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An Analysis of the Development of Modular Building Design Elements to Improve Thermal Performance of a Representative High Rise Residential Estate in the Coastline City of Famagusta, Cyprus

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Abstract: Passive design strategies can reduce heating and cooling demands with integration of more efficient building systems as well as the potential to integrate modular off-site construction technology and its technical systems to offset overall energy consumption. This study evaluates the energy performance of the nationally representative post-war social housing estate in the southeastern Mediterranean island of Cyprus where the weather is subtropical (*Csa*) and partly semi-arid (*Bsh*). This study employed a mixed methods research design approach which was based on a thorough field study that consisted of a questionnaire survey conducted with residents of the social housing estate in the hottest summer month of August, to explore the occupants' thermal sensation votes (TSVs), their habitual adaptive behaviour, and home energy performance concurrently. On-site environmental monitoring was performed, and in-situ measurements of each occupied space were recorded to identify 'neutral' adaptive thermal comfort. The selected representative high-rise residential development was modelled using Integrated Environmental Solutions' Virtual Environment (IES-VE) software, where extensive dynamic thermal simulations have been produced to assess existing energy performance and energy effectiveness of retrofitting strategies. The results demonstrated that a moderate–strong relationship was found between orientation and reasons for thermal discomfort (χ^2 = 49,327, $p < 0.001$, Cramer's $V = 0.405$). Individual levels of thermal comfort were not limited to household socio-demographic characteristics, however; environmental factors were also determinants in the development of adaptive thermal-comfort theory. Furthermore, the occupants' TSVs indicated that in a southeastern Mediterranean climate, 28.5 °C is considered a neutral temperature, and the upper limit of the indoor-air thermal-comfort range is 31.5 °C.

Keywords: building performance optimisation; passive cooling design; retrofit energy design; thermal comfort

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1. Introduction

With increasing concern over national greenhouse gas (GHG) emissions during the last two decades in Europe, efforts are being made to improve energy efficiency in buildings, aiming to reduce energy demand and consumption, which also results in a reduction in associated GHG emissions and mitigation with climate change [1]. It has been argued that residential buildings' consumption in southern Europe is mostly related to summer conditioning (cooling); however, winter demand for heating has risen due to a lack of concern about the importance of occupants' thermal comfort and overheating risks in retrofit interventions [2]. For example, problems in mass housing estates are current topics of research on energy and policy interventions in Famagusta, Cyprus. Modernist low-rise, medium-rise and high-rise residential tower block (RTB) developments often lack indoor air ventilation due to the proximity of other buildings and are often built without consideration of the climatic features of the neighbourhood building site or urban planning laws and regulations [3]. These purpose-built residential building stock models represent only 56% of the existing building stock, but there is growing interest in improving the energy performance of the existing residential building stock, specifically considering occupants' thermal comfort in RTB developments [4].

Many scholarly pilot research projects focusing on European member states have investigated the interplay between government policy on thermal retrofit and current energy efficiency awareness of energy use in the residential buildings at which the policy was aimed [5–7]. In respect to Cyprus, a main concern is the burden resulting from a legacy of inefficiently built post-war housing stocks [8,9]. There are no measures or benchmarks for building energy performance, nor is there an official roadmap for regulating 'retrofit interventions' to address energy efficiency [10].

Previous research has determined that there is a lack of policy initiatives and implications addressing the importance of energy use [11]. According to a previous pilot study, one strategy for rectifying this deficiency is understanding the variance in energy performance in terms of the gap between the design and construction processes [12]. One prevailing opinion here is the need to take advantage of the benefits of implementation of energy efficiency systems. Moreover, researchers have recommended a wider perspective that includes a focus on the energy use of the existing built post-war housing stocks, including a consideration of the importance of occupants' thermal comfort [13].

This study identified key features from policy instruments and retrofitting initiatives across European Union (EU) member states that can improve the possibility of reducing energy consumption and optimising the thermal comfort level of occupants within the housing sector [14,15]. Our study underlines the importance of adopting comprehensive, interdisciplinary collaboration in order to examine and assess the energy performance of base-case representative RTBs in bringing appropriate energy-efficient retrofit interventions to improve building energy performance. We used this novel approach to determine the gaps in knowledge concerning occupants' real-life experiences in energy use and to identify measures that could optimise occupants' thermal comfort and reduce energy consumption through policy instruments.

This paper reports the findings of our environmental monitoring, which we performed during the summer at the post-war social housing estate in Famagusta, Cyprus. The variables measured during the survey are discussed to gain an understanding of the environmental conditions of the surveyed flats and their role in our assessment of both the occupants' thermal comfort level and the risk of overheating experienced in summer. The findings from the thermal surveys, environmental monitoring, and in situ measurements have been critically examined and discussed, and the results of the overheating analysis have been prepared with the intent to offer tangible recommendations for improving the existing energy performance of the flats and the thermal comfort of the occupants. In addition, the findings provide significant insights that can inform future policy decisions.

The aim of this study was to provide a critical insight of previous studies that have applied experimental and simulation techniques to evaluate thermal retrofits, with a focus on data collection and simulation methods. This paper discusses the findings of three different alternative passive design systems as potential solutions to reduce overheating, particularly in the summer season. In these passive design strategies, the use of natural ventilation systems, appropriate shading devices, and fenestration designs to improve both energy performance of a house and occupants' thermal comfort under the climate change impact is shown. The key research aims to demonstrate the state of the art and development of passive cooling design strategies are as follows:

- To investigate how data-driven building performance simulation may be used to improve predictive capacity and develop robust retrofit solutions.
- To compare on-site walk-through thermal imaging survey campaigns in terms of simulation parameters, temporal resolution, and data application, and

- To identify a range of approaches within the literature, with a bias toward simulating simple performance models over detailed data-driven analysis.

The study objectives are threefold. The first objective is to evaluate the current thermal comfort and energy performance of a prototype base-case study building in the coastal city of Famagusta where the weather is hot and dry in summer. To accomplish this evaluation, a high-rise RTB was identified as a base-case scenario development, since such structures represent the most common housing typology and building-construction materials considered in this study. The second objective is to evaluate building fabric thermal performance of each occupied space in order to provide a basis for the subsequent research phase. The third objective is to develop and evaluate the applicability of various passive design strategies as potential retrofit measures for the tall residential buildings to achieve improved thermal comfort and reduced cooling energy loads.

The novelty and scientific significance of this study is firstly, the framework developed for optimisation, which achieves effective building performance evaluation (BPE) tools, datasets, and scripts. The study will contribute to the strategic design of retrofit interventions to effectively reduce cooling energy consumption by considering occupants' thermal comfort, thermal adaptation, and energy use. The following section outlines the novelty of the study in greater detail.

1.1. Novelty of the Study

The novelty and scientific significance of this study lies in the methodology that systematically evaluates the energy-effectiveness of upgrading the thermal efficiency of existing social housing stock under the combined influence of three variables: socio-demographic household characteristics related to energy use, monitored environmental conditions, and the thermal level of conductivity of different buildings' thermal properties to provide background information that will benefit policy implications related to retrofitting older buildings. There are no strict measures or benchmarks for energy performance of buildings in Cyprus, nor are there any official roadmaps to regulate retrofitting strategies that will ultimately improve energy efficiency. No existing research was identified that investigated the energy-efficient retrofitting of any type of building, including existing post-war social housing stock, with such a methodology.

Moreover—and perhaps most importantly—an evidence-based socio-technical-system (STS) approach was developed for this study to measure the feasibility of the proposed passive-cooling retrofitting design strategies by relating human-based factors to the building energy simulation model, including in-situ measurements recorded during a survey to assess the occupants' thermal comfort. This state-of-the-art methodological framework could radically change the manner in which techno-economic studies that are aimed at evaluating building performance and providing a novel design method for building optimisation are undertaken and could also increase the likelihood of implementation of such measures and help to develop a roadmap for policy-making decisions related to energy use throughout all EU member states. Even though the methodology was tested in the Cyprus context, it was designed to be applicable in other countries with similar climate characteristics, building codes, and regulations. It is therefore believed that this study fills a knowledge gap in the area of building optimisation and contributes to knowledge on multiple levels by:

- Adding to the knowledge base for how to methodologically plan holistic retrofitting schemes and passive-cooling design strategies to not only reduce household energy consumption, but also to increase energy saving awareness by presenting schematic illustrations of retrofitting design interventions.
- Suggesting cost-effective mechanisms and priorities and energy-saving targets that could be effectively implemented at the policy level throughout the EU member states.
- Developing a novel energy-efficiency indicator that is more applicable to the development of an Energy Performance Certificate (EPC) of building implementation schemes

than to any existing indicator that has been recommended by the Energy Performance of Buildings Directives (EPBD) objectives.

- Devising a conceptual framework of the STS approach to fill the knowledge gap and apply this to the 'bottom-up' design approach to formulate effective policy-making decisions related to energy use.

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

1.2. Contribution to Current Knowledge

The original contribution of this research lies in the methodology that systematically evaluates both the applicability and efficiency of implementing passive cooling design strategies in order to optimise the thermal comfort of occupants and reduce cooling energy consumption of the representative base-case residential tower block prototype in Famagusta, Cyprus. In this context, no existing research has been conducted on improving energy efficiency of any type of building, residential tower block development projects or otherwise. Most importantly, this study investigates the occupants' behaviour in their cooling energy use and cultural assessment of the embedded energy performance of residential buildings. This new indicator could radically change the way that calibration studies aiming to evaluate and optimise residential buildings' energy efficiency improvement in base-case prototype residential tower block development projects will be conducted, significantly increase the uptake of implementation and encourage both the early design stage and policy decision making process of the retrofitting of post-war residential building stock.

It is therefore believed that this study fills a gap and contributes to knowledge on multiple levels by: *(i)* evaluating the actual effectiveness of passive design systems in a representative sample of the RTBs, *(ii)* exploring the potential relationships between household socio-economic characteristics, home energy use factors, energy performance, and thermal comfort level preferences, *(iii)* identifying the impacts of cooling energy use-related behaviours towards the RTBs' energy performance in the summer, *(iv)* providing recommendations to support policy aimed at reducing energy consumption and increasing awareness of feasible and efficient low-tech building systems' use from the residential sector, *(v)* developing the knowledge framework of an energy-efficient and cost-effective retrofit of a residential tower block to optimise occupants' thermal comfort and thermal sensation preferences, increase their awareness, and increase the efficiency of the project from the users' end. It is noted that this study focuses on testing, measuring, and implementing several passive design strategies and energy efficiency systems into retrofitting rather than investigating the environmental impacts of climate change.

1.3. Significance of the Study

The significance of this research is the detailed design of the scientific framework on which the proposed methodology is based. This method is also illustrated and tested by means of its application in a case study of a post-war social housing development estate in the southeastern Mediterranean climate. In this study, challenges exist in the assessment of the life-cycle cost impact of energy systems and energy services during the decision-making process and the early design stages of building retrofitting strategies. Tools to estimate energy consumption reductions that incorporate dynamic thermal simulations are well established, and the guide to improve design-stage predictions that was laid out in CIBSE TM59: Design Methodology for the Assessment of Overheating Risk in Homes was recently updated to include ventilation strategies for domestic buildings in order to minimise the risk of further spreading COVID-19 throughout households in residential buildings. Indoor air quality assessment has proven to be a challenging process due to the lack of available data and limited standardisation criteria that were put into place, but current design methods are available that seek to diminish the impact of the current pandemic. Due to the unprecedented new variant of the virus that has already rapidly spread around the globe at the time of writing this research article, this study seeks to address the assessment of indoor air quality, occupancy profiles, and the impact thereof on home energy use with sufficient robustness, which can, at times, seem onerous and time-consuming, especially when design scenarios and structures in a post-war social housing estate need to be assessed.

Limitations also currently exist with the energy-efficiency assessment methods for building technologies and the life-cycle cost impact analysis that is specific to the housing sector. These methods include both a top-down analysis, such as industry benchmarks and a multivariate analysis, and a bottom-up analysis, such as a case-study assessment. These limitations coupled with the significant drivers that address the development framework devised via the STS approach were integrated with human-based data to investigate building optimisation schemes to calibrate the energy usage of households. This leads to a strong need for a comprehensive analysis in this field in order to properly understand the true impact of development decisions on building optimisation efforts and a life-cycle cost assessment. Such a novel methodology attempts to identify gaps in the existing body of knowledge by considering occupants' real-life experiences related to energy use and identifying measures that could enhance their thermal comfort and reduce energy consumption through retrofitting interventions.

2. Literature Review

A literature review of overheating risk of buildings and thermal comfort studies across the globe was conducted in an effort to provide a comprehensive understanding of occupants' habitual adaptive behaviour regarding energy use. This review was based on selected key terms—'overheating risk', 'thermal comfort', 'occupant behaviour and energy modelling', and 'building-energy simulations'—to address the knowledge gap in the field of energy efficiency and to develop a new design method for the STS approach. Additionally, information regarding the research context is presented to demonstrate the validity of the nationally representative archetype housing stock in Cyprus and the household population that were selected for the present study, as presented in the following section.

2.1. Identification of Nationally Representative Archetype Housing Stock

The theoretical component of this study consists of a combination of the UK assessment technical procurement and the EU assessment criterion in order to identify the optimum thermal comfort of occupants. Therefore, from the beginning of this study, there were limited pre-existing sources available for the Cyprus context, and this study was aimed at primary data collection to develop the methodological framework. Thus, a case study was necessary to enable the research consortium to achieve the intended aim of demonstrating the condition of the post-war social housing structure. The stages of housing developments from 1950 to 2017 in Cyprus are illustrated in Figure 1.

As shown in Figure 1, Phase I describes the mass housing development from 1950–1974 in the fenced-off Varosha territory from 1950–1960 during the British colonial administration. Varosha and its coastline consisted of single-storey bungalows and two-storey detached houses after the 1960 independence of Cyprus from the British administration [16]. It can be seen that the coastline was handed over to overseas developers where all the high-rise RTBs were built within a 14-year period of rapid mass housing development. According to housing statistics from 1974, 34,000 residential projects were constructed in the Varosha territory; however, this development came to a standstill in 1974 due to the civil war, and the city has been closed to human habitation ever since [17].

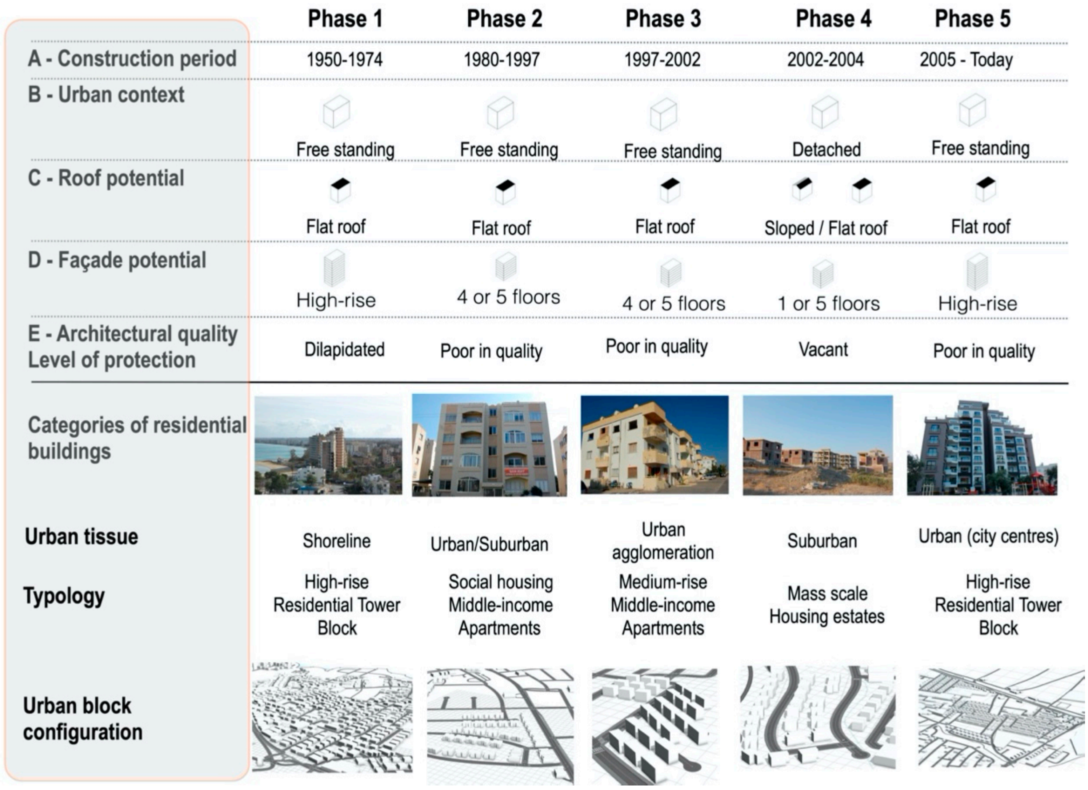


Figure 1. The taxonomy of housing stock in Cyprus.

Phase II delineates the government's social housing estates, which were built from 1980 to 1997, to respond to the needs of the housing shortage for young people [18]. Within a decade of implementing the same residential building typology, these types of housing estates were repeated in all five major cities across the country [19]. All these RTBs had the same floor plan layout, two flats located on each floor, and the same deficient building envelope which did not consider the local climate conditions and topographical conditions of the project sites. The housing stock analysis reveals the way these RTBs were built without informed decision making in respect to land use planning layout [20]. All these RTBs lacked planning for a social housing structure scheme, and this led to the housing estates having poor air quality for its residents and high thermal conductivity in the summer, which caused an overheating risk and a thermally uncomfortable indoor environment for the occupants.

Phase III illustrates that the construction of these housing estates was continued by privately owned construction companies after 1997, when the government's social housing scheme ended. This has continued to this day. These privately owned construction companies are still building estates using exactly the same method of construction as the government's social housing, which has no land use policy, no consideration of environmental and climatic design principles, and no type of ventilation strategies for the occupants' thermal comfort; hence, no lessons have been learnt from this poor construction practice over this 30-year period. Phase IV describes the property boom that was expected after the changing political structure in Cyprus. All these projects were built without the authorisation of the Chamber of Architects or the Department of Town Planning of Cyprus due to the national policy gap from 2002 to 2004 [21]. This resulted in attracting both local private construction companies and overseas developers to engage in the construction of these types of mass housing development estate projects located in five major cities in Cyprus, as well as towns in the rural and mountainous areas [22]. The aim was to build and sell these settlements within the surrounding natural habitat without considering the structure of the housing in relation to its surroundings. This led to the abundance of incomplete housing structures left abandoned all over the country as an eyesore and a detriment to the natural habitat [23].

Phase V demonstrates how the private construction companies' objective evolved into building mass mega high-rise towers and urban block developments throughout the country in towns, rural villages, and mountainous regions without ever considering the respective local climate characteristics and topographical conditions [24]. At present, these are unfortunately the only mass housing schemes that are being constructed, and they will cause more environmental and socio-cultural problems now and in the future.

This evolution of housing stock clearly outlines the stages of building mass housing estates in Cyprus and reveals that, starting with four- or five-storey RTBs in the 1990s, which ultimately led to 25-storey skyscrapers, the stages of development had no defined planning scheme at all, no governmental policy, nor any control mechanisms—all to the detriment of the environment and thermal comfort of the residents [25]. Thus, this study can assist in the establishment of an initial benchmark to guide the development of housing that addresses all the concerns of the residential sector in Cyprus. Based on the findings and related information, government agencies can determine appropriate policies to be implemented in the future for the decision making of retrofit policy design in this southeastern Mediterranean climate.

2.2. Building Performance Implications

A pragmatic way of quantifying the effect of thermal comfort is defined by the CIBSE—Technical Memorandum 52 guidelines for new buildings, major refurbishments, and adaptation strategies should conform to Category II in BS EN 15251 [26]. A further method has been suggested in the CIBSE Guide (2005), the BS EN 13779—Ventilation for residential buildings: Performance requirements for ventilation and room-conditioning systems [27]. This assessment criterion has further been put forward to provide basic subsequent information to assess the quality of indoor air and relate this to fresh air ventilation rates required for each occupant [28]. Studies have focused on the assessment of energy performance in implementing state-of-the-art building systems into building retrofitting that may require prediction of the way air moves through the building [29–31]. This is a research gap that has not been addressed previously in similar studies. Should this approach be employed, it is recommended that the approach to overheating taken here is to measure the indoor thermal comfort independent of the metric used to assess performance of residential buildings [32]. Table 1 delineates the literature review that was undertaken to demonstrate building stock aggregation through archetype buildings.

Another assessment method is provided by standard BS EN ISO 13786—Thermal performance of building components: dynamic thermal characteristics and calculation methods, which is a more direct measure of effective thermal mass which also accounts for the dynamic effects in terms of penetration depth of the temperature fluctuation into the fabric [36]. The adaptive approach is currently implemented in the CIBSE TM59 Guide—Design methodology for the assessment of overheating risk in homes [37]. In order to perform a generally reliable study, a method has been suggested by Fanger in the 1970s, and a practical application has also been demonstrated by Holmes and Connor in 1991 [38–41].

From this point of view, the CIBSE AM 11—Building performance modelling (2015) provides guidance on the use of detailed thermal models. According to what is stated in the norms of BS EN 13786: 2007, it has been assumed that if the heat gain to a space is below 35 W/m^2, there is unlikely to be a need for mechanical cooling [42,43]. It should be noted that state-of-the-art building systems and the implementation of effective retrofit interventions are encouraged in the first instance to reduce requirements before costlier and shorter life span systems are installed. It is noteworthy that this approach improves the cost-effectiveness of energy savings and increases the efficiency of buildings for the duration of their operational lives [44–46]. Furthermore, a recent study suggested by CIBSE Guide F—Energy efficiency in buildings in 2030 gives further detail on low-energy design principles [47]. However, the more that is known about the manner of both applicable and feasible design strategies which are put forward, the more an effective solution is prioritized. Hence, more appropriate energy demand calculations must be undertaken throughout the early design stages of retrofitting scenarios to quantify these measures.

Table 1. Worldwide statistically representative archetypes.

