.9	19.6
January 3, 2018	06:30–08:15	Cloudy/scattered rain; no wind; warm	15.6	11.6	19.1
January 3, 2018	16:00–17:15	Cloudy; torrential rain; slightly windy; warm	15.6	11.6	19.1
January 4, 2018	16:00–17:15	Rainfall AM; cloudy; mild weather	14.8	13.2	17.1
January 6, 2018	06:30–07:45	Cloudy; no wind	15.0	10.1	17.2
January 6, 2018	16:00–17:30	Cloudy/sunny; slightly cold	15.0	10.1	17.2
January 8, 2018	06:30–08:15	Clear sky; cold	13.7	9.4	18.9
January 8, 2018	16:00–17:30	Sunny/clear sky; warm	13.7	9.4	18.9
January 9, 2018	06:30–08:15	Sunny/clear sky; warm	14.1	10.0	18.2
January 11, 2018	15:35–17:30	Sunny/cloudy; warm	16.9	11.9	19.6
January 12, 2018	16:00–17:30	Sunny/cloudy; warm	14.6	9.9	19.5

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

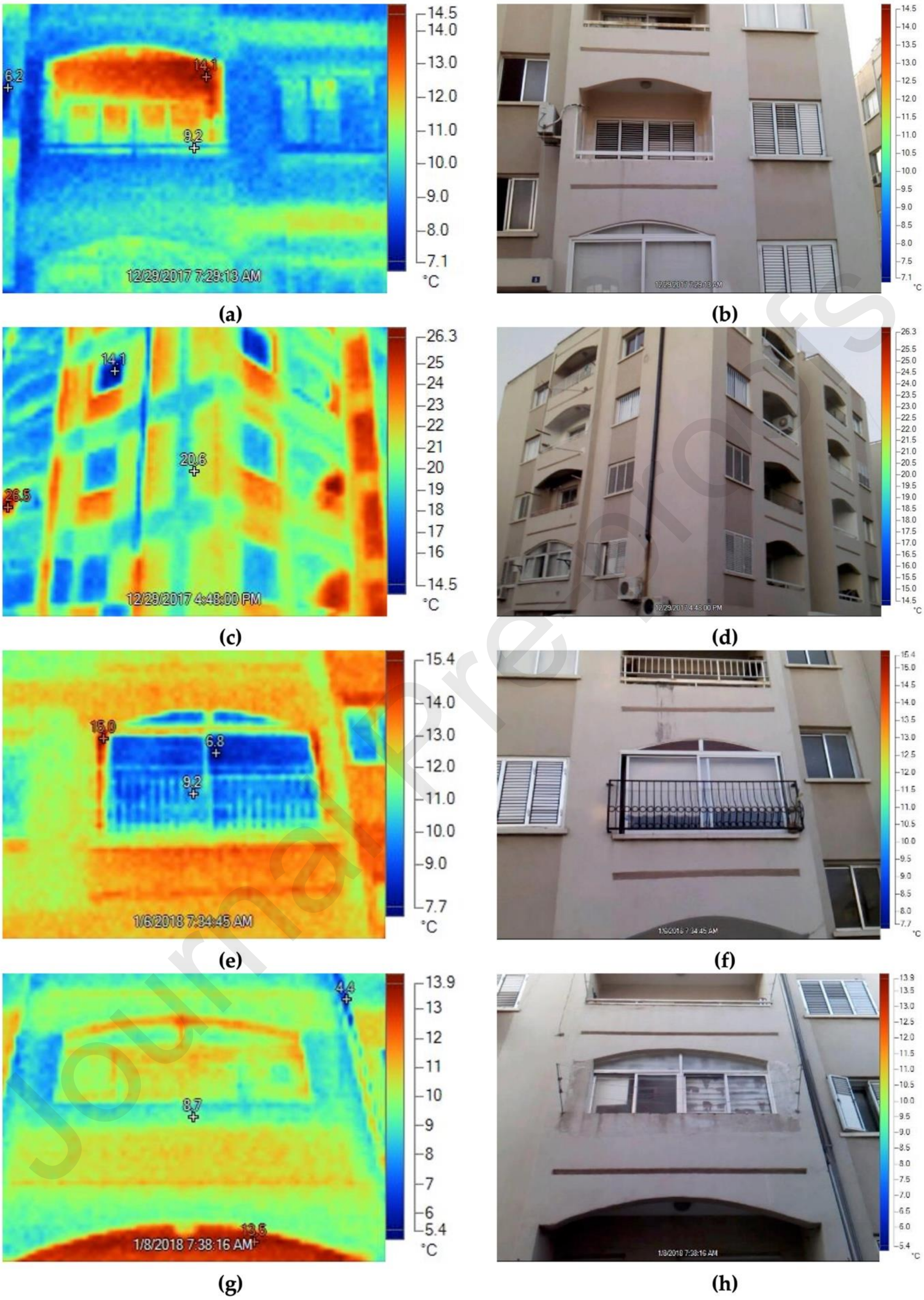


Fig. 15. (a)–(g) IRT survey analysis of base-case RTBs.

Figures 15 (a)–(h) illustrate the findings of the extensive thermal-imaging survey that was conducted between December 27, 2017 and January 8, 2018 to detect the types of thermal anomalies in the RTBs. This analysis examined temperature differences and variations across each RTB building envelope and output of potential thermal anomalies. This resulted in the calibration of the thermal performance of the buildings and an assessment of the overheating risks and domestic energy use by employing a triangulation of the research methods with the energy bills of each household and the BES analysis [148].

As is shown in Figure 15 (a), the southeast elevation exhibited heat loss through the external wall, possibly due to the absence of insulation material. It was determined that the building-envelope surface temperatures ranged between 7.1°C and 14.5°C. The image taken on December 29, 2017 between 06:30–07:30, at which time the outdoor temperatures were recorded at 10°C.

In Figure 15 (b), the occupants of the southeast elevation had installed large, glazed windows and an aluminium external-shutter system to avoid incoming solar radiation. Throughout the *on-site* observations, this was the most common refurbishment effort that had been undertaken by the occupants in order to avoid solar radiation, to acclimatise the indoor air temperatures and to lessen noise pollution.

In Figure 15 (c), the southeast elevation demonstrated significant heat loss through the windows and the wall-junction details, and there were cracks on the building surface. The building-envelope surface temperatures ranged from 14.5°C to 26.3°C. The image was taken on December 29, 2017 between 16:30–17:00, and the outdoor temperatures were recorded at 10°C.

In Figure 15 (d), the southeast elevation revealed that the occupants' installation of a wood-burning stove heating system led to significant heat loss through the building surface, because there was no central heating system installed in the RTBs due to the absence of a natural gas infrastructure system in Cyprus. This demonstrated that this type of housing stock is susceptible to overheating in the summer.

One another issue is that these households installed the mechanical ventilation shafts for the wood-burning stoves without considering health-and-safety guidelines that were recommended by the Chamber of Architects. Throughout the *on-site* survey, we observed that these households installed the service shafts for the wood-burning stove and for the A/C compressor in close proximity to one another, which caused damage to the building envelope and resulted in significant heat losses.

To examine the deficiencies caused by the household modifications on the building envelope, we recorded a series of images from the living room and kitchen balcony to document the type of refurbishment activity. As presented in Figure 15 (e), the southeast elevation demonstrated heat loss through the external wall and the large glazed window surfaces in the living room space. The image shows the most common refurbishment undertaken by occupants to increase the floor area of the living room. Most households had operable double-glazed window systems that were installed to cover the balcony areas in order to adjust the frequency and effectiveness of natural ventilation; the image was taken on January 6, 2018 between 06:30–07:45. In Figure 15 (f), the occupants of the southeast elevation utilised internal roller blinds to avoid sun exposure in summer. Building-envelope surface temperatures ranged between 7.7°C and 15.4°C, and the outdoor temperatures were recorded at 10°C.

Thermal anomalies were detected in Figure 15 (g); the southwest elevation exhibited heat loss through the external wall, possibly due to the lack of space in the kitchen. Most of the households across the surveyed RTBs had refurbished their kitchen spaces; this was motivated by a lack of kitchen floor area and inadequate space for meal preparation, and the modifications led to significant heat loss through the wall surfaces. The image was taken on January 8, 2018 between 06:30–07:54. In Figure 15 (h), the southwest elevation reveals the most common refurbishment activity in the kitchen spaces that was undertaken by occupants; the images reveal that the building-envelope surface temperatures ranged between 5.4°C and 13.9°C. This walk-through site-measurement method enabled us to identify the worst-performing RTB in order to conduct further calibration studies in the building-modelling phase of the study, which is described and discussed in Section 4.4.

4.2 In-Situ Measurements: Walk-in survey

In conjunction with the thermal-imaging survey that was undertaken in the winter of 2017–2018, an internal thermography was performed in the summer of 2018 to measure the heat gains that were coming through the deficient building envelopes at the time of our survey, which was conducted between July 28, 2018 and September 3, 2018; a total of 118 flats were inspected with this technology. Figures 16 (a)–(f) illustrate the recorded temperature readings to demonstrate the detected thermal deficiencies of the different building envelopes.

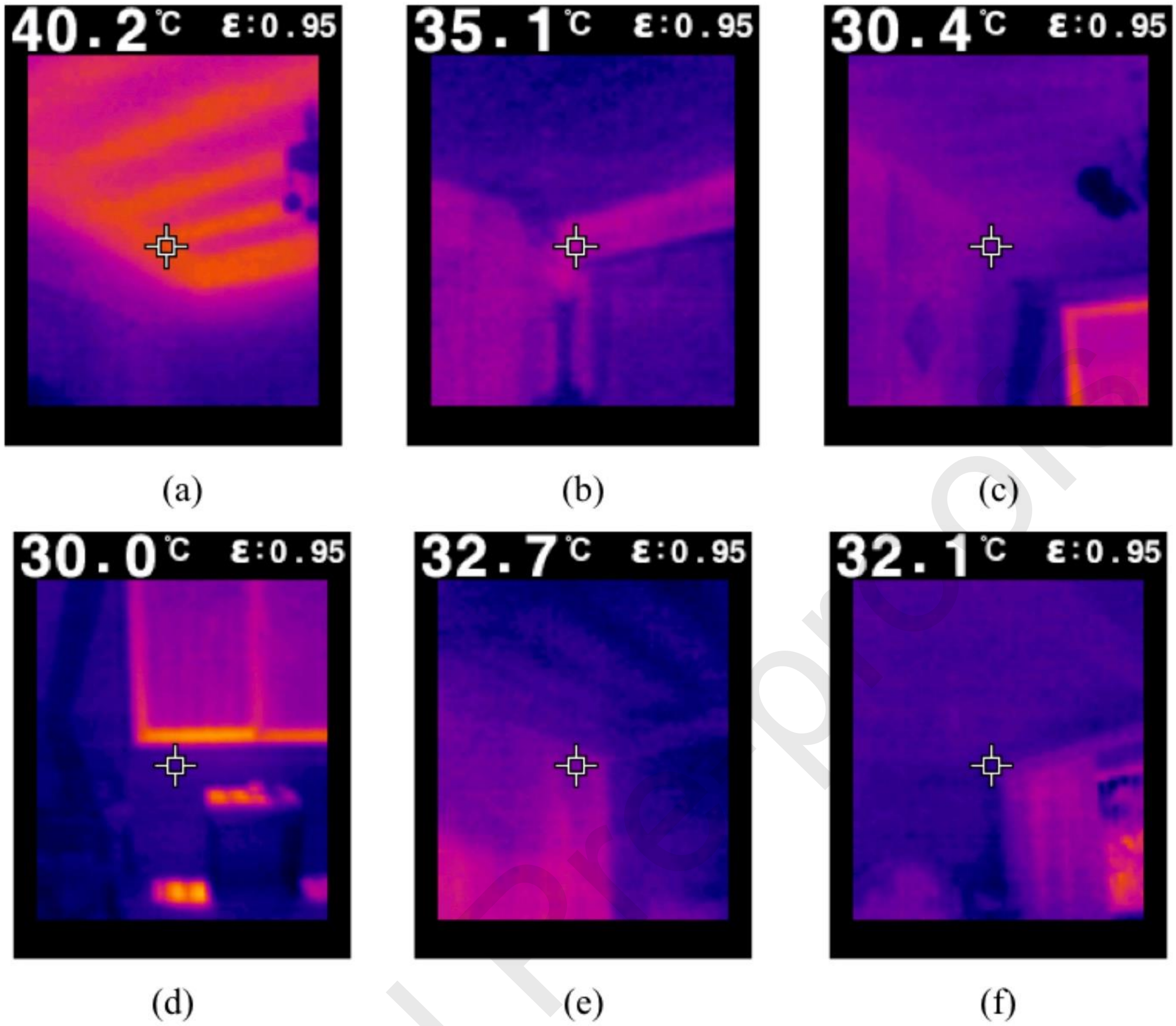


Fig 16. (a)–(f) Sample of summer thermal-imaging analysis.

Figure 16 (a) demonstrates the thermal performance of the ceiling surface, which was measured at 40.2°C in the living room of the top-floor southwest-facing flat at 17:35 on the peak day, August 10, 2018, with an outdoor temperature of 36°C; it can be seen that the roof surfaces absorbed a high level of solar radiation due to a lack of insulation. Figure 16 (b) illustrates the thermal performance of the side wall surface of the kitchen of the top-floor southeast-facing flat, which was measured at 35.1°C; a high indoor air temperature was recorded on the northeast-facing side wall due to heat acclimatisation, and a relatively high outdoor temperature was recorded. The results revealed that the overheating risk of the living room and the kitchen was due to deficient building envelopes. Notably, the windows in both the living room and kitchen spaces were kept open 6–8 hours each day in the summer.

Figure 16 (c) shows the thermal performance of the ceiling surface, which was measured at 30.4°C in the living room of the southeast-facing intermediate-floor flat at 10:05 on the peak day, August 1, 2018, with an outdoor temperature of 29°C. At the time of the thermography survey, the wall-mounted air conditioner set at 19°C and had been in use for approximately two hours. Thermal anomalies of regular shapes and clearly identified boundaries were associated with the underlying structure, and even temperature-distribution within this pattern was demonstrated; this image reveals an area of the ceiling where the flat that was located above had been ineffectively constructed. Figure 16 (d) demonstrates the thermal performance of the side wall of the living room of the southeast-facing intermediate-floor flat, which was recorded as being 30.0°C. The southeast wall exhibited significant heat gains that were coming in through the aluminium-framed single-glazed windows. Moreover, air leakage caused thermal anomalies with irregular shapes; deficiencies in the window-frame structure and large temperature variations that formed characteristic ‘streaks’ or ‘ray’ patterns were detected. In this image, air leakage through the deficient window frame led to notable heat loss, which accounts for the slightly uncomfortable indoor air temperatures, despite the use of air conditioning during the morning occupancy hours.

Figure 16 (e) illustrates the thermal performance of the ceiling surface of the living room in the south-facing first-floor flat, which was recorded as being 32.7°C at 09:25 on the peak day, August 16, 2018, with an outdoor temperature of 29.7°C; at the time of the thermography survey, the windows in the living room had been kept open for natural ventilation. Similar anomalies that were caused by inefficient construction were detected on the ceiling surfaces. This thermography survey captured the predicted heat gains in the enclosed balcony space that occurred through the large glazed opaque window surfaces; it was determined that this type of structural modification by the occupants led to an increase of 2–3°C in the indoor air temperature. In Figure 16 (f), the thermal performance of the ceiling surface of the living room of the southeast-facing ground-floor flat was recorded as being 32.1°C at 11:25 on the peak day, August 1, 2018, at 11:25, with an outdoor temperature of 30.1°C; at the time of the thermography survey, the portable fan was in use and windows were open, and a significant thermal anomaly was detected on the aluminium-framed single-glazed window structure.

The results from the internal walk-through thermography surveys revealed that all of the 36 RTBs and 118 flats that were inspected exhibited signs of potential thermal anomalies that were characterised as either air leakages or conductivity heat sources. Notably, no instances of moisture-related anomalies or service faults were detected. Figure 17 illustrates the overheating-risk mapping of the selected flats to provide an overall understanding of the thermal vulnerability of social-housing stock.

