Assessing energy and thermal comfort of domestic buildings in the Mediterranean region

by

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Abstract

Nowadays, buildings are responsible for the 40% of energy consumption in the European Union, with energy up to 68% being coherent with thermal loads. Acknowledging the great potential of building sector, a substantial amount of the current building inventory must be refurbished, based on the trade-offs between energy and thermal comfort. To this effect, this study investigates the impact of retrofitting measures in residential envelope for areas experience Mediterranean climate. Seven detached houses, located in Cyprus, were modelled, investigating 253 parameters of envelope interventions and also, 7,056 combinations of these measures.

In general, the findings revealed a seasonal performance variation of interventions with regards to the outdoor climate. The application of roof insulation determined as the most economic viable solution during retrofitting (single interventions), achieving a reduction up to 25% of annual energy consumption with enhancement of the indoor thermal environment. In the perspective of synergies between interventions, the application of roof and external walls thermal insulation with upgrade of glazing system with double Low-E demonstrated exemplary levels of performance decreasing on average energy consumption up to 38%.The findings of this research will contribute on the development of guidelines for designers and house builders for a perceptual retrofitting of existing residential envelopes in Cyprus and also, for countries experiencing the Mediterranean climate.

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List of Abbreviations

AC – Air-conditioning

ACH – Air changes per hour

AGC – Asahi glass company

ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers

AV – Actual vote (Thermal Comfort)

BBR – Boverket's building regulations

BMoA – Bureau of Meteorology of Australia

BPIE – Buildings Performance Institute Europe

BRE – Building Research Establishment

CDD – Cooling degree days

CEA – Cyprus Energy Agency

CIBSE – Charted Institute of Building Services Engineers

CO – Carbon monoxide

CO_2 – Carbon dioxide

COP – Coefficient of performance

CVRMSE – Coefficient of variation of the root meat square error

CYS – Cyprus Organization of Standardization

CYSTAT – National Statistic Service of Cyprus

DHW – Domestic hot water

DTM – Dynamic thermal modelling

E+/EPlus – Energy Plus software

ECRC – European Cool Roofs Council

EER – Energy efficiency ratio

EMS – Energy management system (auxiliary program of Energy Plus)

EN/CEN – European Standards

EneService – Energy Service of Cyprus

EnEV – Energy Saving Ordinance

EPBD – Energy performance of Buildings Directive

EPS – Expanded polystyrene

EPW – EnergyPlus weather file

ESM – Energy saving measures

ESRU – Energy Systems Research Unit

EST – Energy Saving Trust

ETS – Emissions trading scheme

EU – European Union

EC – European Union Council

EWC – Efficient Windows Collaborative

FMET – Federal Ministry of Economics and Technology (Germany)

GEBCO – General bathymetric chart of the ocean

GHG – Greenhouse gasses

HBTIR – Hellenic building thermal insulation regulations

HDD – Heating degree days

HSF – High solar factor

HVAC – Heating, ventilation and air-condition

IAQ – Indoor air quality

IDEA – Spanish Institute for Energy Diversification and Saving

IDF – Input definition file

IEA – International Energy Agency

IPCC – Intergovernmental Panel on Climate Change

ISO – International Organization of Standardization

LBL – Lawrence Berkeley National Laboratory

Low-e/Low-E – Low emittance

LSF – Low solar factor

ltr – litre

MCIT – Ministry of Commerce, Industry and Transportation (Cyprus)

MetService – Meteorological Service of Cyprus

MSF – Medium solar factor

NAP – National Action Plan (Cyprus)

NMBE – Normalized mean bias error

NOAA – National Oceanic and Atmospheric Administration

NPV – Net present value

PIR – Polyisocyanurate insulation boards

PMV – Predicted mean vote (Thermal Comfort)

PPD – Percentage of people dissatisfied (Thermal Comfort)

SAW – Simple additive weighting

SAW_{score} – Simple additive weighting performance score

SCRLC – Southern California Research Learning Centre

SEA – Swedish Energy Agency

SHGC – Solar heat gain coefficient

TOE – Tonnes of oil equivalent

TBC – Technical building code

TMY – Typical meteorological year

UN – United Nations

USDOE – U.S. Department of Energy

VOC – Volatile organic compounds

XPS – Extruded polystyrene

Chapter 1. INTRODUCTION

1.1 BACKGROUND OF RESEARCH

Reducing dependence on fossil fuels for energy and thereby, mitigating the impacts of climate change is one of the key challenges of the 21st century. Energy conservation is a complex challenge as it is closely linked to the issues of increasing demand for energy and the need to ensure energy security.

A common European policy has evolved around these issues and aims to ensure an uninterrupted physical availability of energy products and services at an affordable price, while contributing to the European Union's social goals and carbon emissions reduction targets (EC, 2010a). To this effect, the European Council has adopted a policy of reducing greenhouse gasses emissions below 1990 levels by 20%, increasing the share of renewables to 20% and improving energy efficiency by up to 20% by 2020 (EC, 2008).The EU is also committed to reducing greenhouse gas emission to 80-95% below 1990 levels by 2050 (EC, 2011a). For instance, one of the member countries, the United Kingdom, has already mandated an 80% reduction in greenhouse gas emission by 2050 via the Climate Change Act 2008 (UK Parliament, 2008). EU member countries, including new members, are therefore, under increasing pressure to significantly reduce energy consumption and inherent carbon emissions by fossil fuels.

In the European Union, buildings are responsible for nearly 40% (22% dwellings and 18% commercial buildings) of energy consumption (and 36% of GHG emissions) (EC, 2012b). The Europe-wide initiatives on transforming the energy system for a decarbonized future recognize the importance of buildings in reducing carbon emissions (EC, 2011a). By a breakdown of the residential energy use, space conditioning contributes heavily up to 68%. It is then evident that householders consume most of their energy to maintain comfortable conditions, due to a poor building design and operation. By the evolution of technology and industrialization, houses relied on artificial systems, ignoring the adaptive ability of the human body (Clements-Croome, 2000; Roaf et al., 2010). This is a burden for the southern EU counterparts (Mediterranean region), as the residential buildings were constructed without the implementation of any comprehensive legislation on thermal performance. Healy (2003) claimed that the most inefficient housing inventory occurs in Greece, Spain, Italy and Portugal. On the contrary northern countries such as Germany, Sweden, Finland, France, Netherlands and Norway present exemplary levels of efficient dwellings (Lapillone and Wolfgang, 2009). Therefore, the existing southerly residential inventory has a significant potential for energy conservation.

There seem to be two lines of thought with regards to the strategies on existing buildings; demolition or retrofitting. Undoubtedly, demolition and new buildings may be defined as better solutions. However, an enormous amount of the European housing inventory will need refurbishment that will substantially result in energy reduction and its associated CO_2 emissions (Burton, 2012).

A refurbishment strategy will be established which is governed by the trade-offs between energy and thermal comfort. Characteristically, the European Council pointed that the achievement of energy targets must not lead to scarification of thermal comfort and indoor air-quality (Borgeson and Brager, 2011).

1.2 Research Goal

As aforementioned, European southern counterparts and especially, Cyprus are currently confronted by the European Union's targets set out for 2020. In particular, the European targets for 2020 are set to 13%, for new member countries. Acknowledging the vast potential of the housing inventory, the research goal of this study is to provide guidelines for a viable retrofitting of residential envelopes, driven by the trade-offs between energy and thermal comfort.

1.3 Aim and Objectives

This study will investigate the energy consumption and thermal comfort in Mediterranean housing inventory. Particularly, the case of Cyprus will be examined from the perspective of retrofitting the building envelope to reduce energy consumption without compromising thermal comfort.

The objectives of the research are to:

1. Investigate the current European scene from the perspective of energy consumption, housing inventory and evaluation methods of the residential thermal comfort. In addition, the energy scene of Cyprus state will be thoroughly reviewed.
2. Examine the current measures/methods for retrofitting the building envelope.
3. Select the representative type of housing inventory to form the basis for the investigation of building envelope interventions.
4. Collect data (such as as-built drawings, construction materials, infiltration rate, indoor air temperature, energy records etc.) from real houses, in order to be utilized for the calibration and validation of the simulation models. In the same line of thought, the climatic data from the nearest weather station will also be obtained.
5. Develop validated simulation models (based on actual data), for the investigation of the effectiveness of measures that will be applied on the building enclosure.
6. Analyse the impact of single interventions with regards to the energy and indoor thermal comfort performance, for heating and cooling seasons. A parametric analysis will be performed, in order to examine the synergies of the application of combined interventions.
7. Prioritize the measures, based on their performance obtained by the previous objective, following the concept of economic assessment by the application of the Net Present Value (NPV).
8. Develop guidelines and recommendations by using the results obtained from previous objectives.

1.4 STRUCTURE OF THE THESIS

In order to accomplish the overall goal of this research study, the thesis comprises of seven chapters that are outlined as follows:

- **Chapter 1 (current)** introduces the background of the thesis, presenting the goals, aims and objectives.
- **Chapter 2** explores the aspects of energy and residential buildings. Further, it discusses the methods of retrofitting residential building envelopes through the implementation of building simulation, paying attention on thermal comfort. A wider picture is developed for the case of Cyprus.
- **Chapter 3** describes the methodology that is followed throughout the study in order to investigate the effect of envelope interventions (single or combined) on residential buildings. The performance assessment method is also presented, in order to form the basis for the intervention's prioritization.
- **Chapter 4** discusses the calibration procedure and validation assessment of building models, including the results of the application of the mid-season and annual performance validation.
- **Chapter 5** provides the results of the implementation of envelope interventions with regards to the impact of single interventions or the synergies of combined measures.
- **Chapter 6** presents the prioritization of measures within the context of economic evaluation, underlined the trade-offs of energy and thermal comfort.

- **Chapter 7** draws the conclusions and recommendations of the research study, introducing retrofitting guidelines for refurbishing existing residential envelopes.

Figure 1-1 provides the structure of the thesis, correlating the objectives and the Chapters of thesis.

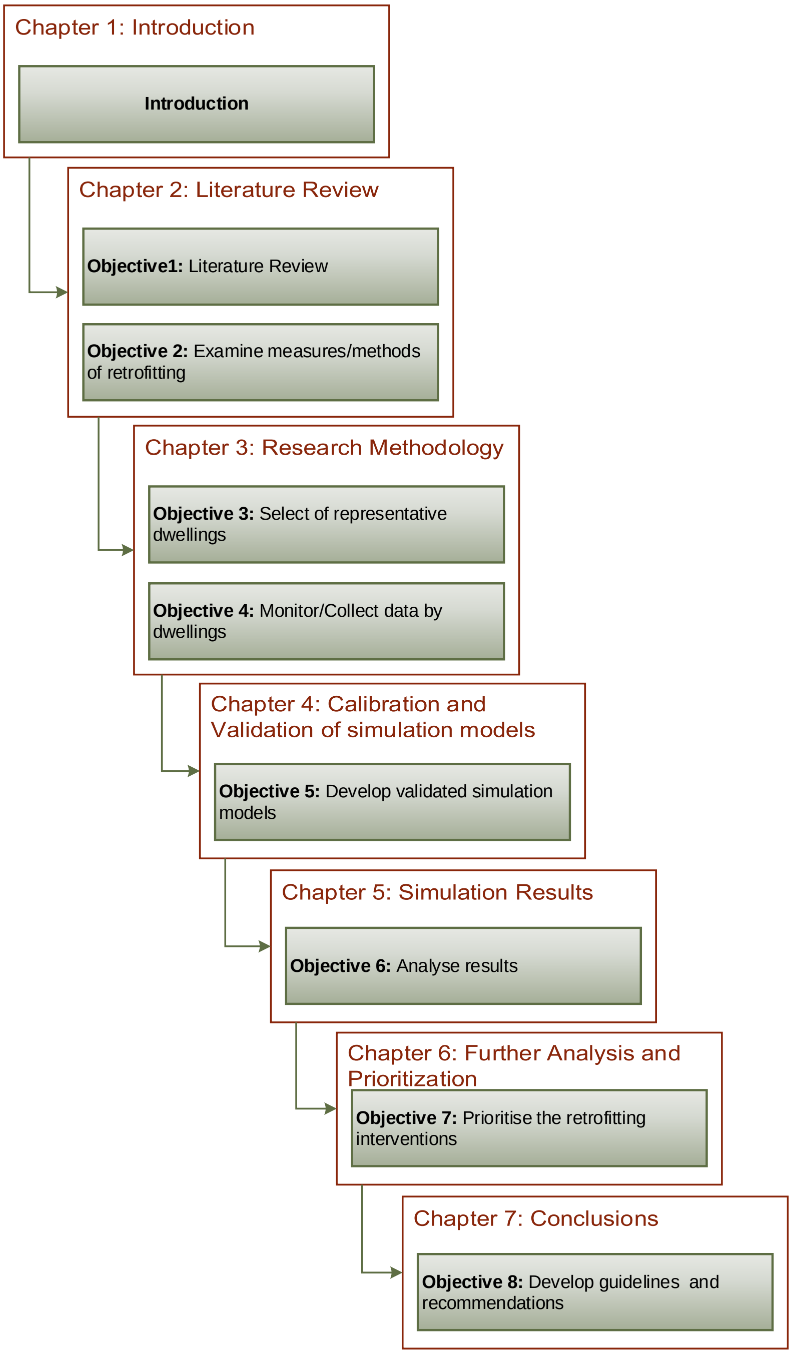


Figure 1-1 Structure of Thesis

Chapter 2. LITERATURE REVIEW ON ENERGY AND RETROFITTING OF EXISTING DWELLINGS

2.1 INTRODUCTION

This chapter reviews the aspects of energy and retrofitting of existing residential buildings, developing a wider picture for the case of Cyprus. More specifically, the first section (2.2) presents energy in the context of the building sector, placing emphasis on the current status of the European housing inventory. Thereafter, section 2.3 deals with the thermal comfort, underlying the post-evaluation assessment of building interventions in the context of the indoor thermal environment. Furthermore, section 2.3 discusses the background of retrofitting measures, while also offering an attention to the aspect of building simulation. Finally, the section 2.4 refers to the case of Cyprus and the current scene of energy and housing inventory.

2.2 ENERGY AND THE BUILDING SECTOR

"*Energy is a resource or, more precisely, a group of resources essential to all branches of economic activity and to the general well-being of man in an industrial society*" (De Carmoy, 1977). Over centuries, the matter of energy has consistently troubled humanity. Most notably, people have worried about reserves or alternative forms of energy since ancient years, shifting consistently to alternative energy sources, i.e., Roman empire, Middle-Ages England (Cassedy and Grossman, 1998; Shepard et al., 1976).

A critical milestone, in the modern history, was the sudden severance of oil supplies due to the Yom Kippur war in 1973 (Hedley, 1981). The nations realized their crucial dependency on fossil-fuels, triggering concerns to ensure energy security and avoidance of possible socio-political dilemmas, inherent with energy sources and prices.

Hence, coherent policies, legislations, standards and actions were established to promote alternative technologies, methods and measures for energy conservation, and/or use of indigenous sources enhancing the security, awareness and independence by the conventional energy sources (EC, 2005).

Further to the aforementioned, the exaggerate energy consumption, especially in the mid-20th century, led to global warming and climate change. Admittedly, the climate change was primarily generated by the wasteful anthropogenic activities. Particularly, the emissions of greenhouse gasses were rapidly increased alongside the industrial revolution, causing the enhanced greenhouse effect which resulted in dramatic global warming (Houghton, 2009). Hence, the earth's average surface temperature has increased compared to 100 years ago (see Figure 2-1) (BMoA, 2003; Houghton, 2009; Svante, 1896).

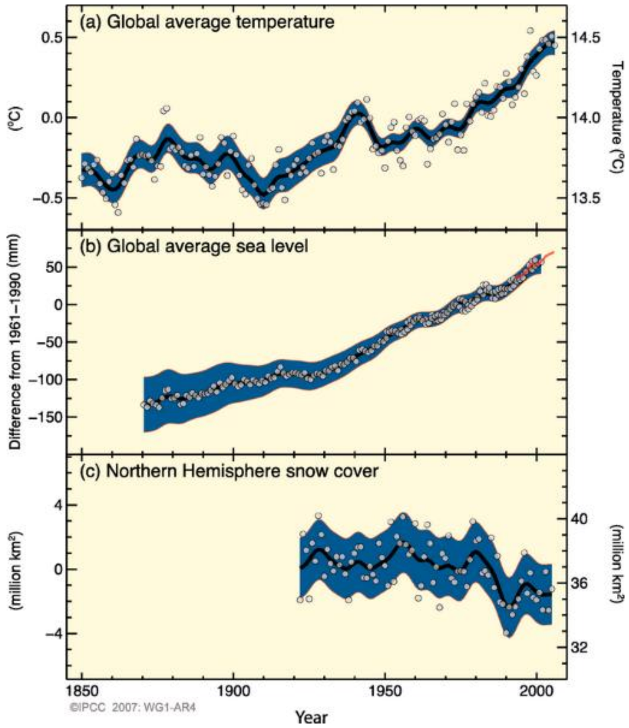


Figure 2-1 Changes in temperature, sea level and Northern Hemisphere snow cover (IPCC, 2008)

To this effect, it is globally accepted that many biological aspects (water, ecosystems, food, coasts and health) will be influenced by the elevated surface temperature. For instance, extinction of species, shortage of freshwater, and also, health will be compromised by frequent heat waves, and coastal erosion due to the sea-level rise (IPCC, 2007).

Thereby, the vital point of the 21st century will be the adoption of effective actions and measures to mitigate the impacts of climate change that may be confronted by the future generations. The reduction of energy consumption must be achieved in a cost effective manner by end-use sectors and offer great potential for immediate results. In essence, the rest of this section will extent the discussion on building sector and its importance on the energy reduction targets.

2.2.1 ENERGY CONSUMPTION BY THE BUILDING SECTOR

In the global scene, the energy is spent by three primary sectors; industry, transportation and buildings. IEA (2011) published the worldwide energy consumption by end-use sectors (IEA, 2011). The results are depicted in Figure 2-2.

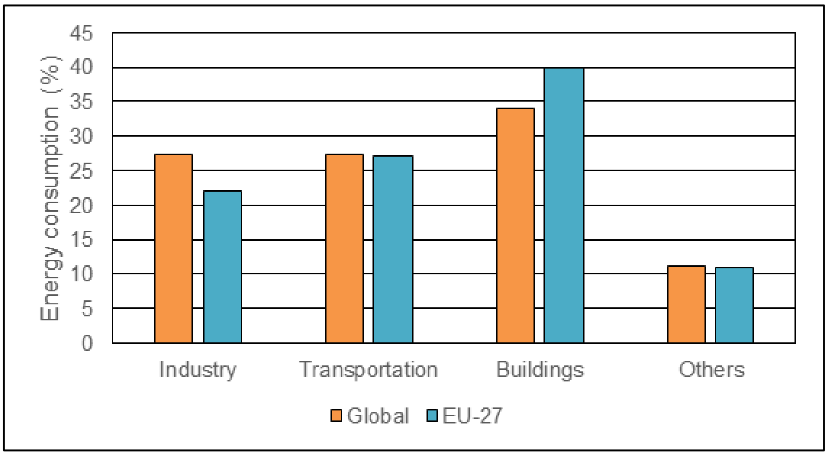


Figure 2-2 Energy consumption by end-use sectors at 2009 (IEA, 2011)

From the Figure 2-2, it can be realized that buildings is the most consuming sector among the end-use categories, for both the global and EU-27 scene, with almost twice the percentage of the other sectors. It was estimated that the energy consumption by the building sector is about 451 Mtoe (Million tonnes of equivalent)(IEA, 2011).

The building sector is comprised by two categories; (a) commercial and (b) residential. According to Kavgic et al. (2010), 22% of energy is absorbed by the domestic buildings, with the rest 18%, consumed by commercial sector. A breakdown of residential energy use according to (Lapillone and Wolfgang, 2009), reveals that the conditioning of spaces requires approximately two thirds of this energy, whilst the remaining third is consumed by cooking, appliances and DHW, as depicted in Figure 2-3.

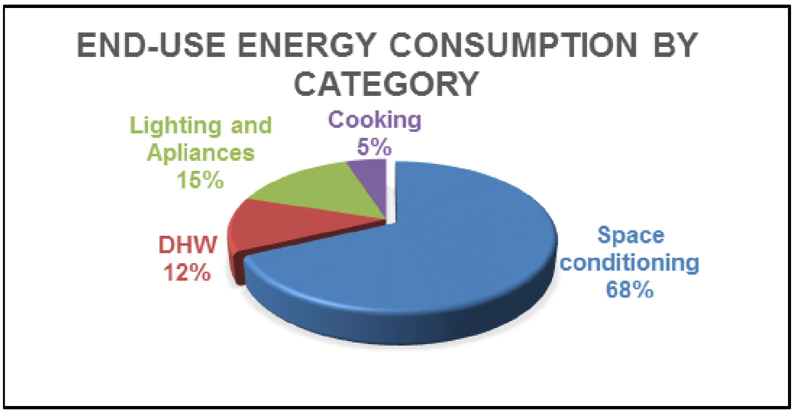


Figure 2-3 Breakdown of household energy consumption by end-use categories in EU (Lapillone and Wolfgang, 2009)

This trend is particularly noticeable in modern societies, where the evolution of mechanisation coupled with the poorer building envelopes has led to the use of artificial cooling or heating to maintain thermal comfortable conditions (Roaf et al., 2010). Clements-Croome (2000) claimed that buildings cannot provide adaptive opportunities, maintaining a moderate indoor climate. Further to this, Roaf et al. (2010) reported that in warmer regions where cooling was necessary for the summer period, a bad design could contribute to the extended use of mechanical cooling.

2.2.2 Status of the European housing inventory

In general, European housing inventory presents an opposed performance between Northern and Southern European counterparts, due to the absence of policies obligating the energy performance of buildings. Healy (2003) pointed out that most of the EU's energy inefficient stock occurs in Greece, Spain, Italy and Portugal, while the accession of other southern countries (i.e., Cyprus) in the EU has burdened the energy efficiency scene of Southern Europe. Despite the fact that some southern countries have some kind of building regulations (i.e., Greece-HBTIR [OHJ 362/4-7-79], Spain-TBC), no significant results occurred (Healy, 2003; IDAE, 2007). On the contrary, northern countries such as Germany, Sweden, Finland, France, Netherlands and Norway present exemplary levels of energy efficiency in the building sector due to stricter policies and regulations (Lapillone and Wolfgang, 2009).

Currently, the EU is running a strategic plan, implementing all the members to accomplish it by 2020, for a smart, sustainable and inclusive growth. The plan is founded on 5 targets related to R&D/Innovation (Research, Development, and Innovation), Employment, Education, Poverty and Climate Change/Energy. In the scope of energy and climate change, the plan aims to reduce the greenhouse gas emissions by 20% compared to 1990 levels or 30% if the conditions are right. The 20% of final energy consumption must be provided by renewable sources and the energy efficiency must be increased by 20% (EC, 2010a).

In the perspective of the building sector, the Energy Performance of Buildings Directive-EPBD (2002/91/EC) was initially published in 2002. As a Directive, it is characterized as a “powerful instrumentation” for the actions in the residential and commercial buildings (EC, 2011b).Thereafter, a recast-EPBD was implemented in 2010 (2010/31/EC), strengthening the provision of its precursor. Basically, the Directive set the minimum performance requirements for building construction and renovation. Implementation of the Directive requires the high performance of new buildings and shifts the existing inventory scene towards energy efficiency.

In general, it is expected that emphasis will be placed on existing dwellings, despite the fact that higher savings can be achieved by new buildings (Boardman, 2007). Typically, new buildings account for only 1-2% of residential stock (Steemers and Yun, 2009). Apart from this, most of the housing inventory was constructed before the implementation of EPBD. As it is stated by Balaras et al. (2007), new dwellings consume 28% less energy than houses built before 1985, while the efficiency in the residential sector has increased by 60% since the oil crisis of 1970s.

2.3 Retrofitting existing houses in Mediterranean region

It is widely accepted that new dwellings are governed by higher levels of efficiency due to regulations, better construction and advanced products, fostering the awareness on the existing housing inventory. A debate has arisen in terms of demolition or refurbishment with inherent issues of heritage, environmental impacts, community stability, costs, and life-cycle analysis and it can be concluded that the demolition and construction of new buildings offer a better solution. However, this cannot diminish the need to refurbish large amounts of the housing inventory, for energy conservation and associated CO_2 emission reduction (Burton, 2012).

As aforementioned, the efficient scene is burden by the South (Mediterranean region), skewing the performance of the northern European counterparts (Lapillone and Wolfgang, 2009). Apart from the fact that the vast majority of dwellings were constructed prior to the implementation of any legislation (most directives were based on North countries), resulting in poor building envelopes, a critical factor to be considered is the climate experienced across the Mediterranean region. Steemers and Yun (2009) highlighted the importance of climate, a factor inherent residential energy use, while Humphreys (1996) has also expressed a similar view on the aspects of living that are influenced by. The inability of buildings to adopt to the external climate, contributes to the energy profligate (Steemers and Yun, 2009).

Mediterranean climate[1] is described by mild, rainy winters and warm, dry summers with high annual solar gains. Regions that experience this particular climate are presented in Figure 2-4.

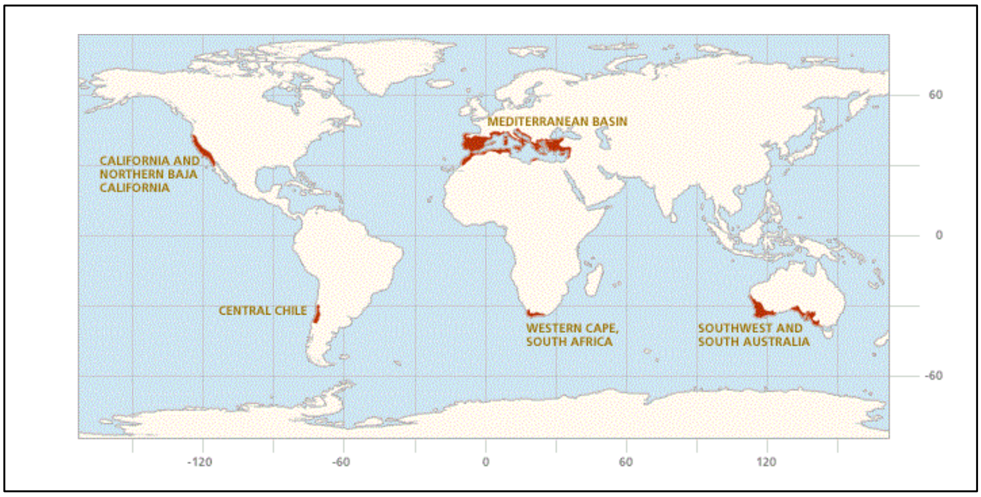


Figure 2-4 Regions with Mediterranean Climate (SCRLC, 2012)

In the context of thermal loads, the Mediterranean countries are generally characterized by a warm climate, however, they endure winter seasons with average temperatures of about 6°C (Healy, 2003). Generally, the climate may

[1] According to Koppen-Geiger, the Mediterranean Climate is indexed as C_{sa}-dry subtropical climate (Peel et al., 2007).

not be defined as severe; however three distinct weather periods occur: (1) an under-heating period (winter months), (2) neutral period and (3) an overheating period (summer months). Due to this, the ability of the building to deal with such outdoor conditions will be primarily established by a dynamic design and operation (Joanna et al., 2012).

Another crucial characteristic of the Mediterranean region is the excessive insolation. For instance, in Cyprus low lands the average annual hours of bright sunshine is 75% of the time that the sun is above the horizon. In essence, this corresponds to average time of 11.5 hours per day during the summer period and 5.5 hours per day during the cloudiest months, December and January, of the winter period. Meanwhile, at the highest areas the sunshine is estimated as 11 hours and 4 hours, during the summer and winter period, respectively (MetService, 2012a). Admittedly, the measures and actions must be driven by the adaption of the buildings to the particular climate or even microclimate, without ignoring crucial factors such as the solar gains.

Performing alternation to the building envelope, may compromise positively or negatively on the current indoor conditions. The EPBD stated that the achievement of energy goals must not lead to sacrifices of thermal comfort and indoor air quality (IAQ) (Borgeson and Brager, 2011). It is then mandatory to evaluate thermal comfort prior and after refurbishment to estimate the impacts on thermal conditions, which may result on the employment of mechanical systems. In essence, a perceptual refurbishment will be founded on the trade-offs of energy and thermal comfort.

Through the rest of this section, thermal comfort and energy saving measures will be extensively presented in the perspective of retrofitting dwellings. The last part of this section describes building simulation and its implementation to the dynamic investigation of measures to reduce energy consumption in houses.

2.3.1 THERMAL COMFORT

The conceptual definition of thermal comfort is, "*…that condition of mind that expresses the satisfaction with thermal environment…"* (ASHRAE, 2010). The analysis of the topic is backdated to the early part of the 19th century, when Heberden claimed that the thermal sensation is not only influenced by the air temperature. However, the first study on thermal comfort was established in 1905, when Haldane (1905) attempted to establish design temperatures in England. In the mid-20th century people were able to manipulate the indoor environment to their expectations and according to Shove (2004) it was then when comfort adopted its acknowledged meaning, rather a "shelter" from the severe environmental conditions.

Thereafter, a plethora of studies was published, based on findings from environmental chambers and field studies with different climates, genders, ages, cultures and building types. The majority of the studies were mainly driven by the investigation and establishment of criteria, thresholds and standards to define the range of conditions that people are satisfied by their thermal environment.

There seem to be two lines of thought with regards to the perception of thermal comfort. The first relies on the globally accepted predicted mean vote (PMV), so-called *static* approach, which is based on a study carried out by Ole Fanger in a climate chamber (Fanger, 1970). The PMV was governed by controlled indoor conditions, neglecting the transient conditions of real life scenarios. On the other hand, a group of people accepted that people are not passive recipients of the environment, but tend to interact with it (Roaf et al., 2010). The principle of adaptive model, *dynamic* method, was initially defined by Humphreys and Nicol (1998) as: *"if a change occurs that produces discomfort, people will tend to act to restore their comfort"*. The method was founded by field studies carried out in 'real' buildings during 'real' environmental conditions, without marginalizing the pragmatic activities and actions of the subjects.

WELL-BEING, PRODUCTIVITY AND HUMAN HEALTH

It is internationally accepted that thermal comfort is defined as a condition of mind. However, academic researchers debate whether thermal comfort is related with well-being, productivity and human health. Although it is an open debate, concrete evidence indicates that the aforementioned aspects of human 'mortality' are inherent with thermal comfort.

For instance, Parson (2003) stated that the performance of children in schools was reduced when they were subjected to uncomfortable. In addition, a study carried out by Ramsey et al. (1983) shows that temperature higher or lower than the preferable influenced the safety-related behaviour of workers. Moreover, Niemela et al. (2002) observed that productivity in telecommunication centres decreased by 5-7% when the workers are sensing high indoor temperatures. Seppanen et al. (2006) wrote that the performance in offices is reduced by about 9% when occupants are subjected to a temperature of 30^{o}C. Similarly, Cao and Wei (2005) claimed that low temperatures tend to cause aggression, while elevated temperatures have the tendency to cause aggression, hysteria and apathy.

Considering performance (or productivity) in a workplace as the output of the system, the well-being of each individual person is substantially contributing to the quality and quantity of the productivity. For instance, Warr (1999) concluded that high levels of performance are coherent with greater well-being. Apart from personal or social-economic factors, Clement-Croome (2000) pointed out that the environment is considered as another determinant factor of well-being. In essence, the previous studies presented that the performance (output) of workers was negatively affected, as a consequence of indoor thermal discomfort which is directly reflected on the well-being of people. To this effect, the provision of thermal comfortable environments are associated with higher levels of performance, as health and well-being are enhanced (Clements-Croome, 2000).

Evidently, well-being and health are important factors on the mortality of people. Since workplaces are conditioned to maintain moderate climates in order to enhance well-being and health, people indisputably have the same expectations of thermal comfort at home. In the case of residential buildings, a range of adaptive opportunities (siesta, open/close window, clothing, etc.) might be undertaken to maintain the indoor thermal environment. The adaptivity and control of environment, gives more “forgiveness” on the fluctuation of indoor thermal environment (Leaman and Bordass, 1999).

However, due to the “nature” of interactivity with the mechanical systems in residential buildings, the operation of HVAC systems may be considered another opportunity to maintain moderate climates within spaces. To this effect, in a poor-designed environment, the impact of the adaptive options (not artificial system) might not be substantial, leading on the necessary operation of a mechanical system for the maintenance of an acceptable living environment.

ENERGY AND THERMAL COMFORT

Previous evidence presents the significance of thermal comfort on people. However, as already mentioned, the occupants, in order to provide comfortable conditions, are forced to the mandatory employment of artificial systems. This results on the energy profligate due to poor building envelope, inefficient systems and lack of energy awareness.

As already observed, a trend on mechanical systems was observed due to the modern lifestyle and architectures. The indoor thermal environment is artificially maintained in acceptable levels of comfort resulting in excess energy consumption, particularly in the severe climate periods of winter and summer (Auliciems and Szokolay, 2007). However, the energy, consumed by mechanical systems, is stipulated by the difference of the outdoor environment and the desired indoor thermal conditions (Alders and Kurvers, 2010).

At this point, it is necessary to recall the findings from the review of the energy scene in the European Union. In numbers, 40% of energy is consumed by the building sector, of which 22% is consumed by the residential buildings. By rough estimation, space conditioning accounts for more than 11% of energy consumption in the EU-27 (estimation based purely on the residential sector). By summing up the space conditioning of commercial buildings, the total space conditioning (both residential and non-residential buildings) may be estimated at 20-25% of the total energy consumption in the EU-27. In essence, the thermal comfort or the provision of comfortable conditions is definitely acting as a catalyst in European energy scene and carbon emissions.

From a refurbishment perspective, energy saving measures must be implemented on the building envelope, based on the body's ability to adapt with the environment (Clements-Croome, 2000).Consequently, the evaluation of thermal comfort must be carried out before and after renovation to ensure that thermal comfort is maintained or optimized, shifting away from the utilization of conventional systems (Nicol and Pagliano, 2007).

EVALUATING THERMAL COMFORT IN RESIDENTIAL BUILDINGS

Through retrofitting, the 'current' (as experienced by occupants) internal environment may possibly alternate. As Holmes and Hacker (2007) claimed the energy conservation must not compromise thermal comfort and essentially, it is the trade-offs between energy and thermal comfort that will establish whether the renovation of a building was felicitous. Thereby, the thermal comfort must be quantified in the context of accredited standards.

Currently, ASHRAE-55: 2010, ISO 7730: 2005 and EN 15251: 2012 standards govern the criteria for thermal comfort evaluation on mechanical and natural ventilated buildings. The standards contain categories and criteria for buildings. Reference to Roaf et al. (2010) shows that the standards are almost identical for artificial heating and cooling, founded on the static approach. **Error! Reference source not found.** presents the building categories for mechanical heating and cooling.

Table 2-1 Temperature ranges for buildings with mechanical heating and cooling **(CEN, 2005; CEN, 2007)**

CATEGORIES		EXPLANATION	PMV LIMIT	OPERATIVE TEMPERATURE (^{O}C)	
ISO 7730	EN 15251			Summer	Winter
A	I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons	±0.2	23.5-25.5	21.0-23.0
B	II	Normal level of expectation and should be used for new buildings and renovations	±0.5	23.0-26.0	20.0-24.0
C	III	An acceptable, moderate level of expectation and may be used for existing buildings	±0.7	22.0-27.0	19.0-25.0
	IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year	PMV<-0.7; or PMV>+0.7		

Notes:
Clothing Insulation: Summer= 0.5Clo, Winter= 1.0Clo
Metabolic Rate: 1.2 met (seated, quite), 0.7 (sleeping) (CEN, 2007, p.15251; CIBSE, 2006b)

For the case of non-mechanical system, EN 15251 introduced the dynamic (adaptive) approach, for estimation of the operative temperature. In natural ventilated buildings the operative temperature is a function of the running mean temperature, and is given by:

External running mean temperature:

Eq. 2-1

$$\theta_{rm} = (1 - a).\{\theta_{ed-1} + a.\theta_{ed-2} + a^2.\theta_{ed-3} + \cdots\}$$

where,

θ_{rm}: Running mean temperature for today (^oC)

θ_{ed-1}: the daily mean external temperature for the previous day (^oC)

θ_{ed-n}: the daily mean external temperature for day n (^oC)

a: constant (0-1), 0.8 is recommended

Operative Temperature:

Eq. 2-2

$$\theta_{op} = 0{,}33.\theta_{rm} + 18{,}8$$

where,

θ_{op}: Operative temperature (^oC)

Table 2-2 shows the temperature ranges for building categories in the context of an adaptive model.

