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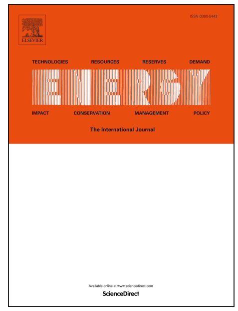

Significance of occupancy patterns and habitual household adaptive behaviour on home-energy performance of post-war social-housing estate in the South-eastern Mediterranean climate: Energy policy design

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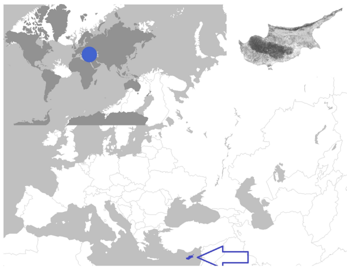
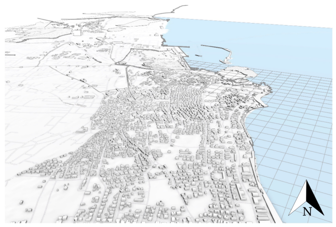
Energy performance of buildings directives in EU-27



EU and Southeastern Mediterranean basin



Eastern Mediterranean city of Famagusta

- South-eastern Mediterranean climate of Cyprus where the weather is subtropical (*Csa*) and partly semi-arid (*Bsh*)
- Post-war social housing stock was selected as archetype buildings in four different climatic zones.
- Four climatic zones:

Zone 1 - semi-mountainous
Zone 2 - coastal
Zone 3 - mountainous
Zone 4 - inland

European Commission

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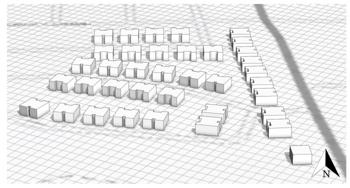
Occupancy patterns and habitual adaptive behaviour



Representative post-war social housing estate

High-rise residential tower blocks

- To evaluate the existing cooling energy performance and overheating risk in occupied spaces in a representative sample of RTBs
- To explore the potential relationships between the socio-demographic characteristics of households, home energy use factors and energy performance
- To provide recommendations to support policy aimed at reducing cooling energy consumption in the residential sector

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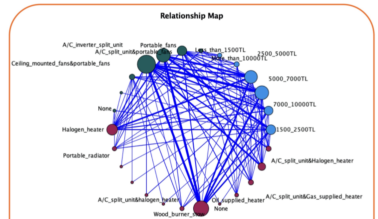
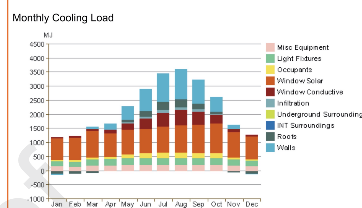
A model development of socio-technical-systems approach



Occupant energy-use patterns



Cooling-consumption patterns

- 21% of the households turned on their living room cooling systems for 0-4 hours per day during the week
- 34% kept their cooling systems on for 10-12 hours per day
- Human-based inclusive approach for residential buildings was developed
- Energy-efficiency measures are recommended at the local and nationwide levels

REHVA

Federation of European Heating, Ventilation and Air-conditioning Associations

Significance of occupancy patterns and habitual household adaptive behaviour on home-energy performance of post-war social-housing estate in the South-eastern Mediterranean climate: Energy policy design

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Full Length Article (17,957)

Abstract: The concept of retrofitting is an important milestone in the evolutionary development toward upgrading the energy efficiency of residential buildings. Various policy instruments have been introduced to retrofit existing social housing stock, many of which have failed to acknowledge the significant role of occupancy patterns in energy use. The aims of this empirical study are to statistically determine occupant behavioural patterns associated with heating and cooling energy consumption and to identify household socio-demographic characteristics that contribute to the development of energy-user profiles. This article presents the results of a questionnaire-based survey undertaken during August of 2018 with 118 households in base-case representative residential tower blocks in the South-Eastern Europe. The survey revealed weekday cooling consumption patterns were significantly and strongly related to weekend heating consumption patterns on weekends ($\chi^2 = 54{,}590$, $p < 0{,}001$, Cramer's $V = 0{,}522$). These findings will lead to a greater understanding of how occupancy patterns can predict household energy use in decision-making processes related to energy-efficiency upgrades in dwellings. By exploring some of the core lessons learned from the survey, this research seeks to both inform and improve uptake-and-delivery of future retrofitting initiatives in energy policies.

Keywords: Energy-efficiency; Energy policy; Energy use; Occupant behaviour; Retrofit delivery; Social housing

Nomenclature	
A	Area (m^2)
°C	Degree Celsius
CV	Coefficient of variation (%)
df	Degree of freedom
E	Energy (kWh/m^2)
f	Frequency
m^2	Square meter
MJ	Mega-joule
N	Number of data
p	Significant level
r	Number of elementary effects per parameter
y	Statistical variable
Abbreviations	
A/C	Air conditioning
ANOVA	Analysis of variance
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BS	British Standards
CEA	Cyprus Electricity Authority
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon dioxide
CY	Cyprus
DTS	Dynamic thermal simulation
EEM	Energy-efficiency measures
EPBD	Energy Performance of Buildings Directives
EPC	Energy Performance Certificate
EU	European Union
EUI	Energy-use intensity
EN	European Norm
GIS	Geographical Information Systems (software tool)
IEE	Intelligent Energy Use
LCCA	Life-cycle-cost assessment
M	Mean
MANOVA	Multivariate analysis-of-variance
MFH	Multi-family house
MM	Multi-objective
N	Normality
NAS	National Administration System
NC	Northern Cyprus
NV	Natural Ventilation
RTB	Residential tower block
SD	Standard deviation
SFH	Single-family house
SPO	State Planning Organisation
SME	Small-and-medium enterprise
SPSS	Statistical Package for the Social Sciences
STS	Socio-Technical-Systems
UBEM	Urban Building Energy Modelling

1. Introduction

With a growing world population that is characterised, in part, by an increasing number of people seeking to live in urban areas, achieving holistic sustainable behaviour poses numerous significant challenges [1]. Among these is overcoming the barriers that society itself poses—those of behavioural and social patterns that, in turn, drive energy consumption and resource use [2]. This is why the high density of residential developments and soaring land values in the South-eastern Mediterranean Europe, have prompted residents to maximise their liveable spaces by retrofitting their properties to increase living quality [3].

Government initiatives at various levels have been made globally, which seek effective policy making decisions to the problems related to demand on households' energy consumption and CO_2 emissions, especially for vulnerable residents in all spheres of the economy [4]. Understanding the importance of the energy performance of existing building stock constitutes a cultural and societal challenge [5]; this factor plays a crucial role in efforts to reduce the negative environmental impacts of inefficient construction activity [6]. Energy and carbon reductions in the existing building stock are a high priority in both the construction and residential sectors [7]. The main objectives of energy-saving targets are cost savings and reduced CO_2 emissions [8]. Two critical issues in the Cyprus housing sector, however, are the absence of regulatory bodies to oversee the process of construction and the fact that a majority of the housing stock was poorly built by privately owned construction companies [9, 10]. Without institutional structures within the country to oversee building initiatives, it is nearly impossible to bring the building sector into European Union standards [11, 12].

Moreover, it is essential to specify information requirements and exchange procedures during the legislative process of the Energy Performance of Buildings Directives (EPBD) for energy-efficiency upgrades of buildings [13]. Research has shown that energy has become a significant issue in the member states of the European Union (EU); one of the pilot studies found that European buildings consume 40% of the total energy, and this amount is projected to be around 55% by 2030 [14]. It can be assumed that approximately two-thirds of this usage will be by the residential sector, even though the amount varies among EU countries [15]. These conclusions support the idea that improving energy efficiency has become a priority and that action plans need to highlight the lack of stringent policies in the residential sector [16, 17]. To tackle the issue of high heating and cooling energy demand, emergency plans that are currently the subject of government initiatives, stakeholders and local municipalities with taking into consideration of significant reduction of households' energy bills and develop effective policy making decisions for upgrading buildings' thermal efficiency across Europe [18, 19].

Couched within this emerging energy debate, the EU Framework Programme for Research and Innovation 2014–2030 recommends an effective decision criterion that underscores the energy efficiency awareness gap in the residential sector in order to outline the priorities of the EU-27 Member States for energy consumption reduction in 2030 [20]. This plan recommends long-term energy efficiency upgrades and aims to address nationwide energy transitions to tackle energy-demand issues in the EU and elsewhere [21]. This strategy highlights the necessity of different policy implications related to domestic energy use, including the significance of occupancy patterns and various socio-demographic characteristics that are considered during the decision-making process for retrofitting efforts of existing residential buildings. It is important to note that current methods of design in energy efficiency gap focus on such social challenges as secure, clean and efficient energy resources and technologies; smart, green and integrated transportation; resource efficiency; raw material-secure, clean and efficient energy; climate action; and measures to adapt to climate change [22].

In Cyprus (an EU member state) and Northern Cyprus (a non-EU member state), government initiatives have made attempts to tackle the burden of existing housing stock by changing the legislative framework for adopting the EPBD guidelines and net zero energy building schemes to upgrade the thermal efficiency of existing building stocks [23]. This indicates that such legislative frameworks were not devised by taking into consideration the occupants' habitual adaptive energy use behaviour, which could provide effective guidelines to reduce energy consumption and optimise occupants' thermal comfort concurrently in the residential sector even though they are not yet mandatory.

Additionally, the government of the Republic of Cyprus (RoC) has promoted a multilateral agreement with the objective of implementing energy efficient buildings systems in retrofit interventions to improve the efficiency of existing housing stock [24]. This transformation technology and its technical legislation procurement, and know-how about how to implement energy efficiency policies, in particular with regard to the European International Organisation for Standardisation (EU-ISO) calculation benchmarking legislation and energy-rating systems [25]. Given this context, the philosophical underpinning of this research could assist the transformation into energy efficient and optimised occupants' thermal comfort for policymaking decisions in domestic energy use [26].

In this present study, it was aimed to investigate and consolidate the current energy consumption patterns (heating and cooling demand) of the existing residential tower blocks (RTBs) and the importance of implementing energy efficient technologies into testing energy effectiveness of retrofit design strategies. The study also intends to propose cost-effective adaptation of retrofit strategies that would bring about significant energy savings and carbon reductions to this residential sector. The main research question was: What are the main energy efficient design approaches for upgrading energy performance of the RTBs? The sub-questions are raised as such: How can cost-effective retrofit strategies contribute to the retrofitting of existing RTBs? These questions would help to achieve the research objectives as:

- To evaluate the existing cooling energy performance and overheating risk in occupied spaces in a representative sample of RTBs;
- To explore the potential relationships between the socio-demographic characteristics of households, home energy use factors and energy performance;
- To identify the impacts of cooling energy use-related behaviours towards the RTBs' energy performance;
- To provide recommendations to support policy aimed at reducing cooling energy consumption in the residential sector;
- To develop the knowledge framework for low-energy design strategies in the retrofitting of a residential tower block that aims to regulate occupant behaviour, increase their awareness and increase the efficiency of the project from the users' end.

This study seeks to improve current methods of design in energy efficiency in order to develop an effective methodological framework for policy making decisions and long-term holistic retrofitting of existing buildings enacted in EU member states that can improve energy consumption that takes occupant energy-use behaviour into account. This study employs mixed-methods research based on a comprehensive field study consisting of a questionnaire survey conducted with households of the case study in summer 2018 to explore occupants' socio-demographic characteristics, home energy use and cooling strategies, occupancy patterns, energy bills, amongst other variables. The longitudinal field study was performed as one of the base-case high-density pilot social-housing developments currently under delivery of implementation of systemic retrofit plans by Famagusta Municipality in Cyprus.

This study is set to design and execute in order to understand residents' occupancy patterns, their habitual adaptive behaviour on window opening schedules and explore how households' energy efficiency awareness has impacted on their home energy performance to provide evidence-based retrofitting design solutions to social household owners in Cyprus. Therefore, the findings are not only limited to Famagusta households, but it could also be generalised for other EU-27 countries, particularly for the South-eastern Mediterranean Europe where the climate is hot and humid and have similar building codes, regulations and policy implications on energy use.

The rationale of the study is a detailed record of the development of a socio-technical-systems (STS) conceptual framework, as shown in Figure 1. The novel methodological workflow was developed through a comprehensive, interdisciplinary study that informed the applicability of evidence-based retrofitting interventions as energy-policy design tools, and the case-study RTB prototypes delineated in the present study will serve as examples in the development of future BES studies in academia and in practice.

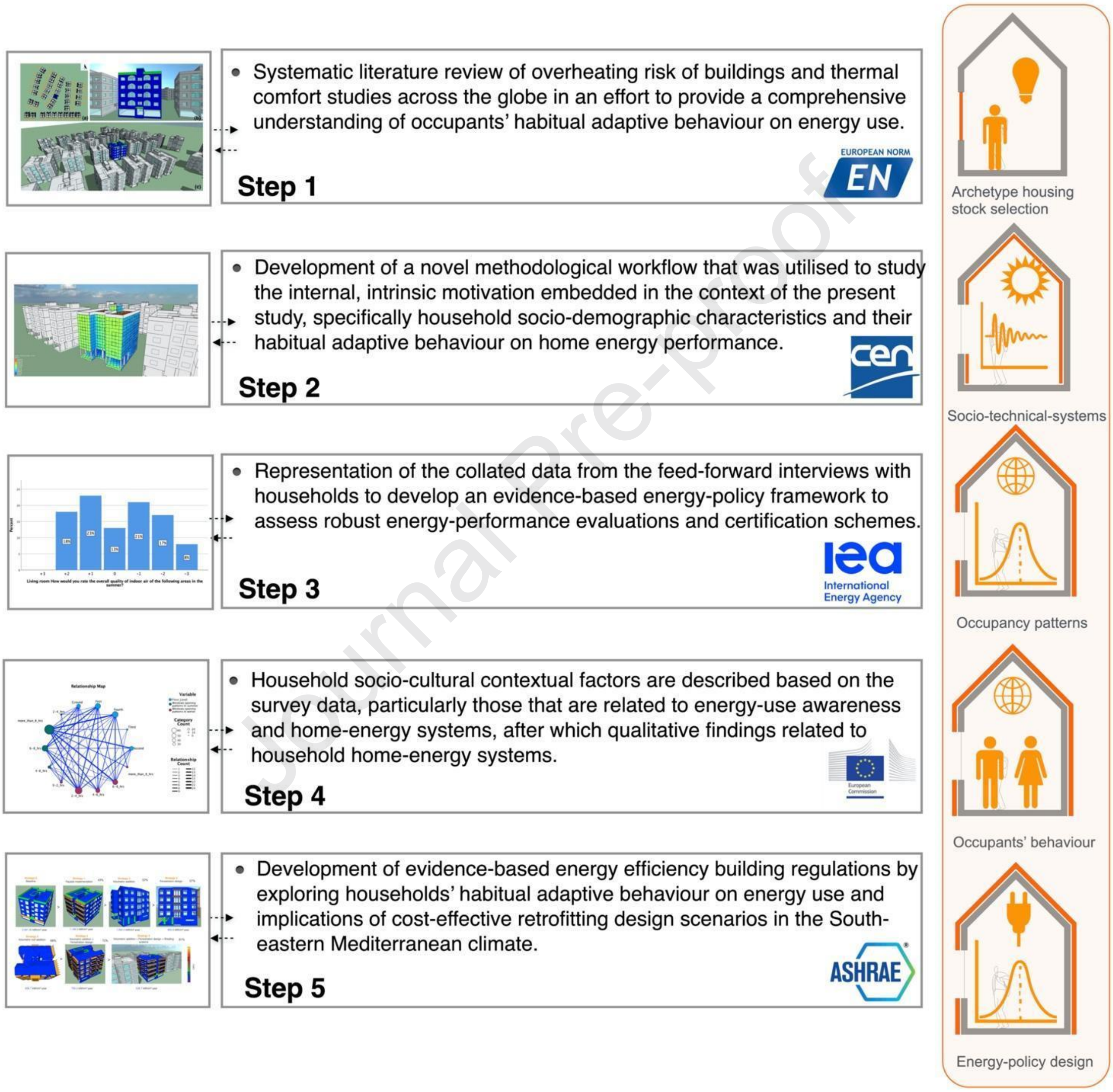


Fig.1. Stages of development of the STS conceptual framework.

Section 1 describes the knowledge gap and outlines the research aim, objectives and questions that informed every stage of the STS conceptual framework and the integration thereof into the existing body of knowledge and highlights the novelty of the study. Section 2 details a systematic literature review of occupants' energy use behavior. Section 3 describes the mixed-method research design that was utilised to study the internal, intrinsic motivation embedded in the context of the present study, specifically household socio-demographic characteristics and the influences thereof on home energy performance. Section 4 reports the collated data from the feed-forward interviews with households to develop an evidence-based energy-policy framework to assess robust energy-performance evaluations and certification schemes. Section 5 discusses main research findings for the present study, in addition to any further work that could be carried out the enhance the current knowledge of the STS conceptual framework in energy-policy design. Section 6 articulates the concluding remarks of the present study.

1.1. Rationale of the study

The present study investigated the thermal performance of 118 flats in 36 representative archetype buildings in a post-war social-housing estate in the coastal city of Famagusta, Cyprus, where the climate is subtropical (*Csa*) and partly semi-arid (*Bsh*); these designations are according to the Köppen-Geiger climate classification system. An empirical framework was developed to integrate the STS design approach, which provided information about the household feed-forward interviews that were conducted in the summer of 2018 to better understand the socio-demographic characteristics, energy use and thermal comfort of the surveyed households. It is important to highlight that this empirical study demonstrates a ground-breaking epistemological approach in two ways. First, it is the first pilot research project to investigate domestic energy use by considering the patterns of occupants and their real-life experiences with energy use in conjunction with assessing their thermal comfort by taking into account environmental parameters concurrently. Second, it also quantifies the impact of the buildings' thermal properties on the occupants' thermal comfort and the households' energy use, an area in which there is little research in the South-eastern Mediterranean climate.

1.2.Novelty of the study

The novelty of the study presented here is that a series of difficult-to-quantify home energy performance factors have not been thoroughly considered, especially those of the occupants' socio-demographic characteristics and their real-life experiences with energy use, which could establish a novel research design approach in building retrofitting. There exists a wealth of retrofit interventions for more effective policy delivery that need to be methodically planned and carefully put into action. While many scholars have published works on upgrading the thermal performance of buildings in many aspects, including considering the occupants' habitual adaptive behaviour and thermal comfort, few have approached this topic from a time-limited, output-driven perspective of conducting a field survey through adopting the STS design approach. This empirical study—on assessing domestic energy use and the occupants' thermal comfort—aims to fill this gap.

In this context, no existing research was identified that applies energy efficiency standards of retrofitting to any building types, whether large-scale social housing developments or otherwise. The initial pilot field survey study attempted to ascertain what household members identified to be energy inefficient uses of their cooling systems and how they adapted these cooling systems for their thermal comfort in changing climate conditions, particularly in the hottest summer month—August. This helped build the picture of occupancy that reflects on the households' resultant energy use in order to compare and validate energy consumption in the building modelling simulation. The present study attempts to identify key features from policy instruments and retrofitting initiatives across EU member states, which could improve the possibility of reducing energy consumption and optimise the thermal comfort level of occupants within the housing sector in Famagusta, Cyprus.

This study implies the importance of adopting comprehensive, interdisciplinary collaboration to examine and test the energy performance of base-case representative RTBs for appropriately making energy efficient retrofit interventions to improve the energy performance of buildings and their occupants' thermal comfort. Such novel methodology seeks to identify the gaps in existing knowledge by considering the occupants' real-life experiences with energy use and identifying measures that could optimise their thermal comfort and reduce energy consumption through policy instruments of retrofit interventions in accordance with the EPBD for EU-27 countries.

2. Systematic literature review

In this section, socio-technical systems of housing energy consumption that consider occupants' interaction in the decision-making process are described. An attempt is made to evaluate previously undertaken bottom-up energy policy models by using several novel methodological approaches to illustrate the development of step-by-step retrofit policy design implications on energy-consumption reduction for the European housing stock.

To address the question of energy efficiency of residential buildings in the EU, former and current energy policies and current energy consumption demands are discussed. The barriers to and motivation for the identification of archetype residential buildings are also presented, followed by a systematic review of the literature related to the development of evidence-based energy-policymaking framework and retrofitting schemes for existing housing stock that addresses the knowledge gap in energy use in the South-eastern Mediterranean Europe.

2.1. Empirical studies on socio-technical variables that influence energy consumption

In South-eastern Mediterranean Europe and other EU-27 countries, there is a wealth amount of literature review studies were undertaken on the effect of occupant behaviour on energy use that was pointed out to identify correlations between social and technical approaches [27, 28]. There is a dearth of research on occupant behaviour on energy use that considers environmental conditions and explores the detrimental effects of climate change on the thermal comfort of occupants. In a study by a top-notch building physicist Hitchcock in 1993, it was noted that the STS design approach theory provides a ground on understanding correlations between energy use and occupant behaviour in the housing sector [29]. In his review of occupant-related energy consumption factors, Hitchcock argued that due to the complexity of both dependent and independent variables involved in integrating both technical and economical approaches in retrofit interventions, a human-based approach needs to be properly understood from the systems perspective [29]. It is universally accepted that residential buildings should provide an optimum thermal environment for occupants by offering adequate space conditioning, lighting and hot water, among other considerations. A study by Pretlove and Kade contend that in domestic buildings, energy consumption is strongly correlated with the required level of nationwide policy making decision criterion development and the energy efficiency upgrade plan with which provided significant reduction of households' energy bills, particularly for space conditioning both in summer and winter [30]. This was confirmed in a study of social householders both in Europe and in the UK conducted by Rinaldi et al., which determined that domestic energy consumption is predominantly driven by the needs and/or behaviour of occupants, the thermal properties of dwellings or both [31].

Within the extant energy forecasting and retrofit design studies, there is a plethora of theoretical adaptive frameworks that underpin dependent and independent variables and covariates of household socio-demographic characteristics on home-energy use in social housing [32, 33]. These determinant factors significantly contributed to the energy-calibration methods used in the analysis and identification of effective policy making decisions both at conceptual and nationwide levels in relation to improve households' energy efficiency awareness and thermal deficiency of buildings which directly has led impact on reducing the risk of thermal vulnerability of buildings to global warming, particularly frequently occurred long-term heatwaves in the last decade across continental Europe. The work of Rodrigues et al. and Rouleau et al. in 2018 highlighted the manner in which limitations on disciplinary methods strongly correlates with occupant behaviour and habitual adaptive behaviour as it relates to the opening of windows to provide a thermally comfortable indoor air environment [34].

A number of previous studies have investigated the effects of occupant behaviour on energy use [35, 36]. Further analysis in the form of energy-calibration studies has highlighted the importance of an economic appraisal of the multi-disciplinary frameworks that identifies factorial analysis of home-energy performance when a human-based approach is taken into account [37–40]. Those variables that cause or explain a social-science-based framework were stated by Swan and Ugursal in 2009 in a deterministic design approach on energy use in vulnerable households, which helped to highlight the general circumstances thereof before undertaking further actions to assess the ingrained energy-use habits of households through a field-survey approach. Interestingly, van den Brom et al. in 2019 argued that both the STS and the economic approach are incomplete when attempting to gain a comprehensive understanding of the complexity of occupant interactions as they relate to home-energy performance.

An integrated and long-term multivariate analysis of households' energy use were developed that comprehensively studies on occupant behaviour and seeks to address the energy policy gap as per of the limitation of the pilot studies were conducted by Yun and Steemers in 2011 and Yohanis et al in 2008 [41, 42]; this is because no modelling technique has yet been proposed that completely captures these socio-technical systems. Such a technique would provide an effective multi-decision criterion approach that could be adapted by policymakers. Understanding the importance of different variables in energy-calibration studies that constitute either the deterministic or stochastic approaches in decision-making processes is essential, therefore, because it is important to review all extant findings related to the socio-technical indicators that affect the housing energy sector.

2.2. Epistemology of investigating household energy use

The literature has considered the relevance of the habitual adaptive energy-use behaviour of occupants while also considering environmental conditions that were observed during longitudinal and transverse surveys of the home-energy performance in residential buildings. A previous study, for example, conducted longitudinal surveys with vulnerable social households in New Zealand [43]. The sampling size of the pilot study conducted by Indraganti and Rao in 2010 indicate that this study was the largest housing survey due to the quota sampling method that was implemented to conduct the questionnaire survey [44]. The findings suggested that the subject respondents' who lived in hot and humid climates are reliant on using air-conditioning (A/C) systems or mix-mode ventilation systems to provide a thermally comfortable environment at the time of occupancy that was set at a very low temperature. Further statistical tests demonstrated that the thermal comfort preferences of these occupants strongly correlated with behavioural factors that were related to the annual income level and health conditions of occupants, coupled with a lack of air infiltration systems installed at home [45]. The absence of a mix-mode ventilation systems installation suggested that the occupied rooms were ventilated on a one-by-one basis, which indicated that the occupants remotely adjusted the temperatures of each room according to their thermal preferences [46]. Based on the buildings' energy performance, therefore, and in order to validate the findings of the questionnaire survey, Fumo and Rafe in 2015 suggested that monitoring the comfort level on a room-by-room basis would be an effective methodology to investigate any biases in the responses of the sampling population [47].

In contrast to the previously cited work, the pilot study that succeeded this effort conducted several statistical analyses in order to properly understand the significance of multivariate analysis between the occupant's behaviour and their energy use [48]. This study focused on high-performing RTBs as base case scenario development and a longitudinal field study was conducted to identify energy performance gaps and to document the social households' degree of thermal discomfort [49]. The findings revealed the significance of human-based factors on home energy use [50]; the authors concluded that the behaviour of the occupants influenced their use of energy in accordance with the socio-demographic characteristics and thermal comfort preferences of each household. After investigating the meta-analysis of buildings, it was determined that occupants' poor energy performance was due to designers who had ignored the behaviour interactions of the occupants [51, 52]. As such, the authors further concluded that designers should institute a human-based approach when developing an appropriate methodology to evaluate building performance in their designs.

Another thought-provoking study by the scientists emphasised that challenges in building-energy calibration studies are derived from the failure of regulatory provisions to capture real-life energy-use experiences of occupants; this study investigated five high-performance state-of-the-art prototype houses in Australia which was aimed to assess the thermal vulnerability index of buildings thereof in order to meet relevant regulatory housing standards [53]. The findings of this study revealed that targeted regulatory concepts have failed to meet expectations due to occupant behavioural activity, which had failed to be taken into account during the building-performance evaluation. One of the other reasons for this was that generic occupancy profiles were assigned in the simulation model that did not consider the climate and other localised effects on energy consumption [54]. It should be noted, however, that the standards and regulations in question were unable to predict the comfort levels of occupants and low-zero energy-consumption targets [55]. The study findings further underscored the fact that having a thorough understanding of current lifestyle of households and their different associations with home energy performance are crucial to develop an effective assessment methodology [56].

The findings of these studies established that it identifies correlations between a given environment and behaviour in and around residential buildings is of utmost importance. This is partly because of discrepancies that have been found between predicted and actual energy use during calibration studies that were undertaken to investigate the actual energy-use of households [57]. As this is the case, the Chartered Institution of Building Services Engineers (CIBSE) TM59 technical memorandum on *Design Methodology for the Assessment of Overheating Risk in Homes* recommended that the representative dominant occupancy patterns could benefit from a significant STS approach that would calibrate the energy performance embedded within actual gathered data through longitudinal surveys related to behavioural–environmental interactions in residential buildings [58]. The studies presented thus far offer evidence that the methodological approach plays a decisive role in the calibration of building-energy performance. As such, this debate predominantly lies within the STS approach, which highlights the importance of upgrading the energy efficiency of buildings within an appropriate methodology and effective retrofit interventions implemented in decision-making processes that are influenced by human actions.