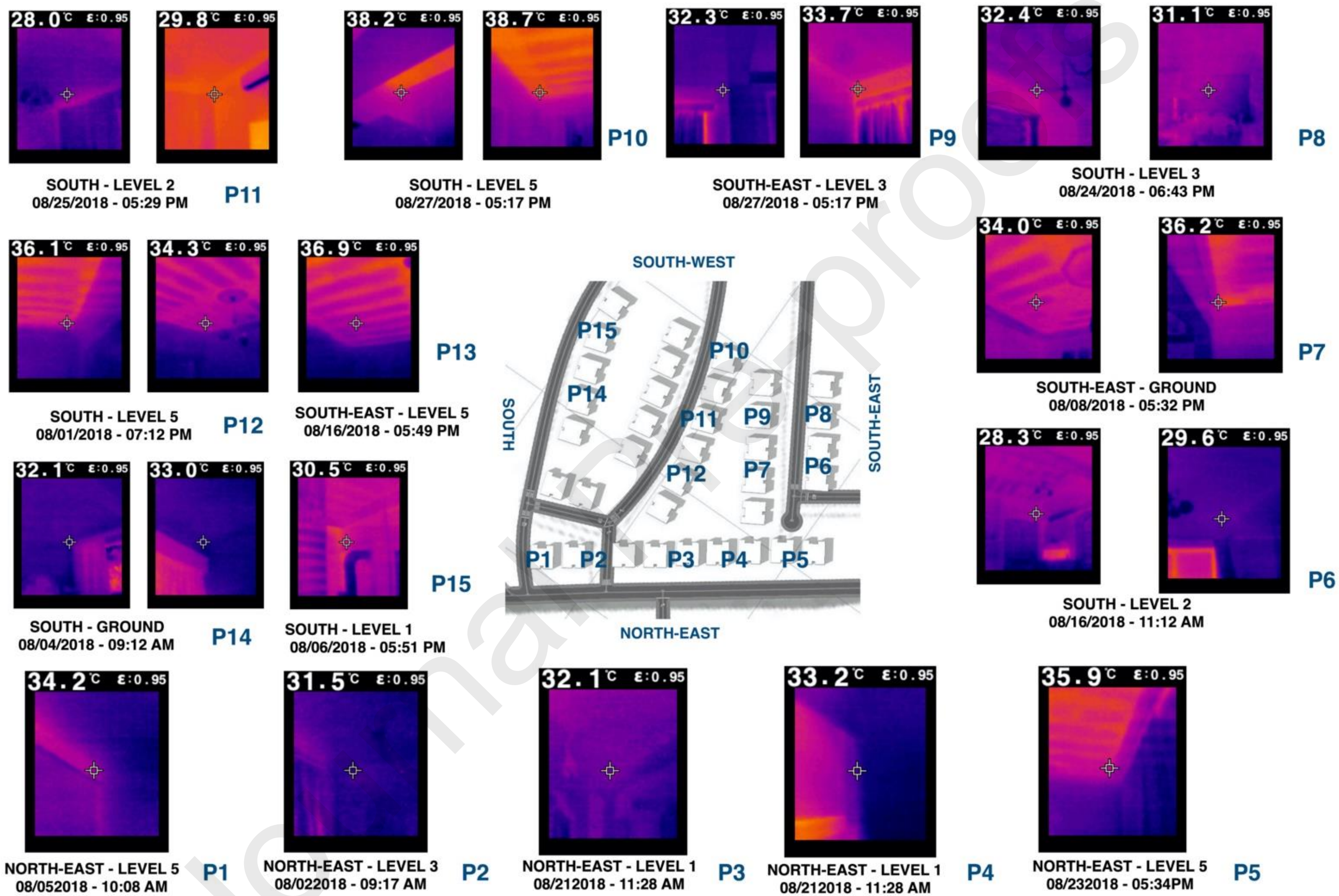


Fig.17. Point-by-point mapping of indoor walk-through thermal-imaging survey conducted, taking different floor levels and impact of different time of day on overheating risk assessment into account.

4.3 Household energy bills

An evidence-based factor that was used to validate the thermal anomalies that were detected throughout the IRT survey was the monthly utility bills for each household. For the calibration analysis, monthly electricity bills were collected to assess the thermal performance of the RTBs, especially during the hottest period in August. In order to assess the overheating risk of the investigated flats, the orientation of each representative flat was taken into consideration; based on these data, it was found that the orientation of each block was an important factor in the energy consumption patterns of each household. These data cover the winter of 2014–2015 (December through February) and the summer of 2015 (June through August). Figures 18(a) and (b) illustrate the energy bill analysis for each household, which took the orientation factor of the sample flats into account.

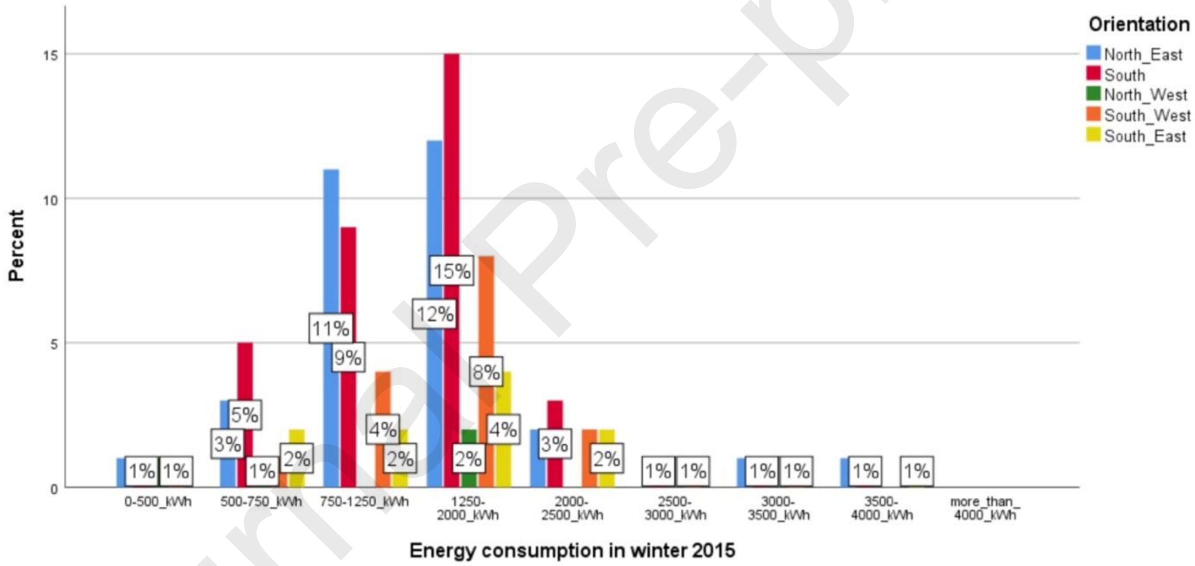


Fig. 18 (a) Percentage distribution of the energy consumption of households with different orientations in the winter.

Figure 18 (a) illustrates the energy consumption of the occupants in the winter of 2014–2015: Of the households living in south-facing RTBs, 5% consumed 500–750 kWh; 8% consumed 750–1250 kWh; 15% consumed 1.250–2000 kWh; 3% consumed 2000–2500 kWh; another 3% consumed 2500–3000 kWh; and a final 3% consumed 3500–4000kWh. The energy-consumption patterns in the southwest-facing RTBs were as follows: 4% of the households consumed 750–1250 kWh; 6% consumed 1250–2000 kWh; 5% consumed 2500–3000 kWh; and a final 5% consumed 3500–4000 kWh. The northeast-facing RTBs showed higher energy-consumption rates because in the south and southwest-facing RTBs, 3%

consumed 500–750 kWh; 11% consumed 750–1250 kWh; 12% consumed 1250–2000 kWh; 4% consumed 2000–2500 kWh; and a final 4% consumed 3500–4000 kWh. Contrary to expectations, the northeast-facing RTBs revealed that the household energy consumption was higher than the average of the entire sample, and it can be seen that the south-facing RTBs exhibited the highest energy consumption of the entire sample.

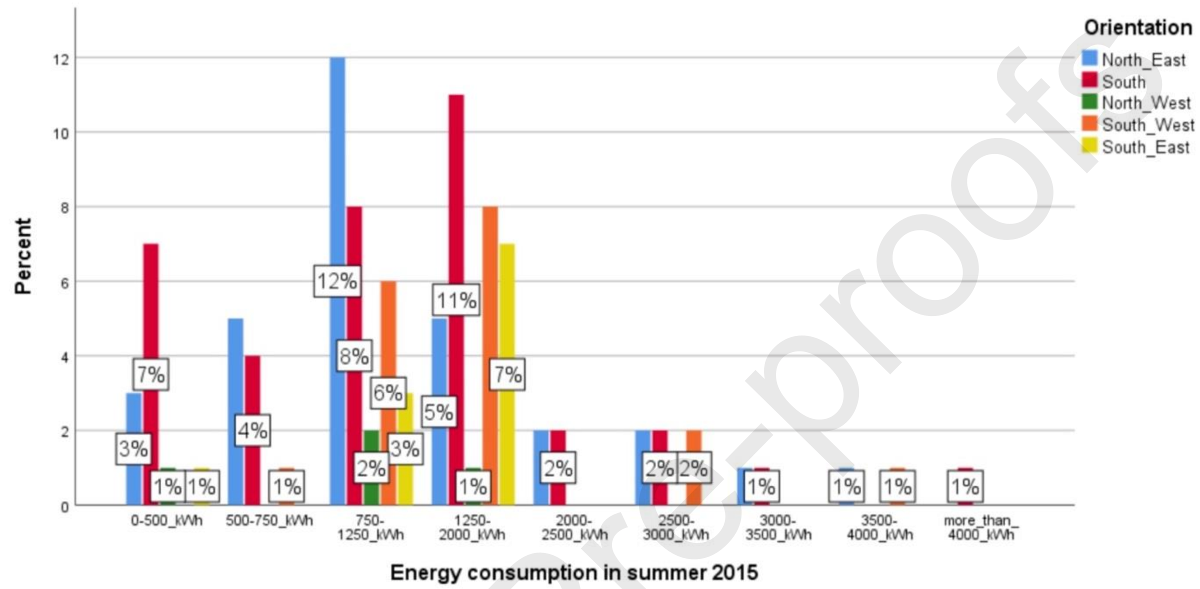


Fig. 18. (b) Percentage distribution of the energy consumption of households with different orientations in the summer.

Figure 18 (b) illustrates the household energy consumption patterns in the summer of 2015. It was determined that the south-facing flats consumed the most energy: 7% of the households consumed 0–500 kWh; 4% consumed 500–750 kWh; 8% consumed 750–1250 kWh; 11% consumed 1250–2000 kWh; 3% consumed 2000–2500 kWh; and a final 3% consumed more than 4000 kWh. This energy consumption pattern was followed by that of the southwest facing blocks: 6% of the households consumed 750–1250 kWh; 8% consumed 1250–2000 kWh; 2% consumed 2500–3000 kWh; and 1% consumed 3500–4000 kWh. The highest level of energy use was observed in the south-facing RTBs: 3% of the households consumed 0–500 kWh; 5% consumed 500–750 kWh; 12% consumed 750–1250 kWh; 5% consumed 1250–2000 kWh; 3% consumed 2000–2500 kWh; and a final 3% consumed 3500–4000 kWh.

These findings demonstrate that the households that were situated in the southwest-facing blocks consumed more energy because of the absorption of strong solar radiation through the building envelopes of the RTBs. Moreover, the households with a northeast orientation consumed similarly the same amount of energy as the south-facing blocks. It can be deduced from these data that even though orientation is an important factor related to the level of energy consumption, the real cause of high consumption was heat losses came through RTB building envelopes and the absence of insulation material on the external walls.

The effects of the different floor levels on the energy consumption of each representative flat were investigated. The results revealed that the flats that were situated on the fifth floor consumed more energy, because they were cold due to heat loss through the uninsulated roof surfaces; and the first-floor flats were cold because of their floor position, which caused them to not get adequate exposure to the sun. It was found that the energy consumption of the ground and first floors was similar to that of the top floor due to the high number of occupancy patterns observed on the first-floor level flat. Table 11 delineates the minimum, maximum, mean and standard deviations (*SD*) of the actual household energy consumption in the summer of 2015 and winter of 2015–2016.

Table 11
The descriptive analysis of households' actual energy bills in the summer of 2015 and winter of 2015-2016 and in August of 2015 and 2016.

Energy Consumption	Minimum kWh	Maximum kWh	Mean kWh	*SD* kWh
2015 Winter	355	3961	1454	734.280
2015 Summer	171	4639	1366	824.537
2016 Winter	355	3961	1454	734.280
2016 Summer	291	4798	1583	986.622
2015 August	27	1658	465	317.612
2016 August	63	1223	374	262.500

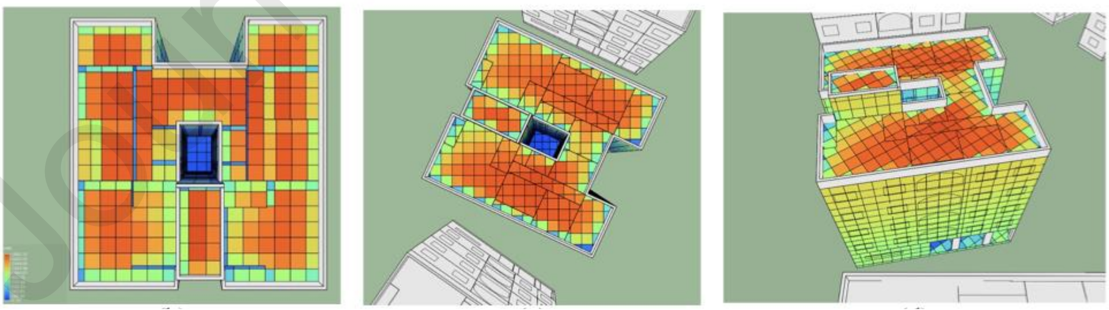
Table 11 reveals that the households expended approximately the same amount of energy to keep their respective indoor air environments warm in the winter and cool in the summer. These results also confirm that the occupants experienced highly uncomfortable indoor conditions due to the RTBs' building envelopes. The energy consumption of each household provides information that will validate the *on-site* questionnaire survey, *in-situ* measurements and the building-modelling simulation results that are described and discussed in the following Section 4.4.

4.4 Building energy simulations

Building-energy and thermal-modelling simulations were undertaken using the IES software suite, and the results thereof were used to validate the survey findings. The aim was to develop a viable model that could be adopted into the development of a methodological framework to identify the discrepancies between actual and predicted energy use, including the identification of thermal lags that were observed during the IRT survey analysis.

4.4.1 Solar exposure analysis

The SunCast simulation module was used to validate the qualitative and quantitative analyses of the survey findings that were obtained from the on-site observations, thermal imaging and *in-situ* measurements before conducting DTS studies for the purpose of model calibration. The solar-exposure analyses were divided into three stages in order to fully understand the impact of the building envelope on the overall energy performance of the development. (see **Dataset B**). The first stage was carried out for the entire building simulation between January and December of 2018; the second phase was undertaken between May and September of 2018, which is the cooling period that was recommended by *CIBSE TM 52* to assess the risk of overheating in residential buildings; and the final phase focused on the peak cooling month of August of 2018 to provide a basis to compare the simulation results with the survey findings. The percentage of hours that fell into different design-strategy zones offered a relative idea of the solar irradiance factor and thermal absorptivity levels of building envelopes as shown in Figures 19 (a)–(c).



(a) (b) (c)

Fig. 19. (a)–(c) Solar absorptivity of building envelopes, which shows that the flats were susceptible to overheating in the summer.

Figures 20 (a)–(f) show the maximum solar radiation, as well as the mean values for each of the three different analyses that were adopted in the worst-case scenario for the southwest-facing RTB.

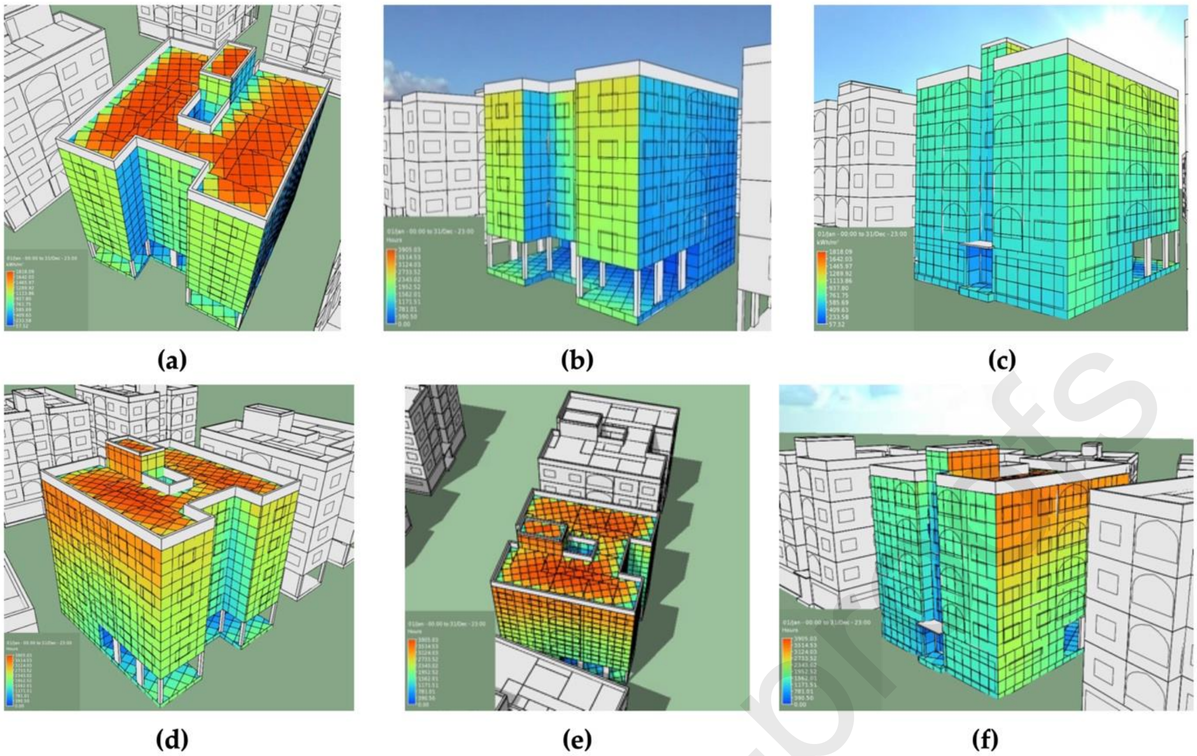


Fig. 20. (a)–(f) Step-by-step solar exposure analysis of the southwest-facing prototype RTB for the worst-case scenario.

In Figure 20 (a), the SunCast simulation analysis reveals that the annual maximum conduction gains due to higher absorptivity were characterised by a high-transmittance roof construction with a U-value of 1.20 W/m^2 K. The image illustrates the position of Bedrooms 2 and 3 with a southeast orientation; it can be seen that between January and December of 2018, the deficient building surfaces absorbed 1.818.09 kWh/m^2.

In Figure 20 (b), the SunCast simulation demonstrates that the annual exposure to solar radiation on the southeast- and southwest-oriented façades between January and December of 2018 reached a total of 3.905.03 hours. Throughout the year, the shading factor from the adjacent building had a significant impact on the southwest-oriented façade of the building.

In Figure 20 (c), the SunCast simulation analysis shows that the maximum annual conduction gains due to higher absorptivity were characterised by high-transmittance external wall construction with a U-value of 3.47 W/m^2 K. The image illustrates the south-oriented front façade, where all living room spaces are positioned; and it also illustrates the southeast-oriented flats, where the living room, kitchen and Bedrooms 1 and 2 spaces were positioned. It can be seen that between January and December of 2018, the deficient building surfaces absorbed 1.818.09 kWh/m^2.