Table 2-2 Design temperatures for buildings without artificial cooling system (CEN, 2007)

EN 15251 CATEGORIES	OPERATIVE TEMPERATURE, K
I	±2
II	±3
III	±4

Currently, the evaluation standards on thermal comfort describe primarily the cases of office buildings, leaving a gap on the residential sector. This is mainly due to limited availability of literature on domestic houses. However, it is claimed that the static approach is applicable on static conditions (mechanical systems in operation), but it is unable to predict realistic (dynamic) cases.

For instance, in a study published by Ealiwa et al. (2001), investigating ISO 7730, pointed differences of PMV-AV in traditional buildings (naturally ventilated) were in adequate agreement with new buildings (mechanical). In addition, de Dear and Leow (1990) discovered temperatures in high-rise public houses that exceeded the recommended laid out by ISO 7730. Similarly, the work by Han et al. (2007), shows that there are differences of actual vote and PMV estimated by the Fanger model, particularly in houses at central southern China(Han et al., 2007). Furthermore, de Dear et al. (1991) concluded that discrepancies occurred between predicted vote (ISO 7730) and actual vote, in an evaluation of 'free-running' houses and air-conditioned offices in Singapore(De Dear et al., 1991). De Dear (2004) reported that the PMV-PPD model seems to under predict thermal comfort in naturally ventilated buildings(De Dear, 2004). Howell and Kennedy (1979) noted a weakness of the static approach to evaluate thermal comfort in real life scenarios(Howell and Kennedy, 1979). Humphreys (1996) claimed that the use of ISO-PMV standard may lead to excessive cooling in warm climates and overheating in cool climates. Short and a long term studies have been carried out in natural ventilated houses and offices, respectively. Heidari and Sharples (2002) concluded that people can achieve comfort at higher temperatures rather than the proposed temperatures of ISO 7730. Oseland

(1994) claimed that ISO 7730 overestimates the room temperature based on a study undertaken in UK homes, especially in winter.

Evidently, the static model losses the predictive ability in cases governed by dynamic state. As Peeters et al. (2009) also noted the Fanger's model is not satisfactory for buildings with variable thermal zones, unpredictable activities and a wide range of opportunities to adapt in the environment (Peeters et al., 2009). These characteristics can be found in dwellings, where the maintenance of the internal environment may rely either on mechanical heating/cooling or entirely on natural ventilation. In addition, occupants may change clothing value and activities in small time scales. Evidently, dwellings are described by a wide range of adaptation opportunities, such as: opening windows, using shading devices, drinking cold or warm drinks, siestas, expected temperatures in summer, fan usage etc. (Nicol and Humphreys, 2002; Peeters et al., 2009). Thereby, it is obvious that houses are merely dynamic buildings and cab be defined as mixed-mode buildings.

In northern EU countries the majority of residential buildings may be assumed as free-running (with mechanical heating system), while the Mediterranean housing inventory can be described as mixed-mode. This assertion seems to be valid, as more than three quarters of the residential EU market on air-conditioning (cooling capacity) is hosted by the southern countries (Spain 37%, Italy 20%, Greece 15% and southern France 11%) (EC, 2012a).

The EN 15251 standard proposes that the evaluation of mixed-mode buildings may be assessed by the static approach. Therefore, the evaluation of the indoor thermal environment will be based on the static approach (EN-15251), as the primary objective is to examine the heating and cooling periods under full operation of the mechanical systems.

2.3.2 Energy Saving Measures (ESM)

The main objective of this study is to examine the performance of measures and actions during refurbishment of the housing inventory. In this context, Dokka and Rodsjo (2005) developed the Kyoto pyramid, categorizing the actions that must be considered during the "passive" design or renovation of buildings. According to Meiling (2013), it was initially established to guide the construction of low energy buildings in Norway, and it is based on the Trias Energetica method described by Lysen (1996). Later it was updated in the IEA ECBS Annex 44 (Grynning et al., 2013).

In general, the Kyoto pyramid classifies the reduction of heat losses as the primary measure for the reduction of energy consumption, followed by the reduction of electricity use, utilization of solar energy, regulation of energy and selection of local energy source (see Figure 2-5).

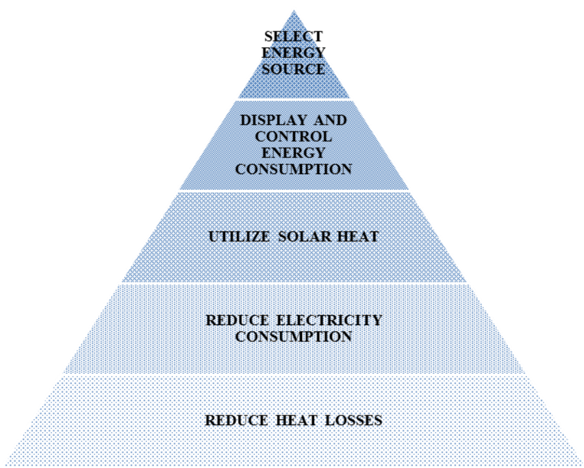


Figure 2-5 The Kyoto pyramid (Dokka and Rodsjo, 2005)

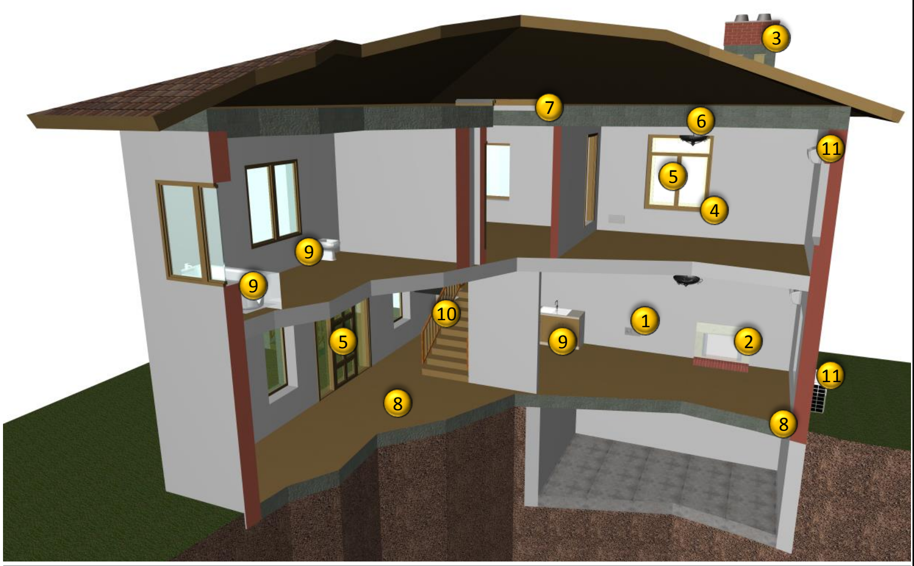
The element of a building, directly associated with the heat losses, is the external envelope which literally determines the physical boundaries between the indoor and outdoor environments. In terms of heat losses, three primary mechanisms (referring to heat transfer principles) are responsible; conduction, convection and radiation. In essence, by regulating the impact of the heat transfer mechanisms, the effect of outdoor environment will be minimized, resulting on a thermally stable indoor environment and reduced energy demand.

In this section, the measures associated with the retrofitting of residential envelopes are highlighted, presenting also the current minimum standards in the EU.

INFILTRATION AND AIR-TIGHTNESS

"Air leakage is the fortuitous infiltration and exfiltration of air through a building envelope or component due to imperfections in its construction" (CIBSE, 2000). ASHRAE also determines air infiltration as *"the flow of outdoor air into a building through cracks and other unintentional openings and through the normal use of exterior doors for entrance and egress"* (ASHRAE, 2009).

In general, infiltration is uncontrolled and driven by the wind and the differences of the internal and environmental temperatures. This causes the flow of air through pathways due to abnormalities on the building structure. The possible leakage areas are numerous within a building. Possible air pathways are depicted in Figure 2-6.



1. Gaps in and around electrical fittings
2. Fireplace wall
3. Chimney flue and penetrations
4. Cracks around doors, windows and panels
5. Windows and doors itself
6. Recessed lighting and ceiling services
7. Attic access
8. Rim joists, foundation, porous materials and joints between walls, floors and ceilings
9. Plumbing services penetrating the building enclosure
10. Framing staircase at external walls
11. HVAC systems penetrating opaque elements of the envelope

Figure 2-6 Envelope-leakage areas (CIBSE, 2000; EST, 2005; USDOE, 2010)

The excess air infiltration is usually inherent with the irrational energy consumption and indoor thermal comfort. For instance, the warm air is leaking through the gaps and cracks, enhancing the heat losses of the envelope. As a result, an amount of energy is wasted to condition air which escapes from the building, enhancing the production of CO_2 emissions (EST, 2005). In a study by Chen et al. (2012), it was concluded that a reduction of 12.6% was achieved when the permeability was reduced from 0.98-0.5 ACH. Additionally, in an investigation of different air-tightness scenarios, Logue et al. (2013) observed a reduction of residential energy demand when the houses' leakage was decreased.

Another common notion, referring to infiltration impacts, is the negative effect on the efficiency of thermal insulation due to deterioration of the insulation.

Due to excessive leakage, the air may penetrate the structure and thus, the effectiveness of insulation is reduced (CIBSE, 2000). Moreover, USDOE (2010) exemplary states that infiltration is like an open window for 24 hours, annually. In essence, the addition of thermal insulation may reduce the transmission loses, however a convective link will still encounter between indoor environment and outdoors (“short-circuiting”, (CIBSE, 2000)). Furthermore, in the context of thermal comfort, draughts arise, due to the unintended flow of air, causing discomfort and complaints to the occupants (EST, 2005).

The improvement of building permeability and thereby, the reduction of the unintended flow of air will enhance the indoor environment while the residential energy demands will be reduced. However, it is mandatory to mention and point out the cases where the ventilation of the whole building is reliant on infiltration. Due to the leakage areas on the existing envelope, the ventilation requirements may be occasionally satisfied, but the target rates are unreliable in the context of time and location (EST, 2006). By tightening the envelope, there is an indoor air quality risk because of the possible increased concentration of hazardous pollutants (VOCs, CO, CO_2, dust, moisture) generated by residential actions such as smoking, combustion, cooking or furniture. Thereby, it is indispensable to provide an alternative ventilation solution such as a mechanical ventilation system or a well-versed natural ventilation system.

Currently, air tightness minimum requirements are national requirements in Germany, the Netherlands, Denmark, Norway, Great Britain, Belgium, Switzerland, Finland, Estonia and Czech Republic. Amongst the southern EU counterparts, only Spain is regulated by partial requirements, concentrating on the windows' performance (Erhorn-Kluttig et al., 2009). Pan (2010) summarizes the current air-tightness standards, which are ranging from 1-10 $m^3/(h.m^2)$ at 50 Pa.

INSULATION OF OPAQUE ELEMENTS

In conventional buildings about 50% to 75% of the heat losses are influenced by the transmission losses of the building envelope (Hastings and Wall, 2007). The transmission loses determine the quantity of energy that flow through the building envelope (in Watts). Primarily, the losses are affected by the temperature difference between the outside and inside surface of building's element and the thermal resistance of the element, constructed by different layers of materials (Goulding et al., 1992). In order then to prevent the heat flow through the external constructional fabrics, the thermal resistance (R-value) of the element must be increased. This can be achieved by the application of an insulant with high thermal resistivity.

The performance of the thermal insulation materials is governed by their structure, as still air is entrapped. The thermal conductivity (λ) of an insulant is relatively close to the conductivity of a non-ventilated space (λ= 0.024 W/m.K) (Hastings and Wall, 2007). The principle of insulant is governed by the fact that the air is encapsulated and remains still, whereas the moving air will transfer heat by convection. Although, thermal conductivity is an indispensable property of the material, in the context of thermal losses, specific heat and density also contribute to the overall performance. Table 2-3 presents typical values of properties for various construction and insulation materials.

Table 2-3 Properties of construction and insulation materials (Data obtained by (ASHRAE, 2009; CIBSE, 2006b; EneService, 2010), the values are typical and may vary by different manufactures)

MATERIAL		THERMAL CONDUCTIVITY, λ (W/m.K)	SPECIFIC HEAT, C (J/kg.K)	DENSITY, ρ (kg/m³)
Common Structural Materials	Clay Bricks	0.4	1000	1000
	Reinforced Concrete	2.5	1000	2400
	Ceramic Tiles	1	800	2000
	Screed	1.35	1000	2000
	Render-Plaster	1	1000	1800
Thermal Insulation Materials	Polyurethane Foam	0.025	1400	30
	Expanded Polystyrene (EPS)	0.04	1450	15
	Extruded Polystyrene (XPS)	0.035	1400	40
	Rock Wool (batts)	0.038	1030	25
	Vacuum	≈0.005	-	

The application of insulation material is well established in northern regions of Europe, on account of the colder climate and need to reduce the heating demand due to the flow of heat to the outdoor environment (Goulding et al., 1992). Thermal insulation can also be applied in warmer climates to reduce the risk of overheating during the summer period, as heat flows from the warmer external environment into the cooler indoor environment.

Apart from the energy point of view of thermal insulation, the condensation risk of surfaces will reduced as the surface temperature of the space will be maintained above the dew-point temperature of the air (McMullan, 2002).

Condensation is a critical factor associated with the insulation techniques and it is extensively mentioned in the literature. The impacts of condensation are the mould-growth due to the dampness on the material, corrosion, deterioration of the structure and degradation of the insulation's thermal resistivity as moisture will increase the water content levels within the insulation. In essence, during a refurbishment of an existing wall, the condensation risks must be addressed. In Appendix A, methods/techniques for applying insulation on an existing envelope are described.

In the European Union, most of the member states are now obligated by minimum requirements regarding the thermal transmittance of opaque elements. However, as earlier mentioned, the requirements for the southern countries are higher. Figures (2-7), (2-8) and (2-9) present the current minimum U-value requirements along the European continent (BPIE, 2013).

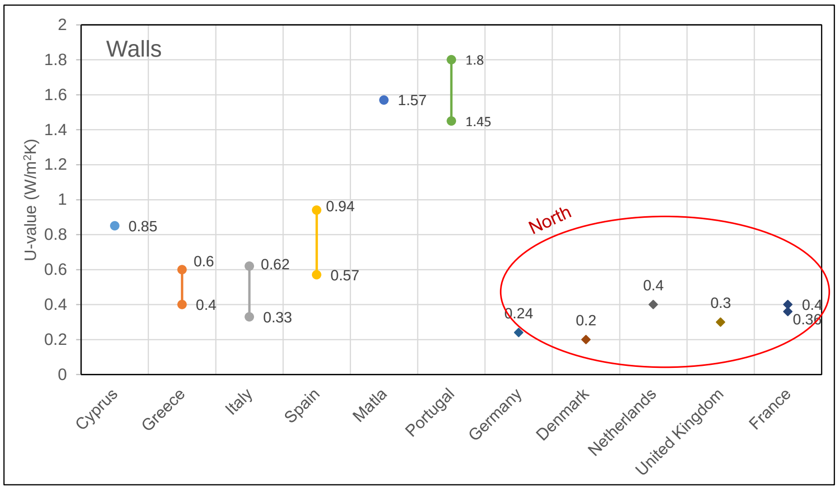


Figure 2-7 External walls, minimum U-value requirements

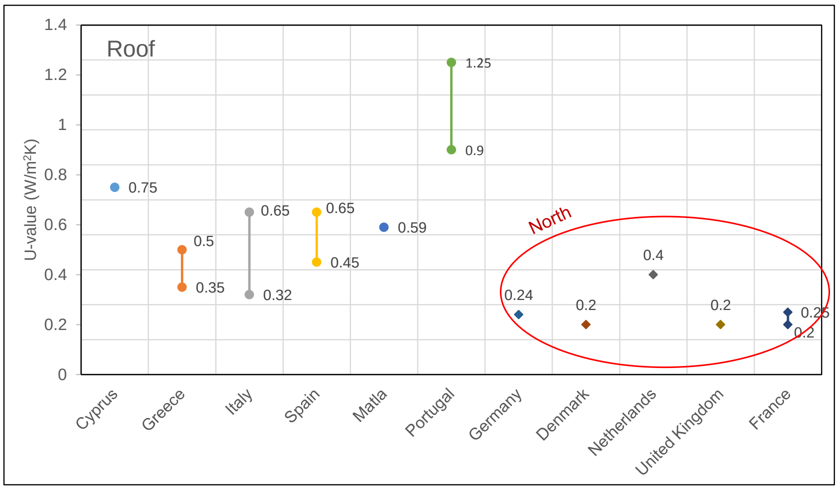


Figure 2-8 Roof, minimum U-value requirements

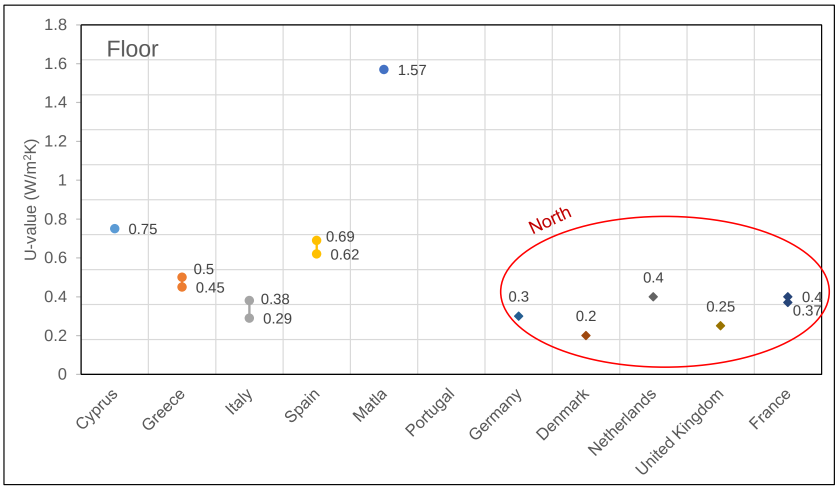


Figure 2-9 Floor, minimum U-value requirements

It is evident that the southern counterparts are governed by higher requirements. Some exceptions are present for Greece, Italy and Spain where the requirements for colder regions are closer to the northern countries.

Fabric Coating (Cool Roofs and Walls)

In earlier sections, the reduction of transmission losses (heating period) or gains (cooling period) was presented with regards to the application of thermal insulation on opaque elements. Through this section, the concept of surface coating will be presented.

Primarily, this method is adopted in hot and tropical climates for the reduction of transmission gains due to the dominant cooling period (Goulding et al., 1992). Locations with high solar radiation, encounter high amounts of solar radiation, resulting in the mandatory use of mechanical systems to maintain the indoor environment during summer period.

Figure 2-10 White-washed buildings, Santorini-Greece (Panoramio, 2014)

Light coloured surfaces can block the transmission of the radiation into the building (Brown, 1985). The surface coating is governed by the principles as described in a BRE report: *“The solar spectrum includes both visible and ultraviolet light, most of this absorbed energy will be in the form of infrared radiation (commonly referred as long-wave radiation), felt as heat. A portion of this incident infrared radiation will either be drawn away from the envelope by convection or emitted back to the sky. The remainder will be absorbed and transmitted through conduction of the building elements and then will be radiated in the internal space and surfaces”* (Halewood and de Wilde, 2010). The level of absorption is related to the materials, (a) reflectance and (b) emissivity. The relation of the properties and their impact on radiant heating is not trivial, however it is accepted that high levels are contributing to lower surface temperatures (Berdahl and Bretz, 1997).

Romeo and Zinzi (2013) investigated the impact of cool roof in an existing non-residential building in Sicily, Italy. They found a reduction up to 54% of cooling demand, and they concluded that cool roof was the most energy efficient technology among the other cooling methods that were compared. Boixo et al. (2012) discovered that cool roofs contribute to energy savings of about 7-19%, for residential buildings in Andalusia, Spain.

The concept of reflective coating is also introduced in northern countries (dominant heating), in order to study the impact of cool elements and the mitigation of overheating due to climate change. Kolokotroni et al. (2013) concluded (the study was carried out in London, UK) that the hours of overheating were reduced significantly, resulting in the reduction of the cooling load, but the heating load was increased. Similarly, Halewood and de Wilde (2008) investigate the impact of cool painting in a building in Birmingham. It was concluded that the cooling demand was decreased, while the heating load was increased, by applying Rome weather data, in order to simulate the future climate of the UK.

Commercially, a range of coating materials are available for application either in residential or commercial buildings. Currently, a database hosted by the European cool roof council presents the reflectivity for more than 100 materials and their availability in the European market. The range of reflectivity values varies from 22% to 90%, referring to the material and the company (ECRC, 2014). Table 2-4 shows typical ranges of solar reflectivity of common building structures and materials.

Table 2-4 Solar reflectivity values (ECRC, 2010)

TYPE	SOLAR REFLECTIVITY (%)
Highly Reflective Roof	60-70
Corrugated Roof	10-15
Coloured Paint	15-35
White Paint	50-90
Tar & Gravel	3-18
Red/Brown Tile	10-35

It is evident that the coating of external surfaces with cool painting will contribute to the reduction of cooling demand. However, in locations with high solar radiation, the application of reflective coatings may counteract on the performance of the building envelope during the winter period, as the building may not take advantage of the excess insolation.

FENESTRATION

The term “fenestration” refers to the openings on the building envelope, movable or fixed, including windows, doors, louvers and skylights. It may be considered that the elements, in this category, provide a “link” between the indoors and outdoors either physical or visual. However, a crucial characteristic describing this particular category is the weak thermal performance on comparison to the other building elements due to the lower thermal resistivity of the assembling parts (glass, frame material). Usually, in a residential structure, openings mainly exist in the form of windows and thereby, this topic warrants further investigation.

The principles describing windows are not straightforward, as the overall performance is driven by the assembly of the parts as well as the technologies that are founded. In principle, the performance of windows is described by two properties: a) U-value and b) solar factor. These characteristics are coherent with thermal comfort and energy performance when referring to the conditioning of the indoor thermal environment.

Apart from heat losses and thermal environment, on the design and selection of a window system, other considerations arise such as daylighting, visual comfort and condensation. For instance, the inability to retain natural lighting within spaces will result on the operation of artificial lighting, increasing the energy demand of the building. As transparent elements also provide a direct view to the exterior, offer the occupants a natural living environment. In the context of condensation, a poor performance window may contribute to the possibility of condensation risk, due to the lower surface temperatures (EWC, 2014).

In the scope of this study, particular attention will be given to thermal transmittance and solar factor, as they are related with the heat losses and solar gains, respectively. Alternations on these parameters may affect the energy requirements of a building, in terms of heating or cooling demand.

A typical window structure mainly consists of two systems; glazing and frame. Due to the area ratio (approximately 80% glazing-20% frame), glazing may be determined as the primary system of a window. It is composed by the glass panes, the gas fill (air, argon, krypton) and the spacers. The frame system is determined by the structure and materials of the frame. A typical window structure is presented in Figure 2-11.

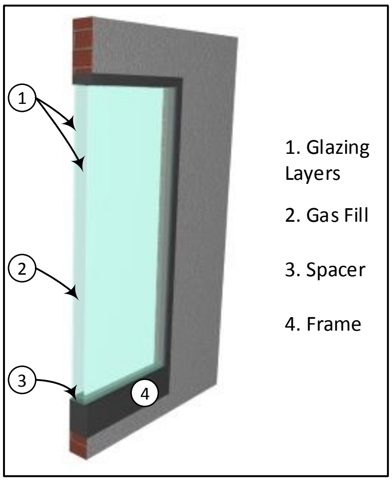


Figure 2-11 Double window structure

The overall thermal transmittance of a window structure is calculated, based on the frame and glazing of the element. According to EN 10077:2006, the thermal transmittance of a single window is given by the following equation:

$$U_w = \frac{\sum A_g . U_g + \sum A_f . U_f + \sum l_g . \Psi_g}{\sum A_g + \sum A_f}$$ ***Eq. 2-3***

where,

A_g: *glazing area (m^2)*

A_f: *frame area (m^2)*

U_g: *thermal transmittance of glazing (W/m^2.K)*

U_f: *thermal transmittance of frame (W/m^2.K)*

l_g: *total perimeter of the glazing (m)*

Ψ_g: *linear thermal transmittance due to the combined effects of glazing, spacer and frame*

Considering the Eq. (2-3), the overall transmittance of a window can be reduced either by decreasing the fenestration area or by reducing the thermal transmittance of the individual parts. Referring to the first option,it is not always suitable as the visual comfort and daylighting may be compromised which is sometimes undesirable in residential or any other buildings. Thereby, attention must be given towards the reduction of thermal transmittance of the glazing and frame system.

In glazing systems, the heat losses may be reduced either by adding extra glass layers (double, triple glazing) or filling the inner gap with low conductivity gas (argon, krypton). Regarding the latter strategy, in practise it is considered that 0.25% of leakage may occur in a well designed and fabricated glazing system (10% in 20 years). Recent years has seen the application of glass panes, with an oxide layer having low emissivity properties (so-called Low-E glazing). Usually, the film is coated on the surfaces facing towards to the cavity (i.e., double glazing), in order to protect and maintain their performance from external factors (dust, weather conditions).

Nowadays, evacuated double-glazing is commercially available, offering greater performance than a typical glazing with dry air. The heat losses may be reduced by up to one tenth, in comparison to a single pane system (Goulding et al., 1992). Although they’re commercially available, the technology, knowledge and cost are not well established and thus, were not considered in this study.

Figure 2-12 presents the effect of gap thickness, gap fill and film emissivity, based on previous studies (ASHRAE, 2009).

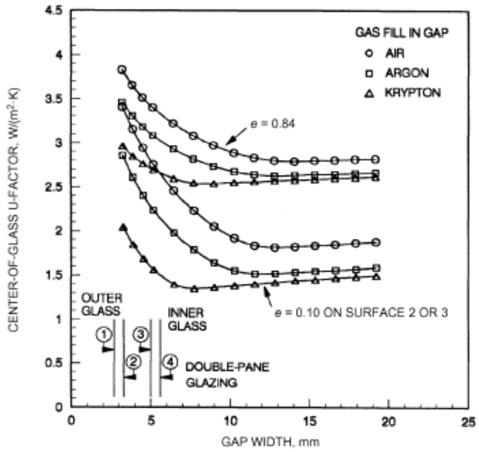


Figure 2-12 U-value as a function of emittance and gap width-Double glazing (ASHRAE, 2009)

Additional thermal resistance may be achieved by the integration of thermally improved window frame. Commercially, the most common structural materials for frames are timber, uPVC and aluminium with thermal break. Table 2-5 summarizes the characteristics for each category.

Table 2-5 Window frame-materials

FRAME TYPE	U_f-VALUE (W/m^2K)[1]	PROS[2]	CONS[2]
Timber	1.5-1.7	• Good environmental profile • Sympathetic to architecture	• Less durability • Maintenance • Cost
uPVC	1.6-2.8	• Versatility • Low maintenance • Cost-competitiveness • Good strength to weight ratio	• Environmental impact (Chlorine) • Lack of mechanical strength • Loss of colour due to extensive exposure on sunlight
Aluminium with thermal break	1.4-2.8	• High-tech look • Better environmental profile than uPVC	• Lower environmental profile than timber • Cost

Notes:
[1] Data obtained by (Gustavsen et al., 2007)
[2] (Waterfield, 2011), (Rock, 2013)
** The thermal transmittance for each material, may vary with regards to the manufacturer.*

The scene of the minimum requirements is similar to the aforementioned requirements for the other elements. The northern countries are obligated by stricter standards, due to sever climatic conditions of the winter season. Figure 2-13 presents the minimum U-value requirements for 10 European countries (BPIE, 2013).

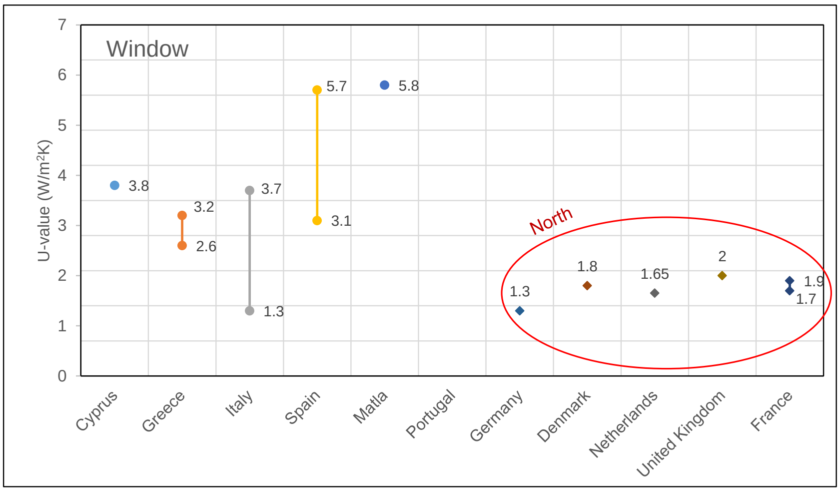


Figure 2-13 Windows, minimum U-value requirements

Previously, the concept of thermal transmittance was presented, focusing on the options to improve the thermal performance of a window system. In this section, the parameter related with solar gains is introduced, the so-called solar factor (g-value, Europe) or solar heat gain coefficient (SHGC, USA). It is defined as the dimensionless measure of the amount of solar heat gain transferred into the indoor spaces through a glazed fenestration, expressed in values between 0-1; lower values equals to lower solar penetration (EC, 2010c).

In order to lower the solar gains from windows, two primary ways are presented; a) coating and b) external shading. The latter is more effective, as the direct radiation is intercepted before it reaches the glass panes. A fully shaded window may experience 80% less solar heat gain than an unprotected window (ASHRAE, 2009). External shading can be achieved either by the application of overhangs, projections, side-fins, awnings or by natural manners such as trees and hedges. During the design of an outdoor shading device, the geometry, orientation and sun position must be considered for an effective application. Internal or attached shading (curtains, insect screens, and venetian blinds) are not in the scope of the study and thus, will not be extensively presented. However, their performance is lower than external shading, as the solar radiation reaches the fenestration, causing an additional radiative heat transfer. For example, for a window with internal shading, heat transfer occurs between glass-room, glass-shading and shading-room (ASHRAE, 2009).

Apart from external shading, the solar gains can also be reduced by the integration of absorbent glass (body-tinted), coated glass or an additional glass pane. The production of absorbent glasses is based on the addition of metal oxides, offering the ability to the glass to absorb some solar energy before emitting it back or inside. The solar factor depends on the colour and thickness of the pane. The coated glass is based on the reflection of the incident solar energy and their development is described by the deposition of metal oxide-based pyrolytic or vacuum coatings (AGC, 2013). Also, a reduction is achieved by the integration of an additional glazing layer. For instance, a single pane clear glazing has a g-value approximately of 0.86, while a double clear glazing’s g-value is about 0.8 (AGC, 2013). However, a potential reduction is achieved by the application of solar control glasses (absorbent or coated).

Table 2-6 shows the g-value for common types of glazing available in the market.

Table 2-6 g-value for different types of glazing (database of AGC (2013b))

GLAZING TYPE	g-VALUE
Single, clear	≈0.86
Single, tinted	≈0.62
Double, clear	≈0.77
Double, tinted	≈0.51
Double, Low-e, high solar gain	≈0.66
Double, Low-e, moderate solar gain	≈0.42
Double, Low-e, low solar gain	≈0.3
Triple, Low-e, high solar gain	≈0.6
Triple, Low-e, moderate solar gain	≈0.4
Triple, Low-e, low solar gain	≈0.26

A consideration for visible transmittance must be taken when using solar control glasses, as the lighting introduced in the space is also affected (higher values-neutral colours (LBL, 1997)). For residential applications, some tinted or reflective glasses are not suitable as the visible transmittance is reduced to 0.30 (recommended 0.6 or higher (LBL, 1997)) (Krigger and Dorsi, 2013).

Currently, there is not any standard that obligates the value for g-value. A general rule-of-thumb indicates lower values for cooling dominant climates and higher for heating dominant climates. However, in climates such as the Mediterranean, both seasons are experienced, complicating the selection of g-value. For instance, by using lower values the cooling demand is reduced, but the winter solar gains are blocked and vice-versa. Therefore, it is important to establish suitable solutions to balance the excessive winter solar gains and the summer overheating.

2.3.3 Building simulation

In the academic literature, “simulation” is a multi-disciplinary concept, representing the imitation of real life systems and processes. When this is applied at a point in time, it is referred to as static, while mimicking systems in transient time periods is defined as *dynamic*. It is not a novel concept, as it originated in the mid-20th century, when it developed alongside the evolution of technology and computerization.

Nowadays, building simulation is routinely applied to energy and environmental performance assessments of buildings. Through simulation, the building physics can be investigated, statically or dynamically, providing the potential to study thermal comfort, predict energy performance and/or sizing the systems in the buildings. The importance of simulation has been highlighted through the years by its advantageous benefits. Hong et al. (2000) mentioned that *“before the advent of computer-aided building simulation, building services engineers relied heavily on manual calculations using pre-selected design conditions and “rules of thumbs”*. For instance, the impact by altering the building envelope can be merely investigate on a computer-based simulation software, rather than altering the actual building causing higher costs or possible inconvenience to owners by inaccurate decisions. In essence, the simulation is repeatable, allowing the user (designer- engineer) to replicate numerous experiments, on the contrary with the real world where due to its uncontrollable parameters is difficult to allow precise experimentation (Pidd, 2004). Also, through building simulation the human safety is enhanced. For instance, the exposure of people to extreme conditions to study their actions for maintaining thermal comfort may be a dangerous experimentation (Pidd, 2004). It is evident that there is a growing acceptance of building simulation and it is now acknowledged as the best practise to imitate the real life scenarios (Clarke, 2001).

However, real life and buildings are governed by complex dynamic-principles, which require realistic simulations, rather than simple imitation (Clarke, 2001). Evidently, uncertainties arise during the transition from reality to simulation, compromising the accuracy of the model and thus, the rationalistic application of the outcome. In particular, sources of uncertainty may be the simulation software itself, the input data (i.e., availability, detail and accuracy), user's knowledge-simulation skills and the pragmatic outcome.

A well-established approach to achieve reliable and consistent models, is the calibration of the model based on actual data, followed by an evaluation assessment of the overall performance. The whole simulation procedure must be performed in a simulation software which is already validated by global-accredited tests. In the following sub-sections, the calibration and validation procedures will be described in the context of thermal modelling.

CALIBRATION OF BUILDING SIMULATION MODELS

In the ASHRAE-Guideline 14, the whole building calibrated simulation approach is defined as "the approach which involves the use of an approved computer simulation program to develop a physical model of the building in order to determine energy and demand savings. The simulation program is used to model the energy used by the facility before and after the retrofit. The pre- or post- retrofit models are developed by calibration with measured energy use, demand data and weather data" (ASHRAE, 2002).

With reference to the definition, the realistic imitation of a building contributes to the reliability of the model's outcome and hence, to the pragmatic intervention of energy conservation measures on existing buildings (Reddy, 2005).

An extensive review on the calibration procedure and its approaches has been carried out by Reddy (2005). He indicated the essential steps during calibration, as follows: (1) data collection, (2) importing data to model, (3) comparison of predicted performance over actual, and finally, (4) evaluation whether the desired accuracy has been achieved (Reddy, 2005).

In general, calibration procedures are categorized into (Reddy, 2005):

A. *Manual, Iterative, and Pragmatic Intervention*

The category is founded on collection of as-built drawings, site interviews, plug-load electricity and thermal measurements. It is based on the experience and expertise of the analyst and may be applied in an ad-hoc manner (Reddy et al., 1994; Pedrini et al., 2002; Yoon et al., 2003; Filippin et al., 2008).

