Assessing Energy use and Overheating risk for Retrofitting A Residential Tower Block Prototype in Northern Cyprus

Bertug Ozarisoy[1] and Heba Elsharkawy[2]

[1] PhD Researcher, School of Architecture and Visual Arts, University of East London, United Kingdom, b.ozarisoy@uel.ac.uk;

[2] Senior Lecturer in Architectural Design and Technology, School of Architecture and Visual Arts, University of East London, United Kingdom, h.elsharkawy@uel.ac.uk;

Abstract: This study evaluates the energy performance of a residential tower block (RTB) development in Northern Cyprus in providing thermal comfort for its occupants. Severe summer temperature conditions in the coastal city of Famagusta includes significant daily oscillations in air temperature (14°C-45°C) and high levels of solar radiation, which contributes to the overheating of thermally inefficient building envelopes. Notably, 43% of the domestic buildings in Northern Cyprus are RTBs. As could be expected in residential buildings located in a hot and humid climate the cooling and heating comprise the largest part of the total energy consumption (73%). The aim of this is to investigate the applicability of passive design elements for the case study using three representative residential tower blocks (RTBs) each representing a different orientation (south-west, south-east and north-west). The research adopts a 'quantitative' research design; primarily building performance evaluation using modelling and simulation. The selected three RTBs are modelled using Integrated Environmental Solutions (IES) software where extensive dynamic thermal simulations have been produced to test passive design measures applied to improve thermal comfort and energy performance. This paper presents an analysis of the thermal performance of the three RTBs before different retrofit scenarios are applied to optimize the buildings energy performance and occupants' thermal comfort. According to the results of the dynamic thermal simulation, cooling energy consumption saving of around 81% are achieved. The findings demonstrate the necessity to consider passive design strategies for effective retrofitting of existing RTB developments in Northern Cyprus.

Keywords: Building performance evaluation, Dynamic thermal simulation, Overheating, Thermal Comfort, Retrofit.

Introduction

Many post-war European buildings were designed and built in accordance with criteria that typically lacks addressing reduced energy demand (Corrado et al., 2011). To date, many of these residential buildings have not undergone any retrofitting interventions; hence, the residential building stock is characterised by poor energy performance and thermal comfort issues. As per the European Council conclusions in the 2011 Energy Efficiency Plan, the residential sector is estimated to be responsible for 41% of all energy consumption in the European Union (EU) (EPISCOPE, 2016). Northern Cyprus is marked by a lack of standards, codes of practice and building regulations related to building energy performance; which does not help resolve issues of overheating of thermally inefficient building envelopes, particularly in post-war residential building stock (Sani and Ulucay, 2011). There are also no benchmarks for building energy performance, nor an official roadmap for regulating any 'systematic retrofit' to address energy efficiency (Serghides et al., 2016). The absence of energy conservation measures derives mainly from the fact that EU recommendations are not binding in Northern Cyprus (Ozarisoy and Altan, 2017). In 2015, the Town Planning Department, allowed architects to design buildings according to their clients' requirements, taking into consideration only a limited number of guidelines related to the building thermal properties (State Planning Organisation, 2015). Yorucu and Keles (2007) note that construction-led growth has significantly changed the physical characteristics of the larger states in Northern Cyprus, particularly in the coastal town of Famagusta.

The present study aims to investigate the current energy consumption patterns of a number of representative flats in sample residential tower blocks (RTBs) in the city of Famagusta, Northern Cyprus as research case studies. The focus of this paper is on developing and testing passive design strategies aimed at optimising the thermal comfort of occupants whilst also reducing cooling energy demands. The study seeks to identify the potential improvement of thermal comfort and reduced energy savings associated with passive design strategies through combinations of building fabric enhancement, appropriate shading and ventilation strategies. In this study, the applicability of passive design strategies has been extended to take into account and demonstrate how the orientation of representative RTBs and flat units become vital components in energy consumption, supported by the critical insights of occupants' energy use variations. For this study, three different RTBs with different orientations (southwest [RTB1], southeast [RTB2] and northwest [RTB3]) have been selected. Sample flats on three different floor levels are investigated and evaluated in terms of their energy performance and occupancy patterns. The paper starts with a background of the research, followed by the research methodology, and the discussion of the results.

Thermal comfort approaches and overheating risk assessment

Several studies have been conducted on ensuring indoor comfort conditions and predicting the comfort level of building spaces in line with reference to European CEN BS EN 15251 (CIBSE, 2017). A number of works have been published evaluating the assessment methods related to the summer performance of unair-conditioned residential buildings (Ferrari and Zanotto, 2009; Nicol, 2017; Nicol et al., 2012). The adaptive approach is currently featured in the main international standards concerning thermal comfort (ASHRAE 2004; EN 15251 2007). With this in mind, it is usually considered the best assessment method related to the summer performance of unair-conditioned residential buildings. In fact, it is worth noting that, following the work of Humphreys (1978), de Dear and Brager (2001) and many others, there has been an increasing realisation that the predicted mean vote (PMV) model is inappropriate, especially in naturally ventilated buildings that are in free running mode, in hot and cold seasons. This has led to new formulations of various standards throughout Europe, including CEN standard BS EN 15251 (BSI, 2007), which includes 'adaptive' temperature limits for naturally ventilated or free running residential buildings.