In Figure 20 (d), the SunCast simulation demonstrates that between January and December of 2018, the annual exposure to solar radiation of the southeast-oriented façade reached a total of 3.905.03 hours. It is evident from the illustrations that throughout the year, the upper floor of the southeast-oriented unit absorbed a particularly high proportion of the solar radiation throughout the year.

In Figure 20 (e), the SunCast simulation demonstrates the annual hours of solar radiation exposure of RTBs between January and December of 2018. It can be seen that south- and southeast-facing exposed surfaces absorbed high levels of solar radiation due to inefficient building envelopes. The results reveal that in the upper-floor flats, occupants experienced significant overheating. It therefore appears as if the SunCast simulation for the entire building analyses provides indications that validate the results of the thermography walk-through survey and the *in-situ* measurements that were undertaken in the winter and summer.

Based on the field-survey findings, it was observed that most of the south-facing RTBs and upper-floor flats experienced high indoor air-temperature ranges that were above the upper threshold comfort limit of 25°C. In Figure 20 (f), the SunCast simulation demonstrates that between January and December of 2018, the annual exposure to solar radiation on the southeast-oriented façade reached a total of 3.905.02 hours. It can be seen that the base-case RTB was constructed in an angular line; the illustration shows the significant effect of orientation and the distance from adjacent buildings on energy performance.

As seen in Figures 20 (a)–(e) of the representative flats, only three external surfaces were exposed, and all three exhibited different heat gains throughout the year with noted exacerbations in the summer. This created overheating risks due to poor insulation in the exposed wall. Upper-floor flats demonstrated the greatest risk of overheating due to the impact of the deficient building envelopes and the solar panels for the hot-water tanks that were placed on top of the original surface. For this reason, all the bedroom spaces in the upper- and intermediate-floor flats experienced a greater likelihood to overheat, compared to the *CIBSE TM 52* overheating criteria [149]. The living rooms of these flats were also susceptible to overheating, but from different factors: The rooms had large window-opening ratios with no shading, and the spaces all faced either south or southeast and were thus exposed to high-intensity sunlight throughout most of the day; while the external walls, which were constructed from brick and exterior rendering without insulation, were also exposed to high solar-heat gains. The combination of these factors led to overheating issues and significant occupant discomfort, especially in the summer [150,151].

4.4.2 Overheating risk assessment

This section focuses on reporting the collated data, along with providing an analysis and interpretation thereof in order to explain the findings of the methodological approach that was developed to diagnose the thermal performance of the existing housing stock by adopting the international *CIBSE TM 52* benchmarks related to an overheating risk assessment (see **Dataset C**). The building's indoor environment conditions and the thermal comfort thereof in the summer were analysed and are shown in Table 12.

Table 12
Simulation-based thermal comfort of all occupied rooms in the baseline model.

Occupied Spaces:	Temperature (℃)		RH (%)		PPD (%)	
Flat Location, Room Name	Max.	Min.	Max.	Min.	Max.	Min.
FIRST_FLOOR_Livingroom	36.2	23.0	100	26.6	100	13.1
FIRST_FLOOR_Bedroom1	35.2	23.0	100	25.9	95.6	11.7
FIRST_FLOOR_Bedroom2	36.2	23.0	100	24.6	98.9	10.9
FIRST_FLOOR_Bedroom3	35.2	23.0	100	26.0	93.5	11.3
INTERMEDIATE_FLOOR_Livingroom	35.2	23.0	100	25.8	97.6	12.5
INTERMEDIATE_FLOOR_Bedroom1	34.4	23.0	100	27.4	94.5	10.1
INTERMEDIATE_FLOOR_Bedroom2	35.4	23.0	100	25.6	98.9	10.1
INTERMEDIATE_FLOOR_Bedroom3	35.1	23.0	100	26.2	94.1	10.5
UPPER_FLOOR_Livingroom	36.4	23.0	100	26.2	100	12.8
UPPER_FLOOR_Bedroom1	35.3	23.0	100	25,7	98.0	11.7
UPPER_FLOOR_Bedroom2	36.1	22.3	100	24.7	99.1	7.6
UPPER_FLOOR_Bedroom3	35.6	23.0	100	25.4	96.4	11.1

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

Table 12 shows the performance of each occupied space at three different floor levels in terms of Criteria 1 and 2. The upper-floor flat outperformed the other floor levels: It maintained indoor temperatures above 34.4°C in all rooms for the entire year and only exceeded this temperature when it reached 36.4°C. The highest temperature of 36.4°C was observed in the living room of the upper floor, while Bedroom 2 experienced overheating with a temperature of 36.1°C. It is remarkable to note that all occupied spaces on the three floor levels exceeded the benchmark of 33°C for the thermal-comfort criteria for southern European countries [152].

As it relates to Criterion 1, the representative flats were shown to exceed the limits of failure, with the corresponding upper-floor flat demonstrating the greatest signs of overheating; in this flat, the living room surpassed a 6°C increase-per-hour for a total of 115 days each year, while Bedroom 2 surpassed a 6°C increase-per-hour for a total of 77 days each year. In addition, Bedroom 1 in the first-floor flat exceeded a 4°C increase for 4 and 11 hours each year, respectively; which indicates that this flat will be extremely uncomfortable for its occupants for a significant portion of the year. The results for both the first and middle floors were similar for each occupied space, with high predicted percent dissatisfied (PPD) levels (see **Dataset D**).

It is important to highlight that in terms of Criterion 3, the bedrooms in each of the tested flats also exceeded a 4°C increase-per-hour during the simulated summer period. This can be attributed to the classification of the bedrooms as 'night zones', which means that they were only occupied at night; when the external night-time temperatures rose above a certain point, the internal heat gains of the occupants were significant enough to increase the temperature above T_{upp} [153]. These results also indicate that in comparison, the living room was either partially or fully occupied at all times (see **Appendix A.4**).

Figures 21 (a) and (b) through 24 (a) and (b) show the overheating hours for each occupied space in the first-floor Flat A. These results can be extrapolated to the other two floor levels to fully understand the overall thermal performance of the building fabric of the base-case residential tower blocks (RTBs).

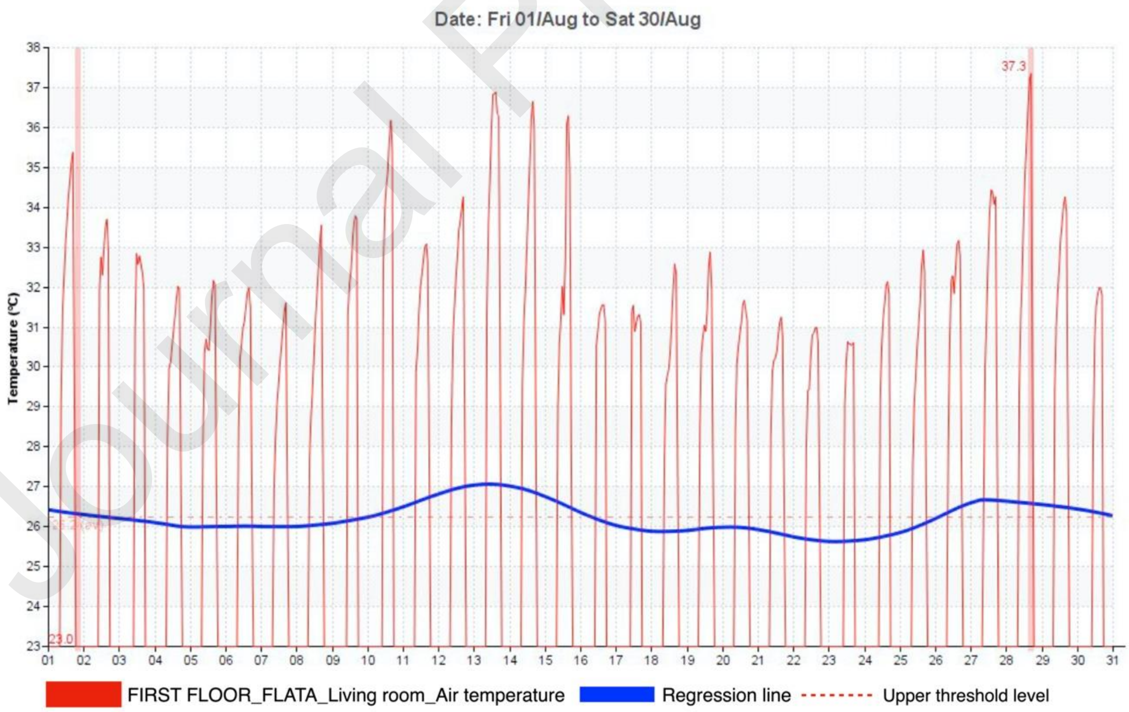


Fig.21. (a) Maximum temperature of first-floor living room in August was 37.3°C.

Figure 21 (a) illustrates the simulation period for the living room, where thermal-comfort levels should be between 23–25°C. Starting on August 1, indoor-air temperatures reached

35.5°C; this does not correlate with CIBSE TM59 Criterion 1, which recommends a 33°C upper threshold for operative air [154]. There were significant signs of overheating risks[1], and these indoor-air temperatures negatively affected the occupants' physiological thermal adaptation to their environments [155]; elevated temperatures fluctuated with high and low peaks, but always rose above the recommended 25°C upper thermal-comfort threshold. Notably, the highest indoor-air temperatures were predicted between August 14–16, and they reached 37.3°C on August 28; a peak outside temperature of 43.2°C was recorded on August 16 at 14:55 by the weather station that was installed on the site.

Even though the recommended overheating threshold is 28°C, the indoor- and outdoor-air temperatures followed a pattern of overheating. Peak indoor-air temperatures, which are shown in Figure 21 (a), were +5.3°C above the comfort-level zone; the regression line fluctuated between 25–27°C, which is near or above the upper comfort threshold margin. These fluctuating temperatures could be perceived as acceptable thermal-comfort levels, however, due to the psychological adaptation of the occupants to their local climate [156].

The daily weighted exceedance and maximum adaptive temperature for the first-floor living room were evaluated to assess the degree of overheating that was experienced in line with the test reference year (TRY) weather file assigned in the ApacheSIM module of the IES software and to validate the *in-situ* physical measurements and *on-site* environmental monitoring findings. The thermal-comfort survey findings, complaints from the Flat A occupants that their unit was consistently too warm, and temperature data from the *in-situ* measurements confirmed that the flat was slightly overheated during the field-survey period; indoor-air temperatures were recorded at 27.5°C, and the outdoor heat-stress index (HSI) was 43.2°C. Despite these findings, however, a range of factors—such as high glazing ratios, window restrictors and a lack of external shading devices—suggest that during a period of warm weather, the case-study flat may be difficult to thermally regulate.

[1] This finding, in general, is notable as it relates to the 33°C threshold.

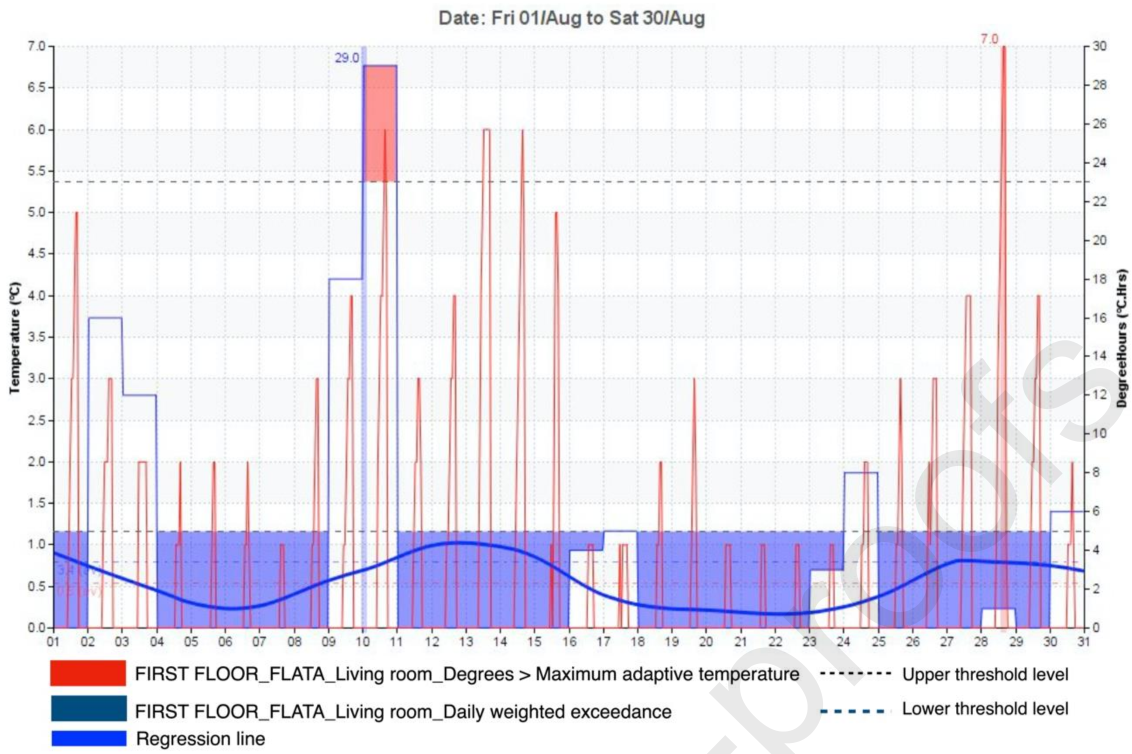


Fig.21. (b) Daily weighted exceedance hours of living room temperatures peaked at a 29°C increase-per-hour on August 10.

Figure 21 (b) depicts the indoor-air temperature fluctuations to assess the percentage of hours that exceeded the daily acceptable thermally comfortable temperatures and the maximum adaptive temperature differences in the living room. The plotted line illustrates the lower margin of a 5°C increase-per-hour and the upper margin of a 23°C increase-per-hour for the living room; temperature fluctuations were mostly within the aforementioned recommended adaptive thermal-comfort threshold [157]. On August 28, however, temperatures peaked at a 7.0°C increase-per-hour, which indicates that the indoor-air temperature was +7.0°C higher than the recommended 25°C upper comfort threshold.

Daily weighted exceedance fluctuations within the adaptive comfort range that surpassed the 29°C increase-per-hour limit were recorded on August 9; this is well above the maximum 1–5% of annual hours per year recommended by the CIBSE TM59 Criterion 1. The results revealed that a significant portion of August was extremely uncomfortable for the occupants in this flat; when ambient indoor-air temperatures rise by more than +5.3°C per hour, significant cooling-energy is required to cool down indoor environments.

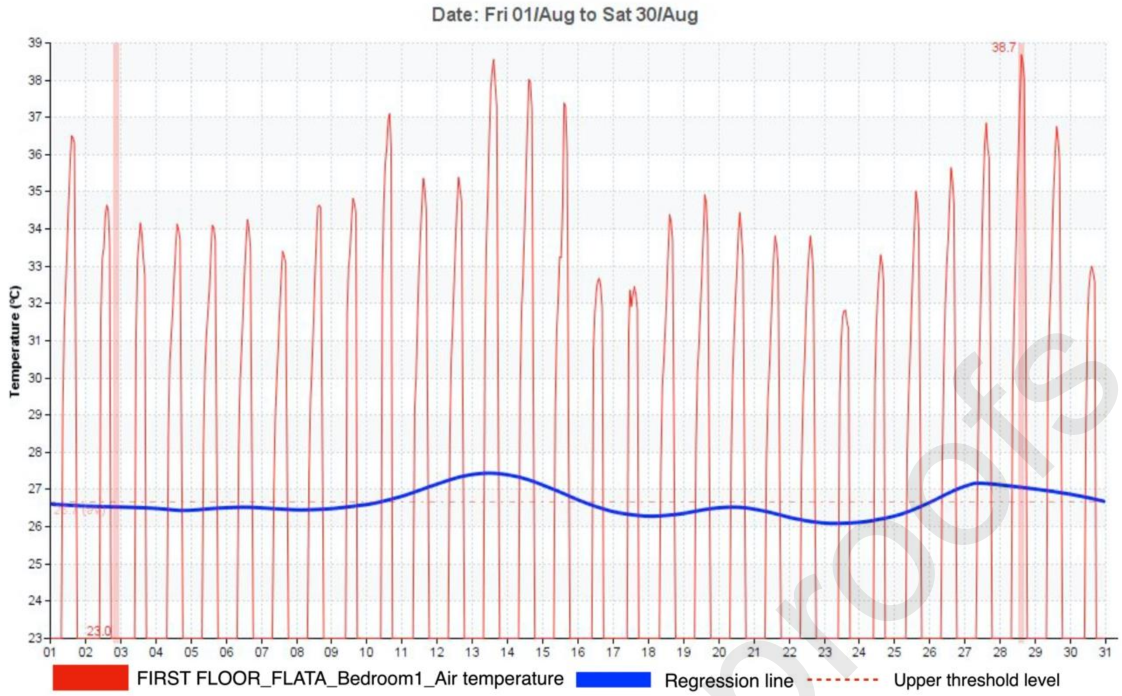


Fig.22. (a) Maximum temperature of first-floor flat Bedroom 1 in August was 38.7°C.

Figure 22 (a) illustrates the indoor-air temperature fluctuations in Bedroom 1 on the southeast-facing first-floor in August, which is the hottest summer month. In the beginning of the month, indoor-air temperature was 36.5°C and remained the same; during this time frame, outdoor-air temperature was 38.1°C, then decreased slightly to 34.0°C. On August 9, outdoor-air temperature was 39.8°C, and indoor-air temperature rose to 38.2°C by August 14, which is well above the recommended 30°C upper limit for overheating. A peak temperature of 38.7°C was predicted for August 28, which indicates that depending on the orientation of the simulated room in the case-study flat, there continued to be a high risk of overheating from high internal heat gains (IHGs) and elevated levels of solar radiation due to low-quality construction materials in the building envelopes.

Taken together, these results suggest an association between the *U*-values of building properties and the occupants' thermal comfort. The daily variation ΔT exceeded a 6.2°C increase-per-hour on several occasions over the simulation period in August, which highlights the importance of considering *on-site* environmental monitoring data when assessing overheating risks and developing neutral adaptive thermal-comfort thresholds.

