
# Energy Modelling of Multi-Family Residential High-Rise Buildings in the South-Eastern Mediterranean Climate: Retrofit Policy Design

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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 paper presents an analysis of the development of modular building design elements to improve thermal performance of a base-case high rise residential development before different retrofitting scenarios are undertaken to optimise the building's energy performance and the occupants' thermal comfort in the coastline city of Famagusta, Cyprus. This study adopts a quantitative research design primarily using multi-objective optimisation and the energy simulation of a base-case prototype building in both extreme seasons (summer and winter). The selected representative high-rise residential development is 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 representative apartment units were modelled using dominant representative energy profiles, and in all cases the preliminary results demonstrated that the physical properties of the building led to high levels of discomfort as well as higher than average heating and cooling loads. The results demonstrated that in the non-retrofitted case, the cooling and heating comprised the biggest part (67%) of the total energy consumption, helping with the second phase of the study, which is investigation of effective district scale retrofitting scenarios in the decision-making process to uptake delivery of policy implications with taking into account households' real occupancy profiles in the South-eastern Mediterranean climate.

**Keywords:** Building performance optimisation; Climate responsive design; Passive cooling design

## 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 a 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 38% 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. In respect to Cyprus, a main concern is the burden resulting from a legacy of inefficiently built post-war housing stocks [5,6]. There are no measures or benchmarks for building energy performance, nor an official roadmap for regulating 'retrofit interventions' to address energy efficiency [7].

Previous research has determined that there is a lack of policy initiatives and implications in understanding the importance of energy use [8]. 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 [9]. 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 considering the importance of occupants' thermal comfort [10].

The 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. Our study underlines the importance of adopting comprehensive, interdisciplinary collaboration in order to examine and test 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. Also, 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 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, it showed 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. The key innovations 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 prototype base case study building in the coastal city of Famagusta where the weather is hot and dry in summer. To accomplish this evaluation, high rise RTB was identified as a base case scenario development, since such structures represent the most commonly built 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 test the applicability of various passive design strategies as potential retrofit measures to 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.

*1.1. The composition and evaluation of Cyprus's 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. This documentary highlights the stages of housing developments from 1950 to 2017 in Cyprus, as illustrated in Figure 1.

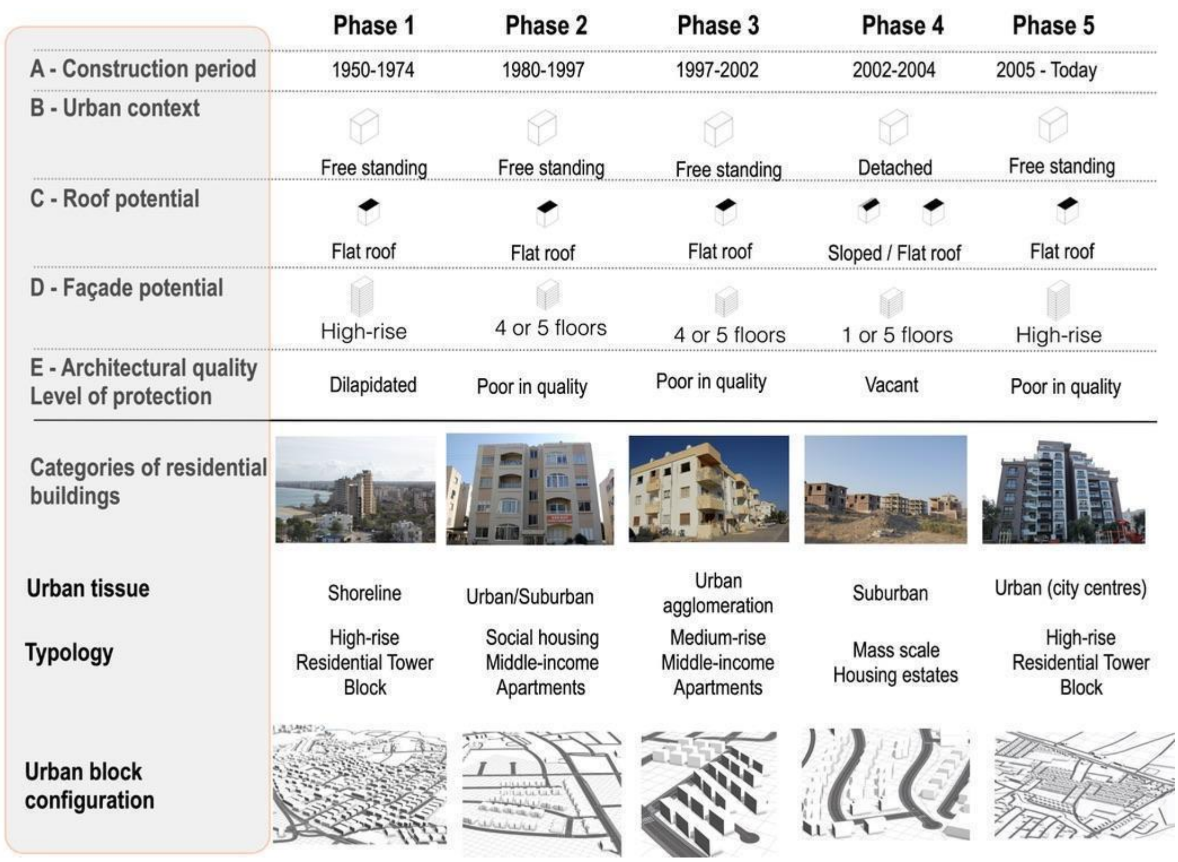



**Figure 1.** The taxonomy of housing stock in Cyprus.

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. 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 [11].

Phase II delineates the government's social housing estates, which were built from 1980 to 1997, to answer the needs of the housing shortage for young people. 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. 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. 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 occupant's 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 and the Department of Town Planning of Cyprus due to the national policy gap from 2002 to 2004. 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. 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 detrimental to the natural habitat.

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. 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 detriment of the environment and thermal comfort of the residents. 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 south-eastern Mediterranean climate.

### *1.2. 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 [12]. 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 [13]. This assessment criterion has further been put forward to provide basic subsequent information to assess the quality of indoor air and relate these to fresh air ventilation rates required for each occupant [14]. Studies have focused on the assessment of energy performance of implementing state-of-the-art building systems into building retrofitting that may require prediction of the way air moves through the building [14]. 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 [15].

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, also accounts for the dynamic effects in terms of penetration depth of the temperature fluctuation into the fabric [16]. The adaptive approach is currently implemented in the CIBSE TM59 Guide – Design methodology for the assessment of overheating risk in homes [17]. 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 [18-21].

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 stated in the norms BS EN 13786: 2007, it has been assumed that if the heat gain to a space is below 35W/m2 there is unlikely to be a need for mechanical cooling [22,23]. 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 [24-26]. Furthermore, a recent study suggested by CIBSE Guide F - Energy efficiency in buildings in 2020 gives further detail on low-energy design principles [27]. However, the more it is known about the manner of both applicable and feasible design strategies which are put forward and the most 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.

## 2. Materials and Methods

A quantitative research design was employed, involving the development of a building energy models 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 a 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 [28]. In this study, the dynamic thermal performance simulation studies of each representative apartment unit were carried out in an analytical energy simulation environment between May and September, the peak demand period for cooling energy use, as shown in Figure 1.