B. *Suite of Informative Graphical Comparative Displays*

Through the approach, graphical methods are employed to estimate the possible existence of discrepancies between measured and predicted hourly data, as it seems reasonable that the analyst will be overwhelmed by the enormous amount of data points. Such graphical plots may be carpet plots, three-dimensional time-series plots, superposed and juxtaposed binned box, whisker and mean plots, and also, two dimensional plots, i.e., scatter plots and time-series (McCray et al., 1995; Bou-Saada and Haberl, 1995; Haberl et al., 1996).

C. Special Tests and Analytical Procedures

The third category lies on the implementation of specialized tests for the calibration of the model, such as (1) intrusive blink tests, (2) STEM tests, (3) macro parameter estimation methods and (4) signature analysis methods. Overall, the approaches are based on intrusive short term (weekend, 3 to 5 days) recording of data of plug-loads and other system consumption, to describe the long-term performance of a building (Soebarto, 1997; Subbarao, 1998; Wei et al., 1998; Reddy et al., 1999; Haves et al., 2001).

D. Analytical/Mathematical Methods of Calibration

The last category is akin to an optimization problem, driven by elimination of monthly mean square errors of recorded and predicted data. It is noted that the application of the particular approach is fostered when minimal number of parameters is used (Caroll and Hitchcock, 1993; Heo et al., 2012; Tahmasebi and Mahdavi, 2012; Tahmasebi et al., 2012).

The adoption of a suitable approach is primarily driven by the modeller's preferences. Their applicability is inherent with the type of the building, availability and interval of input data, time availability and also, skills of the modeller which results in a heuristic tuning of the model.

Backward stepwise approach

The backward stepwise approach is mainly described by the category A of the calibration procedure, founded on the key concept of mid-season calibration (Lyberg, 1987; Yoon et al., 2003). As an approach is suitable for cases, where data is absent, resulting in insufficient information during the calibration of a model. A common example of such cases are the private properties (houses), where the collection of consistent data is deteriorated by their privacy, their operation and a limited literature on approaches for residential model calibration.

The method was initially introduced by Lyberg (1987) and later by Yoon et al. (2003), due to the absence of hourly energy data. Earlier, the term "mid-season calibration" was mentioned due to the fact that the backward stepwise approach utilizes the energy disaggregation to classify the loads regarding to their weather dependency. The base-load is usually occurred during the transition months (mid-season) where no heating or cooling are required, calibrating initially the model on its base-load. Figure 2-14 presents the mid-season calibration theory, as initially introduced by Lyberg (1987).

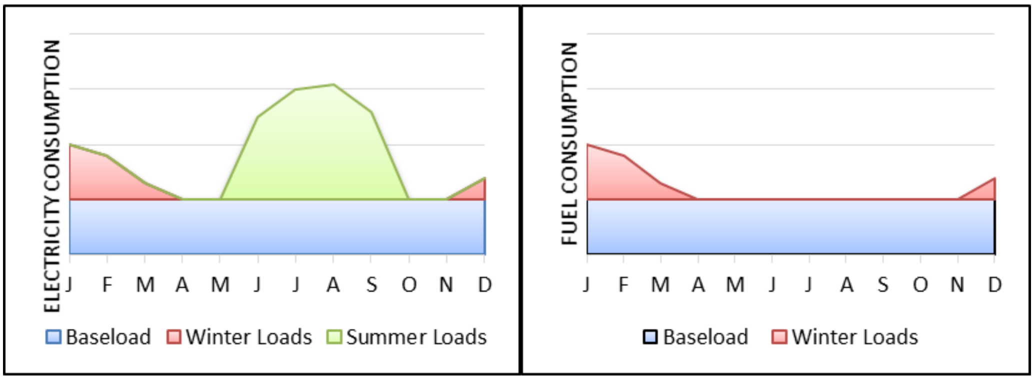


Figure 2-14 Energy breakdown by weather dependency (reproduced by (Lyberg, 1987))

The initial step of the method is to define the base-load of the building. The base-load is usually recorded during the transition periods where the heating or cooling systems are not operated. In essence, the base-load is established by the weather-independent loads which are coherent with the electrical appliances, lighting and/or any plug-devices that are not affected by the outdoors. On the contrary, the weather dependent loads are driven by the conditioning of the indoor environment and critically based on the variations of the external environment (HVAC systems) (Lyberg, 1987).

By the establishment of the base-load, the modeller is initially calibrating the model to imitate the base-load of the building, and thereafter, upgrading the parameters related with the weather driven loads to describe the annual performance of the building. The model's performance is finally evaluated against actual data to quantify the validity of the model.

EVALUATION OF MODEL'S PERFORMANCE AND VALIDATION METRICS

As aforementioned, the robustness of a model to imitate real life is primarily based on the whole design procedure and the reliability of the outcome. In order to assess and quantify the reliability of the model's performance, the simulated data is compared with the actual data. This particular validation technique is wide spread applied, and it is known as “Empirical Validation” (Bowman and Lomas, 1985).

The validity of the model is usually determined by the application of metrics that are primarily quantifying the discrepancies between actual and simulated data, setting also acceptable limits of validity. ASHRAE published Guideline-14, a comprehensive documentation on the calibration and validation of thermal models of buildings. In the current literature, Guideline-14 is widely used for the validation of models, using energy data. In particular, ASHRAE G-14 recommends the application of normalized mean bias error (NMBE) and coefficient of variation of the root mean square error (CVRMSE) (ASHRAE, 2002). The NMBE estimates the closeness of the predicted data to the actual data, where the CVRMSE measures the variability (dispersion) of the data. Both statistical metrics can be estimated by Eq. 2-4 and Eq. 2-5, as follows:

Normalized mean bias error (NMBE):

$$NMBE = \frac{\sum_{i=1}^{n}(da_i - dp_i)}{\overline{da} \times n} \times 100$$

Eq. 2-4

Coefficient of variation of the root mean square error (CVRMSE):

$$CVRMSE = \frac{\left(\sum_{i=1}^{n}(da_i - dp_i)^2 / n\right)^{1/2}}{\overline{da}} \times 100$$

Eq. 2-5

where,

da: Actual data

dp : Predicted data

$\overline{da}$ *: Mean of actual data*

i : 1…n (data points)

ASHRAE G-14 indicates that for monthly validation the NMBE shall be ±5% and CVRMSE is ±15%. When hourly data is used, the coefficients shall be ±10% and ±30%, respectively. In essence, values closer to zero indicates higher levels of model predictability (ASHRAE, 2002).

2.4 MEDITERRANEAN REGION-THE CASE OF CYPRUS

2.4.1 OVERVIEW

Cyprus is an island state (land area: 9,251 km^2 (Lyssiotis and Kokoti, 2006), population: 0.84 million (CYSTAT, 2011b)), located at the south-east of Mediterranean Sea, as shown in the Figure 2-15. The latitude and longitude of Cyprus are $34^{o}33^{'}$-$35^{o}34^{'}$ North and $32^{o}16^{'}$-$34^{o}37^{'}$ East, respectively. The economy is small and liberated; historically has a great performance and is dynamic in its ability to adapt to global changes, mainly driven by the tourism and service sectors (Lyssiotis and Kokoti, 2006). Cyprus shows great dependency on imported energy, especially oil, which accounted for the 96% of the country’s gross inland production (Eurostat, 2012).

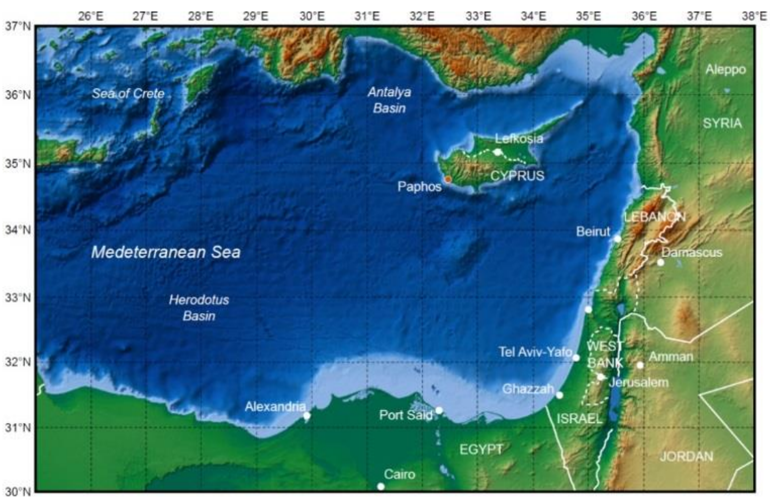


Figure 2-15 Cyprus location (Data were obtained by (GEBCO, 2008; NOAA, 2013))

The energy situation is burden due to the isolation of the island, as there is not any ground or underwater connection to the neighbouring energy systems. This affects the national energy security as the volatility in the international energy markets are directly influencing the country's energy market (Europa, 2011). A significant share (62%) of the national export earnings is spent on national oil imports (Koroneos et al., 2005). In EU-27, Cyprus is ranked among the highest "pedestals" of energy dependency (see Figure 2-16).

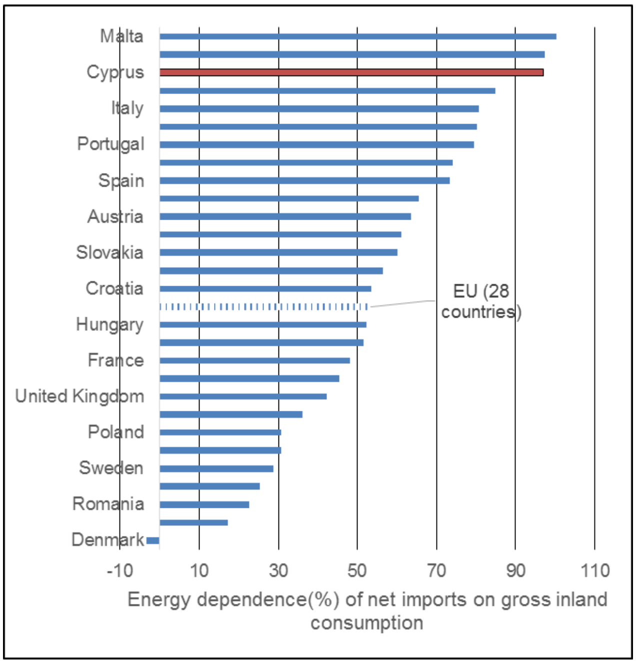


Figure 2-16 Energy dependency for 2012. Data obtained from (Eurostat, 2014)

In addition, the country's strong dependency and the vulnerable energy system reflects on the expenditures for electricity. The state holds the highest place on electricity tariffs among its European counterparts. In essence, the Cypriot households have excessive charges for their daily amenities.

As a result, the national strategy gives an emphasis on the reduction of energy consumption, and thus, ensuring the national energy security by minimizing the dependency on conventional energy sources. This was enhanced, since Cyprus joined EU on 2004. As a member of the EU, Cyprus is obligated to participate in the EU Emissions Trading Scheme (ETS) and hence, is committed to the 2020 targets (EC, 2007). However, the targets for the reduction of GHG for new EU members such as Cyprus are lower, at 13% (Eurostat, 2009). In 2006, a comprehensive National Action Plan (NAP) was launched, followed by a recast version in 2011. Both plans govern the energy efficiency at the final energy consumption. These plans will provide Cyprus with an opportunity to leapfrog in terms of technological innovation and energy efficiency, as well as bringing Cypriot energy systems and its economy in line with the rest of Europe (EC, 2010a).

Both plans recognize that residential sector presents the greatest potential for energy and CO_2 emissions reduction, in spite the dominance of transportation on consumption, rising by the lack of efficient public services. Since 1990 the residential sector presented an upward trend, where in 2004 placed second, surpassing industry. Figure 2-17 presents the energy consumption of end-user sectors for the period 1990-2012.

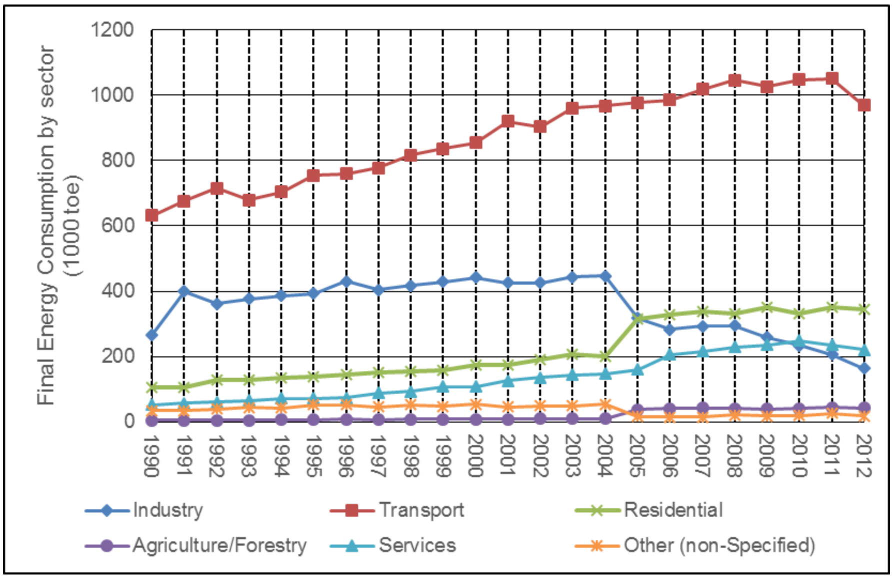


Figure 2-17 Final energy consumption from 1990-2012, by sectors. Data collected from (Eurostat, 2014)

In the report published by the Ministry of Commerce, Industry and Tourism (MCIT), the contribution of residential sector was underlined. Table 2-7 shows the contribution of each sector towards energy targets set by the EU.

Table 2-7 Energy savings by sector (MCIT, 2011)

#	SECTOR	CONTRIBUTION TO 2010 MID-TARGET (60,000 TOE)		CONTRIBUTION TO 2016 TARGET (185,000 TOE)		CONTRIBUTION TO 2020 TARGET
		toe	%	toe	%	toe
1	Residential	51,164	85.27	161,877	87.5	**232,109**
2	Tertiary	8,942	14.9	23,681	12.8	34,061
3	Industrial (agriculture is included)	1,714	2.86	1,284	0.69	1,141
4	Transport	3,909	6.52	3,909	2.11	3,909
	Total	65,729	109.55	190,751	103.1	27,122

It is obvious that the targets of 2010 and 2016 are mostly met by the actions and measures on the domestic sector. This is mainly enhanced by the implementation of EPBD in the national legislation, governing the construction of new buildings and renovations of existing.

As in the European scene, where buildings are responsible for nearly 40% of energy consumption (and 36% of GHG emissions) both national and Europe-wide initiatives on transforming the energy system for a decarbonized future recognize the importance of buildings in reducing carbon emissions (EC, 2011a; EC, 2012b).

2.4.2 Dwellings in Cyprus

In 2011, the national building stock was approximately 548,216. The dominant sector of residential buildings amounts to 432,736, where the 298,662 are permanent residences and the 134,074 are temporary or unoccupied houses. In Figure 2-18, the proportion of the building inventory is presented.

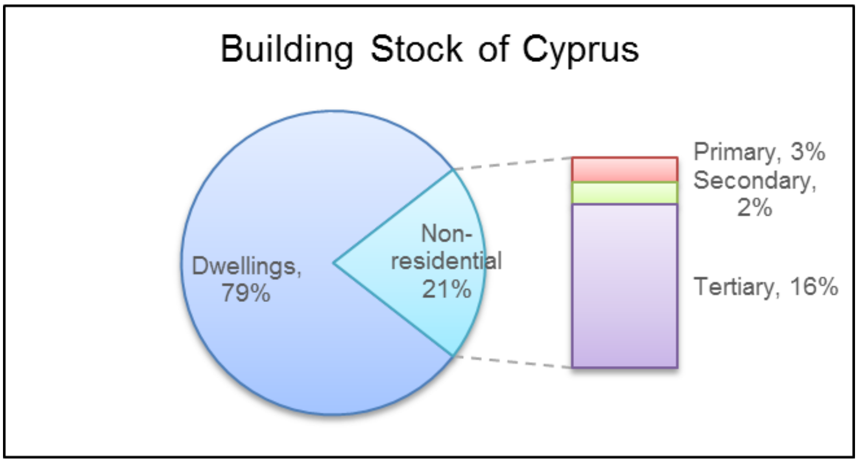


***Figure 2-18 National Building Stock*[2]**

[2] The values of non-residential obtained by the number of electricity consumers. **Primary** =Agriculture, Mines, Quarries, **Secondary**= Industry, Processing, Construction, **Tertiary**= Services, Government, Education

Further to the aforementioned, by breaking down the housing inventory, it can be clearly observed the dominancy of single-detached type (see Figure 2-19). Due to the population distribution and town planning, the majority of dwellings are constructed at coastal areas of Cyprus.

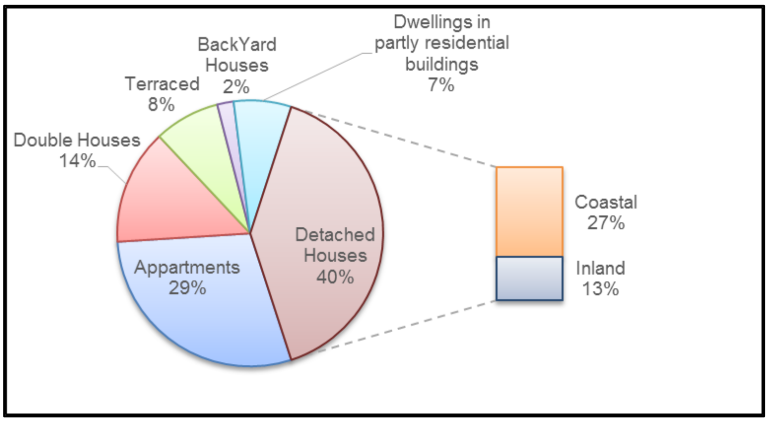


Figure 2-19 Types of Residential Sector

In particular, the distribution of the dwellings was mainly affected by the morphology of the island[3] and the military events in 1974, which caused the growth of residences at the western part of the country. In numbers, approximately 63% of the houses are located at coastal areas, where the residual proportion is distributed at low lands, semi mountainous and mountainous areas (CYSTAT, 2011b). Through the 20th century, the housing inventory was under a great evolution, presenting variety and influence from foreign designs.

[3] Climate zones: Zone1=Coastal Areas, Zone2=Low Land, Zone3= Semi Mountainous Areas, Zone 4=Mountainous Areas

CONSTRUCTION PERIODS

Generally, the construction era is described by three periods regarding to the design of the houses. At the beginning of 20th century, houses were constructed based on the availability of the local natural materials and micro climate conditions. As a result, occupants were enjoying a comfortable environment in harmony with the external natural environment without utilizing any type of mechanical system. For instance, at high altitude areas, the main construction material for the external walls were the stones due to their great availability for use, whereas in the Mesaoria plain the stones were replaced by mud mixed with straw. In addition, at Mesaoria valley the buildings were characterized by high ceilings which are the norm in hot climates (Florides et al., 2001).

Thereafter, the independence of Cyprus in 1960, styles and foreign ideas were initially introduced. There were applied without any changes regarding to the local climate causing the loss of thermal comfort and contributed to the mandatory need of a mechanical system (Florides et al., 2001). For example, large windows were introduced from northern countries such as Great Britain, due to the need to capture as much solar radiation as possible (Nazife, 2005).

Then, the sudden increase of population, due to the division of the country in 1974 and migration, resulted in the next period of building stock, enhanced by the foreign architecture design. Panayi (2004) claimed that "*There is no classification or typology system that distinguishes the various types of Cypriot dwellings"*. The architectural landscape shows a great variety and as a result the absence of homogeneity of the building stock. This is also attributed to the freedom of architects to design buildings based mainly on clients' needs, provide them with buildings that have aesthetic appearance and, picturesque views. There are however certain construction restrictions regarding the plot such as height, distance from the road, maximum area and surface, shifting to the mandatory use of artificial systems for conditioning houses.

Overall, the vast majority of dwellings, built before 2004 (approximately 76%), were governed only by landscape and anti-seismic legislations, marginalising the thermal performance or passive strategies for heating/cooling. Thus, the energy profligate was inevitable, due to the poor building envelope and latent priorities (i.e., aesthetics). Nevertheless, Cyprus is considered as the leader on the installation of solar thermal system per capita. More than 90% of dwellings utilize solar collectors for DHW, revealing the potential of solar energy in the Mediterranean region (Kalogirou, 2004). In spite that, no other exemplary measures were taken in the residential sector. This was highlighted, by a report of the National Statistic Service, demonstrating the unacceptable number of houses employed with thermal insulation, after the adoption of EPBD. Particularly, 54.4% of households is not utilizing any type of thermal insulation. A small proportion of dwellings are insulated at external walls and roof, 7.5% and 5.5% respectively. Only the use of double glazing is relatively developed which accounts for 43.2% of households (CYSTAT, 2011a), due to subsidy given by the government (30% of cost)

BREAKDOWN OF RESIDENTIAL ENERGY CONSUMPTION

In 2009, the National Statistical Service published a report indicating the main sources of energy for the average household and the distribution. The study was founded on a sample of 3,300 households. It was estimated that the average household consumes approximately 1,142kgoe corresponding to about €1,374.00 of expenditure.

On an average, the typical Cypriot household consumes annually 6,288kWh of electricity, 355ltr of heating oil, 125kg of LPG, 244kg of wooden biomass and 48kg of coal. Figure 2-20 shows the breakdown of households' energy consumption for EU-27 and Cyprus. Due to the severity of external conditions in northern countries, the average energy consumed by space conditioning in EU-27 is higher by 15%. However, in both situations the space conditioning is the dominant end-use category.

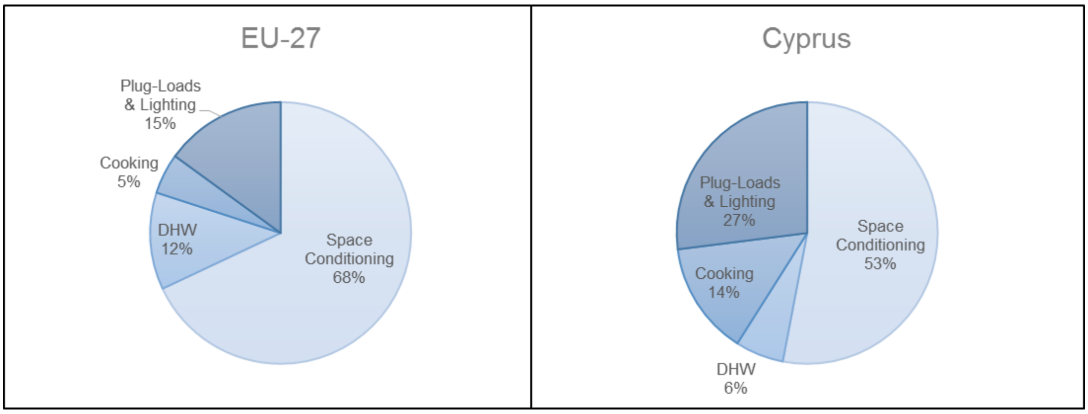


Figure 2-20 Breakdown of household's energy consumption

This is directly linked to the lack of any comprehensive framework, governing the construction of dwellings in the past. The building envelope presents inability to maintain the indoor thermal environment and thus, excessive energy is consumed for space conditioning.

LEGISLATION FRAMEWORK

As most of the Mediterranean countries, the legislation framework on energy performance in buildings has been early implemented on the construction of new buildings. The first attempt was carried out in 1999, where the CYS98:1999-a voluntary standard for the insulation and rational use of energy in dwellings was examined under the scope of adaption by the national legislation. Thereafter, the implementation of EPBD was the first comprehensive legislation on the regulation of energy consumption in the building sector. The EPBD was translated on the national legislation, so-called Ministerial Order 2007 and a recast version, the Ministerial Order 2009. The Ministerial Order Κ.Δ.Π. 466/2009 set the minimum requirements for building construction, presenting the maximum U-values of building's elements. The requirements govern the thermal insulation of building envelope, for all new buildings and buildings over 1000 m^2 total useful area that are undergoing major renovation. The maximum U-values for each element are presented in Table 2-8 . In 2013, the Ministerial Order Κ.Δ.Π. 432/2013 introduces lower values of U-value, the limit of 1000m^2 reduced to 500m^2 and for the first time, a requirement related to the shading factor was presented. The requirements are also presented in Table 2-8.

Table 2-8 Minimum Requirements for all new buildings and buildings over 1000 m² (or recast 500 m²) total useful area that are undergoing major renovation (MCIT, 2009; MCIT, 2013a)

ELEMENT	**U_{max} (W/m²K)**		**COMMENTS**
	Κ.Δ.Π. 466/2009	Κ.Δ.Π. 432/2013	
Floors	2		*In contact with unheated spaces*
Horizontal structural elements of the shell	0.75	0.63	*Exposed to external environment*
Walls, columns and beams	0.85	0.72	*Not applied to passive systems*
Windows, Doors	3.8	3.23	*Not include shop windows*
Shading factor	0.63		
Building mean thermal transmittance (U-mean)	1.3		

STUDIES ON ENERGY PERFORMANCE OF DWELLINGS IN CYPRUS

Overall, limited studies have been published in terms of thermal and energy performance of residential buildings. Moreover, the methodology, adopted by the vast majority of the studies, was the dynamic simulation, founded on typical conditions rather than real world situations. Broadly, the implementation of energy savings was examined in the perspective of energy reduction during the heating and cooling periods. No critical attentions was given on the trade-offs of savings measures and thermal comfort. This may result on sacrificing thermal comfort, which may result on the inevitable use of artificial systems (Borgeson and Brager, 2011). It is then worthwhile to describe the current knowledge, adopting examples and avoiding sources of uncertainty.

Initially, the first study has been carried out by Florides et al. (2000). The study aimed to investigate the heating and cooling loads for various constructions of a typical Cypriot house. Florides et al. (2000) claimed that the insulation of the roof has a great importance. Particularly, the heating load was reduced up to 75%, while the cooling demand was decreased up to 45.5%, by roof insulation. Furthermore, the ventilation, internal shading devices and the alternation of flat roof to inclined roof were examined. A limitation was mentioned by authors regarding to the validation of results with actual weather.

Then, a study examined the impact of the construction period on heating and cooling load, based on the use of TRNSYS. Thus, 3 categories of typical houses were investigated: a traditional, a conventional and a dwelling employing thermal insulation. All cases were modelled, driven by the same characteristics such floor area, orientation and glazing location. However, the traditional building was designed with higher ceiling, describing the older architecture of the country's inland area. A remarkable outcome was the similar performance of the insulated and traditional house. The proper construction of a traditional house with high ceiling and appropriate positioning of doors and openings, result in the same performance as an insulated and expensive modern dwelling (Florides et al., 2001).

Kalogirou et al. (2002) investigated the impacts of a thermal wall on running loads for space conditioning. Overall, the thermal mass is believed to be ideal for the Mediterranean conditions, as important diurnal variations of temperature can be observed. As a result, a model of a typical dwelling was constructed in TRNSYS and the effects of thermal mass on south facing walls were examined. The results present a decrement of 47% of heating load, while the cooling load for the same zone is slightly increased by 4.5%. Moreover, the effect of the implication of thermal mass was investigated, in relation with other energy saving measures. Kalogirou et al. (2002) underlined that the optimum overhang is about 1m, while the thickness of thermal mass is about 25cm. This study has also pointed the insulation of flat roofs.

Another study of the same group examined the cost effectiveness of energy savings for energy conservation. Particularly, natural and controlled ventilation, solar shading, different types of glazing, orientation, shape of building and thermal mass were investigated. The measures were integrated in a typical house with total floor area of 196m^2, with external walls dimensions of 14m length and 3m height. The windows were aggregated, resulting in 5m^2 of glazing for each wall. Florides et al. (2002) reported a 7.7% reduction of cooling load by ventilation rate of 9 air changes per hour for maintaining temperature at 25^{o}C. The use of low-emissivity double-glazing windows results in 24% reduction of annual cooling load, on a well-insulated building. In addition, the integration of overhangs with length of 1.5m resulted in a decrement by 7% to 19% of cooling demand for a dwelling insulated by 50mm polystyrene at external walls and roof. It was claimed that the heating load was influenced by the shape of the house. For instance, an elongated house presents a raise of heating demand from 8.2% to 26.7% according to the construction materials. The authors suggest that the best orientation of symmetrical house is to face the four cardinal points, where the long side of the elongated house must face the south. Again, the importance of the roof in the climate of Cyprus was highlighted (Florides et al., 2002).

In order to provide guidance for the forthcoming European legislation, Panayi (2004) prioritized energy saving measures with regard to the performance of residential buildings. For the first time, the thermal comfort was evaluated through the adaptive model. The study focused on single-family houses, located inland. The base cases were consisted by an apartment and detached type, modelled in TAS. He also investigated different types of glazing, thickness of insulation, as well as thermal mass and orientation. The measures were prioritized, driven by the cost and contribution to energy conservation by thermal loads. He concluded that the national priority must turn to the reduction of the cooling load, due to the considerable running expenditures, compared to the fossil fuels.

By the implementation of EPBD, the awareness on building’s energy performance was raised, resulting to an extensive analysis of the housing inventory. Thus, a project was launched by a group of researchers to investigate the residential footprint on energy performance. As a result, two comprehensive results have been published. The first was promulgated in 2010 by Panayiotou et al. (2010). The characteristics of domestic buildings were investigated in the perspective of the Directive 2002/91/EC. The methodology was based on the development of formulated questionnaires for a sample of 500 houses and in-situ measurements for 20 houses. The sample covers all types of dwellings. The energy behaviour and characteristics of the dwellings were recorded. It was recognized that the dominant type of residential stock, is the single-detached houses. According to the findings, the plethora of dwellings does not employ thermal insulation. Additionally, Panayiotou et al. (2010) claimed that the installation of solar thermal systems which is a common practice in Cyprus.

Then, a study, by Fokaides et al. (2011), compared the calculated and actual performance of the buildings. Through the study, 10 houses were chosen and monitored for one year. The measured energy use was estimated by questionnaires and by bimonthly electricity bills, oil and gas consumption. The calculated energy use was determined by the utilization of SBEM software tool. They concluded that a large gap exists between measured and calculated energy use. Also, an important impact is presented on the measured energy by the occupant’s behaviour. The heating load is in a good agreement between the two methods, whereas cooling load shows a deviation greater than 150%. Consequently, they suggested the adoption of a factor of 0.6 for cooling (Fokaides et al., 2011).

2.5 SUMMARY

Chapter 2 reviews the current scene on energy, giving attention to the residential sector. Initially, section 2.2 presents energy within the context of the building sector, reviewing also the current status of the European housing inventory.

Through section 2.3, a review has been carried out on the aspects related with the retrofitting of existing residential buildings. The first sub-section (2.3.1) presents the importance of thermal comfort in human well-being and productivity and how it influences the energy consumption within the buildings. An attention is also given on the current evaluation standards and their adoption in the residential sector. In the second section (2.3.2), the energy saving measures, related with the refurbishment of existing domestic envelopes, were described. The latter part (2.3.3) deals with the building simulation and specifically, with the calibration procedure during the design of realistic models, presenting also the validation metrics of ASHRAE G-14.

Finally, in section (2.4), the Cyprus energy state was introduced, presenting the current scene on national energy, housing inventory and legislation on buildings performance. Based on the review of the studies quoted in this section, it was primarily concluded that the main aim was to examine the direct impact of energy saving measures in the context of energy reduction, based primarily on typical conditions and building layouts. Most of the studies did not examine the trade-offs between energy and thermal comfort, a mandatory subject (underlined by the EU) during the design of new or retrofitting existing buildings.

Chapter 3. RESEARCH METHODOLOGY

3.1 INTRODUCTION

The study seeks to examine the implementation of energy saving measures during the renovation of existing residential envelopes, in order to achieve minimum energy requirements associated with thermal loads, without compromising thermal comfort.

This chapter describes the methods adopted for the investigation of the measures, providing a clear view on the approaches, equipment and motivation for data collection (site monitoring, site visits, etc.), explanation and description of thermal modelling procedure (i.e., simulation engines). Finally, the parameters of interventions and the optimization analysis will be studied within the context of prioritization of the measures with regards to the energy consumption and indoor thermal environment.

3.2 RESEARCH METHOD

The scope of the study is in line with the notation by Diakaki et al. (2008) “As innovative technologies and energy efficiency measures are nowadays well known and widely spread, the main issue is to identify those that will be proven to be the more effective and reliable in the long term”. In order to prioritize such measures, two key points must be considered prior to the experimentation; (a) the trade-offs between energy and thermal comfort and (b) the future rationalistic application of the measures. While the first may be accomplished during the analysis of the models by introducing an additional evaluation metric, the second is strictly based on the development of realistic models that imitate actual cases. This constituted the study's modelling backbone, as a calibration procedure was applied in order to enhance the pragmatic reflection, enhancing the reliability of the models' outcome.

Due to this fact, for the accomplishment of the whole procedure, both quantitative and qualitative approaches were adopted. An abstraction is presented in Figure 3-1.

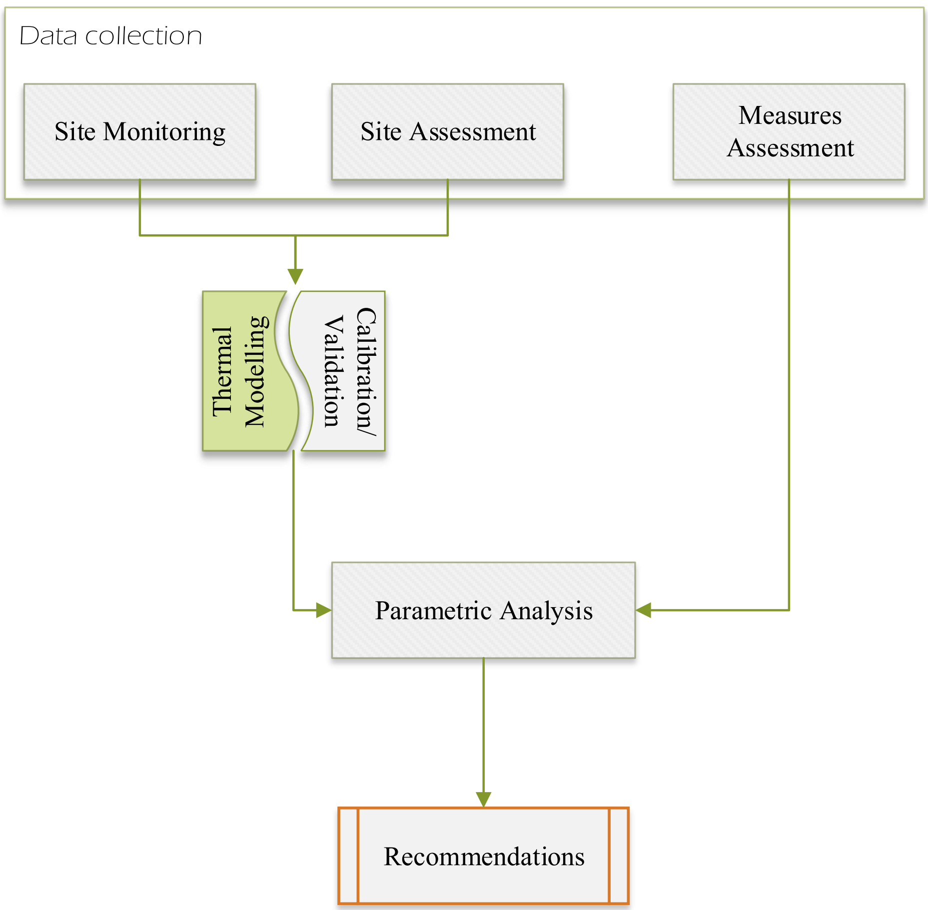


Figure 3-1 Diagram of Research Method

From Figure 3-1, 3 notable steps can be inferred. Initially, the data collection included; (a) indoor temperature monitoring, (b) energy records, (c) site visits and (d) retrofitting measures assessment. The latter part has been carried out to collect information about the available technologies and materials for refurbishment, whereas the first three contribute to the construction, calibration and validation of thermal models of actual dwellings.

The data collection procedure was followed by the generation of the models. Through this step, the models were constructed driven by the data collected during the data collection and following a calibration procedure, their performance were finally evaluated with the actual data, based on statistical metrics.