Figure 25 (a) also includes a regression line that fluctuated between 26–27°C, which is well above the recommended upper thermal-comfort limit [158,159]; this is because relatively high outdoor-air temperatures were recorded at the time of the survey. It can be concluded from these temperature fluctuations that the indoor-air temperature in Bedroom 1 was not thermally comfortable, and the occupants likely experienced heat-related challenges while they slept. In fact, the occupants reported that they experienced a high degree of thermal discomfort in Bedroom 1 because they had poor control of the window openings, which resulted in a lack of natural ventilation (NV) that would have optimised the environment.

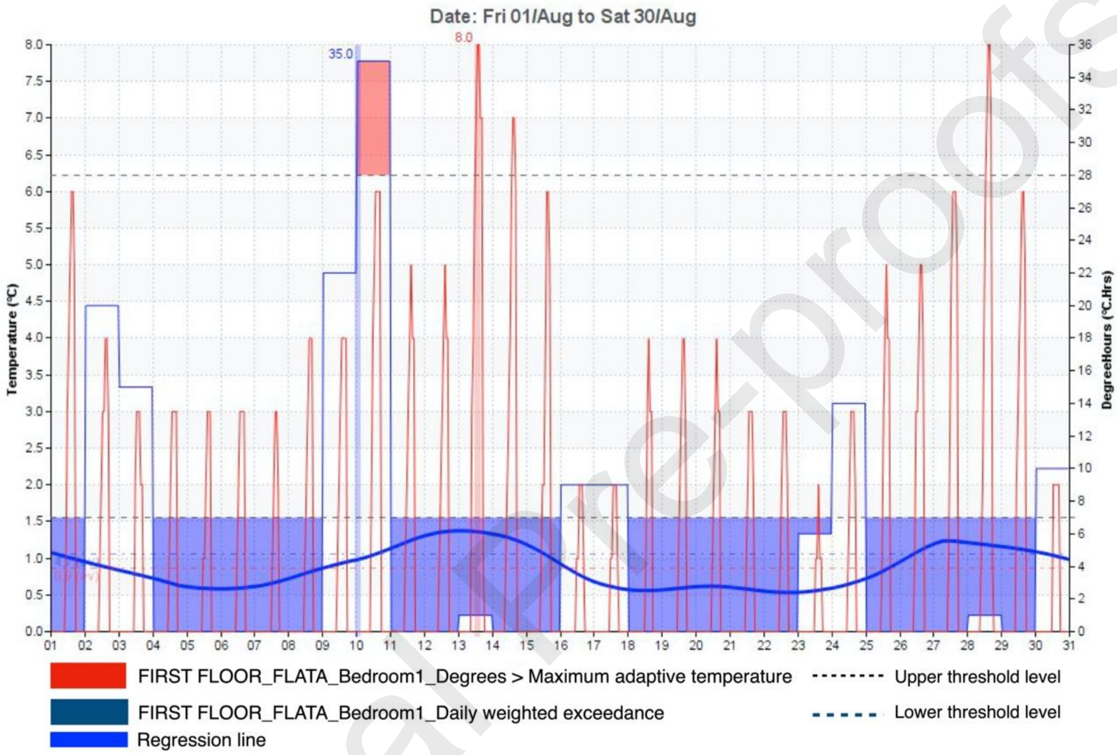


Fig.22. (b) Daily weighted exceedance hours of Bedroom 1 temperatures peaked at 35.0°C increase-per-hour on August 10.

The daily weighted exceedance and maximum adaptive temperatures for Bedroom 1 are shown in Figure 22 (b). The 7°C increase-per-hour lower comfort margin and 28°C increase-per-hour upper comfort margin are shown for Bedroom 1; this limits the variation factor that identifies acceptable night-time adaptive comfort thresholds [160]. The simulated-air temperature increased beyond the 25°C upper comfort threshold of by 3.0°C per hour; this was the same as the margin line, which had a 28°C lower overheating threshold. Notably, the maximum adaptive temperature peaked at a 10.0°C increase-per-hour on July 14.

Indoor-air temperatures experienced an hourly increase that was 10.0°C higher than the acceptable thermal-comfort level; on August 9, the daily weighted exceedance temperatures fluctuated within the adaptive comfort range, but exceeded the 35°C increase-per-hour threshold, which is well above the maximum 1–5% of annual hours per year that is recommended by Criterion 1 in the CIBSE TM59 standards. There was a 1.5°C lower margin and 6.2°C upper margin for the daily weighted exceedance in Bedroom 1, which is a strong indication of overheating risk due to local environmental conditions and the thermal properties of Flat A.

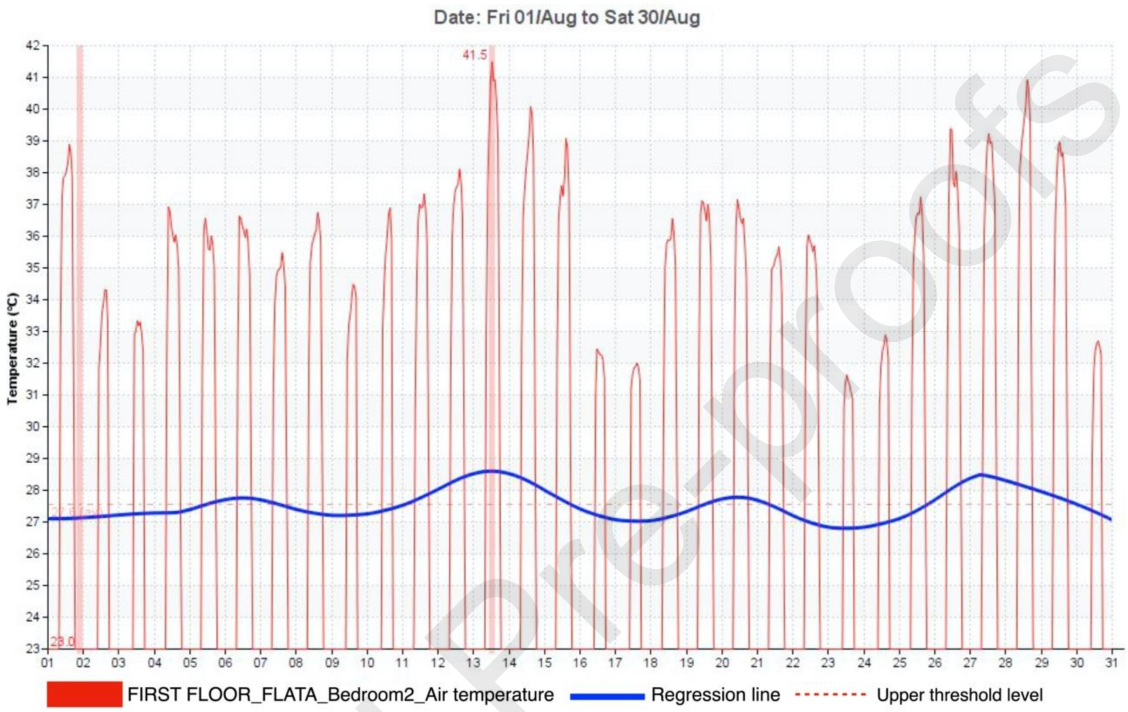


Fig.23. (a) Maximum temperature of first-floor flat Bedroom 2 in August was 41.5°C.

The indoor-air temperature fluctuations for Bedroom 2 in the first-floor flat are shown in Figure 23 (a). This room, which had a single window opening, was similar in size to Bedroom 1 and followed similar trends, even though the north-east orientation of this space resulted in more sunshine early in the morning. A peak temperature of 44.5°C was predicted for August 13, and the indoor-air temperature was 41.5°C on that day. The overall recorded temperatures were above the 25°C upper comfort threshold and the 30°C upper overheating threshold throughout this period; furthermore, the average mean temperature across all of the indoor occupied spaces was recorded at 24°C, which is above the recommended 23°C lower thermal-comfort threshold. A regression line fluctuated between 26.5–28.5°C, which is slightly above the 25°C upper comfort threshold.

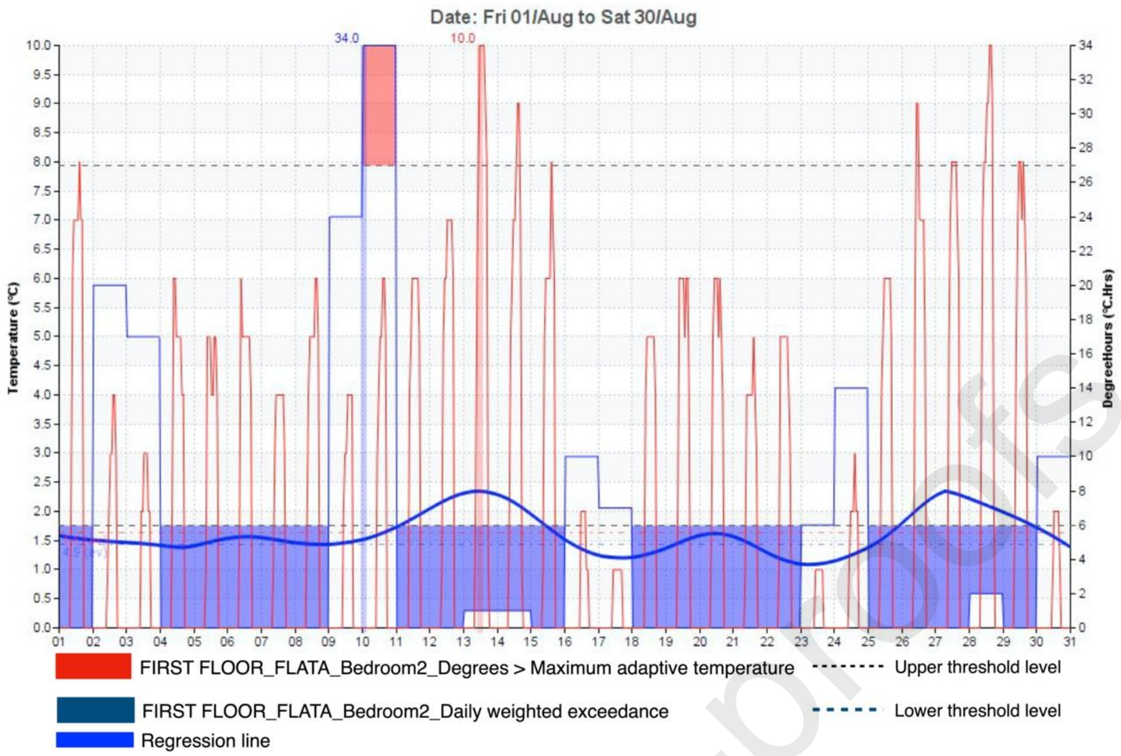


Fig.23. (b) Daily weighted exceedance hours of Bedroom 2 temperatures peaked at 34.0°C increase-per-hour on August 10.

The daily weighted exceedance and maximum adaptive temperatures for Bedroom 2 are shown in Figure 23 (b): The 6°C increase-per-hour demarcation indicates the lower acceptable adaptive temperature limit, and the 27°C margin was the maximum limit for comfortable temperatures; a 6–27°C increase-per-hour is the acceptable range of degree-hours to ensure the thermal comfort of occupants. Air temperature fluctuations peaked at a 10.0°C increase-per-hour on August 13, which indicates that significantly high indoor-air temperatures were recorded due to the pronounced impact of direct solar gains from the north-east façade of the building on the air temperatures in Bedroom 2; a T_{max} of a 34.0°C increase-per-hour was recorded on August 28, and the daily variation ΔT exceeded the 8°C upper limit on several occasions over the simulation period. Notably, temperatures that exceeded 30°C were limited to relatively brief periods (i.e., a one-hour duration) and did not affect late-afternoon and evening temperatures.

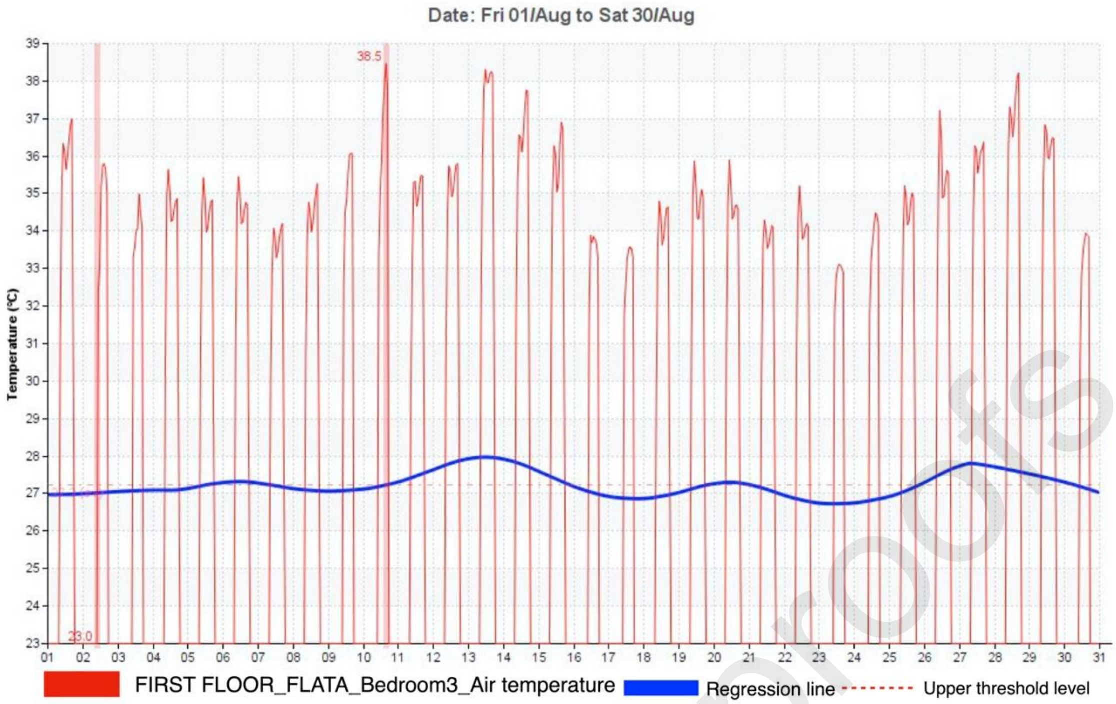


Fig.24. (a) Maximum temperature of first-floor flat Bedroom 3 in August was 38.5°C.

Figure 24 (a) illustrates the indoor-air temperature fluctuations of the first-floor Bedroom 3, which had a northeast–southeast orientation, in August. The indoor-air temperature of this space fluctuated between 23.0–37.0°C from August 1 to August 30; temperatures reached 38.5°C on August 10, then fell to 33.5°C in mid-August; temperatures decreased to 33.0°C and continued to fluctuate at this level until August 24, then steadily increased to 37.2°C. The second highest peak of 38.0°C was recorded on August 28. When Figure 24 (a) is compared to the graphs for Bedroom 1 and Bedroom 2, a significantly different pattern emerges; this is because two adults occupied this bedroom space and only utilised a portable fan at night, while keeping their windows open to provide NV. A regression line fluctuated between 27.0–28.0°C, which was slightly above the 25°C upper comfort threshold limit and was in line with the 28°C overheating threshold.

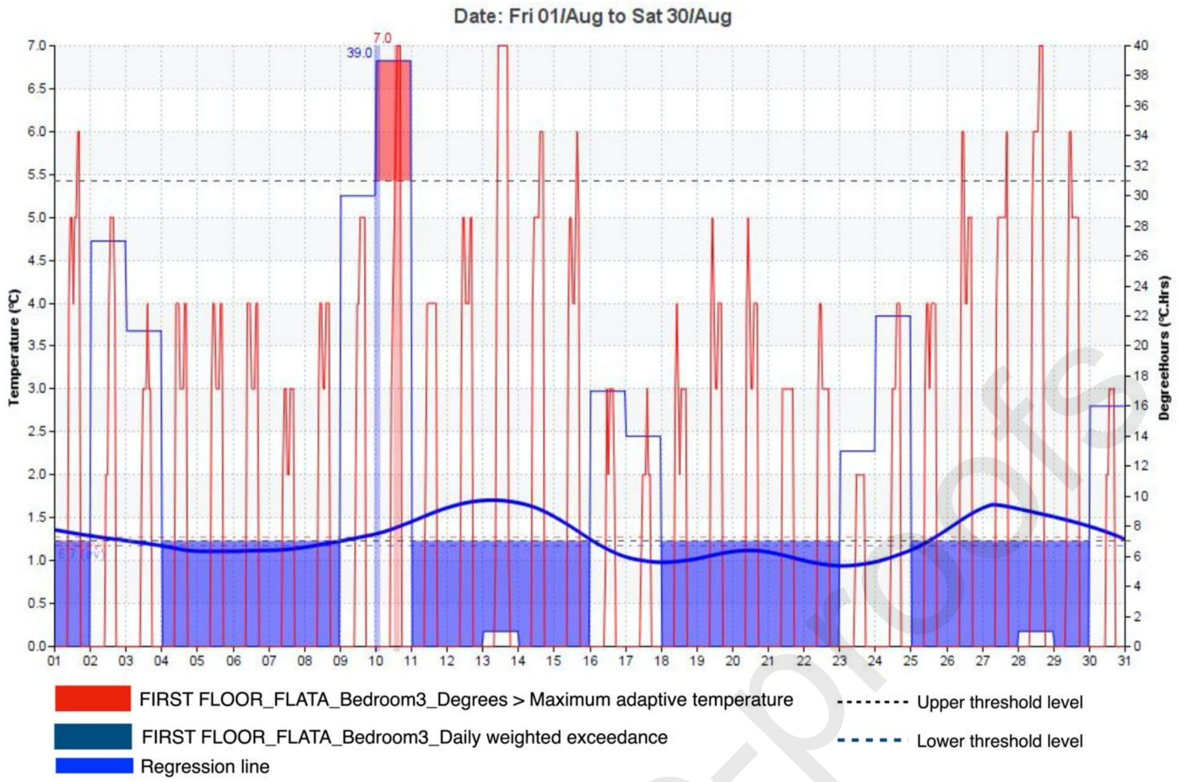


Fig.24. (b) Daily weighted exceedance hours of Bedroom 3 temperatures peaked at 39.0°C increase-per-hour on August 10.