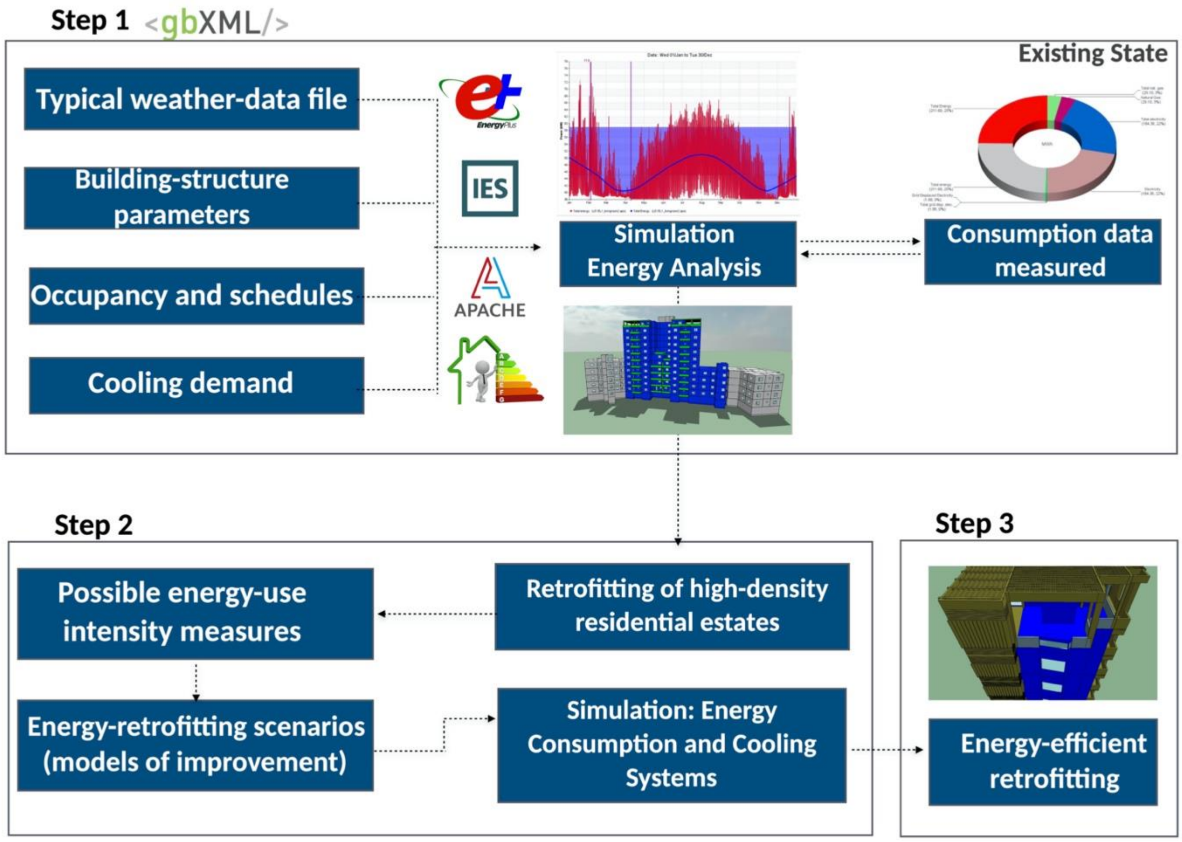



**Figure 2.** The methodological workflow developed for the building energy simulation study.

To fulfil the research aim 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 were taken of the characteristics needed for energy use per area (naturally or mechanically) in order to take into account occupancy, the electrical energy use of equipment, internal temperature, the energy use of artificial lighting and of mechanical plants (A/C units). The aim of the selection is to capture a variety of space energy uses using relatively simple assessment benchmarks to import the data to the IES-VE simulation software for testing the validity of simulation results by investigating the daylight impact factor into each occupied space and thermal properties of representative apartment unit's under-investigation.

### *2.1. 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 [29]. 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 meters long and 13 storey high, as shown in Figure 3.

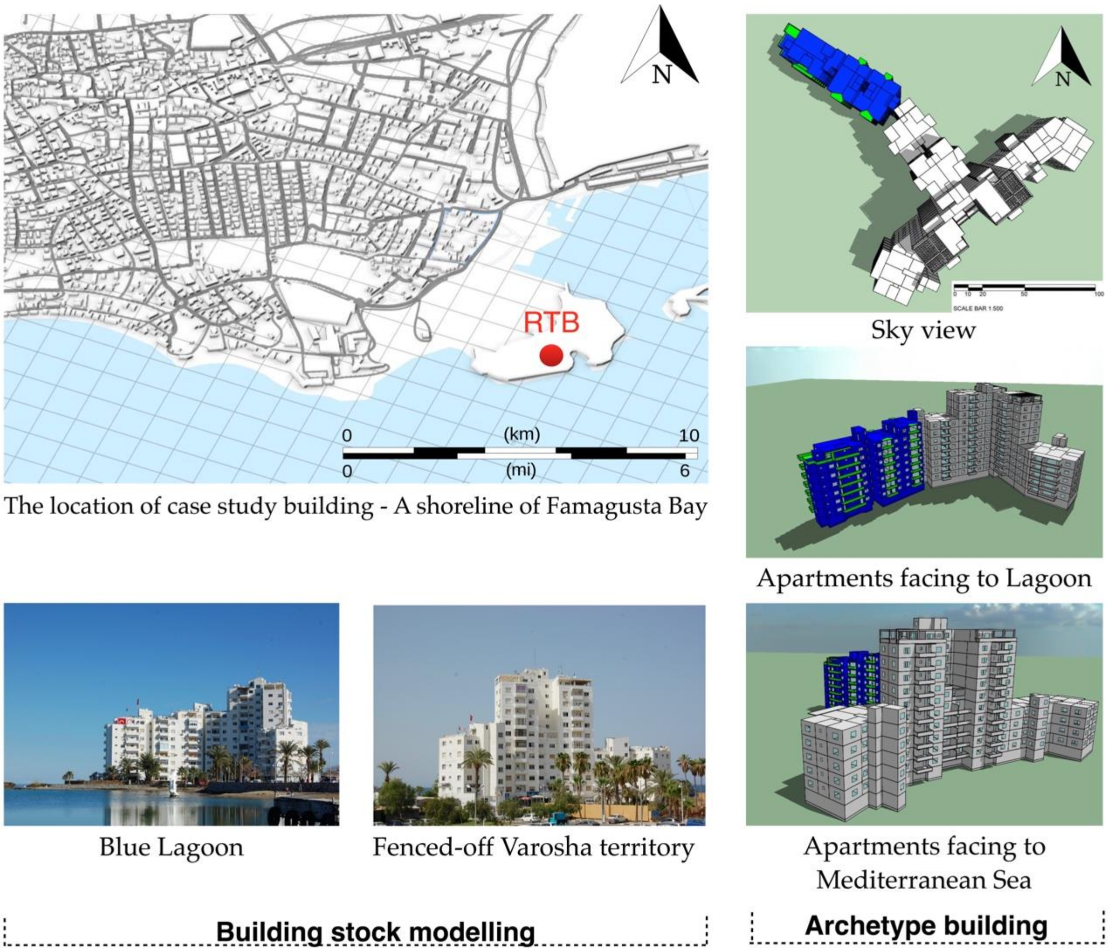



**Figure 3.** The location map of high rise post-war social housing development estate in Famagusta, Northern Cyprus; base-case RTB development, built in the 1970s; analytical energy simulation model of a southwest-facing apartment unit within the adjacent RTBs.

The case study building is representative of high-rise residential developments constructed by privately owned construction companies in the 1950s and 1970s. The conditioned gross floor area of the case study multi-family apartment unit is 75 m2. The original U-values were 2.35 W/m2K for external walls, 1.23 W/m2K for the internal walls, 1.2 W/m2K for the roof and 2.10 W/m2K for the windows and doors. Thermal specifications of construction materials are made according to the benchmarks of the British Construction Codes and Practices – Law 1959, which is the most recent data set available at the time of undertaking the research for this study [30].

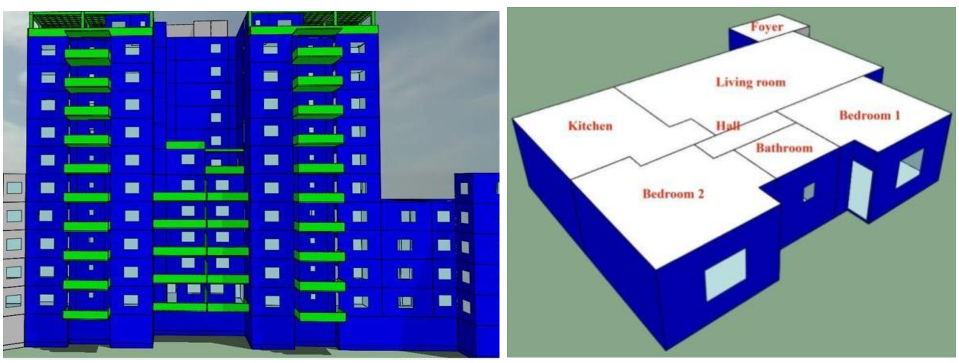



**Figure 4. (a)** The tested and simulated prototype RTB for a base case scenario development; **(b)** The analytical energy model of a representative apartment unit's under-investigation.