2.3. Benefits and constraints of the socio-technical-systems conceptual framework

Much of the available literature on home-energy performance surrounds the question of whether the complexity of household socio-demographic characteristics can be corroborated in a building-modelling simulation [59, 60]. Hitchcock (1993) was significantly more concerned, however, with the environmental aspects of a household, consisting of three main dependent variables: the climate, economic and cultural systems [29]. In a review of different environmental parameters, Hitchcock highlighted the importance of a climate system that consists of external temperatures, insulation, and wind levels, and he posited that all of these variables work together in a seamless manner to influence household energy consumption. He further found that energy consumption in domestic buildings is correlated with household income. These findings are also visible in other studies of social housing tenants conducted in Europe and the UK [61-63]; these studies indicate that energy consumption is driven by the needs and behaviours of occupants and/or by the thermal properties of dwellings, as shown in Figure 2.

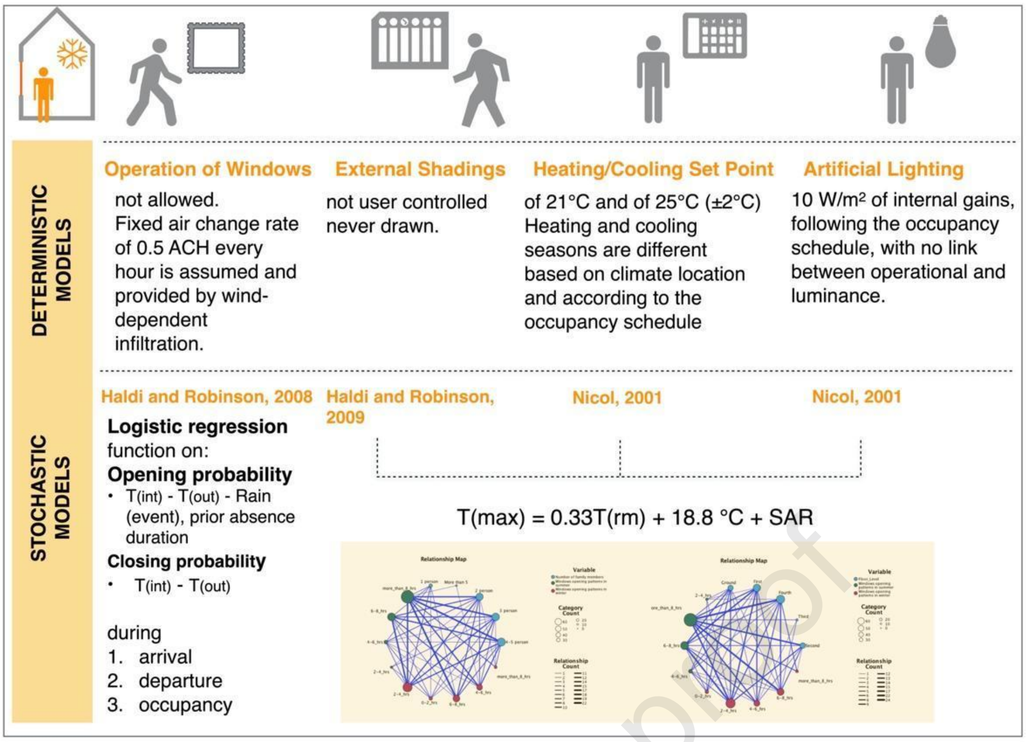


Fig.2. Different approaches to modelling building-occupant behaviour.

Guerra-Santin *et al.* (2018) emphasised the importance of considering interactions between energy consumption and occupants' socio-demographic characteristics like income and household size [64]; they argued that larger households or households with higher incomes tend to consume more energy, compared to average mean-sized households. Sonetti *et al.* (2020) examined household consumption by employing a mixed-methods research design with a methodological approach that was based on the concept of occupants' metabolic activity at home [65]. In this present study, to thoroughly investigate the physiological parameters of households, statistical analyses were carried out in accordance with the STS conceptual framework, as shown in Figure 3.

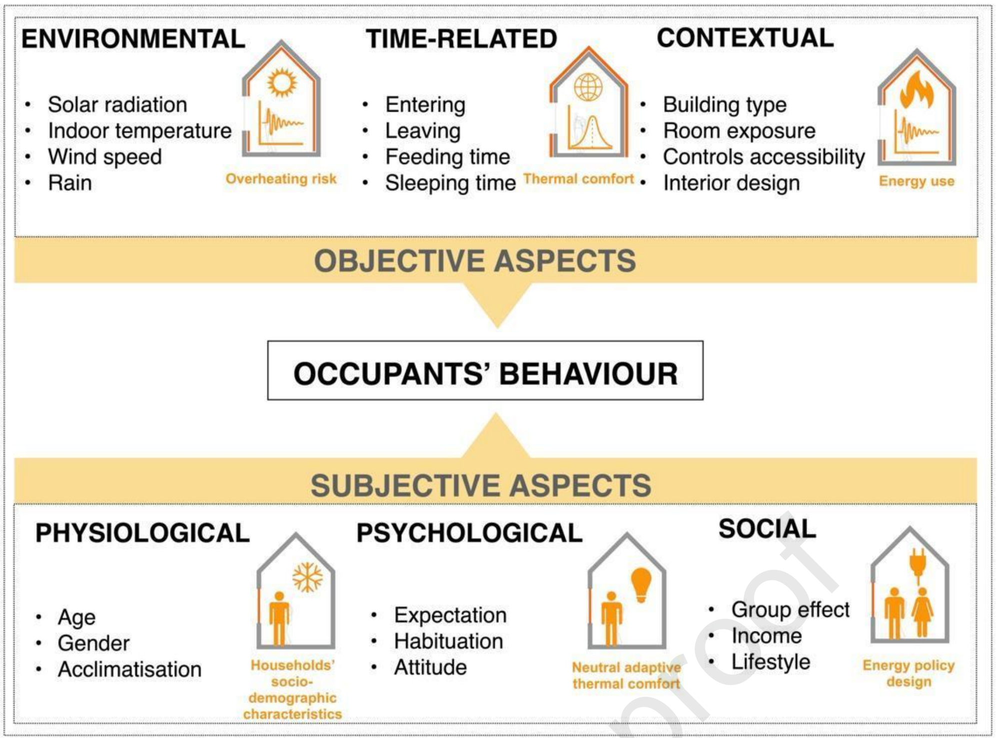


Fig.3. Categorisation of triggers for user adaptation.

A study by Bartiaux and Gram-Hanssen (2005) considered the correlation between socio-political variables and household energy consumption by comparing the EPC datasets of Denmark and Belgium [66]. The findings of that study reveal that the most energy-intensive apartments have a technical constraint in conducting energy-efficiency measures (EEMs) and should anticipate the adoption of cost-effective retrofit design strategies. A study by Abrahamse and Steg (2011), which was proposed as a meaningful, accessible approach that could be adopted by policymakers for upgrading the energy efficiency of post-war social housing stock in Europe [67], further clarified the importance of the correlation between psychological and socio-demographic variables that influence home-energy performance. That study's findings raise questions as to how long-term retrofit design strategies might be developed such that they will improve indoor-air environment quality and reduce household energy consumption, taking into account interactions between involved householders dependent on local needs.

While several studies have highlighted the potential of the housing sector to contribute to both energy-consumption and CO_2-emission reductions, other studies have investigated different attitudinal and socio-demographic variables and found that an explanatory theory is the most effective approach for identifying income and size of household as the main dependent variables for energy-saving measures [68, 69]. Additionally, many studies have empirically explored the importance of occupant behaviour as related to socio-demographic characteristics and household size [70-72]. These findings reveal that there is an association between occupancy density and energy consumption, indicating that longer occupancy hours lead to increased energy use.

Some authors have primarily expressed an interest in households that exhibit different behavioural patterns that exemplify adaptive thermal comfort [73-75]. These studies highlight that the frequency of opening windows, occupancy hours and setting the temperature of wall thermostats or air conditioning (A/C) systems are all associated with influences on household energy use. This is why the STS approach was employed in the present study to investigate these concerns via a questionnaire survey; variables related to the socio-demographic characteristics of households and environmental conditions of the research context were also investigated. This study attempted to fully understand respondents' environmental attitudes toward optimising occupant thermal comfort and thereby provide a basis for subsequent analysis that can be used in building-modelling optimisation efforts.

2.4. Building a stock model for energy-policy design

To fill the energy-efficiency gap, improvements in the physical quality of housing stock that are directly related to human-based factors are needed. This need led to the development of a novel methodological framework for assessing domestic energy use, as shown in Figure 4.

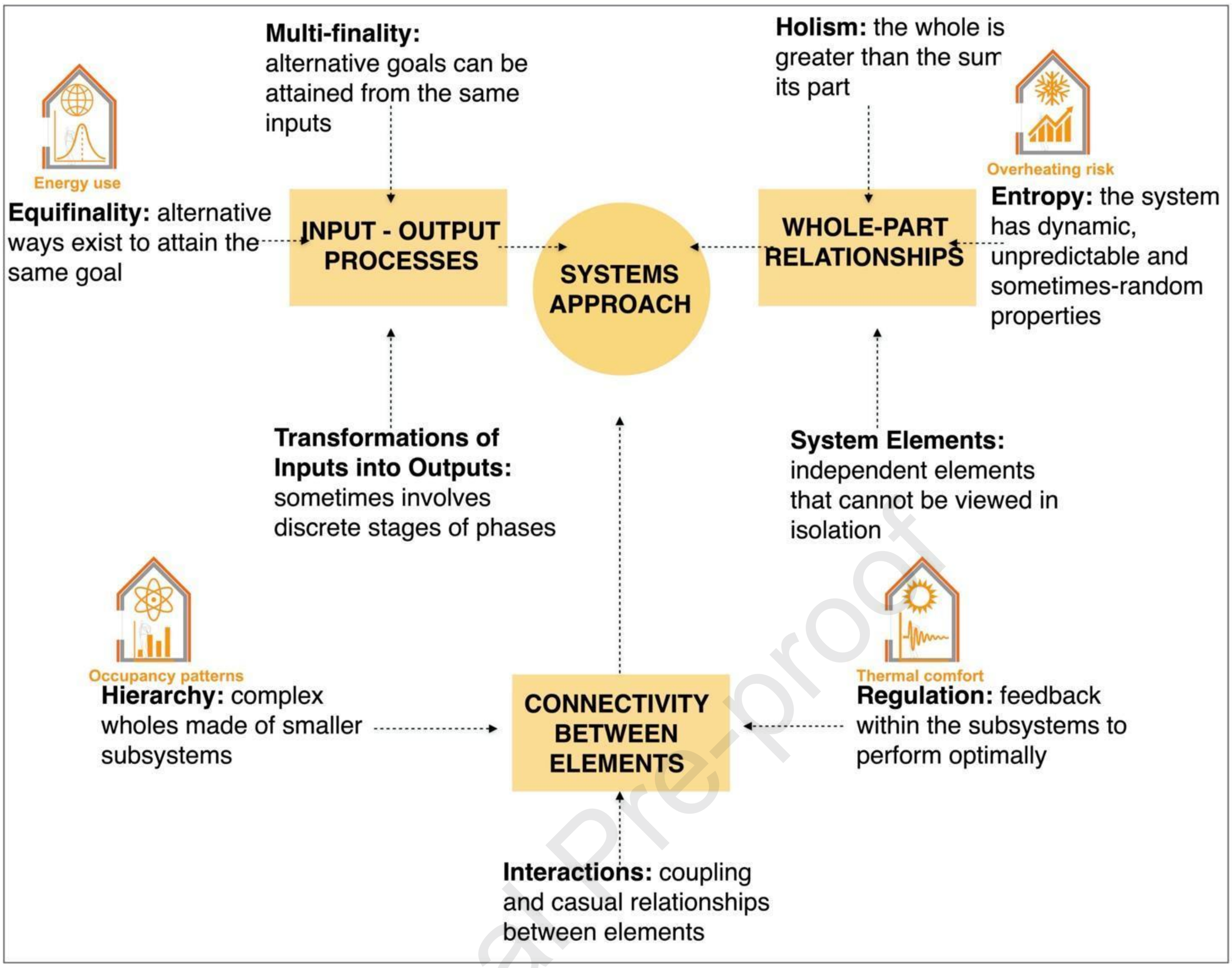


Fig.4. Stages of development of the STS conceptual framework.

One of the main goals of the present study was to encourage social housing occupants to assess and adopt principles of retrofitting design policies to improve the extant mass-housing stock. This approach will investigate buildings that were built under the governmental social housing scheme, but that have not yet undergone any refurbishments to make the structures more energy efficient and adapted to the local environment. The present study revealed an urgent need for governmental bodies to devise effective policies for the mass-housing sector so that the construction industry applies necessary retrofitting strategies on a rapid and large-scale basis to reduce energy consumption. Tables 1 (a) through (d) delineate previous scholars' work on the development of statistically representative housing archetypes across the world.

Table 1 (a)
The literature on building stock aggregation through archetype buildings.

References	A. Study Location	B. Building Type	C. Sampling Size	D. Primary Aim of Model	E. Methodology	F. Main Findings
[76] Mata *et al.* (2014)	France, Germany, Spain and the UK	Single-family dwellings (SFD); terraced houses (T); multi-family dwellings (MFD)	France – 99 archetypes (54 R, 45 NR), Germany – 122 R archetypes Spain – 120 archetypes (40 R, 80 NR) UK – 252 archetypes (168 R, 84 NR)	To assess the possibility of describing the European Union (EU) building stock for the purpose of forming a basis for analysing the effect and costs of applying different energy efficiency intensity (EEI) measures to the entire EU building stock	A dynamic Building Stock Model was used; archetype buildings were selected to represent the building stock of the country; the segmentation was applied to both residential (R) and non-residential (NR) buildings; a total of 593 archetype buildings were investigated; census data and national reports were used; the 3CL-DPE Method was used to define building geometry and *U*-values of building envelope parameters	A final total energy demand that differs by -6% to +2% from statistics for the four countries investigated; the share of space heating of the total energy demand ranges from 59% to 82% in R buildings
[77] Ballarini *et al.* (2014)	Thirteen EU countries, representation of Italian building typology in three different climatic zones	Single-family houses (SFHs; detached or semi-detached); terraced houses; multi-family houses (MFHs); apartment blocks	Six SFHs; six MFHs; six apartment blocks built between 1901–1920 and 1991–2005	Development of methodology to identify reference buildings for assessing energy-saving potentials; to design a harmonised structure for 'European building typologies' in order to estimate the energy demand; to identify a national 'Building Typology' according to the IEE-TABULA project	The Building Typology Matrix was developed by region/climate area; The Real Example Building (*ReEX*), The Real Average Building (*ReAv*) and The Synthetical Average Building (*SyAv*) approaches were developed; statistical data was used to support the archetype housing stock analysis; the building energy assessment model was developed; a quasi-steady-state monthly model was chosen in order to meet the consistency both with European standards and with national standards; retrofitting interventions applied to the national building stocks were considered	Annual primary energy need for space heating and domestic hot water ranged from 41% (Czech Republic) to 75% (Italy, Middle Climatic Zone); on average, more than 40% of energy savings could be obtained by the whole analysed European residential stock just applying a 'standard' retrofitting scenario
[78] Wang *et al.* (2015)	Stockholm, Sweden	Swedish low-rise residential buildings	2-3–storey low-rise MFHs purpose-built housing estates built between 1965 and 1975	To investigate energy effectiveness of retrofit measures applied onto building envelopes by an exploratory case-study analysis	A typical Swedish multi-family archetype was selected; the IDA ICE 4.6 (indoor climate and energy performance simulation programme) was applied for the simulation of thermal performance	Adding insulations on roof and improving air-tightness level achieved a 16% and 18.4% energy consumption reduction, respectively

Table 1 (a) identifies representative housing typologies for the development of bottom-up energy policy frameworks in European countries. The study by Mata *et al.* (2014) investigates the implementation of energy-efficiency strategies by aggregating 593 archetype buildings to represent the entire housing stock, using the national housing databases of France, Germany, Spain and the UK [76]. The sampling population was extracted from the Eurostat database in 2011. This dataset consists of the building characteristics, energy consumption levels and CO_2 emissions of each country and provides a benchmark for the validation of the final energy demand for a reference year. By contrast, the present study only includes data on medium-rise residential tower blocks (RTBs), which represent 56% of the dwellings in Northern Cyprus (NC)[1]. The two studies show differences in terms of the development of methodology for building stock aggregation. Mata *et al.* (2014) primarily investigates the building thermal properties of both single family houses (SFHs) and multi-family houses (MFHs) and the energy use of these dwellings was validated through measures of indoor-air temperature [76], while, in the present study, the nationally representative housing stock data was gathered from the Housing Construction Statistics from 2015 to 2019[2] and applied to the most representative medium-rise RTBs and the energy simulations were validated by integration of human-based data through a questionnaire survey.

In the present study, 100 households' data was integrated into the building energy model to develop an evidence-based energy policy framework, and the findings were generalised across eight cities in Cyprus; this method of design provides a universal design approach that could be extrapolated to other South-eastern Mediterranean countries. To prove the validity of the methodological framework developed as an output of this field study investigation in Cyprus, the analysis of the archetype presented here also considers the work of Ballarini *et al.* (2014). In this study, three different archetype housing typologies were selected to represent the entire the Italian housing stock and three different climatic zones were considered: *(i)* the Mediterranean zone up to 2,100 heating degree days; *(ii)* the middle climatic zone from 2,100 to 3,000 heating degree days and *(iii)* the Alpine zone, having more than 3,000 heating degree days [77].

In the present study, the representative archetypes selected from the urban context enable the research findings to be applied to other post-war social housing estates located in other major cities in NC. This chosen method allows identification of both the upper- and lower-neutral adaptive

[1] Data obtained from the *Annual Statistical Report*, published by the Northern Cyprus Statistical Office: http://www.stat.gov.ct.tr/IST-YIL-2019.aspx (pp. 16–23).

[2] This is the most reliable dataset available. It was selected to identify the nationally representative archetype building typology in NC. The data consists of the Housing Census and Construction Report, and statistics were derived from various resources dated pre-2015. These sources have shown various indicators in construction projects that were completed, such as high-density measures both in urban and suburban regions of NC.

thermal-comfort thresholds of each city across the island; this also contributes to an ability to benchmark to the ASHRAE Global Thermal Comfort Database II[3]. Another study, that of Ballarini *et al.* (2014), only considers the development of a method of design for the identification of building typology according to the Typology Approach for Building Stock Energy Assessment (TABULA) [77], Intelligent Energy Use (IEU), European Union project[4]. Additionally, the pilot study conducted by Ballarini *et al*. used secondary data sources for the development of aggregate energy models, and the occupants' thermal comfort was neglected in the project's assessment of the energy-saving potentials of European residential building stocks. This indicates that the study conducted by Ballarini *et al.* has shortcomings in terms of applying the research outputs to other EU countries' energy policy frameworks [77]. In contrast, this present study provides a universal design approach in terms of integrating a household's *in-vivo* experiences in energy use and validating the findings with the statistical analysis of data collected through a questionnaire survey.

Wang *et al.* (2015) only considers low-rise residential buildings as nationally representative archetype houses in Stockholm, Sweden [78]. In the present study, by contrast, post-war social housing estates were selected as an archetype of housing typology to represent the demand for government social housing schemes in the mid-1980s and early 1990s in NC. The study included 6,646[5] buildings that were constructed during this era and the building typology was extrapolated with the most reliable housing stock data from between 2015 and 2019 to identify a nationally representative housing stock that accounts for 56% of the low-, medium- and high-rise RTBs[6] in NC, as shown in Figure 5.

The pilot study conducted by Wang *et al.* (2015) used a building energy modelling approach by integrating the statistically representative Swedish housing stock for energy policy design [78].

[3] The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Global Thermal Comfort Database II is the result of a project led by an international team of experts to collate field measurements of thermal comfort for public use. The dataset was processed via a project web tool for quality assurance before being published in the open access ASHRAE Global Thermal Comfort Database II. Available at http://www.comfortdatabase.com

[4] During the IEE project, TABULA residential building typologies were developed for 13 EU countries to contribute to the EPBD. Each national typology consists of a classification scheme grouping buildings according to their size, construction age, the *U*-values of the buildings' properties and a set of archetype buildings representing the building types. Available at https://episcope.eu/iee-project/tabula/

[5] Data obtained from the Ministry of Housing Department of Rural Affairs and Development in NC. This data consists of government social housing development projects built between 1984 and 1996.

[6] The Housing Census and Construction Report statistics were collated to identify the nationally representative housing typology between 2015 and 2019. Due to the limited availability of pre-existing sources on the quantification of housing data in NC, the most-up-to-date statistical data was applied on the verification of the archetype building typology for this empirical study, which was prepared by the Statistical Institute of Northern Cyprus in 2019. Available at http://www.stat.gov.ct.tr/INSAAT-YIL-11.aspx

Additionally, this study investigates building fabric thermal performance of case-study buildings by testing energy efficiency measures (i.e., thermal bridge, air-tightness retrofitting (S1), ventilation retrofitting (S2), window retrofitting (S3), attic/roof retrofitting (S4) and external wall insulation (S5) applied on the existing state of building envelopes while in the present study six passive cooling design strategies were developed and applied on the base-case scenario by considering bio-climatic design elements of the Cypriot context and testing energy effectiveness of each strategy with integration of the questionnaire survey outputs into the building energy model.

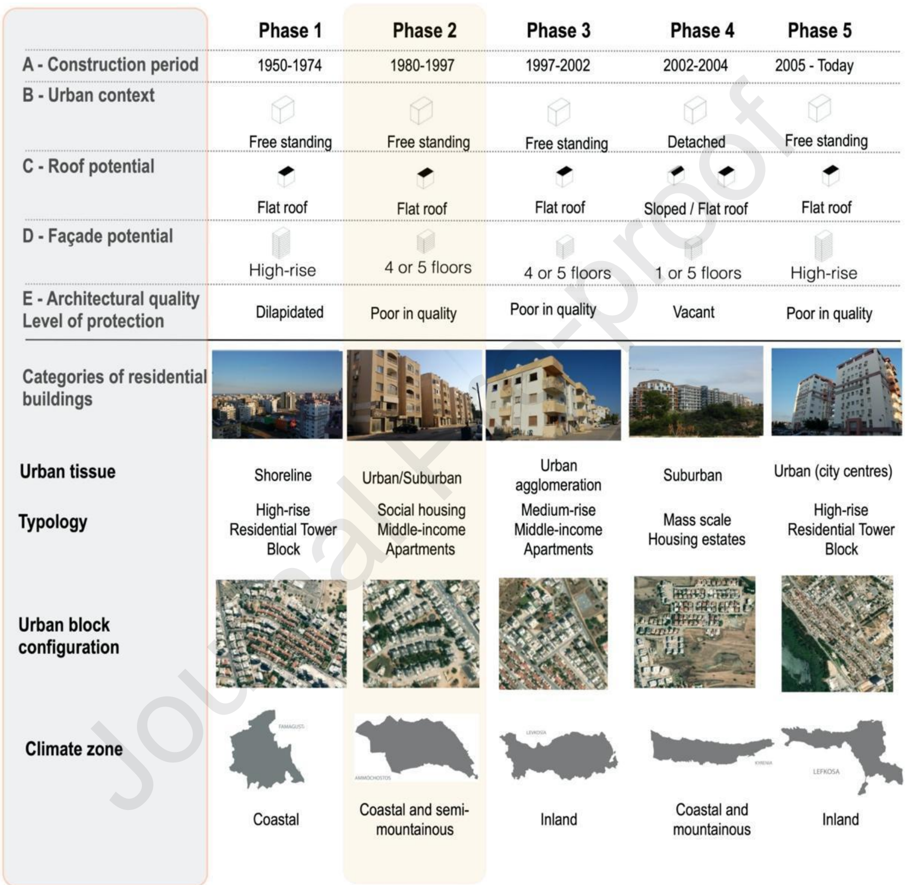


Fig.5. National representativeness of high-, medium- and low-rise residential tower blocks in NC.

It should also be noted that Wang *et al.* considers the traditional method of design for testing energy effectiveness of state-of-the-art retrofit interventions applied onto building envelopes without the integration of actual data collection or any other research instruments to measure building fabric thermal performance [78]. The outputs of the *Wang et al.* study predominantly represent the assumptions of energy consumption profiles. In the present study, however, the data collected through 100 samplings of questionnaire survey outputs and *in-situ* recordings of indoor environmental conditions were integrated into the building energy model to validate the findings from dynamic thermal simulations (DTS). Table 1 (b) delineates the development of statistical sample criteria for archetype housing stock analysis.

Table 1 (b)
The literature on building stock aggregation through archetype buildings (Continued).

References	A. Study Location	B. Building Type	C. Sampling Size	D. Primary Aim of Model	E. Methodology	F. Main Findings
[79] Dineen *et al.* (2015)	Ireland	2-storey semi-detached houses; 1-storey apartments; 2-storey detached houses; 2-storey terraced buildings; 1-storey detached houses (representing 87% of all dwellings)	The National Administration System (NAS) database was used, which contained details of 253,875 dwellings that represent 19% of the total dwelling stock of 1.6 million housing units	To demonstrate a novel bottom-up approach to modelling the energy-saving potential of energy efficiency improvement measures applied through the retrofit of existing dwelling stock	Archetype housing stock analysis was selected; the housing census data of 2011 was used for the calibration analysis; 145 archetypes were used for the model calculations; Global Sensitivity (GA) analysis was conducted; six retrofit measures were examined; energy demand analysis was conducted	There was approximately a 7.5% change in energy consumption for every 1° C internal temperature fluctuation; the energy model underestimated the heat energy demand of the 2011 stock by just 1.2%
[80] Belpoliti and Bizzarri (2015)	Emilia Romagna, Italy	More than 2-storey and up to 8-storey standalone apartments	70 buildings that were constructed under the Italian social housing scheme between 1991 and 1995.	To develop an effective method of design for the energy performance audit of the social housing stock; to elaborate a parametric calculation protocol to boost effectiveness of the energy audit analysis	A bottom-up energy policy development approach was chosen; national housing census data was used; energy performance analysis was conducted; carbon emission profiles were assessed; three retrofit energy interventions were applied onto the building envelope	Replacing the heating system and single-pane windows with double-pane ones was characterised by a sustainable cost/benefits ratio that ensures a 39.5% reduction in energy consumption
[81] Gulotta *et al.* (2021)	Cambridge, Massachusetts, United States of America	Low-rise residential buildings with 1-4 dwelling units	A training set of 339 homes was assessed, then a larger test set of 2263 homes was assessed	To develop a methodology for probabilistic Urban Building Energy Modelling (UBEM) archetype characterisation	Archetype dwellings representing housing data between 1970 and 1990; measured energy data was used; a Bayesian calibration approach was adopted; an hourly weather dataset was created; six high-uncertainty variables were chosen for the calibration analysis	Using a calibration error based on monthly energy resulted in 16.5% of the buildings being compared to 0.03% when using annual error margins
[82] Serrano-Lanzarote *et al.* (2016)	Valencia, Spain	Terraced buildings; isolated linear buildings;	1,698.470 dwellings were built between 1960 and 1980	To quantify the energy-saving potential and the related CO_2 emissions of the housing stock	A top-down approach was used by splitting the actual energy consumption of the regional building stock among the total number of buildings; building energy simulations were conducted	Energy consumption could be reduced up to 2% in 10 years, representing a savings of 247,871 Mwh

Dineen *et al.* (2015) adopted bottom-up modelling by integrating the statistical power of housing census data available for Ireland from 2011 [79]. Representative datasets were gathered from the national energy balance datasets as part of Energy Performance Certificate (EPC) calculations. To define the aggregate energy models, 253,875 dwellings were selected from the National Administration System (NAS), representing 19% of the total dwellings in Ireland. In the present study, the nationally representative data obtained from the *Annual Statistical Report* published by the Northern Cyprus Statistical Office in 2019 represents approximately 11,512 dwelling units[7] consisting of residential tower block projects built on a mass scale across the island between 2015 and 2019. This statistical data, extrapolated with the total dwellings, shows that these buildings represent 38% of the building stock in NC[8].