It is fortunate that the ISO standard concerned with indoor environments (BS EN ISO 7730) is also used as an applicable benchmark for measuring nighttime ventilation in residential buildings. BS EN ISO 7730 provides a means for calculating both the PMV and predicted people discomfort (PPD) indices, together with some guidelines for the estimation of certain localised effects, such as shading and natural ventilation. Apart from that, Chartered Institution of Building Services Engineers (CIBSE) Technical Memorandum 52 has asserted that a new approach to the definition of overheating is necessary, particularly in residential buildings without mechanical cooling. This is in line with the methodology and recommendations of BS EN 15251 (BSI, 2007), which aimed to determine whether an existing occupied building can be classed as at risk of overheating, or whether a proposed building design may be in danger of becoming overheated, particularly in summer. As previously mentioned, within the greater Famagusta area, there is a high risk of overheating within its existing built environment (Ozarisoy and Elsharkawy, 2017). One pragmatic way of quantifying the effect of thermal comfort is defined in CIBSE TM52; it states that new buildings, major refurbishments and adaptation strategies should conform to Category II in BS EN 15251, as shown in Table 1 (BSI, 2007).

Table 1. Overheating assessment criteria (CIBSE, 2016)

	Assessment Criteria*	**Acceptable Deviations**
Criteria 1	Percentage of occupied hours during which ΔT (ΔT=Top-Tmax rounded to the nearest whole degree) is greater than or equal to 1°C	Up to 3% of occupied hours
Criteria 2	Daily weighted exceedance (We) in any one day >6°C.h (degree hours)	0 day
Criteria 3	Maximum temperature level (Tup) ΔT> 4°C	0h

The chosen criteria for thermal comfort analyses in the present study are: Criterion 1: Percentage of hours above 33°C, Criterion 2: Percentage of hours above 35°C and Criterion 3: Percentage of hours below 18°C. To take into account the contextual features and simulation benchmarks of the representative RTBs, Criteria 1–3 all use indoor dry resultant temperatures. The percentages of hours are taken as the percentage of hours out of total hours in a year. It is important to note that the previously mentioned assessment criteria do not refer only to the occupied hours in each building, as exact information on occupancy patterns was difficult to find. Further, non-working family members are more likely to spend the afternoon inside than outside. For this reason, the assessments of all hours are based on the assumption that a representative flat unit should provide thermal comfort at all times of day. It is important to highlight that the temperatures 33°C and 35°C used to assess overheating were derived from the 'CIBSE A' criteria for overheating in the UK, which assigned maximum values of 5% and 1% for temperatures of 25°C and 28°C, respectively (CIBSE, 2017). These are clearly unsuitable for Famagusta's hot and humid climate, which is the context of this study. As previously stated, adaptive thermal comfort model CIBSE TM52 was selected to take into consideration and assess performance against three criteria, yielding a classification of 'overheating' if a room fails to meet any two of the three criteria. A brief summary of the key indicators of the TM52 assessment method is mentioned here, but a more detailed explanation of the method can be found in IES's TM52 descriptive explanation report (IES, 2017). The three criteria are: (a) Hours of exceedance:

> The number of hours during which ΔT is greater than or equal to one degree (°K) shall not be more than 3% of occupied hours. ΔT is defined as operative temperature [dry resultant temperature] less the maximum acceptable temperature [;]

(b) Maximum daily weighted overheating exceedance: Assesses the severity of overheating across a day, in terms of both duration and magnitude of temperature, including its units are degree hours accordingly. Notably, it is weighted to account for both of these terms, with a value greater than 6°Chr resulting in failure in this criterion; and (c) Upper limit on temperature: Sets an absolute maximum value for indoor operative temperature where the maximum ΔT is set to 4°C (CIBSE, 2016). It is also important to note that the maximum acceptable temperature is the upper limit of the thermal comfort threshold. This is calculated as:

$$T_{max} = 0.33T_{rm} + 18.8 + SAR$$

where T_{rm} is the exponentially weighted running mean of the daily mean outdoor air temperature and the suggested acceptable range (SAR) is 4°C (CIBSE, 2017), even though the maximum benchmark range suggested by the CIBSE as performance expectations is lower for the context of this study. A further method has been suggested in 'CIBSE Guide A,' BS EN 13779: Ventilation for buildings is an applicable performance requirement for ventilation and air-conditioning systems (CIBSE, 2016). This study takes into account basic definitions of thermal comfort benchmarks in occupied spaces and relates these to focus on the assessment of passive measures' performance. This may require an assessment methodology to measure overheating in an occupied space. It is recommended that the approach to 'overheating' considered for measuring indoor thermal comfort be independent of the metric used to assess the energy performance of residential buildings; however, the more we can learn about the manner of both applicable and feasible passive design strategies put forward, the closer we will be to prioritising the most effective solution to overheating problems.