Figure 24 (b) illustrates the indoor-air temperature fluctuations for Bedroom 3 to assess the percentage of hours that daily acceptable thermally comfortable temperatures were exceeded and the maximum adaptive temperature differences. The plotted line illustrates the 7°C increase-per-hour lower margin, and the upper margin is a 31°C increase-per-hour; most of the temperature fluctuations were well above the recommended adaptive thermal-comfort threshold [161]. There was a peak 7.0°C increase-per-hour on August 10, which indicates that the indoor-air temperature was 7.0°C higher than the 25°C recommended upper comfort threshold limit [162].

On August 10, the percentage of discomfort hours in Bedroom 3 during the occupied hours (i.e., OP3) exceeded a 39.0°C increase-per-hour, which is well above the maximum 1–5% of annual hours per year that is recommended in Criterion 1 of the CIBSE TM59 standards. Based on these findings, a significant proportion of August was extremely uncomfortable for these occupants. Interestingly, the upper maximum adaptive temperature limit was at a 31.0°C increase-per-hour; this is partially due to the absence of an air conditioning system and the high occupancy density of this room, compared to Bedroom 1 and Bedroom 2.

4.4.3 Orientation factor when assessing cooling-energy use

The building-energy modelling results of the representative RTBs—specifically those facing to the southeast (SE-45°), southwest (SW-45°) and northeast (NE-90°)—are detailed and discussed in this section. The results of the cooling-energy consumption of the occupied spaces are shown in Figures 25 (a)–(d); all three floor levels in each orientation and in relation to the peak hourly cooling consumption of the base-case on a typical day in August between 06:00–00:00 are delineated. When all locations were taken into account and all representative sample flat units were simulated with the relevant thermal conductivity level of the RTBs, the results reveal that the living room in the southeast-facing upper-floor flat exhibited the highest cooling demand with an increase of 21.69%, while Bedroom 2 demonstrated a cooling demand of 21.60%, as shown in Figure 25 (a). These values reveal an increased demand for cooling-energy of 78.49 kWh/m^2 in the intermediate floor and 69.79 kWh/m^2 on the first floor.

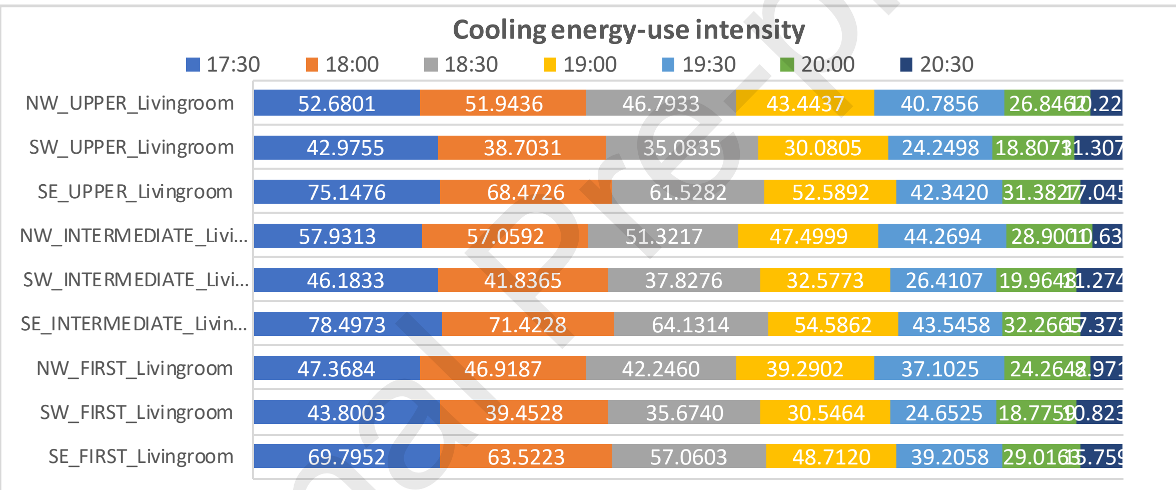


Fig. 25. (a) Calibrated existing cooling-energy consumption of the living room units in the worst-case southwest-facing RTB.

The southwest-facing Bedroom 1 unit also demonstrated a higher cooling-energy demand, compared to the southeast-facing Bedroom 1 unit, with an increase of 25.84% on the intermediate floor and 24.16% on the first floor, as shown in Figure 25 (b). These values indicate an increase in cooling demand of 19.28 kWh/m^2 on the intermediate floor and 22.66 kWh/m^2 on the first floor.

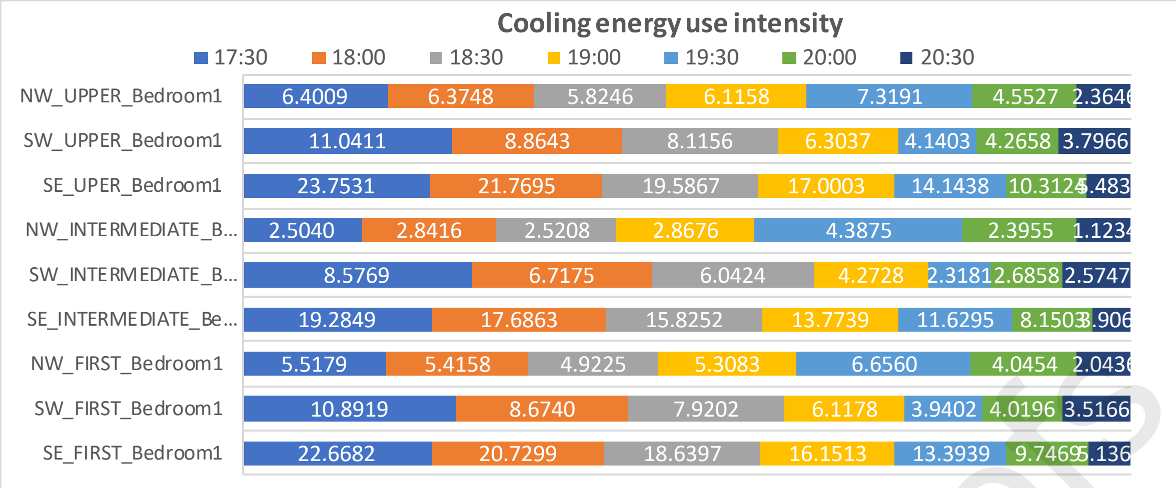


Fig. 25. (b) Calibrated existing cooling-energy consumption of the Bedroom 1 units in the worst-case southwest-facing RTB.

As shown in Figure 25 (c), Bedroom 2 in the southeast-facing unit continued to be the orientation with the highest cooling-energy demand with an increase of 21.42% (32.24 kWh/m^2) on the upper floor and 21.10% (32.12 kWh/m^2) on the first floor, and a greater increase in cooling-energy demands in the summer. In contrast, Figure 25 (d) shows that Bedroom 3 of the northwest-facing top-floor unit displayed an increase in cooling-energy demand of 25.05% (16.23 kWh/m^2); and the demand for Bedroom 3 of the southwest-facing upper-floor unit increased by 22.46% (14.46 kWh/m^2).

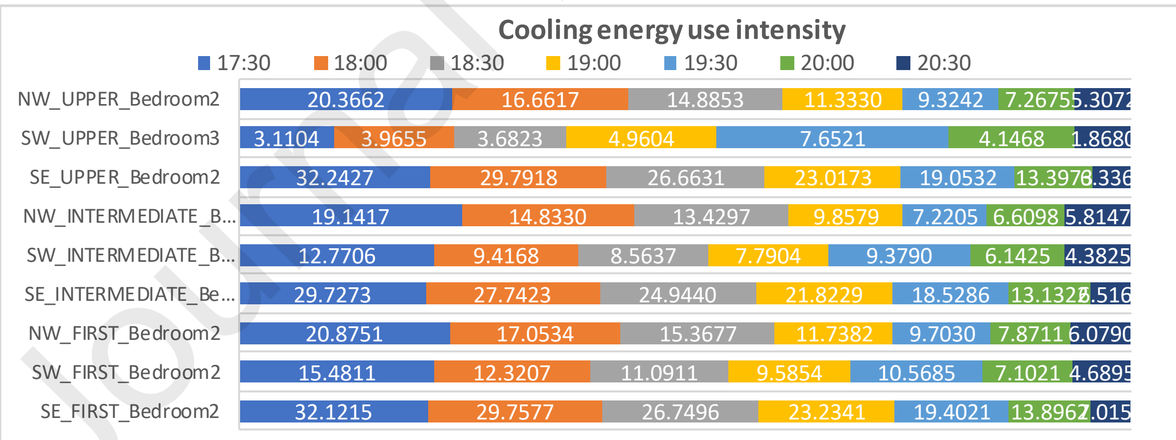


Fig. 25. (c) Calibrated existing cooling-energy consumption of the Bedroom 2 units in the worst-case southwest-facing RTB.

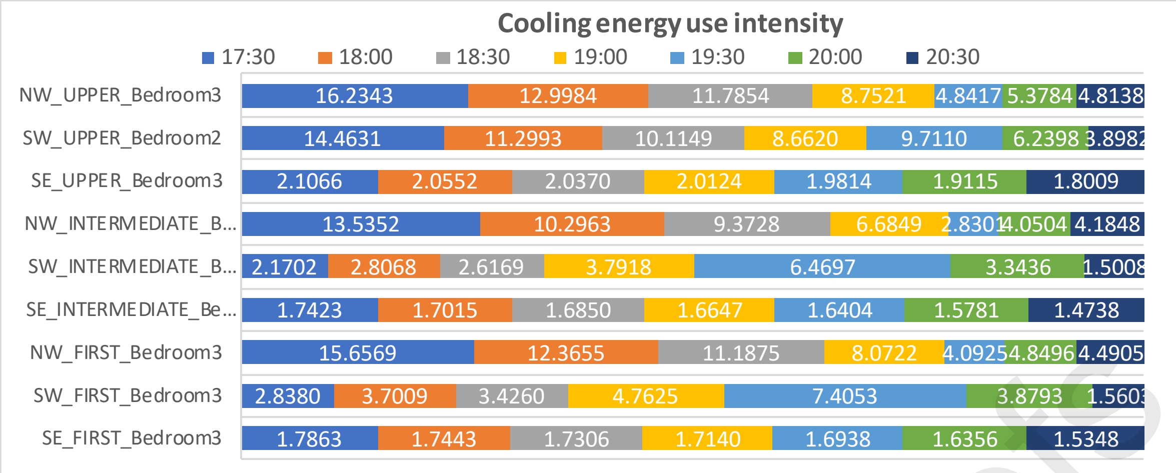


Fig. 25. (d) Calibrated existing cooling-energy consumption of the Bedroom 3 units in the worst-case southwest-facing RTB.

The simulation results of the existing performance for the representative RTB indicated that the greatest share of the heat losses were the result of air infiltration and exterior walls that had windows but lacked insulation, thereby provoking a high annual demand for cooling energy. Furthermore, according to these base-case studies, when the adaptive set-point was implemented, a decrease in cooling demands was noted due to additional ventilation, in particular for units with heavier construction materials and systems [163]. During the peak cooling season, the occupied spaces revealed significant differences based on the adaptive temperature set-points of heavy-weight construction materials when the building envelope lacked thermal insulation.

At the same time, a base-case prototype RTB was subjected to the effects of buoyancy-driven air movement because of an insufficient number of window openings [164]. This natural ventilation system allowed hot air from the lower levels to rise up through the building, and with no chance of escaping the occupied spaces, fresh air was accumulated on the uppermost levels of the building-envelope surfaces. It can be seen that during the peak cooling season, the occupied spaces demonstrated significant differences based on the adaptive temperature set-points of the heavy-weight construction materials, in particular the materials of the base-case model, which was not provided with any insulation on the building envelope prior to when this retrofitting and optimisation study was undertaken.

4.4.4 Overall electricity-consumption assessment

This section examines the overall electricity consumption for the base-case representative flats, and the different floor levels of the flats were taken into consideration for purposes of the building-performance evaluation. These results were also compared to the actual energy bills of the occupants for purposes of data validation. Figures 26 (a)–(c) demonstrate the overall energy consumption of the first-, intermediate- and upper-level base-case representative flats between January and December of 2018.

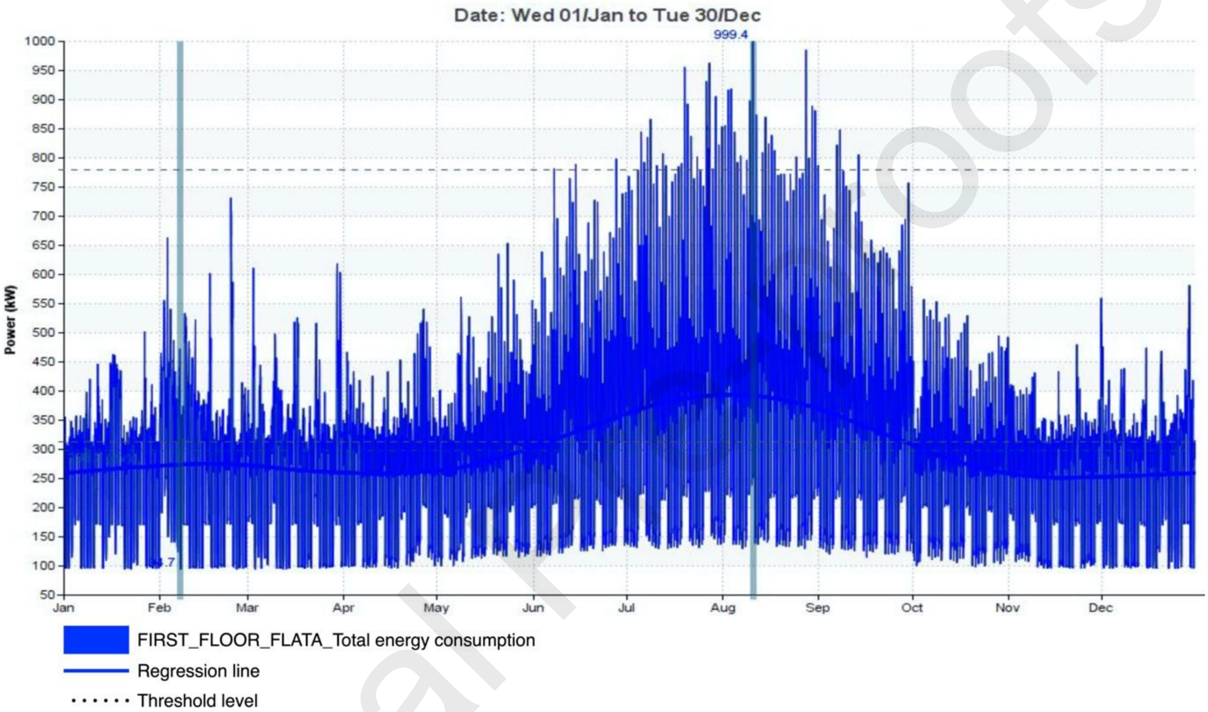


Fig. 26. (a) Total monthly energy consumption of the worst-performing south- and southwest-facing first-floor flat reached a maximum of 999.4 kWh in August.

The graph in Figure 26 (a) depicts the energy-consumption simulation for the south- and southwest-facing first-floor flats. The dashed line at 780 kWh indicates the upper limit of the recommended average energy consumption, and the margin line at 310 kWh delineates the lower limit of acceptable energy consumption; acceptable levels of energy-consumption fluctuations throughout the year fell between these two levels, and excessive energy demand was greater than 780 kWh. For Flat A, the energy consumption from January to February began to fluctuate between 350–450 kWh and peaked at 650 kWh in the first week of February; after this spike, energy consumption decreased to 350 kWh, peaked above 740 kWh in the first week of March, then dipped to 400 kWh in the second week of March.

Figure 26 (a) illustrates that from the second week of March to mid-July, consumption fluctuated between 520–800 kWh; from mid-July until September, usage hovered above the upper limit, between 740–950 kWh; and it peaked to its highest level at 999.4 kWh in the first week of August. Energy consumption then steadily decreased throughout September and October, from 740 kWh to 550 kWh; and from the first week of October until November, usage hovered around 500 kWh. Consumption continued to follow this trend until reaching the lowest recorded energy consumption of 310 kWh in the first week of December, after which usage increased and peaked at 580 kWh in the final week of December.

It should be noted that the upper limit of recommended energy consumption for this case-study flat was 780 kWh, which was significantly surpassed in the first week of August at 999.4 kWh. According to the energy-bill analysis, however, the actual mean energy consumption was calculated to be 540.7 kWh, which means that at its peak, the energy consumption of this case-study flat was shown to be just below the level delineated in the relevant criterion.

In accordance with the simulation prediction, the overall energy consumption between January and December was determined to be 2740.5 kWh. Notably, the actual energy-consumption of the occupants between January and December of 2016 was calculated to be 3079 kWh. It can therefore be concluded that in the peak cooling summer month of August, the average energy-consumption level for this case-study flat was above the benchmark level for the energy that the occupants needed for cooling purposes. This can also be validated from the analysis of the actual energy bills, which concluded that the peak energy consumption in the first week of August was 910 kWh.