The study conducted by Dineen *et al.* included a step-by-step development of energy demand calculations and model calibrations by using secondary data sources [79]. In the present study, the building-energy-simulation set-input parameters were developed through a questionnaire survey and *in-situ* physical measurements for environmental conditions were used to validate research findings.

Also of note in the Dineen *et al.* study, the Global Sensitivity analysis approach was used to determine energy-saving measures and rebound effect calculations for each retrofit measure applied onto the building envelope [79]. Whereas in the present study, overall energy-efficient implementation measures of six passive cooling design strategies and their life-cycle cost assessments were examined to demonstrate implications for energy policy design.

One study that shows a similar design approach to the present study is that conducted by Belpoliti and Bizzari (2015) [80]. That study investigates the existing social housing stock in the Emilia Romagna region of Italy and adopts only the nationally representative standalone RTBs that were built in the 1990s [80]. This type of social housing stock represents 19.5% of the buildings in Italy. For the present study, the post-war social housing stock was identified as a nationally representative building typology and outcomes were extrapolated using the same design approach as that used by Belpoliti and Bizzari [80]. A main difference between these two studies is that where the Belpoliti

[7] This data only consists of the number of dwelling units that were built in apartment projects across five major cities in NC in 2019. These dwellings account for 38% of the overall building stock that was built between 2015 and 2019. These high-density projects were constructed by small and medium enterprises in NC that are predominantly regulated by family or privately-owned construction companies. The 1998 withdrawal of social housing schemes led to increased demand for construction projects built by the SMEs.

[8] According to the Housing Census and Construction Report statistics. The data on the representation of the national building stock is not available on the Eurostat database due to the fact that NC is a *de-facto* state in terms of gaining international recognition and being allowed to implement EU directives for any type of industry, including achieving the net-zero-energy building (nZEB) targets that were recommended for the residential sector in each EU country.

and Bizzari study only considers a steady-state analysis of energy retrofit strategies tested to calculate energy savings in the residential sector, the present study sets out to demonstrate the DTS of each of six passive cooling design strategies applied onto the existing state of the archetype buildings [80]. The present study also validates the building energy simulations with use of household energy bills and the socio-demographic characteristics of households gathered through a questionnaire survey.

The study of Gulotta *et al.* (2021) develops the Urban Building Energy Modelling (UBEM) design method for exploring energy efficiency solutions on urban or district scales [81]. In this territorial exploratory case-study approach, 339 low-rise residential buildings were selected as an archetype housing typology in Cambridge, Massachusetts, USA. In this pilot study, the Energy Use Intensity (EUI) of the archetype dwellings was assessed to calibrate data with the electricity and gas use of the households. The error margins between the predicted and measured data were calculated to demonstrate annual energy calibration for the region, but the selected sample size does not represent the entire population of this region. To avoid research bias and provide a generalisation of research outputs, the available dataset was multiplied with a larger test set of 2,263 dwellings, applied to measure the accuracy of the validation of the methodology. In the present study, an even larger dataset of 6,646[9] dwellings were used. These dwellings were identified as nationally representative archetype buildings in both an urban district and also in rural locations in NC. The urban district of Famagusta was selected as a baseline to extrapolate research findings to other cities, as shown in Figure 6. The main methodological difference between the pilot study conducted by Julia *et al.* and the present study involves the questionnaire survey used in the present study. In the present study, the statistical method of bootstrapping was used to increase the sample size to test associations between households' actual energy bills and their socio-demographic characteristics gathered through a questionnaire survey. Additionally, DTS were undertaken to predict the energy use of the identified archetype housing stock by integrating dominant representative occupancy profiles gathered through a questionnaire survey.

A top-down energy policy design approach was utilised by Serrano-Lanzarote *et al.* (2016) in Valencia, Spain [82]. In this pilot study, four different archetype housing typologies were studied that represented 1,698.470 dwellings built between 1960 and 1980 in 12 climatic zones in Spain. Only steady-state analyses of energy-efficiency measures were calculated through use of the aggregated data of households' actual energy consumption, the census population and dwellings, national

[9] Data extracted from the State Planning Organisation, Department of Rural Affairs and Development in NC. Available at https://www.devplan.org/index_en.html

statistics regarding the energy consumption of the residential sector, and 500 surveys about the actual energy consumption for this region referenced to climatic zones.

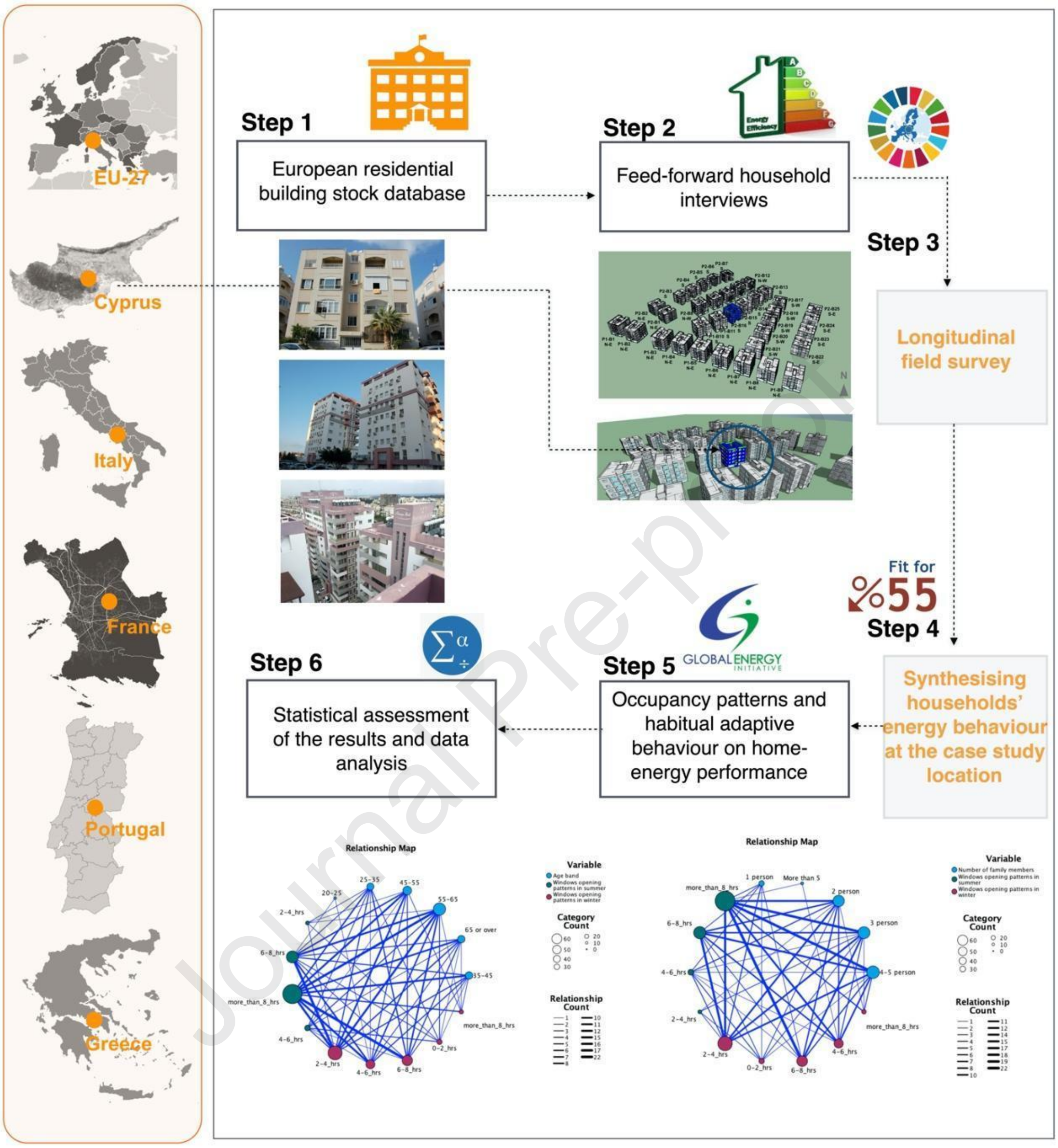


Fig.6. The method of design used to demonstrate extrapolation of archetype buildings.

The traditional method of design used by Serrano-Lanzarote *et al.* was also used in this present study, after being adopted for the development of a district-scale retrofitting design approach suitable for NC. It should be noted that the study undertaken by Serrano-Lanzarote *et al.* developed a top-down design approach as these scholars were testing the energy-saving measures of building retrofitting design strategies [82]. In contrast, the present study uses a bottom-up design approach that was developed by integrating the STS conceptual framework within the extrapolation of field study investigation findings on energy use. Table 1 (c) demonstrates the development of statistical methods to aggregate building energy model studies.

Table 1 (c)
The literature on building stock aggregation through archetype buildings (Continued).

References	A. Study Location	B. Building Type	C. Sampling Size	D. Primary Aim of Model	E. Methodology	F. Main Findings
[84] Loga *et al.* (2016)	20 European countries	SFHs; end-terraced houses; mid-terraced houses; MFHs; apartment blocks; tower buildings	17 EPISCOPE case studies at national, regional and local levels were used; the sample fraction consisted of more than 600 datasets	To develop a common methodological framework with the aim to enable a quantitative comparison of the energy performance of the exemplary buildings; to develop a standardised classification scheme for residential buildings by using an open-access web tool	Cross-country comparisons of building and supply system features were analysed; bottom-up building stock models were used; the energy balance of 'average buildings' was calculated by use of standard energy rating software; *U*-values of both existing buildings and new-build dwellings were gathered; thermal envelope areas were calculated for improvement of building energy models; heating supply systems were identified	Supporting national energy advice activities for illustrating the impact of policy instruments; development of strategies for tracking and understanding actual energy performance achievements
[84] Stefanovic and Gordic (2016)	Kragujevac, Serbia	Free standing tower block; high-rise buildings; apartment blocks; city block; staggered blocks	10,771 multi-family residential buildings were selected in six different construction periods	To improve awareness of energy performance of buildings at the city level	Energy modelling for archetype buildings was constructed; 86 staggered block buildings built between 1981 and 1990 were identified as archetype buildings; a bottom-up design approach was used; a building geodatabase was identified; EnergyPlus software suite was used to undertake building energy simulations	Implementation of polystyrene thermal insulation achieved 17.91%, 21.20% and 22.70% annual heating energy consumption reductions
[85] Cerezo *et al.* (2017)	The residential district of AlqQadisyah, Kuwait	Villa-type multi-family residential buildings	336 dwellings built in the 1980s and 1990s under the 1983 Energy Conservation code, representing 42% of the housing stock	To propose a new method for the characterisation of occupant-related parameters in building archetypes using Bayesian calibration with annual energy data	Both deterministic and probabilistic approaches were adopted; urban data gathering; archetype characterisation; UBEM model generation; archetype Bayesian calibration; energy demand simulation; uncertain and probabilistic archetype parameters explored	EUI of archetypes showed a reduction of percentage errors for the 10 and 90 percentiles of 13%-45% against deterministic methods
[86] Pittam and O'Sullivan (2017)	Cork City, Ireland	End-of-terrace (ET) and mid-terrace (MT) MFHs	1551 asset-rating surveys were used	To use the extracted geometrical building information to demonstrate the effects of using default settings	Representative thermal construction properties were identified; 43 variables were identified that were deemed necessary to represent a detailed disaggregated housing stock database	There is a mean 21.5% variation in the predicted annual energy performance of EUI measures

Loga *et al.* (2016) reviewed the European housing database to develop a common methodological framework for the holistic retrofitting of existing residential buildings [83]. In this statistical analysis method, 600 samples were used for each included EU country across 16 pilot case studies that are available in the TABULA Web Tool[10]. This open-source database offers researchers the ability to extract only those national datasets that were developed under the EPISCOPE-European Union research project[11] to determine the development of EPCs for EU countries. This database consists of the *U*-values of building properties for each nationally representative housing typology identified for each EU country available in the database. In the present study, 36 RTBs that were built under the government's social housing scheme in four major cities across NC were identified as archetype housing stock for conducting the statistical analysis. The Housing Census and Construction Statistics, in conjunction with the most-up-to-date statistical data available from 2015 to 2019, were used to extrapolate representativeness of post-war social housing estates. The data was examined to validate the representativeness of archetype buildings and to provide subsequent background information for the development of a black-box energy model to undertake building energy simulations.

For this study, 100 households were recruited across 36 RTBs in a post-war social housing estate located in the coastal city of Famagusta where the climate is subtropical (*Csa*) and partly semi-arid (*Bsh*), according to the Köppen-Geiger climate classification data. This densely urban district was selected as a base-case scenario where the statistical findings could be generalised and applied to other cities in Cyprus. To prove that the chosen archetypes were statistically representative, this study first examines statistical data for the construction sector by region, as available in the Eurostat data. The findings demonstrate that 7.9% of the gross domestic product (GDP) of the Republic of Cyprus (RoC) and an average of 5.3% of the GDP for the 27 EU countries was accounted for by investment in housing in 2019. The housing census statistics demonstrate that 38% of residential building stock in NC consists of multi-family residential buildings, SFHs and apartments. These statistical findings further validate the national representativeness of the archetype selected for this study, as shown in Figure 7.

[10] The TABULA Web Tool is based on the common DATAMINE data structure and the experiences of typological classification. The TABULA project launched in 2009. This open-source platform set out to make an agreed systematic approach to classifying building stocks according to their energy-related properties. Available at https://webtool.building-typology.eu/#bm

[11] This project set out to make the energy refurbishment processes in the European housing sector transparent and effective. Pilot studies were conducted in 16 EU countries to track the implementation of energy saving measures and their effect on consumption in practice. Available at https://episcope.eu/welcome/

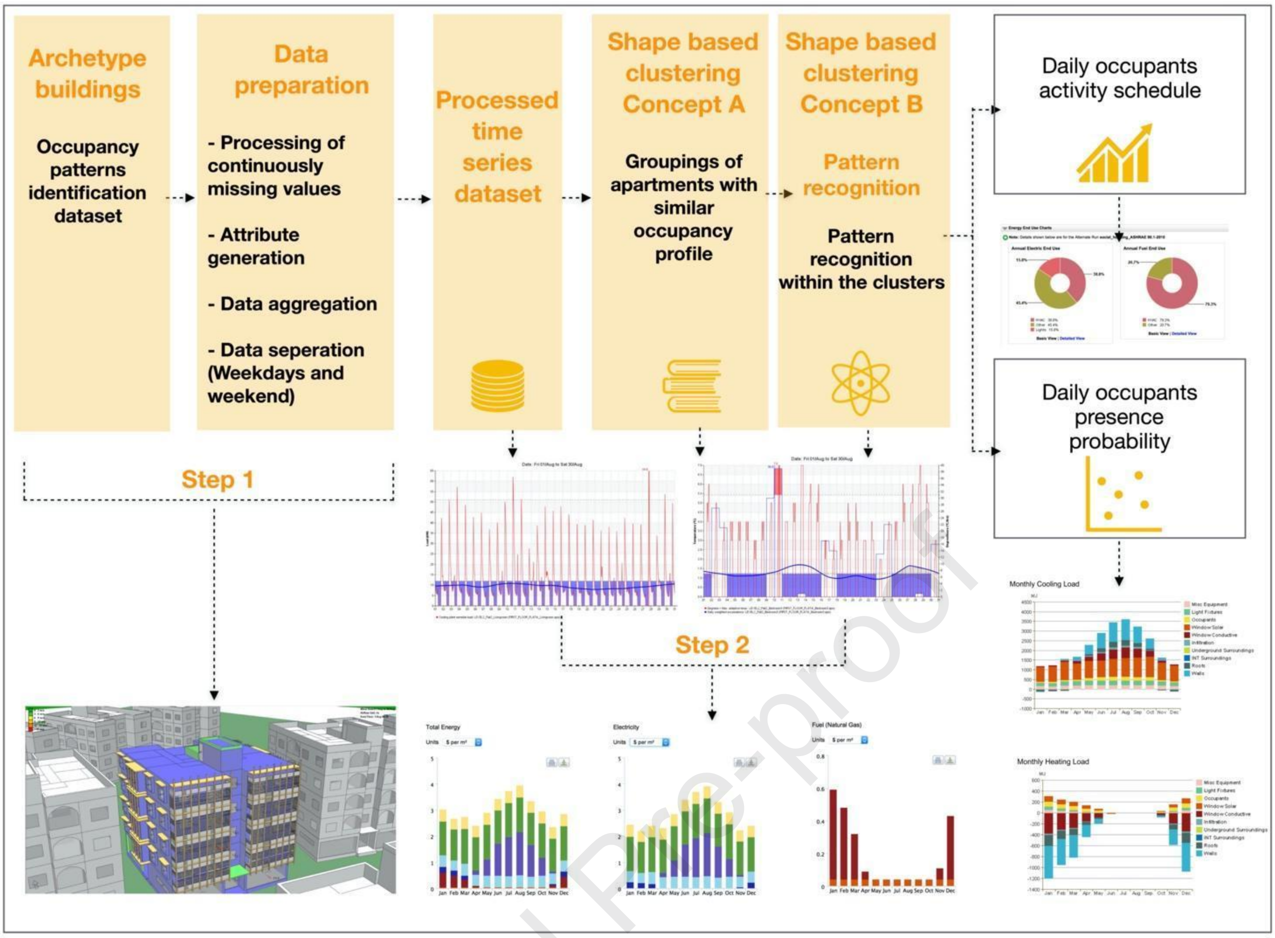


Fig.7. Aggregation of archetype building stock for energy policy design.

The study conducted by Loga *et al.* (2016) considered a relatively large sample size for statistical analysis [83]. The international database they used includes the building typology and *U*-values of representative archetypes, offering cross-country validation for the development of effective EPC development schemes in EU-27 countries. By comparison, in the present study, the sample size was relatively small. It consists of 100 households' *in-vivo* experiences in energy use that were collected across 36 RTBs in the same region; however, these findings could be applied to other post-war social housing estates in the four different climatic zones in Cyprus because RTBs have similar floor plan layout designs and *U*-values of thermal properties. The dataset that was the output of this empirical case study can therefore contribute to the development of bottom-up energy modelling in the South-eastern Mediterranean region, as shown in Figure 8.

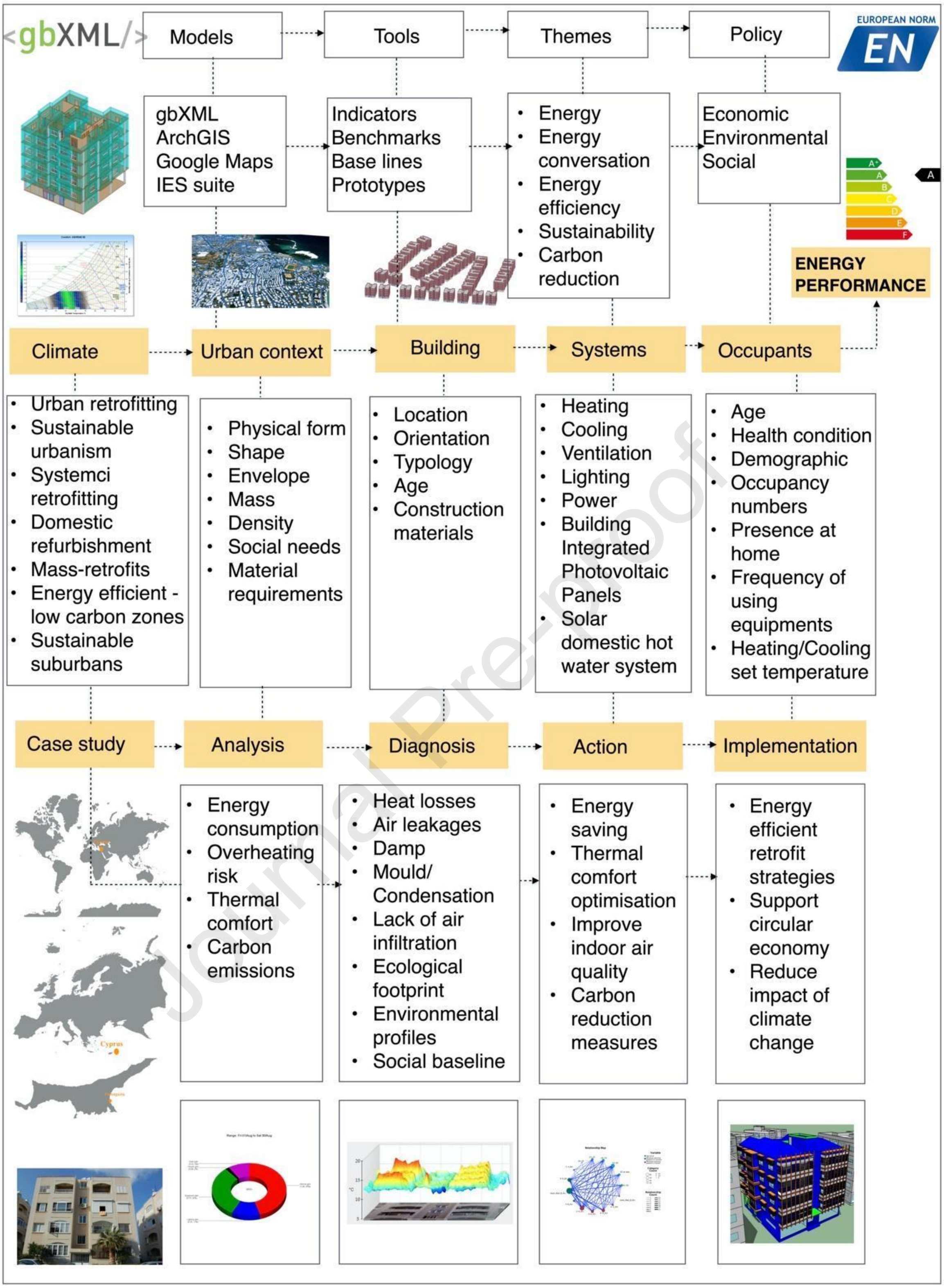


Fig.8. Steps for developing an evidence-based energy policy framework that considers households' adaptive behaviour on home energy performance.

Stefanovic and Gordic (2016) identified 10,771 multi-family residential buildings, including freestanding RTBs and high-rise apartments, in densely-built urban districts in Serbia [84]. In the Stefanovic and Gordic study, 86 RTBs were identified as archetype buildings to develop a method of design for improving energy efficiency in the housing stock [84]. The methodological framework developed by Stefanovic and Gordic shows a similar design approach to the present study by investigating potential thermal improvements in the building envelopes of residential multi-family staggered block buildings constructed between 1981 and 1990 [84]. However, Stefanovic and Gordic's study only considered assumptions generated through building energy modelling and simulations.

In the present study, the building-energy-simulation model was developed by gathering 100 households' socio-demographic characteristics, their habitual adaptive behaviours on home-energy performance, occupancy patterns, and thermal-sensation votes on occupants' indoor-air environments, all to feed model calibration while undertaking DTS. The findings were validated with occupants' actual energy bills. The methodological framework was set to develop simulation set-input parameters and was evidence-based; it predominantly relied on the responses of 100 households across 36 RTBs in a post-war social housing estate, as illustrated in Figure 9.

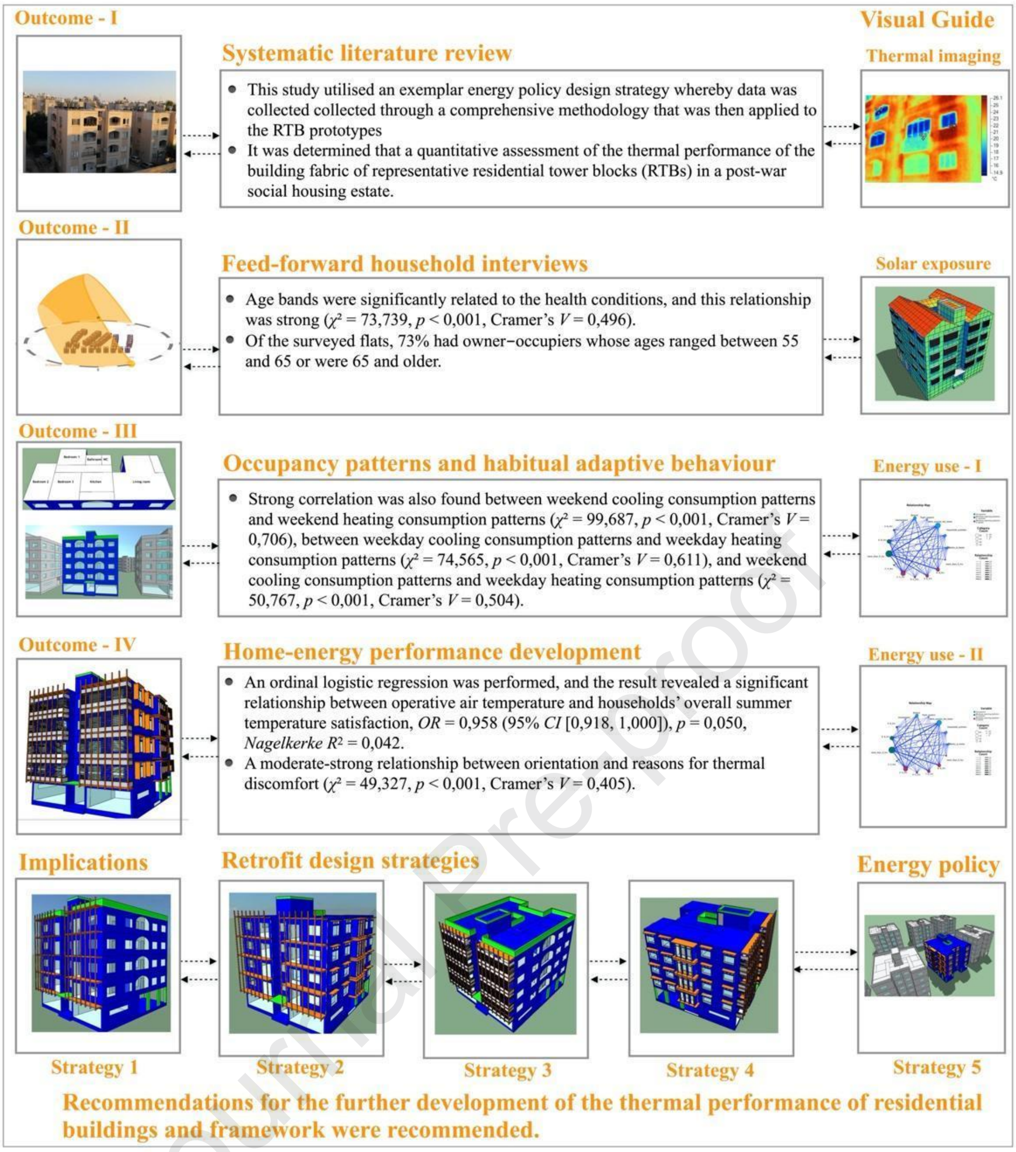


Fig.9. Inquiry strategy of the archetype analysis for developing an evidence-based energy policy.