The building geometry was created for its initial existing state, every floor and apartment with correspondent thermal zones and subdivisions, as shown in Figures 4 (a) and (b), indicating clearly which zones and spaces are not heated like balconies, and storage areas.

*2.2. 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. The Integrated Environmental Solutions Virtual Environment (IES-VE) 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 to European standard EN 15251 as previously discussed in section 1.2. It is also necessary that the IES software suite offers 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 5.

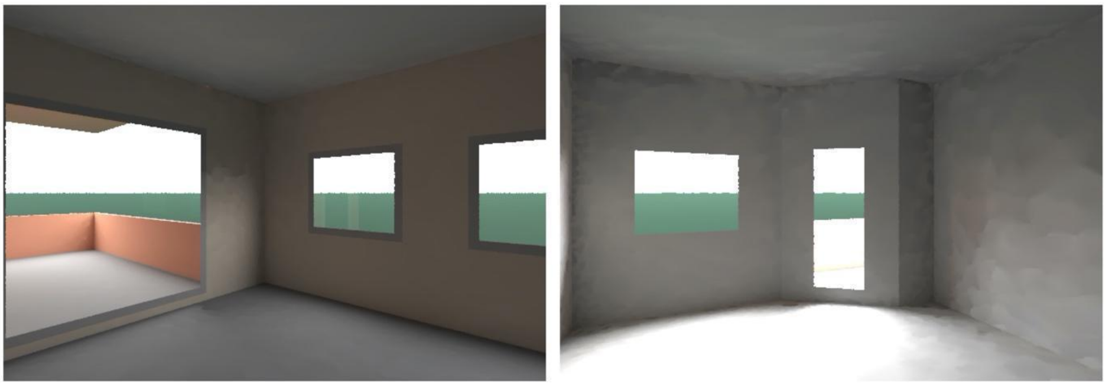


**Figure 5.** The interior view of thermal zoning of a living room and bedroom spaces for each representative flat unit in the RTBs.

The IES version used throughout was IES-VE 2021.1.0.0. Specifically, the Thermal Comfort assessment task of the IES software suite was found to be an application that could offer to measure the 'adaptive thermal comfort' of a prototype RTB. It is also of interest to consider that in combination with the dynamic thermal Simulation (DTS) components of the IES 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 define the space conditioning systems (Apache Systems) and gain variation profiles for zones within the building, as shown in Table 1.

**Table 1.** 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 | Appliances 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 x 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 | |

As previously mentioned, the aim of the selection is to capture a variety of space energy uses using relatively simple assessment benchmarks to import the data to the IES simulation software for testing 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. Results and Discussions

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.

### *3.1. Thermal imaging survey*

The case study RTBs were 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. The thermal imaging survey investigating heat losses and assessing the overheating risk of a building were undertaken between 25/12/2017 and 12/01/2018. (see Appendix A.1 and A.2). A thermal imaging survey was carried out before this work to diagnose the building and, taking these data into account, to define optimal retrofitting strategies. The survey results of 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 Figures 6 (a) and (b).

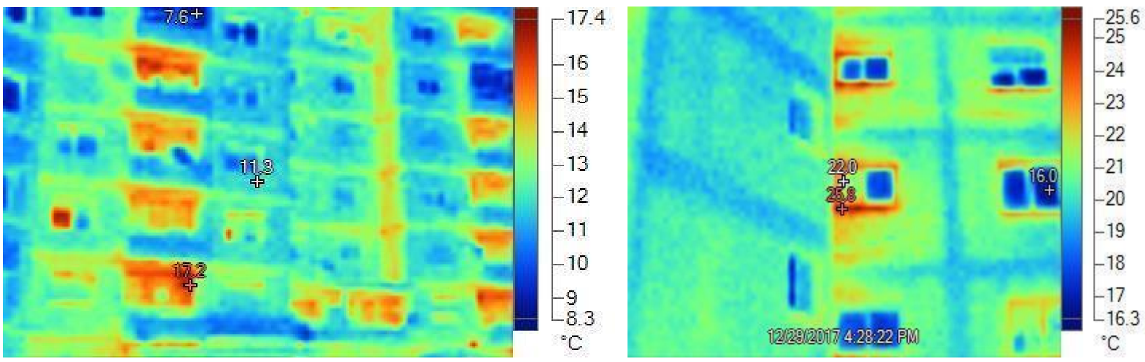



**Figure 6. (a)** Southeast elevation showing heat loss through the external wall, possibly due to insufficient building envelope insulation. Image taken 28/12/17 between 06:30 and 07:54 a.m. **(b)** Southeast elevation showing significant heat loss through windows and heat loss through wall junctions and cracks on building surface. Image taken 28/12/17 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 3.2.

### *3.2. 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 Integrated Environmental Solutions software suite. The objective is to identify the worst-case scenario before testing efficiency of systemic retrofit strategies in the following phase of this study. This section explicitly describes the building modelling simulation studies and analysis that were carried out and outlines the results of daylight impact factor on overheating, thermal comfort and energy use aimed at optimizing occupants' thermal comfort and reducing energy consumption concurrently.

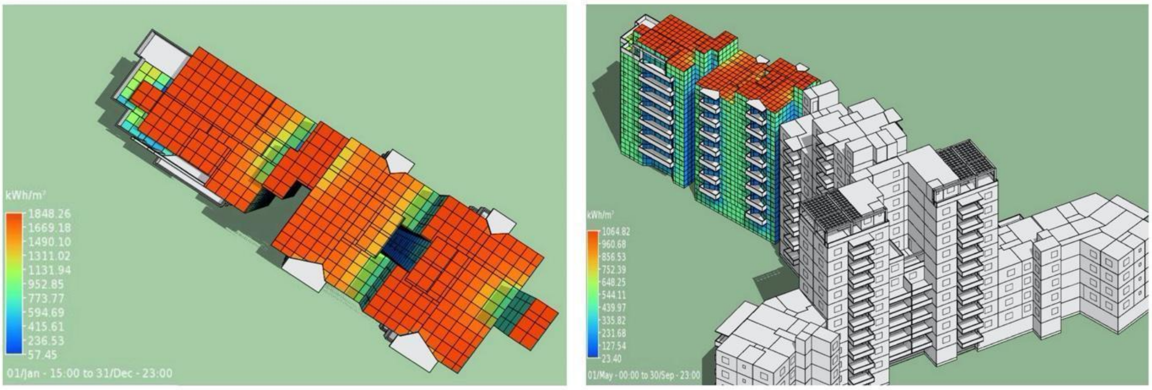



**Figure 7.** SunCast simulation demonstrating that monthly exposure to solar radiation exposure on the roof surface reaches 1,848.26 between January and December 2020 and, the southwestern building envelope reaches 1,064.82 between May and September 2020.

Figure 7 illustrates 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 1,848.00 hours), followed by the southwest facade of the building (approximately 1,064.92 hours). 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 8.** 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.

Additionally, in Figure 8, 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 1,848.26 W/m2K during the year.

*3.3. Daylight impact factor on occupant's thermal comfort and energy use*

The daylight simulations shown in Figure 9 were taken from the analysis carried out 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 in regard to overall understanding about the overheating issues experienced in the RTBs. As previously mentioned in section 3.2, the inefficient building envelopes absorb high solar radiation throughout the year, and it creates a thermally uncomfortable environment for its residents.

Figure 10 illustrates the daylight factor (DFs) on the surfaces within the main rooms are above 292.5lux 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 while assessing the overheating risk of each occupied space at home. Nevertheless, the daylight analysis provides subsequent information to identify energy efficient and cost-effective retrofit interventions that will be taken in the following phase of the study.