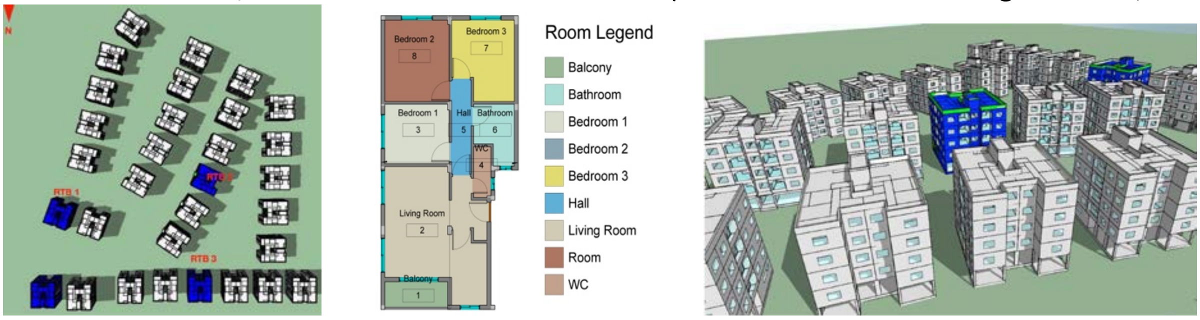
Research Methodology

Case study: Residential tower block (RTB) as a research case study

The primary underlying aim of the research is to investigate the impact of passive design strategies on energy use and to improve the energy efficiency of post-war residential buildings in

Famagusta, Northern Cyprus. Cyprus is the third-largest island in the Mediterranean, after Sicily and Sardinia. It is located in the eastern Mediterranean area and sits at latitude 35° North and longitude 33° East. According to the Köppen Geiger climate classification, Cyprus has climate characteristics that are typically Mediterranean, mostly a subtropical (Csa) type climate, with a partly semi-arid (Bsh) type in the northeastern part of the island (Kottek et al., 2006). In short, Cyprus is hot and humid during the summertime.

The research case study, Famagusta's city centre residential estate, is a government-owned social housing development with 288 dwellings, facilities and commercial units for citizens with average incomes; as shown in Figures 1 (a), (b) and (c). The estate was built in the 1990s, and there are 32 RTBs with similar floorplan layouts and construction characteristics. The original U-values of the structure are 4.05 W/m^{2}K for external walls, 2.94 W/m^{2}K for the internal walls, 5.26 /m^{2}K for the roof and 1.39 W/m^{2}K for the windows and doors (Construction and Housing Statistics, 2013).



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

Figure 1 (a) Selected Residential Tower Blocks (RTB1, RTB2 and RTB3) developed in 1990s; **(b)** The floorplan of the residential tower block; **(c)** The analytical energy simulation model of the RTBs. (Source: Researcher, 2017).

The quantitative research design analyses the present energy performance of three representative prototype RTBs using building energy performance modelling and simulation methods. The dynamic thermal performance simulation studies of each building were carried out in an analytical energy simulation environment between May and September, during peak demand months for cooling energy. The assessment periods were spread throughout the summer, with the aim of measuring the risk of overheating. In each of the occupied zones (i.e., living, kitchen and bedroom spaces), were made of the characteristics needed regarding space energy use (naturally or mechanically), in order to take into account occupancy, electrical equipment energy use, space temperature, artificial lighting energy use and mechanical plant (A/C units) energy use. The aim of these studies was to capture a variety of space energy uses via relatively simple assessment benchmarks. Then, all data were imported into the IES simulation software to test the validity of the simulation results by embedding the CIBSE TM52 thermal comfort assessment add-ins to the IES software package. To create the model for the building performance simulation analyses—the set of information used to describe the overall building construction and occupancy schedules—a set of energy use data and a room data schedule that describes the occupancy patterns of the occupied spaces in the RTBs' representative flats is developed, as shown in Table 2.

Table 2. Building features and simulation parameters of the prototype RTB (IES, 2017).

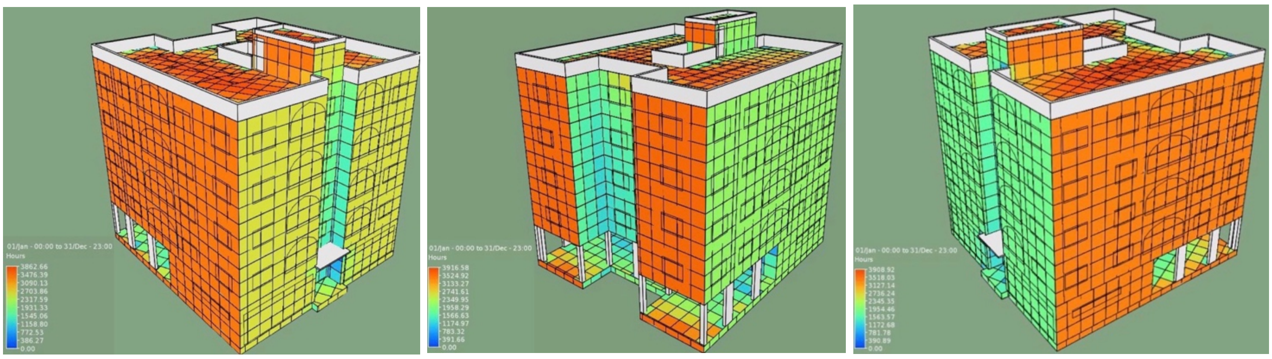
Building Performance Factors		**Internal heat gains in the simulation**
Number of floors	5	Occupants: 3 W/m^2
Area-to-volume ratio [m^{-1}]	0.33	Appliances equipment: *8* W/m^2
Floor surface of a typical tested room	32.5 (m^2)	Lighting: *2* W/m^2
Room volume of a typical tested room	102.7 (m^3)	
Window size	1.5 x 1.2 (m^2) per window pane	
Exterior Window Ratio	0.21	
Number of the subjects involved	1 male and 1 female (parents), 1 boy and 1 girl	
Age of the subjects	Between 2 and 40	

An initial observation exercise was undertaken for each prototype RTB. This involved reviewing the building plans, construction materials and feasible room schedules. A sample of three RTBs at three different site locations and orientations were investigated, for the following research stage to be based on the worst-case scenario with regards to overheating risk. The occupancy schedules for the flats is based on four people: one of them stays indoors throughout the day in the living room; all four occupants spend nights in their bedrooms. The air conditioning system schedule was considered for the cooling period between May and September based on the schedule of the occupants, in an attempt to obtain feasible results regarding energy consumption. The air-conditioning system' set point is set at 23°C. Regarding the definition of air change rate, the reference parameters are assumed according to EN 15251 (2007). Once the parameters are defined, the Larnaca Airport - ASHRAE Climate Zone 4 weather file is used.