Thereafter, the interventions were investigated through a parametric analysis, in order to prioritize and also, establish the optimum effect of energy saving measures. By the outcome of the study, guidelines were drawn within the context of optimising the residential envelope for reducing energy consumption while thermal environment is maintained or enhanced.

3.3 Residential Buildings-Case studies

3.3.1 Foreword

Before continuing to the modelling procedure, the case studies will be introduced. This section seeks to justify the selection of the case studies, emphasizing the reason for selecting single detached houses for investigation and also, describing their main characteristics.

3.3.2 Case Studies

An early introduction of the national housing inventory was presented in section 2.4. Recalling the findings, the detached houses are the dominant type of dwelling, distributed primarily along the coastal areas of the country. Figure 3-2 presents the population and distribution of dwellings.

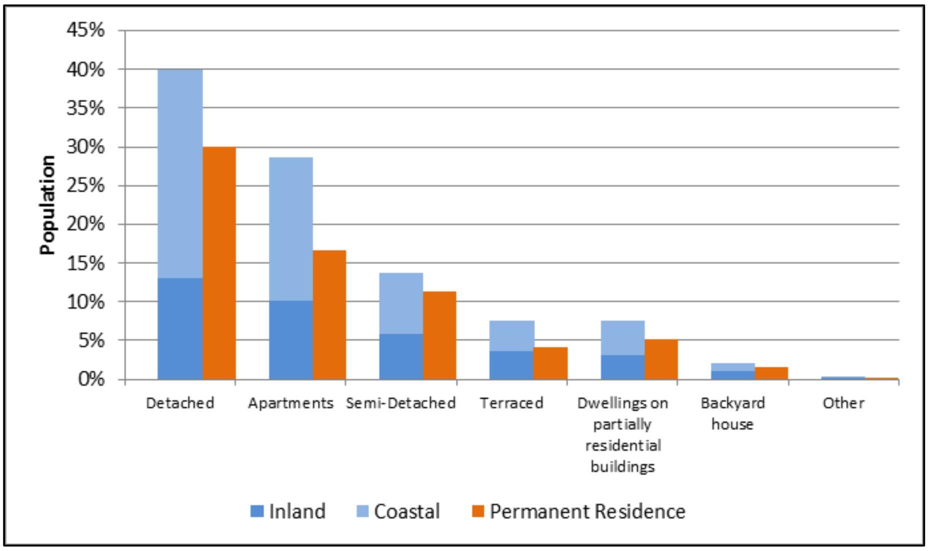


Figure 3-2 Housing inventory population per type (CYSTAT, 2011b)

In numbers, detached dwellings account for the 40% of the national stock, followed by apartments with a fraction of approximately 28%. The detached houses are primarily used as a permanent residence, approximately 30%, where the second category (Apartments) is slightly above the 15% (CYSTAT, 2011b).

Another critical characteristic of the particular type is the exposed area to the external conditions. McMullan (2002) discussed the different shapes of residential buildings and the effect on the exposed area. Table 3-1 presents a common rule of thumb for exposed areas for dwellings having the same floor area.

Table 3-1 Exposed area of dwellings (McMullan, 2002)

TYPE OF DWELLING	EXPOSED PERIMETER AREA (%)
Detached	100
Semi-detached	81
Terraced	63
Flat on multi-storey (2 external walls)	32

Evidently, the envelope of the detached dwellings is entirely exposed to the outdoors, and as a result, it is subjected to the harshness of weather conditions.

In essence, selecting detached houses for investigation, seems to be suitable as they are representing the major type of the national housing, providing also the opportunity to study the impact of alternating the whole envelope.

Generally, the selection of case studies was primarily driven by the need to examine buildings constructed prior to the reference year of 2007 (implementation of EPBD in the national legislation).

The sample covered three distinctive construction periods before 2007, as it can be seen from Figure 3-3. In spite the different construction periods, the majority of the housing inventory was constructed by reinforced concrete and hollow clay bricks covered by plaster (Panayi, 2004) .

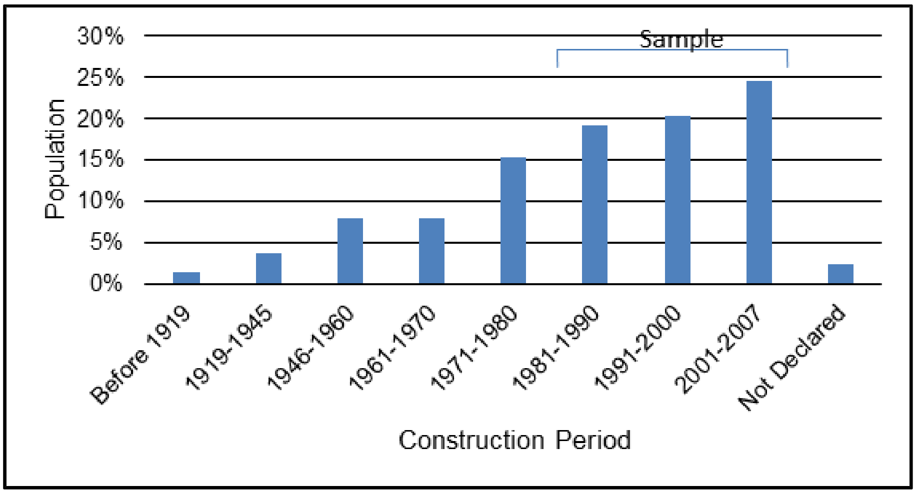


Figure 3-3 Detached houses population per construction period (CYSTAT, 2011b)

In the context of floor area, 35% of detached houses constructed in the period 1981-2007 are within the range of 200-299m^2, followed by the 27% of 150-199m^2, 14% of 102-149m^2, 11 % of larger than 300m^2 and 6% of 100-119 m^2. Figure 3-4 presents the categories of floor area for detached houses constructed in the period 1981-2007 (CYSTAT, 2011b). The sample covered a range of floor areas, as will be presented later.

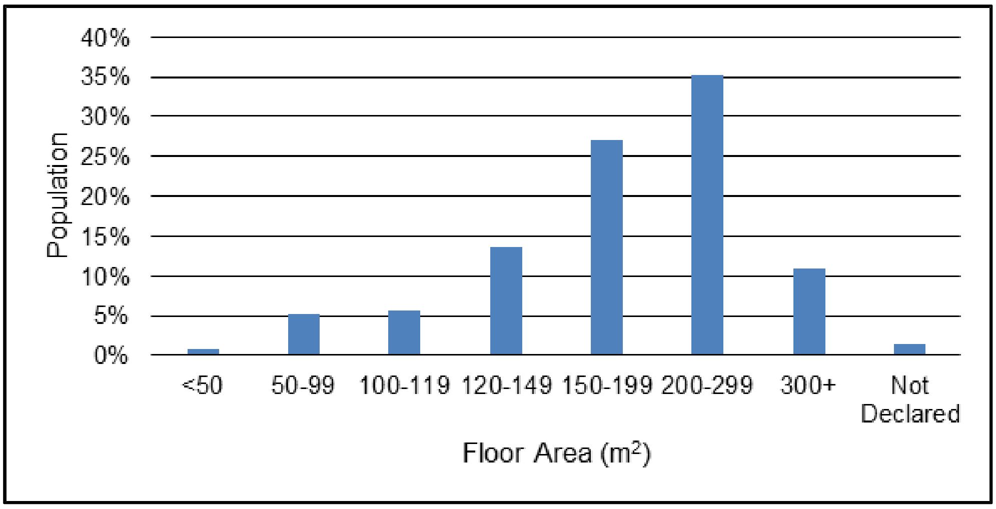


Figure 3-4 Floor area for detached houses constructed in the period 1981-2007 (CYSTAT, 2011b)

Earlier, the typicality of construction materials and architecture was mentioned. In particular, the majority of domestic buildings were constructed by slabs, columns and beams. Their bearing structure is founded on reinforced concrete (2% steel) with hollow clay bricks on horizontal alignment coated with plaster. The construction is either single or double story, with flat slab roof or inclined concrete slab finished by roof tiles. The typical construction of Cypriot houses was extensively described by (Florides et al., 2002; Florides et al., 2000; Lapithis et al., 2007; Panayi, 2004). The selected houses represented the typical bearing structure, differing primarily on the roof construction, floor materials and window configuration.

Based on stratified sampling, Table 3-2 and Figure 3-5 present the selected houses for investigation and a short description of the construction year and floor area. In detail, information for each case study and construction materials, can be found in the Appendix B.

Table 3-2 Sample description

INDEX		CONSTRUCTION YEAR	FLOOR AREA (m^2)
CATEGORY A	SD1	1995	290
	SD2	1987	188
	SD3	1996	384
CATEGORY B	SD4	1994	176
	SD5	1987	117
	SD6	2007	120
	SD7	2006	208

Figure 3-5 Exterior view of investigated dwellings

Initially, 8 case studies were selected, comprising of two categories (A and B). Category A represents the buildings that are primary using heating oil during the heating season, whereas Category B consists of buildings that rely on grid-electricity for both seasons. However, during the data mining, one case study from category A was removed due to insufficient information, which rendered the calibration of the model impossible.

In addition, during the air-tightness test, 2 houses constructed after 2007 were examined, in order to compare their performance against the rest of the sample in terms of infiltration.

3.4 Data Collection

This section will concentrate on the data collection procedure. The performance and characteristics of the case studies were observed for one year period through indoor environment monitoring, energy consumption recording, walk-through visits, site-surveys, acquisition of the electrical appliances' nameplate power, lighting fixtures and finally, a blow door test for the estimation of building's air permeability. In addition, a market survey has been carried out to establish the current scene of the interventions. The surveys undertaken throughout the study complied with the ethical considerations of Loughborough University. The results from the data collection were mainly used to develop validated models, either by assigning them as inputs in the models or as metrics during the validation procedure. Figure 3-6 summarizes the content of data collection.

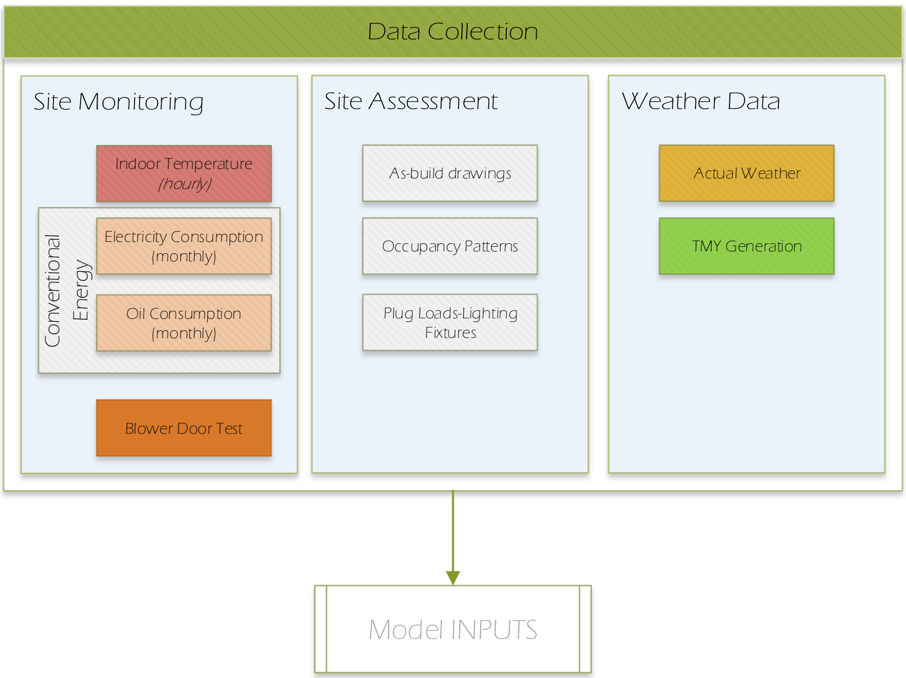


Figure 3-6 Data collection procedure

3.4.1 SITE MONITORING

TEMPERATURE MONITORING

The whole monitoring period was undertaken in the period of February 2012-February 2013. The indoor temperature was measured by HOBO pendant sensors. Figure 3-7 illustrates the devices that were used and their technical characteristics are presented in Table 3-3. The sensors were placed in 4 primary spaces referring to the daily occupied areas within the house such as living room, kitchen and bedrooms.

Figure 3-7 Sensor devices, right to left: HOBO UA-00108, HOBO U12-012 (TEMPCON, 2014)

Table 3-3 Technical characteristics of data loggers (TEMPCON, 2014)

Parameter	HOBO U12-012 4 Channel Logger	HOBO Pendant Temperature Data Logger (UA-001-08)
Temperature	-20ºC to +70ºC, Acc. ±0.35ºC (0-50ºC)	-20ºC to +70ºC, Acc. ±0.53ºC (0-50ºC)
Relative Humidity	5-95% RH, Acc. ±2.5% (10-90%)	-
Light	1 to 3000 lumens/ft^2	-
Response Time	6 min	10 min
Time accuracy	±1 minute per month at 25 ºC	

The choice of a representative location for the data loggers was critically considered. Ideally, the sensors must be placed in the core of the space in order to measure the average indoor temperature, eliminating the impact of heating sources and radiation by the building elements. However, in actual building this case may not be possible as occupants are directly interacting with their environment. Therefore, driven by this limitation, the sensors were placed at the most suitable locations within the building, considering also the guidance of the householders. The sensors were also positioned away from heating sources (i.e., radiators, refrigerators, oven, fireplace, TV), air path of AC units, windows, doors or solar radiation, at a mid-height level, avoiding the impact of radiation by building element and intrusion to occupant's daily activities. An example is depicted in Figure 3-8.

Figure 3-8 Location of a sensor during the monitoring period

An hour interval was selected based on the battery life and memory of the data loggers for long term monitoring in order to avoid the frequent visits. However, in order to examine the consistency of data and the operation of the sensors, the data was downloaded every 2-3 months.

The temperature data collected during this stage of the study were primary used for the midseason calibration of the simulation models that will be described in Chapter 5. Additionally, the fluctuation of temperature contributed to the further understanding of the HVAC operation. An example is presented in Figure 3-9.

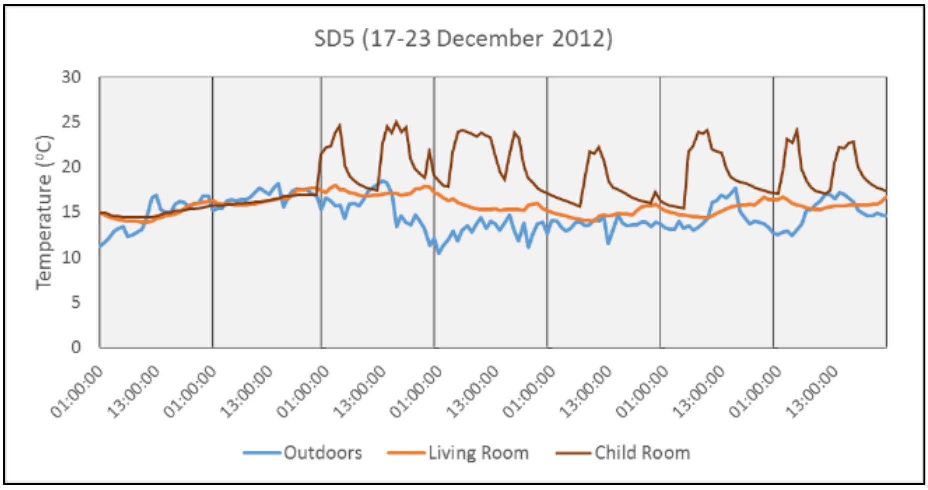


Figure 3-9 Monitored space and outdoor temperature, house SD5

From this figure, it can be inferred that the AC unit was operated in the child's room, whilst the AC unit in living room was switched-off.

ENERGY CONSUMPTION

The case study buildings are primary supplied by grid electricity for their daily needs. In the cases of category A, heating oil is used as a mean of heating during the winter period. Regarding to the validation procedure, the energy consumption must be, at least, recorded in a monthly interval. This was achieved by in-situ measurements of the recordings by the residential electricity meter. In addition, the monthly oil consumption was established by the volumetric difference in the oil storage tank and oil supplier, as no oil or gas network is presented in the country.

BUILDING AIR-TIGHTNESS

In the current literature, a critical input during the generation of the building models is the air infiltration of the envelope. For instance, Purdy and Beausoleil-Morrison (2001) mentioned that the heating load can be skewed up to 27% by the use of a typical data. In order to minimize the risk of uncertainty by adopting an assumption, a blower door test has been carried out, measuring the air permeability of the building enclosure. Figure 3-10 presents the attachment of the experimental equipment in the main door of the dwelling.

Figure 3-10 Photo of the Blow-Door equipment (left to right SD1, SD2, and SD4)

Overall, the procedure was aligned with the EN 13829:2001 (CEN, 2001), with additional enhancements by ATTMA (2010). The guidelines were strictly followed, initially to avoid any damage on the envelope of the private properties during the depressurization of the building and also, to ensure the quality of the results. The step by step procedure is further explained in the Appendix C.

3.4.2 Site Assessment

This part of data collection deals with the qualitative collection of data, which was accomplished through walk-through visits and site surveys. The main purpose of the site assessment was the discussion with the householders, in order to establish a clear picture about the operation of the building, characteristics of the building envelope, occupancy patterns and any other information related with the dwelling. In addition, the architectural drawings were obtained.

An additional mandatory data associated with the development of the building models is the energy consumption of plug-devices such as lighting, appliances, DHW, boilers, split units, pumps, fans etc. The study was limited to the monitoring of the actual load of those devices by energy meters and thus, an alternative approach was adopted, following the guidance of (ASHRAE, 2002). During the walk through visits and the site surveys, the nameplate power (Watts) was collected in order to develop an abstraction of the energy distribution within the buildings. The utilization of data obtain for this section will be further described in Chapter 5. In the Appendix D, the related documentation developed for the collection of the data is attached.

3.4.3 Weather data

In the present study, the hourly weather data, for the period 2001-2012, have been acquired from the local meteorological station of Paphos National

Airport, which is situated at the south-west coastal region, 34°72' N 32°48' E, of Cyprus (MetService, 2012b). However, due to a lack of global radiation data for the period 2001-2004, additional databases were employed, providing a comprehensive data for the Typical Meteorological Year (TMY) development (NOAA, 2013; SolarGIS, 2013; Kalogirou, 2003).

The data acquired by the weather station was initially used for the construction of an actual weather EPW file and also, a TMY file (see Figure 3-11).

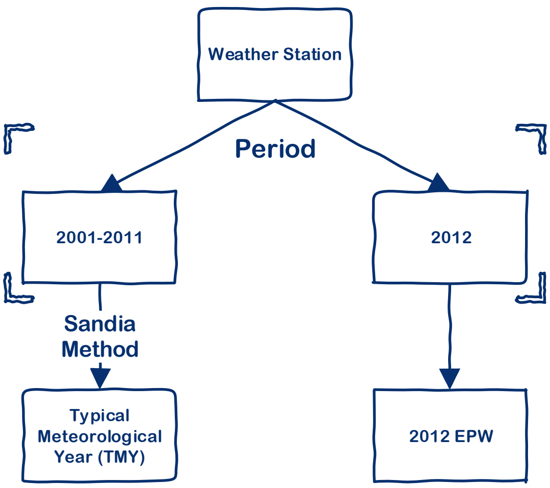


Figure 3-11 Procedure of weather data manipulation

As a part of this study, a TMY file was generated for south-west coastal area, based on the modified Sandia method. The Sandia method is an empirical approach where a TMY consists of 12 calendar months (Ebrahimpour and Maerefat, 2010). Additionally, a further investigation on the impact of weighting factor during the aggregation of TMY file was examined. The whole procedure is extensively described in Appendix E.

The actual weather EPW file was used through the calibration procedure to represent the outdoor environmental conditions, where the TMY was used at the later analysis of the ESM, in order to normalize the outcome with regards to typical weather conditions rather than an actual year.

3.4.4 Energy Saving Measures assessment

This is the last part of the data collection procedure, which aims to gather information about the technical data and cost of available energy saving measures for retrofitting a residential building envelope. This was accomplished by providing questionnaires to companies related with thermal insulation materials, windows materials (glazing system, frame) and labor cost. Generally, the national market is small, and thus, the objective was to collect as much information as possible, in order to establish a reliable sample. Table 3-4 summarizes the categories of the questionnaires and the feedback from the companies. The questionnaires for each category are presented in the Appendix F.

Table 3-4 Questionnaires completed during the ESM assessment

CATEGORY	**# QUESTIONNAIRES**		**RESPONSE-RFE (%)**
	Distributed	Completed	
(A) Thermal Insulation Materials	22	19	86
(B) Glazing Systems	7	7	100
(C) Frame and Windows Installation Cost	24	19	80
(D) Labor during retrofitting-Cost	10	9	90

3.5 Dynamic Thermal Modelling (DTM)

Dynamic thermal modelling is often used to give an overview of a building's performance throughout a typical year (Cook and Short, 2009). Since this study aims to propose retrofitting solutions and investigate the balance between energy consumption and thermal comfort, DTM models are suggested as an appropriate tool to predict thermal and energy performance of building models.

Data collected during the first section of the research were used either as inputs on the dynamic models or as validation metrics. The whole calibration and validation procedures are described in Chapter 4, presenting also the results from the validation assessment.

Following the concept of the calibration procedure, the modelling tools were selected based on the availability, flexibility and suitability for in-depth thermal analysis.

A comprehensive directory, currently hosted by the U.S. Department of Energy, so-called "Building Energy Software Tools Directory", provides information for about 402 building software tools for assessing energy efficiency, renewable technologies and sustainability in the built environment (USDOE, 2014). The software products are generally categorized with regards to their suitability to the whole building analysis, compliance to codes and standards and other applications in the building performance (Jankovic, 2012). In order to investigate retrofitting analysis in residential buildings, EnergyPlus is considered one of the most robust software packages, with comprehensive libraries of materials and systems (Jankovic, 2012). Through the rest of this section, a description of the software products will be presented.

3.5.1 EnergyPlus (E+, EPlus)

EnergyPlus (E^+, EPlus) is a stand-alone simulation engine, founded on the features of BLAST and DOE-2 programs. It was developed by the U.S. Department of Energy in late 70s and it’s an open-source license software, under specific user license agreement. Like its predecessors, the E^+ is an energy analysis and thermal load simulation software, founded on the thermal network method. It has been tested against the IEA BESTest building load and HVAC tests (USDOE, 2014).

The input definition file (*.IDF file) is based on text format, complicating the friendly interface for the user. This is mainly observed during the design of the building geometry, which relies on the Cartesian system (x, y, and z) for each single point of a surface. However, the availability of user-friendly front-end softwares (i.e., DesignBuilder) offers an advantage to design the geometry of a building by simple tools, which later can be imported in EPlus as an IDF file. Overall, EPlus has great capabilities such as the simultaneous solutions, user’s definable time steps, ASCII weather files, thermal comfort models, ground temperature calculation, energy management system (EMS) for control strategies, compatibility with other softwares for design, analysis and parametric solutions (USDOE, 2012c).

In 2005, Crawley et al. (2005) published a report comparing 20 major building simulation engines, hosted by (USDOE, 2014). The report was based on the data provided by the program developers for 14 categories. According to the findings, EnergyPlus had the most of capabilities and futures, followed by ESP-r, TRNSYS and IES. While ESP-r is another open-source software with great capabilities, its learning method is an important drawback (ESRU, 2013).

Therefore, the open-source license, the great capabilities and the plethora of front-end softwares compatible with EnergyPlus, make EnergyPlus attractive software tool to be used throughout this study.

3.5.2 DesignBuilder

The DesignBuilder was developed in UK, based on EnergyPlus for thermal simulation. It is commercially available under non-free license. Its greatest capability is the easy and friendly end-user environment to construct complex building geometries, while offering built-in templates and datasets for different buildings, operation patterns and systems. However, in case of more complicated systems, the user may refer to EnergyPlus to accomplish the design of them (USDOE, 2014).

3.5.3 JEPlus

JEPlus is a parametric tool which offers the opportunity to perform complex simulations and thus, multiple parameters can be examined. By its application, the amount of simulation runs will be decreased, reducing also the running time. It is developed as an auxiliary program for EnergyPlus, written on Java language and can be obtained on free-license. An additional advantage is the friendly user-environment (Zhang and Korolija, 2014). The implementation of JEPlus and the parametric analysis will be further looked at through section 3.6.

3.6 Envelope Interventions, Parametric and Evaluation Analysis

This section discusses the approach and the evaluation assessment related to the investigation of retrofitting interventions. In Chapter 2, the background theory of available measures was studied. In this section, more emphasis will be given on the technical characteristics and particularly, on the measured parameters that will be examined.

In order to examine the interventions, a normalization of the models was considered appropriate. The simulations were normalized in the perspective of weather conditions, occupancy patterns and HVAC operation. This is due to the fact that the study aims to develop a global guidance about retrofitting measures and therefore, it is not wise to base the study on extreme values. Regarding to the weather, the simulation will be based on two TMYs databases; coastal (Paphos Station) and low lands (Athalassa Station). In essence, the outcome was founded on a typical year rather than actual year as in the case of the calibration procedure. In the same line of thought, a typical occupancy pattern (for residences) was applied for all buildings, to minimize the effect of people and their different lifestyle. The normalized occupancy pattern was founded on the studies (Panayi, 2004; Papakostas and Sotiropoulos, 1997) and it is listed in Table 3-5.

Table 3-5 Normalized occupancy pattern

SPACE	OCCUPIED HOURS	
	Weekdays	Weekends
Living Room	17:00-22:00	08:00-13:00 & 14:00-22:00
Kitchen	13:00-14:00 & 20:00-21:00	13:00-14:00 & 20:00-21:00
Bed Room	22:00-07:00	22:00-07:00

The interventions was examined during the heating and cooling periods and at any time of occupation, setting the HVAC set-point temperature according to (CEN, 2007), Table 3-6, assuming a metabolic rate; 1.2 met (seated-quite) and 0.7 met (sleeping) and clothing value; 1.0 Clo and 0.5 Clo, for winter and summer, respectively.

Table 3-6 Heating and cooling set-point temperatures

SPACE	SET-POINT TEMPERATURE (^{O}C)	
	Winter	Summer
Living Room	20	25
Kitchen		
Bed Room		

3.6.1 SINGLE INTERVENTIONS

As aforementioned in earlier chapters, the study tends to investigate the retrofitting measures for the building enclosure, which can be categorized as; thermal insulation and solar control strategies. Initially, in order to establish the optimum single intervention, all the parameters were individually examined. In particular, the study was based on the data gathered through the ESM assessment, driven by the current market scene.

AIR-TIGHTNESS

The air-tightness of a building is an ambiguous measure as currently there is not any available data about the cost and the characteristics on achieving tight building envelopes. In addition, air-tightness is sometimes coherent with other measures such as thermal insulation or windows frame, where the value of infiltration may be reduced during the integration of the external insulation or a well-designed frame system. Due to this fact, the investigation of the impact by tightening a residential envelope was examined through the adoption of scenarios, in order to establish a guideline within the context of infiltration and air-tightness. The scenarios are listed in Table 3-7.

Table 3-7 Air tightness scenarios

	AIR PERMEABILITY($m^3/(h.m^2)$ @ 50 PA)	**DETAILS**
Scenario (A)	-	*Default building's air permeability*
Scenario (B)	≈3	*This requirement is based on Energy Saving Trust best practise and Germany average of 2.8~3.0 $m^3/(h.m^2)$) @ 50 Pa*
Scenario (C)	≈1	*Passivhaus Standard*

The last scenario was also based on the results from the blower-door test (see Appendix C). As recent constructed buildings are under no obligation to any legislation relating to air tightness they achieve remarkably low levels of air permeability, motivating the study to examine the impact of the Passivhaus Standard.

THERMAL INSULATION

This category deals with the application of an insulant, externally or internally, to reduce the overall U-value of the building element. The parameters addressed in this category are the position, material and thickness. Table 3-8 summarizes the parameters that will be investigated.

Table 3-8 Thermal insulation parameters under investigation

CATEGORY	ELEMENT	PARAMETERS		
		Position	**Material**	**Thickness (mm)**
Thermal Insulation	Roof	External, Internal	EPS, XPS, Rock Wool, PIR*, Polyurethane Foam**	10-100
	Wall			
	Floor	Internal	EPS, XPS, Rock Wool	

Notes:
**The PIR defines the prefabricated structural panels with available thickness of 50mm.*
***The foam polyurethane is applied up to 50mm.*
Abbreviations:

- *EPS - Expanded Polystyrene*
- *XPS - Extruded Polystyrene*
- *PIR - Polyisocyanurate insulation boards*

As a part of the study the properties, characteristics and cost of application for each material were gathered to follow as much as possible the real life scenarios. As aforementioned, the questionnaires were successfully completed by 28 companies related to thermal insulation supplying and application. As a result an abstraction was developed with regards to the availability of materials, characteristics and cost of application. Figures (3-12), (3-13) and (3-14) show the effect of material and its thickness when this are applied on opaque elements. In particular, the figures present the change on the default (base case) R-value of the different elements by the application of a thermal insulant. For the case of the PIR, commercially only thickness of

5cm is available and thus, a point is presented for the cases of roof and external walls insulation.

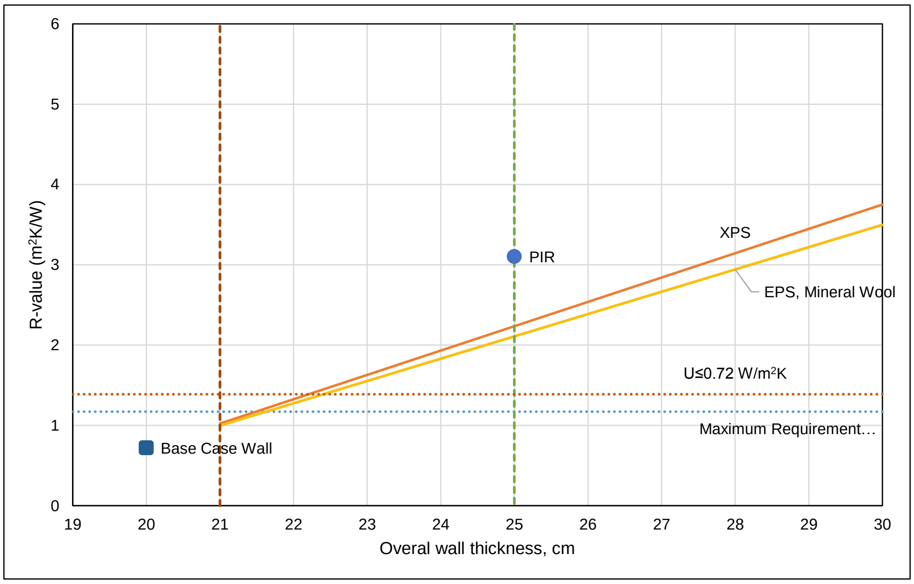


Figure 3-12 External walls R-value by material and thickness

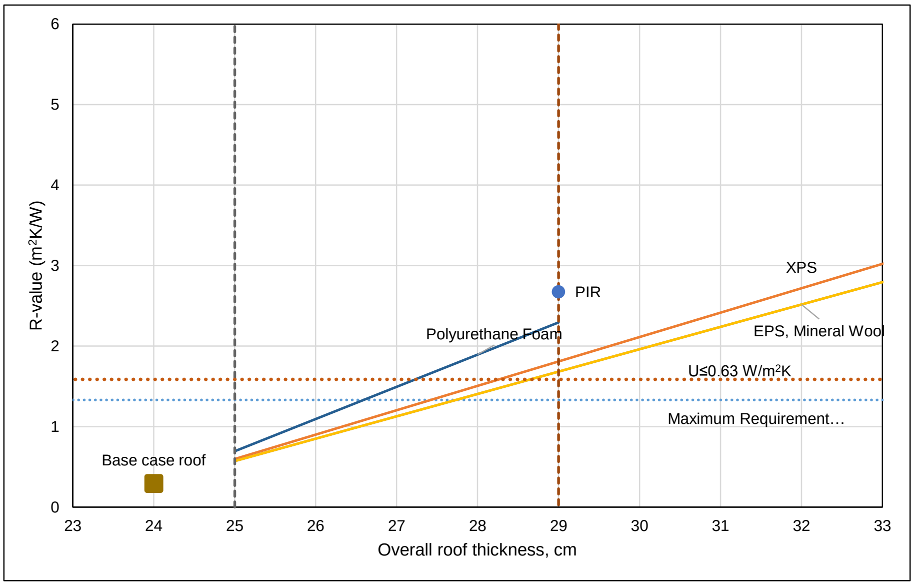


Figure 3-13 Roof R-value by material and thickness

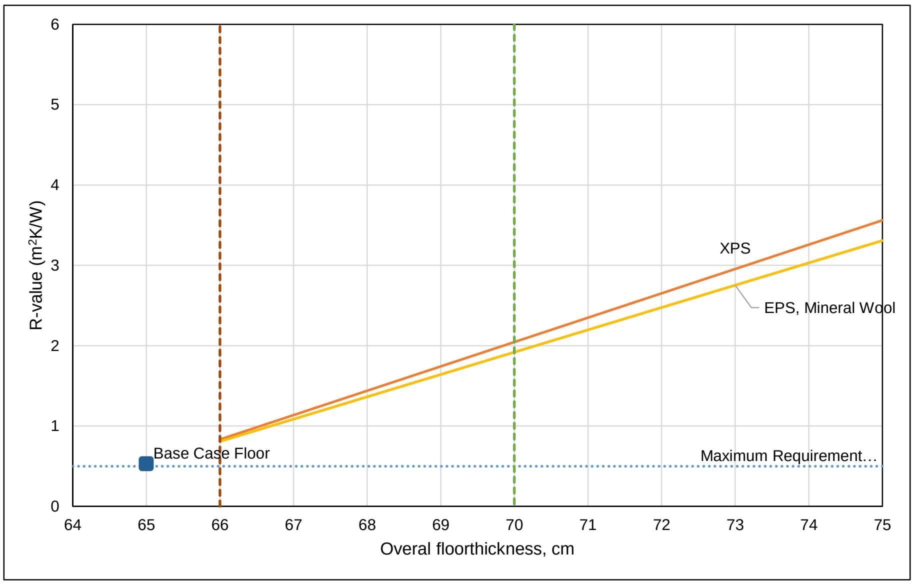


Figure 3-14 Floor R-value by material and thickness

Figure 3-15 presents the linear relationship of the cost (€/m^2) for insulating materials, currently available at the national market; a) Rock wool, b) Expanded-Polystyrene(EPS) and c) Extruded-Polystyrene(XPS).

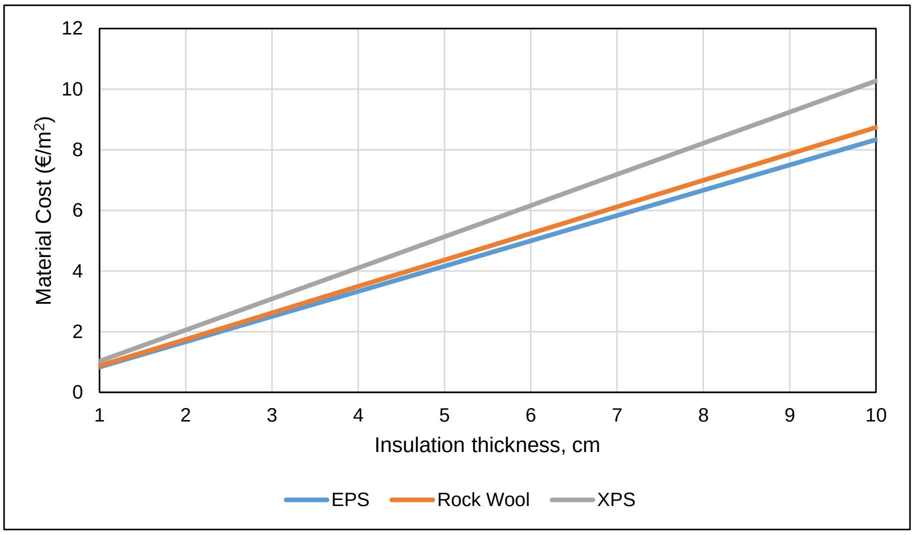


Figure 3-15 Average material cost by thickness

While polystyrene is primarily used for thermal insulation, the Rock wool is preferred for its soundproofing characteristics. In general, the extruded polystyrene is slightly more expensive than the other materials, with lower thermal conductivity. The cost on Figure 3-15 represents only the cost of the material.