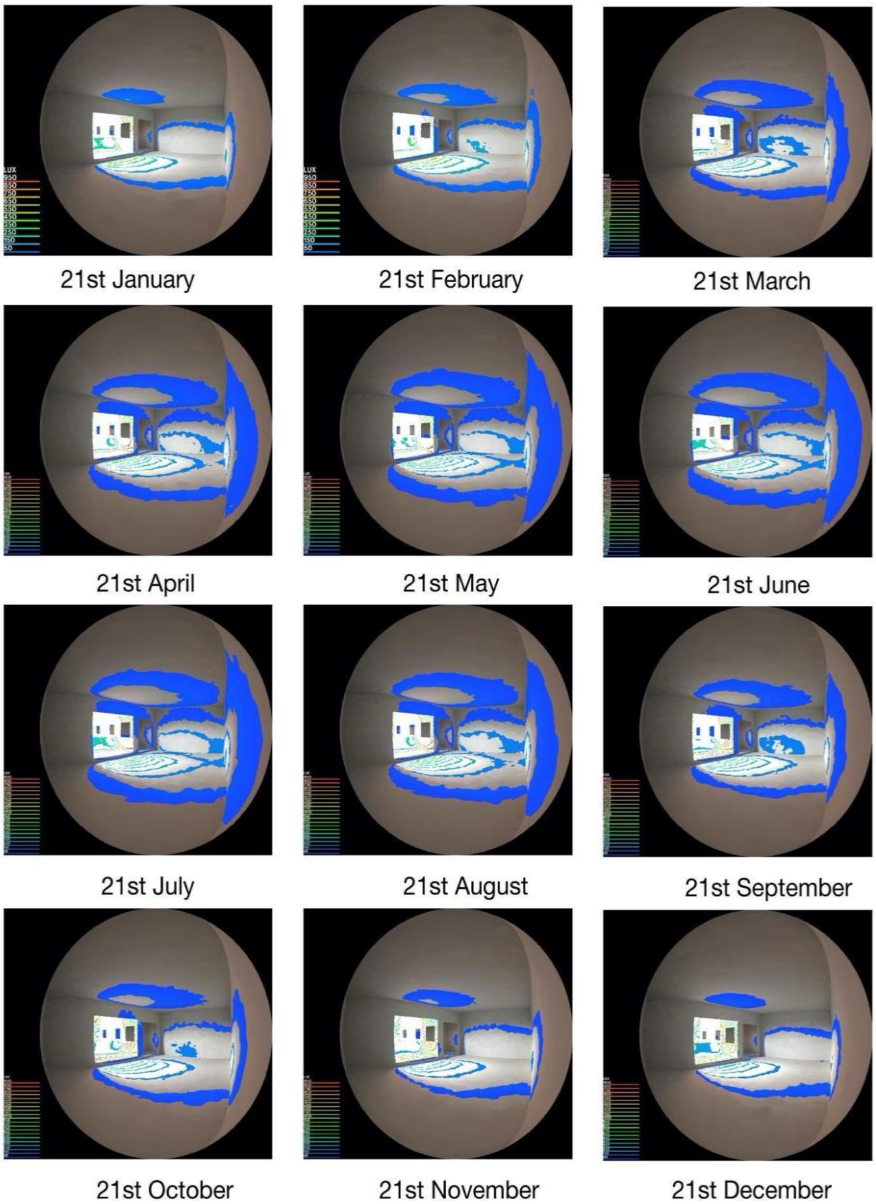
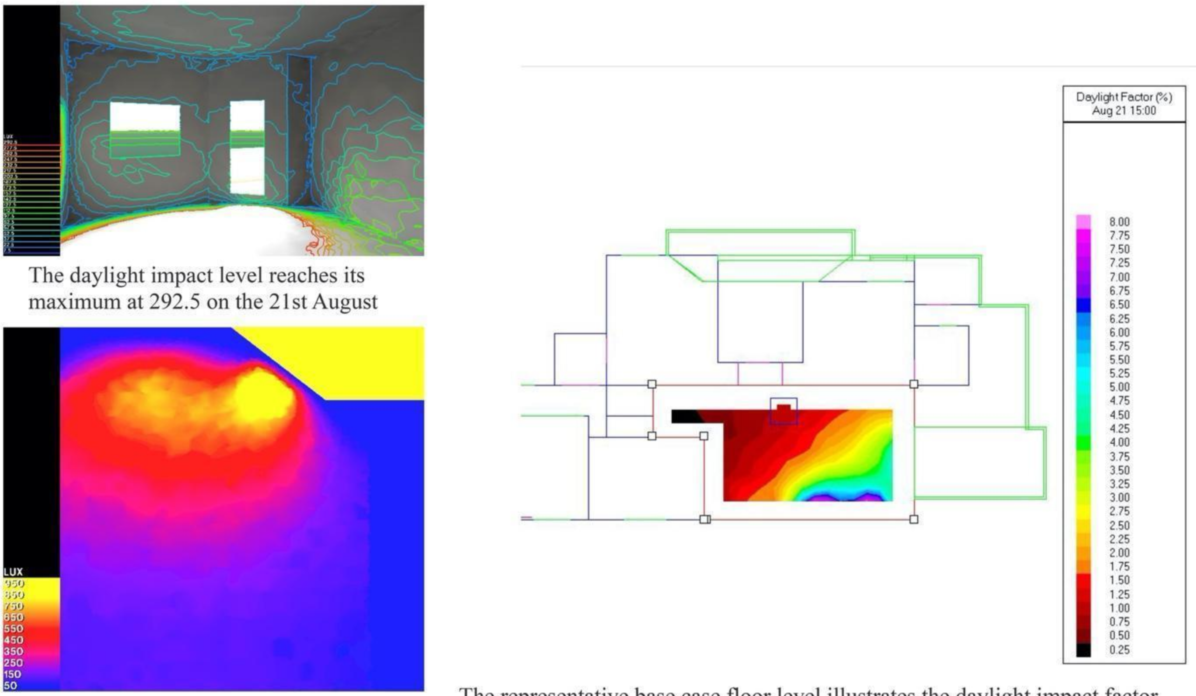



**Figure 9.** The daylight impact factor analysis of the upper-floor representative flat's living room between January and December 2018.




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

As can be seen in Figures 9 and 10 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 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 on 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 from different factors; they have large window-opening ratios with no shading, and all of them face to southwest orientation, exposed to high intensity sunlight through most of the day. These factors together lead to overheating issues and a high degree of occupants' discomfort, particularly in the summer.

### *3.4. Energy use*

As previously stated, the Apache-Sim (Dynamic Thermal Simulation) tool was used to carry out thermal analysis performing predictions of the heating/cooling energy loads in this ill-performing occupied space in the flat and 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. In Figure 11 shows that the specific monthly peak demand for electricity use in the base-case reached up by 77.8 kW between January and December.

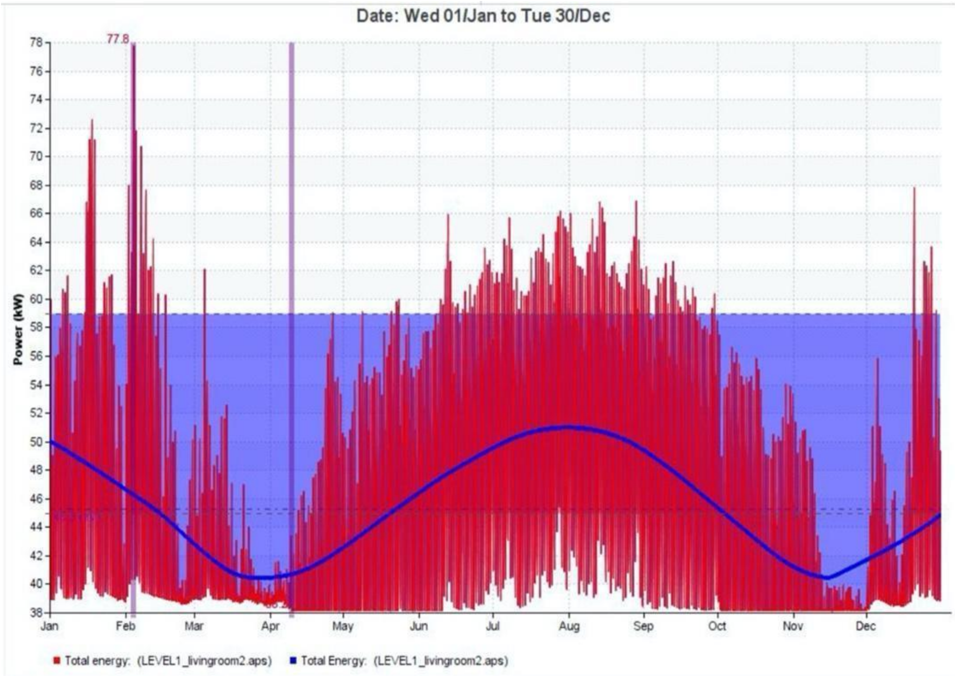



**Figure 11.** The overall energy consumption of the worst-case representative flat unit reached its peak at 77.8 kWh in February.