References	A. Study Location	B. Building Type	C. Sampling Size	D. Primary Aim of Model	E. Methodology	F. Main Findings
Bianco and Marmori (2021) [33]	Italy	Single and Multi-family houses	Typology 6 was selected as an archetype to represent housing stock built after 2005—represents 8000 new buildings per year	- To estimate the energy savings obtained when specific energy efficiency measures are applied; to bridge the identified gap and introduce a novel calculation tool	- Geometric and thermal features of buildings were used; I-REM energy modelling framework was used; energy consumption data was extracted from the Eurostat and Odysee databases for the validation study	- A savings of 76.8 kWh is fixed for 2030, double with respect to the EU Policy scenario, and 100 kWh for 2040
McKenna et al. (2013) [34]	Germany	- Single- and two-family houses - Multi-family houses	- 10,000 objects related to energy use was used; 4575 single- and two-family houses; 5491 multi-family houses were selected as an archetype	- To analyse the role of refurbishment measures in the reaching, or not, of these energy political goals by developing an aggregated building-stock model	- Building stock projection data for 2011 to 2050 was gathered; micro-census survey data was used; age categorization of housing stock was applied; renovation measures were predicted by using statistical analysis methods	- The renovation probability of the SFH is increased by 2020 from 1 to 4%; the model results regarding total final energy demand are significantly higher than in other studies
Famuyibo et al. (2012) [35]	Ireland	Residential buildings	13 representative archetypes were identified for the statistical analysis	- To present a methodology for the development of archetypes based on information from literature and a sample of detailed energy-related housing data	- Multilinear regression analysis, clustering, and descriptive statistics were used; the Energy Performance Survey of Irish Housing and the Irish National Survey of Housing Quality databases were used	The linear regression indicates a coefficient of determination, R^2 0.391, indicating 39.1% of the variance in household total energy use.

2.3. Thermal Comfort in Residential Buildings in Europe

Many scholars have been focused on simulation studies to identify base-case scenarios in order to exacerbate overheating in residential buildings [48–50]. Researchers recommend shading, ventilation, and thermal mass as effective solutions for concerns as first base-case strategies to mitigate temperature rises in residential buildings in the summer [51,52]. Moreover, studies have also investigated the energy efficiency of passive cooling design strategies which assume a cross-ventilation defined as a multi-zone airflow network driven by wind direction, speed, orientation of the window openings, and temperature between the indoors and outdoors of each occupied space [53]. It has been widely assessed that natural ventilation strategies alone are insufficient to reduce energy consumption and optimise occupants' thermal comfort, particularly in the hot and dry climate regions in the southeastern Mediterranean basin [54]. For this reason, an external shading device has been assigned to the base-case model and a window opening has been reduced to 30% to account for security measures in a social housing block [55]. Within these studies, the propensity to overheating has shown significant impact on the indoor temperature measures, and this could be applied to a similar housing typology which has targeted improving energy efficiency [56].

It is evident that the implication of passive measures of retrofitting of a residential building is relevant to clearly identify a common methodology to assess occupants' thermal comfort in a similar geographic location and building typology across Europe [57]. Studies indicate that overheating and its impacts on occupants' thermal comfort is already a problem in prototype-tested residential buildings across different climates in Europe [58–61]. Many studies have been carried out by environmental scientists with the aim to understand the occupants' thermal comfort levels that trigger users' actions and to classify them in order to develop an evidence-based energy policy design [62–64]. These studies demonstrate that one of the major unresolved issues regarding overheating concerns the insufficient building envelope and building systems (e.g., windows, shutters) throughout the post-war social housing estates in Europe [65]. Apart from that, there are also records which suggest that European residential building stock which has undergone systemic retrofit schemes to improve the thermal performance in winter is now facing overheating issues in summer [66]. A pilot study by Brotas and Nicol was conducted in 2015 for a representation of the energy consumption for heating and cooling for a mid-floor flat in different countries in Europe in order to take into account the climate change predictions of 2020, 2050, and 2080, as shown in Figure 2.

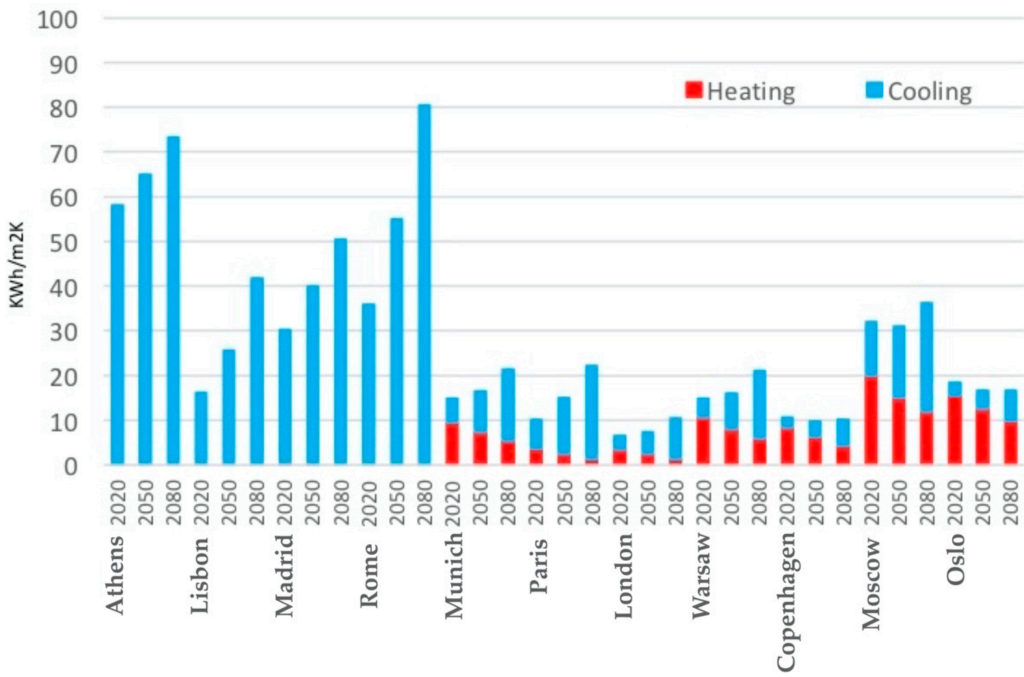


Figure 2. Heating and cooling energy consumption of dwellings in capital cities in Europe in 2020, 2050, and 2080. Source: Brotas and Nicol (2016) [67].

As shown in Figure 2, the findings highlight that the high internal gains from using domestic appliances in residential buildings led to an increase in the predominance of cooling loads even in mild climates across Europe [67]. This can be further exacerbated with climate-change-aggravated temperature rise scenarios and Urban Heat Island (UHI) phenomena [68]. Moreover, it has been suggested that the implementation of passive cooling design strategies such as natural ventilation are viable options to mitigate the overheating issues related to climate change in residential buildings [69]. Researchers who analysed the overheating issue in mild climates highlight the possibility of adopting passive design strategies that can be effective in avoiding or reducing the need for mechanical systems for cooling in the summer [70–72]. Another pilot study was conducted on assessing energy use and overheating risk in net-zero-energy residential buildings under the Horizon 2030 research project with case studies in Cyprus, France, Italy, and the UK. Design, optimisation, implementation and monitoring of advanced energy efficiency solutions to upgrade the building envelope of the inefficient residential building stock were assessed [73–76].

Studies carried out in nationally representative dwellings found that overheating or summer thermal discomfort are major issues both in existing dwellings and in newly built dwellings [77,78]. More evidence which supports the significance of the overheating risk issue has shown that undertaking passive measures into a retrofit of residential building systems reduces the overheating risk of buildings, decreases energy running costs, and increases society's awareness of implementing effective adaptation packages during the retrofitting process [79]. It becomes particularly clear that the potential benefits of greater energy consumption reduction and the value of the built asset increase in various studies [80–82].

In order to highlight the importance of this pilot research project conducted in the hot and dry climate of the eastern Mediterranean island of Cyprus, it is important to highlight that this empirical study demonstrates a ground-breaking epistemological approach in two ways. First, it is the first published research project to investigate domestic energy use by considering the patterns of occupants and their real-life experiences with energy use in conjunction with assessing their thermal comfort by taking into account environmental parameters at the same time. Second, it also quantifies the impact of the buildings' thermal properties on the occupants' thermal comfort and the households' energy use, an area in which there is little research.

3. Methodology

This section presents the research methodology by explaining the overall aims and approach of the research, including a brief explanation of the main data collection and modelling set-input parameters of the prototype retrofit housing model. It also explains selection criteria for selected prototypes of RTBs. A combination of quantitative research methods; on-site observations, thermal imaging, modelling and simulations, and a questionnaire in parallel with in-situ measurements are all contained within this underlying approach.

3.1. Eastern Mediterranean Island of Cyprus

Cyprus is situated in the north-eastern area of the Mediterranean Sea between latitudes 34′33″ and 35′41″ north and longitudes 32′15″ and 34′35″ east [83]. It is located approximately 40 miles north of Turkey, 60 miles east of Syria, 250 miles south of Egypt, and 300 miles west of the Greek islands. The island has an area of 9.251 km^2; it is the third largest island in the eastern portion of the Mediterranean Sea. This location has four distinct topographical characteristics—semi-mountainous (Zone 1), coastal (Zone 2), mountainous (Zone 3), and inland (Zone 4)—all of which give rise to varied climate conditions [84], as shown in Figure 3.

Figure 3. 3D model of the coastal city of Famagusta, Cyprus.

An exploratory case-study approach was undertaken for the coastal city of Famagusta, which is directly connected to an intercontinental body of water, the Mediterranean Sea, as shown in Figure 3. Famagusta is an exposed frontline city that has been subjected to frequent changes in its construction industry in the last three decades as a result of policy gaps in town planning and building regulations.

3.2. Climate Characteristics

Cypriot climates are determined by geographical positions in the northeast corner of the Mediterranean Sea, the morphological characteristics of ground plains, and the meteorological variations of the region [85]. According to the Köppen climate classification system (World Köppen climate classification data was reviewed; the dataset is available to researchers), Cypriot climate characteristics are typical of the Mediterranean region. Köppen climate data show that the overall climate type for Cyprus is subtropical (*Csa*) and partly semi-arid (*Bsh*) in the northeast part of the island [86]; this means that Cyprus is hot and dry during the summertime, as illustrated in Figure 4.

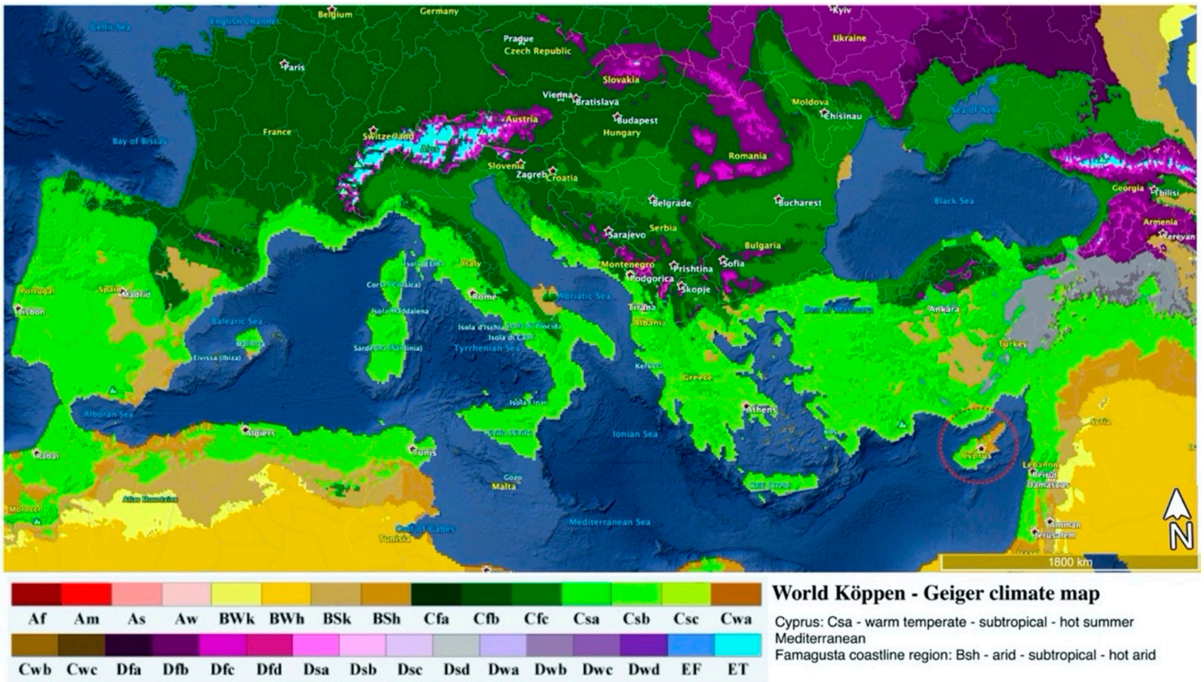
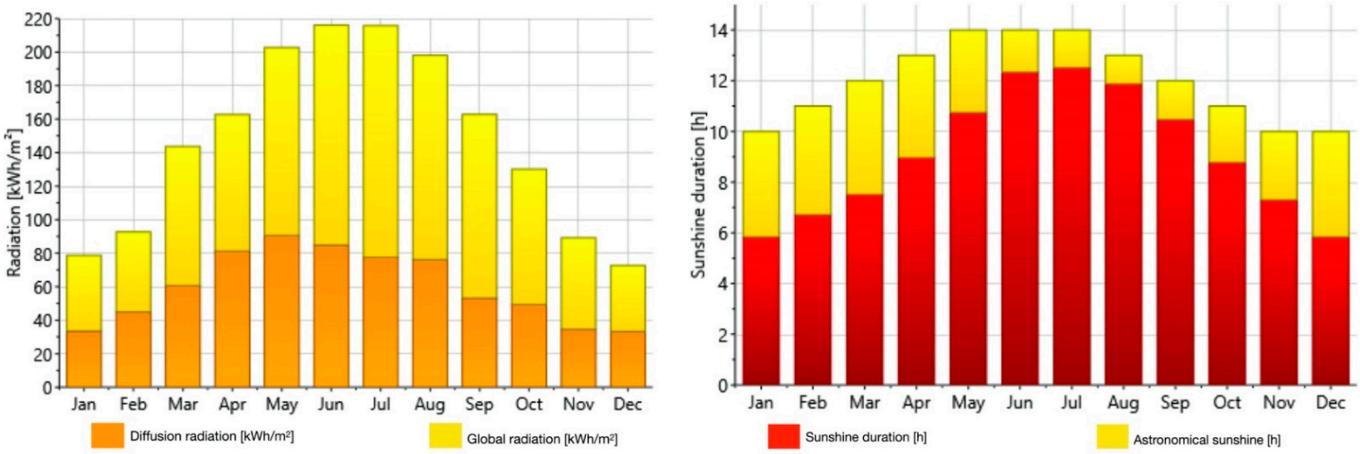


Figure 4. Map of Geiger climate classifications of the Mediterranean region. Source: Rubel et al., (2017) [87].

Solar radiation statistics reveal that most regions of the island have, on average, 75% bright sunshine hours during the period when the sun is above the horizon [88]. A horizontal surface in Cyprus typically receives 4.7 kWh/m^2 of sunshine per day in December and 11.6 kWh/m^2 per day in June, as shown in Figure 5a. Due to the island's geographical location, during the cloudiest months of December and January, the average duration of sunshine is 5.5 h per day; this increases to an average of 12 h a day in the summer, as shown in Figure 5b. Diagrams for Figure 5a,b were extracted from Meteonorm Version 8; software suite developed by Meteotest AG in 2020 (Germany). The data shows that there is a significant difference between mid-summer and mid-winter temperatures. Winter temperatures vary between 18 °C inland and about 14 °C on the coast [89]. There are also wide differences between day- and nighttime temperatures, especially inland in summer. These differences are dependent on the four climatic zones mentioned above. Winter temperatures differ between 8 and 10 °C in the lowlands and between 5 and 6 °C on the mountains. Summer temperature differences have increased to 16 °C on the central plain and from 9 to 12 °C in the coastal areas [89].



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

Figure 5. Environmental conditions of case-study location: (**a**) solar irradiance; (**b**) sunshine hours.

Figure 6 demonstrates the psychometric chart that can be utilised to plot the temperature and relative humidity (RH) occurring over a period of 2.385 of 8.760 h in accordance with the annual weather climate data generated from the Energy Plus weather database. EnergyPlus is an open-source whole-building energy-simulation program; the EnergyPlus weather format (i.e., .epw) is compatible with the weather data for more than 2100 locations (https://energyplus.net/weather, accessed on 7 March 2021). This illustrates different comfort index parameters that are represented by specific zones on the psychometric chart. Furthermore, the percentage of hours that fall into different design strategy zones offer a relative understanding of the solar irradiance factor and thermal-absorptivity levels of building envelopes.

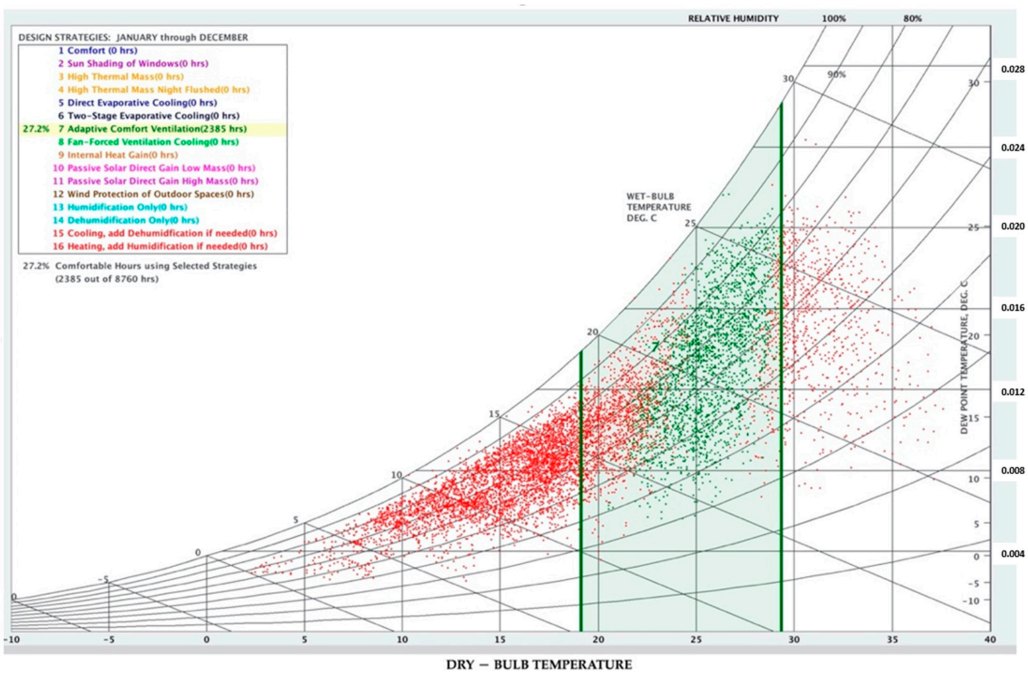


Figure 6. Air temperature and RH in Famagusta from 1 May to 30 September plotted on a psychometric chart; timeframe reflects the Cypriot cooling period.

A climatological analysis of the research context reveals that hot, dry summers and moderate, wet winters are the primary climate characteristics for Cyprus and have a direct impact on annual cooling and heating demands due to the need for space conditioning in the summer and winter [89]. Famagusta demonstrates mild Mediterranean climate characteristics. Maximum Dry Bulb Temperature (DBT) can reach as high as 42 °C in the summer; minimum DBT can drop down to 6°C in the winter [89]. Mean-minimum DBT varies from 6.8 to 22.3 °C, and mean-maximum DBT varies from 16.3 to 33.3 °C [89].

3.3. Conceptual Framework

The primary underlying basis of the research was to investigate the potential of low-tech passive cooling design elements in cooling energy use reduction and optimising occupants' thermal comfort in Famagusta, Cyprus. To ensure systematic analysis of the key aims and objectives, this research adopts a 'quantitative' research design primarily undertaking building performance evaluation using dynamic thermal modelling and simulation validated with a comprehensive thermographic survey and a questionnaire distributed to the occupants of the RTB prototype. Figure 7 summarises the developed methodology and data collection process. The procedure for quantitative data collection and analysis needed to be conducted sequentially such that adequate sampling, source of information, and data analysis were undertaken. This paper presents the quantitative national data set, the statistical analysis of this data set, and then the calibration studies and their analysis.

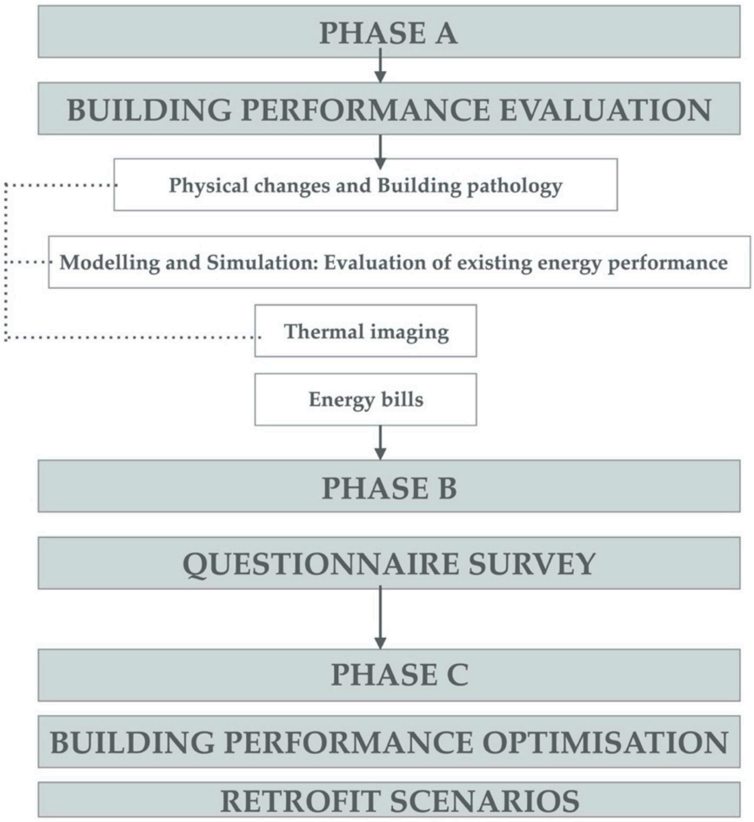


Figure 7. The methodological framework developed for the study.