Results and Discussion: Residential Tower Blocks

Solar Analysis and Overheating risk assessment

Figures 2 a, b and c show the maximum solar radiation, when it occurs and the mean values for each floor level in the chosen RTBs. This Suncast simulation analysis demonstrates that the annual maximum number of hours during which surfaces are exposed to solar radiation occurs on the roofs' surfaces (4382 hours), followed by the southwest facade of the buildings (3916.58 hours).



(a) (b) (c)

Figure 2 Suncast simulation demonstrating the annual number of hours of solar radiation exposure of the RTBs; **(a)** Southwest-facing RTB1, **(b)** Southeast-facing RTB2 **(c)** Northwest-facing RTB3. (Source:Authors)

The total surface area of the exposed building envelope to solar radiation flux reaches a maximum value of 1524.78W/m^{2}K during the year. There is relatively high absorption of this value by all of the three RTBs' orientations, as the walls have absorptivity levels of 0.63–0.69. The inefficient building envelope absorbs a particularly high proportion of this solar radiation. Further, there are periods of relatively high solar gain during the year, with southeast-facing RTB 2 absorbing the highest heat gains through its building envelope (approximately 3916.58 hours). By contrast, southwest-facing RTB 1 absorbs slightly less radiant energy than RTB 2 (approximately 3862.66 hours), while RTB 3 absorbs approximately 3908.92 hours, due to its location on the ground floor and lower absorptivity levels. These findings highlight that high radiation gains, combined with an inefficient building envelope and a lack of shading systems, results in more overheating risks in southeast-facing RTB 2 when compared to southwest-facing RTB 1. This is not entirely due to solar gain, as it is the most susceptible to conduction gains due to its higher roof absorptivity, characterised by a high thermal transmittance value (5.26 W/(m^{2}K). Because of this, the CIBSE TM52 overheating criteria were assessed using the total number of days in a calendar year where the air temperature exceeds 6°C Hr while that zone was occupied (CIBSE, 2013). As previously stated in the literature, in compliance with Criterion 2, a zone should never exceed this value (CIBSE, 2017).

The results for the southeast-facing top floor spaces of RTB 2 are shown in Table 3. All occupied rooms significantly exceed the limit of Criterion 2. The flat on the middle floor shows worse thermal performance than the ground floor flat. Bedroom 2 in this unit is the worst performing occupied space, with a performance that exceeds the limiting factor by over three times, with a value of 22.5%. This trend is followed by the living room, with a value of 20.5%. Therefore, the flat at most risk of overheating is the south-east facing unit on the top floor of RTB 2 with three exposed external walls.

Table 3. Results for TM 52 Criteria I, II and III for study year (ΔT is room temp. minus maximum adaptive temperature) for the RTB 2.

Room Name	Occupied days (%)	Criteria 1 (%Hrs Top-Tmax>=1K)	Criteria 2 (Max. Daily Deg.Hrs)	Criteria 3 (Max. ΔT)	Criteria failing
SE_GROUND_Livingroom	100	1.4	13	3	2
SE_GROUND_Bedroom1	100	3.1	23	5	1 & 2 & 3
SE_GROUND_Bedroom2	100	4	22.5	5	1 & 2 & 3
SE_GROUND_Bedroom3	100	0.4	10	3	2
SE_MIDDLE_Livingroom	100	3.4	20.5	4	1 & 2
SE_MIDDLE_Bedroom1	100	2	17	4	2
SE_MIDDLE_Bedroom2	100	4	22.5	5	1 & 2 & 3
SE_MIDDLE_Bedroom3	100	0.4	9.5	3	2
SE_TOP_Livingroom	100	3.4	16.5	4	1 & 2
SE_TOP_Bedroom1	100	4.1	26	5	1 & 2 & 3
SE_TOP_Bedroom2	100	3.3	21	5	1 & 2 & 3
SE_TOP_Bedroom3	100	0.5	11	4	2

As the data above indicate, the flats exceed the appropriate limits, with the top floor flat showing the greatest risk of overheating. Within this flat, the living room surpasses 6°CHr, 16.5% of the occupied time, and bedroom 1 surpasses 6°CHr, 26% of the occupied time. This indicates that the occupied spaces within the flat are at relatively high temperatures throughout the year. Simultaneously, the flat on the ground floor has been found to perform better than those on the middle and top floors. Ground floor bedrooms 1 and 2 are observed as the critical occupied spaces within the flat that fail Criteria 1, 2 and 3. The differentiation in the performance of the occupied spaces on the ground floor is attributed to the airflow speed differentiation of the rooms. It is also important to note that the unit with two exposed walls has a reduced capacity for providing thermal comfort within the adaptive comfort limits. Bedrooms 1 and 2 in RTB 2 on the ground floor exceed 6°CHr, with values of 23% and 22.5%, respectively. The building's indoor environmental conditions and thermal comfort in the summer are analysed and displayed in Table 4.