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 12 demonstrate that the monthly peak energy demand in the flat was above 57.4 kW between mid-May and mid-September, and further simulations led to a consumption of 53.2 kW in August on the monthly cooling load of the living room unit, while in the worst performing bedroom unit 1 specific monthly heating load reached up approximately 35.3kWkW in February as shown in Figure 13.

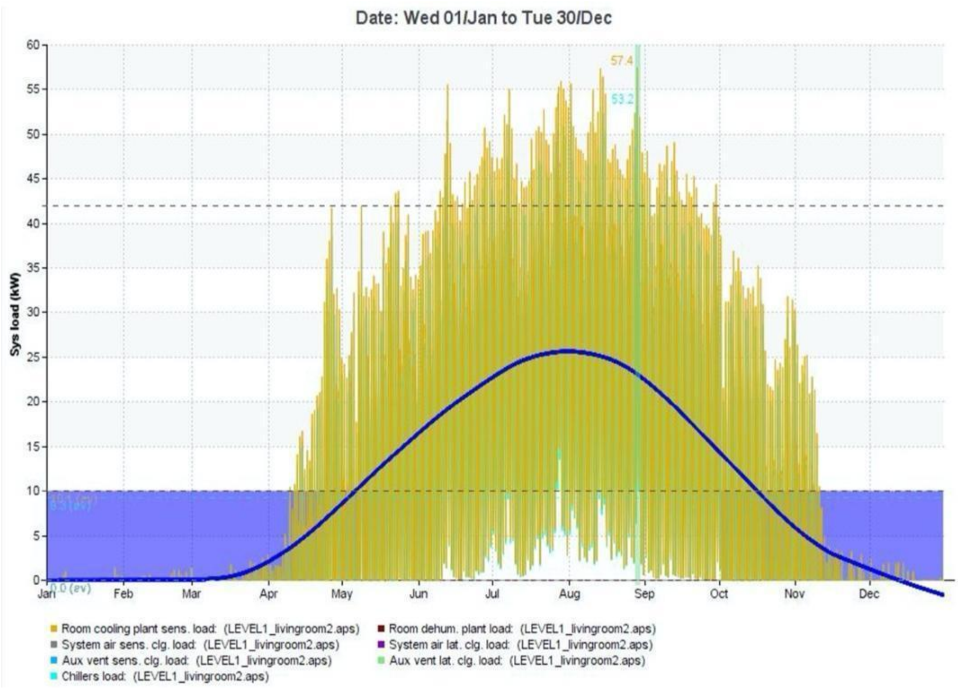



**Figure 12.** The overall cooling energy consumption of the worst-case representative flat unit reached its peak at 57.4 kWh at the end of August.

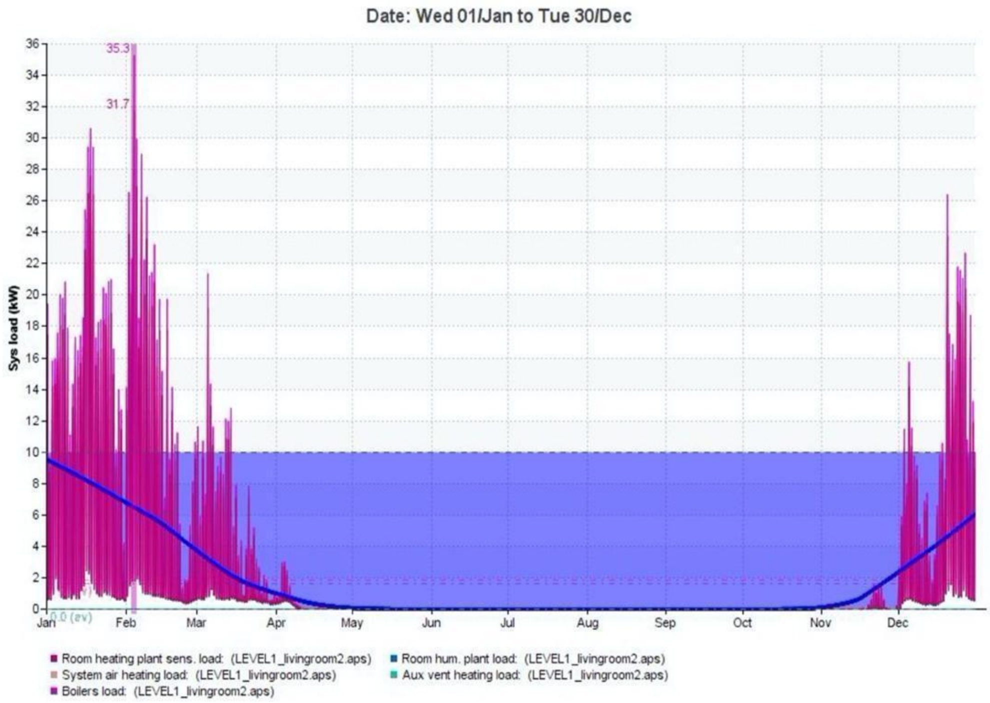
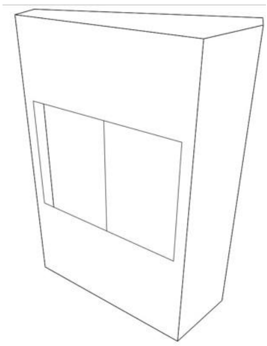
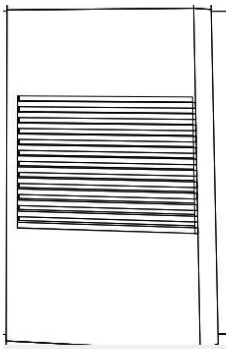
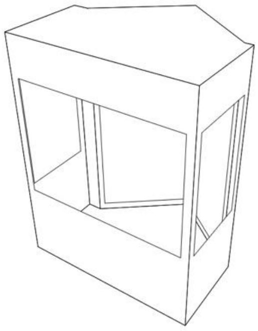
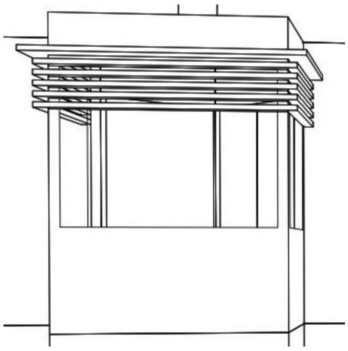


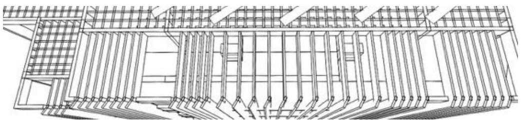
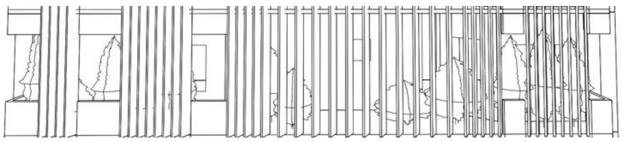

**Figure 13.** The overall heating energy consumption of the worst-case representative flat unit reaches its peak at 39.3 kWh in February.

From the dynamic thermal simulations in order 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 overheating risk of the case under study with a focus on the 10th floor-level 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 tested to assess the efficiency of each as a potential retrofit scenario, as shown in Table 2.