One another similar methodological framework to that used in this study is that of Cerezo *et al.* (2017) [85]. This study identified 336 villa-type multi-family residential buildings built between 1980 and 1990 in an urban setting in Kuwait as an archetype building. In this pilot study, the authors set out to demonstrate an energy calibration method with households' actual energy bills to identify discrepancies between metered- and simulated-EUI distributions of the housing stock. In the present study, an evidence-based model calibration was developed to aggregate building energy simulations by using 36 RTBs as a base-case scenario that could be extrapolated to other post-war social housing estates in four different climatic zones in Cyprus. To prove the validity of the universal design approach for the STS conceptual framework, the study examines the pilot research project conducted by Pittam and O'Sullivan (2017) [86]. This pilot study used 1,551 samples gathered from the available

EPC database to measure the building-energy performance of residential terraced housing stock (identified as an archetype building typology) for aggregating energy performance of base-case archetype buildings before and after retrofitting.

To validate the energy model, a reasonably large sample size was identified by using *U*-value parameters of building elements to use the power of statistical analysis, with the goal of impacting the research for local policymakers and practitioners. In the present study, Housing Census and Construction Statistics were used to identify the national representativeness of archetype housing stock in four different climatic conditions in Cyprus; the findings were then extrapolated to determine the base-case post-war social housing estate by undertaking a longitudinal field study investigation to create the building energy simulations. It should be noted that there is no EPC data available for NC, and this study set out to develop an evidence-based energy policy framework to assess robust energy-performance evaluation and certification schemes in South-eastern Mediterranean countries. In the present study, 100 households were recruited across 36 RTBs in the same region; this sample was reasonably small compared to the statistical method used by Pittam and O'Sullivan [86]. This is due to the fact that the pilot study conducted by Pittam and O'Sullivan used already available EPC datasets for Ireland, while in the present study the most-up-to-date construction statistics of the RoC were generated to fulfil this technical constraint at the time of identification of archetype building typology for NC, and there is no such available EPC data for NC. To avoid research bias and eliminate the research limitations in the present study, the bootstrapping method was used to increase sampling size to test associations between households' socio-demographic characteristics and their actual energy bills to provide reliable energy-efficiency implications for the residential sector in NC.

Table 1 (d) demonstrates the development of a design for an energy policy framework to determine the selection criteria for archetype buildings across the world.

Table 1 (d)
The literature on building stock aggregation through archetype buildings (Continued).

References	A. Study Location	B. Building Type	C. Sampling Size	D. Primary Aim of Model	E. Methodology	F. Main Findings
[87] Streicher *et al.* (2018)	Sweden	SFHs and MFHs located in urban, suburban and rural regions	10,400 Cantonal Building Energy Certificates; 54 archetypes were identified; SFHs represent 14.4% and 14.1% of the total housing stock; MFHs represent 55% of the total housing stock	To provide the current thermal performance level of the Swiss residential building stock in 2015 based on an analysis of the data available from energy certificates; to estimate a thermal performance level of archetype buildings and their respective building elements	Cantonal Building Energy Performance Certificate data was used; archetype housing stock data was analysed; the statistics of the Federal Register of Buildings and Dwellings were examined; current state of the Swiss residential building stock was assessed; potential improvements in the building stock were proposed	Approximately 75% of all building elements do not yet reach the thermal performance of buildings constructed in the last 15 years; the *U*-values of building elements would have to be reduced by an additional 0.3-0.7 W/m^2K to reach low-energy standards
[88] Yi and Peng (2019)	Seoul, South Korea	High-rise apartment stock, MFHs	The total number of households was 2,830,857, of which about 58% (1,641,383) lived in apartments	To introduce an ‘archetype-in-neighbourhood’ framework to develop cooling energy supply planning; to demonstrate estimated increases of the maximal month cooling energy demand	A bottom-up hybrid approach was adopted; empirical urban data modelling was used; EnergyPlus was used for model calibration; electricity use data of 659 apartment buildings (51,351 households) sampled from 18 city districts; characteristics of residential energy use during the hottest month (August) was examined	The coefficient of determination from the scatter plot between the observed and the predicted was 0.969, representing about 97% variance in observed peak cooling energy use
[89] Li *et al.* (2019)	Chongqing, China	Urban residential blocks; MFHs in urban residential districts	Households with one elderly retiree and elderly retired couples accounted for 4.86% and 4.40%, respectively, of all households	To develop a localised residential building stock-space heating and cooling modelling approach to estimate energy consumption and related carbon emissions	A bottom-up engineering approach was used; development of residential archetypes; space heating and cooling energy consumption simulation and aggregation; stock total floor area calculation and construction age distribution; EnergyPlus was used for model calibration	The total energy consumption for space heating and cooling can be significantly reduced, with estimated reductions of 57.6%–60.70% in 2020 and 55.3%–57.2% in 2050
[90] Pittau *et al.* (2019)	EU 28	SFHs; MFHs	Post-war buildings built between 1945 and 1969, representing 30% of housing stock	To investigate the effect of massively storing carbon in bio-based construction products	A statistic-based geo-cluster model was developed; a dynamic life-cycle assessment was performed; Eurostat data was used for the archetype housing identification	Up to 3% of the total GHG annually emitted by all sectors in 2015 can be removed by 2050

Streicher *et al.* (2018) conducted a pilot study on the assessment of the current thermal performance of the Swiss residential building stock [87]. In this study, a 10,400-household sample of the EPC of buildings was used to determine the *U*-values of building fabric elements and identify feasible retrofit design scenarios. The representative housing typology was identified through investigation of the construction periods between 1920 and 2015. This study assessed the thermal performance of housing stock by using available EPC datasets. Findings were examined against the recommended benchmarking criteria for the purpose of developing energy policy for the Swiss context at both a regional and national level.

In the present study, a bottom-up approach was adopted to develop a method of design for the integrity of the STS design approach while conducting a longitudinal field study investigation in the South-eastern Mediterranean Island of Cyprus. The archetype buildings were identified from the Housing Census and Construction Statistics of Northern Cyprus in order to represent a general base-case scenario development that could contribute to retrofit energy policy design within the integration of the STS design approach. In the present study, 100 households were recruited from a post-war social housing estate and the findings were applied to other similar post-war social housing estates built between 1984 and 1997 across the island. The large sample size (10,400 available datasets) of the Streicher *et al.* study allowed the authors to present an accurate energy policy design [87]. The sample size of the present study was relatively small in comparison; however, the present study utilised the bootstrapping method to increase the sample size while assessing the impact of households' socio-demographic characteristics on home energy performance.

A distinct point of difference between the two studies is that while the study conducted by Streicher *et al.* considered a technical aspect by using the available EPC datasets, the present study used households' *in-vivo* experiences on energy use and the thermal performance of building elements and retrofit design strategies, all of which were developed through an investigative field study, as shown in Figure 10. One of the prominent scientific contributions of this longitudinal field study investigation in Cyprus is the step-by-step development of the STS energy policy design.

Yi and Peng (2019) conducted a comprehensive pilot study by using archetype high-rise multi-family residential buildings in South Korea [88]. To develop the statistical analysis, 659 apartment buildings (51,381 households) were identified as archetype buildings across 18 city districts in Seoul. This study was conducted by using available datasets for the *U*-values of thermal properties of buildings and households' energy bills. All the collected data was calibrated by using the EnergyPlus software suite to develop an archetype-in-neighbourhood framework for modelling the cooling energy demand of a city's housing stock.

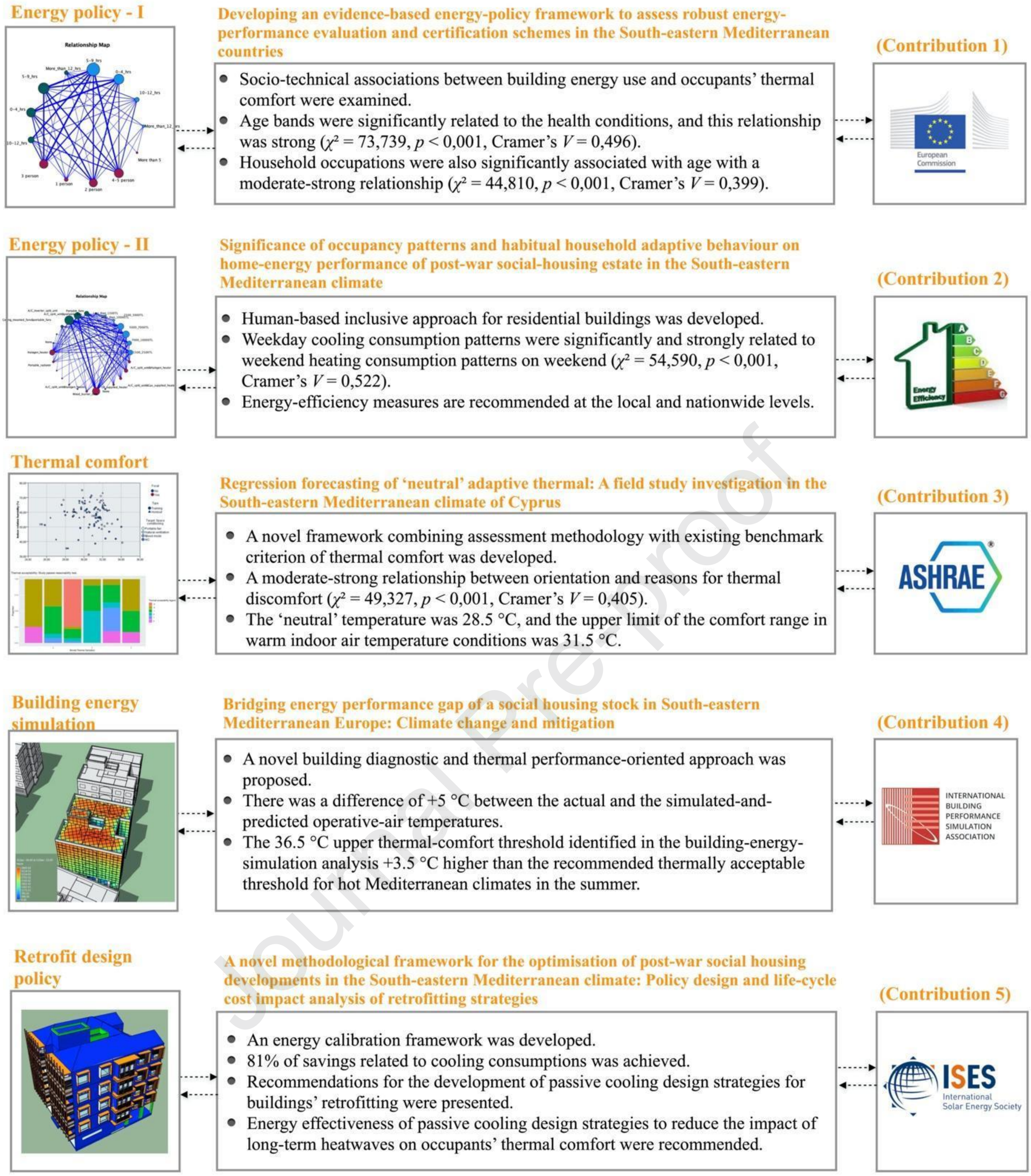


Fig.10. The set-up of the field study investigation and data processing methods for the study.

The Yi and Peng study shows distinct similarities to the present study, as this study collected households' energy bills in the peak cooling period of August and undertook a multiple regression analysis to identify key determinants of cooling energy use in South Korea [88]. Additionally, Yi and Peng used the EnergyPlus software suite to undertake the energy calibration analysis, and households' sub-metering data was also used to identify discrepancies between predicted and measured data on home-energy use [88]. In the statistical analysis conducted by Yi and Peng, a k-fold ($k = 4$) validation method was applied to verify the accuracy of the regression model that was integrated for the retrofitting of buildings in South Korea, but in their study no field investigation was conducted to collect households' *in-vivo* experiences on energy use and thermal comfort was not assessed [88].

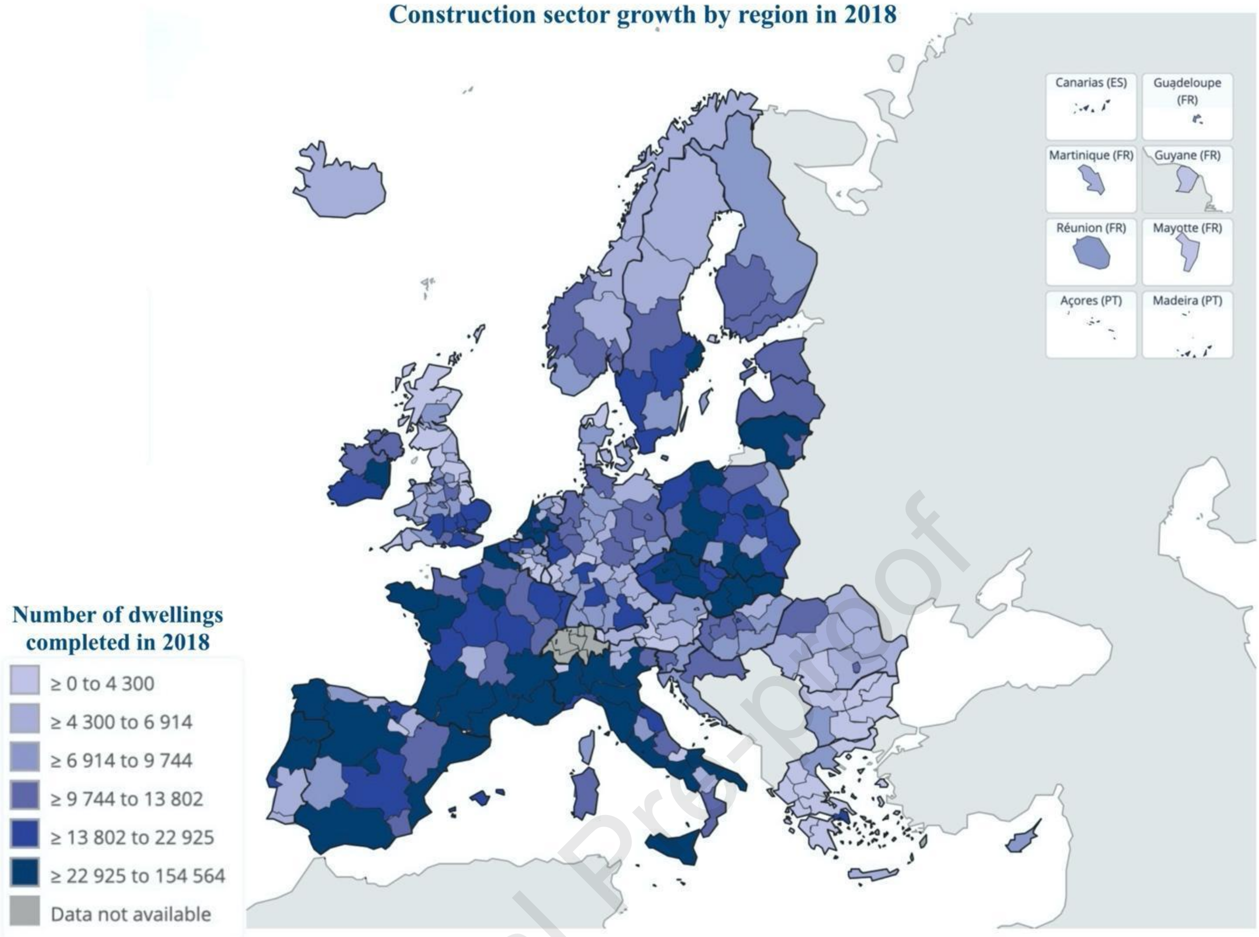
A prominent contribution of the present study is that dominant representative occupancy profiles were integrated into a black-box energy model. This data was gathered through a questionnaire survey, and energy benchmarking of the existing post-war social housing stock was assessed accordingly. While the study conducted by Yi and Peng only considered standardised benchmark criteria to assess thermal energy performance of its 659 apartment units, the present study set out to develop a reliable black-box energy model to undertake dynamic thermal simulations [88]. In this study, the findings rely on the accuracy of the BES to inform retrofit policy design, while the study conducted by Yi and Peng demonstrates BES findings predominantly based on estimations that predict scenarios of the cooling energy demand of Seoul's housing stock [88].

A bottom-up engineering approach for building stock energy modelling was developed by Li *et al.* (2019) [89]. In this pilot study, archetype multi-family residential buildings in urban residential districts were identified as archetype housing stock for an energy calibration analysis in China. To identify the national representativeness of housing stock, census data was used to conduct a statistical analysis. It was found that households containing one elderly retiree or elderly retiree couples accounted for 4.86% and 4.40%, respectively, of all households in densely built residential urban districts in China [89]. The statistical analysis confirmed that 93% of all housing-type categories were covered by the selected household structure for the purpose of aggregate energy modelling. In the study, the black-box energy model was verified by using both *on-site* environmental monitoring and *in-situ* physical measurements of indoor occupied spaces. The study proposed retrofit energy measures as an outcome of the analysis.

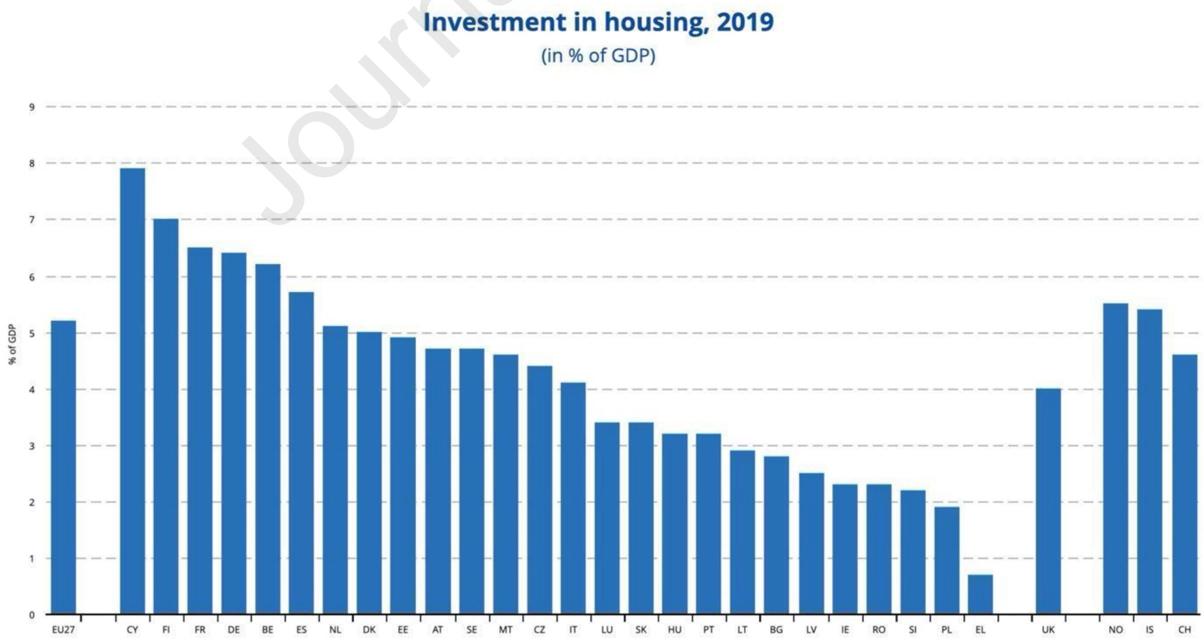
The study conducted by Li *et al.* shows distinct similarities with the present study in terms of the integrity of the field measurements and the building energy simulations used to calibrate energy performance of archetype buildings [89], but their study did not undertake a questionnaire survey to determine energy use according to households' socio-demographic characteristics [89]. The strength of the Li *et al.* study is that the sampling size was large enough to represent the entire population in 18 districts in China. To reflect the method of design applied by Li *et al.*, in the present study, findings were applied to four other cities where the post-war social housing estates were also built between 1984 and 1997. The census data supported the nationally representative nature of the post-war social housing estates, and the post-war social housing estate selected for reference enables a generalisation of research findings. To understand the impact of this field study investigation, outcomes were integrated with the EPBD for the 27 EU countries.

A contrasting study, the pilot study conducted by Pittau *et al.* (2019), presents the carbon-storage potentials of the EU housing stock [90]; however, this study does have a similar design approach to that developed in the present study. To identify the representativeness of housing stock in the EU, the pilot study conducted by Pittau *et al.* used the geo-mapping cluster technique to evaluate the thermal performance of buildings in seven climatic zones in the 28 EU countries and develop an effective energy policy design for each country [90]. One of the prominent similarities of this pilot study with the present study is that post-war buildings built between 1945 and 1969 were selected as the archetype building typology. These post-war buildings represent 30% of overall residential building stock in the EU 28. The Pittau *et al.* study tested the energy effectiveness of bio-based construction products applied onto the building envelopes of post-war social housing estates; their analysis included a life-cycle cost assessment that was used to demonstrate the economic viability of these state-of-the-art building materials for retrofitting existing social housing stock. In the present study, modular off-site passive cooling technologies were applied on the archetype housing typology by considering the bio-climatic design elements of evidence-based retrofit energy policy designs, specifically in the South-eastern Mediterranean region.

After reviewing the extant worldwide literature on the identification of archetype building typologies and their integration in the development of building energy models for determining effective energy policy design, it can be concluded that a method of design that undertakes a parametric analysis by integrating collated data gathered through a questionnaire survey and field measurements can play an important role in decision-making criteria regarding domestic energy use. To reflect the statistical methods used by previous scholars, the present study examined the EU's construction statistics by using the geo-mapping cluster method, as shown in Figure 11 (a), and the findings were validated with the available housing census data for the EU countries, as shown in Figure 11 (b).



(a)



(b)

Fig.11. (a) Distribution of dwellings built in EU member states in 2018; **(b)** Distribution of investment in housing in 2019 in percentages of GNP.

As shown in Figure 11 (a), there is a high demand for construction projects in the South-eastern Mediterranean region. While Portugal, Spain and Italy accounted for the highest number of residential buildings built in 2018, (for these EU countries, it was found that number of dwellings constructed was between 22,925 and 154,564 annually), these figures were followed by Greece and Cyprus were the number of dwellings built ranged from 9,744 to 13,802 annually [91][12].

The Eurostat data figures show those South-eastern Mediterranean countries offer a wide range of SFHs and MFHs for both locals and foreign buyers. According to the Eurostat data, in 2018, 60% of Spanish households lived in flats, 53% lived in flats in Italy and 47% lived in flats in Portugal [91]. In Greece, while the number of dwellings built in 2018 was slightly less than in these other EU countries, about 57% of Greek households lived in flats. While about 27% of Cypriot[13] households live in flats, the population of the island is relatively smaller than most other EU countries in the South-eastern Mediterranean basin, so that 27% of residency in flats is high for the Cypriot context. For the 27 EU countries overall, it was found that 47% of residents live in flats [91]. The obtained average of 27% can be classified as a reasonable fraction to represent the archetype building typology for the RoC. It should be noted that the Housing Census and Construction Report statistics in NC reveal that the low-, medium- and high- rise RTBs account for 56% of the overall residential building stock. This generated statistical data proves that the NC housing stock was slightly above the EU-27 average.

Interestingly, the NC housing stock data is not included in the Eurostat database due to NC being only a *de-facto*[14] state. Northern Cyprus is also underrepresented by the RoC, which does not give a reliable representation of any type of housing stock data for the island of Cyprus. From this statistical analysis, it can be deduced that 56% of high-density residential buildings are nationally representative for NC[15]. This data confirms that high-rise apartments are the representative archetype to be investigated as part of the bottom-up energy policy design. To prove the demand for housing projects, this study investigated housing projects in 2019 by assessing the GNP rate for each of the 27 EU

[12]Geo-cluster mapping of the number of dwellings built in EU countries in 2018 extracted from the Eurostat database. Available at https://ec.europa.eu/eurostat/databrowser/view/SBS_R_NUTS06_R2__custom_139216/bookmark/map?lang=en&bookmarkId=6c9d0532-05e5-46a6-b53d-9ee4b98a73e2 (Accessed on 18/09/2021).

[13]Data only represents population and housing stock in the southern territory of the RoC; NC housing stock is not included due to being a *de-facto* state.

[14]In law and government, '*de facto*' describes the constitutions that exist in reality, even though they are not officially recognised by law. NC has a parliamentary system that is the result of a unilateral declaration of a republic. Notably, the EU security council condemned the declaration and called on EU member states to respect the independence, sovereignty and territorial integrity of the RoC.

[15]Data extracted from the State Planning Organisation: http://www.stat.gov.ct.tr/INSAAT-YIL-11.aspx. The statistical analysis was undertaken to generate the most-up-to-date construction statistics available from 2015 to 2019, and the findings were applied to a cumulative percentage calculation of overall housing stock in NC.

member states, as shown in Figure 11 (b)[16]. It was found that the island of Cyprus accounted for the highest share rate at 7.2% of GDP spent on housing[17]. These figures were followed by 6.6% in Finland, 6.4% in Germany, 2.3% in both Slovenia and Ireland, 2.2% in Poland, 2.0% in Greece and 0.7% in France [91].

As the EU-27 average was found to be 5.3% of GNP spent on housing, Cyprus's rate was relatively higher than that of other EU countries [91]. This demonstrates that there is high demand in Cyprus for housing projects. It should be noted that Cyprus's population is smaller than other EU countries, and yet the GDP rate shows that the economy is dominated by the construction sector in Cyprus. This statistical data proves that the selected archetype housing typology is appropriate for developing aggregate energy models to validate the data collection findings integrated into the black-box energy model for this study. In the present study, the representative archetype buildings were selected from four different regions and then one of these post-war social housing estates was chosen to extrapolate data to other dwellings in Cyprus, as shown in Figure 12.[18] To identify the representativeness of each post-war social housing estate, both the census data and Housing and Construction Report statistics were investigated to provide a reliable representation rate for each of the cities where the government's social housing estates were built between 1984 and 1996. An up-to-date statistical analysis was undertaken to comply with the most reliable data available for the housing stock between 2015 and 2019[19]. It was found that in the coastal city of Famagusta where the base-case post-war social housing estate is located, in urban areas, 62% of dwellings are residential buildings, 28% are apartments and 10% are houses. In suburban areas in Famagusta, 44% of dwellings are residential buildings, 37% are apartments and 19% are houses. It should be noted that according to the Statistical Annual Report in 2019, 38% of the overall buildings represent all housing typologies in NC. In mapping representativeness of post-war social housing estates, it was found that apartments in suburban areas in Famagusta represent 37% of dwellings, which proves the appropriateness of the representative archetype of RTBs for the study.

[16] Data on the distribution of investment in housing by each EU country in 2019 extracted from the Eurostat data. Available at https://ec.europa.eu/eurostat/databrowser/view/NAMA_10_AN6__custom_138747/bookmark/map?lang=en&bookmarkId=22dc747f-7535-4c8f-90af-f3264fc51d5b (Accessed on 18/09/2021).

[17] This GDP rate demonstrates both the high demand for housing projects in the RoC and that the construction sector accounts for the highest share of the economy in Cyprus. It should be noted that this statistical data does not include NC. To provide reliable background information, the most-up-to-date statistical data was extracted from the Housing and Construction Statistics in NC and applied to the identification of representative archetype buildings in NC.