Table 4. Simulation based thermal comfort of all occupied rooms in RTB 2.

	Temperature		***Relative Humidity***		***PPD***	
Room Name	**Max°C**	**Min°C**	**Max %**	**Min %**	**Max %**	**Min %**
SE_GROUND_Livingroom	36.2	23.0	100.0	26.6	100.0	13.1
SE_GROUND_Bedroom1	35.2	23.0	100.0	25.9	95.6	11.7
SE_GROUND_Bedroom2	36.2	23.0	100.0	24.6	98.9	10.9
SE_GROUND_Bedroom3	35.2	23.0	100.0	26.0	93.5	11.3
SE_MIDDLE_Livingroom	35.2	23.0	100.0	25.8	97.6	12.5
SE_MIDDLE_Bedroom1	34.4	23.0	100.0	27.4	94.5	10.1
SE_MIDDLE_Bedroom2	35.4	23.0	100.0	25.6	98.9	10.1
SE_MIDDLE_Bedroom3	35.1	23.0	100.0	26.2	94.1	10.5
SE_TOP_Livingroom	36.4	23.0	100.0	26.2	100.0	12.8
SE_TOP_Bedroom1	35.3	23.0	100.0	25.7	98.0	11.7
SE_TOP_Bedroom2	36.1	22.3	100.0	24.7	99.1	7.6
SE_TOP_Bedroom3	35.6	23.0	100.0	25.4	96.4	11.1

**** The PPD max limit value is 15% - PPD is the percentage of people that will find the room thermally uncomfortable.***

Table 4 shows the performance of each occupied space at three floor levels in terms of Criteria 1 and 2; the top floor flat outperforms the other floor levels. It maintains indoor temperatures above 34.4°C in all rooms for the entire year, only exceeding this number to reach 36.4°C. The highest temperature was observed in the living room of the top floor (36.4°C), while bedroom 2 experienced overheating with a temperature of 36.1°C. It is remarkable to note that all the occupied spaces in the three floor levels exceeded the benchmark of 33°C for thermal comfort criteria in Southern European countries (EN 15251, 2007). As for Criterion 1, the representative flat units are shown to exceed the limits of failure, with the corresponding top floor flat unit showing the greatest signs of overheating. In this flat, the living room surpasses 6°CHr for 115 days, while bedroom 2 surpasses 6°CHr for 77 days out of 365 days. Additionally, bedroom 1 in this flat on the top floor exceeds 4°C by 4 hours and 11 hours annually, respectively. This indicates that, for a significant proportion of the year, the flat will be extremely uncomfortable for its occupants. The results for both the ground and middle floors were also similar for each occupied space, with high Predicted people discomfort (PPD) levels. The results show that the indoor temperature follows a consistent pattern during the four weeks of August; however, important differences in absolute values due to outdoor conditions can be observed. The data demonstrates that the warmest and coldest weeks of August are the third and fourth weeks, respectively. This explains the differences found when temperature profiles are compared. Moreover, it must be highlighted that the indoor temperature is, in the majority of cases, greater than 32.5°C, at times reaching maximum temperatures close to 37°C.

The zones under consideration within RTB 2 were found to exceed the acceptable limits of two or more of the CIBSE TM52 criteria. The occupied spaces of concern are the two bedrooms, as they absorb the internal heat gains from the living room, from which one accesses these spaces. The occupied spaces with the poorest thermal performance were in the flat on the top floor. This is attributed to the thermal properties of the building envelope's structural features. These occupied spaces (bedrooms 1 and 2) have two external walls, which allows for a higher heat transfer rate.

At all three floor levels, in each orientation and in relation to base case peak hourly cooling consumption (on a typical day in August between 06:00 and 00:00), the southeast-facing living room on the top floor has the highest cooling demand, with an increase of 21.69%, while bedroom 2 has a cooling demand of 21.60%. These values suppose an increase in cooling demand of 275.14 kWh/m^2 in the living room and 132.24 kWh/m^2 in bedroom 2. The southwest-facing bedroom 1 unit also has a higher energy demand, when compared to the southeast-facing bedroom 1 unit, in terms of cooling demand, with an increase of 25.84% on the middle floor and 24.16% on the ground floor. These values suppose an increase in cooling demand of 119.28 kWh/m^2 on the middle floor and 122.66 kWh/m^2 on the ground floor. Therefore, the southeast-facing bedroom 2 unit continues to be the orientation with the highest cooling demand, with an increase of 21.42% (132.24 kWh/m^2) on the top floor and 21.10% (132.12 kWh/m^2) on the ground floor, and a greater increase in cooling demand in the summer. By contrast, the northwest-facing top floor bedroom 3 unit can anticipate an increase in cooling demand of 25.05% (116.23 kWh/m^2), while the demand is 22.46% in southwest-facing top floor bedroom 3 unit (114.46 kWh/m^2). The simulation results of the existing performance for the representative RTB 2 indicated that the greatest share of the heat losses comes from air infiltration and exterior walls that lack insulation but have windows (provoking a high annual energy demand for cooling). Additionally, starting from these base case studies, when the adaptive set-point is used, a decrease in cooling demands due to additional ventilation is required, in particular for heavier construction materials and systems. During the peak cooling season, the summer, the occupied spaces reveal significant differences based on the adaptive temperature set-points of heavy weight construction materials, when the building envelope lacks thermal insulation.