**Table 2.** Specifications of passive design strategies on those of existing base case.

| Sunscreen fixed blade (S1) | Venetian blinds (S2) | Overhang (S3) | Venetian blind – Roller blind (S3) |
|---|---|---|---|
|  |  |  |  |
| Outdoor solar shading, pre-oriented blades fixed to the façade. This shading could also have vertical blades; this case, most effective for south/west orientation, is more frequent in residential building applications.<br><br>The blades can also be applied to shield balconies.<br><br>Blade selection: ellipsoidal, arcaded, triangular, gull wing etc.<br><br>Blade materials: extruded aluminium, formed aluminium sheet or bent, wood, PVC, porous ceramic etc.<br><br>Horizontal blade height (mm): 25–1,200<br>Blade intersection (mm): 70–150<br>Max length (mm): 8, | Solar shield for outdoor use with adjustable and packable blinds.<br><br>The packaging of the blinds allows a very compact folded element once rolled in.<br><br>The typology can also be applied to screen balconies other than windows.<br><br>The opening of the shutter can be the classic hinged, folding, sliding.<br><br>The blinds can also be adjustable, allowing good modulation of radiation and light.<br><br>Blind material: wood, aluminium, PVC, etc. | Overhang fixed opaque, made out of different materials, consisting of horizontal and vertical elements to create a grating pattern.<br><br>Blind section: arched<br>Blind materials: aluminium, alloy etc.<br>Blind supports: steel etc.<br>Blind height (mm): 58–95<br>Blind width (mm): 500–4,500<br>Screen height (mm): 400–5,000 | Double glazing, integrating into the interior chamber of variable thickness a venetian blind, roller or pleated.<br><br>The sliding of the tent takes place in a sealed package containing desiccants to ensure the control of humidity and vapour condensation.<br><br>Venetian blind, with respect to roller blind, provides a vision of the outside, even screening down, because it has oriented slats.<br><br>Max 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 façade.<br><br>Blind material: extruded aluminium, bent or formed aluminium sheet, PVC-coated copper, wood, glass.<br><br>Structure material: aluminium, galvanised steel.<br><br>Blade height (mm): 70–1,500<br>Blade length (mm): max 6,000<br>Blind step (mm): 70–150 | Overhang, fixed vertical, opaque, made with different materials (sheet metal, treated wood, plastic materials etc.).<br><br>Anchored to the wall with an autonomous structure or structurally integrated.<br><br>The shields may also have a vertical arrangement perpendicular to the façade; in this case, they are most effective for east and west orientations |

When all strategies were taken into account and all representative sample flat units were simulated with the relevant thermal conductivity level of the RTBs, the results reveal that the living room in the southeast-facing upper-floor flat exhibited the highest cooling demand with a decrease of 21.69%, while Bedroom 2 demonstrated a cooling demand of 21.60%, as shown in Figure 14. These values reveal a decreased demand for cooling-energy of 78.49 kWh/m2 in the intermediate floor and 69.79 kWh/m2 in 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 per year.

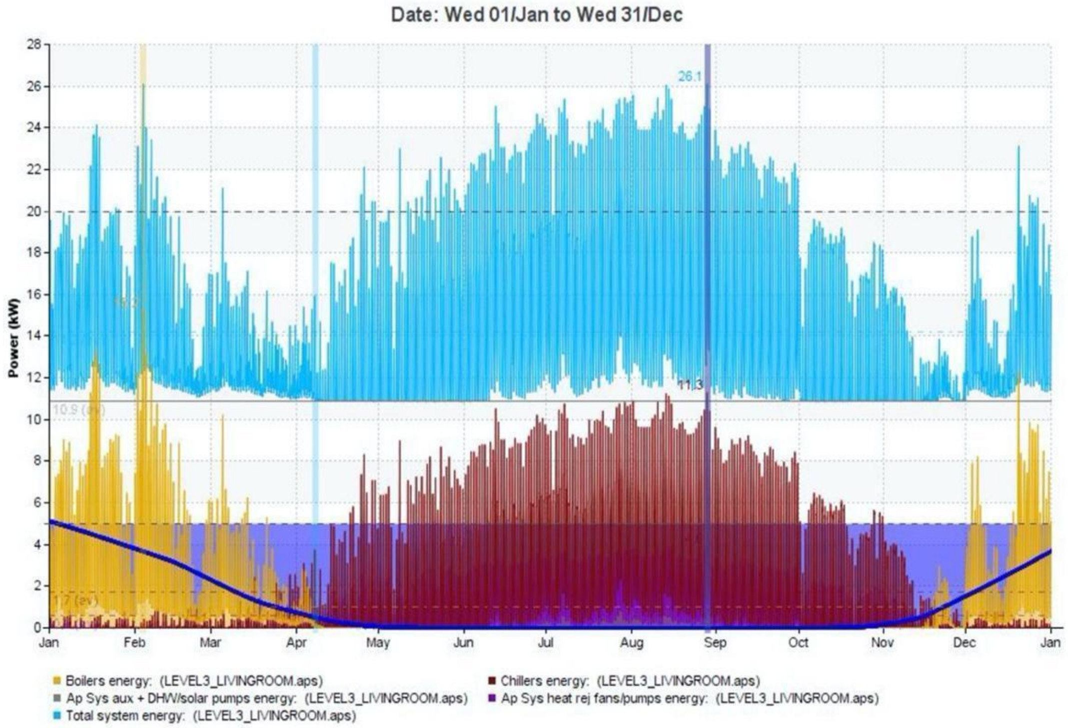



**Figure 14.** The overall energy consumption of the worst-case representative flat unit after implementation of state-of-the-art energy efficient materials onto the building envelope between January and December.

Additionally, starting from these base case studies, when the adaptive set-point is used, the decrease in the cooling demand is related to taking into account passive design measures such as natural ventilation, in the case of the heavier construction materials and its systems. This is due to the strong effect of heat loss from the heavyweight structures caused by additional discharge rate during the night-time. 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 tested indoor space. This is due to the fact that the measured outdoor temperature is above the comfort level zone which is shown in Figure 15. The findings illustrate that there is a significant temperature difference between outdoor and benchmark comfort levels of the indoor environment.

In addition, the annual energy consumption of the typical multi-family apartment unit with a medium weight and light weight structure are more or less the same as the one with heavyweight structure. The annual energy consumption of medium weight 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 S 4 is slightly lower than the S5 (ranging from 0.3% to 2.0%) for all other three design interventions' thermal fabric efficiency.

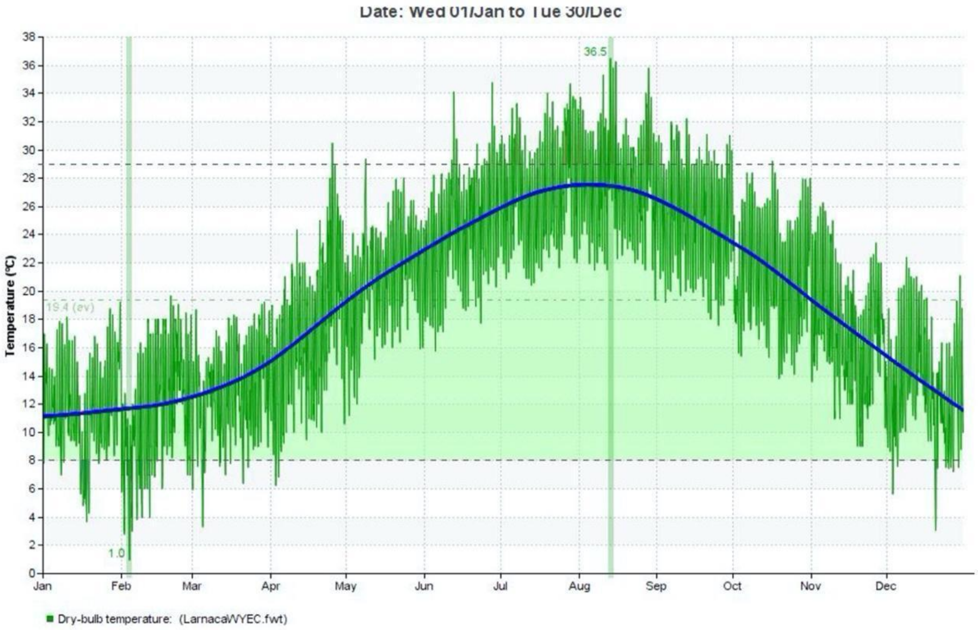



**Figure 15.** The indoor air temperature fluctuations of representative upper-floor level flat units before retrofit interventions were undertaken.

Figures 16 and 17 summarise the overall cooling demand reductions connected to the introduction of the variable set-point in summer are shown 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 heavy weight 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 heavy weight conventional building.