More emphasis was given to the quantitative results, leading to the conclusion that this study highlighted the findings of quantitative research (building performance simulation and questionnaire). However, these reports in the results from the two databases were followed by an analysis of key findings in which both primary and secondary quantitative results were compared for supportive and non-supportive findings. In this study, the researcher merged the two databases in a side-by-side comparison.

3.4. Developing a Dynamic Method of Design for Energy Policy

A quantitative research design was employed, involving the development of a building energy model for the existing residential tower blocks (RTBs), incorporating high-level building parameters and the energy use of the occupants; analysis of the existing energy performance of post-war social housing development estate; undertaking solar exposure analyses and dynamic thermal simulations (DTS); the investigation of representative apartment units to model the energy performance of retrofitted RTBs' energy demand for cooling and occupants' thermal comfort during the overheating period, taking into account passive cooling design principles; and designing a prototype residential tower block as a climate-responsive building to improve energy efficiency using the simulation data for building performance evaluation. As an initial step, the performance of a case study building was modelled and simulated by employing Integrated Environmental Solutions' Virtual Environment (IES-VE) software add-in Apache-Sim Dynamic Thermal Simulation. Additionally, an ASHRAE 7-point scale was used to assess indoor air thermal comfort temperature levels to validate the adopted benchmark criterion as recommended by the CIBSE TM59 during the hottest summer month of August. In this study, the dynamic thermal performance simulation studies of each representative apartment unit were conducted in an analytical energy simulation environment between May and September, the peak demand period for cooling energy use, as shown in Figure 8.

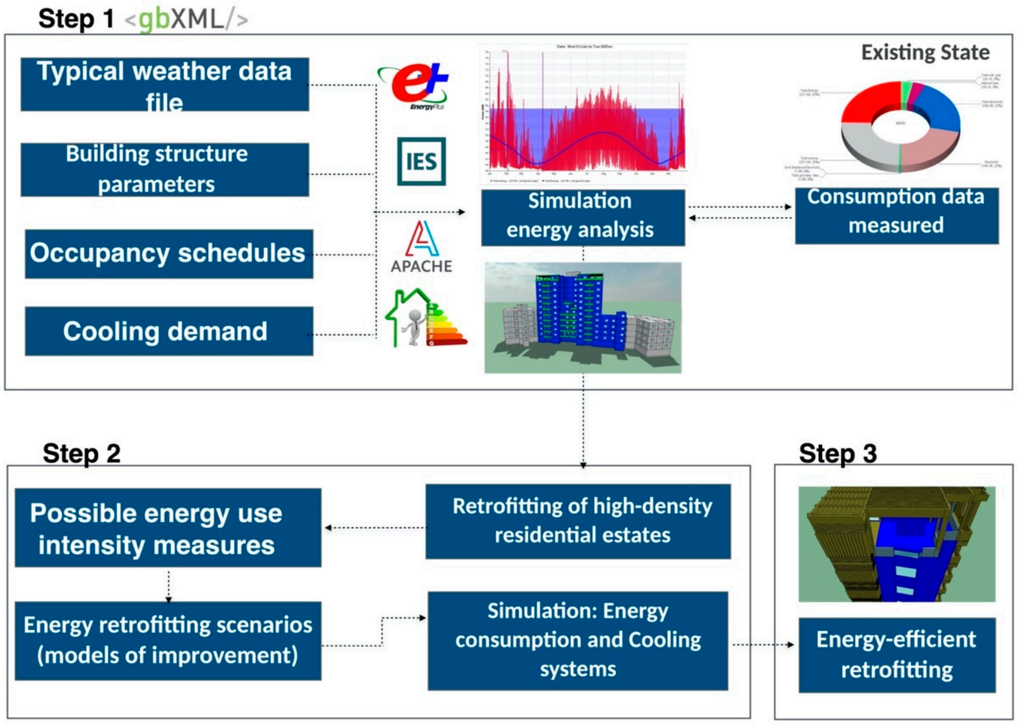


Figure 8. The methodological workflow developed for the building energy simulation study.

To fulfill the research aims and objectives, the periods were spread throughout the summer with the aim of measuring the risk of overheating in the RTBs. In each of the occupied zones (i.e., living rooms and master bedroom spaces), calibration studies of the characteristics needed for energy use per area (naturally or mechanically) in order to consider occupancy, the electrical energy use of equipment, internal temperature, and the energy use of artificial lighting and of mechanical plants (A/C units) were conducted. The aim of the selection was to capture a variety of space energy uses using relatively simple assessment benchmarks to import the data to the IES simulation software. This was carried out for the purpose of assessing the validity of simulation results by investigating the daylight impact factor on each occupied space and the thermal properties of representative apartment units' under-investigation.

3.4.1. Prototype Residential Tower Block Development as Base-Case Scenario

The Lordos RTB development is a miniature city, built in phases, which took over five years to complete; it is home to multiple storeys of flats, interconnected public spaces, vegetated private balconies, thresholds, passageways, and vegetation. The main aim was to build a continuous urban landscape using a combination of staggered volumes, which move forward and backward in relation to the street and waterfront. The construction of the apartments began in 1968; the first dwelling was occupied in 1973 [90]. Most dominant in the district were the large high-rise blocks. This housing estate contains 118 apartment units in 12 different floor plan designs; the blocks are 30–40 m long and 13 storeys high, as shown in Figure 9.

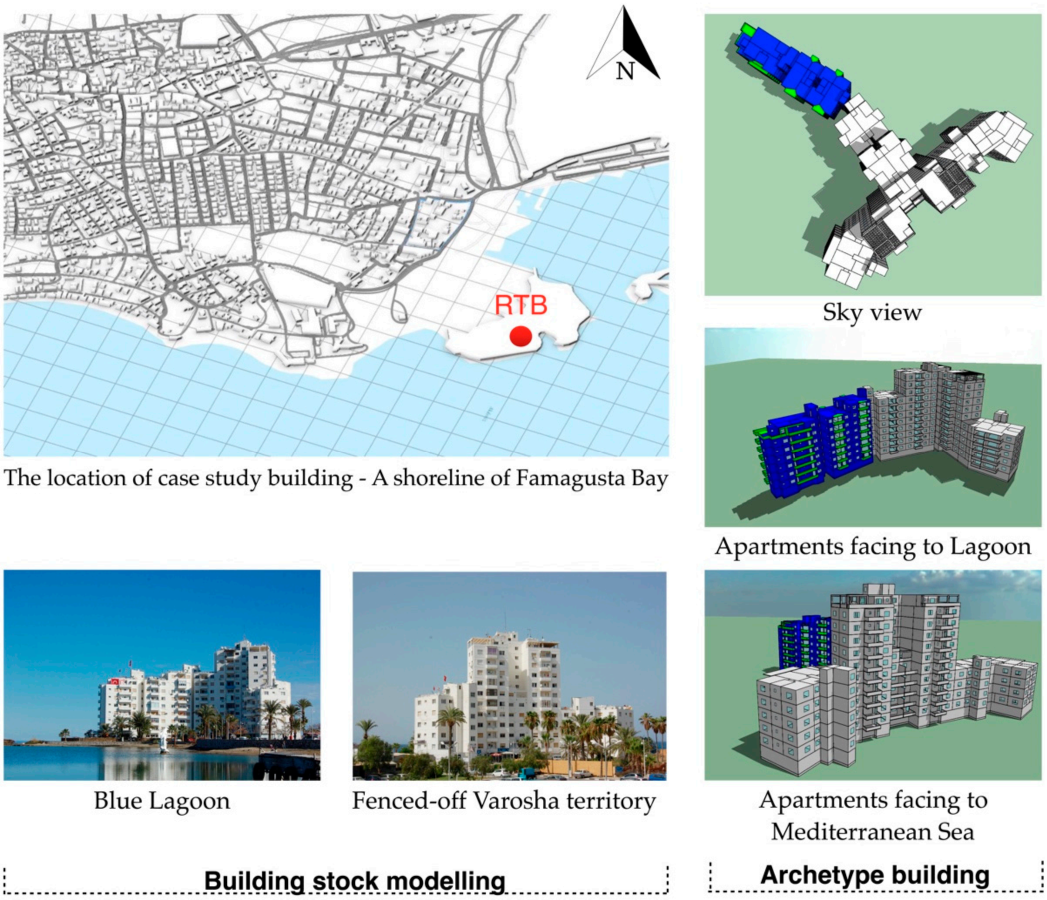


Figure 9. The location map of the high-rise post-war social housing development estate in Famagusta, Northern Cyprus; base-case RTB development, built in the 1970s; analytical energy simulation model of a southwest-facing apartment unit within the adjacent RTBs.

The case study building is representative of high-rise residential developments constructed by privately owned construction companies in the 1950s and 1970s [91]. The conditioned gross floor area of the case study multi-family apartment unit is 75 m^2. The original U-values were 2.35 W/m^2K for external walls, 1.23 W/m^2K for internal walls, 1.2 W/m^2K for the roof, and 2.10 W/m^2K for the windows and doors. Thermal specifications of construction materials were made according to the benchmarks of the British Construction Codes and Practices—Law 1959, which was the most recent data set available at the time of undertaking the research for this study [92,93].

3.4.2. Building Modelling Simulation

To provide sufficient resolution for the analysis of occupants' thermal comfort it was deemed necessary to use a dynamic thermal simulation (DTS) model [94]. The IES-VE software suite was selected as the most appropriate application for this purpose. In terms of validated performance, IES-VE is understood to meet a number of international standards including CIBSE TM 59 and is also accredited for use by European standard EN 15251 as previously discussed in Section 2.2 [95]. It is also necessary that the IES-VE software suite offered a number of features collectively that were found to be beneficial to the analysis. These included the following: close reproduction of the existing building geometry, detailed breakdown of the energy results by end use and zone, and ability to externally control the model settings (construction and zone profiles) to measure both the quasi-steady state and dynamic thermal scenario analysis, as shown in Figure 10.

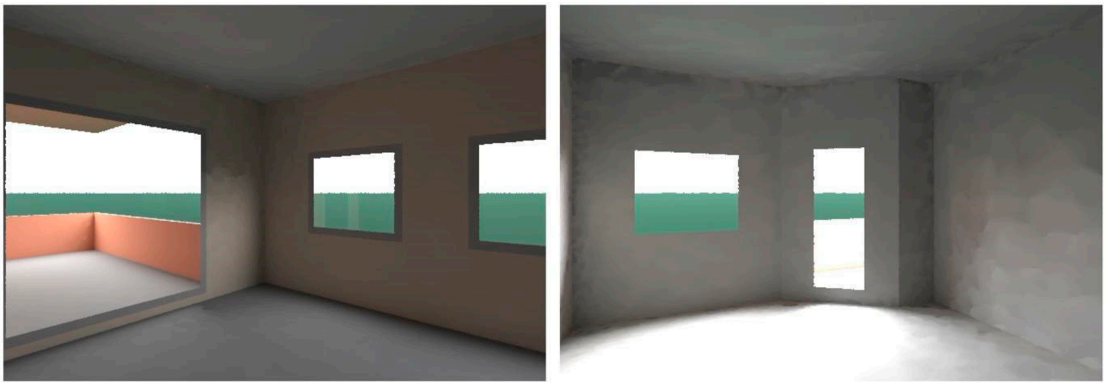


Figure 10. The interior view of thermal zoning of a living room and bedroom spaces for each representative flat unit in the RTBs.

The IES version used throughout was IES-VE 2021.1.0.0. Specifically, the Thermal Comfort assessment task of the IES-VE software suite was found to be an application that could measure the 'adaptive thermal comfort' of a prototype RTB [96]. It is also of interest to consider that in combination with the Dynamic Thermal Simulation (DTS) components of the IES-VE software, it was possible to assess the energy performance of material changes concurrently. To assess the energy performance of a prototype RTB, thermal templates were constructed in the IES platform of Apache-Sim. These templates defined the space conditioning systems (Apache Systems) and gain variation profiles for zones within the building, as shown in Table 2.

As previously mentioned, the aim of the selection was to capture a variety of space energy uses using relatively simple assessment benchmarks to import the data to the IES simulation software for assessing the validity of simulation results. Notably, all simulations were performed utilising CIBSE Test Reference Year (TRY) weather files from the neighboring city, Larnaca, for evaluating whole year building performance, including Design Summer Year (DSY) for the summer. Finally, three criteria were used for quantifying building performance: (i) annual energy demand, (ii) overheating risk assessment, and (iii) thermal comfort in the summer. Comfort analysis was based on BS EN 15251 for identifying adaptive thermal comfort temperature limits, considering fixed limits in the summer for a naturally ventilated building.

3.4.3. Thermal Properties Assigned to a Building Energy Model

To define the building model set, by limiting the number of the variables, the internal structures remained constant-based on the traditional construction materials of the era, hollow brick walls and concrete slabs, while the horizontal envelope components had minor changes depending on the sample flat plan design of the RTB. Hence, the main variation regards the construction materials and building envelope, and involves a window percentage and a construction solution that are representative of likely practices based on the 1970s' housing stock data. For this purpose, the building envelope solutions (i.e., shading and ventilation) have been taken into account, with hollow brick walls and a window surface equal to 1/8 of the floor area, which is a common construction code to provide natural ventilation and lighting. The horizontal components were simple un-insulated concrete and masonry elements. The thermal characteristics of all the considered constructions are summarised in Table 3.

Table 2. Contextual features and simulation parameters of prototype RTBs.

Building Performance Factors		Internal Heat Gains in the Simulation
Number of floors	12	Occupants: 3 W/m^2
Area-to-volume ratio [m^{-1}]	0.33	Appliance equipment: 8 W/m^2
Floor surface of a typical tested room	32.5 (m^2)	Lighting: 2 W/m^2
Room volume of a typical tested room	102.7 (m^3)	
Window size	1.5 × 1.2 (m^2) per window opening	
Exterior window ratio	0.21	
Number of subjects involved	1 male and 1 female (parents), 1 boy and 1 girl	
Age of the subjects	Between 2 and 40	

Table 3. Thermal characteristics of the construction elements of the 1970s residential building stock for climate zone 1—Famagusta.

	S[cm]	U [W/(m^{2}K)]	M [kg/m^2]	C [kJ/(m^{2}K)]
Vertical walls	35.0	0.98	305	264
Roof	36.0	0.91	317	302
Windows	N/A	2.91	N/A	258
Internal floors	28.50	1.63	298	256
Internal walls	11.0	1.57	92	84

3.4.4. Space Conditioning Data Assigned to the Building Energy Model

The main activity of the room survey was to identify a standardised room schedule recording the occupancy patterns of each room. This schedule included the following fields, separated by principal characteristics as shown in Table 4.

Table 4. The principal characteristics of the constructed building energy model.

Room Occupancy	Peak Occupancy
Materials	Glazing type, ceiling finish, floor finish, partitions, doors
Lighting	Source, fitting type, number of fittings
Space conditioning	Ventilation type, cooling type, space control method

For expediency, the surveyed data were imported to the IES-VE software interface of the ApacheSim application for the further undertaking of Dynamic Thermal Simulations (DTSs). The data allowed the software to simulate the spaces where it was not possible to inspect certain rooms, typically owing to privacy reasons of respondents. For the questionnaire, appropriate assumptions were made on their occupancy patterns based on similar representative rooms, as shown in Figure 11.

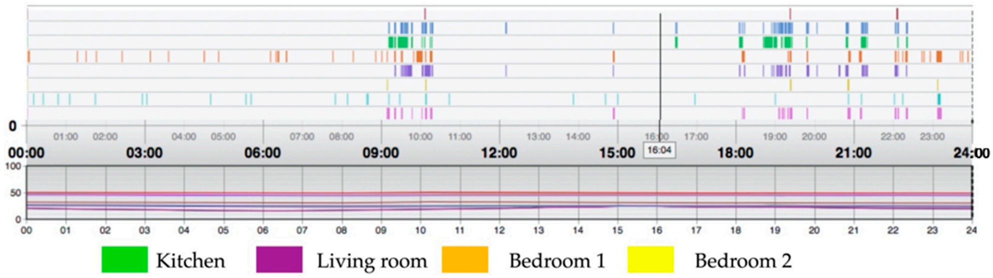


Figure 11. Assigned occupancy patterns into building energy models.

Apart from that, the room materials were determined largely by archival documentation for the particular floor plan layout of the nationally representative RTB prototype and by photographic documentation during the field study period. Where a mixture of types was observed, the predominant type was recorded. For the lighting system, the main type of fitting was recorded, and the number of fittings was counted during the questionnaire in the hottest summer month of August. The lighting control type was usually ascertained by the presence and type of lightbulbs in the room. Furthermore, the space conditioning was assessed by the equipment present in the room, such as external fans or air-conditioning units for cooling. The control method was determined by the presence of types of control devices in the room, for example, remote control systems and wall-mounted air-conditioning local control units. At the same time, the equipment inventory survey was undertaken in each room in order to obtain accuracy of the total energy use in the occupied spaces through simulation studies.

3.5. Thermal Imaging Camera

Table 5 illustrates the technical specifications of thermal imaging cameras for investigation of heat losses. Assessment of overheating risk of a building was undertaken between 25 December 2017 and 12 January 2018. While the surveys were conducted, the indoor environmental parameters were also monitored. These included air temperature (°C), relative humidity (RH), and air velocity. It was ensured that the accuracy of the instrumentation used for the field studies could meet the requirements of CIBSE 2015b: Building energy and environmental modelling CIBSE AM11 [97]. The details of the instrumentation used in the field studies are summarised in Table 5.

The coverage areas of the measurement include the occupied spaces involving the living room, kitchen, and bedrooms. In order to ensure the representation of the readings throughout the interviewed occupants' spaces, the best measurement location was identified by carrying out in-situ measurements in different locations within a space, as shown in Figure 12.

The physical measurement covers the whole period of the surveys with occupants in various orientations of buildings in the selected nationally representative RTB prototype. The measurements were undertaken using the Fluke 63 Infrared Thermometer. These measurements, along with the subjective thermal sensation responses, were aimed to allow for the calculation of comfort temperature within the embedding of the Griffiths method at the time of identifying the 'neutral' adaptive thermal comfort.

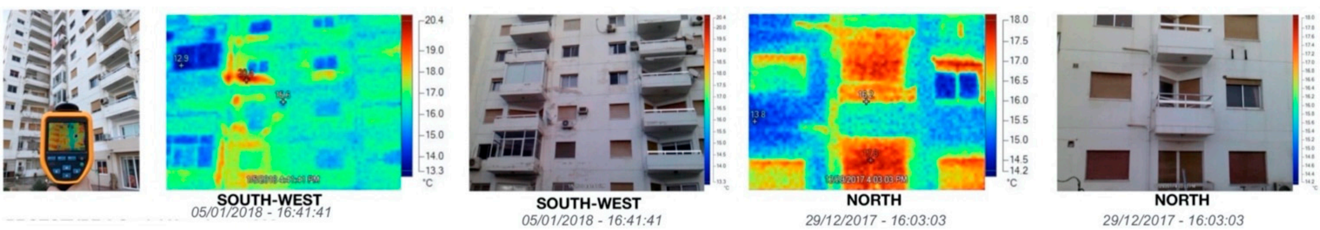


Figure 12. Demonstration of the in-situ thermal imaging survey.

Table 5. In-situ measurement range and accuracy physical features of the instruments used for the field study.

Parameter	Instrumentation Model	Range	Accuracy	Accuracy Requirements CIBSE 2015b
Air temperature	Fluke 63 Infrared Thermometer	−25–85 °C	±0.5 °C (for range 0–40 °C)	Minimum: ±0.5 °C Ideal: ±0.2 °C
Relative humidity	Fluke 63 Infrared Thermometer	0–95%	±3% (at 25 °C)	±5%

3.6. Questionnaire

The duration of field work was about four weeks (1 August 2018–1 September 2018) in order to clarify the diagnosis of the thermal performance of the building envelopes. The survey was conducted on representative RTBs to measure the quality of the indoor thermal comfort level of occupants and their awareness on energy use and energy efficiency, as shown in Figure 13.

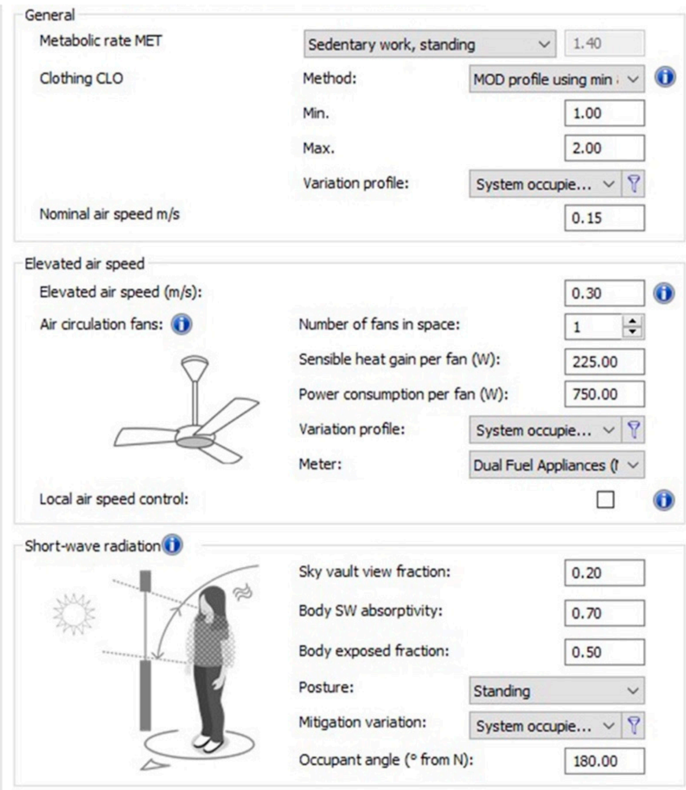


Figure 13. Assigned thermal comfort parameters gathered through a questionnaire.