[18] For the identification of representative archetype buildings and the sampling size for the survey, an online calculator was used to aggregate the statistical power of the survey. Available at https://www.calculator.net/sample-size-calculator.html

[19] Data extracted from the State Planning Organisation: http://www.stat.gov.ct.tr/INSAAT-YIL-11.aspx

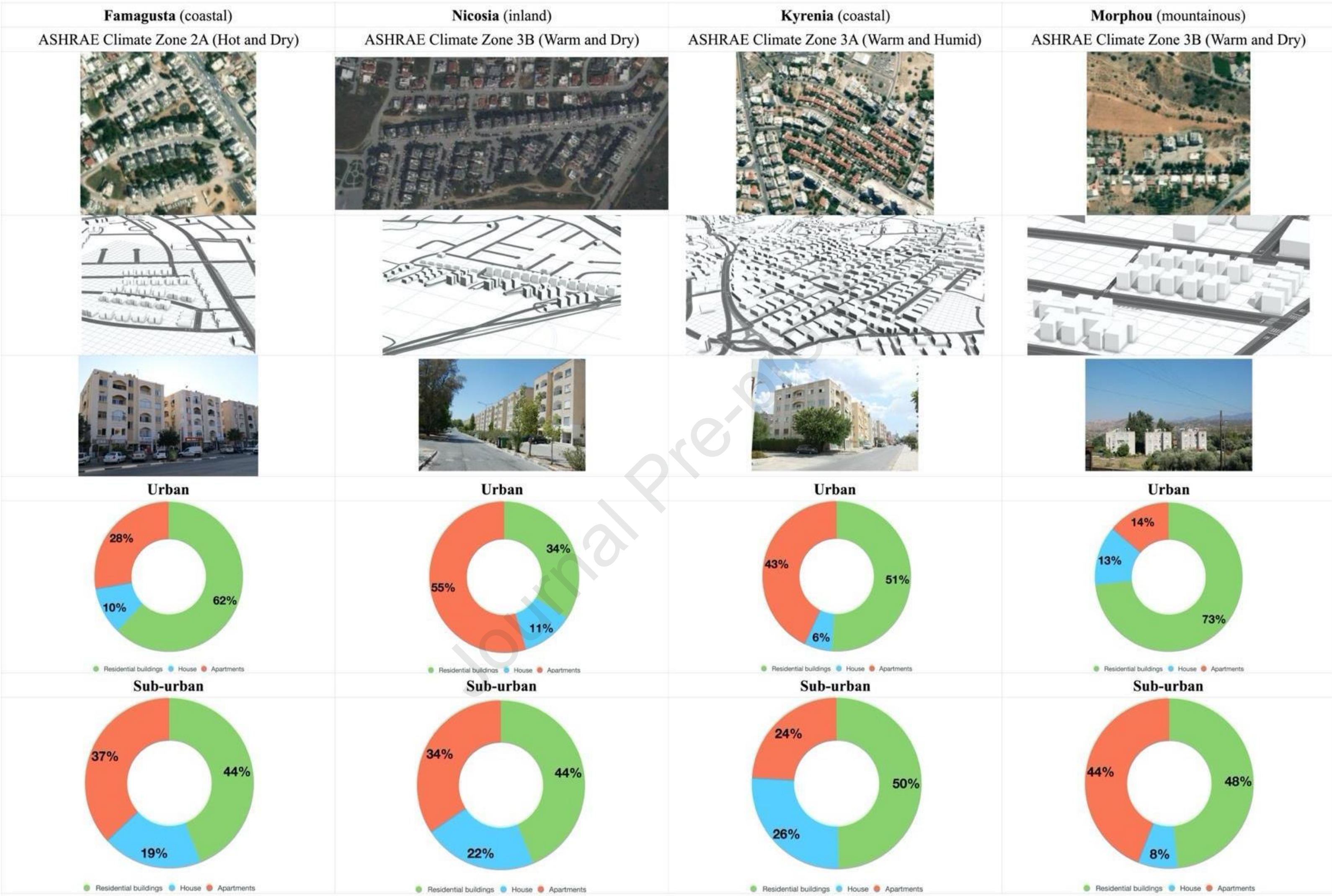


Fig.12. Distribution of representative post-war social housing estates.

In the inland region of Nicosia, apartments comprise the highest share of the overall housing stock at 55% in urban areas, followed by 34% residential buildings and 11% houses. In suburban regions, 44% of housing stock is residential buildings, 34% is apartments and 22% is houses. The vast majority (78%) of housing stock is either residential buildings with two to four storeys, or apartment buildings that are more-than-four-storey high-rise MFHs.

In the coastal city of Kyrenia, 51% of dwellings are residential buildings, 43% are apartments and 6% are houses in the densely built urban region, but recent rapid construction activity has had an impact and in suburban regions 50% are residential buildings, 24% are apartments and 26% are houses. Overall, in Kyrenia, 95% of housing stock is residential buildings and apartments, which proves the applicability of research findings in the coastal city of Famagusta to this context where the climate is warm and humid in the summer.

As shown in Figure 12, in the mountainous region of Morphou, it was found that the housing stock is 73% residential buildings, 14% apartments and 13% houses in the urban region. Noticeable in this region is a record of residential buildings that account for 48% of overall housing stock, followed by 44% apartments and 8% houses in the suburban area. It should be noted that this region shows the highest percentage of apartments built amongst the suburban regions of the other cities, as illustrated in Figure 12. It can be deduced that both residential buildings and apartments are nationally representative archetypes, which allows an extrapolation of research findings gathered in the base-case post-war social housing estate in the coastal city of Famagusta to an evidence-based energy policy framework for the South-eastern Mediterranean basin.

3. Methodology

The purpose of this section is to present the study's research methodology by explaining the rationale for the research, its hypotheses and its aims and objectives. Subsequently, the case study location is presented and discussed, and the research design model adopted to address the research problem. The case-study residential buildings are described and the research design model that was adopted to conduct field surveys is explained.

3.1. Case study of a post-war social-housing stock in South-eastern Mediterranean

3.1.1. Selection criteria of case study location

The research on the base-case representative was deployed with the general aim of providing a series of guides, tools and findings that may inform the energy consumption reduction and retrofitting processes of both existing and recently built housing stocks as well as their neighborhood urban blocks in Famagusta, Northern Cyprus. The researcher identified the sample city, Famagusta, and its densely built city centre area, located on the eastern periphery of Cyprus, as a model and proxy for other coastal cities in Cyprus, as shown in Figures 13 (a) through (c).

Fig.13. (a) The location map of the coastal city of Famagusta and its urban peripheries; **(b)** The location map of the social housing development under investigation.

The territory is characterised by a fragmented and endlessly repetitive stream of self-built residential areas and privately owned construction company-built mass housing estates with no recognisable distinctions between them and the city centre [92]. In comparison with other densely built Mediterranean cities, Northern Cyprus is dominated by large-scale residential developments not only in its coastal regions but also in its mountainous regions, including urban agglomerations, as shown in Figures 13 (a) and (b). At the same time, almost half (45%) of the owner-occupied building stock consists of self-built houses, often detached. The rest are low-rise flats (13%) or high-rise flats (44%) [93]. It is also noted that most urban agglomerations consist of a mix of housing types, such as single- and multi-family mix, single- or multi-family and apartment block mix or apartment block and high-rise mix.

Large-scale residential tower blocks and mass housing development estates are built and regulated by privately owned construction companies. Such projects are often the size of entire city districts but are rarely geared towards the concept of a socially and functionally diverse and structurally open city [92, 93]. Current problems are aggravated when considering that the implementation of energy efficient technologies is required, which better suit the occupant's thermal comfort needs, that is, mass housing estate developments. It is obvious that the supplied building stock could not match the energy efficiency implications and current tools for linking existing construction practices and the power of adopting energy design strategies for retrofitting existing post-war social housing estates.

3.1.2. Archetype housing typology selection

A post-war social-housing stock was used as a base-case representative scenario development to develop an evidence-based methodological framework for retrofit policy design and improve current methods of design in buildings' retrofitting. The study was aimed to provide a series of design guidelines and policy tools in order to provide a roadmap for effective policy making decisions in energy use. To fulfil research, aim and objectives, this study seeks to inform the significant importance of households' energy use and the issues are arisen as a result of their high lifestyle expectancy at the time of implementing long-term holistic retrofitting for policy making decisions with taking into account both the existing and recently built housing stock, as well as neighbourhood urban blocks in Famagusta, Cyprus. To provide exemplar pilot study in energy network transitions both conceptual and nationwide levels and contribute to the EPBD mandates accelerated for EU-27 Member States, the researcher identified the sample city, Famagusta, and its densely built city-centre area, which is located on the eastern periphery of Cyprus, as a model that could serve as a proxy for other coastal cities in Cyprus, as shown in Figures 14 (a) and (b).

Fig.14. (a) The coastal city of Famagusta; **(b)** position of RTBs in the social housing development estate; **(c)** physical condition of RTBs; **(d)** representative floor-plan layout of a nit in the RTBs. ***Sources:*** (a) and (b): Maps are extracted from the ArcGIS Pro Version 2019.01 software suite.

It should be noted that this layout for social-housing estates was used as an exemplar development project under the governmental social-housing scheme in the mid-1980s and early 1990s, because it was affordable and practical to accommodate a large number of residents in a short period of time, which indicates that the government took a decisive role in replicating this same housing project in four other major cities in NC. It should also be highlighted that this social-housing project was not limited to Famagusta households; it was also representative of the entire social-housing stock in NC. Notably, terraced houses were built under the governmental social-housing scheme concurrently with medium-rise RTBs, but only a limited number were constructed, because construction materials for these structures were more expensive; hence, the government offered less-affordable options to social-housing residents. This is why medium-rise RTBs were the subject of the present study.

In summary, these indicators reveal the determinant factors for the selection of Famagusta as a case-study location and medium-rise RTBs as archetype buildings to develop an evidence-based STS framework for policymakers.

3.1.3. A post-war social housing estate selection criteria

A representative sample of residential buildings was selected, and these buildings were inspected to verify the constructive features and ensure that the structures conformed to the corresponding sub-typologies to develop an analytical building-energy model for the present study. Due to the repeatability of the typologies in the spatial-plan layout organisation and the construction features that were found, the thermal properties of the existing RTBs were able to be identified.

Regarding the analysis of existing social-housing stock, it should be emphasised that the same building design, technology, material and spatial organisation, which has shown high potential for retrofitting efforts of the prototype RTBs, were applied and implemented. There are two types of RTBs in NC: four-storey structures without communal amenities and five-storey structures with commercial premises located beneath the flats, as shown in Figures 15 (a) through (c). There were no lifts, mechanical services or ventilation shafts due to reduced construction costs, and no central-heating systems or infrastructure were available for homeowner use.

(a) (b) (c)

Fig.15. (a) High-density medium-rise post-war social-housing development estate; **(b)** current condition of prototype RTB and southwest-facing RTB; **(c)** building façade designed without considering climate characteristics.

Residents of these buildings were selected by the Famagusta Municipality Housing Department according to criteria related to household income, occupation, marital status, family structure and home-ownership status; these occupants were eligible to apply to the governmental social-housing scheme in mid-1980s and early 1990s. It should be noted that these apartment units were sold to the occupants at affordable prices, and no regulatory relationship was implemented with the social-housing structure to accommodate the low-income and vulnerable populations in the council estates, as there are in the U.K.; this is the reason for the lack of available centralised maintenance mechanisms to restore these buildings, which is why the majority of the RTBs are in disrepair after only 30 years. There is currently an urgent need to undertake long-term holistic retrofitting schemes to upgrade the energy efficiency of post-war social-housing stock, but the Famagusta Municipality is not in an economic or political position to initiate a retrofitting agenda to improve the thermal resilience of the building fabric of these RTBs.

3.1.4. Energy consumption

In Cyprus, electricity is derived from fuel oil; this is the most expensive form of energy production [94]. Figure 16 illustrates energy-dependency rates for all EU member states between 2008–2018. The lowest energy-dependency rates in 2018 were recorded for Estonia, Denmark, Romania and Sweden; Malta, Luxembourg and Cyprus were almost entirely dependent on primary energy imports, with dependency rates between 92,4–97,8% [91]. Due to its geographic location and energy governance, Cyprus was the third-highest energy importer.

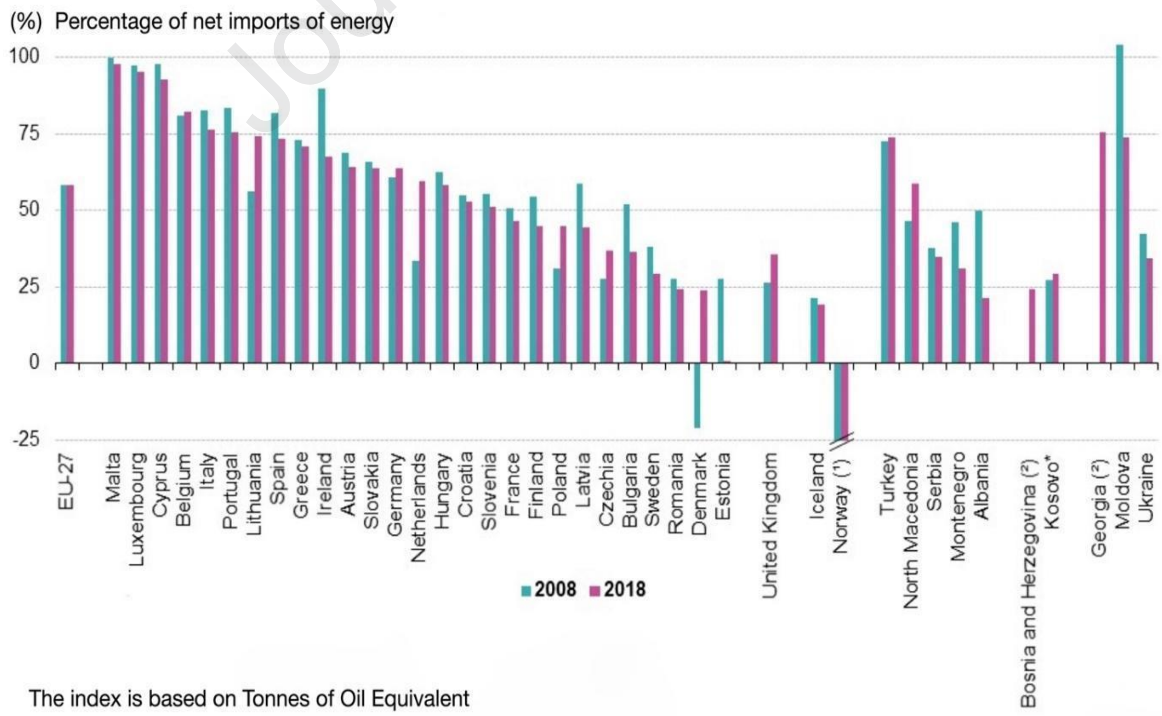


Fig.16. Energy-dependency rates for all EU member states between 2008–2018.

According to the Ministry of Agriculture and Energy statistics (2019), 43,34% of diesel fuel was imported to respond to growing energy demands for central electric units. These results indicate that energy consumption in NC was dominated by oil products, which produced 80% of the total energy; the remaining 20% of production was from coal, an energy source used for cement production and in other heavy industries, and solar energy. Because of the absence of regulatory bodies and NC's status as a *de facto* state, energy conservation was not a priority for the authorities or government initiatives, and total energy consumption rose by approximately 4,5% each year in the period of 1983–2004, with a significant increase in 2005 that was the result of a property boom in the early 2000s [95]. This exponential rise in energy consumption gained momentum in 2017 due to high demand in the RTBs. The 2018 Cyprus Electricity Authority (CEA) statistics indicated that the residential sector consumed 230.367 MkWh (i.e., million kilowatt-hours) in 2003; this figure rose to 377.971 MkWh in 2017 [96].

In 2018, the CEA stated that there were no grid connections going to and from the island, so the eastern Mediterranean island of Cyprus could not trade electricity with surrounding countries. It was estimated that during the 2020–2025 period, renewable energy sources will comprise 20% of the total electricity generation. At the same time, the 2019 annual CEA report suggested that the remainder of the necessary electricity could be generated from fossil-fuelled power plants, the majority of which burn heavy fuel oil and to a lesser extent, diesel fuel.

Increasing energy demand in NC is primarily due to economic growth and better living standards; the absence of regulatory bodies in the area of energy governance makes implementing EPBD mandates problematic [97]. This energy-policy gap caused all sectors to be dependent on imported oil products to meet energy demands. The 2019 *CEA Annual Report* revealed that the power plant system in NC is isolated, resulting in significant barriers related to upgrading energy networks that have caused high energy costs [98]. To fully understand current energy consumption and the impact of construction activity on domestic-energy use, Figures 17, 18 and 19 highlight the greatest energy consumption from among the building stock in NC.

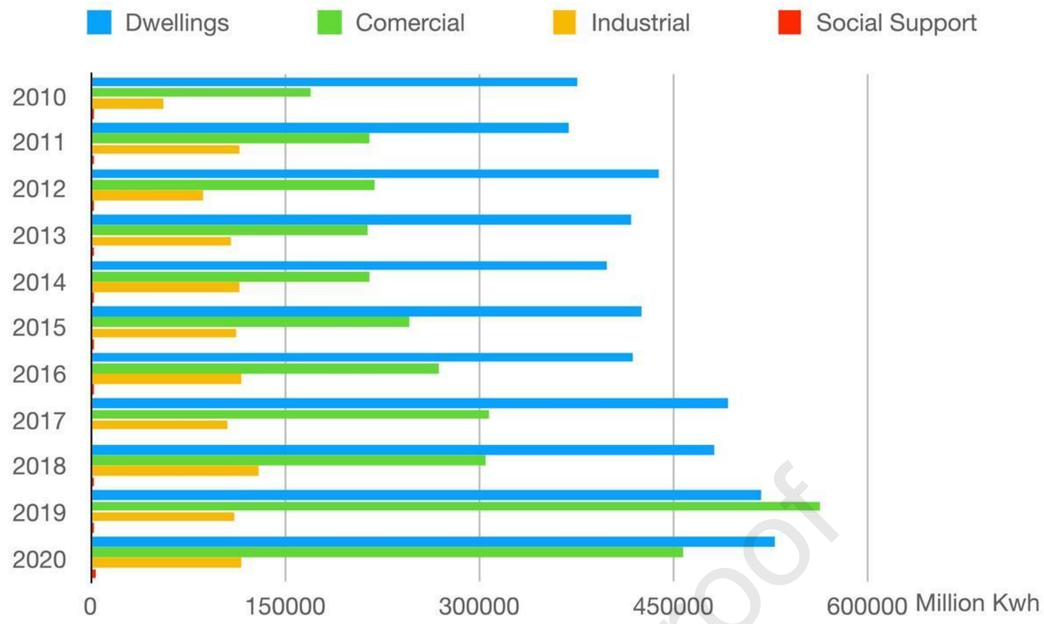


Fig.17. Total energy consumption of buildings in Famagusta from 2010–2020.

Figure 17 demonstrates the overall energy consumption in NC between 2010–2020; this time frame was selected because residential buildings and apartment projects gained momentum during this period as a consequence of demand on the property market by foreign investors. This rapid construction activity led to a sharp increase in the number of energy consumers. As is shown in the graph, energy consumption in dwellings continued to increase, followed by commercial buildings.

According to the 2020 *CEA Annual Report*, dwellings consumed 375.617 MkWh in 2010, and this amount increased to 528.231 MkWh in 2020; notably, data related to social support revealed that households consumed 2023 MkWh in 2010 and 3.246 MkWh in 2020. There was a notable increase in low-income consumers, whose energy bills were paid by government social service programmes; the findings revealed that 2% of the energy consumers were vulnerable households living in energy poverty. This energy-consumption index was used as a base line to validate the type of energy-consumer groups in the social-housing estates in Famagusta.

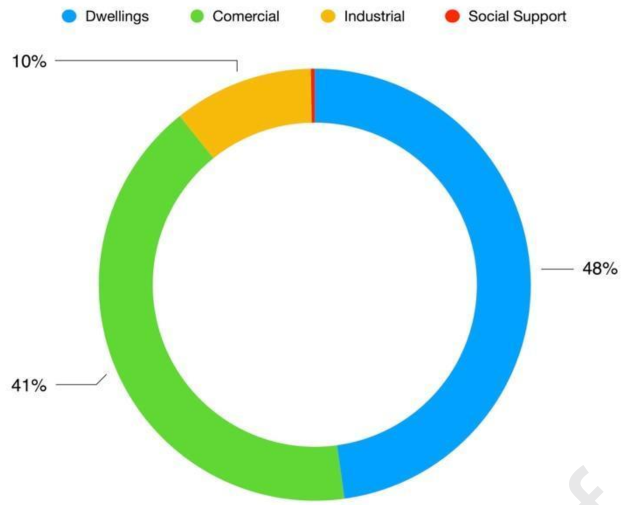


Fig.18. Proportional percentages of total energy consumption of buildings in Famagusta from 2010–2020.

Regarding energy consumption, Figure 18 shows that 48% was consumed by the residential buildings, followed by 41% by commercial buildings, 10% by industrial buildings and 2% by households who received social benefits from the government. These figures lead to an important conclusion, namely that the thermal-conductivity level of building properties could be the cause of high energy consumption.

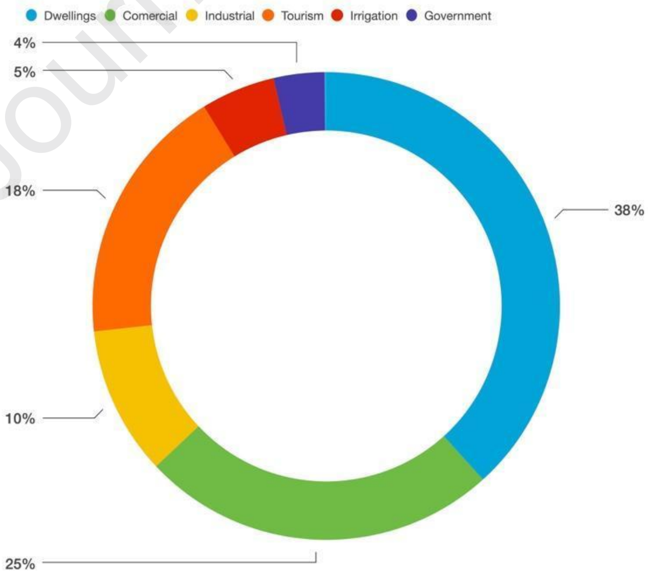


Fig.19. Proportional percentages of different energy consumers in Famagusta from 2017–2019.

Figure 19 demonstrates the overall percentages of energy consumers between 2017–2019. This timeframe was chosen because most of the 2–5-storey medium-rise RTBs and

5–23-storey high-rise buildings were constructed between 2017–2019 [99]. According to 2020 housing statistics, a significant increase in the number of flat units was recorded; approximately 90.000 units were completed in five major cities in NC, and there was a total of 37.458 energy consumers; this growth led to increased energy consumption during this same period.

The residential sector in NC accounted for 38% of the overall energy consumption between 2017–2019; within this same time frame, a majority of the NC housing stock was constructed and 38% of the 2–5-storey RTBs in Famagusta were completed. This is nationally representative of the overall social-housing stock in the urban and suburban territories in NC. To develop the STS conceptual framework, a social-housing estate located in Famagusta was chosen for an exploratory case-study approach. One of the primary reasons for this was because this social-housing estate was the first to be built with random RTB orientations, which did not consider any type of environmental design principles during the decision-making process.

3.2. Survey design and data acquisition

This study predominantly relied on a questionnaire-based survey intended to gauge household characteristics and the habitual adaptive behaviour of occupants on home-energy performance. To collect subjective data from the building occupants about domestic cooling energy use and to evaluate their comfort in specified orientations, a standardised questionnaire survey was developed. The survey was conducted with members of 118 households between July 28, 2018 and September 3, 2018. The research approach that was undertaken strongly correlated with different societal studies that investigated dependent and independent variables by using open- or close-ended questions related to the objective of the current study was undertaken in the coastal city of Famagusta where the climate is subtropical (*Csa*) and partly semi-arid (*Bsh*) and also there is no stringent of building regulations or EPBD mandates to upgrade energy efficiency of any type of buildings in this South-eastern Mediterranean climate. The aim of the survey was to explore the factors that identify the socio-demographic characteristics of different households, occupant knowledge of energy-saving methods, which home-energy systems were used and the summer and winter occupancy patterns of each unit, including window-opening schedules and energy usage, as shown in Table 2.

Table 2
Questionnaire details.

Section	Questions
Section 1: General background information	• Number of interviewed RTBs • Orientation • Floor level
Section 2: Socio-demographic information	• Gender • Age • Tenancy status and length of residency • Number of household members, including non-family members • Employment activity • Income • Education • Ethnicity • Health status
Section 3: Energy-saving awareness	• Did respondents receive energy advice from any type of public or private institution? • Availability of electricity meter readings and frequency of checks • Did the respondents consider any type of energy-saving methods in their daily activities?
Section 4: Home energy use and performance	• Types of domestic heating appliances, available heating-system controls and frequency-of-use • Types of domestic cooling appliances, available cooling-system controls and frequency-of-use
Section 5: Occupancy patterns	• Weekday and weekend heating-consumption patterns • Weekday and weekend cooling-consumption patterns • Window-opening patterns in summer and winter
Section 6: Energy consumption	• Average monthly utility bill amounts

The questionnaire also gauged the knowledge of each household of their individual heating and cooling systems in an attempt to ascertain what household members identified as energy-inefficient use of their cooling systems and how they adapted heating and cooling systems for their personal thermal comfort in changing climate conditions, particularly in the hottest month of summer, August. The field survey was carried out during the peak cooling period in the hot and humid summer season from late-July to September 2018. The survey participants were selected from among 36 residential tower blocks (RTBs) with similar floor plans, layout designs and construction characteristics in five buildings in the social housing estate, each of which had a different orientation (i.e., northeast, northwest, southeast, southwest and south), as shown in Figure 20.

Fig.20. The point-by-point walk through survey of the case study location, the field survey was undertaken on a door-to-door-survey of 36RTBs in the social housing estate.

As is shown in Table 2, the questionnaires included household's socio-demographic information in the interviewed RTBs with taking into account the orientation and floor level differences thereof. A set of questions was developed to inquire about the socio-economic characteristics and tenancy status of each household, including the length-of-residency at the property. Another set of questions focused on the households' energy saving awareness and advice received on information on energy-efficient practices that were provided to each household by the Famagusta Municipality or local energy networking service. Because the longitudinal questionnaire survey was conducted in the summer and the social households were asked to retrospectively indicate on various multi-factorial home energy performance indicators from the previous winter. As was already indicated, the questionnaire survey proforma was set to design in consideration of cultural assets, values and norms of the research context in order to obtain absolute accuracy for the statistical analysis. Table 3 delineates the type of measures for each variable to perform statistical analysis.

Table 3
List of the type of measures for each variable.

Variable Name	Measures
Age bands	Nominal
Type of cooling control at home	Nominal
Education level	Nominal
Reasons for thermal discomfort	Nominal
Ethnicity	Nominal
Orientation	Nominal
Cooling consumption patterns on weekdays	Nominal
Cooling consumption patterns on the weekend	Nominal
Heating consumption patterns on weekdays	Nominal
Heating consumption patterns on the weekend	Nominal
Windows opening reasons	Nominal
Household density	Nominal
Income	Nominal
Heating energy consumption in winter of 2015	Nominal
Heating energy consumption in winter of 2016	Nominal
Gender	Nominal
Economic status	Nominal
Occupation (4 groups)	Nominal
Type of heating system	Nominal
Type of cooling system	Nominal
Windows closing reasons	Nominal
Windows opening patterns in winter	Nominal
Windows opening patterns in summer	Nominal
Cooling energy consumption in summer of August 2016	Scale
Overall cooling energy consumption in summer of 2015	Scale
Overall heating energy consumption in winter of 2015	Scale
Cooling energy consumption in summer of August 2015	Scale
Overall cooling energy consumption in summer of 2016	Scale
Overall heating energy consumption in winter of 2016	Scale

3.3. Step-by-step development of statistical analysis

The Statistical Package for the Social Science (SPSS) Version 25.0 (IBM, Armonk, NY, USA) software suite was used to undertake correlation and multivariate analysis of longitudinal survey inputs were obtained through a questionnaire in the hottest summer month of August. This could provide us to compare the levels of energy use and the rationale for the real-life energy-use and home-energy performance of each household (see **Data Set A**). The raw data of the statistical data set was designed in the SPSS software to include spv. files to be used in future research.