The application cost is alternated with regards to the building element and position (externally or internally). From the data collected about the overall installation cost (miscellaneous materials (i.e., finishing, insulation protection) and labour), the wall's insulation varies from 35-40€/m^2 (external) and 30-35€/m^2 (internal). In the case of the roof insulation, the prices are lower with expenses of about 25€/m^2 (external) and 29€/m^2 (internal) for flat roof and approximately 5€/m^2 less for incline slab roof. On the contrary the cost of applying a thermal insulation on the ground floor above the level of the slab is almost double compare to the roof insulation due to the labours, reaching the price of approximately 58€/m^2.

Further to the available materials for a flat roof insulation, another approach may be adopted, using spray polyurethane (λ=0.025 W/mK) with an estimated cost 24€/m^2 for 30 mm thickness (any additional 10mm will increase the price by 2€/m^2). An alternative method for insulation is the structural insulated panels (PIR- λ=0,021 W/mK) with overall installation cost of about 48€/m^2 for external walls and 38€/m^2 for roof.

LIGHT OPAQUE ELEMENTS

The coating of external surfaces with reflective paint is widespread applied in hot climates due to the excessive solar radiation. However, the compensation of the heating and cooling load must be investigated, as the effective solar insolation during the winter season may be compromised due to its reflection.

Commercially, it was claimed that a reflective white paint may achieve up to 85% of reflectance (Watco, 2014). The cost of the application reaches 15.75 €/m^2 (11.50€/m^2 Coating material (Watco, 2014) + 4.25€/m^2 Labour) . In 30 years of a building's life span, it is recommended that the paint must be applied every ten years due to erosion by the environmental conditions.

WINDOWS

In the context of a windows system, two primary systems will be examined; glazing and framing. In the latter case, a thermally improved frame will replace the existing system, with U_f (U-frame)<2.3 W/m^2K. These values correspond either to the aluminium with thermal break or to the uPVC systems. Data gathered from manufacturing and installation companies for framing systems, indicates the cost of installation of such systems (Appendix I).

In section 2.3.2, the importance of a glazing system in a window was mentioned. In essence, the examination of different glazing systems is more than important, in order to establish a wider picture on the impact of U_w (U-window) and solar factor. Figure 3-16 shows 5 double and 4 triple glazing systems, the variation of cost as acquired from glazing companies, the U_w, solar factor and also, the scenario (green index) for the addition of argon gas within the gap of the glass panes. The outermost glass pane has 6mm thickness, with the internal (double or triple) to be 4mm. The gap was set at 12mm, based on the optimum thickness indicated by ASHRAE (2009).

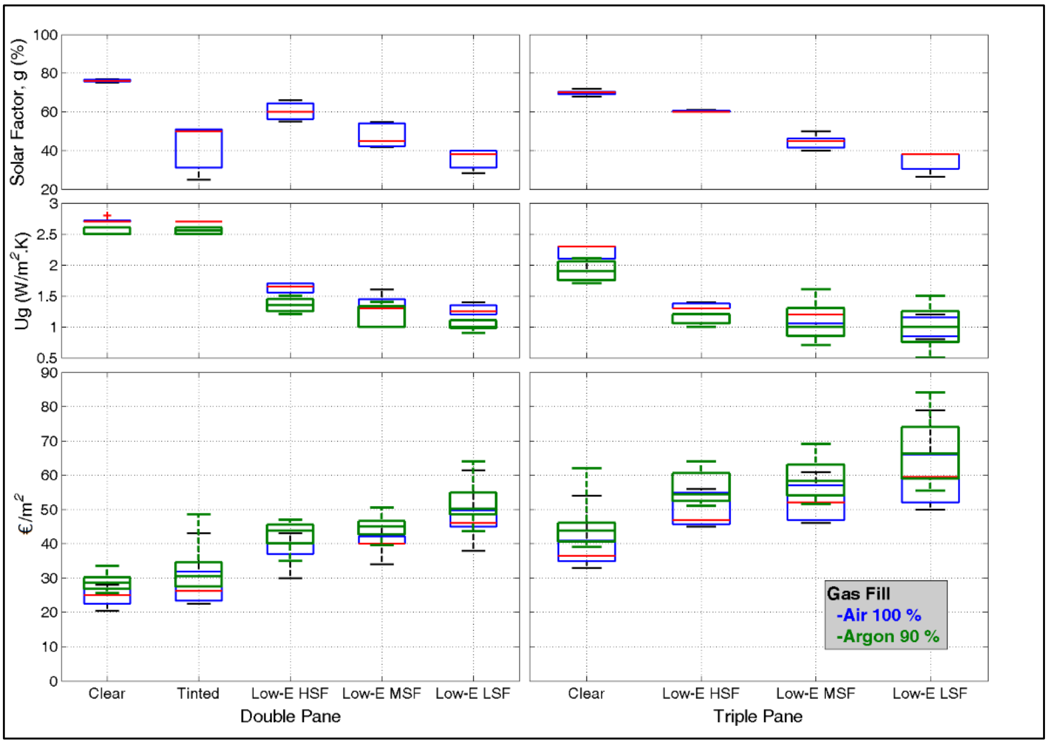


Figure 3-16 Properties and cost for different glazing systems

A preliminary outcome from the figure, it is the impact on the cost and U_g of the system by adding a glass pane, as the price is approximately 4 times higher than the clear double glass, while the U_g (U-glazing) is reduced to about 0.9 W/m^2.K. The addition of argon increases the price by 4-5€/m^2, while the U_g can be reduced by 0.2-0.3 W/m^2.K.

EXTERNAL SHADING

Further to the measures for the fenestration, the implementation of the overhangs and fins was addressed. The initial objective for this category was to examine the effect of fixed external shading and thus, the length of the projection was calculated for each individual case study, based on the orientation and solar angles. The whole procedure is described in Appendix J. As the previous measures, the construction cost for a concrete projection of

10cm (thickness) was obtained during the assessment procedure with an average price of 36€/m^2, on the contrary with an external movable shading application cost ≈175.50€/m^2 (MCIT, 2013b).

3.6.2 Combined Interventions

As a part of the study, the interventions were parametrically examined to establish the optimum combination, under a typical operation of the HVAC systems, for the weather files of coastal and low-lands area.

Figure 3-17 depicts the parametric tree, adapted by Zhan and Korolija (2010), presenting the interventions that were investigated through the JEPlus software. For every dwelling, 7,056 batch files were simulated, resulting in 49,392 simulations for each climate scenario, with an average running time of about 15 minutes, implying a time-consuming process. On the single intervention case, a computer with 8 cores (parallel simulations) was used with moderate time of runs. For the parametric runs, the hyper-computer (HYDRA) of Loughborough University was employed (1,956 cores), overcoming the high running time.

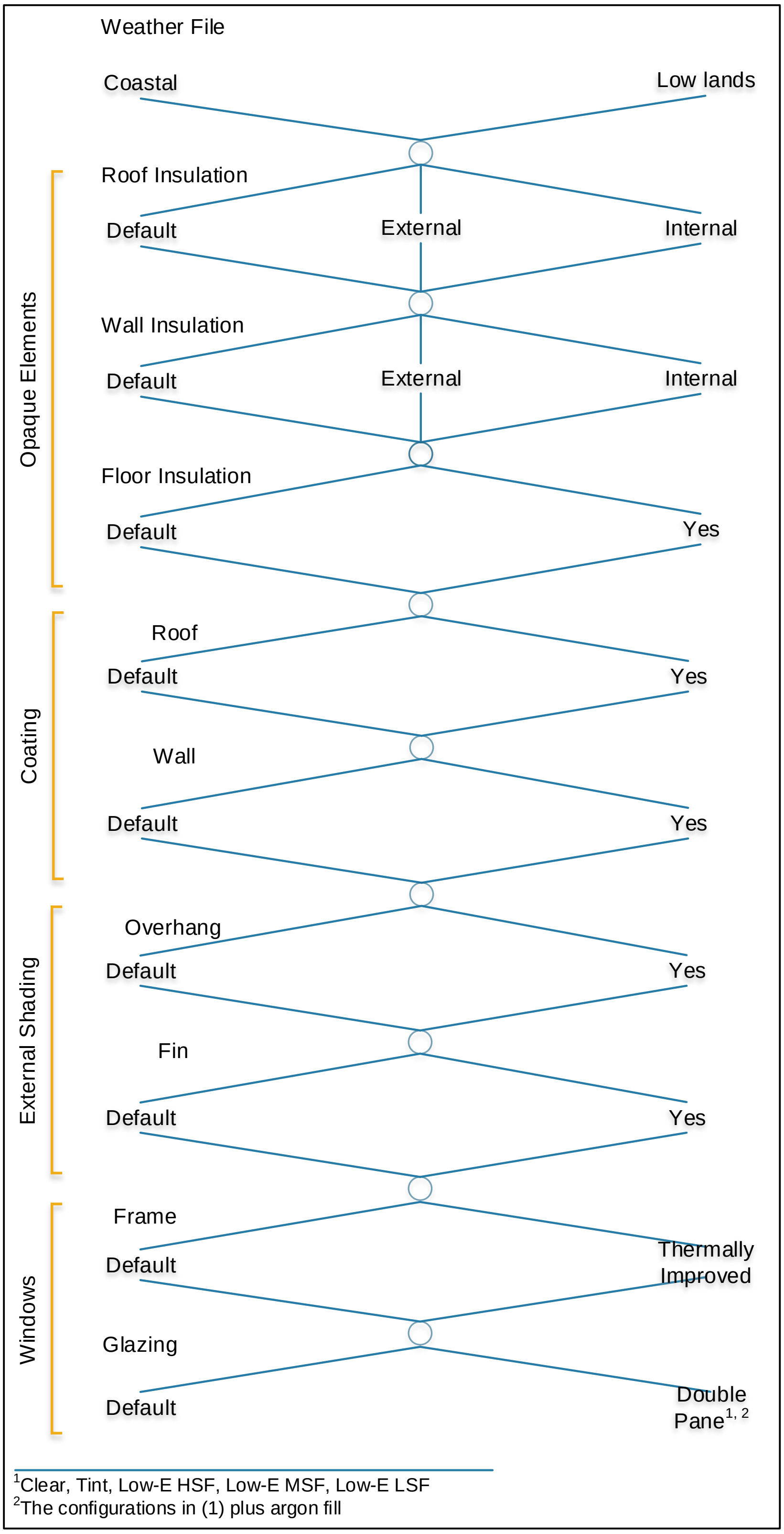


Figure 3-17 JEplus parameter tree (adopted by (Han et al., 2007))

3.6.3 Evaluation Assessment

Through the previous sections, the interventions (single or combined) were discussed. In this section, the evaluation of their performance will be studied, giving attention to the criteria and the methods of the evaluation assessment. The primary objective of the study is to prioritize the performance of alternative solutions with regards to the energy consumption coherent with the thermal loads and the thermal comfort of the indoor environment. The Figure 3-18 depicts the optimization approach, undertaken for the prioritization of the measures.

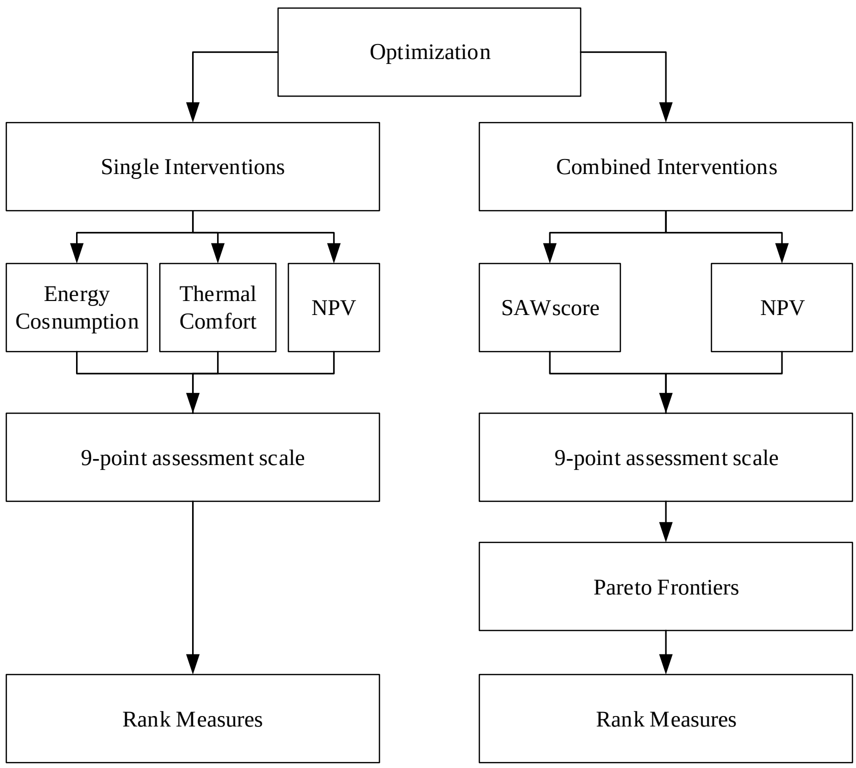


Figure 3-18 Optimization procedure

Particularly, the heating and cooling load were normalized by the conditioned volume, heating (V_h) and cooling (V_c), in order to accommodate with the different geometries and sizes of houses that comprising the sample of this study. The energy performance of each intervention was compared against the default construction, following Eq. 3-1.

$$P_i = \frac{B_d - I_i}{B_d}.100\%$$ ***Eq. 3-1***

B_d= Building default performance (kWh/m^3 heating and cooling loads or comfort score)

I_i= Intervention performance (kWh/m^3 heating and cooling loads or comfort score)

P_i=Performance score of intervention, I (%)

In the case of thermal comfort assessment, the evaluation was governed by the Method A of the EN 15251:2007. According to the standard, the thermal comfort of a space is quantified through the occupied hours that are lying within the comfort limits described by the Class I, II and III (CEN, 2007). Therefore, the comfort hours of the whole building was established by all the occupied spaces, as follows:

$$Class_i = \frac{\sum_{j=1}^{n} \frac{Comfort\ hours_{space j}}{Tocc_{space j}}}{n}$$ ***Eq. 3-2***

Comfort hours $_{space}$= Time the space comfort is within the limits of EN 15251 (hours)

$Tocc_{space}$= Time the space is occupied (hours)

Eq. 3-2 calculates the comfort hours for each class, summing the comfort hours for all spaces. As a primary objective of retrofitting existing buildings is to maintain or even improve thermal comfort, a weighting factor (see Table

3-9) was assigned for the EN 15251 classes, giving attention to the Classes II and III.

Table 3-9 Weighting factor of EN 15251 comfort classes

COMFORT CLASS BY EN15251	WEIGHTING FACTOR
I	0.1
II	0.3
III	0.6

Essentially, a global comfort score for each individual intervention was calculated, based on the weighting factor and Eq. 3-3 :

$$Comfort\ Score_{Measure} = \sum_{i=I}^{III} Class_i * W_i \qquad \textbf{Eq. 3-3}$$

W_i=weighting factor

The previous indicators have been adopted in order to assess the energy and thermal comfort, resulted by the upgrade of the energy saving measures.

In the context of cost effectiveness, an additional indicator was utilized, so-called Net Present Value (NPV). It is defined as "a*s the total present value of a time series of cash flows. It is a standard method for using the time value of money to appraise long-term energy projects. Used for capital budgeting, and widely throughout economics, it measures the excess or shortfall of cash flows, in present value terms, once financing charges are met"* (Wang et al., 2009). Atrill and McLaney (2013) claimed that NPV is the better method to appraise investments as it takes account:

- Timing of cash flows.
- The whole of the relevant cash flows.
- The objectives of the business.

Generally, MCIT (2013) recommends the adoption of 30 year as a period of evaluation, for measures coherent to building envelope, due to the long investment horizon (MCIT, 2013b). However, this long period is usually portending sources of uncertainty related to the assigned values of the parameters, used for the estimation of the NPV. To this effect, a risk analysis was included on the calculation of the mean NPV, to accommodate with the sources of uncertainty, based on the statistical distribution of parameters. The whole procedure is described in the Appendix K. In the perspective of energy measures, the intervention with the highest NPV was considered as the most economically feasible solution.

In the same line of thought, the evaluation of combined interventions may be merely described by the same approach. However, due to the amount of data, a performance score founded on multi-criteria optimization was considered. The score was based on the concept of the Simple Additive Weighting (SAW) multi objective method. It is defined as the aggregation of the normalized criteria, multiplied by their assigned weighting factor. The intervention with the highest score is selected as the optimum solution (Tupenaite et al., 2010). The performance score was estimated by Eq. 3-4 and Eq. 3-5:

$$S = \sum_{i=1}^{m} w_i x_{ij}$$ ***Eq. 3-4***

$$\sum_{i=1}^{m} w_i = 1$$ **Eq. 3-5**

S=Performance score of intervention,

x_{ij}= Normalized performance of intervention for every attribute,

w_i=the weighting factor for each of the criteria

The SAW_{score} was based on techno economic, environmental and indoor environment criteria. Table 3-10 lists the criteria by category and their assigned weighting factor.

Table 3-10 Criteria by category and weighting factor

CRITERIA			
CATEGORY	Techno-economic	Environmental	Indoor Environment
CRITERIA (ANNUAL)	Conventional fuels	CO_2 emissions	Thermal Comfort
WEIGHTING FACTOR	1/3	1/3	1/3

As in the single intervention, the NPV was estimated in order to evaluate also the cost effectiveness of the intervention. In essence, two indicators (criteria) were resulted for each measure, the NPV and the SAW_{score}, formulating a multi-objective optimization problem, where usually there is not a single solution. This was addressed by the adoption of the Pareto frontiers (or Pareto optimal). The concept of Pareto solution was initially introduced by (Pareto, 1906), defining a solution as a Pareto optimal when no other possible solution performs better without compromising any other criteria. The set of Pareto solutions is known as Pareto frontiers (Mastroddi and Gemma, 2013).

3.7 SUMMARY

Chapter 3 has explored the methodology of the study in order to investigate the effect of altering the existing residential envelopes in the Mediterranean region to reduce the energy consumption associated with the heating and cooling loads, while the indoor thermal comfort is not compromised.

Initially, the case studies were introduced, with an attention on the building properties and the overall operation of the buildings. Thereafter, the usefulness and the collection of actual data were extensively described. This was followed by the discussion related to the dynamic thermal modelling. Finally, the envelope interventions were presented in the terms of characteristics, application and evaluation assessment.

Chapter 4. CALIBRATION AND VALIDATION OF SIMULATION MODELS

4.1 INTRODUCTION

In Chapter 3, the research methodology was presented, drawing a clear picture on the methods that are undertaken to achieve the aim of the study. In this chapter, the generation of simulation models will be described within the context of calibration procedure and performance validation assessment.

A substantial objective of this study is the development of reliable simulation models, for the examination of the impact of ESM on the energy and thermal performance of existing residential envelopes. In particular, the data collected (see section 3.4) were assigned as the input parameters of the models. Further to this, the indoor air temperature and energy consumption of buildings were finally compared (following ASHRAE G-14) with the simulated data to ensure the accuracy and reliability of building models. A successful validation of the building models, will enhance the rationalistic application of the outcome of this research.

The overall calibration procedure is based on 3 consecutive steps; (a) upgrading parameters on the existing model, (b) mid-season validation and (c) annual performance validation. Figure 4-1 presents the procedure that was followed, for the generation of the reliable simulation models.

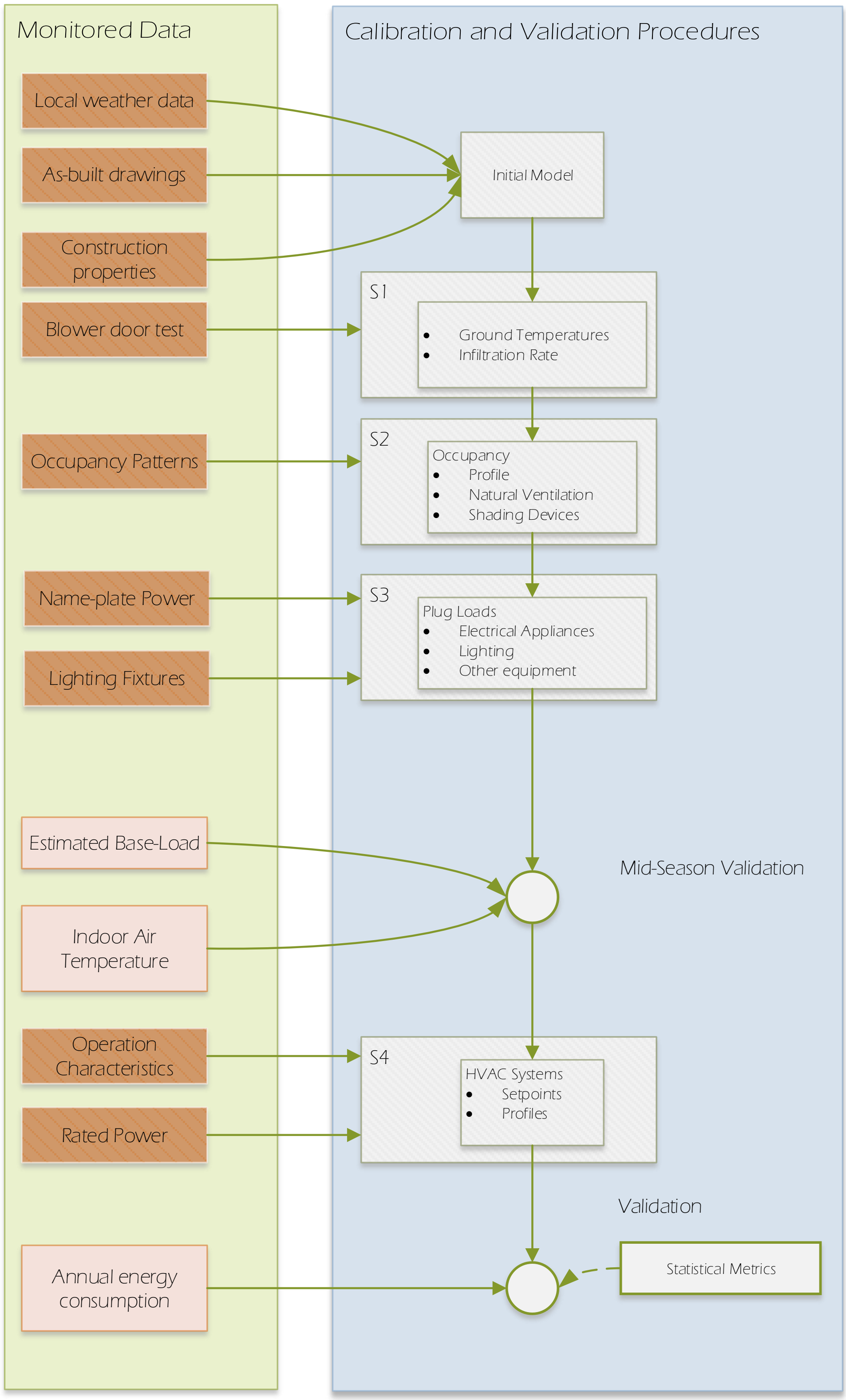


Figure 4-1 Simulation procedure

4.1.1 UNCERTAINTY-SENSITIVITY ANALYSIS IN INPUT DATA

During the development of the simulation models, several parameters of the building are assigned as inputs such as construction material, infiltration rate, orientation, ground reflectance, external environmental conditions, etc. The measurement or assumptions of a parameter are inherent with uncertainties. It is important to diminish the existence of these uncertainties, which can in some cases lead to crucial errors on the final decision. For instance, in the cases the infiltration rate cannot be measured and thus, the designer has not sufficient data of infiltration rate. Purdy and Beausoleil-Morrison (2001) reported that a difference of 1.5 ACH on air-tightness rating resulted in a deviation of the heating load up to 27%. On contradiction, they noted that the changes on windows optical properties are less critical (2% deviation of heating load).

It is evident that the summation of uncertainties may compromise the accuracy of the results, driving the designer to suboptimal decisions. Therefore, a sensitivity analysis must be carried out to assess the inputs to the impacts of uncertainties. The basic concept of sensitivity analysis is presented in Figure 4-2. The input (I) is examined by changing the value of the parameter and observing the response of the model on that change. When the change is characterized by a steep gradient, this corresponds that the model is sensitive to this parameter, whereas a low gradient presents an insensitive relation between model and input parameter.

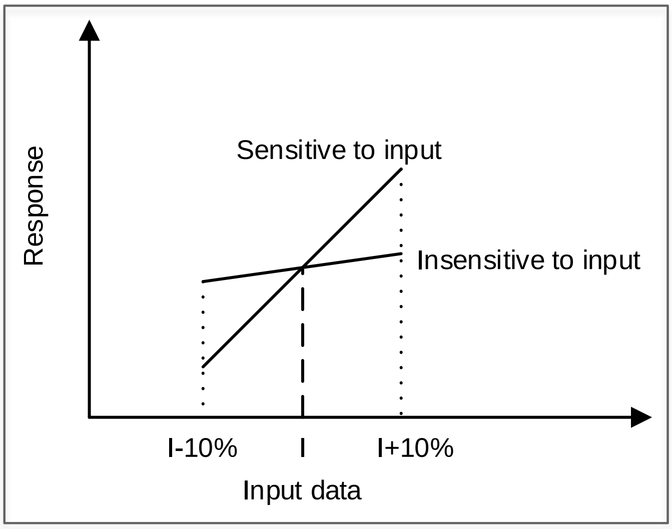


Figure 4-2 Sensitivity analysis (Robinson, 2004)

Sensitivity analysis is a time consuming process, however it offers the designer the opportunity to identify the important parameters and also, enhances the robustness of the output (Robinson, 2004).

It was beyond the scope of the study to undertake a sensitivity analysis for all the input elements. However, an analysis was carried out to examine the impact on thermal loads, by altering the input's value by 10%. Table 4-1 lists the variables that were examined and the absolute percentage difference on heating and cooling loads, for the cases of SD1 and SD4. All parameters were tested according to Robinson (2004), apart from orientation. The orientation of dwellings was assigned on building models, as this was described in the as-built drawings. Due to this, it was considered critical to assess the impact of orientation on the outcome of the building simulation.

Table 4-1 Sensitivity analysis for SD1 and SD4

#	VARIABLE		SHIFT	ABSOLUTE PERCENTAGE DIFFERENCE			
				SD1		SD4	
				Heating	Cooling	Heating	Cooling
V1	Orientation		15 degrees	**3%**	**3%**	**3%**	**2%**
V2			30 degrees	**3%**	**3%**	**2%**	**2%**
V3	Ground Temperature	Density -*Slab*	±10 %	0%	0%	0%	0%
V4		Specific Heat - *Slab*		0%	0%	0%	0%
V5		Conductivity - *Slab*		0%	1%	0%	1%
V6		Weather File Values		**3%**	**2%**	**3%**	**3%**
V7	Blower Door Test *(Infiltration Rate)*			**4%**	**1%**	**2%**	**7%**
V8	U-value	Walls		1%	0%	1%	0%
V9		Roof		0%	0%	0%	0%
V10		Floor		0%	0%	0%	0%
V11		Glazing		0%	0%	0%	0%
V12		Doors		0%	0%	0%	0%
V13		All Elements		1%	0%	1%	0%
V14	Thermal Absorbance	Wall *(Finish)*		1%	0%	1%	0%
V15		Roof *(Finish)*		**2%**	**2%**	**6%**	**6%**
V16	Solar Absorbance	Wall *(Finish)*		0%	1%	0%	0%
V17		Roof *(Finish)*		**1%**	**3%**	**2%**	**4%**
V18	Glazing Solar Factor			1%	1%	1%	1%

As it was expected, the air permeability of the building and the roof absorptive properties cause the greatest impact, skewing the performance of the models. A lower effect is also presented by the alternation of the orientation and the weather data during the estimation of the ground temperatures, while the rest of the parameters may have an impact up to 1%.

4.2 UPDATING PARAMETERS

In general, the design of the models was accomplished through DesignBuilder and EnergyPlus. Additionally, the Slab pre-processor and Energy Management System (EMS) were used in order to calculate the ground temperature and simulate the actions (natural ventilation, internal shading devices and halogen heater) coherent with occupancy behavior, accordingly. Figure 4-3 presents the interaction between EPlus and DesignBuilder during the development of the models.

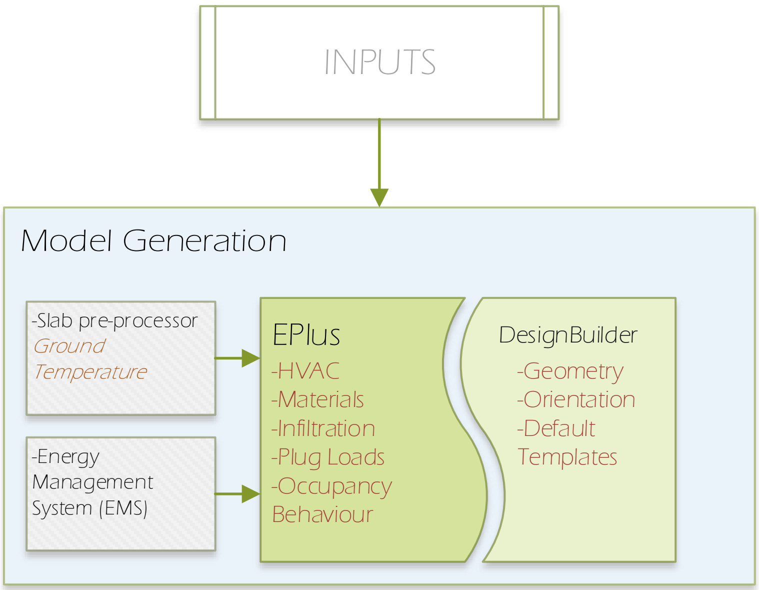


Figure 4-3 EnergyPlus and DesignBuilder relation

Overall, the upgrade of parameters section comprises 4 versions, so-called; Ground temperature and Infiltration rate (S1), Occupancy (S2), Plug Loads & Lighting (S3) and HVAC systems (S4).

Initially, a draft model of each dwelling was determined by the as-built drawings, orientation and construction materials (**S0** version). In spite of the great capabilities that EnergyPlus offers, the buildings were initially designed in the DesignBuilder (interface tool), due to the simplicity and the user-friendly environment. Any other parameter, in the initial model, was specified by the default templates of the DesignBuilder (such as θ_{ground}= 18 ^{o}C (constant), heating and cooling setpoints, profiles, infiltration etc.). Individual parameters such as the zone capacitance were assigned after the version S3. For example, the zone capacitance controls the effective storage capacity of the zone and thus, the impact of internal mass (USDOE, 2012c). Through the calibration procedure, the weather conditions will be represented by the actual data for year (2012) that was elaborated to an EPW file. The resulted model is then imported in EnergyPlus, in an IDF format.

4.2.1 VERSION S1-GROUND TEMPERATURE AND INFILTRATION RATE

The first version (S1) deals with the integration of the ground temperature and infiltration rate in the model. The latter was measured by the Blower Door test, as it is earlier described earlier in section 3.4.1. The values were then used in the model to imitate the effect of infiltration on the building enclosure.

Now, in terms of ground temperature, EPlus recommends the employment of the slab or basement pre-processor to enhance the pragmatic reflection of the simulations. The background EPlus theory, governing the ground temperatures for structural elements that are in contact with the soil, assumes that the ground temperature profile differs for buildings which are conditioned. Due to this, rather than using the “undisturbed” temperatures associated with the weather files, the user may run a pre-processing simulation based on the properties of the soil and the slab to estimate the ground temperature for the particular building. Overall, the slab program produces temperature profiles for the outside surface at the core and at the perimeter of the slab. It also estimates the average based on the perimeter and core areas used in calculations (USDOE, 2012b). As it was presented in an earlier section, the slab of residential buildings in Cyprus is constructed by a reinforced concrete (2 % steel, 1% for floor), covered by screed or sand (for services) and the floor finishing.

The properties of the reinforced concrete are obtained by (EneService, 2010), while for the soil are adopted by the study (Florides and Kalogirou, 2008) summarizing the properties of soil.

Table 4-2 Properties of soil, used for ground temperature calculations

THERMAL CONDUCTIVITY (W/m.K)	DENSITY (kg/m^3)	SPECIFIC HEAT (J/kg.K)
1.69	1950	1200

4.2.2 VERSION S2-OCCUPANCY

This version (S2) deals with the variables associated with people and their daily occupational patterns. As mentioned earlier, the information about people’s actions was collected during the site interviews.

In addition, the emulation of actions associated with the occupational behavior were developed either by the (EMS) or built-in functions of EPlus. Such actions are the natural ventilation and operation of the movable shading devices (in a later section, the operation of halogen heater will also be discussed).

The natural ventilation in simulation environment is associated with unpredictability, as several assumptions must be adopted at the design stage of the base-case model. In a review by Rijal et al. (2007), three major assumptions are presented with regards to the actions related to windows operation, which do not necessarily represent the occupancy-behavior:

1. A window schedule is governed by the levels of occupancy, without any data from the field.
2. In absence of data from the field, assumptions were made for the operation of windows based on temperature, rain and humidity.
3. The windows are controlled to produce certain amount of ventilation rates, driven by minimum ventilation or air quality requirements, neglecting thermal comfort.

A rising interest was observed in the recent years with regards to the window opening behavior. The majority of the studies have been carried out to investigate the office buildings (Fritsch et al., 1990; Nicol and Humphreys, 2004; Rijal, Tuohy, Humphreys, et al., 2008; Rijal, Tuohy, Nicol, et al., 2008; Rijal et al., 2007; Haldi and Robinson, 2009; Yun and Steemers, 2008; Herkel et al., 2008; Yun et al., 2008). On the contrary, the private world of houses lead to a shortage of knowledge about occupant's actions related to windows. Two comprehensive studies were published by Andersen et al. (2009; 2013) for Danish dwellings, which were driven mainly by the examination of opening/closing due to outdoor temperature and CO_2. The findings are aligned with Erhorn (1998), who claimed that the ventilation in dwellings is clearly driven by the outdoor temperature. However, the work of Haldi and

Robinson (2009) indicates that the use of the ambient temperature alone during the prediction of window state are independent of the design of the buildings. Thereby, it is considered appropriate to use both indoor and outdoor temperature thresholds to emulate the window opening/closing behavior, as Raja et al. (1998) have expressed a similar view.

The thresholds of thermal stimuli for windows operation seems to be varied among the published studies. Rijal et al. (2008) discovered in a study in 15 office buildings in the UK that windows are likely to open at 23.1^{o}C and close at 28^{o}C of globe temperature. Haldi and Robinson (2009) claimed that an increasing proportion of windows operation can be observed for indoor temperature rising from 20^{o}C to 28^{o}C. Yum and Steemers (2008) also stated that a high probability to open a window exists in an indoor air temperature of 23.6^{o}C, in UK office buildings. In an article by Yun et al. (2009), it was found that 66% of subjects open windows at 24.36^{o}C and 82% at 26.12^{o}C. Rijal et al. (2001) observed that the windows were opened steeply to 100% from indoor temperatures at 20^{o}C to 27^{o}C. Also, it was mentioned that at outdoor temperatures higher than 25^{o}C, most of windows were open. Overall, Nicol and Humphreys (2004) concluded that few people can feel discomfort between 20^{o}C to 30^{o}C of indoor temperature. Joana et al. (2012) derived the limits of neutral temperature for the fourteen Mediterranean regions, as were determined by (Santamouris and Asimakopoulos, 1996). For instance, the lower and upper limit of neutral temperatures for the XIV section (south-east areas) are 24.6^{o}C and 30.6^{o}C, respectively (Desogus, 2012).

On the perspective of outdoor temperature, Givoni (1994) noted that the effectiveness of comfort ventilation is higher for regions and seasons, where the outdoor temperature does not exceed the 32^{o}C. Additionally, the effectiveness of ventilation for running-mean temperature higher than 28^{o}C was determined only for the case were the T_{out}>T_{i}+5K in warmer climates (Rijal et al., 2008).