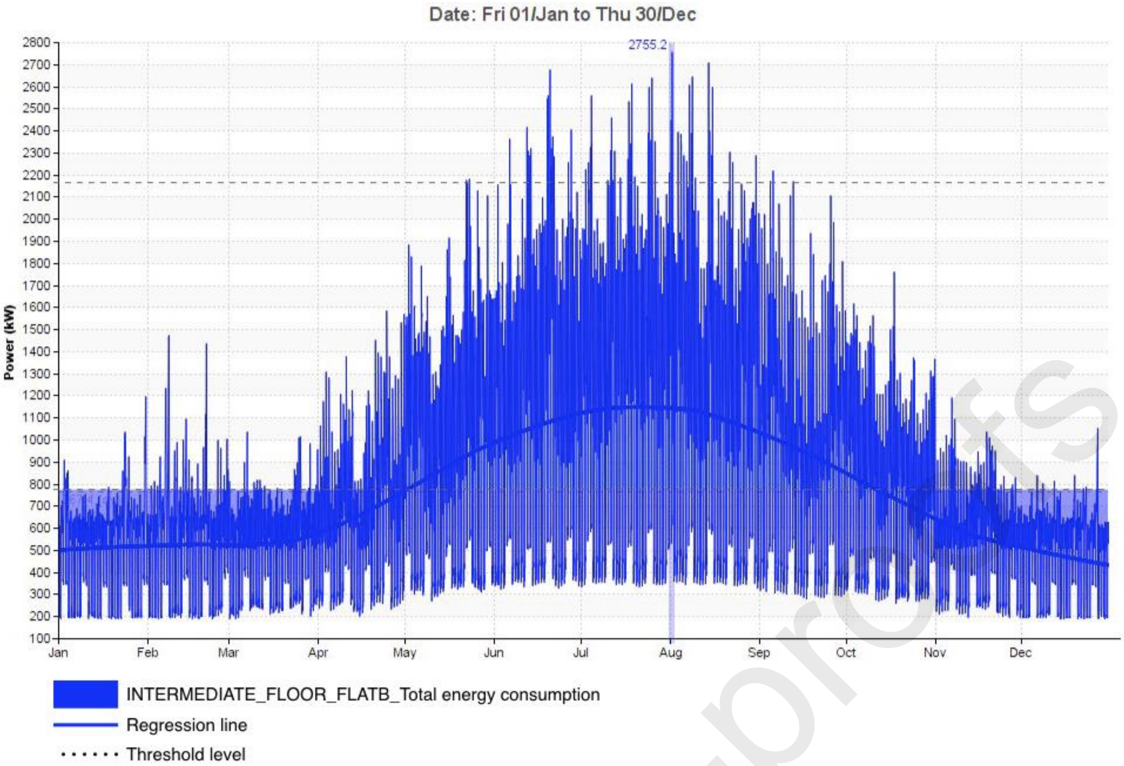


Fig. 26. (b) Total monthly energy consumption of the worst-performing south- and southeast-facing intermediate-floor flat reached a maximum of 2755 kWh in August.

Figure 26 (b) shows the energy-consumption fluctuations in August of 2016 of the intermediate-floor Flat B. The lower margin for energy consumption was 300 kWh, and the upper margin was set at 2200 kWh, which was higher than that of the first-floor flats due to internal heat gains from appliances, the different floor levels and different building-envelope orientations.

The graph shows that starting in January of 2016, energy consumption was 780 kWh, and that it fluctuated until the second week of February, when it reached 1500 kWh; this fluctuation continued through the end of February, when it reached 1400 kWh. At this time, usage dropped to 700 kWh and fluctuated around this level until the end of March, then it steadily increased from 800 kWh to 2200 kWh between April and mid-June. Energy consumption remained near or above the upper-margin line from mid-July through September, peaking in August at 2755 kWh.

It was found that from September until November, energy usage dipped again to 1100 kWh and fluctuated around this level, then continued to decrease slightly until December, when energy consumption peaked at 1000 kWh in the final week of December.

The regression line stayed well-above the lower limit of the recommended average energy consumption of 300 kWh throughout the year. It peaked above the lower margin, with a maximum peak of 1100 kWh in August. It can be concluded that even though there was a potential risk of overheating, the overall consumption was well above the recommended energy consumption benchmark criteria because of the occupants' strong reliance on cooling systems in the summer.

It is worth noting at this point that the heating temperature for the energy simulations was set to 21°C in the construction profiles in the ApacheSIM module. This was because the occupants predominantly used gas cylinder systems to heat in winter, which was why the energy consumption fluctuated around 780 kWh between December and February. It is also notable that the occupants used portable domestic heating appliances in the winter on the afternoons that children were present. Figure 26 (b) shows that between February and March, energy consumption increased slightly and fluctuated from 780 kWh to 1450 kWh; these results strongly indicate that domestic heating systems were used when children were present in the flat in winter.

In accordance with the simulation prediction, the overall energy consumption between January and December was calculated to be 4440 kWh; the actual energy consumption of the occupants between January and December of 2016, however, was determined to be 5259 kWh. It can therefore be concluded that in the peak cooling summer month of August, the average energy-consumption level for this case-study flat was above the benchmark level for the energy that the occupants needed for cooling purposes. This can also be validated from the analysis of the actual energy bills, which revealed peak energy consumption in the first week of August, when energy consumption was found to be 2453 kWh. Specifically, the results suggest that the energy consumption benchmark level for Flat B was given at 2200 kWh.

There was an interesting finding in this study based on these simulation measurements; it can be deduced that the energy consumption of this base-case representational flat consistently remained above the generated benchmark. According to the energy-bill analysis, however, the average energy consumption was determined to be 1999 kWh. In the peak cooling month of August, the energy consumption of this flat was 2755 kWh. From these data, it can be concluded that there was a contradictory finding related to the actual energy consumption; this was because the *CIBSE TM 52* guidelines were intended to assess the overheating risk of existing residential buildings in the UK, yet the findings of the current study were specific to the geographic domain of the research context (i.e., the Mediterranean) and the real-life energy-use experiences of the occupants.

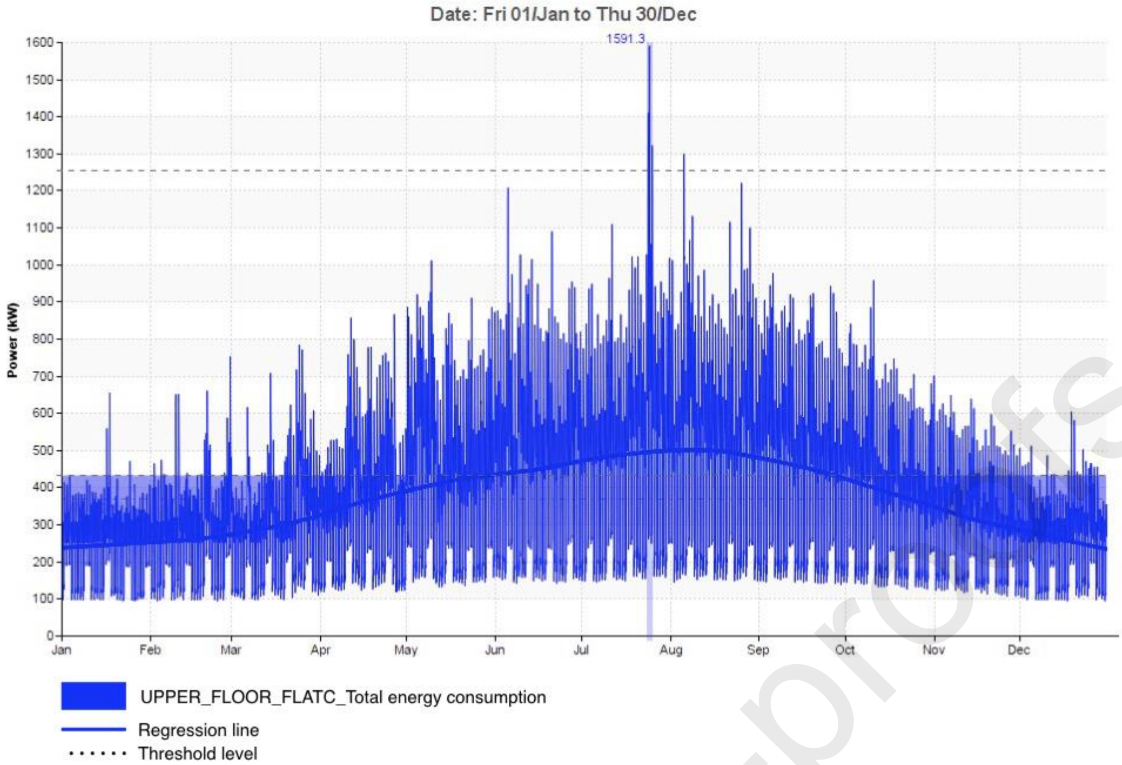


Fig. 26. (c) Total monthly energy consumption of the worst-performing south- and southwest-facing upper-floor flat reached a maximum of 1591 kWh in August.

In Figure 26 (c), the simulation of the energy consumption of the south- and southwest-facing upper-floor Flat C can be seen. The line at 1250 kWh indicates the upper limit of recommended average energy consumption, and the margin line at 410 kWh is the lower limit of average energy consumption.

As is shown in Figure 26 (c), the space between 410 kWh and 1250 kWh is the acceptable level of energy consumption; and the area above the 1250 kWh margin indicates high energy consumption. As shown in the graph, the energy consumption for this flat remained below the indicated benchmark level of 1250 kWh throughout the year. It can be seen, however, that the energy consumption only surpassed the upper limit of the margin line at 1591 kWh at the end of July.

Figure 26 (c) shows that starting in January, the energy consumption of Flat C was 420 kWh, which fluctuated between 450 kWh and 800 kWh until the first week of May, then it increased slightly to 1000 kWh in the second week of May; after this, it decreased to 800 kWh and continued to hover around this level until the final week of July, at which time it reached its peak of 1591 kWh, then plummeted to 750 kWh. From August until mid-October, energy consumption continued to decrease slightly from 750 kWh to 600 kWh; then it sharply decreased from 600 kWh to 400 kWh between mid-October and December and continued to fluctuate at this level until the end of December.

The regression line was initially well-below the lower margin of 420 kWh for average energy consumption. From January to April, it fluctuated around 220 kWh, then it steadily increased to 500 kWh. Peak energy consumption was shown to be 1591 kWh in the final week of July; after which energy usage decreased and continued to fluctuate around 210 kWh, which was below the lower margin. It is important to highlight the fact that the generated benchmark for Flat C was shown to be 1250 kWh. On the graph, it can be seen that the overall electricity consumption frequently fluctuated below the lower limit of the average energy consumption in the final week of July, even though it was still well above the upper limit of the margin line.

In accordance with the simulation prediction, the overall energy consumption between January and December was found to be 9686.9 kWh. The actual energy consumption of the occupants between January and December of 2016, however, was found to be 1000.4 kWh. It can therefore be concluded that in the peak cooling summer month of August, the average energy consumption of this flat was above the benchmark level for the energy that the occupants needed for cooling purposes. As such, the results show that even though relatively high energy consumption was observed that was in line with the simulation predictions and the actual energy consumption, the overall energy consumption fluctuated well-below the upper limit for the recommended average; the findings related to energy consumption during the peak cooling period are therefore validated.

4.4.5 Validation study results based on occupant energy bills

The calibration of the simulation model was performed using the annual energy bills of the occupants. To fulfil the aim and objectives of the study, a calibration of cooling-energy consumption was conducted, with a target error of 1% between the predicted and actual energy consumption. It is worth mentioning at this point that during the model-calibration process, internal temperatures were iteratively adjusted until the simulated annual energy-consumption totals converged with the actual energy totals, with values that were less than the target error. This model, which was based on internal temperatures of 25°C, demonstrated slightly lower energy consumption than the actual consumption, as shown in Table 13.

It can be seen that there was a moderate correlation between the simulation prediction and the actual levels of energy consumption. This was due to the simulation, for which internal temperatures were set to 25°C with a cooling profile that was set from May to September, and which resulted in a considerably higher level of accuracy than the initial model. This model was therefore considered to be the closest representation of the energy performance of the base-case flats that were investigated in this section. Table 13 summarises the validation-study results[2].

Table 13
Comparative results of the overall energy consumption of occupants between the DTS and the analysis of the actual energy bills.

Flat Information	Occupancy-Pattern Type	Simulation Prediction (kWh)	Actual Consumption (kWh)	Difference (%)
FIRST_FLOOR_FLATA	OP1	999.4	3079	20.8
INTERMEDIATE_FLOOR_FLATB	OP2	2755	5259	25.04
UPPER_FLOOR_FLATC	OP3	1591	1000.4	84.13

OP1: Low occupancy
OP2: Moderate occupancy
OP3: High occupancy

From Table 13, it can be seen that most of the base-case representative flats were successfully validated in terms of the actual energy-consumption data for the occupants, and with the exception of Flat C on the upper floor, the results fell within the acceptable percentage difference. During the semi-structured interviews with the households regarding the occupancy hours in their properties, however, it was found that in Flat C, the occupied days during the heating season were almost 25% higher than in the other flats; the retired couple that lived in this flat indicated that they mostly spent their time at home between 9:00–17:00 on the weekends with their grandchildren.

It should be highlighted that these longer occupancy hours led to an increase in these occupants' heating-energy consumption in the wintertime (occupancy type – OP3). This why an 84.13% difference between the simulation prediction and the actual consumption was observed. For this reason, the simulation prediction needed a 25% deduction from the initial prediction to align it with the actual occupancy pattern; after this deduction rate was taken into consideration, the simulation prediction was 2755 kWh (occupancy type – OP2), and the simulation prediction was 25.04%, a difference that was within the acceptable range. The results indicate that the Flat C simulation model can be therefore confirmed as a valid model.

[2] The values of difference have been obtained by using an open-source software of the HOT2000 version 11.10. The HOT2000 is an energy modelling software developed and maintained by Natural Resources Canada to support the EnerGuide Rating System to support residential energy efficiency initiatives for energy-policy making decisions. The present study was undertaken in the South-eastern Mediterranean climate which was aimed to design universal design approach. This is the reason that this software tool was used to calculate differences between the predicted and actual energy use in order to make a generalisation of the study findings.

5 Discussions

The *in-situ* measurements of indoor air environment were conducted to understand the impact of buildings' thermal properties on the overheating risk and occupants' thermal comfort. It should be noted that the use of solar masks form of adaptation to the physical environment which directly influences on occupants' psychology while assessing overheating risk of archetype buildings with the *on-site* environmental monitoring through a walk-through survey [72]. Additionally, the solar radiation readings of building envelopes and time of day factor were associated to avoid research bias on the generated results, as shown in Figure 27.

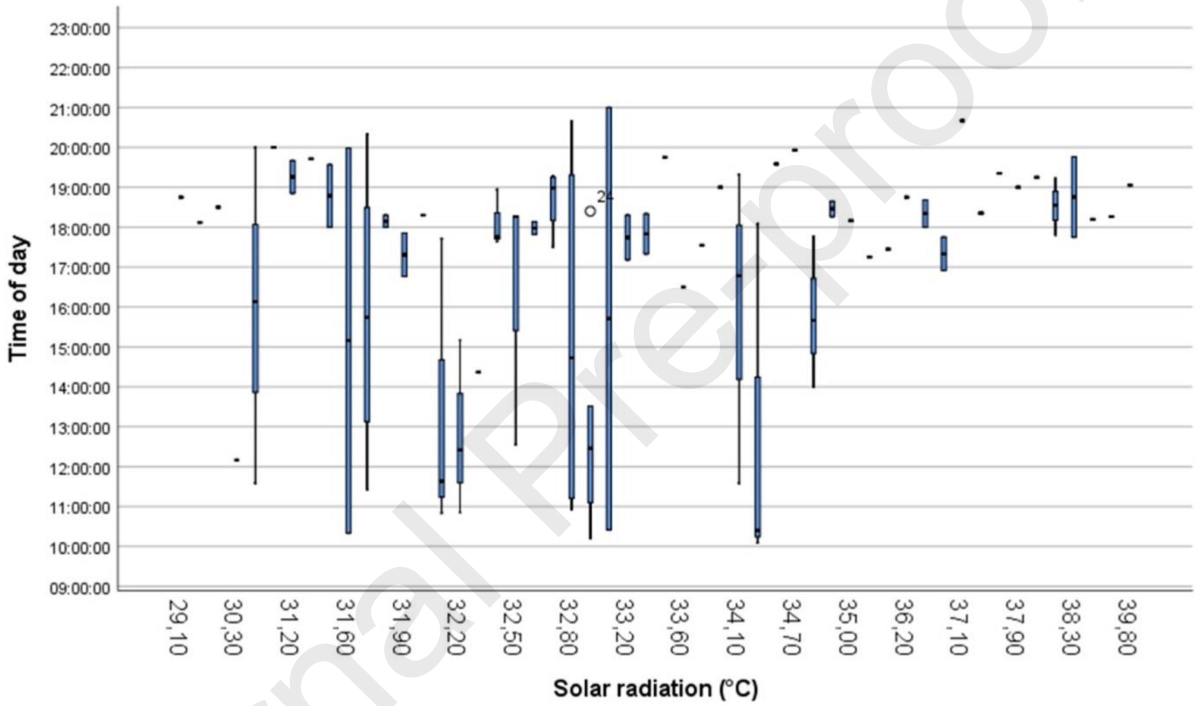


Fig. 27. Distribution of associations between solar radiation and time of day.

The building-envelope temperatures shown in Figure 27 ranged between 29.1–39.8°C; these were recorded on July 27, 2018 and September 3 of the same year between 10:00–21:00, when the *on-site* questionnaire survey was conducted. Most of the scatter-dot lines are positioned between 17:00–20:00, because 73% of the households were recruited in the afternoon; this was intentionally done to increase the sample size. Even though the ASHRAE 55 standards (2017) recommend an optimum thermal-comfort temperature of 25°C [165], according to the *in-situ* measurements findings, indoor-air temperatures during the survey period were never below 29.1°C; it should be noted that 27% of the flats were surveyed late in the morning, when indoor-air temperatures fluctuated between 29.1–34.1°C. These results revealed that the building-envelope *U*-values were a determinant factor of the heat vulnerability of the recruited RTBs.

The static method criteria, as outlined in the CIBSE Guide A (2006), state that overheating is likely when the temperature in a room exceeds a threshold temperature for more than 1% of occupied hours (bedroom threshold temperature is 26°C and living room threshold temperature is 28°C) [166]. The occupied hours of the inspected living room spaces were based on the findings of the questionnaire survey to ensure that the accuracy of overheating risk measures was in line with the *on-site* monitoring of actual weather conditions [167]. Table 14 demonstrates the recordings of operative air temperature by taking the RTBs orientation into consideration.