A step-by-step statistical analysis was undertaken in accordance with the narrative order of the set of questions developed to understand multiple levels of households' socio-demographic characteristics and their home energy performance. For parametric variables (i.e., the normal form), Pearson's product-moment correlation coefficients were used to determine the effects of the energy-use patterns of the occupants. Pearson's correlation coefficients were implemented for continuous-but-abnormal variables. For the dichotomous variables, independent sample *t*-tests were applied to determine the importance of households' socio-demographic characteristics in energy use for the identification of threshold points to address energy efficiency gap [100]. For categorical variables, one-way analysis-of-variance (ANOVA) tests were utilised to determine the differences in energy use among the groups.

Previous studies used analysis-of-variance (ANOVA), multivariate analysis-of-variance (MANOVA), Pearson's correlation and regression analyses, and these statistical tests effectively explored correlations within a set of variables designed in the dataset. To interpret the statistical analysis, the conventional method was used for the interpretations between two continuous variables. Table 4 demonstrates the guidelines are generally in agreement with Cohen's recommended guidelines[20].

Table 4
Measures of association.

r	**Interpretation of Linear Relationship**
0,8	Strong positive
0,5	Moderate positive
0,3	Weak positive
0,0	No relationship
-0,2	Weak negative
-0,5	Moderate negative
-0,8	Strong negative
$\lvert r\rvert < 0,3$ → Weak relationship	
$0,3 \leq \lvert r\rvert \leq 0,5$ → Moderate relationship	
$\lvert r\rvert > 0,5$ → Strong relationship	
Source: Khamis (2008)	

The interview responses were used in the descriptive analysis to determine household socio-demographic characteristics and the occupants' thermal-comfort levels; a correlation analysis of these findings was then conducted to evaluate the correlations amongst the different parameters (i.e., household socio-demographic characteristics and occupant behaviour related to home-energy performance and thermal comfort). Inferential statistics, also referred to as inductive statistics, are techniques employed for the purpose of making generalisations or inferences about the sample size. The main inferential statistical techniques used in this study

[20] For the interpretations of statistical findings, the six possible combinations of variables encountered by researchers are as follows: *(i)* continuous-continuous; *(ii)* continuous-ordinal; *(iii)* continuous-nominal; *(iv)* ordinal-ordinal; *(v)* ordinal-nominal; *(vi)* nominal-nominal. For each of these combinations of variables, one or more measures of association that accurately assess the strength of the relationship between the two variables are discussed in the present study where it is necessary to determine the influences of statistical findings for the development of evidence-based energy policy framework.

include Pearson's correlation coefficient and linear regression analysis. The decisions for all statistical tests are as follows: 95% is the assumed degree of confidence, 0.05 is the level of confidence and 0.000 is the significance level (p). The findings from variables were further used to test for a relationship from participants in order to bring more reliability to the data and to validate the results in the building modelling simulation phase of the study.

3.4. Sample size and validity of results

Out of the 200 questionnaire forms distributed to all 36 RTBs, 118 completed forms were collected for data input and analysis via the SPSS software suite; of these, 18 were excluded due to some households[21] encountering difficulties in accurately answering the questions and unreliable responses to the survey questions from other households. The sample size in this research was therefore 100; and the response rate was 50%, which is a reasonably acceptable sampling rate that would provide adequate primary data findings to represent the majority of social housing stock in Cyprus [101]. The conventions of statistical analysis recommend that to prove the validity of the Pearson's, Kendall's and Spearman's correlation tests, the representative sample set needs to be equal or greater than 25 participants [102]. Therefore, further statistical analyses were required to minimise the risk of discrepancy between dependent and independent variables. One of the main reasons is that a large amount of dataset and large enough sample size are required to give us a nationally representative sample for the study. Moreover, household socio-demographic characteristics were considered throughout the primary data collection for the study [103, 104]. It should be noted, however, that these factors could have affected the representability of the data; but because this is an explanatory analysis, no major consequences were expected to arise from this issue.

3.5. Household selection criteria

The study consisted of a quantitative social survey of 118 social households either owner occupied or private renters, which took place in August of 2018—the hottest month of the summer. To provide subsequent background information on households' socio-demographic characteristics and validity of the questionnaire survey in the South-eastern Mediterranean climate. This study adopted a quota sampling decision making criteria to demonstrate a

[21] The households represent the flats recruited for the study. Throughout the questionnaire survey, the researcher requested from the households to nominate one of the family members who felt confident to respond to the questions.

nationally representative sample of Cyprus's social housing stock. The previous extant literature of field study investigations on social housing estates both in Europe and the UK recommended that quota sampling requires to investigate intrinsic correlations, thus indicating that issuing a set of quota characteristics (i.e., tenure type, orientation, floor different level and the occupancy patterns on energy use in this case) to interviewers and conducting a corresponding number of multi-decision criterion analysis in each category of each households' socio-demographic characteristic.

According to this census data, the population was 382,230 in 2019; the male population was 207,149, and the female population was 175,081. There were 62,299 individuals in the 20–24 age group, which comprised a large proportion of the overall population; there were 37,972 males and 24,372 females in this age group. The 70–74 age group consisted of 9,465 individuals: 4,551 males and 4,914 females [105].

During the rise of post-war social-housing estate developments, 2,712 dwellings were built under the governmental social-housing scheme [106]. An additional 659 dwellings were built in collaboration with local cooperatives in NC.[22] After the completion of mass-scale housing projects, no other social-housing projects were constructed by the government [107]. During the late-1990s and early 2000s, mass-scale housing projects were predominantly regulated by the SMEs [108]. According to housing statistics, an additional 3,275 dwellings were built by privately owned construction companies to fill the gap in social-housing structures implemented between 2000 and 2005 [109].

The aim of the representative sampling size is to prove the validity of the multivariate statistical analysis undertaken to demonstrate the representativeness of the sample size in order to reflect the households' socio-demographic overview for which the interviews were sought. To avoid bias on the households' responses on the set of questions distributed and minimise the risk of discrepancies in the statistical analysis, the quota sampling approach offers an inclusive primary data output. One of the reasons is that it is not possible to determine the exact representatives of a given sample due to the risk of sampling bias during respondent selection. Household selection criteria were stratified by the State Planning Organisation of Cyprus and household-level socio-economic indicators of the social grade of each household reference person [109]. In this exploratory case study approach, representative sample size was selected on a door-to-door survey in order to gauge the absolute accurate information from the social

[22] Due to a high demand for social-housing construction projects, the government enacted a plan to collaborate with local cooperatives in order to speed up construction and reduce upfront costs.

householders about their socio-demographic characteristics and home energy performance for effective policy making decisions in retrofit policy design within each RTB at the social housing development.

3.6. Household electricity use

Throughout the questionnaire survey pro-forma, we developed 10 interview questions to gather the binary categories as follow; owner versus renter, length of residency, awareness of energy saving, type of heating and cooling systems used, type of heating- and cooling-control systems used, occupancy patterns during the weekdays and on the weekends in the winter and summer, window-opening schedules in the winter and summer and the reasons for thermal discomfort—all of which took into account the different orientations of the RTBs and the different floor level of each flat. These quotas were selected because the above-mentioned factors strongly correlate with the significance of energy-consumption patterns in overall energy use. The sample was based on characteristics of gathering background information on overall occupancy of each flat unit in the RTBs, rather than obtaining individual information of subject respondents. One of the main reasons is that this study was aimed to collect data from social households that related to their occupancy patterns and its impact on home energy performance. To fulfil this research objective and avoid risk of bias on the householders' responses related to knowledge of energy use at the household level, the survey method was pilot-tested. A questionnaire-based survey was prepared, partly to hear occupant views on how patterns that impacted their home-energy use, and also to collect concrete examples of identifying dominant representative occupancy profiles, which could be further corroborated in the decision-making process of energy-efficient retrofit interventions.

4. Analysis and Results

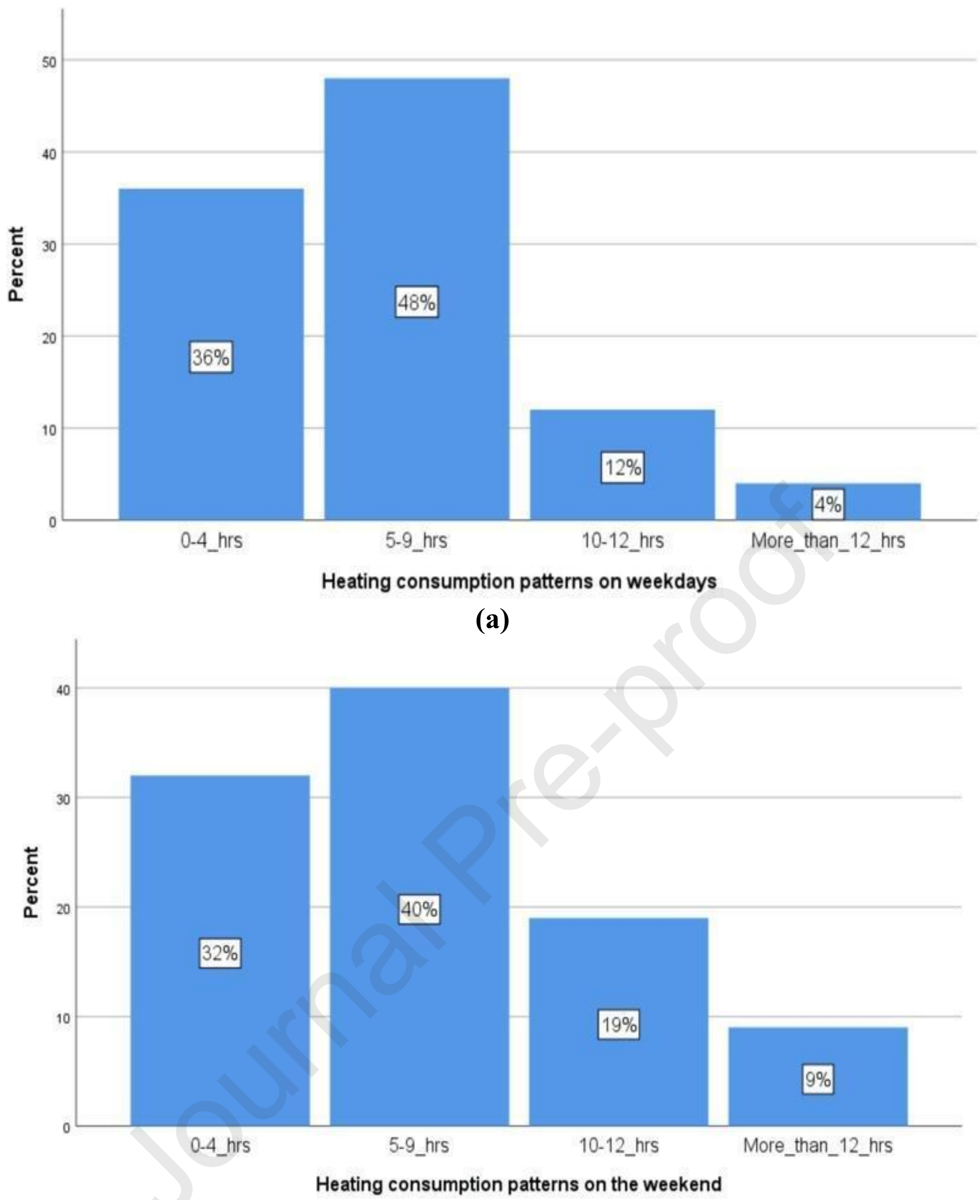
The aims of this section are to statistically determine occupant behavioural patterns associated with heating- and cooling-energy consumption and to identify household socio-demographic characteristics that contribute to the development of energy-user profiles. The collated data are reported, along with an analysis and interpretation thereof. The findings are presented in sequential order based on the order in which the questions were asked to the households. This is followed by statistical testing using cross tabulation with a chi-square test to analyse the relationships of the selected questions for the development of an evidence-based STS conceptual framework for policymakers.

4.1. Occupancy patterns and household adaptive behaviour on energy use

This section presents the *in-vivo* experience of the households' feed-forward interviews that were conducted. Statistical analyses were used to determine the multivariate factors that influence both heating- and cooling-energy consumption, including in the peak cooling month of August. The analyses carried out in this study were explanatory in nature, and the objective thereof was to identify the relationships between different variables; *(i)* types of heating and cooling systems used, *(ii)* heating- and cooling-energy-use patterns, *(iii)* windows opening schedules, *(iv)* households' habitual adaptive behaviour to acclimatise the indoor-air environment and occupancy patterns in energy use, which will them serve to deepen the knowledge of the relative influence and interaction between these variables and will eventually pave the way for energy consumption calibration for certain determinant variables while taking the effect of occupant behaviour on building energy modelling into consideration.

4.1.1. Heating-consumption patterns

The heating-consumption patterns of the occupants are examined in this section. As it relates to understanding the household energy-use habits, the pattern investigation correlated with the household socio-demographic characteristics, which is discussed in detail in Section 4.3. This information provided additional information to assess the thermal-comfort levels of the occupants in conjunction with their energy use in the winter. Figure 21 (a) illustrates the heating-consumption patterns in the living room of each household on weekdays.



(a)

(b)

Fig.21. Percentage distribution of household heating-consumption patterns on **(a)** weekdays and **(b)** the weekend.

According to Figure 21 (a), which shows the household heating-consumption patterns on weekdays, 36% of the respondent households spent 0–4 hours in their living room on weekdays, 48% spent 5–9 hours in their living room, 12% spent 10–12 hours in their living room, and 4% spent more than 12 hours in their living rooms. The most dominant occupancy pattern was 5–9 hours, because most of the family members in 48% of the surveyed households worked full time, and their properties were not occupied on weekdays during working hours, which are between 08:00–18:00. Notably, at 36%, the 0–4 hours occupancy pattern was found to be the second-most-dominant occupancy schedule.

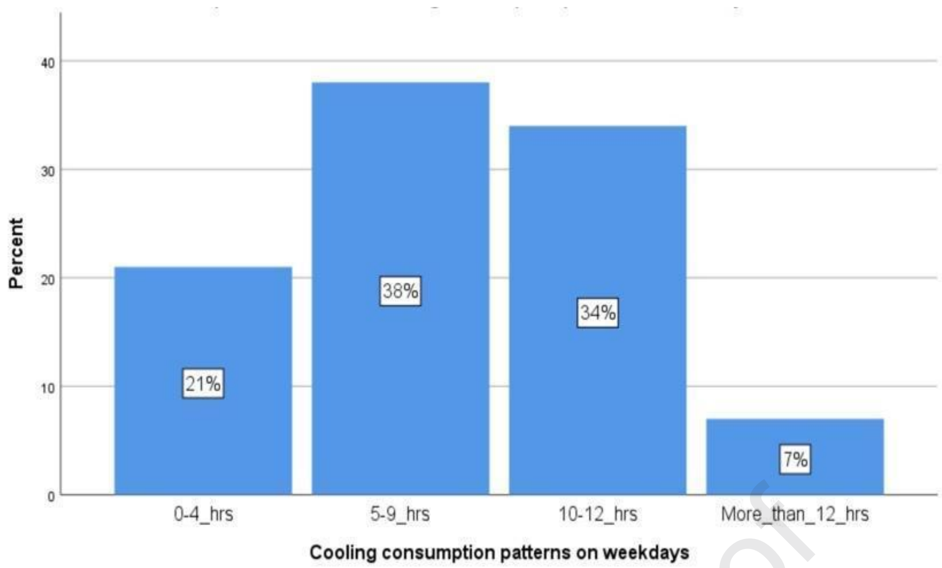
Figure 21 (b), which delineates household heating-consumption patterns in terms of the number of hours spent in the living room on the weekend, shows that 32% of the respondents spent 0–4 hours in their living room, 40% spent 5–9 hours in the living room, 19% spent 10–12 hours in the living room, and 9% spent more than 12 hours in their living room. The 5–9-hour occupancy pattern was the most common occupancy schedule on both the weekdays and on the weekend.

Taken together, these results suggest that there was an association between the age group and the employment status of each household. Based on the questionnaire survey, it was determined that the dominant age groups across the recruited households were 35–45 years of age (16%), 45–55 (20%) and 55–65 (33%), while the 65-years-of-age and older age group comprised 16% of the total households. Moreover, 7% of the male respondents were retired, and one male respondent was semi-retired; while for the female respondents—of whom 11% reported that they worked from home, 16% reported that they did household activities, and 14% reported that they were retired—41% spent a majority of their time in their homes throughout the year.

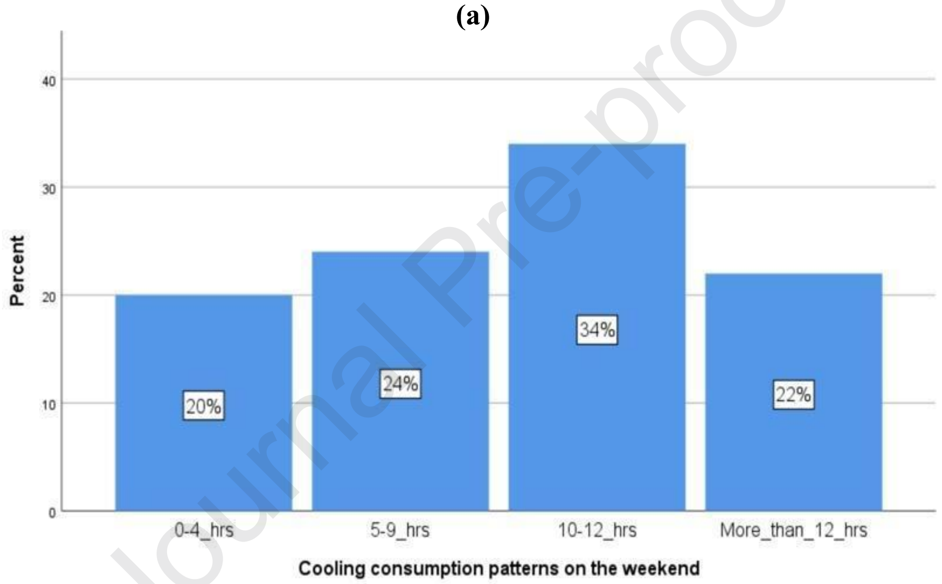
It is important to note that the residents were in their living rooms for slightly longer lengths of time on weekends than on weekdays. No significant differences in heating-consumption patterns were observed between weekdays and weekends, however. Overall, these results indicate that employed occupants spend less time in their homes during the week, but more time on the weekend [110].

4.1.2. Cooling-consumption patterns

The primary aim of the present study was to understand the real-life energy-use experiences of occupants during the peak cooling month of August; these data will be used to identify and tabulate different occupancy schedules and to incorporate them into the building-modelling simulation for the development of evidence-based energy policy design scenarios. Figures 22 (a) and (b) illustrate the household cooling-consumption patterns in the summer.



(a)



(b)

Fig.22. Percentage distribution of household cooling-consumption patterns related to number of hours spent in the living rooms on **(a)** weekdays and **(b)** the weekend.

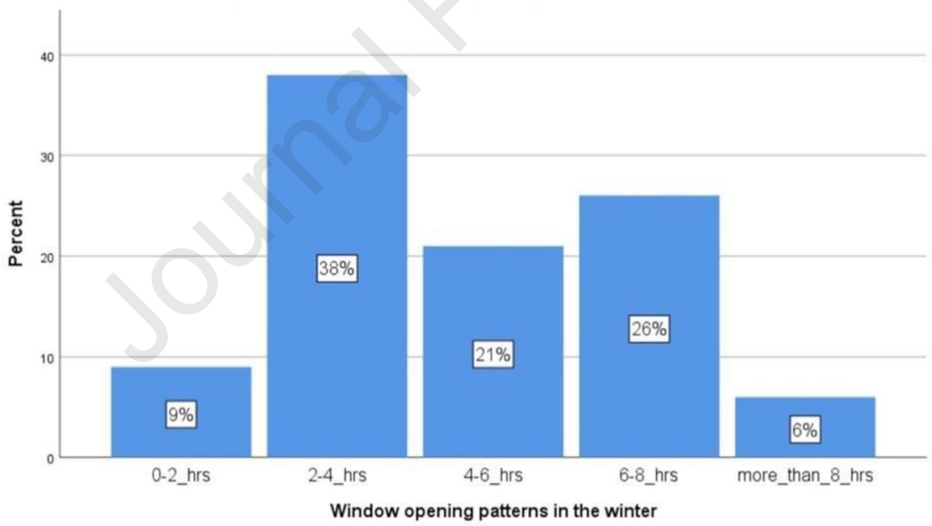
As shown in Figure 22 (a), 21% of the households turned on their living room cooling systems for 0–4 hours per day during the week, 38% turned their cooling systems on for 5–9 hours per day, 34% turned their cooling systems on for 10–12 hours per day; and 7% turned their cooling systems on for more than 12 hours per day.

Figure 22 (b), which illustrates cooling-consumption patterns in terms of the number of hours spent in the living rooms on the weekend, shows that 20% of the respondent households kept their living room cooling systems on for 0–4 hours per day on the weekend, 24% kept their cooling systems on for 5–9 hours per day, 34% kept their cooling systems on for 10–12 hours per day; and 22% kept their cooling systems on for more than 12 hours per day.

There was a noticeable increase in the number of hours of cooling consumption on the weekend. It is also worth noting that the most dominant weekend cooling-consumption patterns were observed in the households that cooled their living rooms for 10–12 hours and more than 12 hours each day; this was due to the high number of households that spent their time at home and preferred to use their cooling systems on the weekend, rather than on weekdays [111, 112]. This correlates with the fact that employed family members who spend more time at home on the weekend are more likely to use their cooling systems to provide thermally comfortable indoor-air temperatures [113, 114].

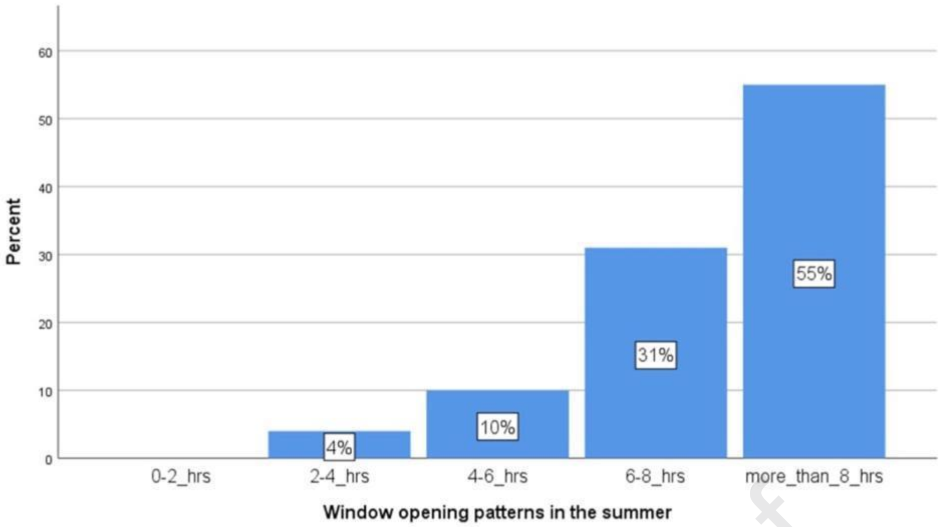
4.2. Window-opening patterns

The winter and summer window-opening patterns for each subject respondent and the frequency that windows were kept open were also investigated[23]. This section presents the distribution of Questions 18-21, 23 and 24 concerning the household window-opening patterns and whether windows were opened or closed when the heating or cooling systems were in use.



(a)

[23] Window-opening patterns were set out as categorical variables to perform correlation analysis accurately.



(b)

Fig.23. Percentage distribution of household window-opening patterns in the living room related to number of hours open in **(a)** winter and **(b)** summer.

Figure 23 (a) illustrates the household living room window-opening patterns in the winter[24]. Of the surveyed households, 9% reported that they kept their living room windows open for 0–2 hours per day during the winter; 38% left their living room windows open for 2–4 hours per day; 21% left their living room windows open for 4–6 hours per day; 26% left their living room windows open for 6–8 hours per day; and the remaining 6% kept their living room windows open for more than eight hours each day.

The most dominant occupancy pattern was observed in the group in which 38% reported keeping their living room windows open for 2–4 hours every day during the winter. This was correlated with the occupant employment patterns, as these households left their windows opened in either the early morning or the late afternoon to facilitate natural ventilation (NV) for the indoor spaces because there were no other ventilation systems (i.e., trickle ventilation) available in these buildings [115-117]. The other two significant window-opening patterns—21% for 4–6 hours each winter day and 26% for 6–8 hours each winter day—was dependent upon the occupancy hours and orientation of the building; it was observed that 6% of the occupants kept the windows open for more than eight hours a day in the winter.

Similarly, it can be deduced from Figure 23 (b) that none of the households reported opening their living room windows for 0–2 hours per day in the summer; 4% kept their living room windows open for 2–4 hours per day; 10% kept their living room windows open for

[24] Categorical variables are sets of variables with values assigned to distinct and limited groups or categories. Categorical variables take on values in a set of categories, different from a continuous variable, which takes on a range of values. Categorical variables are also called discrete or nominal variables.

4–6 hours per day; 31% kept their living room windows open for 6–8 hours per day; and 55% kept their living room windows open for more than eight hours each summer day. The reason for keeping living room windows open was the local climate conditions and the thermal properties of buildings [118, 119].

It was observed that the occupants who lived on the upper floor flats and could not afford the high energy-consumption costs of A/C systems kept all their windows open for more than eight hours each day in the summer, and portable fans were used as needed; the other top-floor occupants who could afford to run a wall-mounted A/C system for 24 hours a day kept all their windows closed, along with their blinds and curtains. This explains why no occupants were included in the 0–2-hour group, as these families ran their A/C systems with their windows close; most of these occupants were economically active and were able to afford high energy bills, so they tended to frequently use wall-mounted A/C systems [120].

4.3. Correlation of exploring household habitual adaptive behaviour on energy use

To follow up the research questions (RQs), the types of relationships that were investigated are explained in Sections 4.3.1 and 4.3.2.

4.3.1. Correlation between household occupation and cooling and heating energy–consumption patterns

Based on the general survey findings, 52% of the respondents stated that they preferred to use electric domestic heating appliances in the winter, and 75% preferred to use either portable fans or wall-mounted A/C systems in the summer to create thermally comfortable indoor-air temperatures. This was shown to be related to a number of multi-domain deterministic factors of household energy use patterns and their home-energy performance, as shown in $Table$ 5.

In this questionnaire survey, the occupants were asked an open-ended question regarding their weekday and weekend heating consumption patterns. 48% of the occupants reported that they turn on heating systems for 5–9 hours on weekdays while 4% of the respondents reported turning on their heating systems for more than 12 hours. For weekends, 40% of the respondents stated that they turn on their heating systems for 5–9 hours while 9% said they preferred to turn on their heating systems for more than 12 hours at weekends. These results indicate that there is an increase in the number of hours the heating systems are turned on at weekends, but this gap is very narrow, which is due to the fact that many of the occupants (mostly female) are at home on weekdays.

Table 5 demonstrates the relationships between household occupation and their heating- and cooling- consumption patterns both on weekdays and on the weekend.

Table 5
Relationships between unit occupation, weekday heating-consumption patterns, weekend heating-consumption patterns, weekday cooling-consumption patterns and weekend cooling-consumption patterns.