Apart from temperature stimulus, another important driving force in dwellings is the indoor air quality which may influence the behavior, as they stated that a high proportion of occupants operate the windows in order to refresh the indoor air (Drakou and Tsangrassoulis, 2012; Drakou et al., 2011). The work of Andersen et al. (2013) also reveal the impact of CO_2 on occupant window-behavior. In practice, the CYS EN 15251:2007 recommends that the concentration of CO_2 must not exceed the 800 ppm above outdoor concentration for the Classes III and IV (CEN, 2007).

As occupancy behavior is an ambiguous and dynamic parameter, the findings from the literature were used to develop a strategy (see Figure 4-4), emulating the actions coherent with natural ventilation and thus, the operation of external openings. In the Appendix G, an example of the EMS code, used during building simulation, is presented.

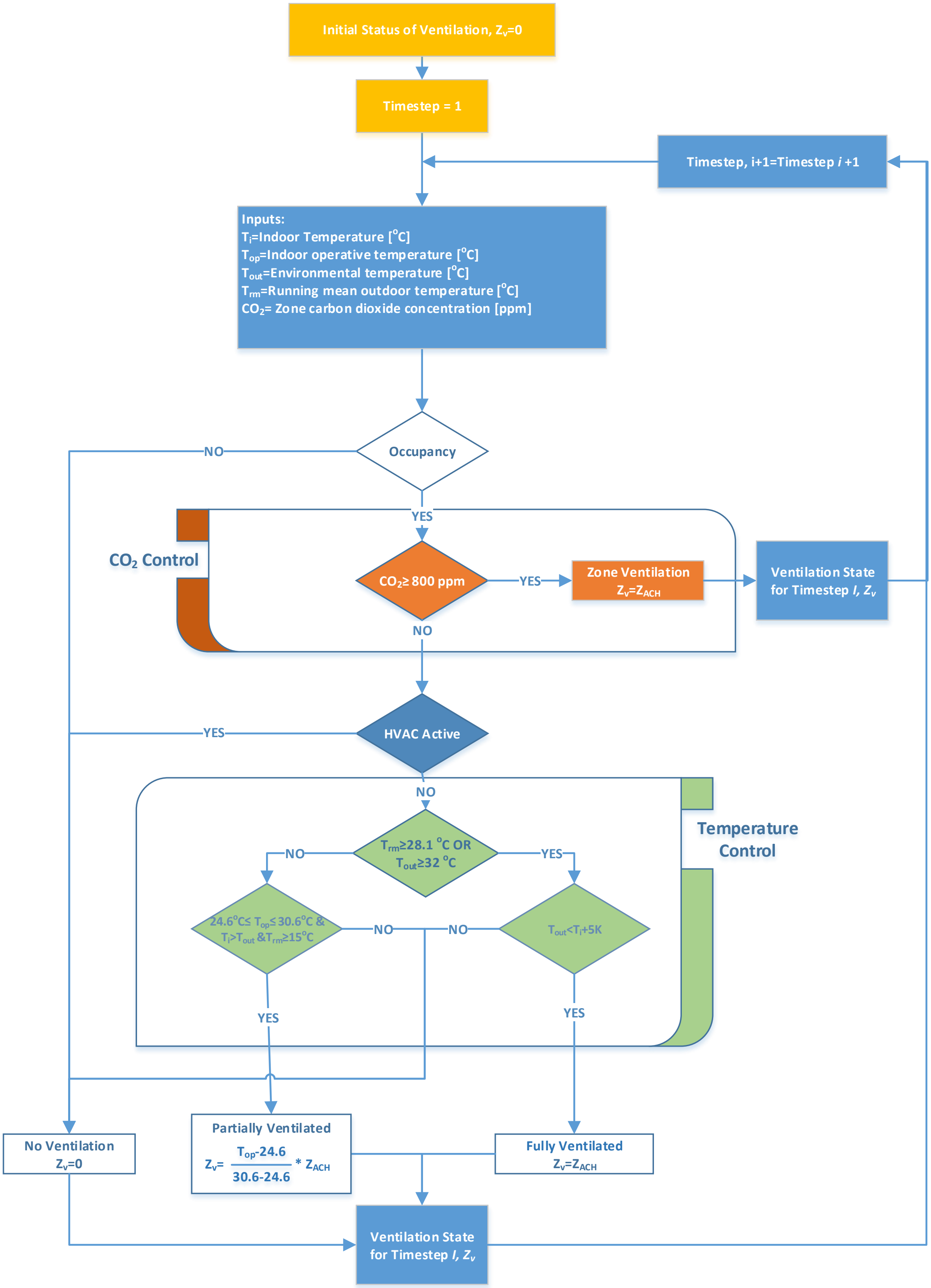


Figure 4-4 Strategy on natural ventilation (based on the current literature)

The scene on operating movable shading lies on the same line with the windows operation, as mimicking the actions related to them is sometimes ambiguous. This is also compromised by the limited knowledge with regards to the particular subject. In essence, a strategy will be developed, founded on existing studies.

Generally, a wide range of devices may be observed in dwellings such as internal (drapes, curtains, shade rolls, internal venetian blinds) or external (louvered or roller shutters). It seems that the devices can be used for decoration and privacy as well as preventing the solar insolation during the summer months or enhancing visual comfort by blocking the glare.

As a result, the driving forces may be categorized as personal and environmental, as for instance, an occupant may lower the shade for privacy or to prevent the exposure of the internal environment to solar radiation (adaptive action). According to Raja et al. (1998), the usage of any shading device seems to increase simultaneously with the increase of indoor and outdoor temperatures. A study by Haldi and Robinson (2008) shows that 50% of occupants in an office building possible use the blinds for indoor temperature at 26ºC and outdoor temperature of 25ºC. Generally, Rubin et al. (1978), Rea (1984) and Inoue et al. (1988) claimed that the blinds are primarily operated due to overheating and glare, while Newsham (1994) has expressed a similar view. Newsham (1994) claimed that the shades will be lowered for solar intensity greater than 233 W/m^2. According to Reinhart and Voss (2003), a glare is caused when the direct sunlight is above 50 W/m^2, which triggers occupants to close the blinds. The outcome was based on a study in private office rooms, which is more reflective of residential buildings, as the worker has a direct access on shading devices, on the contrary to an open plan office. Additionally, it was concluded that the blinds may be lowered if the incident solar gains are greater than 50 klux (450 W/m^2) (Reinhart and Voss, 2003). The direct sunlight, of 50 W/m^2, was also indicated by Inoue et al. (1998) and Reinhart (2004), as a reasonable threshold to trigger people for closing any available shading device. In terms of glare, studies revealed a predominant threshold for Hopkinson daylighting glare index of 20 (just acceptable) or 22 (just uncomfortable), where the people will lower the shading devices (Chauvel et al., 1982; Lee et al., 2002).

Essentially, by the literature, a strategy was designed to follow the actions of the occupants coherent with the movable shading devices (see Figure 4-5). The built-in object **WindowProperty:ShadingControl** in EPlus allows the user to assign a strategy for a movable shading device for each particular element of fenestration in order to emulate the impact of occupancy behavior on shading devices. Currently, ASHRAE (2009) hosts a list of the material properties for each type of shading device (i.e., dark curtain), which were adopted through the calibration procedure for the simulation of the internal shading.

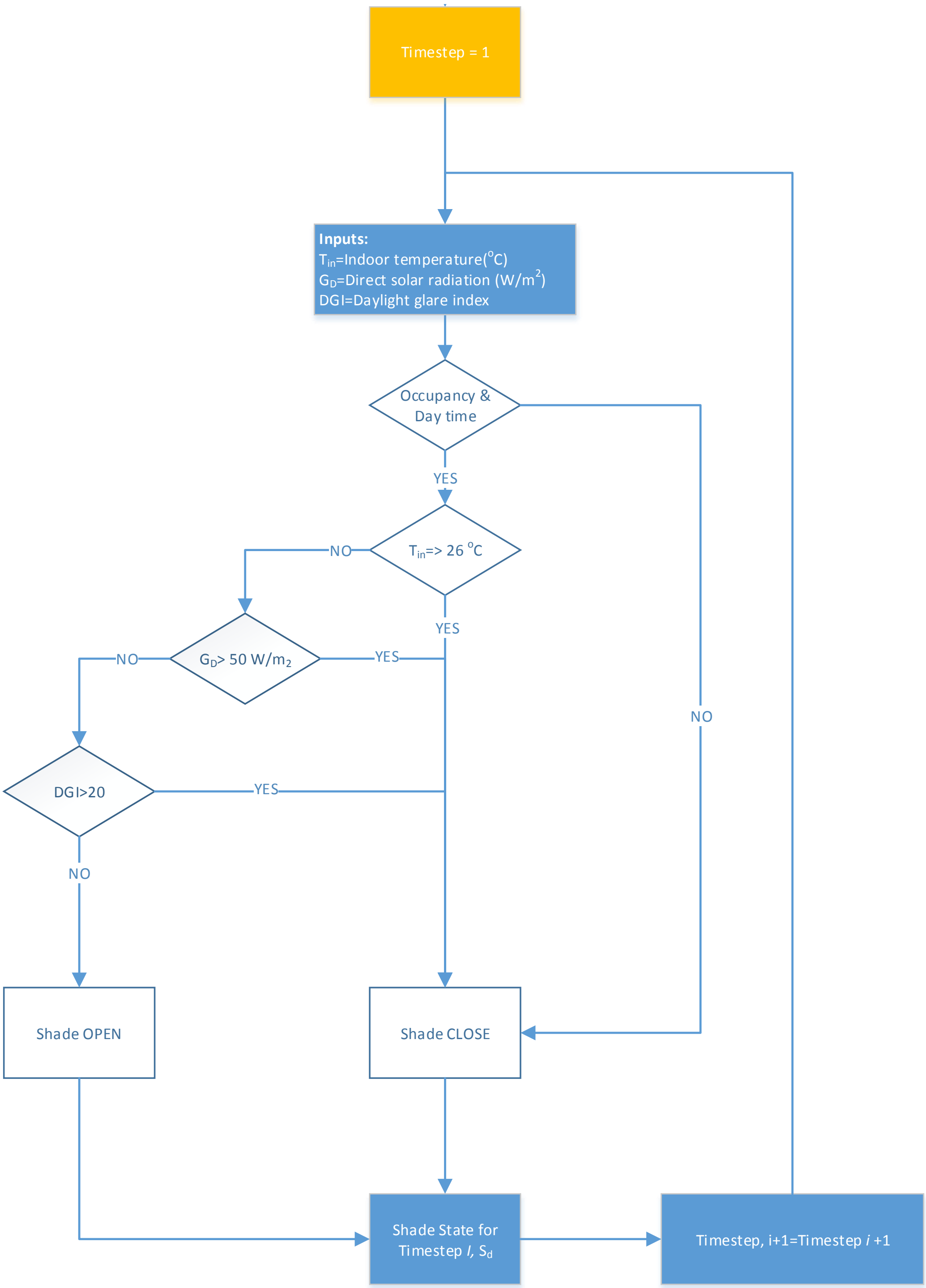


Figure 4-5 Strategy (based on literature review) on movable shading devices

4.2.3 Version S3-Plug Loads & Lighting

The S3 version describes the operation and profile of electrical appliances that are not affected by the seasonality of the weather conditions such as TV, computers, dish-washers, iron, etc. As aforementioned, their nameplate power was established during the walk-through visits for each individual case. Apart from the contribution to the total energy consumption of the building, the heat rejection from the appliances is also affecting the indoor environment. EPlus divides the heat gains from appliances into 4 fractions; Fraction Convected, Fraction Latent, Fraction Radiant and Fraction Lost. Their relation is given by the following equations (USDOE, 2012c):

$$f_{convected} = 1.0 - (Fraction\ Latent + Fraction\ Radiant + Fraction\ Lost) \quad \textbf{\textit{Eq. 4-1}}$$

$$Fraction\ Lost = 1.0 - Usage\ Factor \quad \textbf{\textit{Eq. 4-2}}$$

The calculation of the fractions is adopted by the current literature.Table 4-3 lists the values that were adopted throughout the study for each type of appliance.

In terms of their daily use, the situation in residential buildings may be characterized by ambiguous and random operation, due to the fact that the people are directly interacting with their environment and lifestyle. The only devices with standard operation are freezer, refrigeration, water cooler (24h operation) and the pool pumps (4h winter-8h summer). For the rest of the electrical appliances, details of the daily operation were drawn during the site interviews and questionnaires. In cases where additional information may be required, data were adopted from the findings of field studies such as the study in 158 dwellings by Papakostas and Sotiropoulos (1997) and a national survey by CYSTAT (2009).

Table 4-3 Heat Gains from electrical appliances

APPLIANCE	USAGE FACTOR	FRACTION			
		Lost	Radiant	Latent	Convective
Hobs[1]	0.25	0.75	0.075	0	0.175
Refrigerator[2]	1	0	0.25	0	0.75
Freezer[3]	1	0	0.45	0	0.55
Water Cooler[1]	0.25	0.75	0.075	0	0.175
Oven[1]	0.25	0.75	0.075	0	0.175
Microwave[2]	0	1	0	0	0
Toaster[2]	0.64	0.36	0.0704	0	0.5696
Kettle[1]	0.25	0.75	0.075	0	0.175
Extractor Fan[1]	0.25	0.75	0.025	0	0.225
Dish washer[2]	0.26	0.74	0	0.1664	0.0936
Clothes Washer[1]	0.25	0.75	0.075	0	0.175
Clothes Dryer[1]	0.25	0.75	0.075	0	0.175
Iron[1]	0	1	0	0	0
TV[1]	0.25	0.75	0.075	0	0.175
PC[1]	0.25	0.75	0.025	0	0.225
Hair dryer[1]	0.25	0.75	0.025	0	0.225
Pumps	See note[4]				

Notes:

1 (Mohammad et al., 1999)

2 (Swierczyna et al., 2009)

3 (ASHRAE, 2009)

4 For the pumps the fraction was not used, as their operation was assigned in a neighboring room that does not affect the indoor environment.

4.2.4 Version S4-HVAC Systems

This is the last version during the model generation procedure. It follows only the successful mid-season assessment of models. Particularly, the parameters coherent with the seasonal loads are updated on the models.

These inputs are related with the conditioning of the indoor environment and also, the domestic hot water (DHW).

HEATING/COOLING SYSTEM

In the context of the study, the most critical loads are associated with heating and cooling. In essence, a detailed design of the heating or cooling systems was mandatory, rather than using the ideal loads systems, the simplest version associated with EPlus for heating or cooling. Figure 4-6 illustrates the primary systems of heating and cooling that are investigated throughout the study. Particularly, all of the houses are employed with AC split units which are used either for both heating and cooling or only cooling or as supplementary heating equipment.

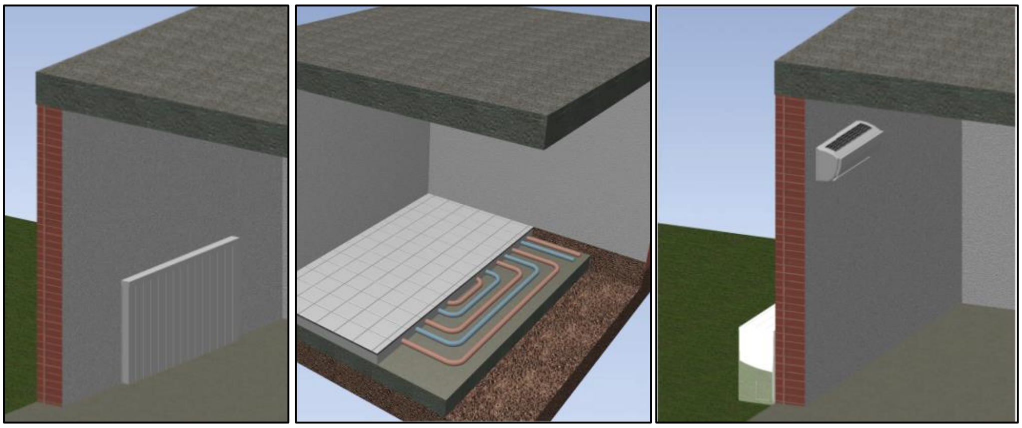


Figure 4-6 Primary Systems (Hydronic [Radiators, Under-floor heating], Split Units)

The design of the systems was governed by the data obtained during the site survey. For instance, the COP and EER of split systems were obtained by the manufacturer's data, as well as their nominal capacity (kW). In the case of boiler systems, the nominal efficiency was initially assumed to be 70%, as it was previously declared for old fired-oil boilers (MCIT, 2013b). The set-points and an average daily profile were acquired by the householders. Additionally, information was obtained by the monitoring of the internal environment. Figure 4-7 shows an example of an AC unit operating during summer days.

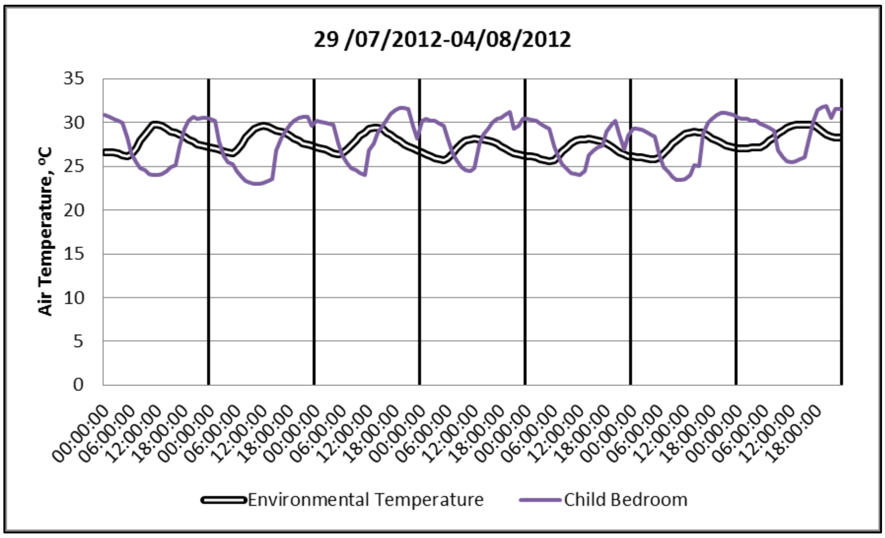


Figure 4-7 Operation of AC split unit at SD4 dwelling-Child Bedroom

In addition, halogen heaters were observed as an alternative equipment for heating. Particularly, the occupants, for an instant heating, use halogen heaters with a capacity of 2 kW, in order to overcome the insufficient or unnecessary operation of any split-unit or the hydronic system. Therefore, a halogen heater was simulated for the cases of buildings which were employed with it. Due to lack of any literature with regards to the occupancy behavior and local heaters, it was assumed that the heater will be operated, based on the lower comfort limit, regardless of the operation of any auxiliary heating system (see Figure 4-8).

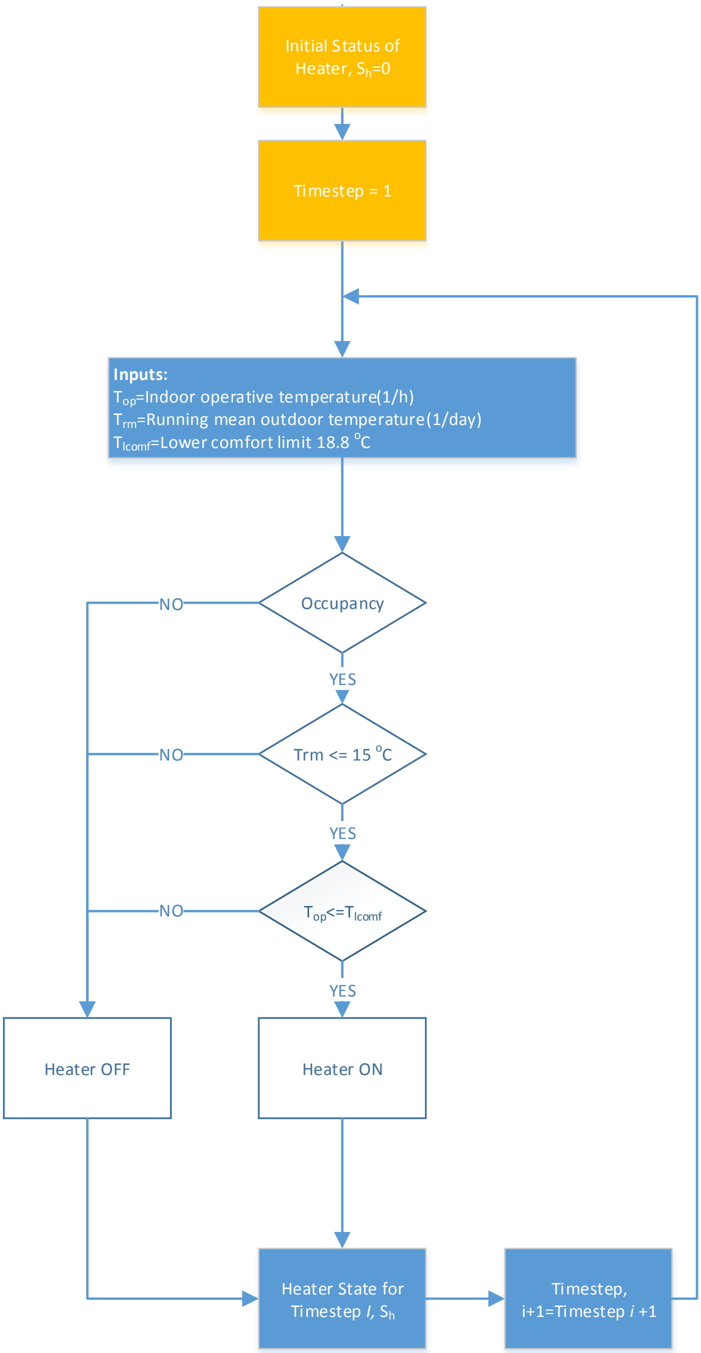


Figure 4-8 Halogen heater strategy

DOMESTIC HOT WATER

Another critical load on the residential energy is the conditioning of domestic hot water (DHW). In this study, two systems are primarily presented. A typical thermosiphon system with flat plate solar collectors with a 3 kW back-up electrical heater and a flat plate solar collector system connected on the primary central heating system. The scheme of the systems is presented in the Figure 4-9.

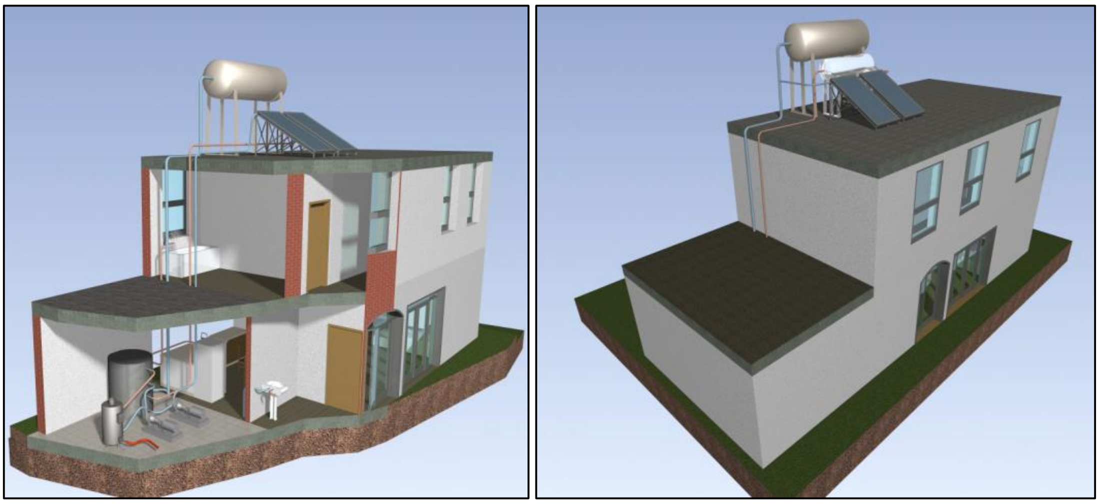


Figure 4-9 Domestic Hot Water Systems-(Left: Combined system featuring oil-fired boiler and solar collectors, Right: Thermosiphon system)

According to Kalogirou (2005), the surface of a flat plate collector lies between 3-4 m^2 and it is connected to a hot water storage tank of 150-180 ltr (Kalogirou, 2004). The major contributor to DHW energy consumption is bathing or washing. A survey by the National Energy Service indicates that a typical person needs approximately 15 ltr/day for a shower (EneService, 2013; CEA, 2013). In essence, to mimic the flow patterns of water consumption in houses, the flow rates, presented in Table 4-4 were used.

Table 4-4 Flow rates of hot water sinks (Trotman and Griggs, 2011)

DEMAND	FLOW RATE (l/s)
Showers	0.05 at 40 ^oC
Kitchen sink	0.1-0.2 at 60 ^oC

The profile of the daily use was adopted by the studies by (Papakostas and Sotiropoulos, 1997; Papakostas et al., 1995). It was concluded that the most frequent time for bathing is 19:00-21:00 and additional usage of DHW is common at early morning and after lunch for washing.

4.3 VALIDATION OF BUILDING MODELS

Following the backward stepwise approach (section 2.3.3), the performance of the models was evaluated against the actual data to ensure the accuracy of the subsequent parametric analysis. This section will present the results of the validation assessment for the calibrated simulation models.

In brief, the section comprises of two validation approaches:

1. Mid-season validation.
2. Annual performance validation

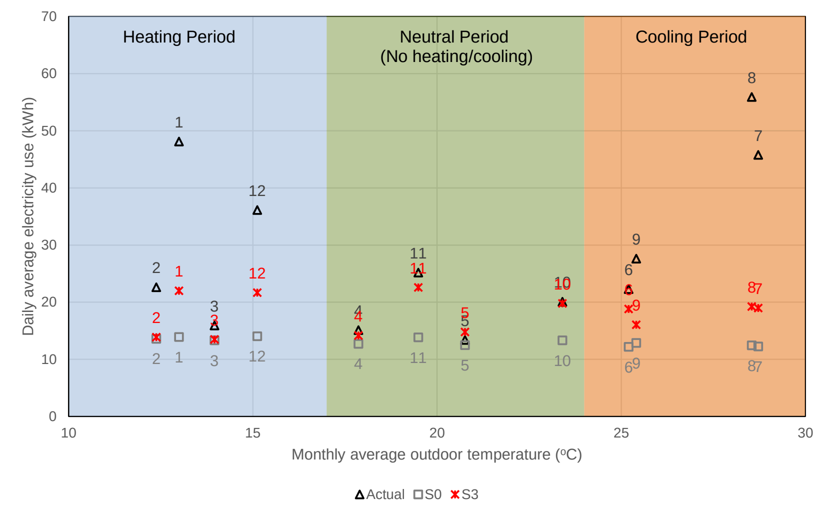
Through the first validation method, the version (S3) will be graphically evaluated against the monitored indoor air temperature and the estimated actual electrical base-load. The base-load is principally described by the weather independent loads (loads during a period with no heating or cooling).

The latter validation method will be undertaken after the successful mid-season validation and the upgrade of the parameters that determine the version (S4). The annual performance will be assessed with regards to the statistical metrics, as described in the ASHRAE G-14. In the rest of this section, the validation assessment will be presented, discussing the results by its application on the building models.

4.3.1 Mid-season Validation

The first validation assessment took place after the update of parameters, associated with the S3 version. Through the mid-season validation two parameters were studied; the electricity consumption and the indoor air temperature. The initial concept of the backward stepwise approach employs only the electricity consumption, validating the models only in the context of energy. In this study, the indoor air temperature was also used in order to ensure the performance of the building envelope, as the measures that will be investigated are associated with the retrofitting of the building shell.

The mid-season validation examines the performance of the building for the periods with no heating or cooling (neutral/transition period). The months of April, May, October and November represent the periods with mostly negligible thermal loads. In essence, the data associated with the actual performance of the aforementioned months will be utilized. Figure 4-10 shows the daily average electricity consumption against the monthly average outdoor temperature for the SD1 house. The same procedure was adopted for all houses and the results are depicted in the Appendix H. In Figure 4-10, only the versions S0 and S3 are presented, as it was considered worthless to include the intermediate versions (S1 and S2), due to the fact that the main contributors on base-load energy are the devices, the equipment and the lighting.



Labels	
Months	No.
January	1
February	2
March	3
April	4
May	5
June	6
July	7
August	8
September	9
October	10
November	11
December	12

Figure 4-10 Daily average electricity against average monthly outdoor temperature, SD1

Looking at the results from all case studies, the calibrated version (S3) can realistically emulate the actual electricity consumption for the transition period, compare to the base-case model (S0 version). As aforementioned, the default templates of the simulation tool determine the S0 version. In some cases, the performance of the S0 model can describe the actual energy consumption. However, by the integration of the actual nameplate data and operation, the simulation scene is dramatically changed. This occurs as a consequence of fact that the templates associated with the simulation software packages tend to describe a typical performance, neglecting special occasions and profiles that may be observed in buildings, especially in dwellings.

Now, in the context of envelope performance, a graphical method was adopted by (Bozonnet et al., 2011). Particularly, the hourly simulated indoor air temperature is plotted against the monitored air temperature, during neutral weather period. An acceptable simulation performance is determined either by the limits of deviation or by the linearity of the data. Figure 4-11 demonstrates the results of the envelope validation assessment.

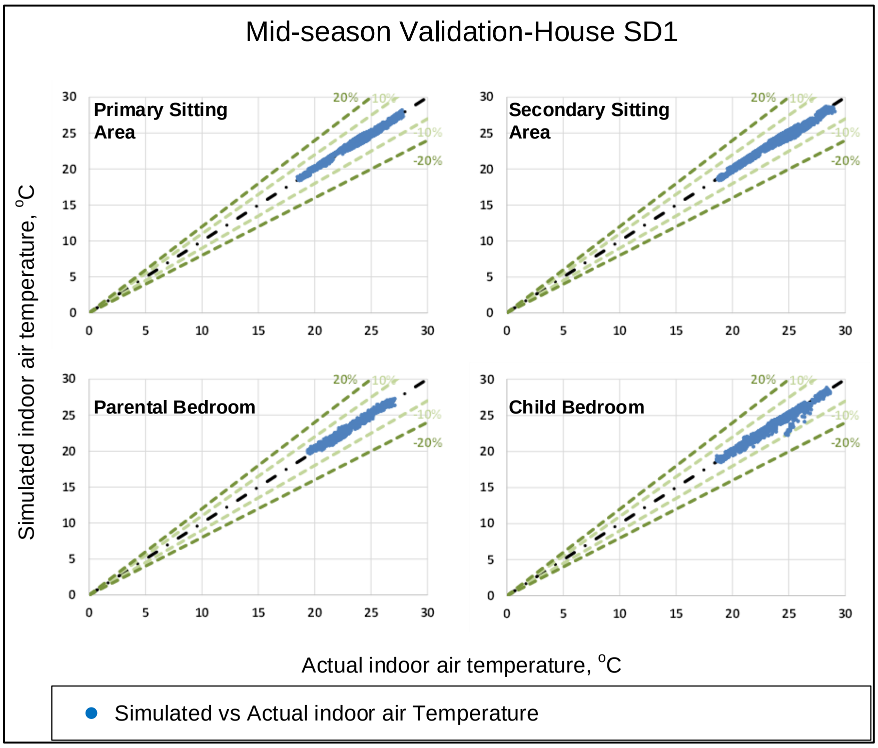


Figure 4-11 Simulated and actual indoor temperature, SD1

It can be observed that for all cases the hourly air temperature lies within the upper and lower thresholds, with a linear relation between the actual and simulated data. This is repeated for all the spaces for every case study, indicating a remarkable performance with most of the data to be within the band of 10%. Table 4-5 presents the maximum deviation occurred for each dwelling and the frequency of the hours that lie within the range of 0-5% during the neutral period, for all versions of parameters.

Table 4-5 Maximum deviation and frequency of indoor air temperature

HOUSE	MAX DEVIATION, S3 VERSION (%)	FREQUENCY OF HOURS WITHIN 0-5%			
		S0	S1	S2	S3
SD1	11	8068	8392	8998	9754
SD2	14	6901	7041	8134	9693
SD3	8	2427	7368	7250	9607
SD4	8	6569	9012	9498	9712
SD5	8	9113	9142	9072	9688
SD6	6	8083	9556	9533	9746
SD7	7	7136	7826	8324	8920

It can be noticed that the number of hours increased from version (S0) to (S3), as more explicit details were updated in the building models.

4.3.2 Annual Performance Validation

The annual performance validation is defined as the last step of the development of realistic simulation models. This part is undertaken after the upgrade of HVAC systems (S4) on the mid-season validated building models. Previously, section 2.3.3 described the application of the statistical metrics, guided by ASHRAE G-14, during the evaluation assessment of the annual energy performance of building models. In the current study, with regards to the availability of monthly energy data, the limits of ±5% and ±15% will be used for the NMBE and CVRMSE, respectively. Figures (4-12) and (4-13) show the results from the application of the statistical metrics for electricity and heating oil consumption.

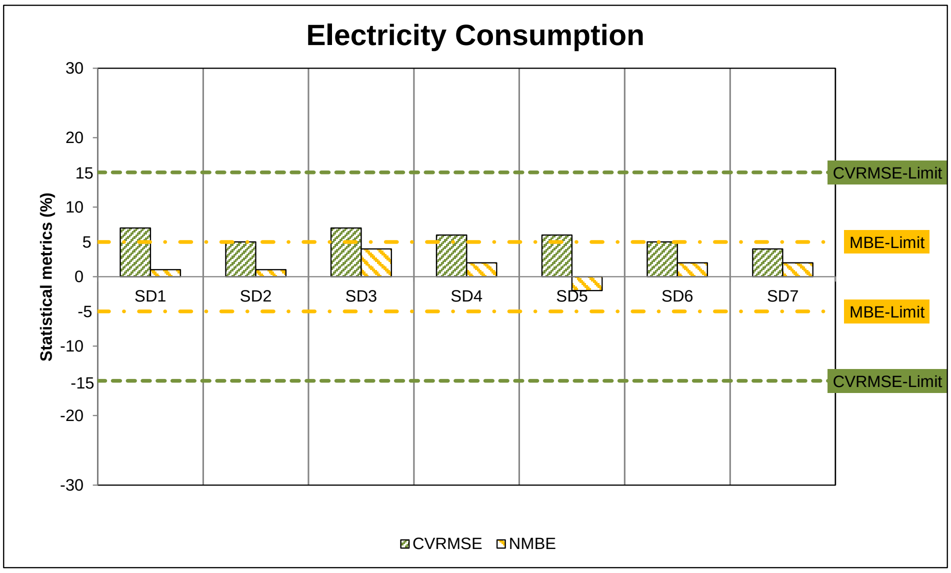


Figure 4-12 CVRMSE and NMBE for electricity consumption

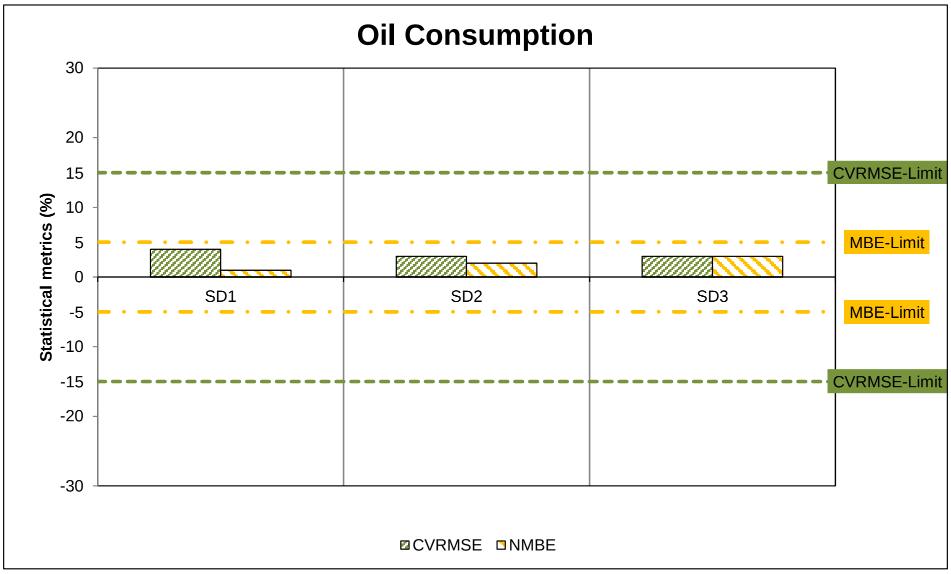


Figure 4-13 CVRMSE and NMBE for oil consumption

As it can be clearly observed, both metrics lie within the ASHRAE limits, establishing the validity of the models and thus, enhancing the reliability of the outcome for the future rationalistic application of the single or combined interventions that will be presented in the next section. Further graphical documentation referring to the monthly energy consumption can be found in the Appendix H.