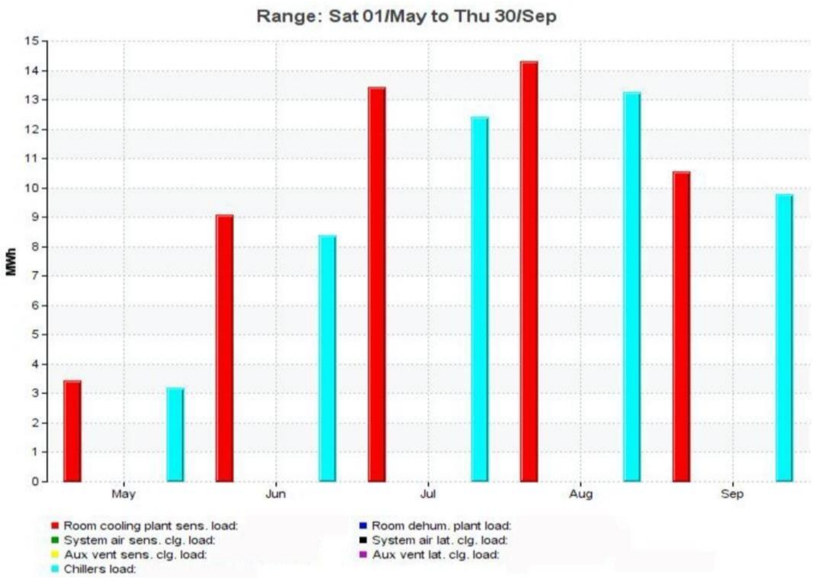



**Figure 16.** Distribution of overall cooling energy consumption of the base case representative upper-floor flat unit before retrofitting.

Furthermore, it is important to highlight the fact that comparing the base case and retrofitted case, the reduction in the cooling demand assesses for the heavy weight constructions tend to decrease as the height of the floor level and orientation of the flat, while 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, medium weight and lightweight structure. For the medium weight structure, with the design parameters of the base-line scenario taken into consideration, the total energy saving is 27%, while with the passive cooling design strategies implemented onto the building envelope, the total energy saving is 67%.

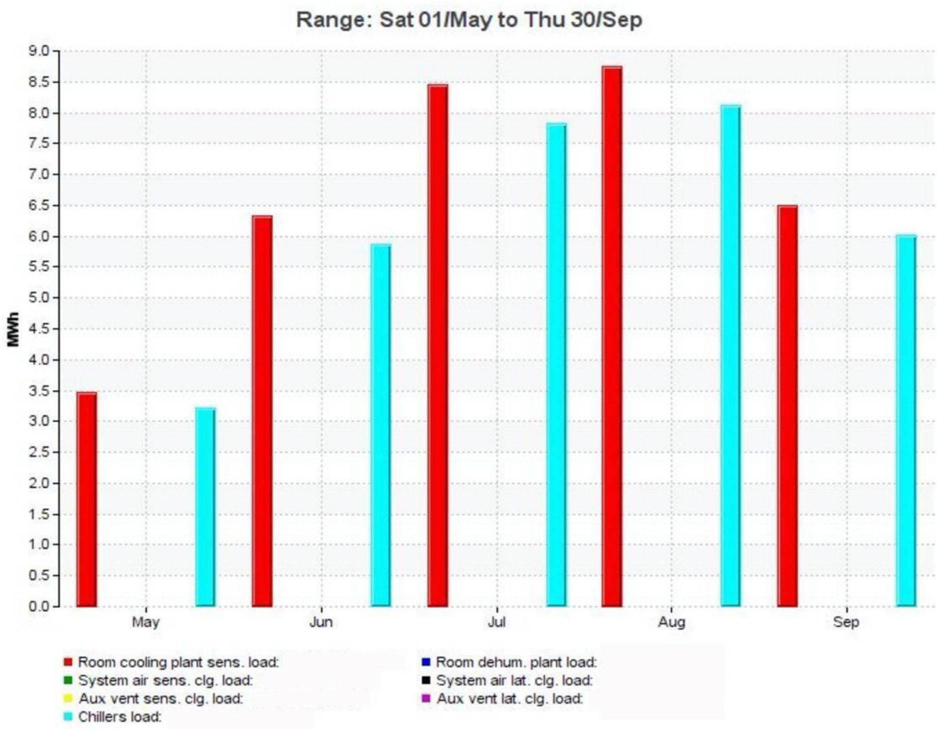



**Figure 17.** Distribution of overall cooling energy consumption of the base case representative upper-floor flat unit after retrofitting.

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 18. The worst-case calculated building space is the living room as it incorporates the internal heat gains from the open plan layout design kitchen as 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 18, in order to take into account, the location of the flat units on a different level, the height of the RTB influences the air infiltration rates of the flat units.

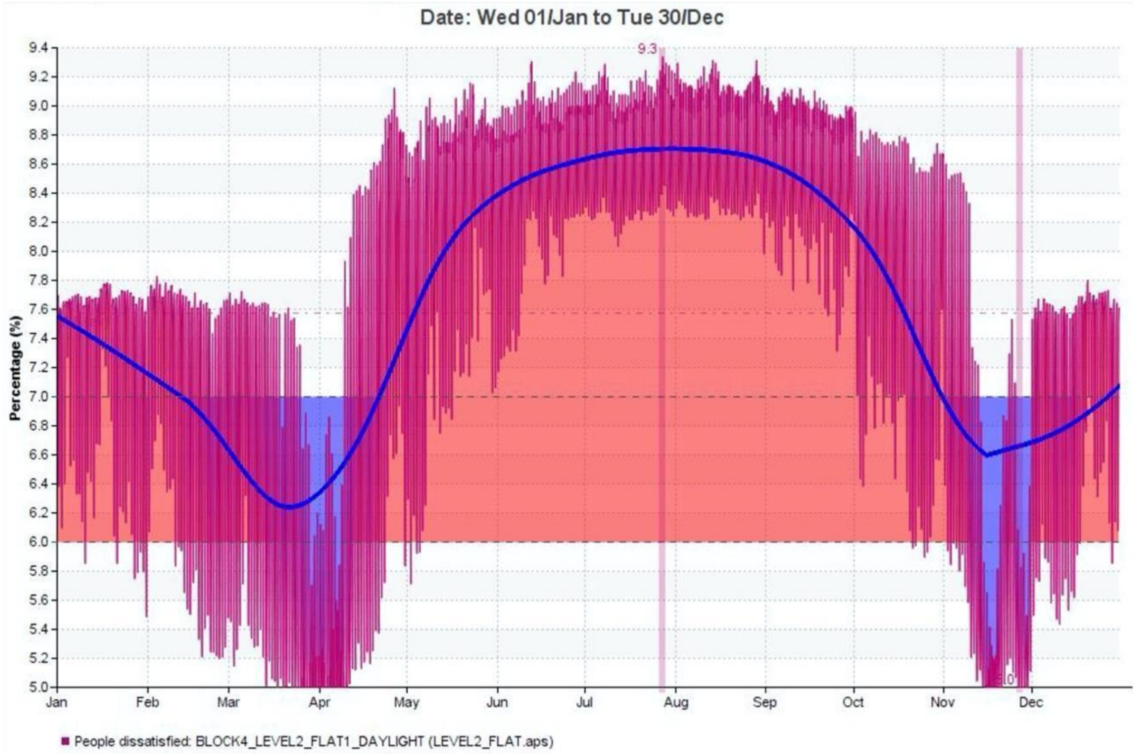



**Figure 18.** The fluctuation diagram represents the Predicted People Dissatisfied (PPD) levels after implementation of all three selected retrofit interventions.

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, as shown in Figure 18.

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. 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. In the three cases of surveyed and simulated RTBs in Famagusta, Cyprus, the positive impact on indoor temperatures and 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 of between 2 °C 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. 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); (b) orientation towards the south for greater solar gains; (c) the position of the dwelling in the building, so that all apartments have the same energy demands and (d) ventilation incorporating occupants' thermal comfort in the RTBs. 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 South-eastern Mediterranean basin.