Research Questions	Occupation	Weekday Heating-Consumption Patterns	Weekend Heating-Consumption Patterns	Weekday Cooling-Consumption Patterns	Weekend Cooling-Consumption Patterns
Q 1.4: What is your occupation?	1	0,253	0,109	0,098	0,167
	—	0,060	0,895	0,938	0,552
Q 16: When do you turn on heating device(s) on weekdays?	0,253	1	0,373**	0,611**	0,504**
	0,060	—	0,000	0,000	0,000
Q 17: When do you turn on heating device(s) on the weekend?	0,109	0,373**	1	0,522**	0,706**
	0,895	0,000	—	0,000	0,000
Q 12: When do you turn on cooling device(s) on weekdays?	0,098	0,611**	0,522**	1	0,774**
	0,938	0,000	0,000	—	0,000
Q 13: When do you turn on cooling device(s) on the weekend?	0,167	0,504**	0,706**	0,774**	—
	0,552	0,000	0,000	0,000	1

Occupation: 0 (work outside the home) to 6 (unemployed)
Weekday heating consumption: 0 (0–4 hours) to 4 (more than 12 hours)
Weekend heating consumption: 0 (0–4 hours) to 4 (more than 12 hours)
Weekday cooling consumption: 0 (0–4 hours) to 4 (more than 12 hours)
Weekend cooling consumption: 0 (0–4 hours) to 4 (more than 12 hours)
Occupation – Weekend heating consumption, $\chi^2(8) = 2{,}25$, $p = 0{,}895$, *Cramer*'s $V = 0{,}109$
Occupation – Weekday heating consumption, $\chi^2(8) = 12{,}07$, $p = 0{,}060$, *Cramer*'s $V = 0{,}253$
Occupation – Weekend cooling consumption, $\chi^2(9) = 7{,}82$, $p = 0{,}552$, *Cramer*'s $V = 0{,}167$
Occupation – Weekday cooling consumption, $\chi^2(6) = 1{,}79$, $p = 0{,}938$, *Cramer*'s $V = 0{,}098$
Weekday cooling consumption – Weekend heating consumption, $\chi^2(4) = 54{,}59$, p = 0,000, Cramer's V = 0,522
Weekday cooling consumption – Weekday heating consumption, $\chi^2(4) = 74{,}57$, p = 0,000, Cramer's V = 0,611
Weekday cooling consumption – Weekend cooling consumption, $\chi^2(6) = 119{,}77$, p = 0,000, Cramer's V = 0,774
Weekend cooling consumption– Weekend heating consumption, $\chi^2(6) = 99{,}69$, $p = 0{,}000$, *Cramer*'s $V = 0{,}706$
Weekend cooling consumption– Weekday heating consumption, $\chi^2(6) = 50{,}77$, $p = 0{,}000$, *Cramer*'s $V = 0{,}504$
Weekday heating consumption– Weekend heating consumption, $\chi^2(4) = 27.89$, $p = 0{,}000$, *Cramer*'s $V = 0{,}373$

In this analysis, the correlation between the respondents' occupation patterns and their heating and cooling patterns was investigated[25]. As shown in Table 5[26] weekday cooling consumption patterns were significantly and strongly related to weekend heating consumption patterns on weekends (χ^2 = 54,590, p < 0,001, Cramer's V = 0,522). This was because 58% of the respondents spent most of their time at home because they were retired, worked from home, or were housewives, students or unemployed [121, 122]. This resulted in a majority of the households consuming more energy.

Specifically, longer duration of heating consumption was related to longer duration of cooling consumption. Similar result was also found between weekend cooling consumption patterns and weekend heating consumption patterns (χ^2 = 99,687, p < 0,001, Cramer's V = 0,706), between weekday cooling consumption patterns and weekday heating consumption patterns (χ^2 = 74,565, p < 0,001, Cramer's V = 0,611), and weekend cooling consumption patterns and weekday heating consumption patterns (χ^2 = 50,767, p < 0,001, Cramer's V = 0,504). This was due to the occupants' need to achieve optimum thermal comfort due to the local climate conditions and the building thermal properties. Notably, the cultural habits of these households were such that they believed their main priority was overall thermal comfort, without taking into consideration high energy bills or alternative solutions to improve energy efficiency of their flats [123, 124]. This suggests that cooling- and heating-consumption patterns are directly related to the thermal conductivity of building materials, because they have led to an increase in household space-conditioning energy expenditures for the summer and the winter [125].

For heating patterns, weekday consumption was moderately associated with weekend consumption (χ^2 = 27,890, p < 0,001, Cramer's V = 0,373). For cooling patterns, weekday consumption was strongly associated with weekend consumption (χ^2 = 119,765, p < 0,001, Cramer's V = 0,774); this highlights the fact that the households' main concern was their optimum thermal comfort [126]. However, household occupation was not significantly related to any cooling or heating consumption patterns. It is also evident from the correlation analysis

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[25] To assess the association between two nominal variables, Cramér's V coefficient is preferred over the x^2 statistic or contingency coefficient, C. To appreciate its advantages, however, a discussion of the x^2 statistic and the contingency coefficient C is also needed.

[26] To interpret the statistical findings according to the convention, Cohen's (1988) suggested interpretation of Phi (φ) and Cramér's V Coefficients - Value of φ or Cramér's V ***(i)*** 0,00 through 0,10 – weak/small effect, ***(ii)*** 0,11 through 0,30 – moderate/medium effect, ***(iii)*** 0,31+ -strong/large effect.

that the number of family members living in a particular household was an important factor in the amount of energy that was consumed [127].

4.3.2. Correlation between household occupation and window-opening patterns

The correlations between occupation and window-opening patterns in the winter and summer were analysed, and the results are shown in Tables 6 (a) and (b).

Table 6 (a)
Relationships between household occupation, window-opening patterns in the winter, window-opening patterns in the summer and heating control.

Research Questions	Occupation	Winter	Summer	Heating Control
Q 1.4: What is your occupation?	1	0,164	0,167	0,170
	—	0,578	0,153	0,773
Q 23: When do you open your windows in the winter?	0,164	1	0,459**	0,283*
	0,578	—	0,000	0,042
Q 18: When do you open your windows in the summer?	0,167	0,459**	1	0,139
	0,153	0,000	—	0,926
Q 24: Do you keep room doors open when you do not have heating on?	0,114	0,246	0,030	1
	0,747	0,109	0,956	—
Q 19: Do you keep room doors open when you do not have cooling on?	0,114	0,262	0,168	0,229
	0,746	0,077	0,245	0,262
Q 20: Why do you open the windows?	0,201	0,124	0,185	0,200
	0,291	0,676	0,182	0,410
Q 21: Why do you close the windows?	0,260	0,230	0,234	0,118
	0,087	0,195	0,205	0,992

Respondents' occupation scale runs from 0 (work outside the home) to 6 (unemployed)
Occupants' winter window-opening patterns scale runs from 0 (0–2 hours) to 4 (more than 8 hours)
Occupants' summer window-opening patterns scale runs from 0 (0–2 hours) to 4 (more than 8 hours)
Keeping internal doors open when heating system was not in use: 0 (no) or 1 (yes)
Keeping internal doors open when cooling system was in use: 0 (no) or 1 (yes)
Reasons for opening windows in the summer: 0 (to get fresh air) or 1 (to dissipate dirty air)
Reasons for closing windows in the summer scale runs from 0 (against the warm/cool air) to 6 (mosquitos/insects)

Table 6 (b)
Relationships between household occupation, window-opening patterns in the winter, window-opening patterns in the summer and heating control (Continued).

Windows opening patterns winter – Doors opening preference in summer, $\chi^2(3) = 6,85$, $p = 0,077$, *Cramer*'s $V = 0,262$
Windows opening patterns winter – Windows opening pattern in summer, $\chi^2(6) = 42,18$, $p = 0,000$, *Cramer*'s $V = 0,459$
Windows opening patterns winter – Doors opening preference in winter, $\chi^2(3) = 6,05$, $p = 0,109$, *Cramer*'s $V = 0,246$
Windows opening patterns winter – Windows opening reason, $\chi^2(3) = 1,53$, $p = 0,676$, *Cramer*'s $V = 0,124$
Windows opening patterns winter – Windows closing reason, $\chi^2(12) = 15,92$, $p = 0,195$, *Cramer*'s $V = 0,230$
Windows opening patterns summer – Doors opening preference in summer, $\chi^2(2) = 2,81$, $p = 0,245$, *Cramer*'s $V = 0,168$
Windows opening patterns summer – Doors closing preference in winter, $\chi^2(2) = 0,09$, $p = 0,956$, *Cramer*'s $V = 0,030$
Windows opening patterns summer – Windows opening reason, $\chi^2(2) = 3,41$, $p = 0,182$, *Cramer*'s $V = 0,185$
Windows opening patterns summer – Windows closing reason, $\chi^2(8) = 10,94$, $p = 0,205$, *Cramer*'s $V = 0,234$
Occupation – Windows opening pattern in summer, $\chi^2(6) = 5,24$, $p = 0,513$, *Cramer*'s $V = 0,167$
Occupation – Windows opening pattern in winter, $\chi^2(9) = 7,57$, $p = 0,578$, *Cramer*'s $V = 0,164$
Occupation – Windows opening reasons, $\chi^2(3) = 3,74$, $p = 0,291$, *Cramer*'s $V = 0,201$
Occupation – Windows closing reasons, $\chi^2(12) = 19,07$, $p = 0,087$, *Cramer*'s $V = 0,260$
Occupation – Heating control, $\chi^2(12) = 8,16$, $p = 0,773$, *Cramer*'s $V = 0,170$
Heating control – Windows opening pattern in summer, $\chi^2(8) = 5,79$, $p = 0,926$, *Cramer*'s $V = 0,139$
Heating control – Windows opening pattern in winter, $\chi^2(8) = 16,03$, $p = 0,042$, *Cramer*'s $V = 0,283$
Heating control – Windows opening reason, $\chi^2(4) = 3,93$, $p = 0,410$, *Cramer*'s $V = 0,200$
Heating control – Windows closing reason, $\chi^2(16) = 5,55$, $p = 0,992$, *Cramer*'s $V = 0,118$

As seen in Tables 6 (a) and (b), windows opening patterns in winter were significantly associated with that in summer ($\chi^2 = 42,177$, $p < 0,001$, Cramer's $V = 0,459$), and this relationship was moderate-strong. It appears that longer opening duration in winter was related to longer opening duration in summer. Regarding the heating control type at home, it was only significantly related to windows opening patterns in summer ($\chi^2 = 16,031$, $p = 0,042$, Cramer's $V = 0,283$). A greater proportion of participants with more than 8 hours windows opening time had none of heating control at home than participants with 6-8 hours windows opening. However, occupation was not significantly associated with any opening patterns or opening reasons.

4.4. *Validation of household habitual adaptive behaviour with energy-user profiles*

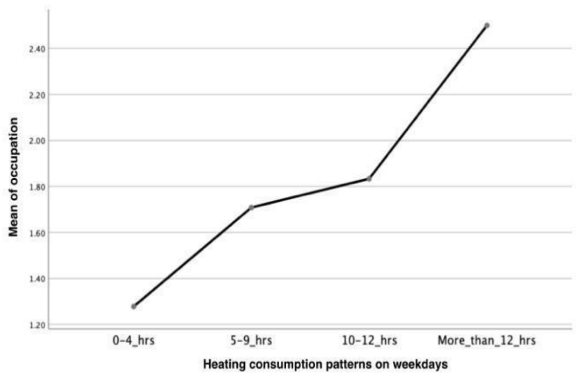
The data provided subsequent information on the multi-domain factors for a parametric analysis that took the significance of summer and winter occupancy patterns into account. As such, the correlation analysis was able to identify relationships among the numerical data and the ordinal data, which followed ordered series or ranking sequences among different categories to tabulate the data within the scope of the RQs, as discussed in Sections 4.4.1 and 4.4.2.

4.4.1. *One-way ANOVA test between occupation and household heating–cooling consumption patterns*

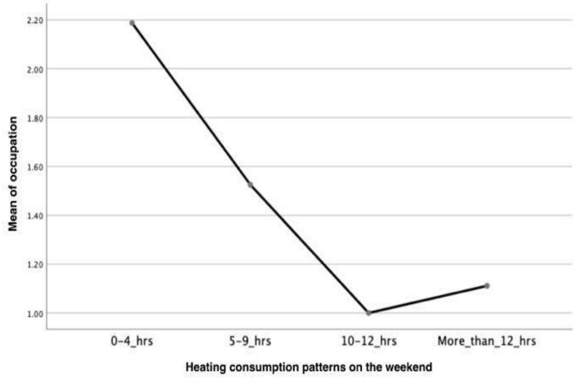
A one-way analysis-of-variance (ANOVA) test was conducted, and the data were categorised as either binary or nominal data, the latter of which were not ordered in a series. Since 'Where and when do you turn on your heating device(s) on weekdays?' and 'Where and when do you turn on your heating device(s) on weekends?' are both binary questions, a one-way ANOVA test was adopted to help interpret significant correlations and detect discrepancies from among the multi-domain factors related to occupancy patterns for the purpose of exploring household energy performance for heating purposes in line with considerations related to different occupations [128].

The survey findings revealed similar weekday and weekend occupancy patterns: According to the survey, 48% of the respondent households preferred to turn their heating systems on for 5–9 hours on weekdays, and 12% kept their heating systems on for 10–12 hours. Alternately, 40% of the households kept their heating systems on for 5–9 hours on the weekend, and 19% kept their heating on for 10–12 hours each day of the weekend.

Another important aspect emerged from the general survey findings: The statistical figures presented below demonstrate that household occupation is an important consideration when seeking to identify occupancy patterns in the interviewed flats. According to the survey, 13% of the respondents worked at home, 16% were housewives, 22% were retired, and 2% were unemployed.



(a)



(b)

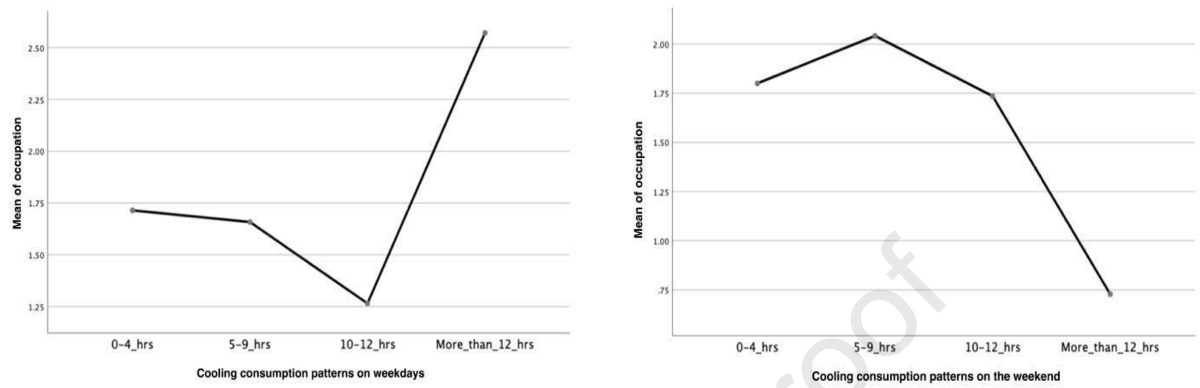
Fig.24. Statistical one-way ANOVA test frequency distribution between household occupation and **(a)** weekday heating-consumption patterns and **(b)** weekend heating-consumption patterns.

Figure 24 (a) depicts the relationship between household occupation and weekday heating-consumption patterns. The lowest peak, $f < 1,40$, was for 0–4 occupancy hours; the first-highest peak, $f > 2,40$, was for more than 12 hours; and the second-highest peak, $f > 1,80$, was for 10–12 hours. Figure 24 (b) illustrates the relationship between household occupation and weekend heating-consumption patterns: The highest peak, $f = 2,20$, was for 0–4 hours, due to a majority of the surveyed occupants who preferred to turn on their heating systems at high temperatures for a few hours, then switch them off to reduce heating costs; and the lowest peak of $f = 1,0$ was for 10–12 hours.

After controlling for household occupation as a dependent variable, the number of hours that heating systems were used was shown to be the independent variable with the greatest deterministic model in relation to an investigation of the significance of weekend occupancy patterns [129]. The flats where some household members were present at home during the day, were found to be those of retirees with high pensions, which resulted in more energy consumption than in the flats where no one was at home during the day or in the households where the presence of family members during the day varied considerably [130]; this also held true for the weekend in all the interviewed flats.

A one-way ANOVA test was also conducted to determine the variance of occupancy patterns on energy use in line with considerations of the different household occupations for cooling purposes. Since ‘Where and when do you turn on the cooling device(s) on weekdays?’ and ‘Where and when do you turn on the cooling device(s) at weekends?’ are both ordinary questions; a one-way ANOVA test was used to help interpret significant correlations.

The survey revealed that 38% of the households kept their cooling systems on for 5–9 hours each weekday, and 34% kept their systems on for 10–12 hours; on weekends, 24% kept their cooling systems on for 5–9 hours each day, and 34% kept their systems on for 10–12 hours.



(a) **(b)**

Fig.25. Statistical one-way ANOVA test frequency distribution between household occupation and **(a)** weekday cooling-consumption patterns and **(b)** weekend cooling-consumption patterns.

Figure 25 (a) shows the occupant weekday cooling-consumption patterns: The highest peak, $f > 2{,}50$, was for more than 12 hours; and the lowest peak, $f = 1{,}25$, was for 10–12 hours. These results were because a majority of the households being retired pensioners who mostly stayed at home on weekdays. Figure 25 (b) shows the household weekend cooling-consumption: The first highest peak, $f > 2{,}0$, was for 5–9 hours; the second-highest, $f > 1{,}75$, was for 10–12 hours; the third-highest, $f > 1{,}75$, was for 0–4 hours; and the lowest peak, $f < 0{,}75$, was for more than 12 hours. The reason for the inverse peaks between weekdays and the weekend was because the households cleaned their flats on the weekend with all their windows and doors left open; notably, residents also spent more time outside of their home on the weekend (Nair *et al.*, 2010).

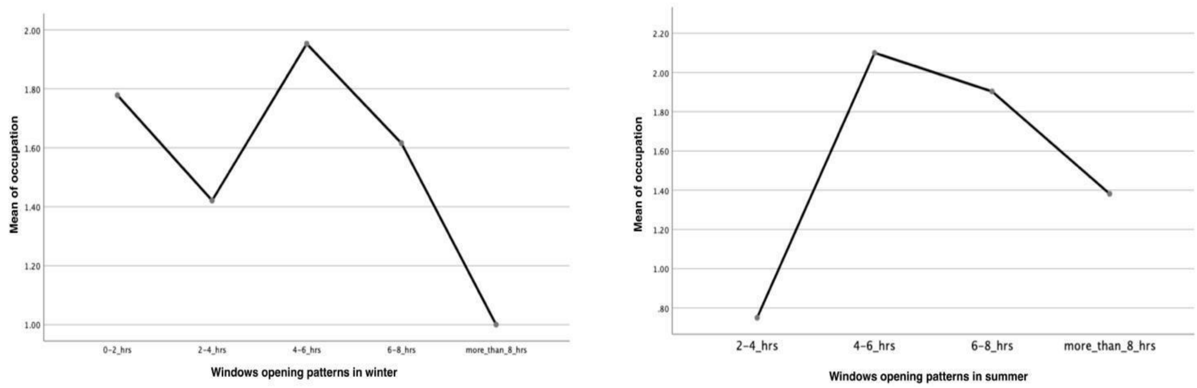
4.4.2. One-way ANOVA test between occupation and household heating–cooling consumption patterns

A dichotomous variable was created to analyse the impact of frequency of window opening patterns. Because the households' ingrained lifestyles and the impact thereof on their home-energy performance were difficult to quantify, a one-way ANOVA test between household occupation and window-opening patterns was conducted to avoid discrepancies in the sample dataset. It should be noted that the survey revealed that during the winter, a majority of the households only opened their windows for a few hours each day.

An independent-samples *t*-test was conducted to compare energy use of the interviewed flats in which the occupants kept their living room windows open for more than eight hours and the flats in which the occupants always kept their windows closed. A small-effect weak positive statistical difference ($r = 0{,}106$, $p > 0{,}01$) was detected with the flats with opened windows. No correlation was found, however, between opened or closed windows in the summer; this was due to occupant behaviour and yielded a general question that facilitated the use of information during the building-modelling simulation phase of the present study.

A one-way ANOVA test was conducted to determine the variance of the window-opening patterns on energy use in line with considerations related to household occupation variations and to provide information for the building-modelling simulation phase. These data enabled the assignment of different window-opening schedules to test the significance of occupancy patterns. As it relates to assessing overheating risks and occupant thermal comfort, window-opening schedules were important to consider when tabulating different infiltration rates into the macro-flow simulations.

Since ‘Where and when do you open your windows in the winter?’ and ‘Where and when do you open your windows in the summer?’ are both ordinary questions; a one-way ANOVA test was implemented to interpret significant correlations. The survey found that 38% of the households preferred to keep their windows open for 2–4 hours every day in the winter, 21% kept their windows open for 4–6 hours, 26% kept their windows open for 6–8 hours, 55% kept their windows open for more than eight hours, and 31% kept their windows open for 6–8 hours every day.



(a) **(b)**

Fig.26. Statistical one-way ANOVA test frequency distribution between household occupation and window-opening patterns in **(a)** winter and **(b)** summer.

Figure 26 (a) reveals a significant relationship between household occupation and winter window-opening patterns: The highest peak of window-opening, $f > 1{,}80$, was for 4–6 hours; the second-highest, $f = 1{,}60$, was for 6–8 hours; the third-highest, $f < 1{,}80$, was for 0–2 hours; and the lowest peak, $f = 1{,}0$, was for more than eight hours. The varied results were due to variations in the occupant profiles: Occupants who worked outside were correlated with windows that were kept open for 6–8 hours; occupants with young children who mostly stayed at home were correlated with windows that were kept open for 0–2 hours; and occupants who closed their windows for more than eight hours were in the slightly older age group and reported that their health was between poor and very poor, which was why they kept their windows closed during the winter.

Figure 26 (b) illustrates the significant relationship between household occupation and summer window-opening patterns: The highest peak, $f > 2{,}0$, was for 4–6 hours; the second-highest peak, $f > 1{,}80$, was for 6–8 hours; the third-highest peak, $f < 1{,}40$, was for more than eight hours; and the lowest peak, $f < 0{,}80$, was for 2–4 hours. The reversal in the graphs was because wall-mounted A/C systems were used during the night to achieve the required thermal comfort due to local climate conditions and the thermal properties of the buildings. The data served as the subsequent information on the multi-domain factors for parametric analysis that took the significance of summer and winter occupancy patterns into account. As such, the correlation analysis was able to identify relationships among the numerical data and the ordinal data, which followed ordered series or ranking sequences among different categories to tabulate the data within the scope of the research question.

It should be noted that the independent samples *t*-test revealed a relationship between the presence of elderly persons in the household and the number of hours that the heating or cooling system was at the highest and lowest temperature setting [131]. It was also determined that the presence of elderly persons was associated with more hours of heating or cooling system use [132, 133]. Moreover, the chi-square tests showed that in the summer, the presence of elderly people was also correlated with the use of portable ventilation systems in addition to the use of wall-mounted air conditioning systems; these occupants preferred to keep their system on the highest setting for a few hours, then to turn their system to lowest setting or off for the rest of the time.

5. Discussions

In this empirical study, different statistical methods were applied according to the types of RQs that were distributed to respondent households that were in line with the research aim and objectives of the present study. The following discussion is structured according to the RQs that guided the findings obtained through feed-forward interviews—(RQ) Which occupant energy-consumption behaviours may have an impact on the energy performance?—in order to outline the energy policy design in the South-eastern Mediterranean climate.

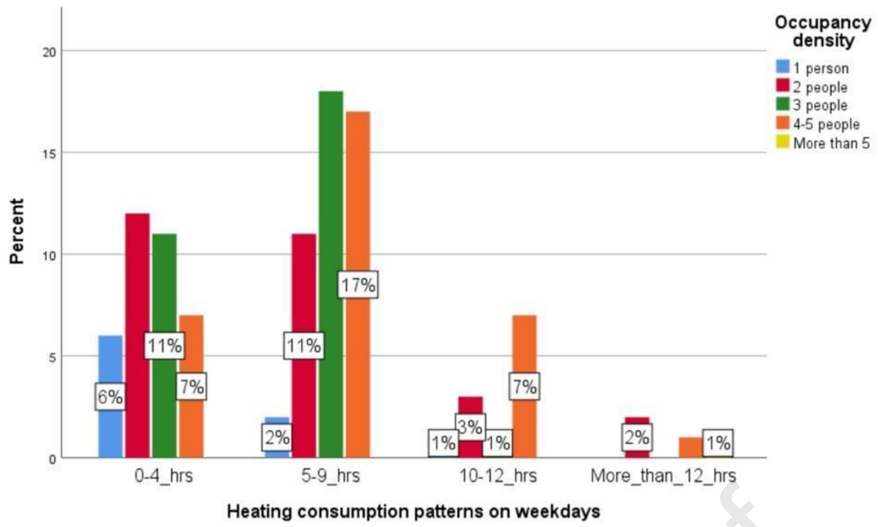
5.1. Household adaptive behaviour on energy use and implications on energy-policy design

The results demonstrated that as a respondent's age increased, their energy consumption also increased; weekday cooling consumption patterns were significantly and strongly related to weekend heating consumption patterns on weekend (χ^2 = 54,590, p < 0,001, Cramer's V = 0,522), which indicated that the older age group consumed more energy than younger residents. This underscores the fact that household age was an important consideration when identifying the occupancy patterns and taking different thermal-comfort preferences—particularly in the summer—into account. Furthermore, strong correlations were found between weekend cooling consumption patterns and weekend heating consumption patterns (χ^2 = 99,687, p < 0,001, Cramer's V = 0,706), between weekday cooling consumption patterns and weekday heating consumption patterns (χ^2 = 74,565, p < 0,001, Cramer's V = 0,611), and weekend cooling consumption patterns and weekday heating consumption patterns (χ^2 = 50,767, p < 0,001, Cramer's V = 0,504). Table 7 demonstrates the descriptive statistics of variables selected to develop evidence-based energy policy design in the South-eastern Mediterranean climate. Figures 27 (a) and (b) demonstrate the relationships between household density, heating-consumption patterns on weekdays and on the weekend.

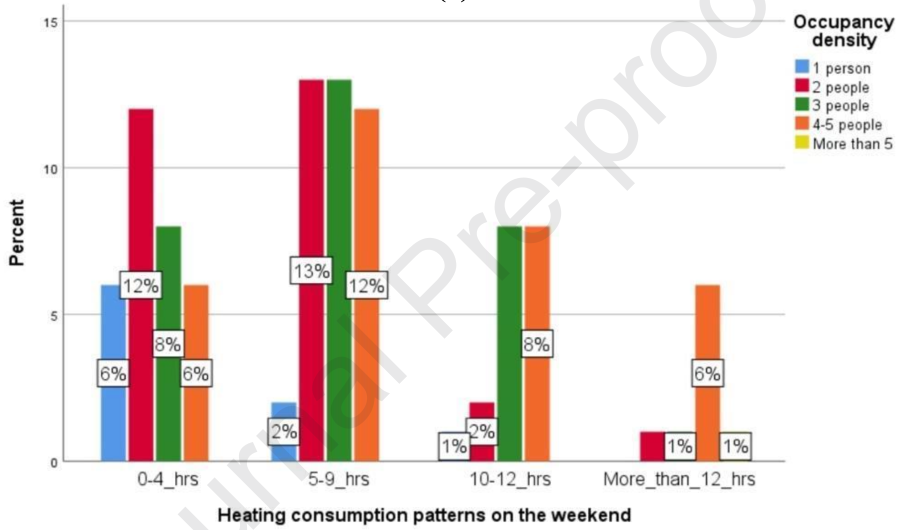
Table 7
Descriptive analysis of the variables related to households' socio-demographic characteristics.