Retrofit strategies investigated in RTB 2

The aim of analysing both the existing and retrofitted energy performance of RTB 2, as presented in this study, is to identify available building variants concerning the applicability of retrofit strategies and building envelopes. This is an important component of any building's structure, as it is the interface between the interior of the building and the outdoor environment. By testing the current condition of thermal issues, we could determine that the building envelope plays an important role in regulating internal air temperatures and improving occupants' thermal comfort levels. This also helps to determine the amount of energy required during the peak cooling demands of summer.

In addition to modelling and energy simulations, passive design strategies for retrofitting have been considered based on the building's geometry, orientation, shading and type of construction material, as these affect the overall improvement of a household's standard of living. The thermal and energy performance of the sample flat units were calculated using ApacheSim for dynamic thermal simulation calculations in IES software package. This analysis was split into six strategies, which consisted of sets of dynamic building energy simulations aimed at assessing the current energy performance of a typical flat unit, which is considered as the baseline design. The second strategy included the energy performance of a combination of passive design measures, including appropriate shading systems, external wall insulation on the roof and the more exposed walls and natural ventilation. The third strategy was a newly proposed architectural intervention for RTBs that includes a new fenestration design and the addition of operable external shading systems. The fourth, fifth and sixth strategies included adaptable passive design to evaluate the improvement in hours of discomfort. A list of the strategies in this building performance evaluation and optimisation study, including their methods for analysis and descriptions, are shown in Table 5.

Table 5. Structure of the step-by-step applicable 'retrofit strategies' and those of the existing base-case.

Strategy	Strategy Description	Analysis Method	Dynamic Building Simulations
Base-case	Base-case Design	Energy Consumption Performance	Current assigned construction materials
Strategy 1 (S1)	Proposed Design	Energy Consumption Performance	Base-case design + Insulation on wall Base-case design + Insulation on roof
Strategy 2 (S2)	Proposed Design	Energy Consumption Performance	Base-case design + Shading devices Base-case design + Insulation on wall Base-case design + Insulation on roof Base-case design + Natural ventilation Base-case design + all strategies listed above except natural ventilation Base-case design + all strategies listed above
Strategy 3 (S3)	Proposed Design	Energy Consumption Performance	Fenestration design Fenestration design + Shading systems + Insulation on wall + Insulation on roof + Natural ventilation
Strategy 4 (S4)	Natural ventilation Analysis	Thermal Performance on living room, Bedroom 1, 2 & 3	Base-case design Not Ventilated Base-case design Day Ventilation Base-case design Night Ventilation Base-case design + all strategies listed in strategy 2 Not Ventilated Base-case design + all strategies listed in strategy 2 Day Ventilation Base-case design + all strategies listed in strategy 2 Night Ventilation
Strategy 5 (S5)	Natural ventilation Analysis	Thermal Performance on living room, Bedroom 1, 2 & 3	Base-case design Day Ventilation Base-case design + all strategies listed in strategy 2 Day Ventilation Fenestration design Day Ventilation Fenestration design + all strategies listed in strategy 2 Day Ventilation
Strategy 6 (S6)	Natural ventilation Analysis	Thermal Performance on living room, Bedroom 1, 2 & 3	Base-case design Fenestration design

The proposed solution for passive design retrofitting of the building envelope was the instalment of a thick, thermal insulated clay tile external facing system, the replacement of windows and door glazing (from single to 'double low-e' glazing) and using timber-framed shading elements. Combined, these should lead to a considerable reduction in heat loss through the building envelope. The presented scenarios were reviewed and studied globally, including the use of energy efficient building systems and local construction codes, and have yielded models of improvement that are particularly suitable for this region. Building energy retrofitting within existing envelopes provides substantial prospects for reducing energy consumption (Giannakopoulos et al., 2010). The retrofitting measures of the design alternative solution are as follows: exterior walls—existing outer layer removed, new 245-mm insulation was affixed to an inner layer and a new outer concrete layer, with external clay tile cladding installed (new U-value of 0.95 W/m^{2}K); roof—old roof mastics and insulation were removed and new 340-mm insulation and a new asphalt mastic cover were installed (new U-value of 0.80/m^{2}K); base floor—additional external insulation (new U-value of 0.94 W/m^{2}K); and renewal of windows, balcony openings and internal doors—replace all existing single-pane windows with double-pane windows (new U-value of 1.39 W/m^{2}K). Table 6 illustrates the assigned construction properties of the base case and the six strategies applied in the simulation.

Table 6. Specifications of the low-tech retrofit strategies and those of the existing base-case.