Table 14
In-situ recordings of indoor environment conditions across 36RTBs.

		Percentiles		
	Orientation	**25th**	**50th**	**75th**
Weighted Average Operative Air Temperature (°C)	North-east	29.50	30.60	31.90
	South	29.85	31.30	31.60
	North-west	31.52	32.25	32.45
	South-west	28.20	29.70	31.72
	South-east	30.10	30.90	32.30

As shown in Table 14 both the northwest- and northeast-facing RTBs show the highest levels of overheating within 75th percentile of cluster group. This is likely due to the position of the RTBs and the properties of the buildings during the summer months. The results presented above indicate that the interviewed flats are prone to overheating during a period of hot weather under the current climate if the static threshold approach is adopted, which does not factor in heat acclimatisation and other adaptation actions the residents may take for their adaptive thermal comfort [168].

Considering that the adaptive capacity of most vulnerable individuals residing in social housing units is likely to be fairly limited, this finding indicates that attention should be paid to the thermal properties of the buildings and occupancy patterns in order to thoroughly assess the overheating risk of archetype RTBs were selected [169]. In order to capture the wider types of occupants and not create the direct generalisation, the time-of-day factor was also considered, as shown in Figure 32.

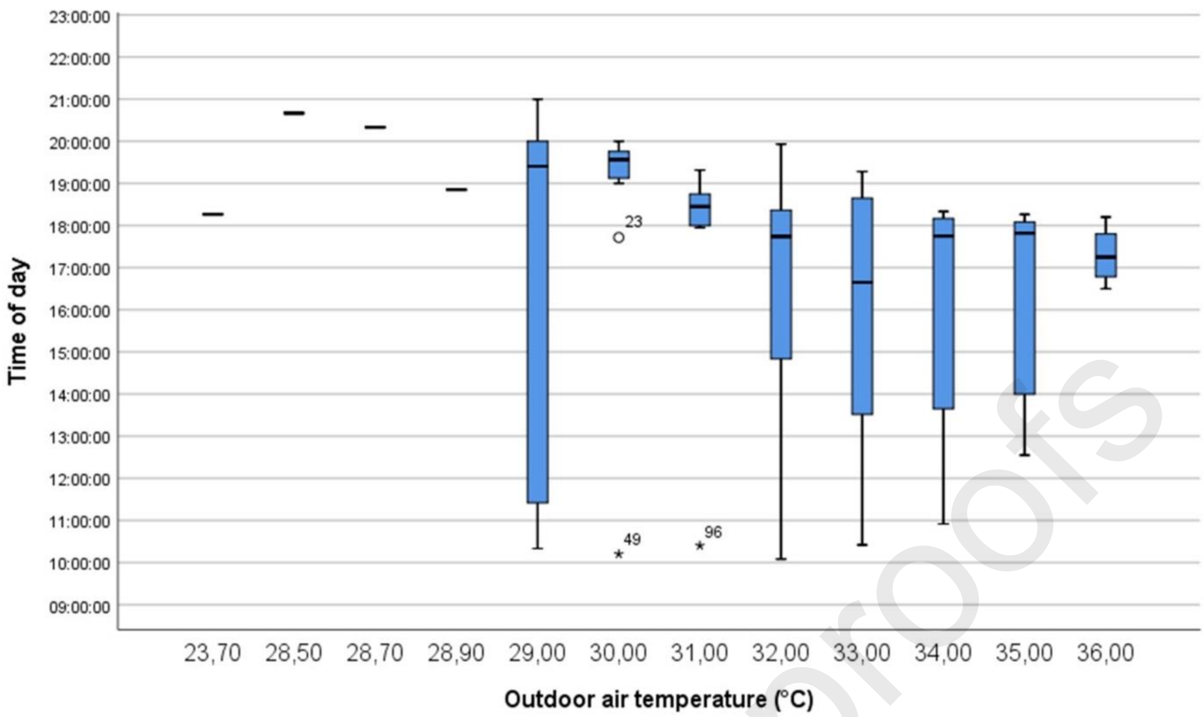


Fig. 28. Associations were found between the outdoor air temperature and time of day.

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

To consider the behaviour related adaption developed by Brager and de Dear in 1998 [170]; tests of associations were explored between the time-of-day and operative air temperatures in Figure 29.

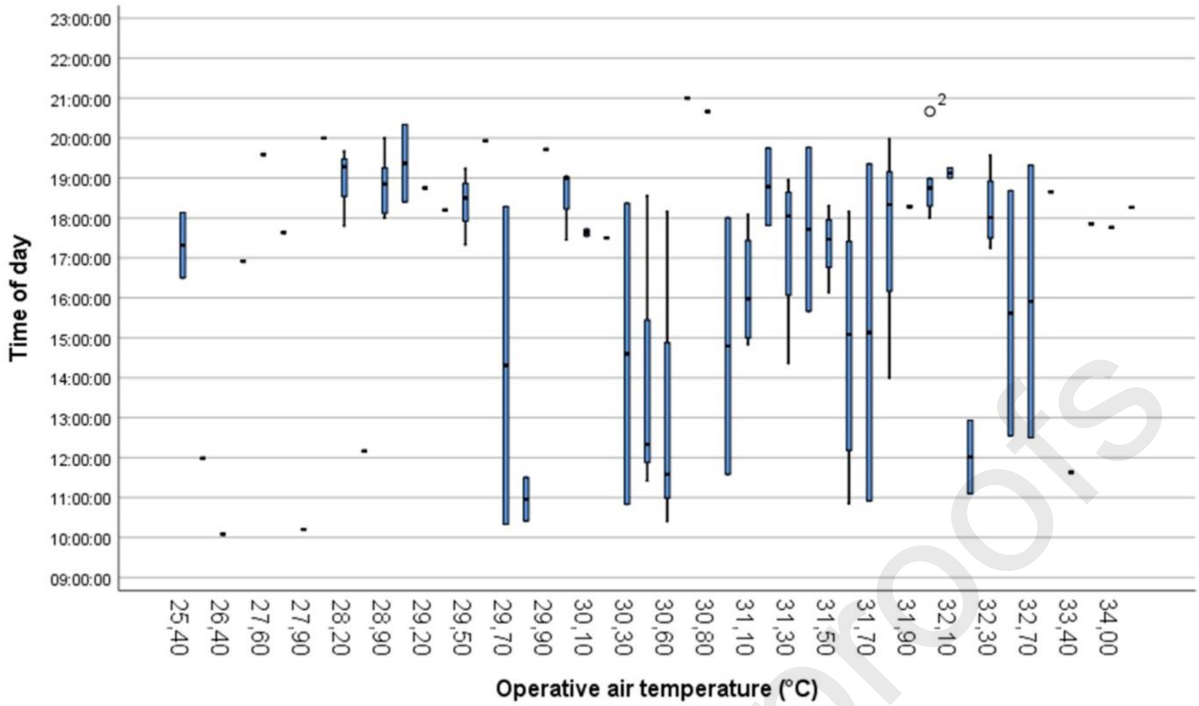


Fig. 29. Associations were found between the operative air temperature and time of day.

According to Figure 29, the indoor-air temperature of the occupied spaces between 16:30–18:00 was 25.4°C. Relatively high indoor-air temperatures were observed late in the morning: the recorded temperature at 10:05 was 29.7°C. The subject participants were interviewed between 17:45–20:45, and scattered patterns were detected in the range of 28.2–34.0°C. *In-situ* measurements that were collected during the field survey showed that the indoor-air temperature in all the flats was above 25°C, which confirms the risk of overheating during the summer. Notably, the maximum outdoor-air temperature recorded during this period was 36°C, and the highest and lowest temperatures in the living room spaces were 34.1°C and 25.4°C—were recorded in the living room spaces of the naturally ventilated multi-family residential buildings.

In-situ measurements influenced the recruitment of households at different times of the day. To reduce risk impact on error margins arising from technical anomalies, these data were compared with outdoor environmental monitoring results. The *in-situ* measurements were recorded in some flats when the wall-mounted A/C system was in use, while the indoor environmental measurements in other units recorded either portable fans that were in use or open windows. These technical variation profiles presented some limitations related to the identification of variables for the statistical analysis. Fig 30 demonstrates the outcomes of this study and its implications on retrofitting of housing stock.

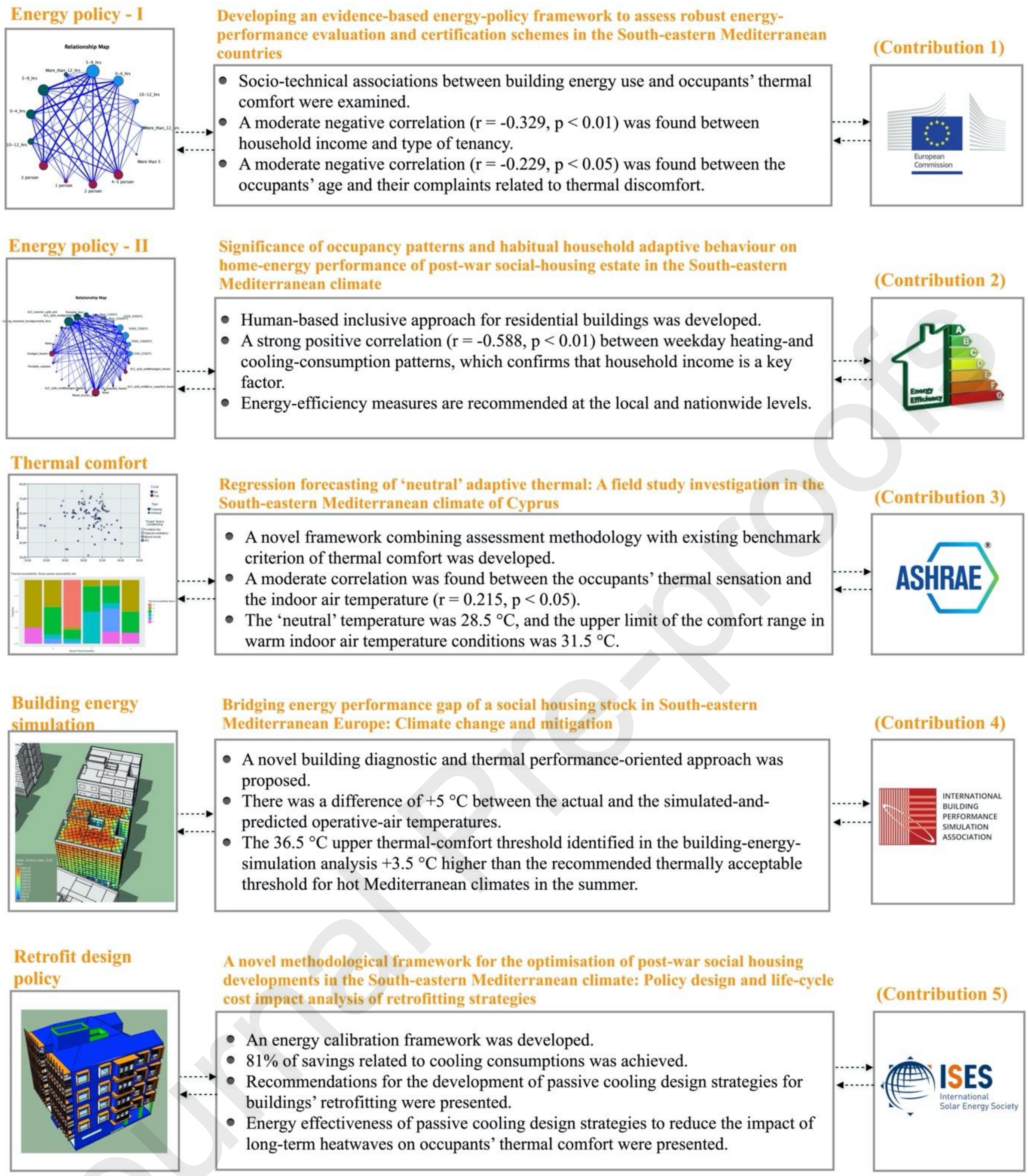


Fig. 30. Step-by-step demonstration of outcomes of the study.

A lack of weather behaviour due to hourly intervals made it difficult to define an appropriate calibration technique to control the physical parameters, especially the solar gains, that were assigned to the energy simulation model [171]. Discrepancies between actual and predicted energy use were observed in the aggregated models during the energy-model calibration process. The present study identified variations in the outliers, between indoor and outdoor air temperatures and between outdoor and indoor RH levels. This situation could affect the degree of overheating experienced in the building-performance evaluation of base-case RTBs.

Additional research is required to better understand the possible link between occupant behaviour and energy consumption [172]. Significantly more work still needs to be done to investigate specific climate conditions and different housing typologies, as well as relevant subjective measures, such as the socio-demographic characteristics, backgrounds and social structures of different households. Moreover, other novel methodologies that include advanced modelling features related to occupant behaviour when evaluating the energy performance of buildings (i.e., stochastic and deterministic models) should be developed.

6 Conclusions

A quantitative research methodology based on *in-situ* measurements—which included recordings of household indoor air-temperature integrated with thermal-imaging surveys and *on-site* heat-flux measurements of the building-fabric elements, along with a concurrent monitoring of environmental conditions and review of household energy bills to accurately determine actual energy use—was employed.

Thermal imaging readings demonstrate that the main reasons for thermal anomalies resulted from air infiltration through the building fabric, a lack of natural ventilation through living spaces and excessive heat gains through sizeable, glazed areas. The findings suggest that the percentage of hours that fell into the Category 1 recommended by the *CIBSE TM 59* overheating criterion have had direct influences of the solar irradiance factor and thermal absorptivity levels of building envelopes. Furthermore, during the field survey period, the outdoor environmental temperatures ranged from 25.3 °C to 38.7 °C, with a mean of 28.7 °C. which indicates the hot and dry weather conditions experienced at the time. In addition, the recorded indoor air temperatures were between 25.0 °C and 35.0 °C, with an average of 27.8 °C and a SD of 1.8 °C. The globe temperatures were between 24.5 °C and 37 °C, with an average of 28 °C and a SD of 1.9 °C.

It was found that occupants felt thermally comfortable in an indoor mean temperature of 29°C (with a standard deviation of 1.1) and a maximum and minimum mean temperature of 31.50°C and 28.50°C, respectively. The findings revealed that the recruited sample size could achieve comfort at higher indoor air temperatures than those recommended by international standards such as ISO EN 7730:2005.

The results revealed that conducting an IRT survey seemed to lead to a better understanding of the thermal behaviour of a building's *U-values* by integrating *in-situ* measurements to develop an assessment methodology for the implementation of the EPCs. The findings also suggest that the building thermal characteristics included in an assessment of the overheating risk of the base-case representative RTBs was intended to further determine the difference between the expected and actual energy consumption rates; and that the thermal lag of building envelopes, which has a significant effect on energy consumption, should be further studied.

In this empirical study, a strong correlation was found between the building fabric and locale climate conditions, which were determined throughout the longitudinal survey in both the summer and the winter. This could lead to the provision of information that is needed to undertake a BES analysis for future energy-calibration studies.

Declaration of Competing interest

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

CrediT authorship contribution statement

Bertug Ozarisoy: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Hasim Altan**: Conceptualisation, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing.

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Graphical Abstract – The methodological workflow developed to calibrate energy use of residential buildings.

Video

Video material to this article can be found online at –

Video A – The analytical energy model of the housing estate.

Video B – The MacroFlow natural ventilation analysis of shading systems implemented on those existing RTBs.

Video C – The computational fluid dynamics demonstration of existing environmental conditions.

Data set in Mendeley

Data set to this article can be found online at –

Dataset A – The raw data of analytical energy model created in IES with its gbxml. file formatting.

Dataset B – Solar irradiance frequency of the research context.

Dataset C – The overheating risk analysis of each occupied spaces of sample flat units in the RTB.

Dataset D – Thermal comfort and cooling energy use results of sample flats for base case scenario development.

Appendix A.1 Selection criteria of building energy simulation software suite

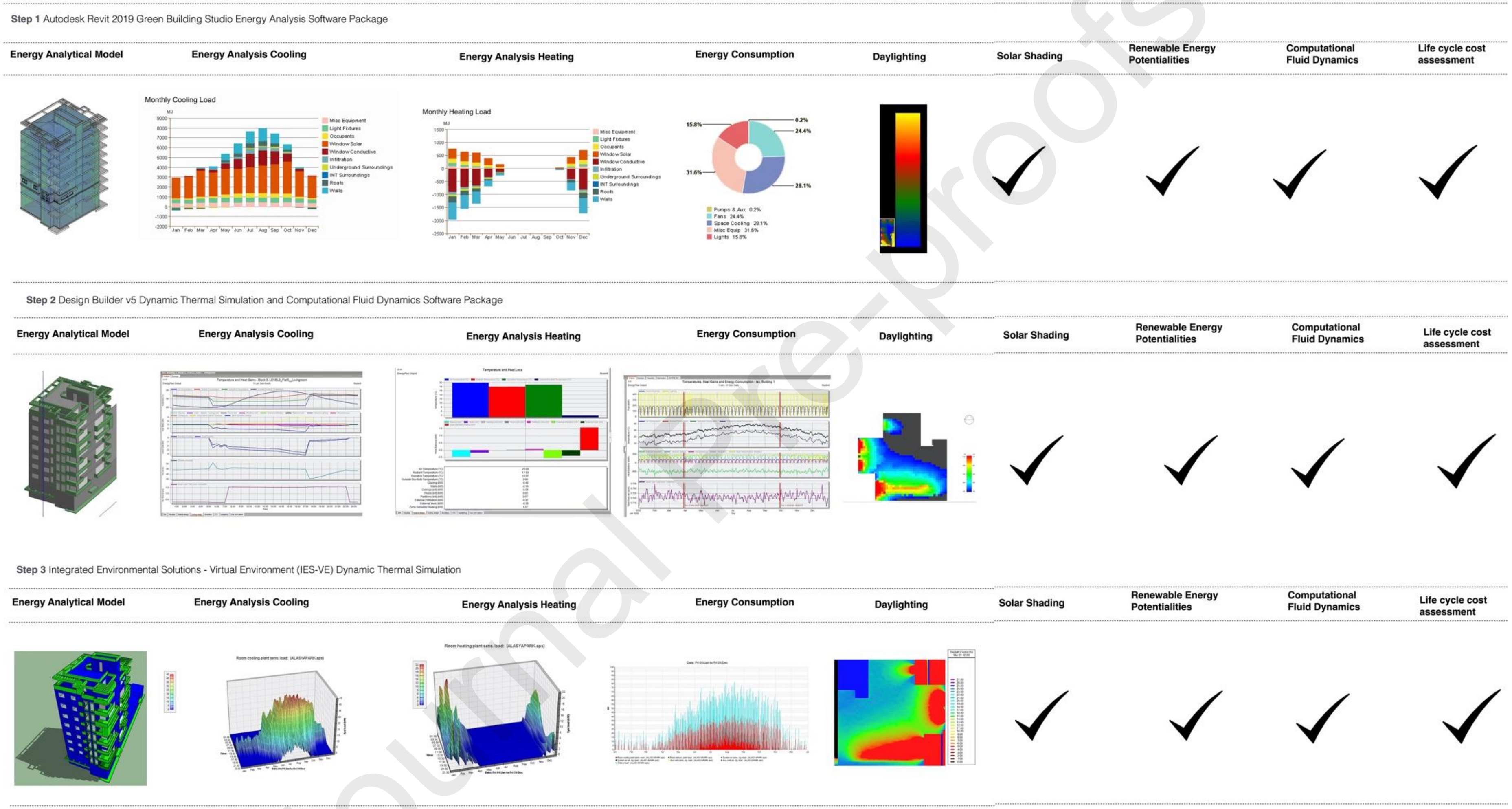

Figure A.1. Preliminary analysis of energy software tested to explore strengths and weaknesses of IES software.