Variable Name	Mean	Median	Mode	Std. Deviation	Minimum	Maximum	Percentiles 25th	50th	75th
Length of residency	2.56	3.00	3.00	0.76963	1.00	3.00	2.00	3.00	3.00
Floor level	1.71	2.00	3.00	1.13079	0.00	3.00	1.00	2.00	3.00
Orientation	2.04	2.00	1.00	0.99412	1.00	4.00	1.00	2.00	3.00
Interviewed room condition	1.99	2.00	3.00	1.17632	0.00	4.00	1.00	2.00	3.00
Household density	1.87	2.00	3.00	0.98119	0.00	3.00	1.00	2.00	3.00
Income	2.51	3.00	3.00	1.08707	1.00	4.00	2.00	3.00	3.00
Occupation	1.59	1.00	0.00	1.70617	0.00	6.00	0.00	1.00	3.00
Windows opening patterns in summer	0.78	1.00	1	0.416	0	1	1.00	1.00	1.00
Windows opening patterns in winter	0.57	1.00	1	0.498	0	1	0.00	1.00	1.00
Cooling consumption patterns on weekdays	1.20	1.00	2.00	0.76541	0.00	2.00	1.00	1.00	2.00
Cooling consumption patterns on the weekend	1.58	2.00	2.00	1.04621	0.00	3.00	1.00	2.00	2.00
Heating consumption patterns on weekdays	0.80	1.00	1.00	0.69631	0.00	2.00	0.00	1.00	1.00
Heating consumption patterns on the weekend	0.96	1.00	1.00	0.77746	0.00	2.00	0.00	1.00	2.00

a. Multiple modes exist. The smallest value is shown.



(a)

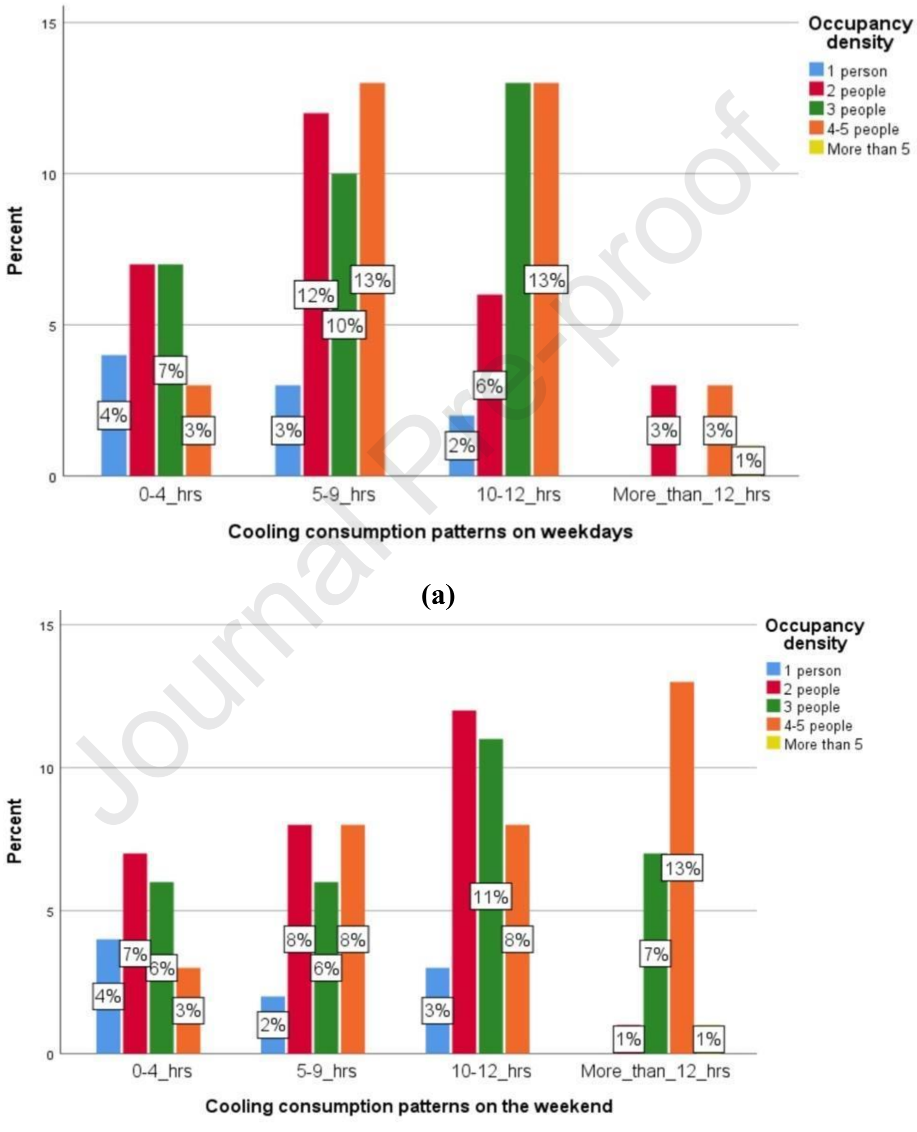


(b)

Fig.27. Percentage distribution of heating-consumption patterns by taking occupancy density type into account on **(a)** weekdays and **(b)** the weekend.

Figure 27 (a) demonstrates that 7% of the 4–5 people occupancy type used their heating appliances for 10–12 hours on weekdays, and 17% used their appliances for 5–9 hours. Of the three-people occupancy type, 18% used their heating appliances 5–9 hours on weekdays, and 11% used their appliances for 0–4 hours. According to Figure 27 (b), 6% the 4–5 people occupancy type used their heating appliances more than 12 hours on the weekend, 8% used their appliances for 10–12 hours, 12% used their appliances for 5–9 hours, and 6% used their appliances for 0–4 hours. A total of 6% of the respondent households were continuously at home on the weekend, and 20% of households preferred to stay at home for longer hours on weekends.

These results reveal a correlation between heating-consumption patterns and occupancy density, which is associated with high energy consumption in the winter. Conversely, for heating patterns, weekday consumption was moderately associated with weekend consumption ($\chi^2 = 27{,}890$, $p < 0{,}001$, Cramer's $V = 0{,}373$); the occupants' weekday and weekend energy usage revealed their deterministic characteristics, which further highlights the strong impact of household size on energy consumption [134, 135].



(a)

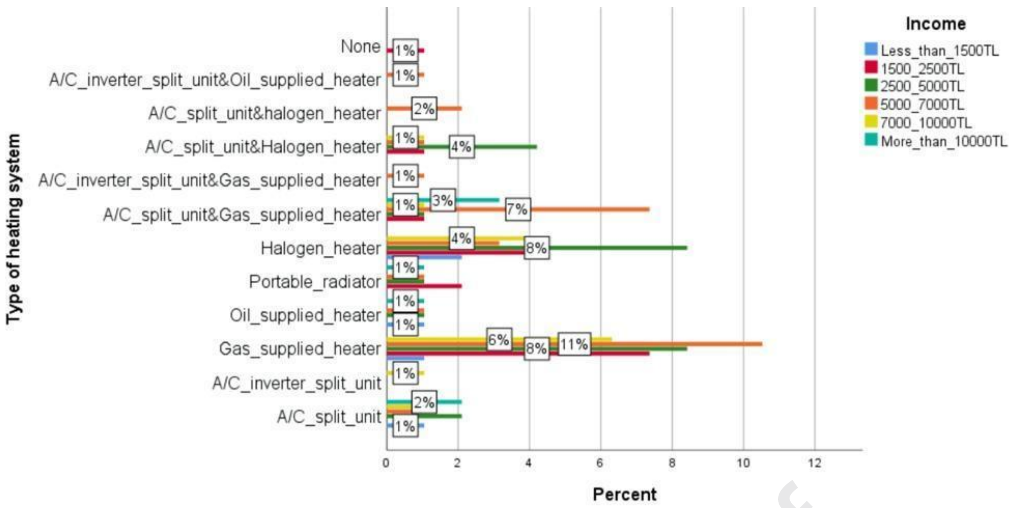
(b)

Fig.28. Percentage distribution of cooling-consumption patterns taking occupancy density type into account on **(a)** weekdays and **(b)** the weekend.

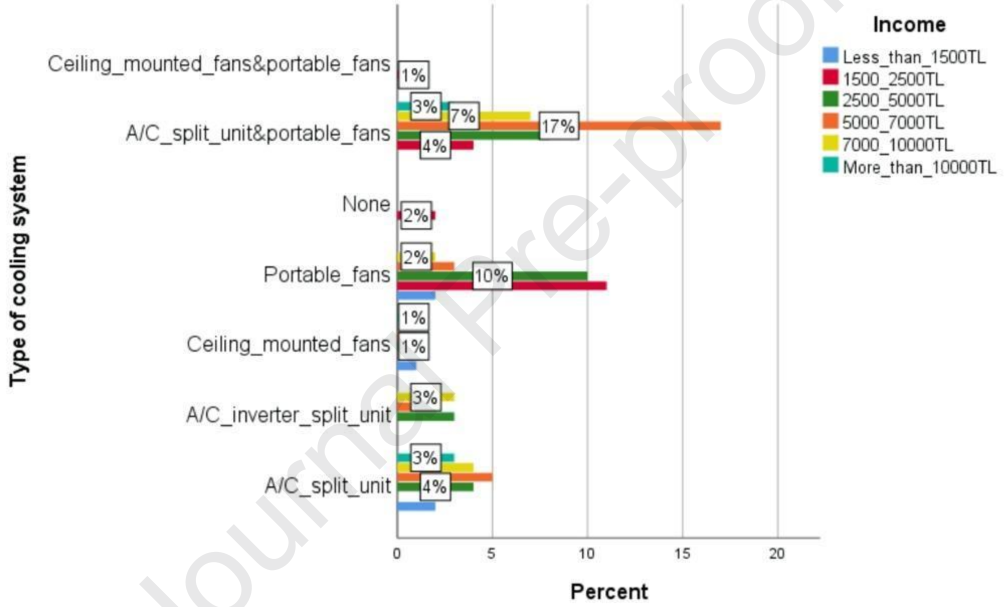
As shown in Figure 28 (a), 3% of the 4–5 people occupancy type used cooling appliances more than 12 hours every weekday, 13% used their appliances for 10–12 hours, 13% used their appliances for 5–9 hours each day, and 3% used their appliances for 0–4 hours. On the weekend, 13% of the 4–5 people occupancy type used their cooling appliances for more than 12 hours each day, 3% used their appliances for 10–12 hours, 8% used their appliances for 5–9 hours, and 3% used their appliances for 0–4 hours; the slight variation was due to the cooling appliances that were used during the night.

According to Figure 28 (b), 7% of the three-people occupancy type used their cooling appliances more than 12 hours each weekend day; this cooling-consumption pattern suggests that household size directly affects the number of hours that cooling appliances are utilised. Notably, cooling-energy consumption patterns were not limited to occupancy density; they were also linked to the household level of income.

For cooling patterns, weekday consumption was strongly associated with weekend consumption ($\chi^2 = 119{,}765$, $p < 0{,}001$, Cramer's $V = 0{,}774$); which indicates that households with high income levels consumed more energy than middle-income or economically inactive households.



(a)



(b)

Fig.29. Percentage distribution of the household's types of **(a)** heating systems and **(b)** cooling systems, taking income level into account.

Figure 29 (a) depicts the associations between types of heating systems and household income: Households that earned $5.000\text{–}7.000\ TL$ per month preferred to use a gas cylinder for heating purposes; 7% of the same group used both A/C and gas cylinder in the winter. Overall, 34% of all households used gas cylinders, 23% used portable halogen heaters, and 14% used both an A/C system and a gas cylinder. It was difficult to predict the households' habitual adaptive behaviour on the selection of type of heating systems when household income was considered to identify heating-consumption patterns [136].

The results revealed a limitation when considering the household heating systems and the influence thereof on the residents' habitual adaptive behaviour related to home-energy performance in the winter. This research approach has been neglected by the previous scholars which were discussed in Section 2. Hence, in this study the focus was to explore variations in household energy use in the hottest summer month of August.

Figure 29 (b) demonstrates that 17% of the $5.000 - 7.000\ TL$ income group used their A/C and portable fans for cooling purposes, 7% of the $7.000 - 10.000\ TL$ income group used both of these cooling appliances, 12% of the $1.500 - 2.000\ TL$ the income group used portable fans. It should be noted that the 2019 State Planning Organisation statistics indicated that 2% of NC households live in energy poverty, and these results confirm the validity of this vulnerable population in social housing estates, as presented in Sub-section 3.2.

Perhaps the most striking result to emerge from the data was that a majority of the interviewed households used electric home appliances for heating and cooling purposes because there were no central gas systems installed in their properties. Taken together, these results suggest an association between household income level, occupancy patterns and energy usage. As has been noted that the larger the household, the more the occupants thereof tend to use heating or cooling systems [137]; this is related to the occupants' tendency to pay more in energy costs to provide a thermally comfortable indoor-air environment for the members of their households in the winter and in the summer due to the low quality of construction materials used in the RTBs and the absence of insulation materials on the external walls.

One of the striking findings emerging from the cross tabulation analysis was that window opening patterns in winter were significantly associated with that in summer (χ^2 = 42,177, p < 0,001, Cramer's V = 0,459), and this relationship was moderate-strong. It appears that longer opening duration in winter was related to longer opening duration in summer. Regarding the heating control type at home, it was only significantly related to windows opening patterns in summer (χ^2 = 16,031, p = 0,042, Cramer's V = 0,283). Because the type of heating- and cooling-control system used in the model seemed to not have a correlation with the household income level that was introduced in the deterministic model [138, 139].

5.2. Retrofit design strategies for the social housing stock

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

The proposed solution for passive-design retrofitting of the building envelope was the instalment of a thick, thermal-insulated clay-tile external-facing system, the replacement of windows and door glazing (from single- to double-Low-E glazing) and the use of timber-framed shading elements [140, 141]. The presented scenarios were reviewed and studied globally, including the use of energy efficient building systems and local construction codes, and these evaluations yielded improvement models that were especially suitable for the specific region.

The retrofitting measures of the design alternative solution were as follows:

- **Exterior walls:** The existing outer layer was removed, 245 mm of new insulation was affixed to an inner layer and a new outer concrete layer, and external clay tile cladding was installed (new U-value of 0.95 W/m^{2}K)
- **Roof:** Old roof mastics and insulation were removed, and 340 mm of new insulation and a new asphalt mastic cover were installed (new U-value of 0.80 W/m^{2}K)
- **Base floor:** Additional external insulation was added (new U-value of 0.94 W/m^{2}K), and all existing single-pane windows, balcony openings and internal doors were replaced with double-pane windows (new U-value of 1.39 W/m^{2}K).

Table 8 illustrates the assigned construction properties of the base-case and the six strategies that were applied in the development of retrofit design strategies for the post-war social housing development estates in Europe.

Table 8
Specifications of the state-of-the-art retrofit strategies and those of the existing base-case.

Strategies	Element Details	*U*-value (W/m^2K)	*R*-value (m^2K/W)	Thickness (mm)	Mass (kg/m^2)	Thermal mass (kJ/m^2K)
Base-case	Common Brick: HF-C4 + Brickwork (Inner Leaf) + Clear float 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 $0.63h^{-1}$	0.80	1.10	285.5	511.65	240.0
S4	Combination S1 + S2 of envelope's rehabilitation with shading and ventilation rate of $0.4h^{-1}$	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 $0.4h^{-1}$	0.80	1.10	285.5	511.65	240.0
S6	Common Brick: HF-C4 + Brickwork (Inner Leaf) + Clear float 4mm + Combination S1 + S2 of envelope rehabilitation with shading and a ventilation rate of $0.4h^{-1}$	1.30	0.5	61.50	38.75	21.39

It should be emphasised at this point that the dominant representative occupancy profiles that were recommended by the CIBSE TM59 criteria were adapted into the simulation model at the time of the energy-effectiveness evaluation of the assigned thermal properties and the ventilation infiltration rates. Notably, the starting point in this study was the human-based data, which enabled us to triangulate the findings from the primary data sources discussed in Sub-sections 4.1.1 and 4.1.2.

5.3. Cost-effectiveness of retrofit design strategies

The aim of analysing the existing energy performance of these selected RTBs presented in this paper is to identify available building variants concerning applicability of deep retrofit strategies and the building envelope, which is an important component in the building structure as the interface between the interior of the building and outdoor environment. By testing the current condition of thermal barriers, the building envelope plays an important role in regulating interior temperatures and optimising thermal comfort levels of occupants [142, 143]. It helps to determine the amount of energy required for heating and cooling. Besides modelling and energy simulations, cost-effective energy retrofit scenarios have considered the architectural measures such as building geometry, occupied floor areas, orientation and type of construction material that affect overall improvement of the households' social standard [144].

The presented scenarios are studied globally, except from sustainable Energy Efficiency Implementation (EEI) measures and local construction practices and have given models of improvement suitable for this research context. Table 9 demonstrates the typical assumptions of energy and carbon results of the building geometry energy performance measures during pre and post retrofitting phases.

Table 9
The economic viability studies of proposed retrofitting design strategies.

Baseline	Retrofit design scenarios
Energy, Carbon & Cost Summary	**Forecasted Energy & Cost Summary**
Annual Energy Cost €1.096	Annual Energy Cost €683
Lifecycle Cost €28.184	Lifecycle Cost €18.214
Annual Energy Use Intensity	**Annual Energy Use Intensity**
Energy Use Intensity (EUI) 174 W/m^{2}K	Energy Use Intensity (EUI) 674 W/m^{2}K
Electricity 12.183 kWh	Electric 9.243 kWh
Annual Peak Demand 5.3 kWh	Annual Peak Demand 3.6 kWh
Lifecycle Energy	**Lifecycle Energy**
Electricity 362.410 kWh	Electricity 318.377 kWh

The proposed solution for energy saving of the building envelope was the instalment of a thermal insulation composite system, replacement of windows and door glazing (from single to double and triple low-e glazing), and wood-framed door/window openings that led to a significant reduction in the heat losses through building envelope. The thickness of additional insulation for the facade and floor (U = 0.04 W/m^{2}K) was 100, 200, 300 mm, for the roof the change of original 175 mm insulation and additional insulation of 50, 150, 250 mm. Three energy saving measures were considered from the upgrading of existing windows (U = 1.5 W/m^{2}K) up to the installation of double-glazed windows (U = 1.2 W/m^{2}K and U = 0.7 W/m^{2}K).

Two different new door options also were considered (U = 1.5 W/m^{2}K and U = 1.0 W/m^{2}K). It is also note that the reference case is a building with its proposed structure and service systems that provide indoor climate according to ASHRAE 90.1-2021 standard (an acceptable, moderate level of expectation). Along with improved energy efficiency, the indoor climate was also upgraded to correspond to ASHRAE benchmark (normal level of expectation) requirements. Additionally, mechanical supply and exhaust ventilation with two types of ventilation heat recovery efficiency was considered:60% and 80% while developing retrofit design scenarios for the selected archetype buildings [145].

One essential element in the strategies proposed was the glazed enclosure of the balconies, which caused an aesthetic change of appearance of the building envelope, by means of sliding glass elements, which created a thermal buffer zone in the winter. Glazed enclosure of the balconies is proposed in the prototype RTBs, it is evident that the greater effect on reducing the need for heating was achieved by upgrading building envelope, from 53% to 73% savings in order to exterior wall orientation and thickness of insulation materials. At the same time, in the summertime, effective ventilation is required to prevent the glazed terraces from generating additional heat load. This is partly due to the fact that current natural ventilation systems are not regulated and apartments are mostly under ventilated. Ensuring that ventilation airflows meet indoor climate standard requirements increases global costs, but energy savings cannot be achieved through lower indoor air quality as indoor air pollutants affect resident's health and well-being [146, 147]. For this reason, a ventilated facade was proposed, which can reduce the amount of heat that the building absorbs due to partial reflection of solar radiation by the covering and the ventilated air gap.

It is also remarkable to note that the discount rate is a key variable for the life-cycle cost assessment calculation (LCCA) [148]. The prices for the energy cost are chosen by the publication of the energy agency in Cyprus. The overall energy use saving and life cycle energy use of retrofitting strategies are shown in Table 10.

Table 10
Energy use intensity and life cycle energy use of the proposed retrofitting strategies.

Energy Use Intensity		**Life Cycle Energy Use and Cost**	
Electricity (Median)	**256 kWh**	Life Cycle Electricity Use	**330.124kWh**
Overall Electricity	**710 kWh**	Life Cycle Energy Cost	**€ 21.172**

The investigation on the basis of prototype RTBs shows that with the conditions of parameters of the calculation, the energy use intensity of heating and cooling demand in relation to the cost optimum is about 330.124 kWh per year. The analysis pointed out that RTBs older than 30 years are profitable for retrofitting because of their low energetic quality. Because of the high effect on the building envelope materials, which requires the feasibility of the energy conscious retrofitting measures, the input parameters, such as the life-cycle parameters, including the discount rate of the energy price inflation, should be planned carefully.

5.4. Future recommendations on energy policy design

This research paves a new way of tools and adoption of retrofit strategies to utilise a real market dataset for sustainable design optimisation, which will allow designers, contractors, suppliers, property owners and researchers to identify both effective and feasible retrofitting options for the rehabilitation of the existing RTBs, to help improve building efficiency. It is noteworthy that building energy performance-related interventions were shown to have impact and to be influential in the success of net zero energy targets, particularly in upgrading the energy efficiency of post-war social housing stock [149-151].

To meet ambitious targets such as those set by the European Union under the Horizon 2030 for achieving near zero and positive energy settlements in Europe using advanced energy technology, all interventions available would need to be considered. It is also noted that those retrofitting schemes would not necessarily be achieved purely by enhancement of building envelope upgrades or testing various building applications without taking into account local building codes and climate. This would include further decision-making criteria that should be planned carefully, such as those relating to identifying dominant representative occupancy profiles. This is further highlighted by the benefit of developing base-case analysis to broaden the residential buildings represented, particularly different construction materials, age, physical condition and the range of interventions considered. This neighbourhood-based analysis provided evidence to suggest which type of tenure consumes the least or most amount of energy and the relationship this, in turn, had to the levels of overheating experienced due to deficient building envelopes from the residential property in question.

Further studies regarding the role of occupants' behaviour on energy use would be worthwhile and interesting. As previously mentioned, the behaviour taken into account in this study was defined as the use of a longitudinal questionnaire survey with householders and other provisions in the dwellings for identifying deterministic approaches on energy use. Therefore, this research only focused on behaviour and its impact on domestic energy use, not on its causes. However, the survey findings indicated that respondents aged 55-56 preferred a much cooler indoor air environment. At the same time, the energy bills analysis results demonstrated that this age group also tended to have higher energy bills in order to provide a thermally comfortable indoor air environment. Notably, there was no correlation found between household characteristics and ventilation behaviour. In terms of direction of future research, further work could explain why some households prefer lower indoor temperatures or more ventilation than others.

Another possible area of future research would be to investigate why occupants' thermal comfort preferences correlate with energy use. In addition, analysis of total social housing stock could lead to different results due to a great variety of occupancy profiles and building characteristics affecting behaviour. As this is the case, this research used self-reported occupant behaviour in retrospective while undertaking a longitudinal field survey in the summer of 2018, thus indicating there might be large differences between actual and predicted energy use. More research into these differences should be carried out in the future by other scholars, practitioners, engineers, or energy consultants to explore correlations between occupant behaviour and actual energy use in the residential sector.

6. Conclusions

This research sought to draw conclusions related to the multi-domain factors of households' socio-demographic characteristics, occupancy patterns and their home energy performance. To gauge households' information on energy use, the field study approach was adopted. The longitudinal field survey was conducted to bridge the energy performance gap of all 36 RTBs in a post-war social housing development estate in Famagusta, Cyprus. As a base case RTBs were selected to recruit social householders (either owner occupiers or private renters) in accordance with the quota sampling criterion. In order to represent 38% of social housing stock in Cyprus, the in-vivo experience of household's feed-forward interviews were conducted. In this endeavour, statistical analyses were used to determine the multivariate factors that influence both heating and cooling energy consumption, including in the peak cooling month of August.

The empirical analyses carried out in this study were explanatory in nature, and the objective thereof was to identify the relationships between different variables (i.e., socio-demographic characteristics of occupants, household awareness of energy-saving methods, type[s] of heating and cooling systems used, occupancy patterns in energy use and household energy usage), which will them serve to deepen our understanding of the relative influence and interaction between these variables and will eventually pave the way for energy consumption calibration for certain groups while taking the effect of orientation and floor-level differences into consideration.

The survey revealed that for heating patterns, weekday consumption was moderately associated with weekend consumption ($\chi^2 = 27{,}890$, $p < 0{,}001$, Cramer's $V = 0{,}373$). for cooling patterns, weekday consumption was strongly associated with weekend consumption ($\chi^2 = 119{,}765$, $p < 0{,}001$, Cramer's $V = 0{,}774$), because this was when occupants spent the greatest amount of time at home and desired optimum thermal comfort. The most compelling finding in this section was that the presence of heating and cooling appliances seemed to have a significant effect on energy consumption. Correlations were found between energy consumption and the type of heating and cooling systems that the occupants used in their homes. However, household occupation was not significantly related to any cooling or heating consumption patterns.

The implication of this study was to develop appropriately tailored design strategies for effective retrofitting interventions in order to fulfil the knowledge gap in energy efficiency, including occupants' thermal comfort. The findings reveal that human-based data is the superscript deterministic factor to uptake delivery of effective retrofit design interventions both at conceptual and policy level. In this study, the longitudinal field survey approach was adopted to explore households' socio-demographic characteristics, buildings' technical parameters and energy efficiency awareness were investigated to contribute to the notion of Socio-Technical-Systems (STS) conceptual framework developed by previous scholars in building engineering field. Therefore, this study is the first of its kind to investigate social householders and high-density social housing estates in the South-eastern Mediterranean climate of Cyprus where there is little research undertaken on understanding difficult-to-quantify occupancy patterns and its significance on domestic energy use.

The findings from the statistical analysis provide subsequent information for the energy simulation input parameters which will be examined to find answers in line with the main research questions outlined for this exploratory case study approach namely' overheating risk assessment, thermal comfort and energy use. The outcomes of this study contribute to the STS design approach as a result of the most accurate data obtained through a questionnaire survey to outline a roadmap to the government initiatives, stakeholders and local municipalities for effective policy making decisions in energy use in Cyprus.

Declaration of Competing interest

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

CRediT authorship contribution statement

Bertug Ozarisoy: Writing – original draft, Conceptualisation, Methodology, Investigation, Writing – review & editing. **Bertug Ozarisoy** conducted the field surveys, computational analysis, analysis of the numerical experiments and the designing of retrofit strategies; and **Bertug Ozarisoy** provided sources (e.g. illustrations, tables and datasets), comments, and major edits to the paper. **Prof. Hasim Altan** provided necessary supervision to check the accuracy of the statistical information included into the article and he supported the author during the writing-up process of the Methodology, Results and Discussions, Conclusions.

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Supplementary Material
Supplementary data to this article can be found online at –
Supplementary Material A – The questionnaire survey proforma - An investigation of cooling energy consumption patterns of households and Thermal comfort.

Data Brief
Data Brief to this article can be found online at –
Data Brief A: The raw data of the statistical data set was designed in the Statistical Analysis in Social Science (SPSS) version 28.0, including spv. file for other scholars' further research work.

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Highlights

- A literature review was undertaken to develop an evidence-based energy policy design.
- A comprehensive methodological framework was integrated in buildings' retrofitting.
- Household occupations were significantly associated with age.
- Age bands were significantly related to the households' health conditions.
- Weekday cooling consumption patterns were strongly related to weekend heating consumption patterns.

Declaration of interests

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

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

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

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