Strategies	*Element Details*	*U-value W/m²K*	*R-value m²K/W*	*Thickness mm*	*Mass kg/m²*	*Thermal mass kJ/m²K*
Base-case	Common Brick – HF-C4 + Brickwork [Inner Leaf] + Clear float 4mm	4.05	0.076	28.0	56.17	11.16
S1	Clay tile – HF-C1 + Vermiculite insulating brick + thermalite-high strength + Thermo-clear 8mm polycarbonate cliffing + Clear float 4mm	0.95	0.88	110.5	83.32	34.6
S2	Asphalt mastic roofing + particleboard – High density + roof insulation + Thermo-clear 8mm polycarbonate cliffing + Clear float 4mm + Insulation board – HF-B2 + Timber solar shield with adjustable blinds [500mm]	0.80	1.10	285.5	511.65	240.0
S3	Combination S1+S2 of envelope's rehabilitation with shading and ventilation rate of 0.63 h^{-1}	0.80	1.10	285.5	511.65	240.0
S4	Combination S1+S2 of envelope's rehabilitation with shading and ventilation rate of 0.4 h^{-1}	0.80	1.10	285.5	511.65	240.0
S5	Combination S1+S2 of envelope's rehabilitation with shading, without passive night ventilation in summer and a constant ventilation rate of 0.4 h^{-1}					
S6	Common Brick – HF-C4 + Brickwork [Inner Leaf] + Clear float 4mm + Combination S1+S2 of envelope's rehabilitation with shading and ventilation rate of 0.4 h^{-1}	1.30	0.5	61.50	38.75	21.39

In terms of examining energy consumption with respect to specific heat losses, between May and September, the base-case southeast-facing top floor flat unit consumed 1143.9 kWh/m^2 of its energy during the pre-retrofitting phase and 8618.4 kWh/m^2 during the post-retrofitting phase. Additionally, the results of the base-case design on the most ill-performing southeast-facing flat in RTB 2 showed an annual energy demand for cooling calculated at 2081.35 kWh/m^2. The greatest gains were from solar energy absorbed through windows. Living rooms were the most affected, followed by the bedroom 1 units and the bedroom 2 units. At the same time, insulation in the roof strategy applied to the case study building's envelope showed a greater percentage of improvement, compared to the base-case design. It is also remarkable to note that applying natural ventilation with shading systems and appropriate fenestration design onto the building envelope led to the lowest energy consumption, with an 81% improvement over the base-case design. Table 7 demonstrates the overall impact of the six implemented retrofit strategies on the cooling energy consumption and Percentage of People Dissatisfied (PPD), which, according to CIBSE TM52, should not exceed 15%.

Table 7. Simulation based cooling consumption and thermal comfort of the occupied rooms for the most-ill performing -east-facing RTB prototype during the pre and post retrofitting phases.

	Cooling Consumption W/m²K		Temperature °C		Relative Humidity		PPD	
Room Name	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit
SE_TOP_Livingroom	1928.69	902.8	36.4	28.1	100.0	71.4	100.0	30.5
SE_TOP_Bedroom1	1709.09	836.7	35.3	25.9	100.0	74.6	98.0	35.3
SE_TOP_Bedroom2	2081.35	538.7	36.1	26.8	100.0	73.0	99.1	32.3
SE_TOP_Bedroom3	822.28	501.4	35.6	27.7	100.0	77.9	96.4	36.3

**** The PPD max limit value is 15% - PPD is the percentage of people that will find the room thermally uncomfortable.***

The energy consumption for each passive design strategy applied to the base-case design on the southeast-facing top floor flat unit is shown in Table 8. As previously mentioned, the annual energy consumption of the base-case design was 2081.35 kWh/m^2. With a combination of systemic and passive design strategies applied, it decreased by 538.7 kWh/m^2. The fenestration design alone showed a decrease in the energy consumption, compared to the base-case design, of 57%. This is because the large-glazed balcony openings with solar shading systems were exposed to the sun, compared to the base-case design where the narrow openings were the ones exposed. Further, there were wide window openings in the living room of the retrofitted flat, compared to base-case design. It is also noteworthy that the solar gains received appropriately by the windows increased during the winter, due to the low solar angle. This design, using a combination of systemic and passive design strategies applied in Strategy 3 (S3), decreased the flat's cooling energy consumption to 902.8 kWh/m^2. It is important to emphasise that insulating the exterior walls showed the greatest reduction in energy consumption. Depending on the location of a room and the ratio of the window area to the facade area, the insulation of the external wall reduced cooling energy use by up to 43% in the summer. The strategy of increasing the insulation layer thickness to greater than 200–300 mm led to only a small reduction in cooling energy use. In addition, the strategy of insulating the roof and floors depends strongly on the location of a given room. We observed that the replacement of roofing material reduced cooling energy use by 6–7%. At the same time, the replacement of windows reduced all occupied spaces' energy consumption by 6%, because of the high thermal transmittance of U-value 1.1 W/m^{2}K (double glazing with a low-emissivity coating). Additionally, adding 150 mm of insulation to floor surfaces improved occupants' thermal comfort.

Table 8. Annual cooling energy consumption of base-case design and proposed strategies.

Strategy	Energy Consumption (kWh/m²)	Percentage of Improvement
Base-case	2081.35	-
S1. Building envelope's rehabilitation	1146.5	43%
S2. Building envelope's rehabilitation + Solar shading systems	1084.5	52%
S3. Building envelope's rehabilitation + Fenestration design	902.8	57%
S4. Building envelope's rehabilitation + Fenestration design + Mechanical ventilation	836.7	68%
S5. S1+S2+S3+S4 + Mechanical ventilation	735.4	72%
S6. S1+S2+S3+S4 + Natural ventilation	538.7	81%

**** The results of the worst-ill performing southeast-facing Bedroom 2 unit on the top floor of the RTB2(approximately 15 m²).***