4.4 SUMMARY

This chapter discussed the application of the mid-season calibration during building simulation, for the development of reliable simulation models. Seven building models were calibrated, based on the concept of the backward stepwise approach. Their performance was evaluated according to the statistical metrics, described by ASHRAE Guideline-14, presenting acceptable levels of validity. In Chapter 5, the validated building models will be used to examine the impact of single or combined interventions on existing residential envelopes.

Chapter 5. SIMULATION RESULTS

5.1 INTRODUCTION

This chapter presents the results by the upgrade of single or combined interventions on existing residential envelopes, for the case of Cyprus. In general, the chapter is divided into two major sections; 5.2 Effect of Single Interventions and 5.3 Effect of Combined Interventions.

Following the successful validation assessment, the simulation models are normalized in the perspective of weather conditions, occupancy patterns and HVAC operation (see section (4.3)). Driven by the distribution of population, the study was concentrated on coastal and low-land (inland) weather conditions (see Figure 5-1).

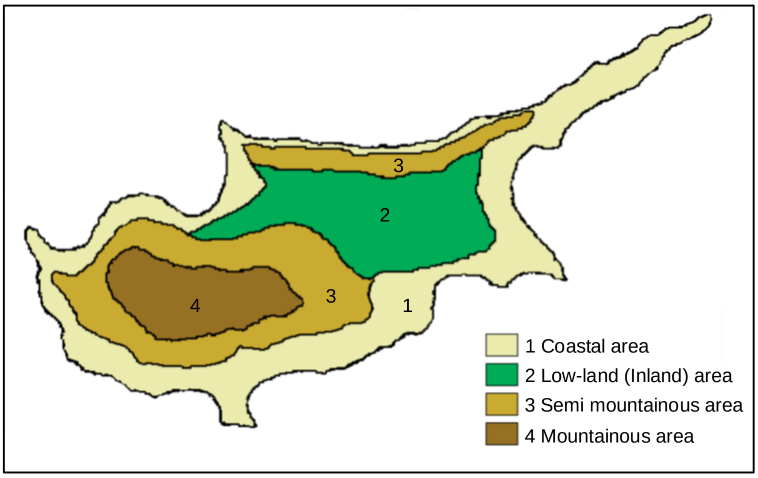


Figure 5-1 Climatic zones of Cyprus (reproduced by (Panayiotou et al., 2010))

As guidance through the chapter, Table 5-1 summarizes the normalized base heating and cooling load (primary energy to conditioned volume) for the dwellings under examination.

Table 5-1 Base case primary energy consumption per volume of conditioned space

	HEATING LOAD (KWh_p/m^3_c)		COOLING LOAD (KWh_p/m^3_c)	
	Coastal	Inland	Coastal	Inland
SD1	11.87	16.17	29.44	34.7
SD2	26.96	36.69	17.04	50.55
SD3	20.61	23.84	17.54	20.66
SD4	30.05	42.64	37.52	44.54
SD5	12.88	20.96	41.98	46.52
SD6	13.08	25.92	23.91	26.18
SD7	18.65	29.32	24.18	26.28

The results are primarily founded on graphical analysis (box-whisker plots and scatter plots), in order to accommodate the large amount of the data and make the outcome comprehensible. However, in some cases (i.e., insulation of opaque elements), the results of the coastal and inland weather climate scenarios presented similar trends, differentiating only by the interwoven values. In order to retain the consistency of the documentation, the outcome coherent with the inland scenario is presented in the Appendix L.

The outcome by the post-retrofitting evaluation will be applied to develop a global guidance about retrofitting interventions.

5.2 Effect of Single Interventions

This section presents the results of upgrading individual interventions on the existing residential envelopes. Figure 5-2 depicts the structure of the section and the relative parameters of measures that were examined. A detailed description on the parameters can be found in section 3.6.1.

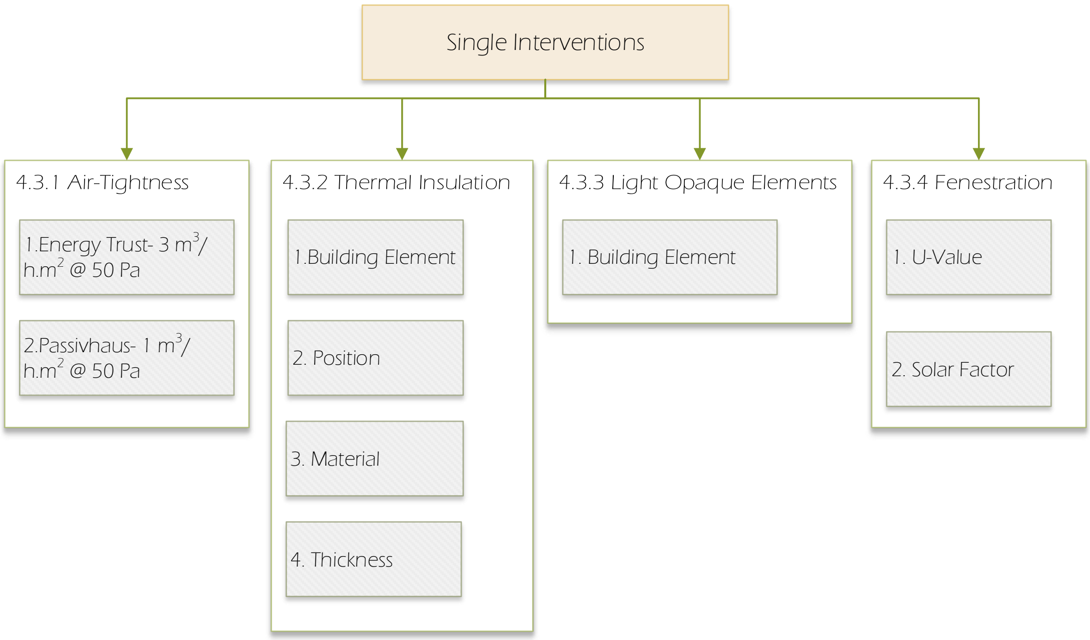


Figure 5-2 Structure of section 5.2 Effect of Single Interventions

5.2.1 Air-Tightness

The effectiveness of tightening the building envelope was initially examined with regards to the standards of Energy Trust (Infiltration 2 or Scenario B) and Passivhaus (Infiltration 3 or Scenario C). The air-tightening of the building envelope was studied, as follows:

- Effect on default construction
- Effect on the performance of thermal insulation and glazing

- Impact on the Indoor Air Quality

The annual thermal performance (loads and thermal comfort) were assessed against the base model scenario.

EFFECT ON DEFAULT CONSTRUCTION

Figure 5-3 presents the impact on annual heating and cooling load of the base construction, by tightening the building under two scenarios (intermediate-Scenario B and strict-Scenario C). Box-whisker plots are applied to analyse the results from a sample of the study.

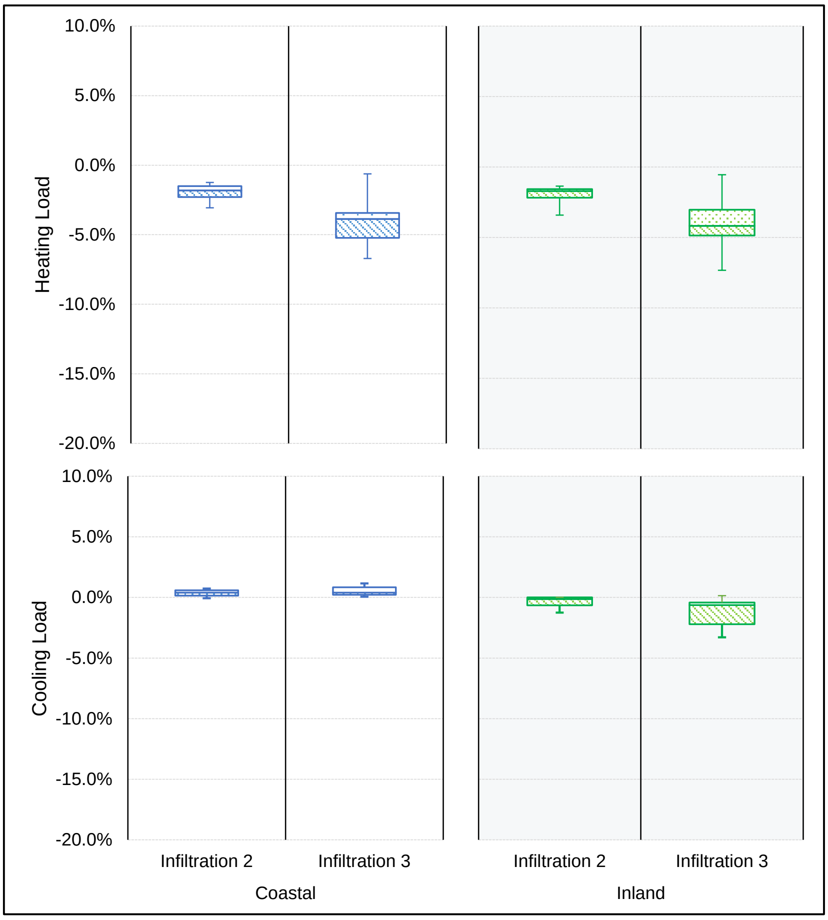


Figure 5-3 Impact on base loads by tightening building envelope

Tightening envelope seems to be more effective during the winter season, as lower impact was observed during summer period. In particular, for both climates the median value of reduction during the winter season is 2% and 4% for Scenario (B) and Scenario (C), respectively. In some cases, the energy consumption may be reduced by up to 7%, with 75% of the samples found between 4-5% for coastal areas and 3-4% for inland areas.

Observing the impact on heating load, it can be noticed that the impact is lower during the summer season. During the cooling period, a reverse relation is noticed between the two weather files. A negligible increment occurs at the coastal conditions, with the median equals to +0.4% (both Scenarios). On the contrary, at the inland conditions the houses presented an average reduction on thermal load by -0.4% and -1.2%, Scenario B and Scenario C, respectively. In order to realize the difference between the weather conditions, Figure 5-4 illustrates the indoor conditions during summer.

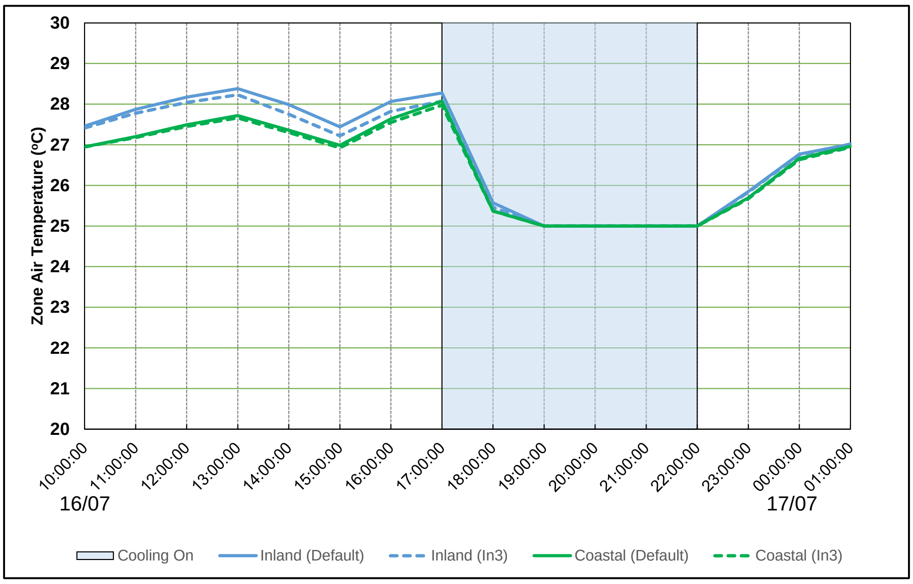


Figure 5-4 Difference of air temperature for coastal and inland-SD1

Due to the higher indoor temperature of the default state (case of inland weather), the Scenario C causes higher reduction of indoor temperature. As a result, the mechanical system operates in lower temperature difference, corresponding to higher energy reduction.

In the perspective of thermal comfort, Figure 5-5 shows the effect of tightening on the seasonal thermal comfort score.

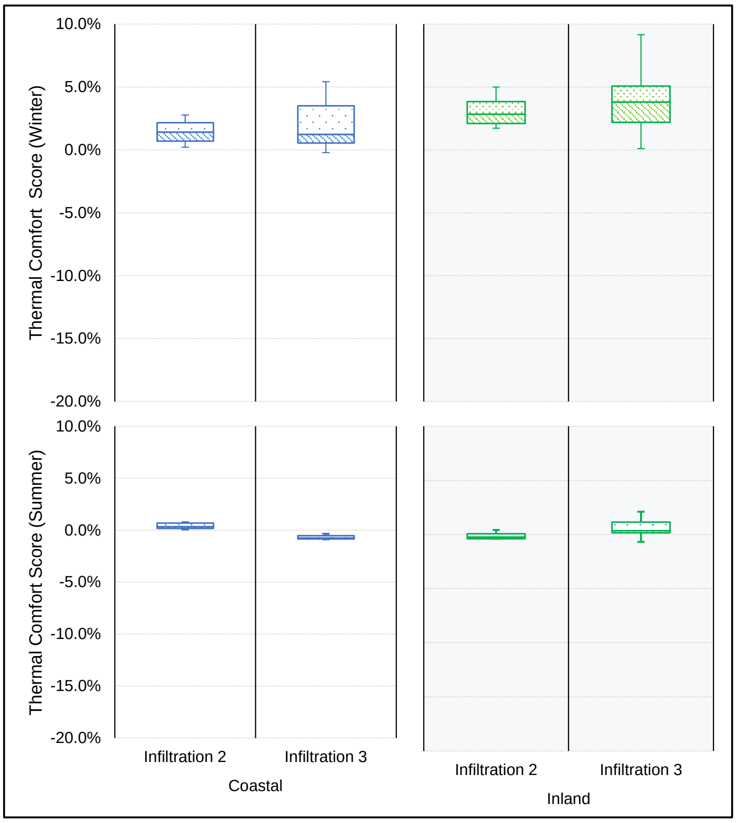


Figure 5-5 Impact on seasonal thermal comfort

As it can be noticed by Figure 5-5, the reduction of the air infiltration improves the indoor thermal conditions, especially during the heating period. In general, the indoor thermal conditions during winter can be improved up to 5% (coastal) and 9% (inland). Moreover, during the winter period, the results of the application of Passivhaus show a substantial variation. This is primarily based on the default properties of the building. Leaky houses (i.e. SD1, S2, and SD5) are associated with higher effect by tightening. For instance (see Figure 5-5, inland section), the 9% is presented in the case of SD1 dwelling, while for the SD4 (tighter building), the impact was estimated at ≈0.2%. Now, in the context of the cooling season, as in the case of energy performance the effect is not substantial, with median values close to 0%.

EFFECT ON THE PERFORMANCE OF THERMAL INSULATION AND GLAZING

The importance of air tightness is also revealed when comparing the performance of interventions with the permeability of base case. Figure 5-6 shows the comparison of the performance for the categories of thermal insulation and glazing systems, when tightening the building enclosure.

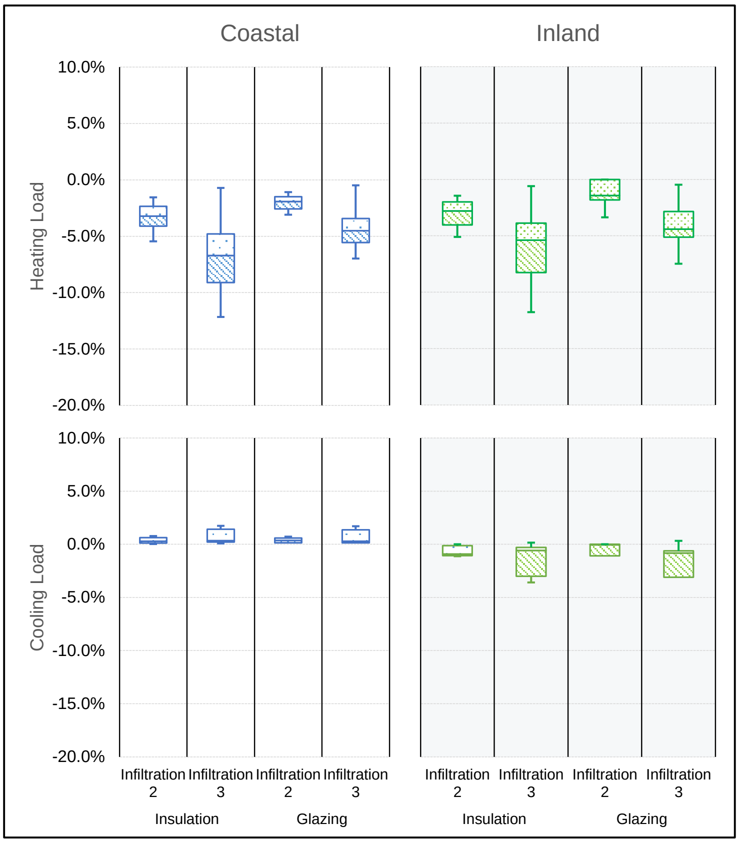


Figure 5-6 Impact on energy saving measures by tightening the envelope

During the winter season, the performance of thermal insulation (roof, external walls or floor) was dramatically improved when the Passivhaus standard was applied. In particular, 50% of the samples lie within the range of 5-9% (coastal) and 4-8% (inland) of heating reduction and can reach up to 12%, while Scenario B may reduce heating demand by 2-6% (coastal) and 2-5% (inland). In the same line, the impact of glazing performance ranges between -0.5% to -7% (both climates).

As in the case of base load performance, the impact of air tightness on the cooling performance is negative for the coastal areas and positive for inland weather conditions. Again, the effectiveness of tightening the building is lower for coastal areas with an increment for both thermal insulation and glazing that can reach up to 2%, while in the inland areas an improvement of approximately 4% is possible for both categories of interventions.

The same scene is also presented within the context of thermal comfort. Figure 5-7 shows the results on alternation of thermal environment by the synergies of air-tightness, thermal insulation and glazing system.

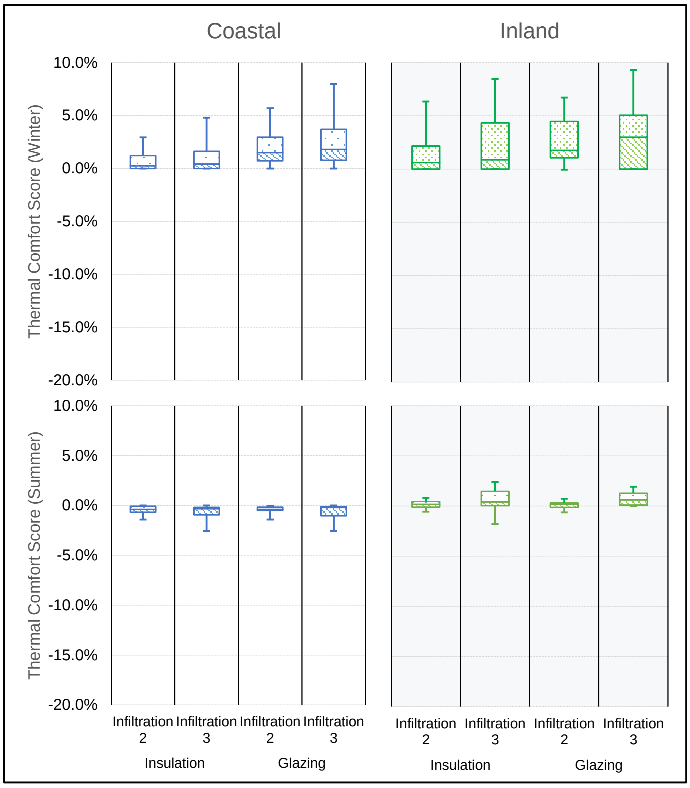


Figure 5-7 Impact of envelope tightening on the thermal comfort of thermal insulation and glazing measures

Again, the effect on winter season is higher for both climates. Comparing with thermal loads, the air-tightness shows greater impact on the glazing system, especially during the winter period. The median values, for glazing systems, are slightly higher than those of thermal insulation.

The thermal comfort score is compromised (not substantially) during cooling season, as at the case of energy performance.

AIR-TIGHTENING AND INDOOR AIR QUALITY (IAQ)

The beneficial tightening of the building envelope may sometimes compromise the indoor air quality, due to the fact that leaky dwellings rely on the mechanism of uncontrolled ventilation (infiltration) to provide occupants with fresh air and dilute pollutants.

By the air tightening of the building envelope the excessive ventilation is reduced, causing a rise of the indoor pollutants' concentration. This effect is outside the context of this study. However, it was considered critical to present the impact of tightening the envelope on the concentration of indoor pollutants. To this effect, the CO_2 concentration of a leaky house (SD4) was simulated, in order to examine the alternation of the IAQ. Figure 5-8 presents the concentrations of CO_2 during the winter period for the living room of the SD4 house, under 3 infiltration scenarios.

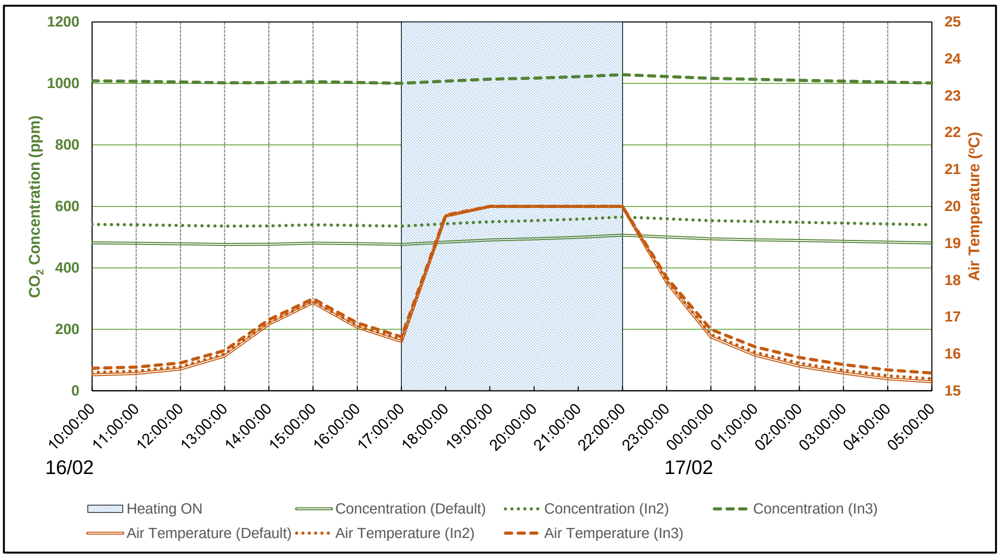


Figure 5-8 Living room CO_2 concentration-SD4

While the graph shows the impact for a period of 1 day, the overall concentration is added throughout the year resulting in higher levels of CO_2 for tighter envelopes, especially for the Passivhaus standard. In essence, by tightening the envelope, the occupants must follow the moto "build tight, ventilate right", in order to allow building to "breathe" (CIBSE, 2005).

SUMMARY

In this section, the impact of envelope tightening was presented under two scenarios of air permeability. In general, the reduction of air penetration seems to affect positively the winter performance of the envelope, with the Scenario C having higher impact. Meanwhile, during the winter season the thermal comfort is enhanced, on the contrary with the summer season, tightening slightly compromises the overall scene. In addition, it is concluded that tightening can beneficially contribute on the performance of the other measures, especially during heating period. The Table 5-2 summarizes the results by tightening building envelope.

Table 5-2 Summary of the impact by air-tightening on the base case scenario

		IMPACT ON ENERGY				**IMPACT ON THERMAL COMFORT (%)**	
		(%)		(kWh_p/m^3_c)			
		Max	Average	Max	Average	Max	Average
SCENARIO B							
WINTER	Coastal	-3	-2	-1.14	-0.35	+3	+1
	Inland	-3	-2	-0.71	-0.31	+5	+3.1
SUMMER	Coastal	-1	+0.1	-0.03	+0.07	+1.3	+0.5
	Inland	-1.1	-0.4	-0.5	-0.15	+0.4	-0.1
SCENARIO C							
WINTER	Coastal	-7	-4	-3.6	-1.15	+5	+2
	Inland	-7	-4	-1.8	-1.1	+9	+4
SUMMER	Coastal	+0.1	+0.5	+0.02	+0.27	-0.2	-0.6
	Inland	-2.8	-1.2	-0.6	-1.5	+1.4	+0.5

5.2.2 THERMAL INSULATION OF OPAQUE ELEMENTS

This section examines the effect of thermal insulation on opaque elements of the existing residential envelope. As it was aforementioned, the analysis of energy and thermal comfort will be graphically presented. In the previous chapters, the properties and the background of thermal insulation of opaque elements was presented. At this point, the properties will be investigated, analysing the impact from different opaque elements. In particular, the study investigates the effectiveness of the thickness and material type either for external or internal insulation with regards to the seasonal performance.

The evaluation is primarily based on the normalized heating and cooling loads, while the indoor thermal comfort was assessed for both heating and cooling seasons, based on the comfort score that was earlier presented (see Chapter 3).

ROOF INSULATION

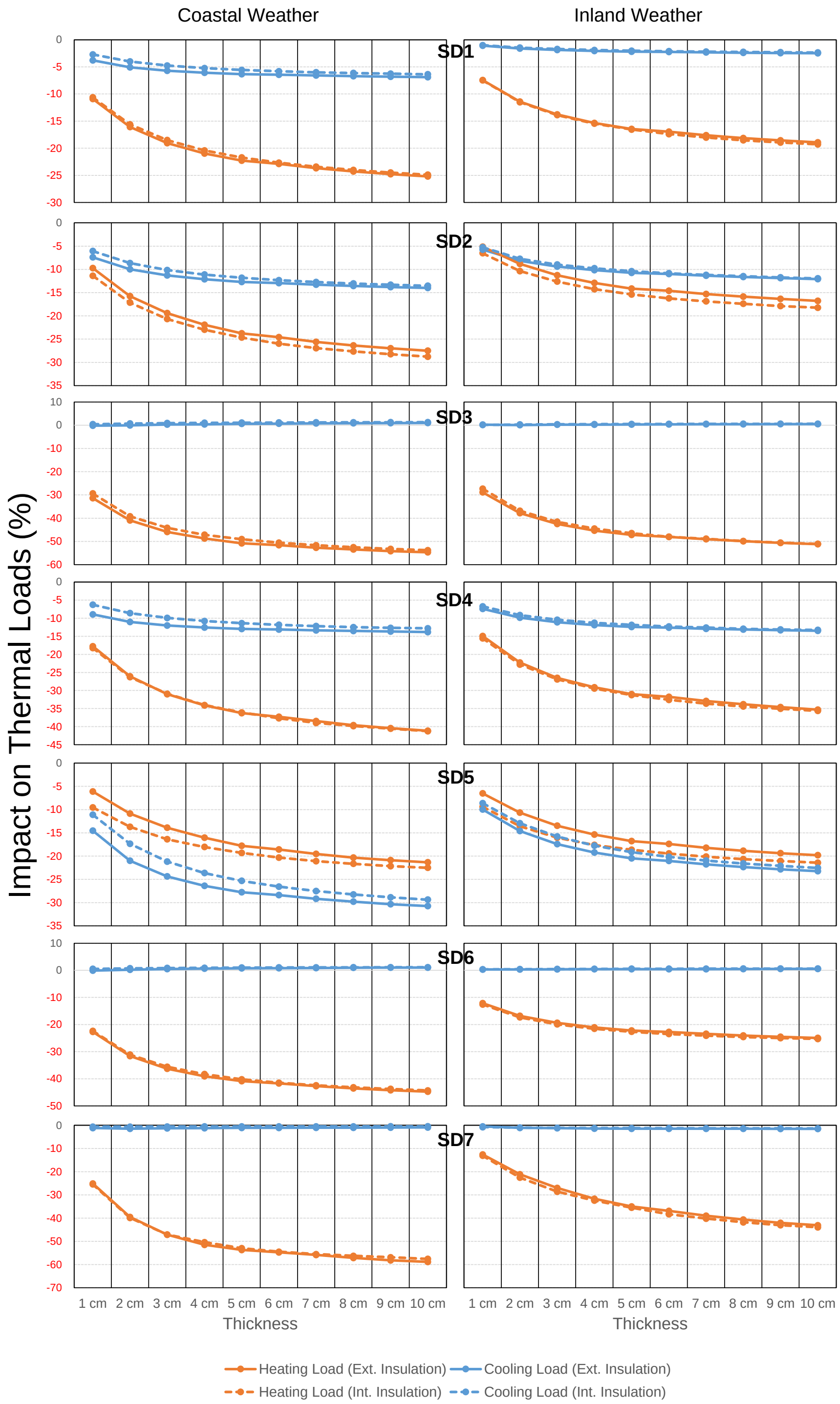


Figure 5-9 Percentage impact of roof insulation

Figure 5-9 shows the effect of roof insulation for the winter and summer period for coastal and inland weather files. As it can be noticed, the impact on the heating load is substantial for all cases, while a minor impact is observed for the double story buildings (SD1, SD3, SD6, SD7) with regards to the cooling load. The reduction of the heating load ranges from 21-59% (coastal) and 17-51% (inland), while cooling was decreased up to 31% (coastal) and 23% (inland).

The impact of parameters such as position (internally, externally), material and thickness were graphically presented (see Figures 5-10 (coastal) and L.1 (inland)), through the estimation of difference between the units of thickness. Particularly, for the case of heating and cooling loads, the average difference for shifting the thickness is presented, while the error bars were applied to highlight the variation between the performances of the materials for each individual thickness. For instance, in the case of SD1 dwelling in Figure 5-10, the average reduction on heating load is approximately 1.17 kWh_p/m^3_{con} for 1 cm, while the difference between 1cm and 2cm is about 0.6 kWh_p/m^3_{con}. The average reduction of heating demand when applying a 2cm insulation is approximately 1.77 kWh_p/m^3_{con}.

Additionally, the thermal comfort score was plotted on the secondary vertical axis, representing the average performance for the particular thickness (i.e., for SD1 at 1cm is 17% increment and for 2cm is 29%).

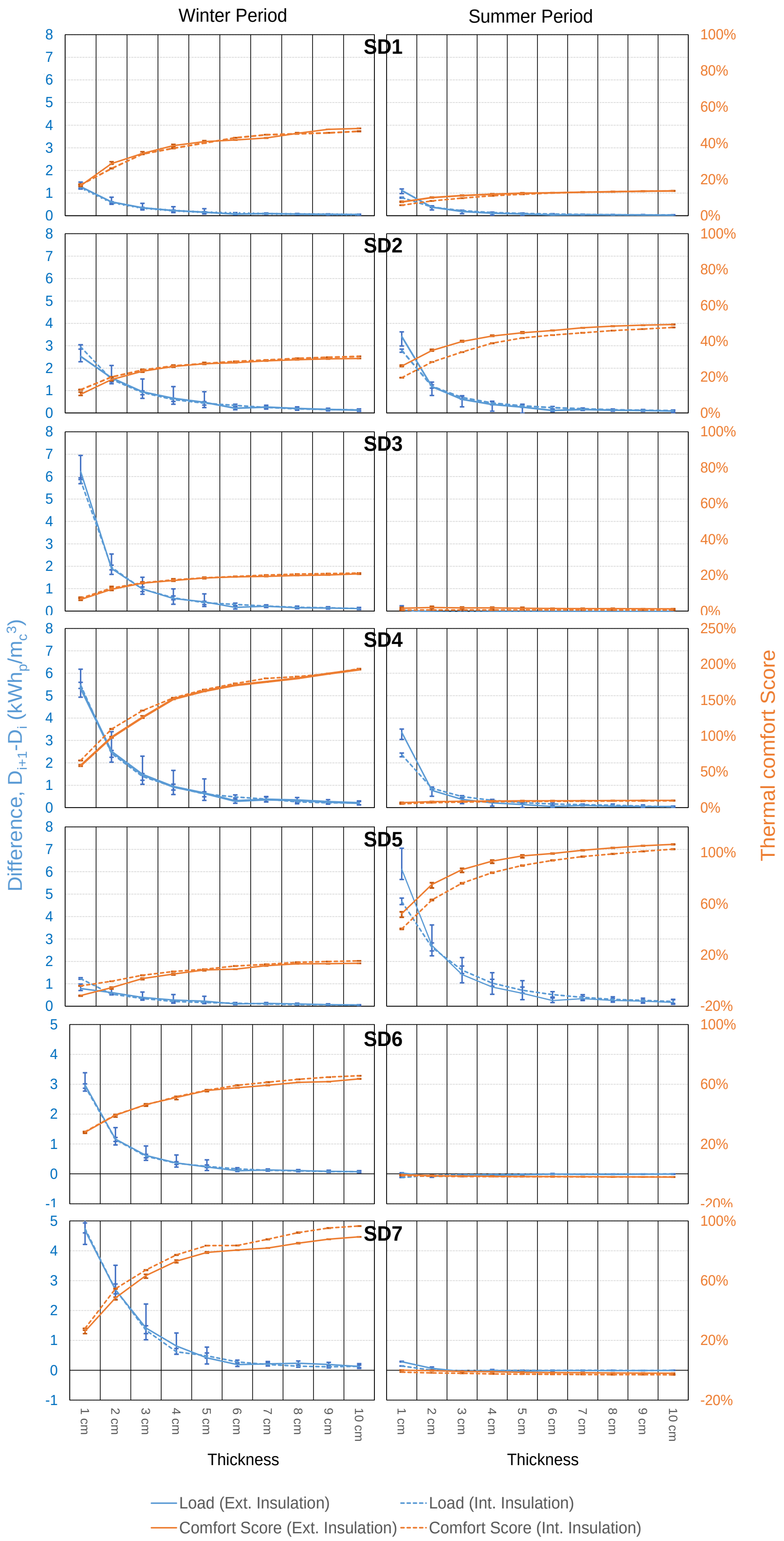


Figure 5-10 Effect of roof insulation-Coastal Weather

The effect of the material type is primarily presented on the heating load, while on cooling load and thermal comfort score, the impact of changing material is not substantial. Looking on the heating load, there is a significant variation on the average performance for the thicknesses of 1-5cm, while above 5cm the variation is critically reduced. The main fact is the presence of foam polyurethane (1-5cm) and PIR (5cm). Figure 5-11 illustrates the percentage reduction of the heating demand, for thicknesses of 1-5cm for external insulation.