Appendix A.2 Thermal-imaging survey

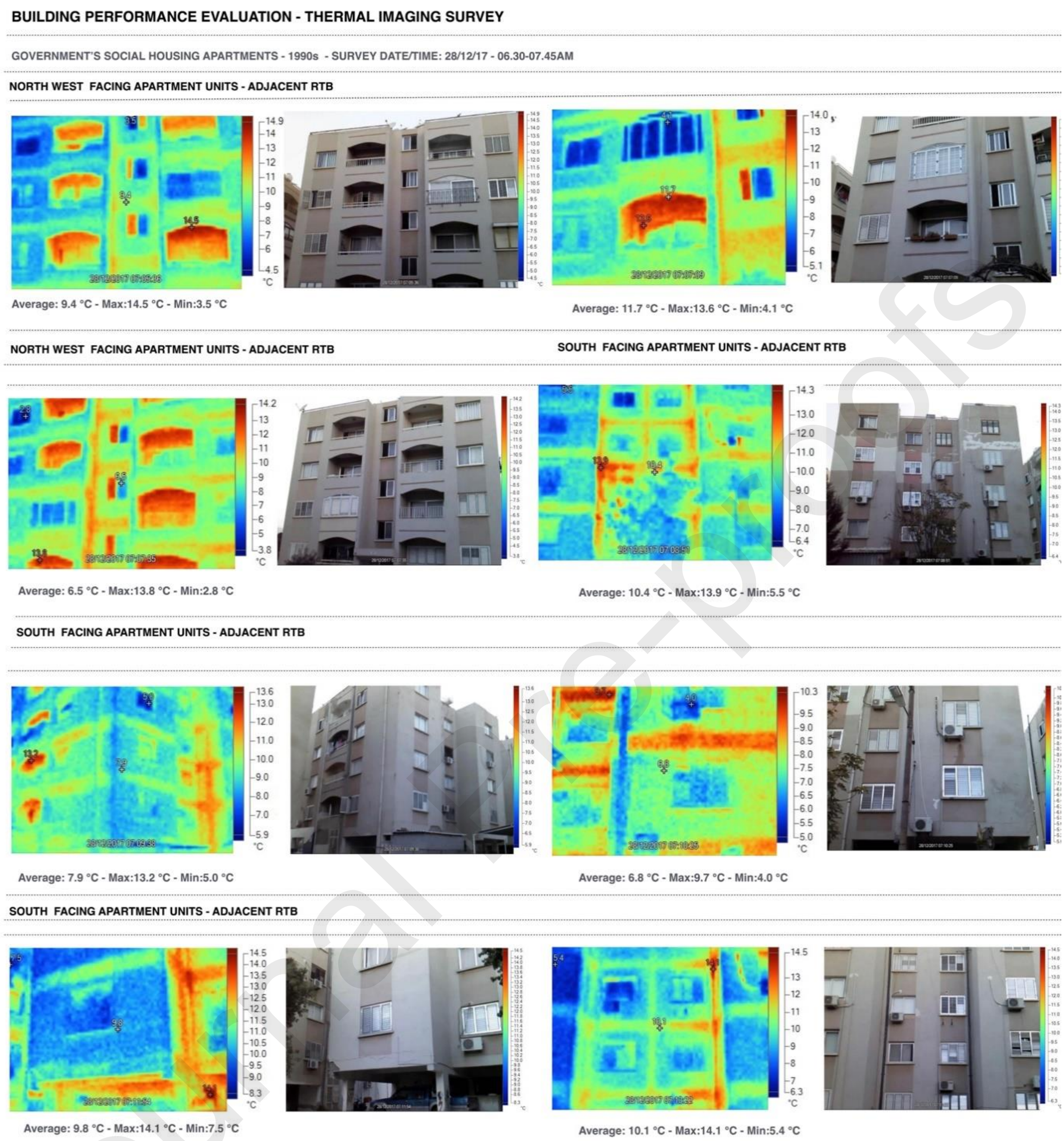

Figure A.2. Physical conditions of building envelopes. Thermal imaging survey conducted on December 28, 2017 between 06:30–07:45; thermal images recorded at back of RTB facing resident-designed public space. Bedroom 1 and Bedroom 2 located on back of RTB absorbed fewer sunshine hours. Readings revealed that building envelopes showed different degree of heat loss due to RTB orientation and location within social-housing estate.

Appendix A.3 Thermal-imaging survey

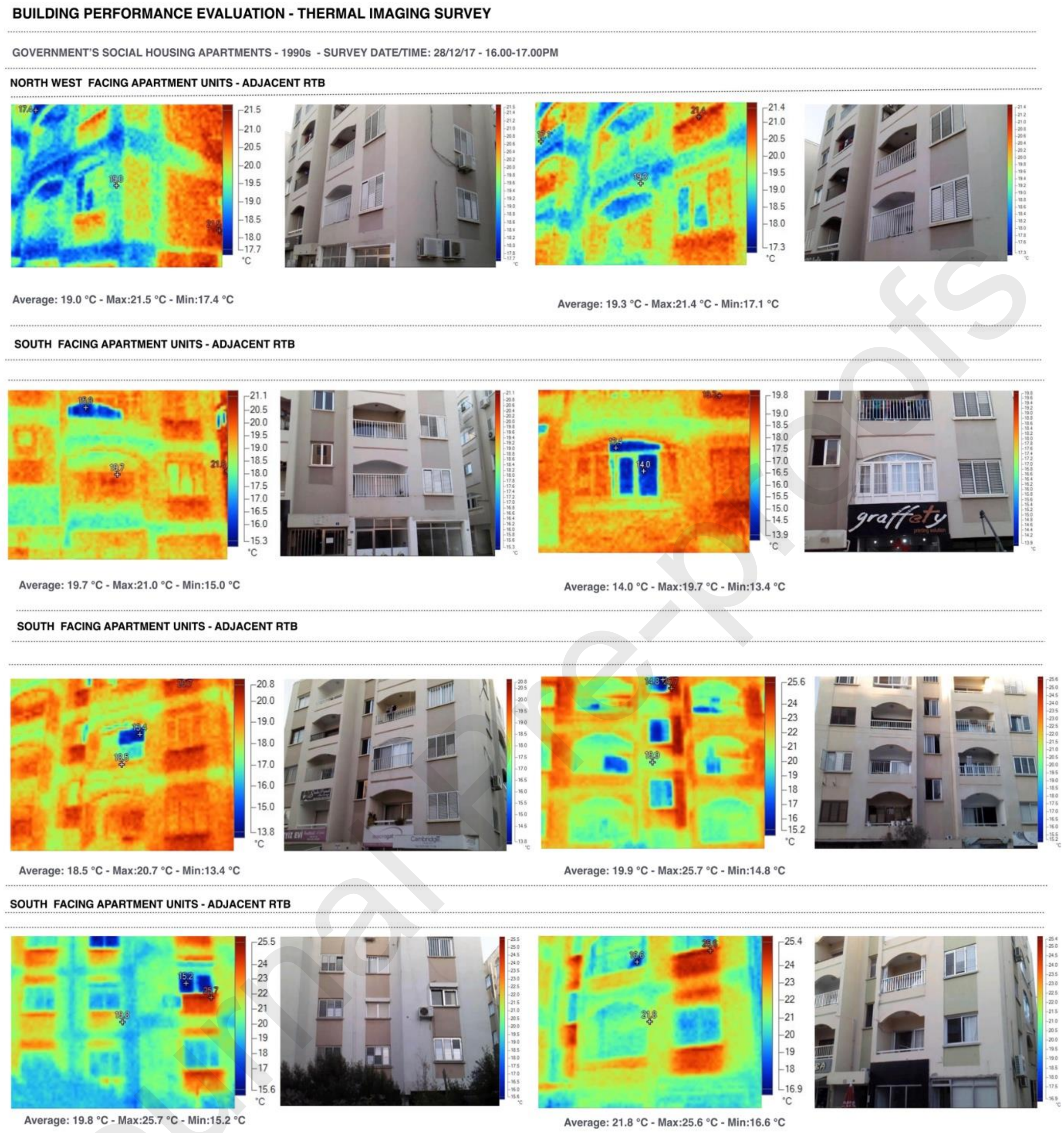

Figure A.3. Physical conditions of building envelopes. Thermal-imaging survey conducted on December 28, 2017 between 16:00–17:00; IRT survey recordings taken on front façade of RTB. Results revealed that living room spaces were susceptible to overheating in summer due to low-quality construction materials and absence of insulation materials on building envelopes.

Appendix A.4 Overheating risk assessment

Table A.1
Multiple comparison analysis between orientation factor and occupied spaces of each flat in the RTBs.

Dependent Variable	(I) Orientation	(J) Orientation	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Living room	**North East**	South	-0.00806	0.40031	1.000	-1.1586	1.1424
		North_West	0.49194	0.86798	1.000	-2.0027	2.9866
		South_West	***1.57527****	0.48414	0.016	0.1838	2.9667
		South_East	-0.07625	0.57337	1.000	-1.7242	1.5717
	South	North_East	0.00806	0.40031	1.000	-1.1424	1.1586
		North_West	0.50000	0.86107	1.000	-1.9748	2.9748
		South_West	***1.58333****	0.47163	0.011	0.2278	2.9388
		South_East	-0.06818	0.56285	1.000	-1.6858	1.5495
	North West	North_East	-0.49194	0.86798	1.000	-2.9866	2.0027
		South	-0.50000	0.86107	1.000	-2.9748	1.9748
		South_West	1.08333	0.90310	1.000	-1.5122	3.6789
		South_East	-0.56818	0.95391	1.000	-3.3098	2.1734
	South West	North_East	***-1.57527****	0.48414	0.016	-2.9667	-0.1838
		South	***-1.58333****	0.47163	0.011	-2.9388	-0.2278
		North_West	-1.08333	0.90310	1.000	-3.6789	1.5122
		South_East	-1.65152	0.62525	0.097	-3.4485	0.1455
	South East	North_East	0.07625	0.57337	1.000	-1.5717	1.7242
		South	0.06818	0.56285	1.000	-1.5495	1.6858
		North_West	0.56818	0.95391	1.000	-2.1734	3.3098
		South_West	1.65152	0.62525	0.097	-0.1455	3.4485
Kitchen	**North East**	South	0.74821	0.39362	0.604	-0.3831	1.8795
		North_West	0.88710	0.85348	1.000	-1.5659	3.3400
		South_West	***1.49821****	0.47605	0.022	0.1300	2.8664
		South_East	-0.15836	0.56379	1.000	-1.7787	1.4620
	South	North_East	-0.74821	0.39362	0.604	-1.8795	0.3831
		North_West	0.13889	0.84667	1.000	-2.2945	2.5723
		South_West	0.75000	0.46374	1.000	-0.5828	2.0828
		South_East	-0.90657	0.55344	1.000	-2.4972	0.6841
	North West	North_East	-0.88710	0.85348	1.000	-3.3400	1.5659
		South	-0.13889	0.84667	1.000	-2.5723	2.2945
		South_West	0.61111	0.88800	1.000	-1.9411	3.1633
		South_East	-1.04545	0.93797	1.000	-3.7412	1.6503
	South West	North_East	***-1.49821****	0.47605	0.022	-2.8664	-0.1300
		South	-0.75000	0.46374	1.000	-2.0828	0.5828
		North_West	-0.61111	0.88800	1.000	-3.1633	1.9411
		South_East	-1.65657	0.61480	0.083	-3.4235	0.1104
	South East	North_East	0.15836	0.56379	1.000	-1.4620	1.7787
		South	0.90657	0.55344	1.000	-0.6841	2.4972
		North_West	1.04545	0.93797	1.000	-1.6503	3.7412
		South_West	1.65657	0.61480	0.083	-0.1104	3.4235
Bedroom 1	**North East**	South	0.57796	0.33437	0.872	-0.3831	1.5390
		North_West	0.91129	0.72502	1.000	-1.1725	2.9951
		South_West	0.99462	0.40440	0.157	-0.1676	2.1569
		South_East	0.70674	0.47893	1.000	-0.6697	2.0832
	South	North_East	-0.57796	0.33437	0.872	-1.5390	0.3831
		North_West	0.33333	0.71924	1.000	-1.7338	2.4005
		South_West	0.41667	0.39395	1.000	-0.7156	1.5489
		South_East	0.12879	0.47014	1.000	-1.2224	1.4800

	North West	North_East	-0.91129	0.72502	1.000	-2.9951	1.1725
		South	-0.33333	0.71924	1.000	-2.4005	1.7338
		South_West	0.08333	0.75435	1.000	-2.0847	2.2514
		South_East	-0.20455	0.79680	1.000	-2.4946	2.0855
	South West	North_East	-0.99462	0.40440	0.157	-2.1569	0.1676
		South	-0.41667	0.39395	1.000	-1.5489	0.7156
		North_West	-0.08333	0.75435	1.000	-2.2514	2.0847
		South_East	-0.28788	0.52227	1.000	-1.7889	1.2132
	South East	North_East	-0.70674	0.47893	1.000	-2.0832	0.6697
		South	-0.12879	0.47014	1.000	-1.4800	1.2224
		North_West	0.20455	0.79680	1.000	-2.0855	2.4946
		South_West	0.28788	0.52227	1.000	-1.2132	1.7889
Bedroom 2	**North East**	South	0.57885	0.30705	0.625	-0.3036	1.4613
		North_West	1.21774	0.66576	0.705	-0.6957	3.1312
		South_West	0.96774	0.37135	0.106	-0.0995	2.0350
		South_East	0.05865	0.43979	1.000	-1.2053	1.3226
	South	North_East	-0.57885	0.30705	0.625	-1.4613	0.3036
		North_West	0.63889	0.66046	1.000	-1.2593	2.5371
		South_West	0.38889	0.36175	1.000	-0.6508	1.4286
		South_East	-0.52020	0.43172	1.000	-1.7610	0.7206
	North West	North_East	-1.21774	0.66576	0.705	-3.1312	0.6957
		South	-0.63889	0.66046	1.000	-2.5371	1.2593
		South_West	-0.25000	0.69270	1.000	-2.2409	1.7409
		South_East	-1.15909	0.73167	1.000	-3.2620	0.9438
	South West	North_East	-0.96774	0.37135	0.106	-2.0350	0.0995
		South	-0.38889	0.36175	1.000	-1.4286	0.6508
		North_West	0.25000	0.69270	1.000	-1.7409	2.2409
		South_East	-0.90909	0.47958	0.611	-2.2874	0.4693
	South East	North_East	-0.05865	0.43979	1.000	-1.3226	1.2053
		South	0.52020	0.43172	1.000	-0.7206	1.7610
		North_West	1.15909	0.73167	1.000	-0.9438	3.2620
		South_West	0.90909	0.47958	0.611	-0.4693	2.2874
Bedroom 3	**North East**	South	**0.86022***	0.28581	0.033	0.0388	1.6817
		North_West	1.44355	0.61972	0.220	-0.3376	3.2247
		South_West	1.13799*	0.34566	0.014	0.1445	2.1315
		South_East	0.64809	0.40937	1.000	-0.5285	1.8247
	South	North_East	**-0.86022***	0.28581	0.033	-1.6817	-0.0388
		North_West	0.58333	0.61478	1.000	-1.1836	2.3503
		South_West	0.27778	0.33673	1.000	-0.6900	1.2456
		South_East	-0.21212	0.40186	1.000	-1.3671	0.9428
	North West	North_East	-1.44355	0.61972	0.220	-3.2247	0.3376
		South	-0.58333	0.61478	1.000	-2.3503	1.1836
		South_West	-0.30556	0.64479	1.000	-2.1587	1.5476
		South_East	-.79545	0.68107	1.000	-2.7529	1.1620
	South West	North_East	**-1.13799***	0.34566	0.014	-2.1315	-0.1445
		South	-0.27778	0.33673	1.000	-1.2456	0.6900
		North_West	0.30556	0.64479	1.000	-1.5476	2.1587
		South_East	-0.48990	0.44641	1.000	-1.7729	0.7931
	South East	North_East	-0.64809	0.40937	1.000	-1.8247	0.5285
		South	0.21212	0.40186	1.000	-0.9428	1.3671
		North_West	0.79545	0.68107	1.000	-1.1620	2.7529
		South_West	0.48990	0.44641	1.000	-0.7931	1.7729

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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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