In this empirical study, the questionnaire was conducted in occupants' homes, particularly in their living rooms where they were most likely to feel most comfortable. This also provided the interviewer with a living context for the questions themselves. During the data collection, the researcher recruited 188 households in the high-rise housing estate. The questionnaire's aim and targets were presented in order to obtain permission from these households to identify the overheating risk of each occupied space in the summer. For this purpose, owner-occupied and privately rented multi-family or single residential apartment units were identified in terms of residents' willingness to participate in the research process. These house owners were representative of the family structure according to the State Planning Organisation in Northern Cyprus statistics from 2018, corresponding to the growing demand in the property market. Their structures and target groups show variations within the location of the residential tower block developments such as low income, middle income, upper-middle income, and high income. This approach combined site visits to the households during the hottest time of the summer season in August for a report on the environmental impact of the built environment (overheating risk) in various building envelopes in the coastal city of Famagusta.

3.7. On-Site Environmental Monitoring

This paper presents two different design approaches to quantify the impact of the passive design strategies implemented in the building envelopes of a prototype high-rise housing estate. The first approach involved placing data loggers in the rooms, enabling us to collect information related to temperature, relative humidity and dew point (the temperature the air needs to be cooled to (at constant pressure) in order to achieve a relative humidity (RH) of 100%) in each occupied space for the duration of the summer of 2018. Internal and external monitoring of temperatures were needed to provide data for heating and cooling profiles in the models. For this reason, button data loggers and TinyTag Ultra 2 devices were used, as shown in Figures 14 and 15.

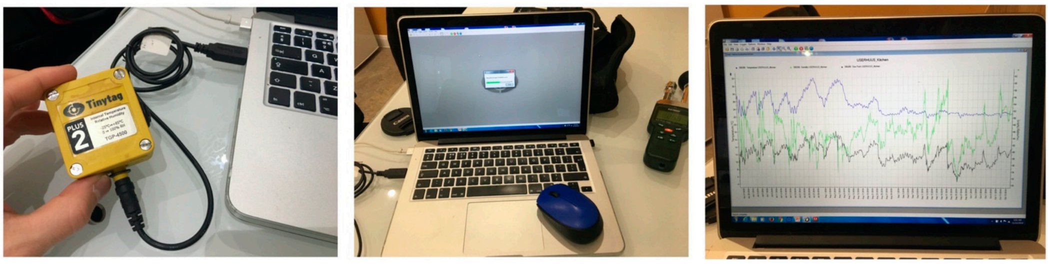


Figure 14. Stages of data collection related to on-site environmental monitoring.

	Units	Current		Today's Highs		Today's Lows
Inside Temp	[°C]	32.2	32.5	12:18	30.3	10:46
Outside Temp	[°C]	34.7	34.7	10:43	25.5	6:22
Inside Heat Index	[°C]	36.1				
Heat Index	[°C]	42.6	42.6	10:43		
THW Index	[°C]	42.6				
Wind Chill	[°C]	34.7			25.6	5:54
Inside Hum	[%]	54	63	0:00	49	10:44
Outside Hum	[%]	55	84	7:22	55	12:40
Inside Dew Point	[°C]	21.7				
Dew Point	[°C]	24.4	25.6	11:48	18.9	5:56
Wind Speed	[mph]	0.0	4.0	0:46		
10 Min Avg Speed	[mph]	0.0				
Wind Direction		220	SW			
Barometer	[mm]	754.9	755.8	0:00	754.8	12:39
Bar Trend		Falling Slowly				
Rain Rate	[mm/hr]	0.0	0.0	----		

		1 min	2 min	5 min	10 min
Avg Wind Speed	[mph]	---	---	---	---
High Wind Speed	[mph]	---	---	---	---

		Daily	Storm	Month	Year	1 Hour	24 Hours
Rain	[mm]	0.0	0.0	0.0	3.0	0.0	0.0

Sunrise: 6:21 Sunset: 19:12 Moon Phase: Last Quarter

Console Message: DANGER! High Heat Index: Heat Exhaustion or Heatstroke Likely

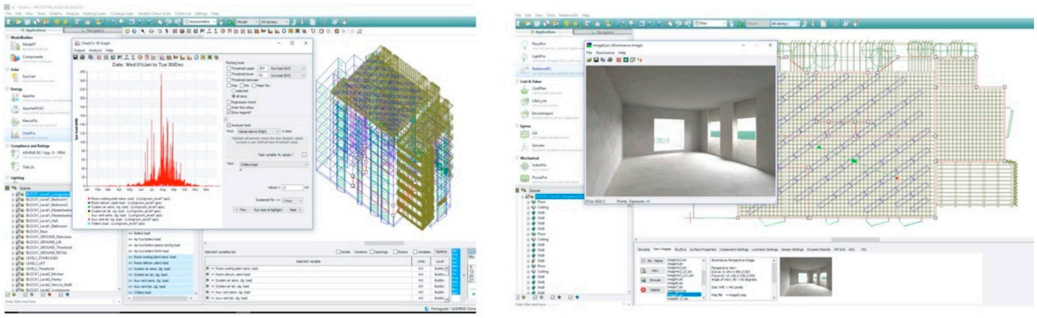
Forecast: Mostly cloudy and cooler. Precipitation possible within 12 hours, possibly heavy at times. Windy.

Figure 15. Demonstration of the recorded on-site environmental data.

These devices were typically used per occupied space, located separately, and average temperatures were recorded to identify overheating risk in apartment units. The zone occupancy needed to be monitored in order to relate the presence of occupants to energy use measurements and to account for the impact of occupants' behaviour on the zone thermal loads. For this reason, the most appropriate system was the TinyTag Ultra 2 data logger that logs motion using passive infrared (PIR) detection. The logger allows the monitoring of motion and lighting use with a time-out period of five-minute intervals. This is a reasonable time setting to import the data to the IES-VE simulation software.

3.8. Building Optimisation

Optimisation studies were implemented on the base-case model of the RTB prototype to simulate the interventions and retrofitting scenarios. The corresponding changes to the thermal sensation of occupants were analysed, as shown in Figure 16.



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

Figure 16. Development stage of retrofitting design strategies: (**a**) the cooling energy consumption of the northwest facing sample flat; (**b**) the daylight impact factor analysis of the base-case northwest facing representative typical floor level of the flat on 21 July.

Guidelines for equivalent new buildings were also developed that adopted modern fabric and system standards but retained the existing operational characteristics, for example, occupancy profiles, indoor temperatures, window-opening schedules, and equipment and lighting use. The corresponding cooling energy consumption patterns and occupants' thermal comfort for the RTB prototype were determined for comparative analysis. The results were compared with the data in the primary database for validation. The relative importance of design parameters on building performance can be verified by carrying out a sensitivity analysis (SA) [98]. It is a quantitative research design method to investigate the effects of different design variables on performance by embedding a building simulation model. The analysis before the optimisation study can help to identify the most efficient design parameters [99]. The results were aimed to help in optimisation and select applicable input, set parameters properly, and/or to set appropriate constraints for optimisation studies [100]. At the same time, major design solutions should be proposed based on the sensitivity index of design parameters affecting related energy performance and thermal comfort parameters depending on the building location, climate, and other circumstances.

3.9. Statistical Analysis

The Statistical Package for Social Sciences (SPSS) version 28.0 was used for analysing the data collected from the field studies, which were exported into spreadsheets to measure the effect size of the studied population and to identify statistic representativeness of housing stock, as shown in Figure 17.

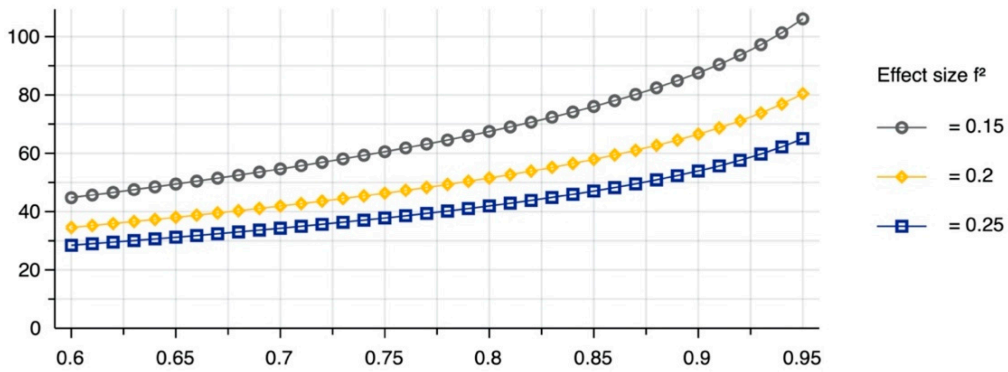


Figure 17. Demonstration of effect size criteria for the statistical analysis.

Separate analysis was carried out according to the interviewed representative prototype RTB and specified locations within the buildings. Pearson correlations were computed to assess the correlation between pairs of variables for the identification of 'neutral' adaptive thermal comfort. Correlations between multiple parameters were collected from the questionnaires in order to investigate the relationship between different parameters. The significant level of the analysis was set to 0.05. The conventional statistical analysis that was conducted in the present study, notably r and R^2, are clearly outlined in Section 4.6 when necessary. To interpret the statistical analysis, the convention indicated below was used. By convention, the relationship between X and Y is [101]:

- perfect if $r = 1$
- very strong if $r > 0.8$
- strong if r is between 0.5 and 0.8
- of medium intensity if r is between 0.2 and 0.5
- weak if r is between 0 and 0.2
- null if $r = 0$

This means that the results were statistically significant when the p-value was <0.05 [101]. First, the descriptive analysis set out to inform the interview findings to report the occupants' behaviour in energy use, then the findings were formulated by the correlation analysis methods in order to evaluate the correlation between different parameters. For this, Pearson (two-tailed) correlation analysis was conducted. Apart from that, with reference to CIBSE TM59:2017—Design methodology for the assessment of overheating risk in homes [102] and ISO 7703:2005—Ergonomics of the thermal environment: Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local comfort criteria, the interviewed respondents' clothing in the questionnaire surveys were converted into numerical figures [103]. In this regard, a binned method was adopted to eliminate the outliers by setting the increments of indoor operative temperature at half-degrees Celsius. In order to assess overheating-risk-related issues that are correlated with occupants' thermal comfort, Griffith's method was embedded for determining the comfort temperature of respondents in studies with relatively small sample sizes [104].

4. Results and Discussion

This section presents the discussion of the nationally representative base-case prototype RTB and demonstrates a visualisation for the guidelines between the findings from energy performance simulations and statistical analyses. This section of the study discusses and examines the possible adaptation scenarios, and their appropriateness and applicability between parameters are examined in order to identify the best solution scenario to design a prototype retrofit housing model based on the representative archetype RTB prototype. It concludes by their adaptation and feasibility with reference to the literature already discussed in Sections 2.1–2.3. The following sections discuss the existing energy performance of a prototype RTB, using the results and analysis of data collected from the outdoor thermal imaging survey, in-situ measurements, and dynamic simulation modelling.

4.1. Building Diagnostics

To feed into the building performance simulation analysis, the target outputs from the data are a set of information to describe the overall building construction and technical systems, a broad set of energy use data, and a room data schedule that describes characteristics of occupied spaces in representative flat units in the RTBs. Figure 18 demonstrates the in-situ inspection of the RTBs and the apartment units. An inspection table was designed to report the building pathology of selected RTBs. These tables were used by the thermal imaging survey investigation to gather in-situ information on:

○ Building, urban, and location characteristics: orientation, geometry, exposure to sunlight, crossed ventilation, etc.

- ○ Constructive characteristics of the thermal envelope (facade, windows, roofs, separation with staircases or other blocks and from the ground slab).
- ○ Non-regulated design interventions made by the occupants on the facade such as replacement of window frames, enclosure of balcony areas, etc.
- ○ Thermal installations: individual, collective, central cooling systems, and energy type.

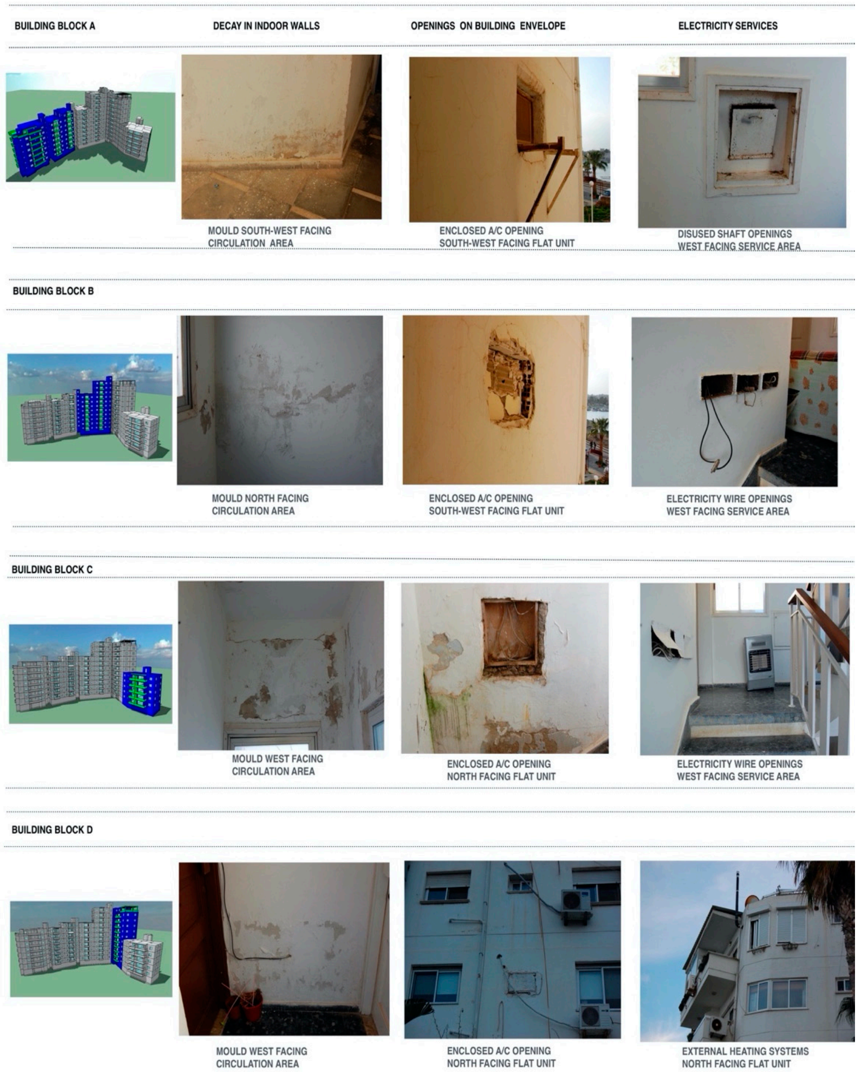
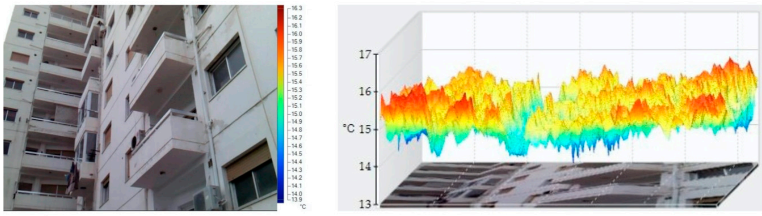


Figure 18. Identification of physical changes and building pathology in the 1970′s representative RTB.

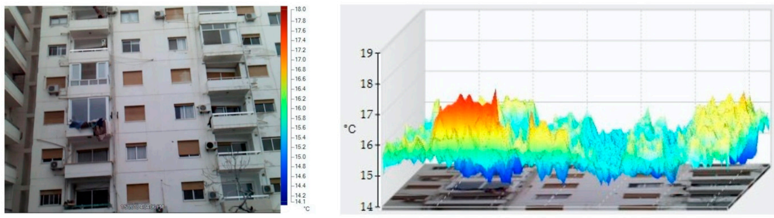
In addition, surveys (semi-structured interviews) were carried out among the residents on aspects of the use of the building in the summer, together with the socio-economic profile of the occupants in order to generalise the sampling size of the questionnaire. It is important to highlight that once the data for the selected representative base-case buildings were obtained, a comparison of their location, climate and construction characteristics were carried out, assigning the same characteristics to a great number of residential buildings.

4.2. Thermal Imaging Survey

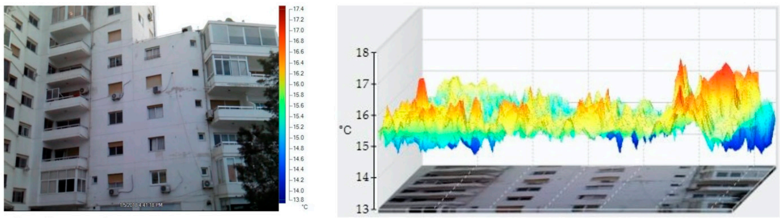
The case study high-rise housing estate was surveyed, and infrared thermal imaging was conducted with a thermal camera (Fluke TiS20) twice each day during the winter period, in the late evening and in the early morning, to avoid possible mistakes due to direct solar radiation, as shown in Figure 19. The thermal imaging survey investigating heat losses and assessing the overheating risk of a building were undertaken between 25 December 2017 and 12 January 2018 (see Appendices A and B). A thermal imaging survey was conducted before this work to diagnose the building and, taking these data into account, to define optimal retrofitting strategies. The survey results for the base case for the RTB buildings demonstrated that most heat losses resulted from air infiltration, mainly through exterior walls without insulation and through windows (provoking a high annual energy demand for heating), as shown in Figure 20a,b.



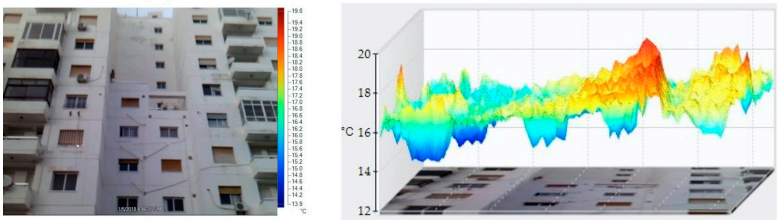
North-east facing apartment units



North facing apartment units

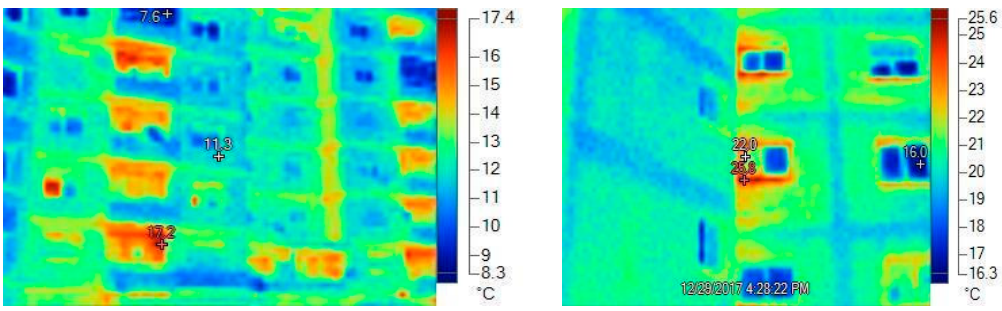


South-east facing apartment units



South facing apartment units

Figure 19. In-situ thermal camera recordings of building envelopes in various orientations. The measurements were undertaken on 5 January 2018 in the late afternoon to understand the overheating risk in the summer.



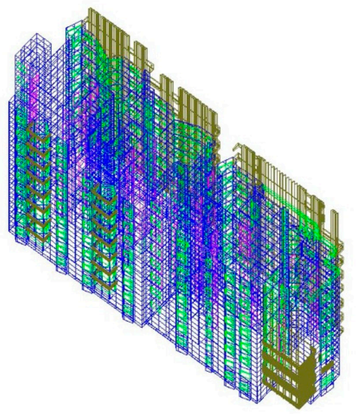
(**a**) (**b**)

Figure 20. (**a**) Southeast elevation showing heat loss through the external wall, possibly due to insufficient building envelope insulation. Image taken 28 December 2017 between 06:30 and 07:54 a.m. (**b**) Southeast elevation showing significant heat loss through windows and heat loss through wall junctions and cracks on building surface. Image taken 28 December 2017 between 16:30 and 17:45 p.m.

All calibration studies were conducted using the SunCast simulation tool platform to validate the data from both the thermal imaging survey and in-situ measurements, as described in Section 4.3.

4.3. Solar Exposure Analysis

In this base-case model, the building performance evaluation simulation tool was used for assessing current energy performance of representative flats as follows: Sun-Cast (Solar Analysis), Radiance-IES (Daylighting), and Apache-Sim (Dynamic Thermal Simulation) platforms of the IES-VE software suite, as shown in Figure 21.