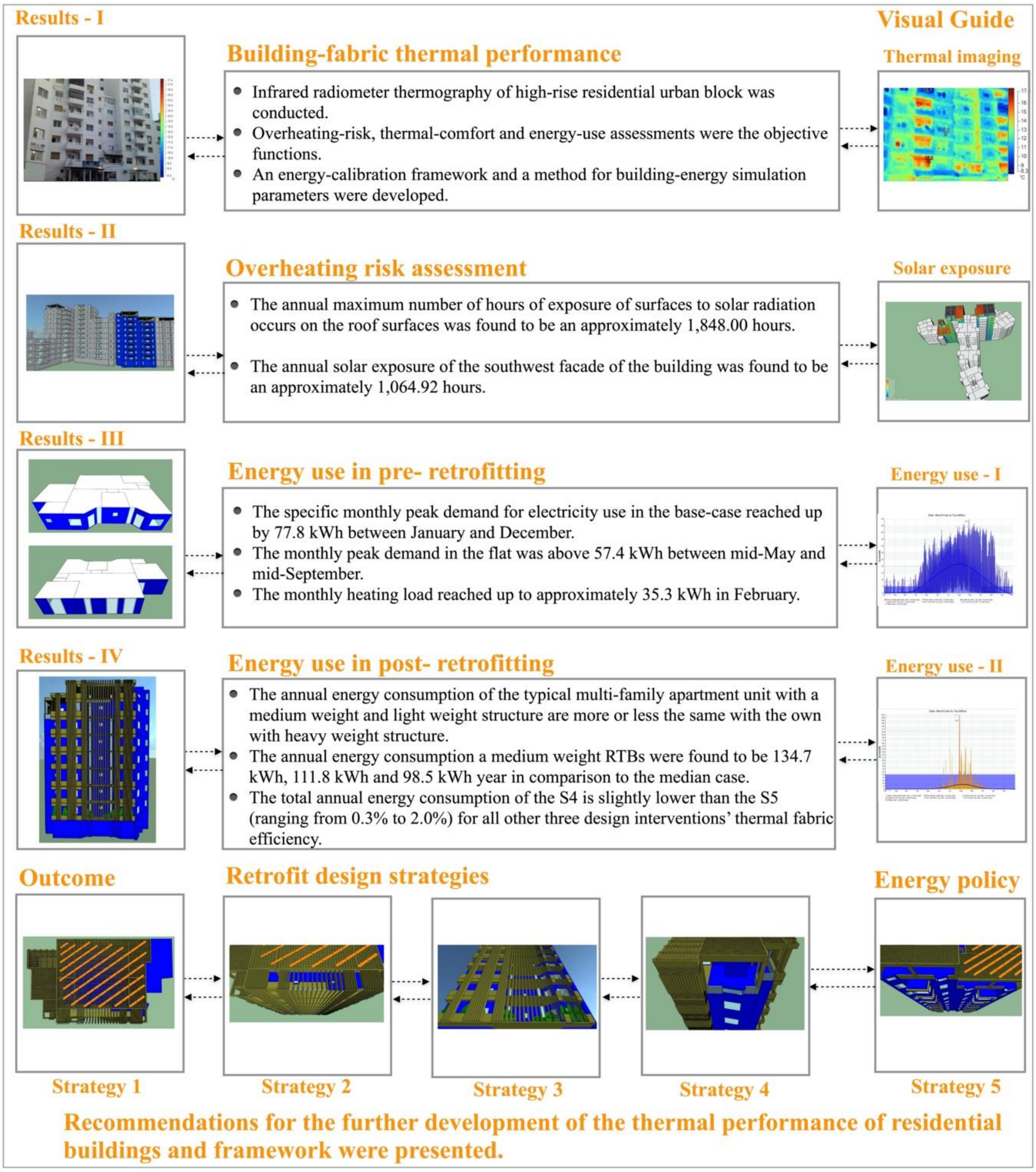



**Figure 19.** The step-by-step development of key research subjects, conceptual framework and outcomes in retrofit policy design.

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 annually exceeds 237.1 kWh/m2. In collective high-rise residential buildings without rehabilitation of the building envelope, overheating and increases in cooling demand are even greater. In southeast-facing RTBs, the cooling energy demand will be over 120.1 kWh/m2 in flats on the intermediate floors and is more likely to be 101.7–153.1 kWh/m2 in flats on the upper floor where, in this building typology, the cooling demand increases 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 socioeconomically vulnerable population.

## 4. Conclusions

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, 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 experience gained from this study as well as the knowledge presented aim to benefit the retrofitting of existing inefficient post-war residential building stock in bringing a significant energy consumption reduction to the residential sector. The study also attempted to identify key features from policy instruments and retrofitting initiatives across EU member states, which currently implement similar policies, most specifically other southern EU member states that have similar building regulations. The climatic condition of Cyprus is also similar to that of numerous Mediterranean countries outside Europe, which are currently in the process of implementing energy performance directives to upgrade their existing residential building stock and reduce energy consumption within energy-efficient building systems. Therefore, this study adds significant value to efforts to achieve energy savings by redefining passive design elements into retrofits of inefficient post-war residential building stock; this is an exemplary study for similar building typologies from similar construction eras across Europe. The findings illustrated the necessity of considering integrations of the off-site modular building technology in any state-of-the-art retrofit of existing high-rise residential buildings in a hot and humid climate zone. Furthermore, the significance and impact of the paper will be valuable for similar district scale retrofits in the area and neighbouring countries with a Mediterranean climate.

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

## Appendix A.1

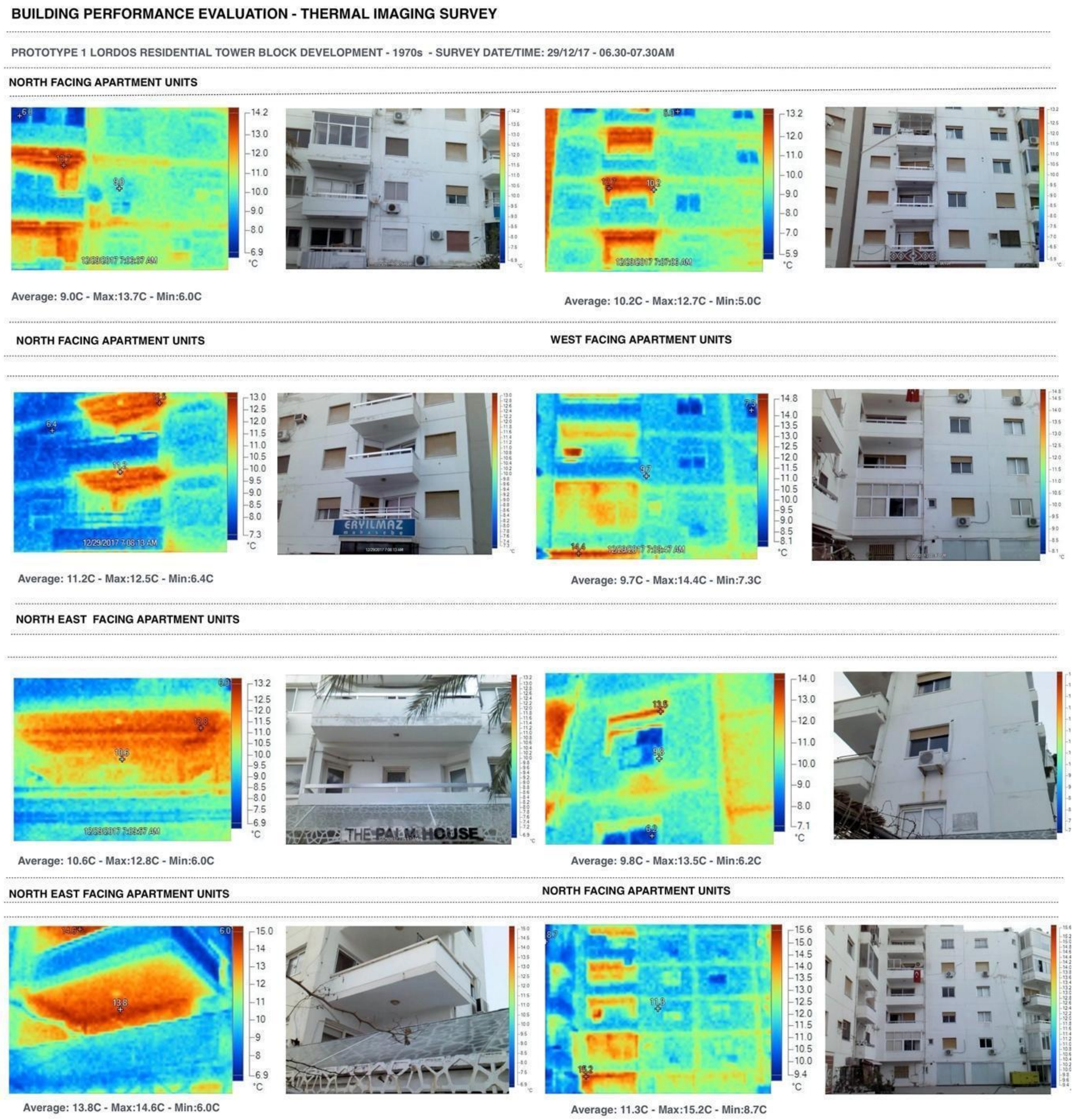


**Figure A.1.** Meta-analysis of building fabric elements recorded early in the morning.

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