The new appearance of the building envelope, with its adaptable openings and shading devices, was created to provide a controlled buffer zone for dealing with summer heat. For this purpose, the fenestration design was proposed, and it is evident that the greater effect of reducing the need for mechanical cooling was achieved. Retrofit technologies are specifically tested, verified and certified by the administrators for effective energy savings and offering comfortable environmental conditions (Santamouris, 2014). In this study, one essential element in the actions proposed was the top window openings on the flats' balconies; these are set within the insulated walls and provide adaptable, double-glazed openings to optimise sunlight and natural air ventilation. A ventilated facade was proposed, as it can reduce the amount of heat a building absorbs, due to the partial reflection of solar radiation by the existing large surfaces of window openings. The building component of the walls for the whole building consists of a ventilated facade with 3 cm of vacuum insulated panels (VIP), which lead to a U-value of 0.246 W/m^{2}K. The outcome of these analyses is the conclusion that the most applicable and feasible retrofitting scenarios are thick thermal insulation, the implementation of a ventilated facade and the installation of solar shading systems.

As previously discussed, these three retrofitting strategies have great potential for use in developing an RTB, and, in particular, when designing nearly (or net) zero energy buildings. In short, these are state-of-the-art technologies. With the modification of the fenestration design in S3 and the implementation of a combination of systemic and passive design systems selected for the most ill-performing southeast-facing top floor flat in RTB 2, the energy consumption of the base-case design was the highest, due to an insufficient building envelope. This is because the new proposed strategies in Strategy 4 (S4) were based on harnessing natural ventilation, and they were effectively exposed to more solar gains. The proposed strategies were based on the principle of harnessing natural ventilation when there is no option of air-conditioning systems in the summer. This is because a previously conducted thermal performance analysis was used for the diagnosis of overheating risk and to analyse, accordingly, the hours of discomfort in each strategy. The evaluation of several passive design strategies for reducing overheating risk and optimising occupants' thermal comfort over various retrofitting strategies needs to be investigated. To compare the overheating risk and comfort delivered by the retrofitting scenarios applied in the most ill-performing southeast-facing RTB 2 when there is no HVAC mechanical system for each case, a thermal performance assessment was made of the occupied spaces to calculate their hours of discomfort using the CIBSE TM52. For this study, six strategies were analysed to assess the efficiency of proposed building systems. Table 9 demonstrates the results of these overheating risk assessments based on the proposed six passive design strategies implemented in the base-case design for the most ill-performing top floor occupied spaces. These help us to determine which led to the best results.

Table 9. Optimisation-based summertime overheating results for the most ill-performing southeast-facing RTB 2 flat unit after retrofitting.

Room Name	Occupied days (%)	Criteria 1 (%Hrs Top-Tmax>=1K)	Criteria 2 (Max. Daily Deg.Hrs)	Criteria 3 (Max. ΔT)	Criteria failing
SE_TOP_Livingroom	100	1.5	4.5	3	-
SE_TOP_Bedroom1	100	1.4	4.5	3	-
SE_TOP_Bedroom2	100	0.5	5.5	3	-
SE_TOP_Bedroom3	100	0.2	5.5	2	-

By running the simulations for overheating and thermal comfort using each strategy (S1, S2, S3, S4, S5 and S6), we can declare several findings. Although all six strategies reduced both overheating risk and optimised the thermal comfort of occupants in the summer, S5 and S6 proved to be the most effective in addressing the three criteria of overheating, as shown in Table 9. The combination of S5 and S6 was also shown to improve indoor thermal comfort by reducing the indoor air temperature in the top floor living room from 36.4°C to 28.1°C (Table 7). However, Table 7 demonstrates the impact of all six implemented strategies on the PPD, which, according to CIBSE TM52, should not exceed 15%. As Table 7 reveals, PPD was reduced from 100% in the base-case scenario to 30.5% with the combination of S5 and S6, but this is still unacceptable and highlights the need for more building performance optimisation interventions.

Conclusion

This study undertook an in-depth investigation into the thermal performance of buildings and the occupants' thermal comfort in residential tower blocks in Famagusta, Northern Cyprus. The paper aimed to evaluate the risk of these structures overheating while also taking into account summertime cooling energy demands and potential ways to overcome them through the implementation of passive design strategies. This quantitative study was designed based on data collected from a dynamic thermal modelling and simulations conducted using IES software. The results from Suncast solar analysis software found that there are significant heat losses due to insufficient building envelopes and large glazed window openings. These finding provided strong evidence of overheating and high levels of thermal discomfort in all occupied spaces in three RTBs, particularly those on the top floor of the southeast-facing building (RTB 2), followed by several spaces in the building's middle floor. Meanwhile, the Bedroom 3 units on three different floor levels, including the ground floor, appeared to remain within the comfort range throughout the overheating risk assessment evaluation period.

The subsequent investigative stage analysed the current thermal performance of southeast-facing RTB 2 and the potential retrofit solutions that could help to improve its occupants' thermal comfort. The strategies incorporated into the most ill-performing spaces in RTB 2 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 louvers 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 are 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. 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.

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 (Crawley et al., 2008). Less energy-intensive passive design strategies are investigated in this study, although the PPD remained higher than the thresholds stipulated in 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. Solar shading systems can be implemented with little cost, given that they are a feature of climate change adaptation in this particular climate. As this study has demonstrated, it appears that passive design strategies can be both energy-efficient and cost-effective for retrofitting RTBs across Southern Europe. This is a crucial finding that needs further investigation to assess and optimise the risk of overheating and understanding occupants' thermal comfort when enhancing feasible retrofitting scenarios in Mediterranean RTBs.

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