Month	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Jan	-	-	-	-	-	-	0.52	11.00	20.19	27.51	32.19	33.59	31.45	26.13	18.36	8.84	-	-	-	-	-	-	-	-
Feb	-	-	-	-	-	-	4.45	15.62	25.68	33.99	39.62	41.59	39.46	33.72	25.33	15.21	4.01	-	-	-	-	-	-	-
Mar	-	-	-	-	-	-	11.77	23.50	34.36	43.61	50.01	52.03	49.02	41.92	32.27	21.18	9.33	-	-	-	-	-	-	-
Apr	-	-	-	-	-	8.55	20.80	32.95	44.58	54.94	62.36	64.05	59.05	49.82	38.67	26.71	14.46	2.27	-	-	-	-	-	-
May	-	-	-	-	2.81	14.54	26.65	38.90	51.02	62.42	71.37	73.11	66.00	55.15	43.19	30.94	18.75	6.87	-	-	-	-	-	-
Jun	-	-	-	-	4.74	16.16	28.07	40.26	52.51	64.43	74.73	77.72	69.80	58.36	46.20	33.95	21.88	10.19	-	-	-	-	-	-
Jul	-	-	-	-	2.67	14.16	26.11	38.33	50.56	62.39	72.55	76.22	69.49	58.50	46.46	34.20	22.05	10.22	-	-	-	-	-	-
Aug	-	-	-	-	-	10.22	22.42	34.66	46.60	57.60	66.04	68.51	63.25	53.52	42.04	29.93	17.67	5.56	-	-	-	-	-	-
Sep	-	-	-	-	-	5.65	17.85	29.68	40.66	49.92	55.90	56.73	52.06	43.55	32.95	21.30	9.17	-	-	-	-	-	-	-
Oct	-	-	-	-	-	0.67	12.41	23.39	33.05	40.55	44.75	44.70	40.41	32.85	23.15	12.15	0.40	-	-	-	-	-	-	-
Nov	-	-	-	-	-	-	6.23	16.44	25.17	31.72	35.28	35.25	31.64	25.05	16.29	6.06	-	-	-	-	-	-	-	-
Dec	-	-	-	-	-	-	1.58	11.64	20.28	26.88	30.76	31.36	28.58	22.84	14.83	5.21	-	-	-	-	-	-	-	-

Figure 21. Annual solar irradiation calculation of base-case RTB prototype.

The objective was to identify the worst-case scenario before testing the efficiency of systemic retrofit strategies in Section 4.5. This section explicitly describes the building modelling simulation studies and analysis that were conducted and outlines the results of the daylight impact factor on overheating, thermal comfort, and energy use aimed at optimizing occupants' thermal comfort and reducing energy consumption concurrently.

Figures 22 and 23 illustrate the maximum solar radiation when it occurs as well as the mean values for each floor level in the representative RTBs. The SunCast simulation analysis demonstrates that the annual maximum number of hours of exposure of surfaces to solar radiation occurs on the roof surface (approximately 1848.00 h), followed by the southwest facade of the building (approximately 1064.92 h). The survey results confirm that the upper-floor-level flat is most susceptible to overheating, followed by the intermediate floor along with the ground floor (Figure 24).

Additionally, in Figure 25, the solar path diagram shows that the angle of the sun varies throughout the year, affecting the solar gain during two periods, particularly in July and August 2020. It was found that the total surface area of the building envelope exposed to solar radiation flux reaches a maximum value of 1848.26 kWh/m^2 during the year.

4.4. Daylight Impact Factor on Occupants' Thermal Comfort and Energy Use

The daylight simulations shown in Figure 26 were taken from the analysis conducted in a selection of the worst-case representative living room unit between January and December under overcast standard sky conditions on the horizontal surfaces. This simulation analysis allowed us to understand the daylight impact factor on energy use with regard to overall understanding about the overheating issues experienced in the RTBs. As previously mentioned in Section 4.3, the inefficient building envelopes absorb high solar radiation throughout the year, and this creates a thermally uncomfortable environment for its residents.

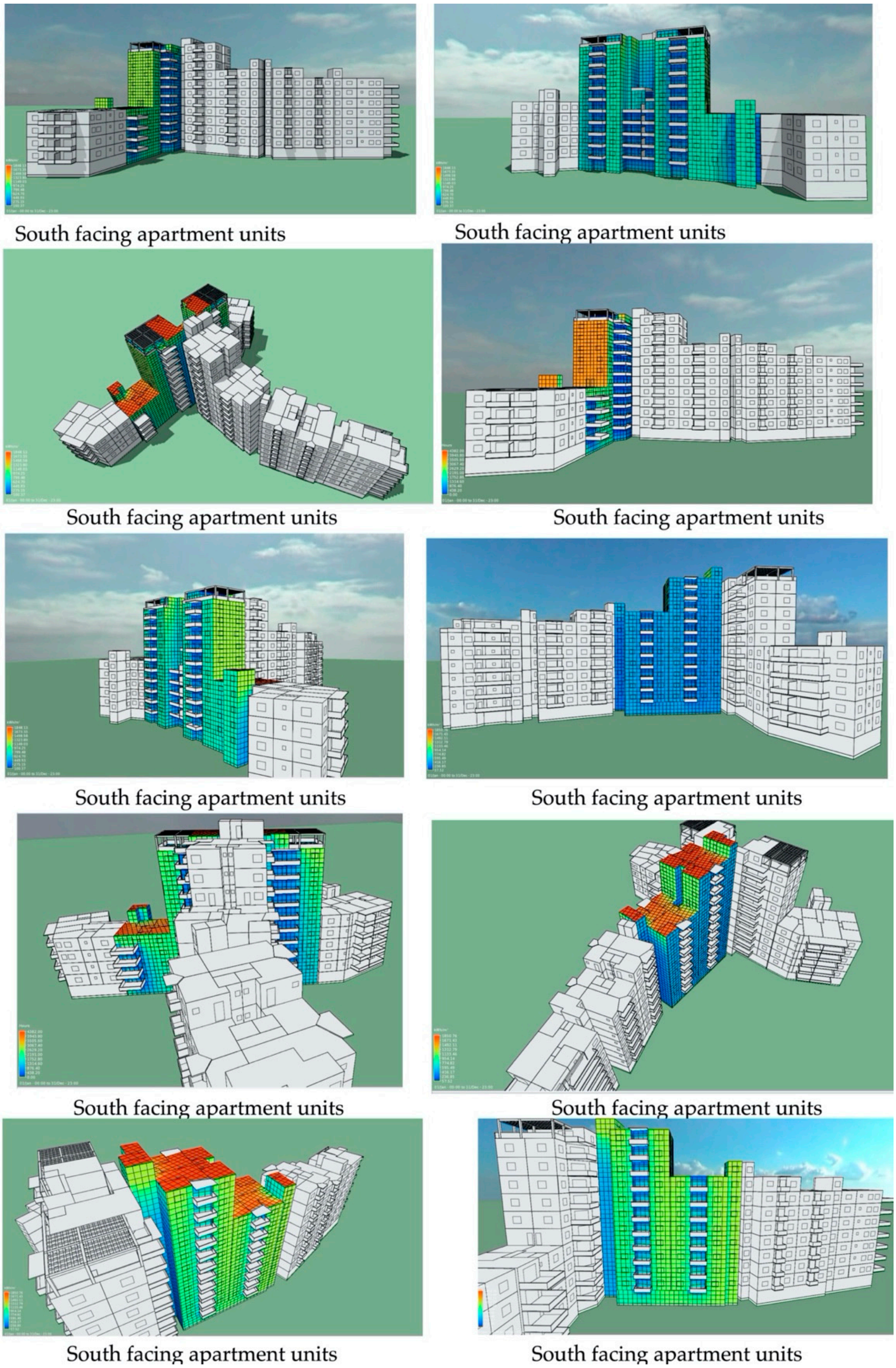


Figure 22. Demonstration of solar irradiance factor on building envelope based on orientation.

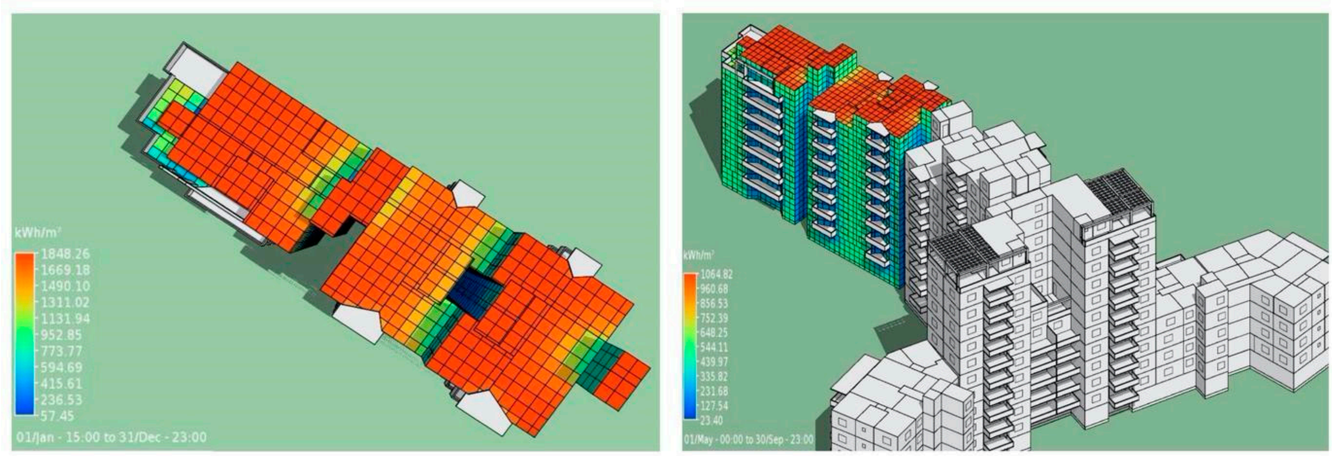


Figure 23. SunCast simulation demonstrating that monthly exposure to solar radiation on the roof surface reaches 1848.26 kWh/m^2 between January and December 2020 and the southwestern building envelope reaches 1064.82 kWh/m^2 between May and September 2020.

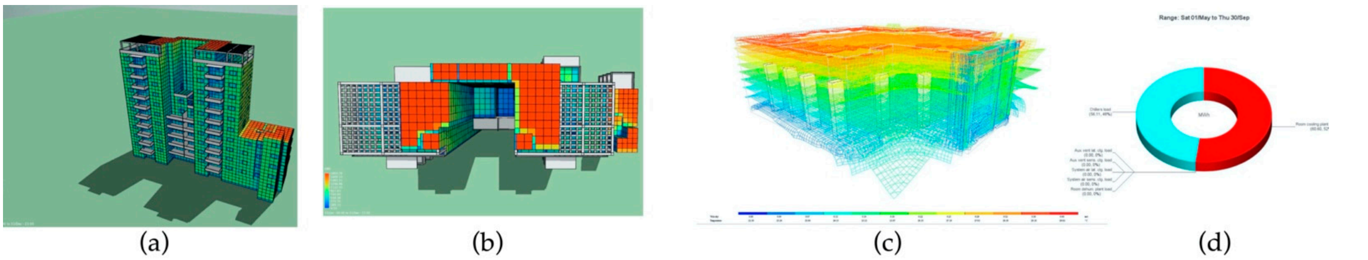


Figure 24. Analysis of the RTB prototype: (**a**) Solar shading; (**b**) Renewable energy potentialities; (**c**) Computational fluid dynamics; (**d**) Total energy consumption.

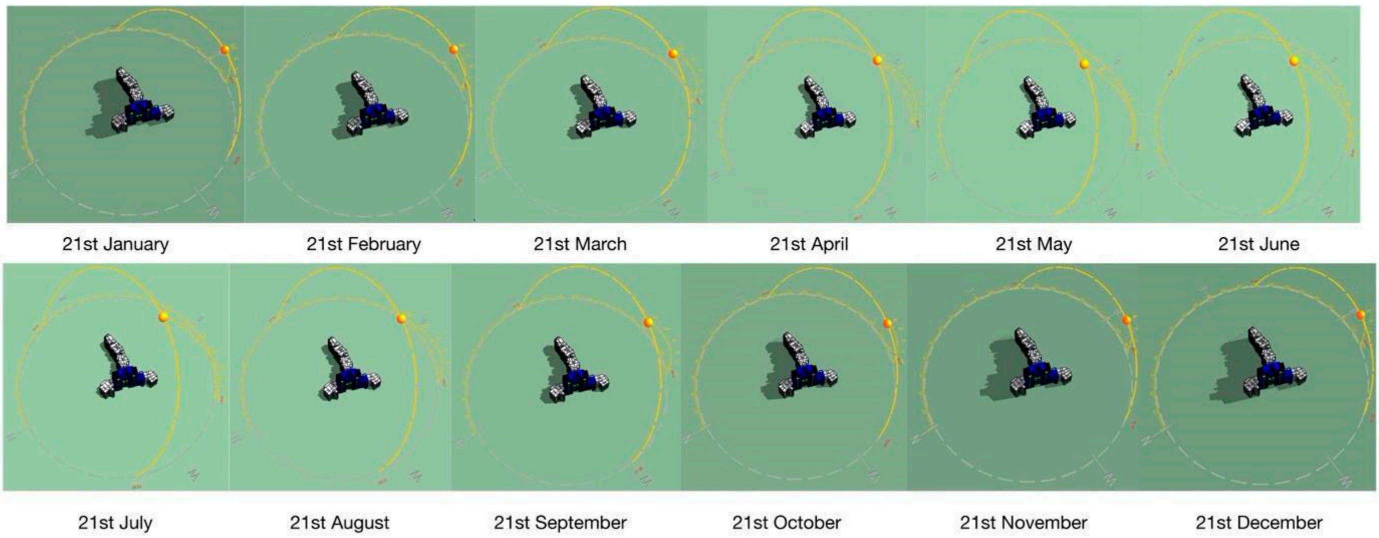


Figure 25. The sun path diagram demonstrates that the southwest-facing block experienced high levels of solar radiation most of the day in July and August 2020.

Figures 27 and 28 illustrate that the daylight factors (DFs) on the surfaces within the main rooms are above 292.5 lux, indicating that the rooms will appear well lit. In the service areas, however, with no direct access to natural light from the windows, the light levels will be below the 50-lux value. From these results, it was found that all occupied spaces, particularly southwest-facing living rooms, have experienced overheating risk issues due to direct solar radiation and high levels of daylight impact on occupants' thermal comfort.

These findings strongly correlate with each other when assessing the overheating risk of each occupied home space. Nevertheless, the daylight analysis provides subsequent information to identify energy-efficient and cost-effective retrofit interventions that will be discussed in Section 4.5.

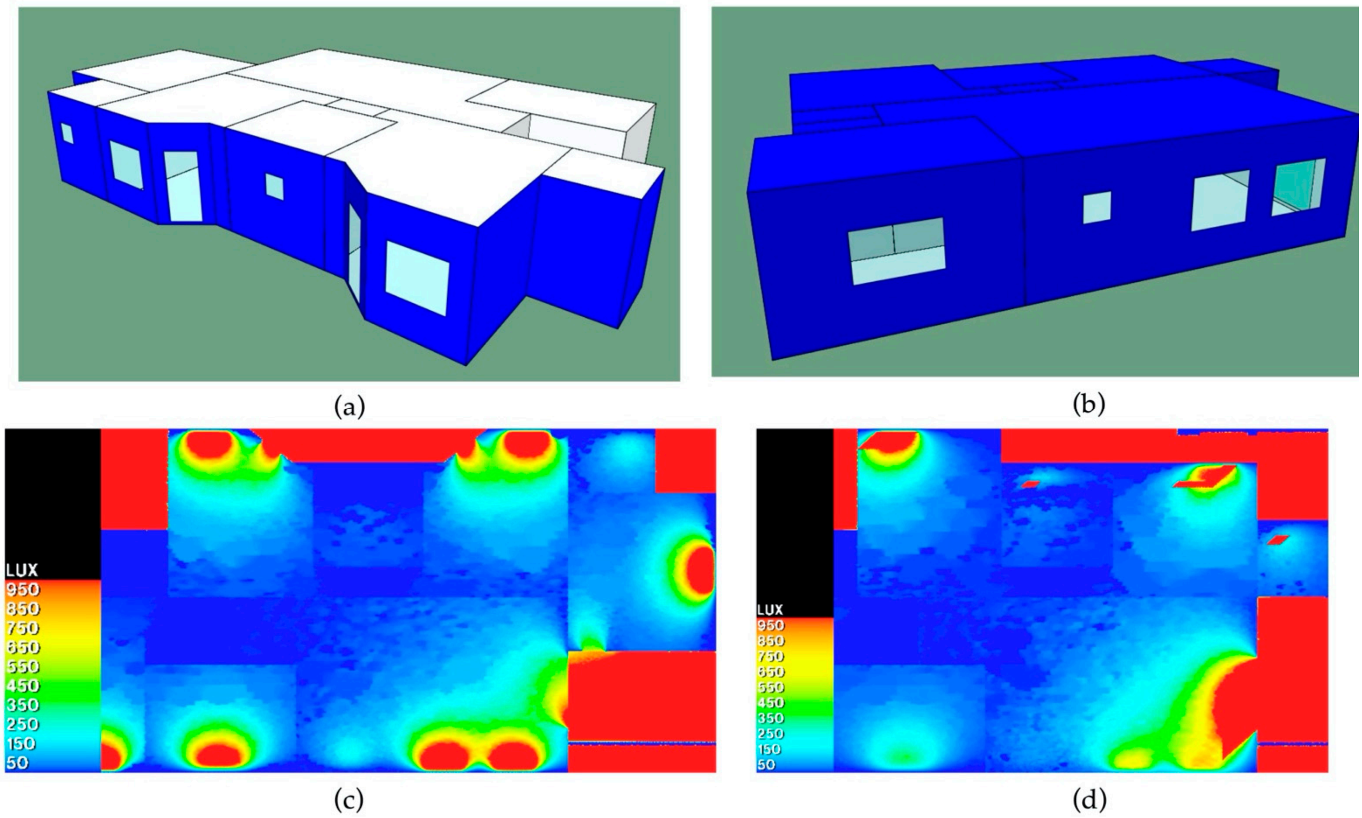


Figure 26. 3D model representation: (**a**) representative three-bedroom flat unit; (**b**) representative two-bedroom flat unit; (**c**) daylighting analysis of 3-bedroom flat; (**d**) daylighting analysis of 2-bedroom flat.

In summary, as can be seen in Figures 19 and 20 of the representative flats, only three external surfaces are exposed, and all three show different heat gains throughout the year with high daylighting levels in the summer. This creates an overheating risk due to the lack of shading systems installed on the building envelope. It should be noted that upper-floor flats showed the greatest overheating risk issues due to the impact of the deficient building envelopes. Hence, all the bedroom spaces in the upper- and intermediate-floor flats are under a higher threat of overheating when compared to CIBSE TM 59 overheating criteria. Notably, the living rooms are also susceptible to overheating, but due to different factors; they have large window-opening ratios with no shading, and all of them face the southwest and are exposed to high-intensity sunlight throughout most of the day. These factors together lead to overheating issues and a high degree of occupant discomfort, particularly in the summer.

4.5. Energy Use

As previously stated, the Apache-Sim (Dynamic Thermal Simulation) tool was used to conduct a thermal analysis performing predictions of the heating/cooling energy loads in this ill-performing occupied space in the flat. The following results are for the living room unit (as an example), which was simulated between January and December in order to assess total energy use. Figure 29 shows that the specific monthly peak demand for electricity use in the base case reached 77.8 kW between January and December.

It can be seen that the house owners are predominantly reliant on using wall mounted air-conditioning units in this particular apartment unit. However, the energy consumption fluctuations in Figure 30 demonstrate that the monthly peak energy demand in the flat was above 57.4 kWh between mid-May and mid-September, and further simulations led to a consumption of 53.2 kW in August of the monthly cooling load of the living room unit, while in the worst performing bedroom unit, one specific monthly heating load reached approximately 35.3 kWh in February, as shown in Figure 31.

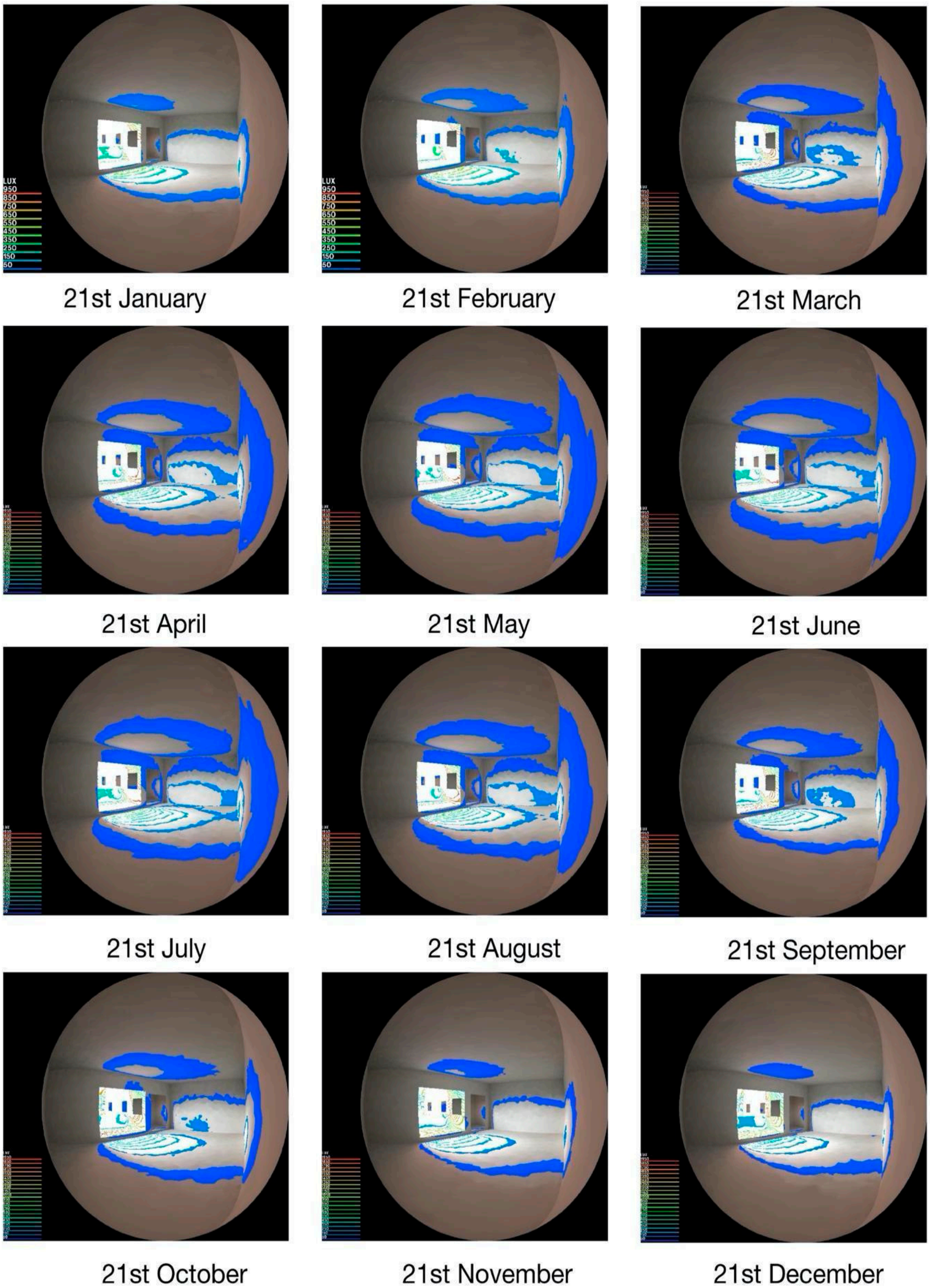
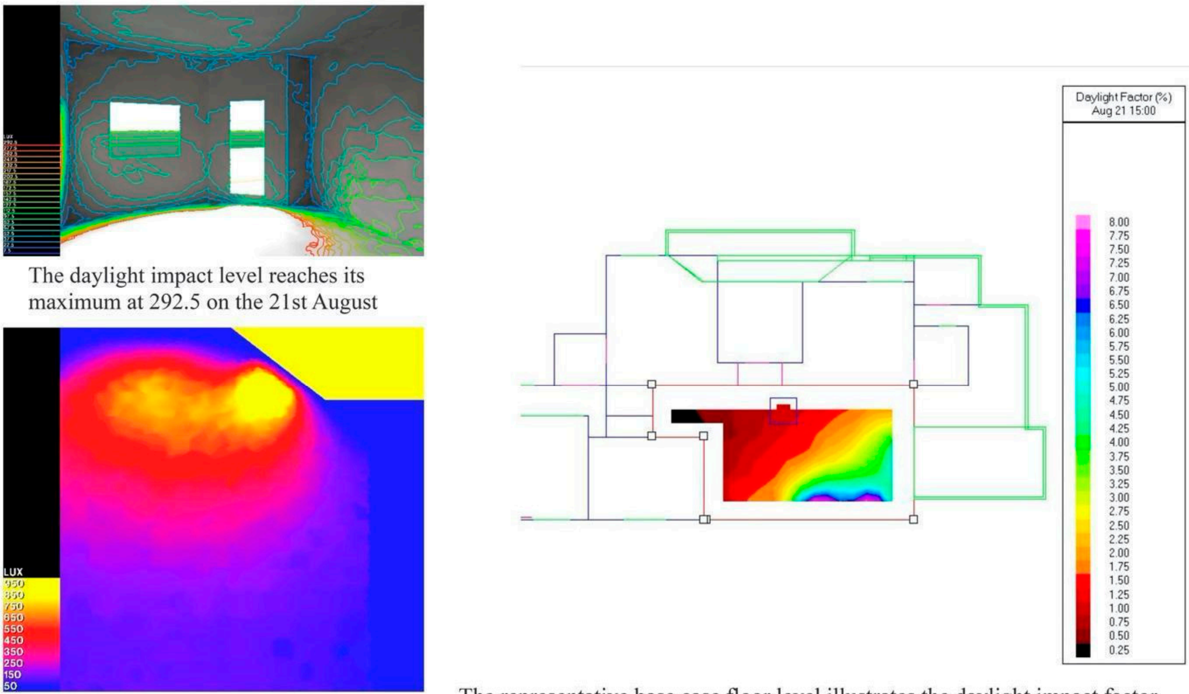


Figure 27. The daylight impact factor analysis of the upper-floor representative flat's living room between January and December 2018.



The daylight impact level reaches its maximum at 292.5 on the 21st August

The representative living room space receives high daylight indices during the day

The representative base case floor level illustrates the daylight impact factor which has shown variation between 0.25 to 8.0 on the 21st August in order to represent worst-case scenario for overheating risk assessment

Figure 28. The daylight impact factor analysis of a representative base-case southwest-facing flat unit during the hottest summer day of 21st August.

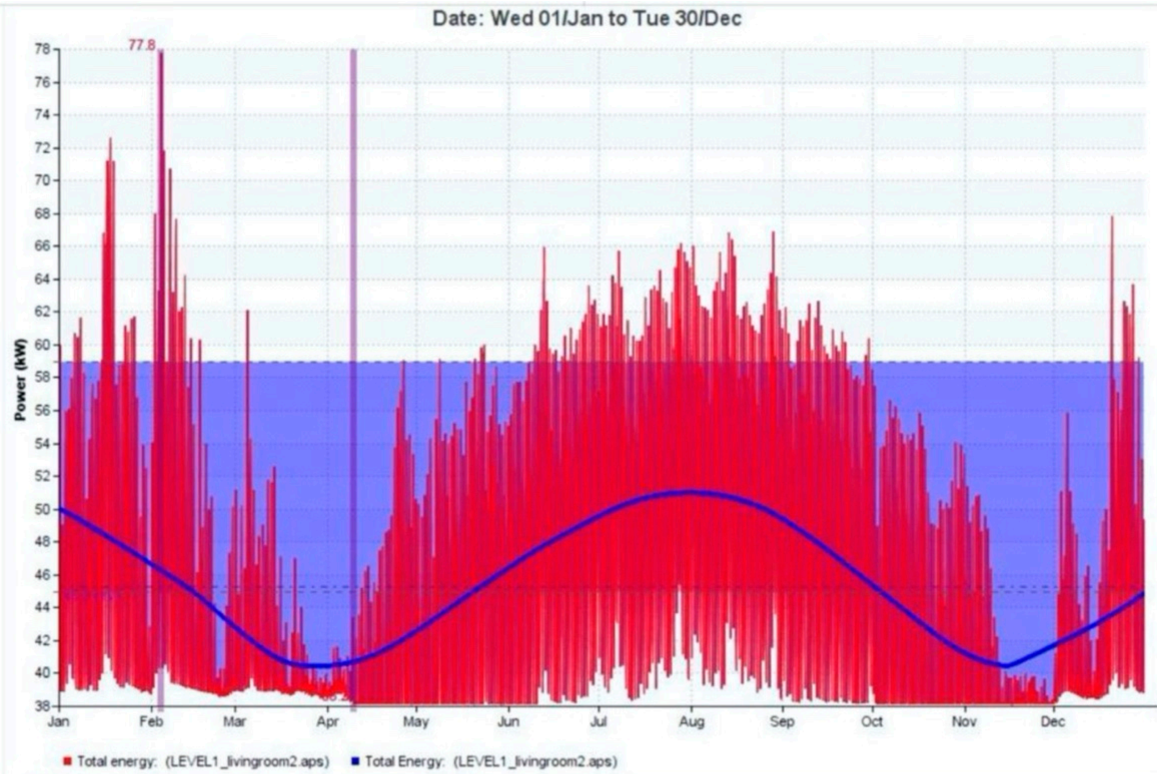


Figure 29. The overall energy consumption of the worst-case representative flat unit reached its peak at 77.8 kWh in February.

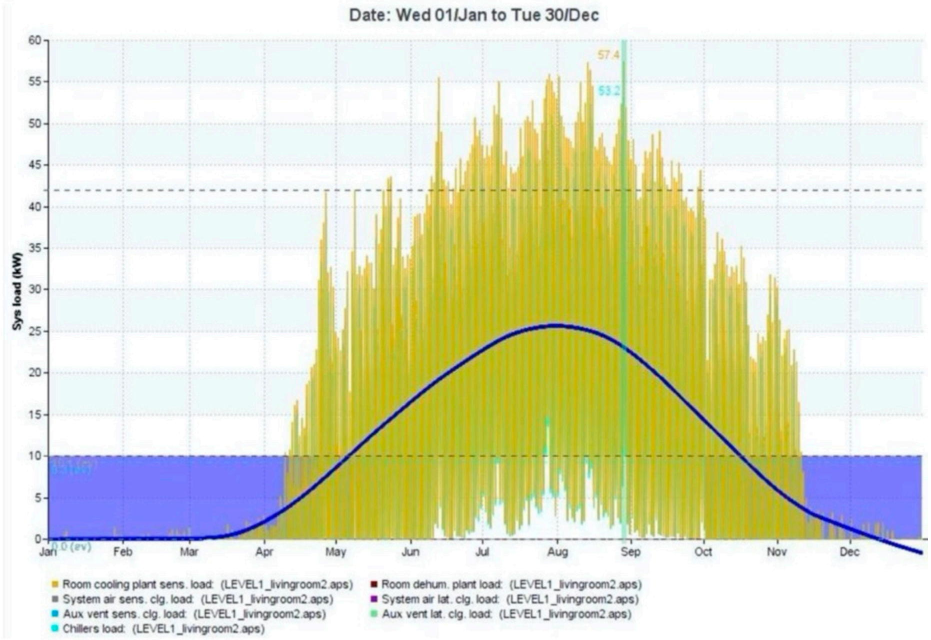


Figure 30. The overall cooling energy consumption of the worst-case representative flat unit reached its peak at 57.4 kWh at the end of August.

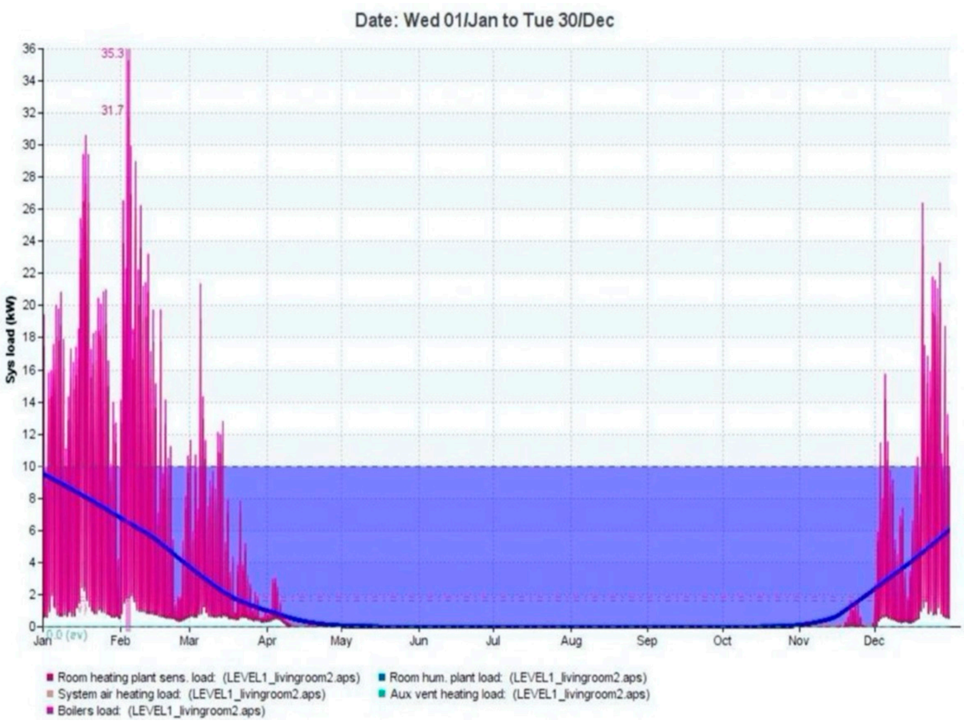
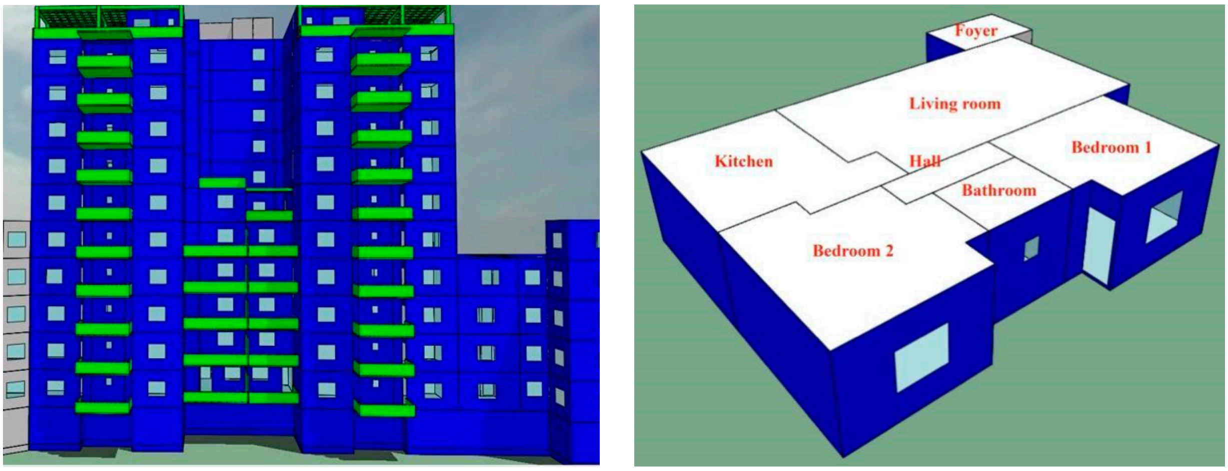


Figure 31. The overall heating energy consumption of the worst-case representative flat unit reached its peak at 39.3 kWh in February.

From the dynamic thermal simulations performed to assess current energy consumption of representative upper-floor flat units, the results reveal that the occupants spent high expenditures for their energy bills, particularly in the hottest summer month of August. In order to reduce energy consumption and optimise occupants' thermal comfort, several retrofit interventions were implemented on the building envelope. The following step has been the evaluation of state-of-the-art passive cooling design strategies implemented on the building envelopes to help reduce the overheating risk of the case under study with a focus on the 10th-floor flat unit. In order to compare the overheating and thermal comfort of various retrofit scenarios when there is no Heating, Ventilation and Air Conditioning (HVAC) system for each scenario, the thermal performance of the upper-floor level was studied, comparing the hours of discomfort by using CIBSE TM 59.

To understand the efficiency of a passive design system and its integration into contemporary residential buildings, it is essential to examine the effectiveness of the thermal properties of the representative base-case RTB development as a case study. The following steps evaluate potential passive design strategies to reduce overheating risk and to optimise occupants' thermal comfort for the worst-performing south-facing RTB. For this analysis, five design alternatives were assessed to assess the efficiency of each as a potential retrofit scenario, as shown in Table 6.

The building geometry was created for its initial existing state. Every floor and apartment have corresponding thermal zones and subdivisions, as shown in Figure 32a,b, indicating clearly which zones and spaces are not heated like balconies and storage areas.



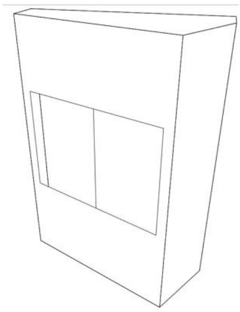
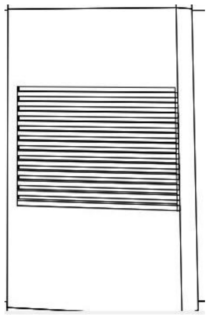
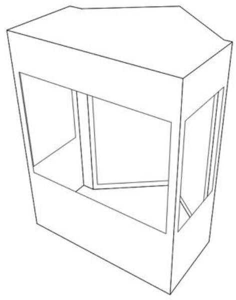
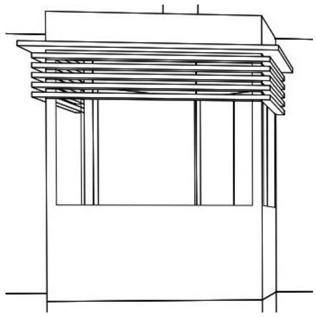
(**a**) (**b**)

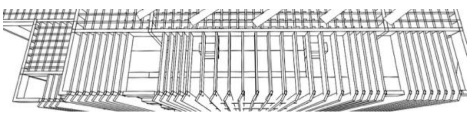
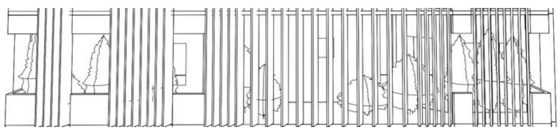
Figure 32. (**a**) The tested and simulated prototype RTB for a base-case scenario development; (**b**) the analytical energy model of a representative apartment unit's under-investigation.

When all strategies were considered and all representative sample flat units were simulated with the relevant thermal conductivity level of the RTBs, the results revealed that the living room in the southeast-facing upper-floor flat exhibited the highest cooling demand with a decrease of 21.69%, while Bedroom 2 demonstrated a cooling demand of 21.60%, as shown in Figure 33. These values reveal a decreased demand for cooling energy of 78.49 kWh/m^2 on the intermediate floor and 69.79 kWh/m^2 on the ground floor. It should be noted that when all strategies are implemented, the annual energy consumption can be reduced by 28.1% (compared to the minimum level case), to 11.3 kWh/m^2 per year.

Additionally, starting from these base case studies, when the adaptive set-point is used, the decrease in the cooling demand is related to considering passive design measures such as natural ventilation and its systems in the case of the heavier construction materials. This is due to the strong effect of heat loss from the heavyweight structures caused by an additional discharge rate during the nighttime. This is because the adaptive indices have been developed according to the occupants' thermal sensations and preferences. In this study, the adaptive comfort temperature represents the acclimatisation system set-point as autonomously managed by the occupants, including the external climatic conditions of the simulated and assessed indoor space. This is due to the fact that the measured outdoor temperature is above the comfort level zone which is shown in Figure 34. The findings illustrate that there is a significant temperature difference between the outdoors and benchmark comfort levels of the indoor environment.

Table 6. Specifications of passive design strategies for the existing base case.

Sunscreen Fixed Blade (S1)	Venetian Blinds (S2)	Overhang (S3)	Venetian Blind—Roller Blind (S3)
			
• Outdoor solar shading and pre-oriented blades fixed to the facade. This shading could also have vertical blades; in this case, most effective for south/west orientation, which is more frequent in residential building applications. • The blades can also be applied to shield balconies. • Blade selection: ellipsoidal, arcaded, triangular, gull wing, etc. • Blade materials: extruded aluminium, formed aluminium sheet or bent, wood, PVC, porous ceramic, etc. • Horizontal blade height (mm): 25–1200 • Blade intersection (mm): 70–150 • Maximum length (mm): 8	• Solar shield for outdoor use with adjustable and packable blinds. • The packaging of the blinds allows a very compact folded element once rolled in. • The typology can also be applied to screen balconies other than windows. • The opening of the shutter can be the classic hinged, folding, or sliding. • The blinds can also be adjustable, allowing good modulation of radiation and light. • Blind materials: wood, aluminium, PVC, etc.	• Overhang: fixed, opaque, made out of different materials, consisting of horizontal and vertical elements to create a grating pattern. • Blind section: arched • Blind materials: aluminium, alloy, etc. • Blind supports: steel, etc. • Blind height (mm): 58–95 • Blind width (mm): 500–4500 • Screen height (mm): 400–5000	• Double-glazing, integration of a Venetian blind, roller or pleated, • into the interior chamber of variable thickness • The sliding of the tent takes place in a sealed package containing desiccants to ensure the control of humidity and vapour condensation. • Venetian blinds, with respect to roller blinds, provide a vision of the outside, even with the screens down, because they have oriented slats. • Maximum dimensions (mm): 32 (pleated and Venetian blinds)

Vertical Sunscreen (S4)	Fixed overhang (S5)
	
• The sunscreen consists of operable vertical blinds or grilles anchored to a structure perpendicular to the facade. • Blind material: extruded aluminium, bent or formed aluminium sheet, PVC-coated copper, wood, glass • Structure material: aluminium, galvanised steel • Blade height (mm): 70–1500 • Blade length (mm): maximum 6000 • Blind step (mm): 70–150	• Overhang, fixed vertical, opaque, made with different materials (sheet metal, treated wood, plastic materials, etc.). • Anchored to the wall with an autonomous structure or structurally integrated. • The shields may also have a vertical arrangement perpendicular to the facade; in this case, they are most effective for east and west orientations

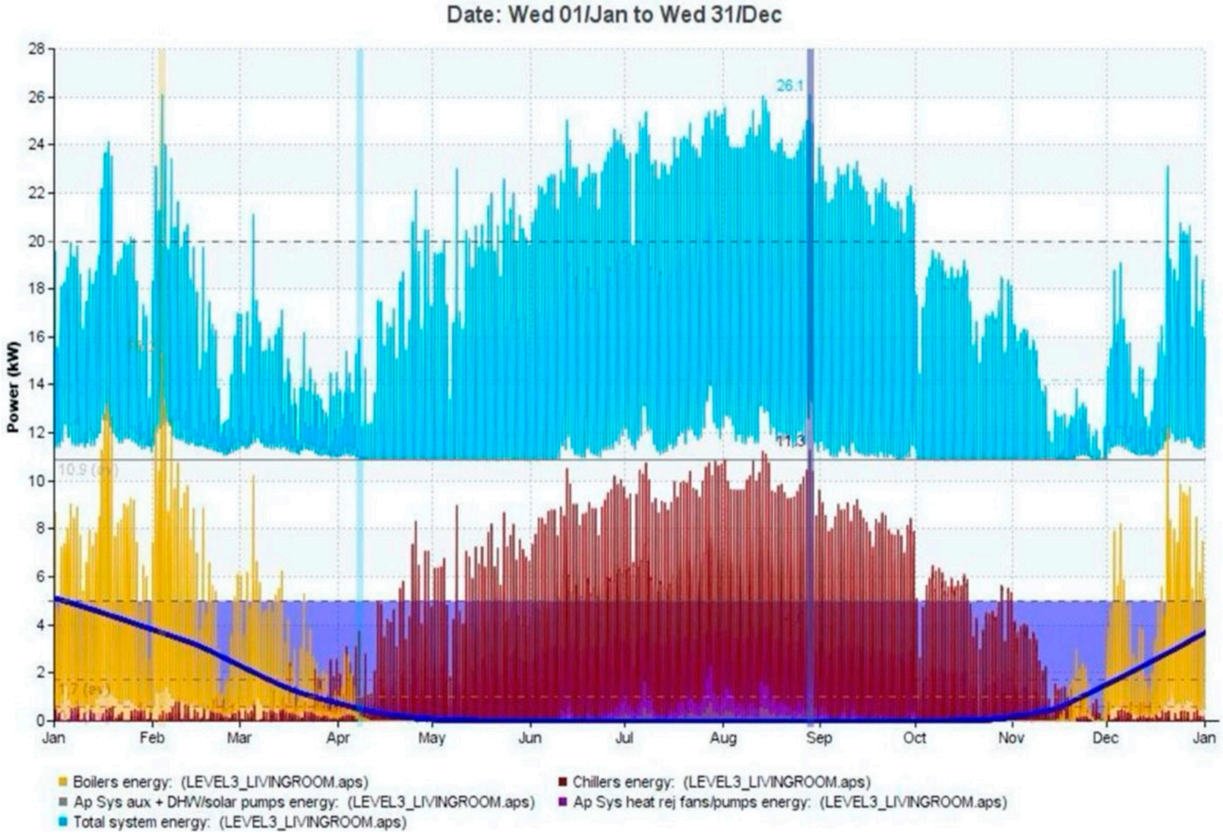


Figure 33. The overall energy consumption of the worst-case representative flat unit after implementation of state-of-the-art energy-efficient materials onto the building envelope between January and December.

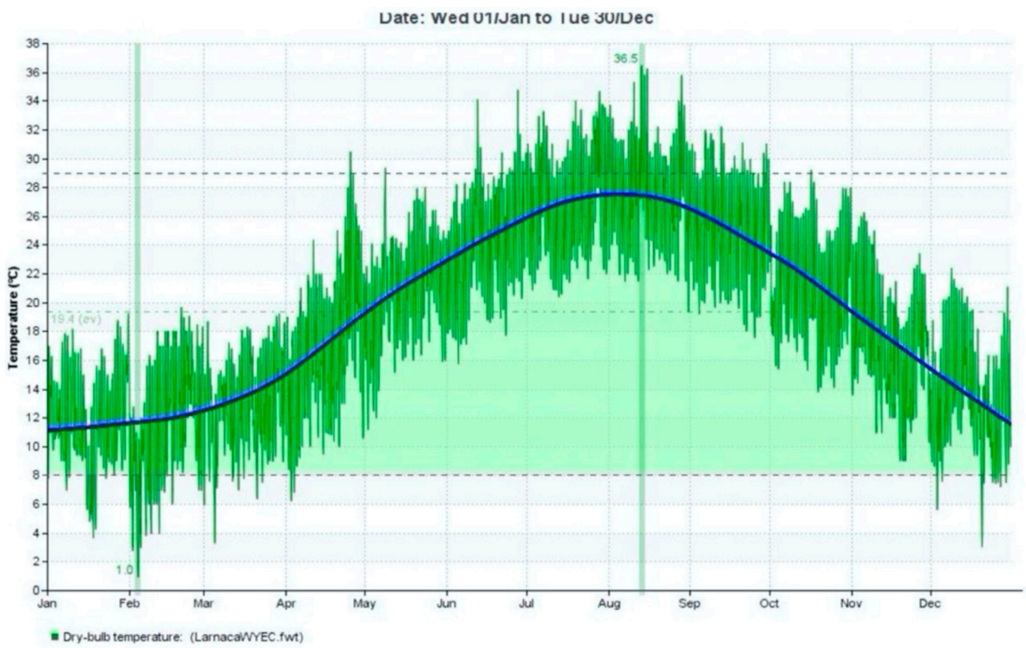


Figure 34. The indoor air temperature fluctuations of representative upper-floor level flat units before retrofit interventions were undertaken.

In addition, the annual energy consumption of the typical multi-family apartment unit with a mediumweight and lightweight structure is more or less the same as the one with heavyweight structure. The annual energy consumption of mediumweight RTBs were found to be 134.7 kWh, 111.8 kWh, and 98.5 kWh per year in comparison to the median case level, respectively. The annual energy consumption of S1, S2, and S3 are 136.6 kWh, 112.6 kWh, and 98.9 kWh for these three design interventions, respectively. The findings revealed that the total annual energy consumption of the S4 is slightly lower than the S5 (ranging from 0.3 to 2.0%) for the other three design interventions' thermal fabric efficiency.

Figures 35 and 36 summarise the overall cooling demand reductions connected to the introduction of the variable set-point in summer for all three representative sample flats. The results point out that during the cooling season, the cases reveal significant differences based on the adaptive temperature set-point of the heavyweight construction materials, in particular for this base-case model RTB, which is not provided with any insulation layer. This can be clearly seen in the base case and in the retrofitted case, while only the night ventilation strategy, allowing the loss of the stored heat, significantly reduces the calculated need of the heavyweight conventional building.

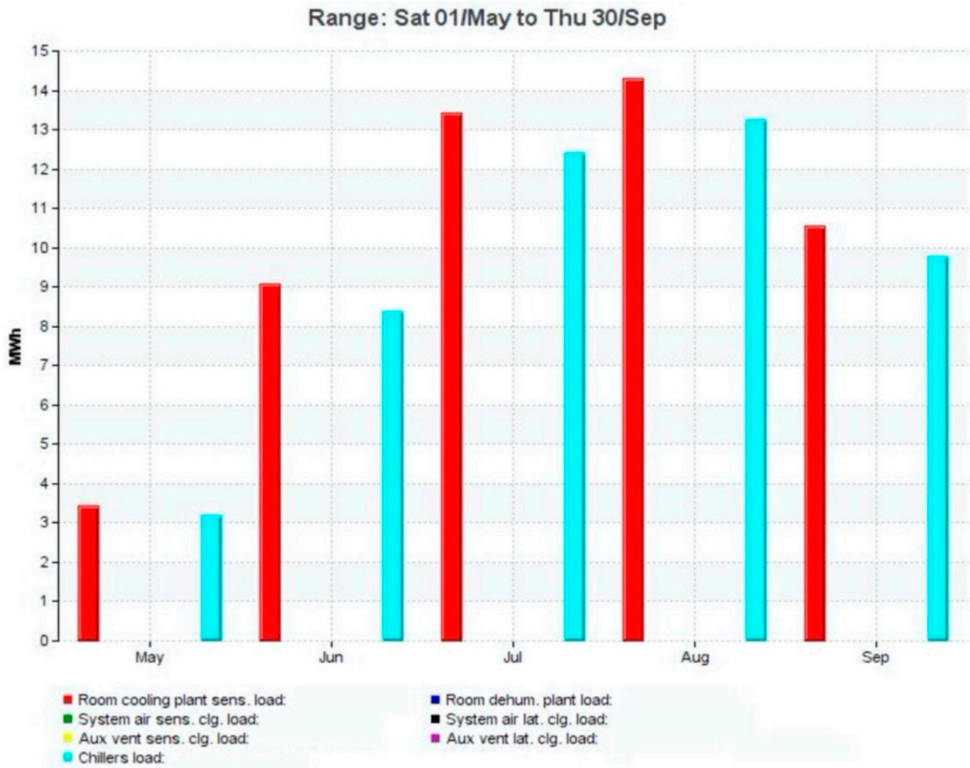


Figure 35. Distribution of overall cooling energy consumption of the base case's representative upper-floor flat unit before retrofitting.

Furthermore, it is important to highlight the fact that in comparing the base case and retrofitted case, the reduction in the cooling demand for the heavyweight constructions tends to decrease with the height of the floor level and orientation of the flat. In case of implementation of state-of-the-art energy-efficient building materials into retrofitting, the trend is inverse. This is due to the fact that in the upper- floor flat unit, there is a larger gap between the conventional set-point temperature and the occupants' expected one.

Moreover, energy savings achieved through improvement of building fabric are similar for the heavyweight, mediumweight, and lightweight structure. For the mediumweight structure, with the design parameters of the baseline scenario taken into consideration, the total energy savings is 27%, while with the passive cooling design strategies implemented onto the building envelope, the total energy savings is 67%.

It can be seen that the zones under consideration within the case study RTB's sample flat units are found to exceed the acceptable limits of the CIBSE TM 59 criteria, as shown in Figure 37. The worst-case calculated building space is the living room, as it incorporates the internal heat gains from the open-plan-layout kitchen; these are interleading rooms. The flat units with poorer ventilation performance were shown to be in the worst-case representative ground floor flat unit. This is attributed to the opening ratios and material properties of the double-glazed windows. These flat units are constructed with three exposed external walls allowing for a higher rate of heat transfer. Comparing the dynamic thermal simulation results shown in Figure 37, in order to consider the location of the flat units on a different level, the height of the RTB influences the air infiltration rates of the flat units.

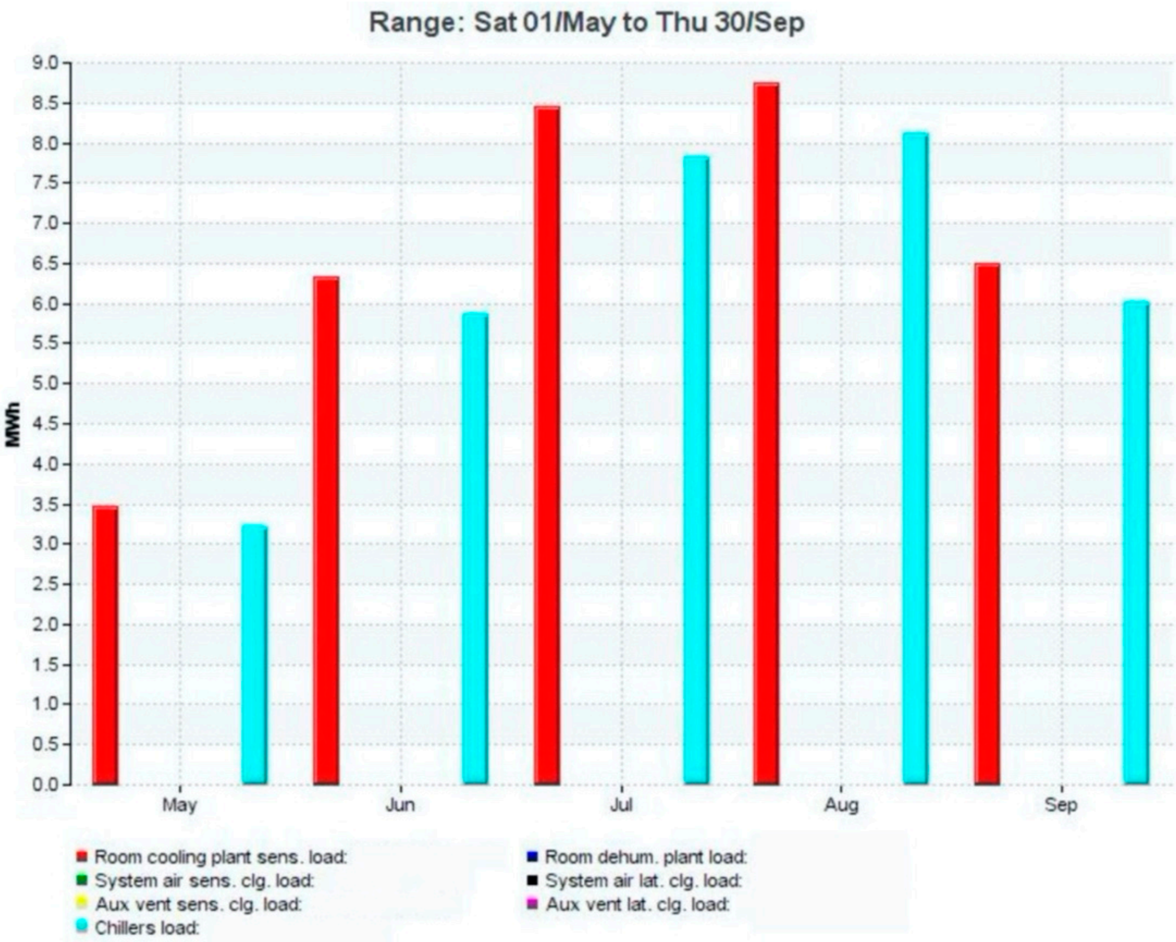


Figure 36. Distribution of overall cooling energy consumption of the base case's representative upper-floor flat unit after retrofitting.

The prototype RTB is subjected to effects from 'buoyancy-driven air movement'. Because of this approach, hot air from the lower levels rises up through the building and with no means of escaping the living zones, accumulates on the top levels. Combining this with the effects from the building envelope corresponds to the inadequate thermal performance of the worst-case first floor flat unit for all three criteria as defined by the CIBSE TM 59, and as shown in Figure 37.

The struggle against climate change requires an investment in retrofitting existing residential buildings, particularly those considered most vulnerable (with uninsulated thermal envelopes) and those whose occupants are more susceptible to energy poverty [105]. In these retrofits, we must actively consider the reduction of energy demands to minimum levels by performing interventions on the thermal envelopes of the buildings [106]. In the three cases of surveyed and simulated RTBs in Famagusta, Cyprus, the positive impact on indoor temperatures and the comfort of retrofitting the envelope was shown. With this action (retrofitting the facades, roof, and windows and reducing infiltrations) and with very minor reliance on cooling systems in the summer, a decrease in indoor air temperature between 2 and 4 °C was achieved.

In both the present situation and by the year 2050, with respect to climate change, the retrofitting measures proposed for the thermal envelope would allow for residential buildings with almost zero cooling demands in some European locations [107]. The key factors which would contribute to this objective are the design criteria for the envelope, taking the following into account: (a) the climate, the differences between floor levels, and the orientation of the buildings will require greater or lesser levels of intervention (i.e., thickness of insulation) [108]; (b) orientation towards the south for greater solar gains [109]; (c) the position of the dwelling in the building, so that all apartments have the same energy demands [110]; and (d) ventilation incorporating occupants' thermal comfort in the RTBs [111]. Figure 19 delineates the key outcomes of this empirical study to demonstrate the contribution to knowledge for the development of effective retrofit design policy in the southeastern Mediterranean basin.

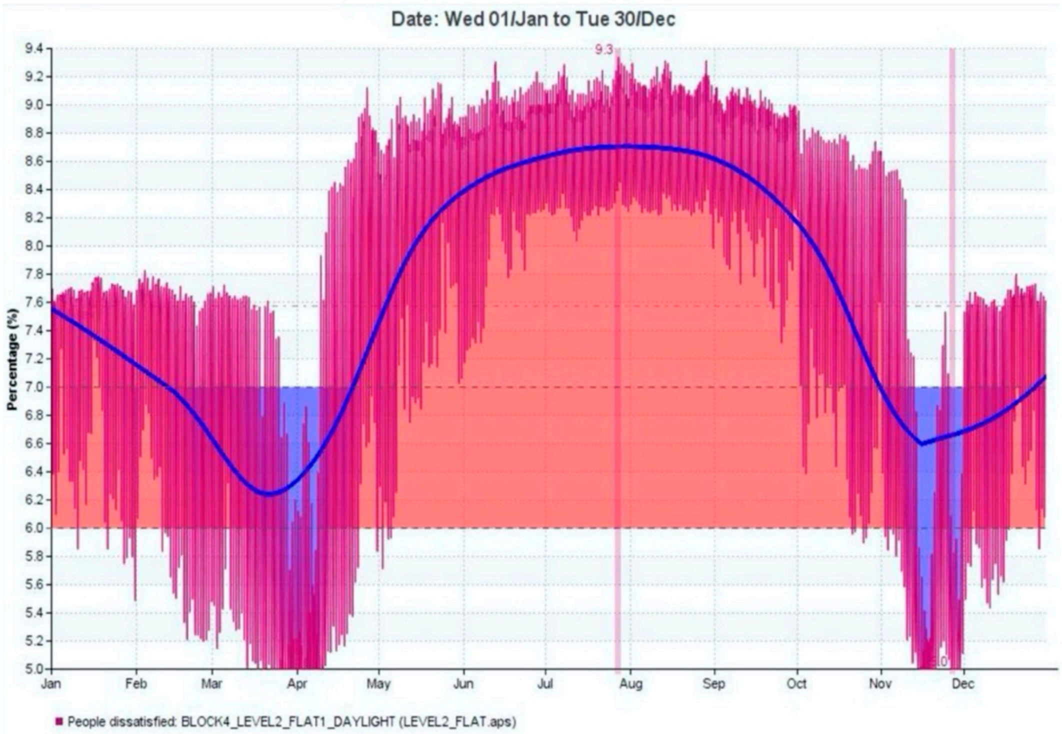


Figure 37. The fluctuation diagram represents the Predicted People Dissatisfied (PPD) levels after implementation of all three selected retrofit interventions.

In the case study building, according to current standards, overheating and the energy demand necessary for maintaining an adequate thermal comfort are boosted significantly. In this southeast-facing building, an excessive risk of overheating has been observed on the ground floor, and there is important overheating on floors under the roof, which creates thermally uncomfortable indoor conditions for households. At the same time, energy demand in use in the upper-floor flats exceeds 237.1 kWh/m^2 annually. In collective high-rise residential buildings without rehabilitation of the building envelope, overheating increases the cooling demand, resulting in even greater energy usage. In southeast-facing RTBs, the cooling energy demand will be over 120.1 kWh/m^2 in flats on the intermediate floors and is more likely to be 101.7–153.1 kWh/m^2 in flats on the upper floor where, in this building typology, the cooling demand increases by an average of 38%. It is worth highlighting that this kind of thermally insufficient building typology occurs frequently in social dwellings, so those flats with the worst conditions will be inhabited by the most socio-economically vulnerable population [112]. Figure 38 illustrates the step-by-step development of passive cooling design strategies implemented on the existing building envelopes of a prototype RTB.

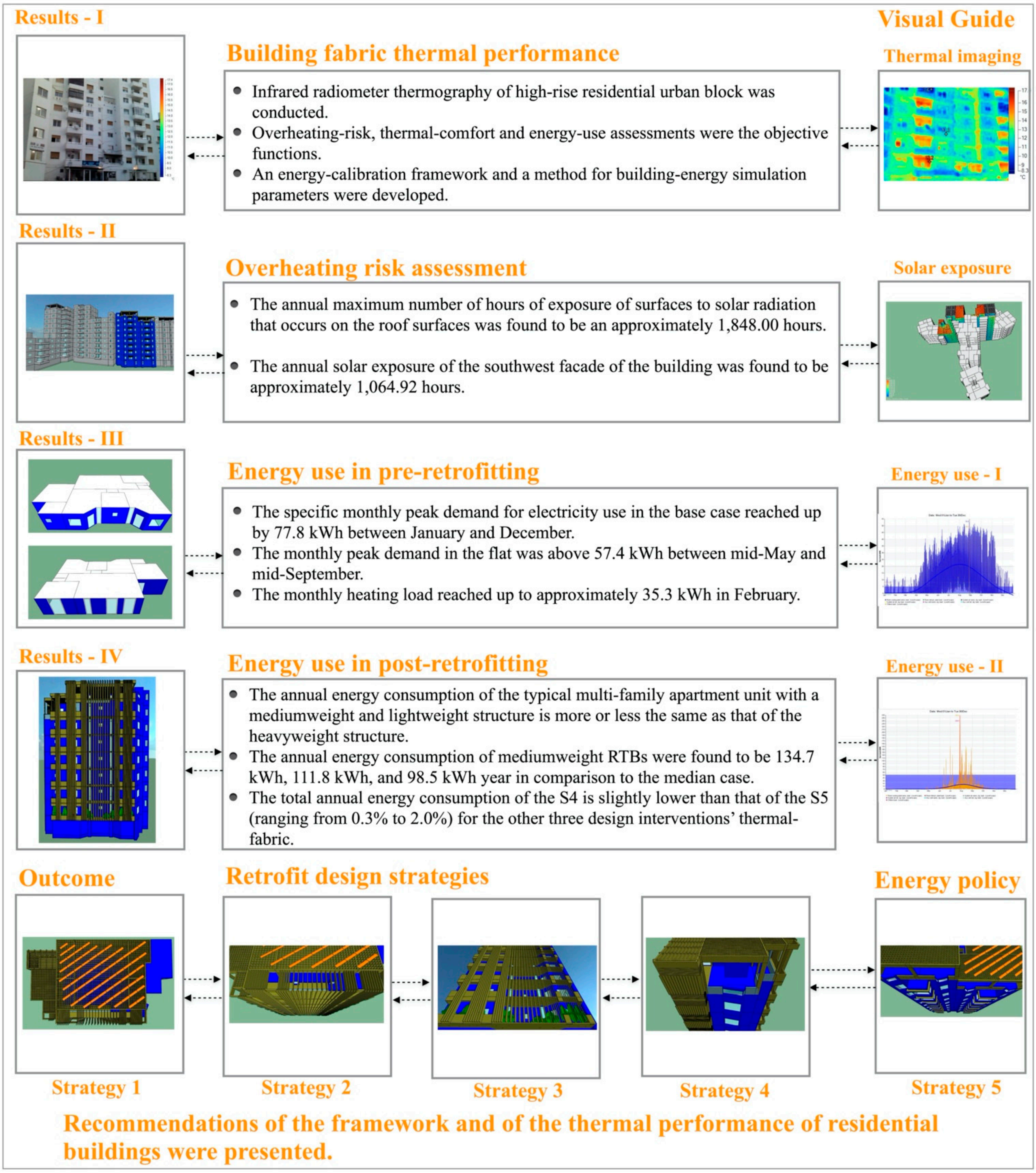


Figure 38. The step-by-step development of key research subjects, conceptual framework, and outcomes in retrofit policy design.

As shown in Figure 38, the subsequent investigative stage analysed the current thermal performance of the southeast-facing RTB and the potential retrofit solutions that could help to improve its occupants' thermal comfort. The strategies incorporated into the most ill-performing spaces in the RTB showed that the building envelope's rehabilitation in strategy 1 (S1) had the greatest impact on reducing cooling energy consumption, a 43% improvement, and that a 52% reduction can be achieved by a combination of building envelope rehabilitation and the implementation of the solar shading system featured in strategy 2 (S2), including horizontal external louvres and overhangs above large, glazed window openings. The fenestration design of the RTB also had an impact on its energy and thermal performance, as was demonstrated in this study. The energy consumption of the RTB decreased by 57%, once the appropriate top window opening design, featured in S3, was applied. Nevertheless, these designs improved the ventilation of the RTB, allowing better thermal comfort for the occupants when the outside temperatures were lower than those inside. It is worth noting that the RTBs' passive cooling systems should harness the prevailing winds to allow for natural ventilation without neglecting the solar gains due to the climatic conditions of the research context [113]. The fenestration design in S3 showed how allowing cross-ventilation in all occupied rooms of the RTB leads to an increase in natural ventilation, thus providing more thermal comfort to occupants throughout the cooling season (May to September), without increasing the total gross area of the RTB, which would implicate higher costs [114].

Considering a combination of strategies 5 and 6, as implemented in the base-case RTB, we observed a net decrease in cooling energy consumption. Cooling consumption decreased by 81% when the outdoor air temperature was higher than indoor temperatures; this also matched a significant reduction of 538.7 kWh/m^2 in cooling load, which was dependent on solar shading implementation. It is important to highlight that increasing outdoor temperatures and consequently increasing the greenhouse gas emissions associated with rising energy consumption for cooling during hot, summer conditions will underdetermine the greater aims of climate change mitigation [115]. Less energy-intensive passive design strategies are investigated in this study, although the PPD remained higher than the thresholds stipulated by the current criteria (approximately 30.5–36.3%).

From a comfort and performance perspective, work completed in Mediterranean climates in the future should be designed to include solar shading appendages, as these proved to be the optimum retrofitting strategy [116]. Solar shading systems can be implemented with little cost, given that they are a feature of climate change adaptation in this particular climate [117]. As this study has demonstrated, it appears that passive design strategies can be both energy-efficient and cost-effective for retrofitting RTBs across south-eastern Mediterranean Europe. This is a crucial finding that needs further investigation to assess and optimise the risk of overheating and to understand occupants' thermal comfort when enhancing feasible retrofitting scenarios in the Mediterranean basin.

4.6. Correlation Analysis

In this empirical study, the occupants were asked to evaluate the overall quality of the indoor-air temperature in an open-ended question form. The question concerning the respondents' rating of the quality of their indoor-air environment was intended to assess the degree of thermal discomfort in the summer. Table 7 illustrates the cross-tabulations using chi-square tests comparing thermal sensations by orientation and floor, as well as Pearson's correlations comparing thermal sensations between the households' thermal sensation votes (TSVs) in the summer and the physical position of the RTBs, and takes different RTB orientations into account. The Pearson correlation coefficient (also known as Pearson's product–moment correlation coefficient), r, is a measure to determine the relationship (instead of difference) between two quantitative variables (interval/ratio) and the degree to which the two variables coincide with one another—that is, the extent to which the two variables are linearly related: changes in one variable correspond to changes in another variable. The Pearson correlation coefficient (also referred to Pearson's r) is the most common measure of correlation and has been widely used in the sciences as a measure of the degree of linear dependence between pairs of data.

As shown in Table 7, several strong and moderate positive correlations related to the occupants' decisions on TSVs in the summer were detected. TSVs in Bedroom 1, Bedroom 2, and Bedroom 3 were strongly and positively correlated with each other (rs < 0.001 = 0.724–0.829, ps). Spearman's rank-order correlation coefficient ($\boldsymbol{\rho}$ or $\boldsymbol{rs}$) is a statistical measure of the strength of a relationship between two variables. Spearman's correlation is a nonparametric variation of Pearson's product–moment correlation, used most commonly for a relatively short series of measurements that do not follow a normal distribution pattern. The Pearson correlation coefficient is traditionally used and referred to as the $\boldsymbol{ps}$ correlation that partials out the subject effect. A moderate positive correlation was noted between the TSVs in the living room and kitchen spaces ($r = 0.462$, $p < 0.001$). TSVs in the living room were significantly but weakly correlated with TSVs in Bedroom 1 ($r = 0.302$, $p = 0.002$) and Bedroom 3 ($r = 0.200$, $p = 0.046$). TSVs in the kitchen were significantly but weakly related to TSVs in Bedroom 2 ($r = 0.205$, $p = 0.041$) and Bedroom 3 ($r = 0.220$, $p = 0.028$), which indicates that the position of the rooms in the flats should be taken into account to assess the occupants' thermal comfort.

Table 7. Relationships between occupant TSVs for each occupied space in the summer.

Variables TSVs		Living Room	Kitchen	Bedroom 1	Bedroom 2	Bedroom 3	Orientation	Floor Level
Living Room	Cramer's V/Pearson's correlation	1	0.462 **	0.302 **	0.146	0.200 *	0.226	0.236
	Significance	—	0.000	0.002	0.147	0.046	0.432	0.376
Kitchen	Cramer's V/Pearson's correlation	0.462 **	1	0.133	0.205 *	0.220 *	0.279	0.222
	Significance	0.000	—	0187	0.041	0.028	0.077	0.467
Bedroom 1	Cramer's V/Pearson's correlation	0.302 **	0.133	1	0.763 **	0.724 **	0.274	0.177
	Significance	0.002	0187	—	0.000	0.000	0.210	0.949
Bedroom 2	Cramer's V/Pearson's correlation	0.146	0.205 *	0.763 **	1	0.829 **	0.272	0.194
	Significance	0.147	0.041	0.000	—	0.000	0.222	0.884
Bedroom 3	Cramer's V/Pearson's correlation	0.200 *	0.220 *	0.724 **	0.829 **	1	0.263	0.221
	Significance	0.046	0.028	0.000	0.000	—	0.143	0.478
Orientation	Cramer's V	0.226	0.279	0.274	0.272	0.263	1	0.197
	Significance	0.432	0.077	0.210	0.222	0.143	—	0.234
Floor Level	Cramer's V	0.236	0.222	0.177	0.194	0.221	0.197	1
	Significance	0.376	0.467	0.949	0.884	0.478	0.234	—

Occupant TSVs for living room, kitchen, and bedrooms 1, 2, and 3 in the summer: (−3) to (+3). RTB orientation: 0 (northeast), 1 (south), 2 (northwest), 3 (southwest), and 4 (southeast). Different floor levels: 0 (ground), 1 (first), 2 (second), 3 (third), 4 (fourth), and 5 (fifth); */**: Representation of statistically significance of findings by exploring correlations between households' TSVs and room conditions.

4.7. Limitations

This study set out to provide effective responses to the aims with available data and resources, although this resulted in certain limitations which should be considered alongside the research outputs. The principal limitations are summarised as follows:

- **EPC data**—Whilst extensive in terms of the number of buildings, the EPC data only comprised the housing stock data, after the implementation of the EPC schemes by the EPBD objectives in 2010 and 2012 for the eastern Mediterranean island of Cyprus, and there is a very little recorded information on understanding the energy rating scheme in Cyprus in comparison to the other EU-27 member states. Additionally, the representative buildings incorporated were also subject to some self-isolation owing to the degree of participation of individual households under the EU project Typology Approach for Building Stock Energy Assessment (TABULA) residential building typologies, which have been developed for 13 European countries.

- **Pre-1974 residential buildings—**For analysis of the archetypes, a subset of the database for pre-1974 residential buildings was used. The redevelopment findings would be limited to this age group, however, some principals may also be relevant to more recently constructed high-rise housing estates.
- **Energy use—**The energy calibration analysis was carried out using a comprehensive benchmarking criterion that was compliant with BS EN 15978: 2011—Sustainability of construction works, although it was based on generic material data. There may be some variation where specific products or alternative data are concerned.
- **Simulation of thermal performance of the nationally representative archetypes—**The households' in-vivo experiences on energy use were assessed using dynamic thermal simulation methods. The tool used was industry-standard and was compiled with third-party verification, although the underlying calculation methods could vary relative to other tool providers, and it is noted that generally, such tools provide a simplification of the phenomena that exist in building engineering practice in general.
- **Retrofitting design schemes—**To give a range of reliable results within the verification of households' actual energy use, a broad selection of residential building design criteria schemes—architectural and structural components—was incorporated, typically based on those observed in the representative RTB prototype. However, these were not comprehensive, and different results may be obtained for other district-scale retrofitting schemes in the southeastern Mediterranean basin.

Energy efficiency programmes often form a core element of local strategies for sustainable development as they deliver social, economic, and health benefits as well as reducing housing management costs and helping the environment [118]. Looking at some of the retrofitting design strategies carried out in the southeastern Mediterranean basin, particularly in Italy, Spain, and Portugal in the last ten years [119–121], it is anticipated that these low-energy retrofitting design interventions will influence the design of the housing sector in the following decades. Domestic buildings will therefore have less impact on the environment, considering that sustainable green design issues are incorporated at the design stage. This should be enforced by the building regulations and supported through existing energy and environmental assessment methods for residential buildings.

4.8. Future Recommendations

This study provides an essential reference for all relevant fields in the sphere of the sustainable development of building environments that are concerned with enhancing the energy efficiency of residential buildings by decreasing the detrimental impact of climate change on the thermal comfort and well-being of occupants. It lays out the guiding principles for a holistic and inclusive practice in building physics, in addition to providing a useful explanation for the development of a novel methodological framework for building optimisation and the impact of occupants' habitual adaptive behaviour on the assessment of domestic energy use in conjunction with an investigation of their overall thermal comfort.

This study also proposes a successful roadmap for architects and building engineers that narrows the knowledge gap between the current level of understanding in this area and the actual performance of existing social housing stock in Cyprus and in other European countries that have similar climate characteristics and building regulations. The layout of this article aims to provide a practical and balanced view of a novel epistemological approach that was developed to provide a way forward in the energy policy arena, in which the structures and processes, as well as the demands placed on its outputs and the available solutions, are rapidly changing.

Furthermore, although the method employed seems appropriate, with the selection of nationally representative housing archetypes, it is not possible to draw strong conclusions based on the output of the retrofitting intervention analysis [122]. However, the constructed analytical energy model gives an indication of the general scale of energy use and changes from interventions which could be useful for comparison with other energy use estimates. Further energy consumption reductions may be achieved through the use of the alternative applicability of bio-climatic building design elements and building energy modelling methods. However, a variety of methods were explored in this study, so at this point of improvement, they are expected to be limited. A larger dataset may also help to reduce the discrepancies between actual and predicted energy use, particularly given the high occupancy hours in the building energy model. However, it is proposed that greater improvements might be made by increasing the extent and precision of simulation set input parameters in order to more closely describe the building energy use characteristics.

Once developed further, such a method could provide advantages over other energy assessment approaches such as benchmarking and dynamic thermal simulation as it allows estimations to be tailored to the specific building characteristics without a significant modelling burden. The inclusion of the current climate change projections at the time of developing the building energy model would also extend the scope of interventions that could be assessed. It is recommended that a more developed model is applied in a real context and validated using measured data from district scale retrofitting schemes.

5. Conclusions

This research article presents energy consumption and thermal comfort in the social housing sector as a complex socio-technical problem that involves the analysis of an intrinsic interrelationship amongst the dwellings, occupants, and environment. A high-density post-war social housing development estate was used as a base-case scenario. At the same time, this article demonstrates how dynamic thermal energy simulation can be used as a learning laboratory for future trends in housing energy consumption reduction over time, especially considering the Energy Performance of Buildings Directives (EPBD) and net-zero energy buildings (nZEB) schemes in holistic retrofitting for upgrading energy efficiency of existing housing stock by 2050. It is the very first of its kind for this context to investigate domestic energy use, overheating risk of buildings, and occupants' thermal comfort by undertaking building energy simulation analyses to assess existing energy performance of the social housing stock.

The study aimed to evaluate the risk of overheating and potential ways to overcome this through the implementation of both energy-efficient state-of-the-art and passive design strategies (i.e., shading and natural ventilation) into a tower block in Famagusta, Cyprus. The results illustrated the necessity of considering passive measures in a state-of-the-art retrofit of existing RTB developments. This paper concludes that a thorough economic appraisal is required to select the most environmentally and economically viable forms of retrofitting. A building performance evaluation method of modelling and simulation was embedded, and to assess the existing cooling energy consumption patterns and thermal comfort levels, conditions in three different RTB developments, with high retrofit potential, and a sample of representative prototypes built over three distinct eras were selected. A thermal imaging survey was conducted at each RTB for both summer and winter seasons to understand heat losses/solar gains through the building envelope and to assess the overheating risk of the occupied spaces.

The findings of this study enhanced the overall understanding of the complex interrelationships between household socio-demographic characteristics, building thermal properties, and occupants' habitual adaptive behaviour related to thermal comfort in heat-vulnerable MFHs. It was found that TSVs in the Living Room were significantly but weakly correlated with TSVs in Bedroom 1 ($r = 0.302$, $p = 0.002$) and Bedroom 3 ($r = 0.200$, $p = 0.046$). TSVs in the Kitchen were significantly but weakly related to TSVs in Bedroom 2 ($r = 0.205$, $p = 0.041$) and Bedroom 3 ($r = 0.220$, $p = 0.028$). An ordinal logistic regression was performed, and the result revealed no significant relationship between occupant TSVs and living room OTs, $OR = 0.993$ (95% CI (0.816, 1.209)), $p = 0.947$, $Nagelkerke\ R^2 < 0.001$. On the contrary, a significant relationship between operative air temperature and overall summer temperature satisfaction, $OR = 0.958$ (95% CI (0.918, 1.000)), $p = 0.050$, $Nagelkerke\ R^2 = 0.042$. The occupants' TSVs indicated that the neutral temperature was 28.5 °C, and the upper limit of the comfort range in warm indoor-air temperature conditions was 31.5 °C; this suggests that occupants in hot and dry climates where thermally uncomfortable indoor environments occur are able to tolerate warmer conditions than residents of other high and medium altitudes.

The developed conceptual framework of this research output fits well into the scope of the sustainable engineering field. This study sought to identify the impact of energy system analysis, simulation, and modelling to provide a basis for the information needed to calibrate a multi-objective domain of optimisation studies. It also envisaged a demonstration that the occupants' real-life experiences with energy use have had a significant impact on calibrating domestic energy use to identify discrepancies between actual and predicted energy use on the dynamic energy simulation platform where there is little research undertaken on improving the energy efficiency of existing social housing stock. The outcomes of this study contribute to the energy policy design goals of the EPBD objectives because they demonstrate a novel methodological framework for the improvement of occupants' thermal comfort, together with reduction of domestic energy use, as well as improving the economy, efficiency, and effectiveness of the implementation of passive cooling retrofit design strategies to achieve their social objectives for national energy policies and energy planning.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

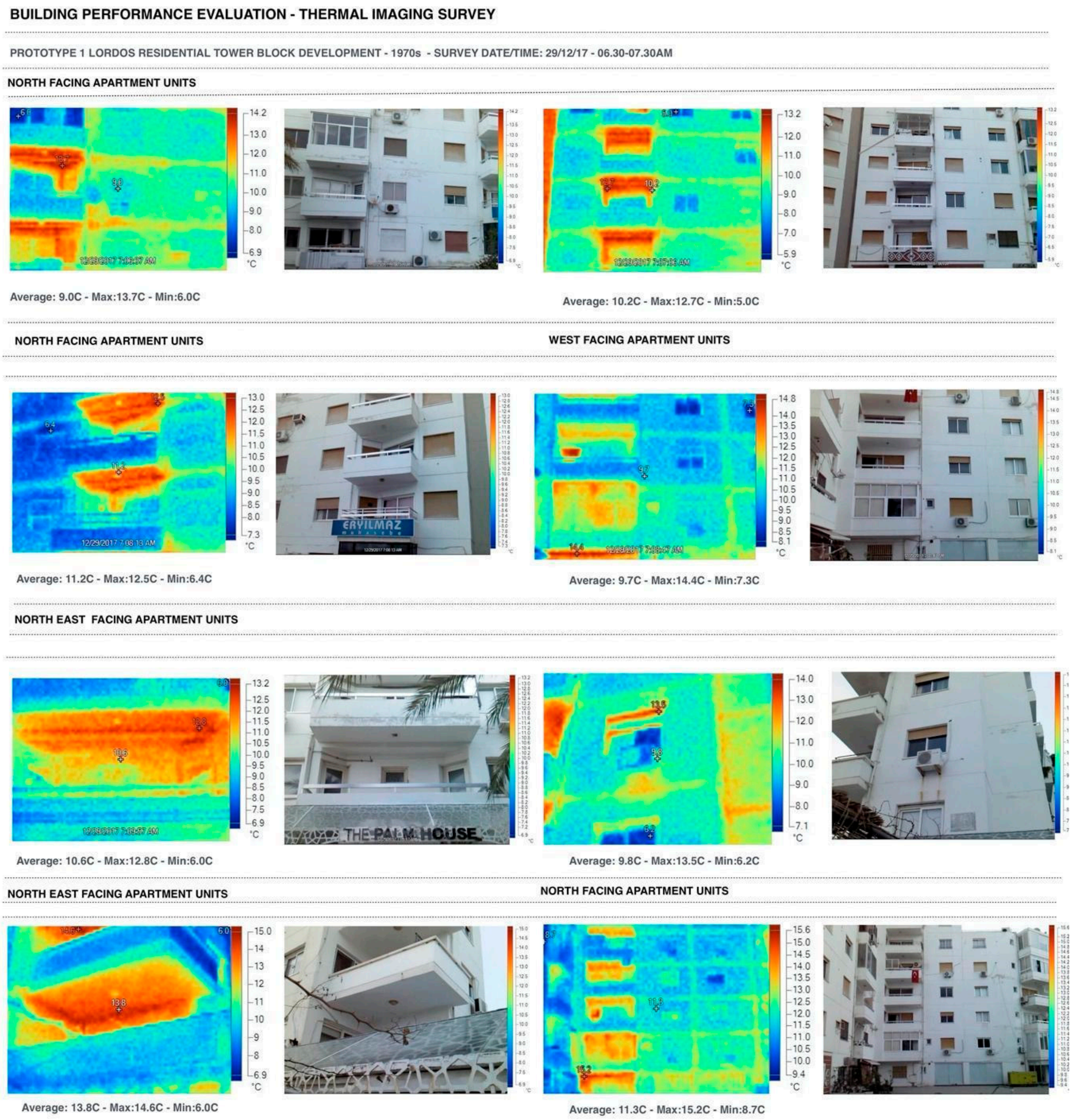

Figure A1. Meta-analysis of building fabric elements recorded early in the morning.

Appendix B

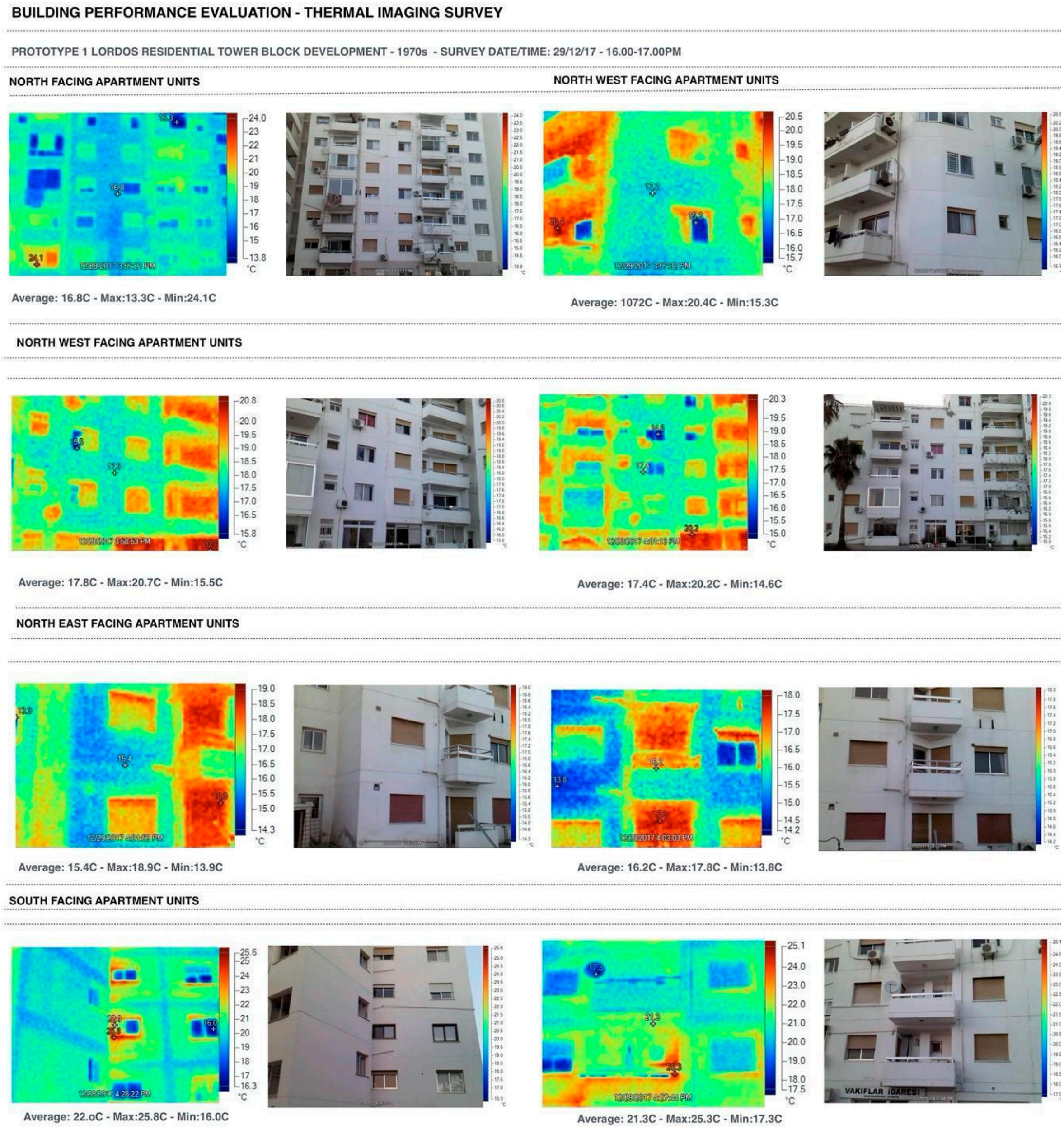

Figure A2. Meta-analysis of building fabric elements recorded late in the afternoon.

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