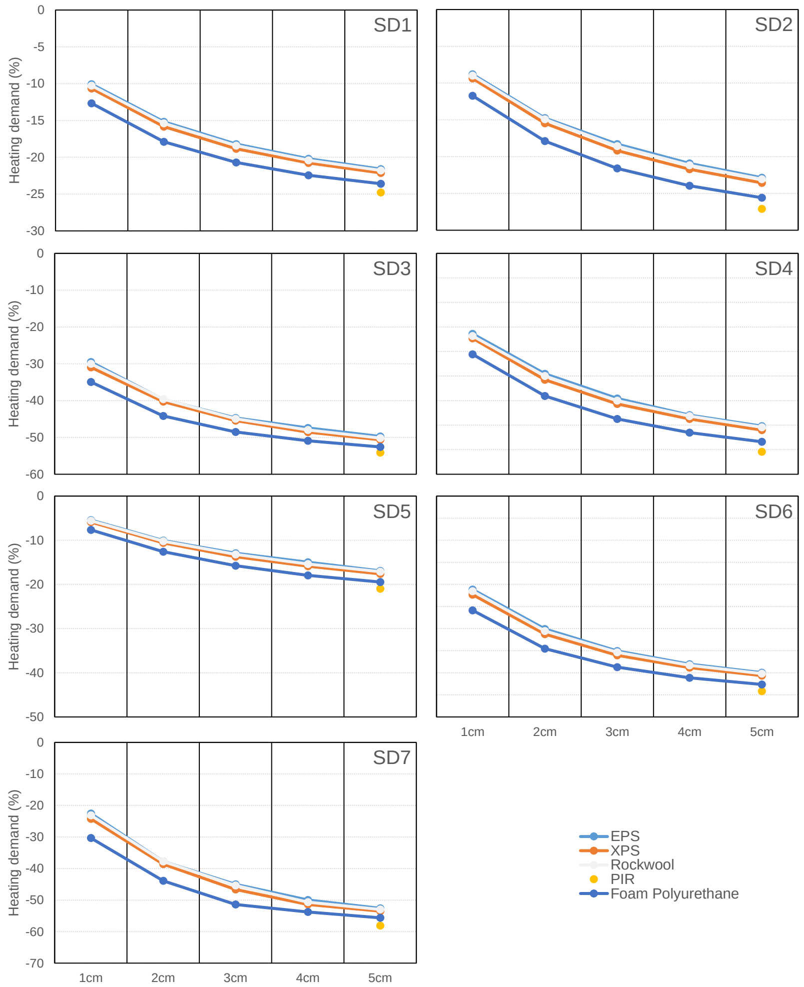


Figure 5-11 Effect of material type on upgrading roof insulation-Coastal Weather

Obviously, the foam polyurethane and PIR have better performance than the rest materials. In terms of thermal conductivity, both materials have lower thermal conductivity and therefore, the impact on heating load is higher. Above 5cm, the presence of only polystyrene (EPS and XPS) and Rock wool does not affect the average performance of insulation, highlighting the similar performance of these materials. In all cases, the foam polyurethane and PIR have higher reduction of heating demand with differences up to 3-4% for polyurethane and 3-5% for PIR compare to the rest materials.

Another important parameter when upgrading insulation on the roof element is the thickness of the material. Adding thicker materials means the overall U-value of the element is reduced, resulting in lower heat transfer to the external environment (winter) and vice versa (summer). However, the outcome shows that in practise, ‘the more, the better’ is not always coherent with better energy performance. From Figures 5-10 (and L.1), three regions of demand reduction can be noticed by the difference of adding 1cm on the material thickness. The first region is 1-2cm, where a sharp reduction is observed due to the high difference between base case, 1cm and 2cm. Then, an intermediate decrement is taking place between 2-5cm, and finally a low effect when moving from 5-7cm. Above 7 cm, the impact of thickness reaches a “plateau ” and the difference for a unit of thickness approaches almost to 0 kWh_p/m^3_{con}. In essence, the region of 5-7cm may be considered as the region where the maximum reduction may be achieved on energy demand for heating and cooling. For the coastal weather, the thermal comfort score follows the same trend as the energy reduction, where in the inland areas, in some cases, thicker materials result in better indoor conditions. Overall, the building's total thermal comfort is not compromised either during winter or summer period.

Now, in the context of the insulation's location, the differences of exposing thermal mass to the environmental conditions (internally) or taking advantage of the thermal capacity of the roof element (externally) are minor, presenting a relatively similar response on the heating and cooling demand. On the perspective of thermal comfort, the internal insulation has slightly better performance during the winter period, whereas the comfort score is greater during the summer season for the case of the external insulation.

An additional outcome, from the investigation of upgrading insulation on the roof, is the effectiveness on the cooling demand with regards to the number of stories. Recalling the characteristics of the dwellings SD2, SD4 and SD5 are single story houses, while the rest are double story dwellings. The impact of roof insulation on the cooling load is higher for the first category of houses, as the roof is the only structural boundary between indoor and outdoor environment. On the contrary, for double story buildings, the effectiveness of roof insulation on spaces at the level of the ground floor is not substantial, due to the presence of the intermediate level. In essence, by the application of roof insulation apart from the reduction of heat transfer, the solar insolation is attenuated, resulting in higher impact on single story dwellings. For example, the cooling load can be reduced up to 13% (SD2 and SD4), while in the case of SD5 (low reflectance finish on the roof) the reduction was estimated up to 31%.

External Walls Insulation

Following the analysis of the roof insulation, the upgrade of the external wall insulation will be described, excluding the application of the foam polyurethane as commercially it is not available for this particular building element. The percentage variation of the wall insulation is depicted in Figure 5-12 for the coastal and inland climatic conditions. As an initial result, the wall insulation presents a relatively good winter performance with maximum decrease of heating demand varying from 9-30% for coastal weather and 10-30% for inland environmental conditions. On the contrary, the effectiveness of wall insulation seems to be minor during the summer period, with most of the cases affected negatively with regards to the energy consumption. In particular, the summer demand was increased from 0-3% for coastal and 0-2% for inland areas. In some cases, a positive impact was presented for inland weather files, equal to 1%.

As in the case of roof insulation, the impact of parameters such as material thickness and type, is graphically represented in Figures 5-13 (and L.2-inland). The thermal comfort score associated with each unit of thickness is also plotted in these figures.

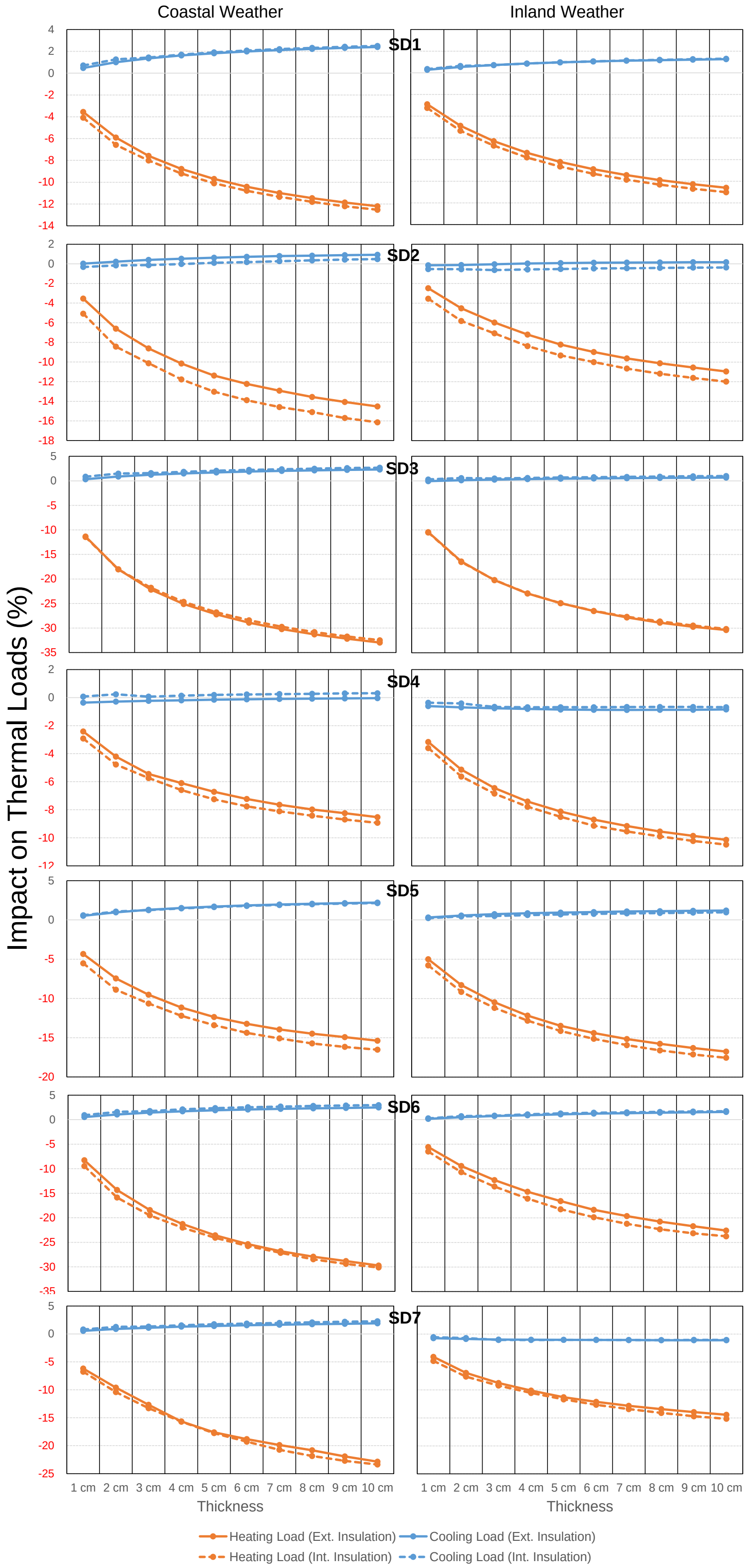


Figure 5-12 Percentage impact of external wall insulation

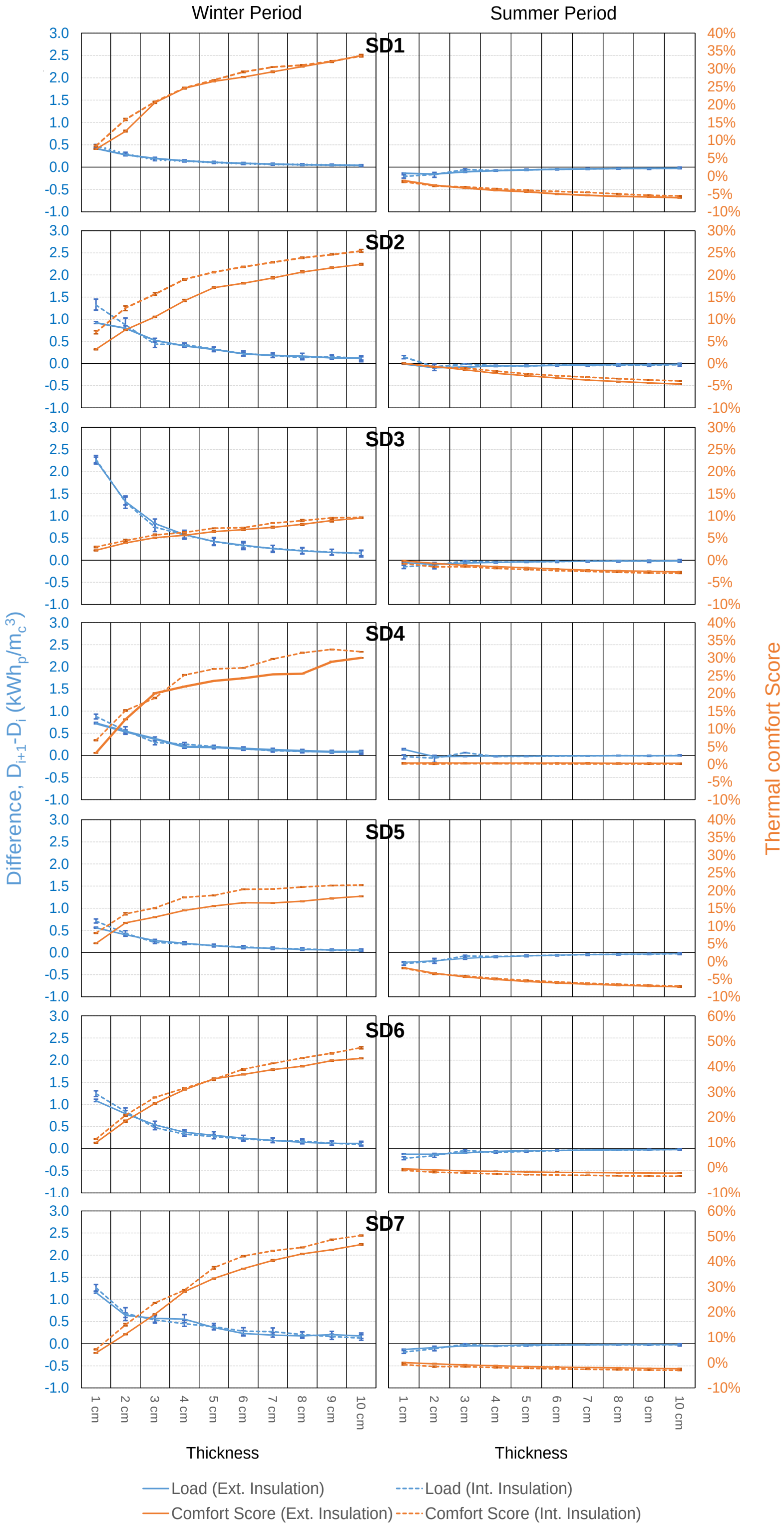


Figure 5-13 Effect of external wall insulation-Coastal Weather

During the winter season, the heating load was decreased, following a similar trend as was the case for the roof insulation, where the impact of thicker insulation tends to be minor, approaching zero. Particularly, above 7cm the effect of thickness is insignificant. Again, the overall indoor environment is enhanced, with gradually better performance for higher levels of thicknesses. From the perspective of insulation material, the impact is minor as for each unit of thickness the variation is not significant. In general, the application of internal insulation presents better performance with regards to winter comfort score.

In spite the relatively good winter performance, the impact on summer season seems to be minor and for most of the cases is negative, for both climates. The energy consumption is increased by the application of insulation, compromising also the indoor thermal environment. Overall, the effect of position and type is inconsiderable, especially in the perspective of energy demand. In the context of thermal comfort, as the thickness is increased the building loses its comfortable environment.

Generally, the application of external wall insulation may be determined ‘seasonal’, as during the heating period the effect is positive, while the cooling may be increased, compromising also the indoor thermal comfort of the dwelling.

GROUND FLOOR INSULATION

This section describes the effectiveness of insulation when upgraded on the internal surface of the ground slab, after removing the tiles or any other material that was previously applied on the concrete slab. Figure 5-14 shows the percentage impact on thermal loads per unit of thickness of insulation. For the case of the SD3 house, the impact of ground floor insulation is negligible due to the presence of insulation on the default constructions (underfloor heating).

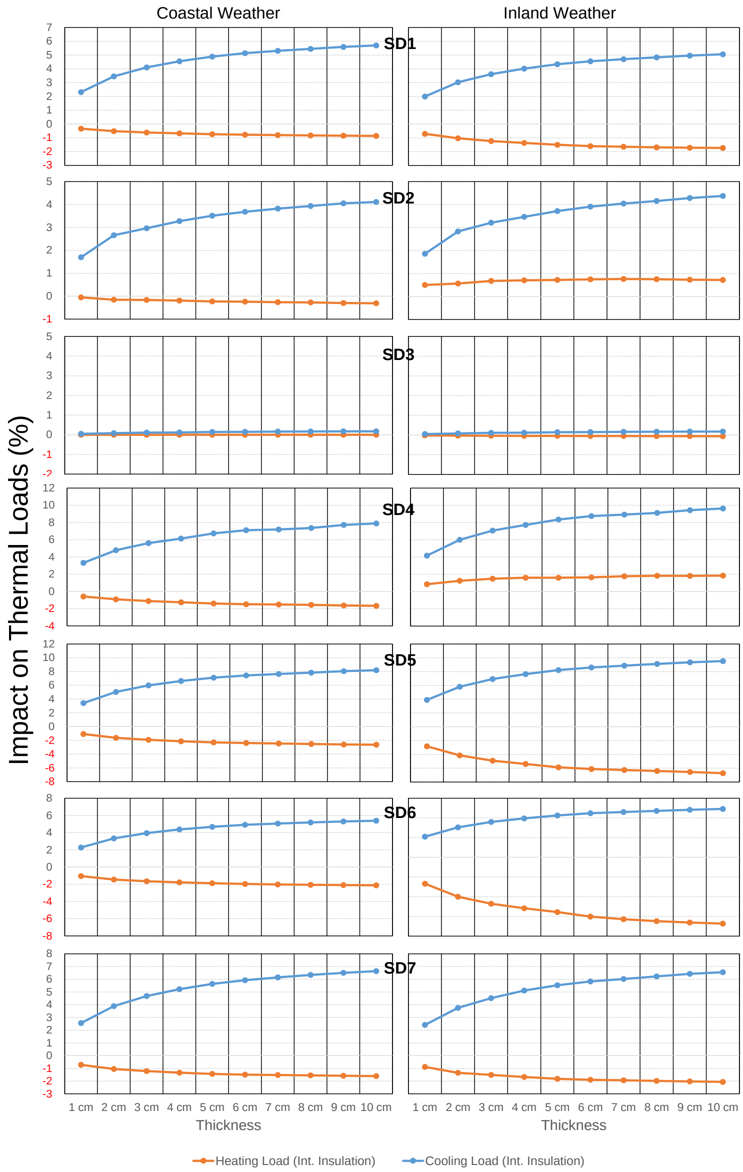


Figure 5-14 Percentage impact of ground-floor insulation

By the upgrade of floor insulation, a 1-21% (coastal) and 2-7% (inland) heating reduction was achieved. For some cases at the inland weather, the application counteracts on the building’s performance, increasing the heating demand up to 2%. On the contrary, the energy scene is adversely affected, causing a rise of about 4-8% (coastal) and 4-10% (inland) of cooling demand. The impact of insulation parameters (i.e., thickness, position and material) are presented in Figure 5-15 (and L.3-inland).

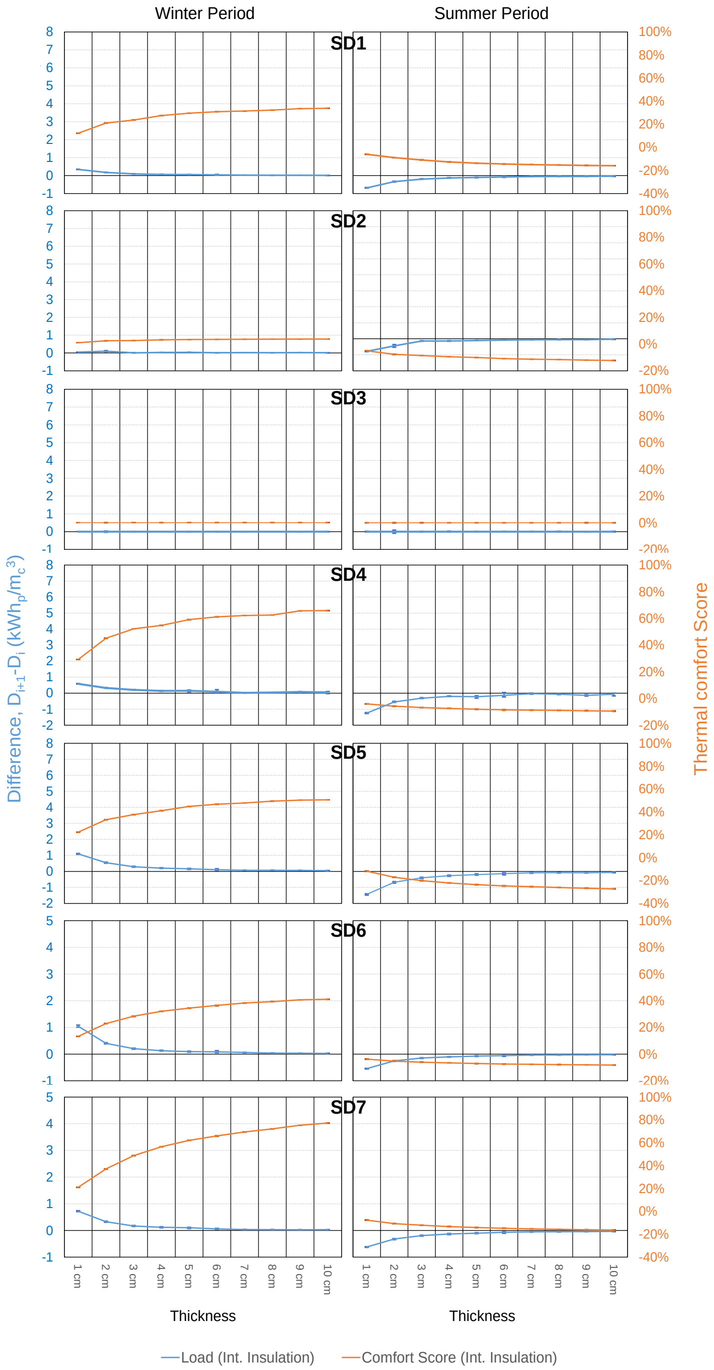


Figure 5-15 Effect of ground floor insulation-Coastal Weather

The analysis shows that the maximum thickness influencing the performance of the building is 3cm, as above this unit of thickness, the impact (either negative or positive) is substantially negligible for winter and summer periods. In particular, for 4-10cm, the difference approaches the 0 kWh_p/m^3_{con}. The material type seems to be a minor factor, as the maximum variation for polystyrene and rock wool insulation lies within the range of 0.09 kWh_p/m^3_{con}.

In the context of thermal comfort, again the material type does not have any significant effect. By shifting the thickness to higher levels, the winter comfort score is gradually increased, while for the analogous unit of thickness the summer indoor environment is compromised.

As the external walls, the application of the ground floor insulation may be considered as a 'seasonal' measure, with higher impact on the heating load.

SUMMARY

Through section 5.2.2, the effect of upgrading insulation on opaque elements was presented, giving attention to the performance of each individual element and its characteristics. At this point the discussion will be further extended on the comparison of the relative performance between the insulation of the structural elements. Figure 5-16 and Tables (5-3), (5-4), (5-5) and (5-6) summarize the average impact on the seasonal primary energy consumption and indoor comfort score, respectively. Figure 5-16 shows the range of the percentage effect, highlighting also the average for each instance. The positive values are expressing the percentage of decrement of the thermal load, and vice versa. Tables (5-3) and (5-4) present the average impact by thermal insulation of each structural element, for coastal and inland conditions. In the case of the comfort score (Tables (5-5) and (5-6)), the positive values are posing the enhancement of the indoor thermal environment.

From Figure 5-16 and Tables (5-3) and (5-4), it can be clearly noticed, that the roof insulation presents the greatest performance compared the external walls and floor insulation, in the context of heating load for both climates. The average reduction of heating load by roof insulation is 3 times higher than floor insulation and 2 times than wall insulation. The contribution of roof insulation is generally beneficial, for the cooling period, while the rest measures seems to adversely affecting energy consumption. The worst performance on cooling period is presented on the case of floor insulation with an average increment about 4% and 5%, coastal and inland weather, respectively.

In terms of thermal comfort score, on average the highest advantageous application may be considered the upgrade of roof insulation, as in the most cases the percentage is higher than the other elements. For the case of SD5, due to the low reflectance-finishing on the roof, the results on thermal comfort are lower or negative (inland) during the winter period. However, the summer comfort score for the same dwelling is substantially increased, overcoming the bad winter performance.

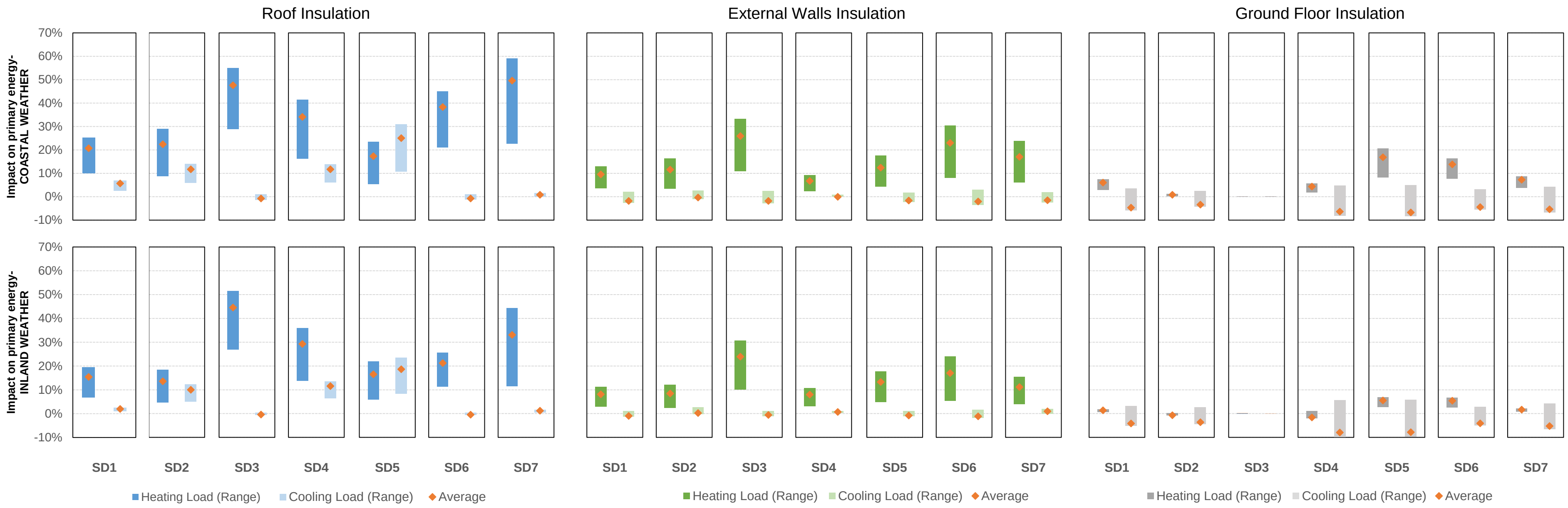


Figure 5-16 Heating and cooling performance of opaque elements

Table 5-3 Average impact by thermal insulation on opaque elements-Coastal Weather

		AVERAGE IMPACT BY THERMAL INSULATION					
		Roof		External Walls		Ground Floor	
		(%)	kWh_p/m^3_c	(%)	kWh_p/m^3_c	(%)	kWh_p/m^3_c
WINTER	SD1	-21	-2.4	-10	-1.1	-6	-0.7
	SD2	-22	-5.8	-12	-3.0	-1	-0.2
	SD3	-48	-9.5	-26	-5.2	-0.02	-0.01
	SD4	-34	-10.2	-7	-2.0	-4	-1.3
	SD5	-17	-2.2	-12	-1.6	-17	-2.2
	SD6	-38	-5.0	-23	-3.0	-14	-1.8
	SD7	-50	-9.3	-17	-3.2	-7	-1.4
	AVERAGE	**-33**	**-6.4**	**-15**	**-2.7**	**-7**	**-1.1**
	MAXIMUM	**-50**	**-10.2**	**-26**	**-5.2**	**-17**	**-2.2**
	MINIMUM	**-17**	**-2.2**	**-7**	**-1.1**	**0**	**-0.01**
SUMMER	SD1	-6	-1.7	+2	+0.5	+5	+1.4
	SD2	-12	-5.4	+0.3	+0.2	+3	+1.6
	SD3	+1	+0.1	+2	+0.3	+0.05	+0.02
	SD4	-12	-4.4	+0.02	+0.01	+6	+2.4
	SD5	-25	-10.5	+2	+0.7	+7	+2.8
	SD6	+1	+0.2	+2	+0.5	+4	+1.1
	SD7	-1	-0.2	+2	+0.4	+5	+1.3
	AVERAGE	**-8**	**-3.1**	**+1**	**+0.4**	**+4**	**+1.5**
	MAXIMUM	**-25**	**-10.5**	**+0.02**	**+0.01**	**+0.05**	**+0.02**
	MINIMUM	**+1**	**+0.2**	**+2**	**+0.7**	**+7**	**+2.8**

Table 5-4 Average impact by thermal insulation on opaque elements-Inland Weather

		AVERAGE IMPACT BY THERMAL INSULATION					
		Roof		External Walls		Ground Floor	
		(%)	kWh_p/m^3_c	(%)	kWh_p/m^3_c	(%)	kWh_p/m^3_c
WINTER	SD1	-15	-2.4	-8	-1.3	-1	-0.2
	SD2	-14	-5.2	-8	-3.2	+1	+0.3
	SD3	-45	-10.6	-24	-5.7	-0.2	-0.04
	SD4	-29	-12.5	-8	-3.4	+2	+0.7
	SD5	-17	-3.5	-13	-2.8	-6	+1.2
	SD6	-21	-5.5	-17	-4.4	-5	+1.4
	SD7	-33	-9.7	-11	-3.3	-2	+0.5
	AVERAGE	**-25**	**-7.1**	**-13**	**-3.4**	**-2**	**-0.3**
	MAXIMUM	**-45**	**-12.5**	**-24**	**-5.7**	**-6**	**-1.4**
	MINIMUM	**-14**	**-2.4**	**-8**	**-1.3**	**+2**	**+0.7**
SUMMER	SD1	-2	-0.7	+1	+0.3	+4	+1.4
	SD2	-10	-5.1	-0.2	-0.1	+4	+1.8
	SD3	+0.4	+0.1	+0.5	+0.1	+0.1	+0.02
	SD4	-12	-5.1	-1	-0.3	+8	+3.5
	SD5	-19	-8.7	+1	+0.4	+8	+3.6
	SD6	+0.5	+0.1	+1	+0.3	+4	+1.1
	SD7	-1	-0.3	-1	-0.3	+5	+1.4
	AVERAGE	**-6**	**-2.8**	**+0.2**	**+0.1**	**+5**	**+1.7**
	MAXIMUM	**-19**	**-8.7**	**-1**	**-0.3**	**+0.1**	**+0.02**
	MINIMUM	**+0.5**	**+0.1**	**+1**	**+0.4**	**+8**	**+3.6**

Generally, the summer comfort is compromised by the thermal insulation, apart from the case of roof insulation. The effect of the number of stories is again presented as the impact on double story buildings is minor (1% or -2%).

For the single story buildings the application of roof insulation is enhancing the summer indoor thermal environment.

Table 5-5 Average comfort score-Coastal Weather

DWELLNGS	**AVERAGE IMPACT ON COMFORT SCORE**					
	Winter			Summer		
	Roof	External Walls	Floor	Roof	External Walls	Floor
SD1	38%	25%	28%	12%	-4%	-13%
SD2	26%	18%	3%	41%	-2%	-10%
SD3	17%	7%	<1%	1%	-2%	<-1%
SD4	151%	23%	56%	9%	0%	-8%
SD5	7%	16%	42%	88%	-5%	-22%
SD6	53%	34%	33%	-2%	-2%	-7%
SD7	73%	33%	59%	-2%	-2%	-14%

Table 5-6 Average comfort score-Inland Weather

DWELLNGS	**AVERAGE IMPACT ON COMFORT SCORE**					
	Winter			Summer		
	Roof	External Walls	Floor	Roof	External Walls	Floor
SD1	45%	40%	15%	7%	-4%	-16%
SD2	52%	38%	2%	29%	-5%	-9%
SD3	9%	5%	<1%	2%	0%	<-1%
SD4	147%	46%	80%	16%	2%	-11%
SD5	-18%	41%	53%	94%	-3%	-27%
SD6	81%	160%	59%	-2%	-1%	-7%
SD7	106%	48%	58%	-1%	1%	-14%

In the perspective of energy reduction and indoor thermal comfort, from the analysis of the insulation of opaque elements in climates with hot-dry summers and mild-wet winters, experiencing high solar gains throughout the year, the overall situation is as follows:

- The application of roof insulation is the best solution in both winter and summer period, with substantial decrement of heating load (up to 59%). In the case of cooling load, the effectiveness of the insulation is primarily based on the number of stories. Overall, the indoor thermal comfort was improved throughout the year.
- The performance of roof insulation is followed by the external walls insulation, where a considerable decrement was noticed on the heating demand, while a minor negative effect occurred during the summer season. In terms of thermal comfort, the indoor thermal environment was compromised at summer.
- The worst performance was presented by the floor insulation, where a minor positive impact was observed during the winter period, with substantial increment of the cooling load. Again, the summer thermal comfort was compromised.
- For roof insulation, the polyurethane foam and PIR show better performance than the polystyrene and rock wool materials, where above 5cm the impact of material is almost negligible. In essence, especially for the cases of polystyrene and rock wool, the selection on retrofitting may be based on the applicability and their physical properties such as hydrophobicity (external insulation), sound insulation and health impact such as pulmonary diseases (when the material is exposed).

- In addition for the roof and external walls insulation, above 5-7cm the impact of thickness is inconsiderable, while for the floor insulation the same trend exists for thicknesses above 3cm.

5.2.3 LIGHT OPAQUE ELEMENTS

In the previous section, the discussion was developed on the effectiveness on upgrading insulation on the opaque elements of the building envelope. This section focuses on the application of high reflectance coating on the external surfaces of roof and external walls. Nowadays, several finishing materials are commercially available for this category of energy saving. In this study, the light elements will be determined by reflectance up to 85% (absorptance≈15%). As a guidance, Table 5-7 lists the default absortpance of the different elements.

Table 5-7 Default building's element absorptance

DWELLING	DEFAULT ABSORPTANCE (X100 %)		
	Roof		External Walls
	Flat	Inclined (Ceramic Tiles)	
SD1	0.85	0.5	0.4
SD2	0.6	-	
SD3	0.7	0.5	
SD4	0.4	-	
SD5	0.85	-	
SD6	0.4	0.5	
SD7	0.5	0.5	

These values are based on the site-visit assessment and for each finishing material are adopted by (ECRC, 2014). The final value was resulted after the calibration procedure (see Chapter 4).

Figures 5-17 (and L.4-inland) show the normalized energy impact and the seasonal thermal comfort score by the application of the reflected coating for coastal and inland weather files, respectively.

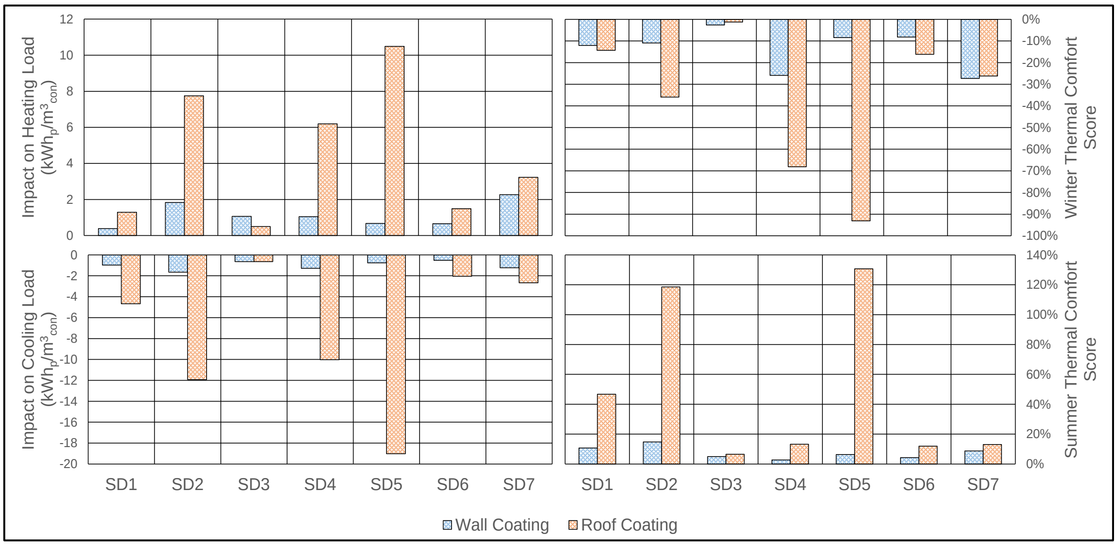


Figure 5-17 Low reflectance impact-Coastal Weather

As it was expected, the influence on the winter and summer performance is inverse but not directly proportional. In particular, the coating of the surfaces with high reflectance material causes the direct increment of heating demand compromising the indoor thermal environment, while the cooling load is decreased and summer thermal comfort is improved. In numbers, Table 5-8 summarizes the average and maximum increase of heating demand over the sample of dwellings.

Table 5-8 Summary of heating demand by light coating

HEATING DEMAND	COASTAL		INLAND	
	Roof	Wall	Roof	Wall
Average ($kWh_p/m^3{}_{con}$)	4.4	1.1	4.1	1.2
Max ($kWh_p/m^3{}_{con}$)	10.5	2.7	10.5	1.9

For both climates, the wall has a minor impact compared to the roof coating, as the average heating demand is almost 4 times higher, while the maximum reaches up to 5 times. Similarly, the outcome of the cooling demand is listed in Table 5-9.

Table 5-9 Summary of cooling demand by light coating

COOLING DEMAND	COASTAL		INLAND	
	Roof	Wall	Roof	Wall
Average ($kWh_p/m^3{}_{con}$)	7.3	1	6.5	1.1
Max ($kWh_p/m^3{}_{con}$)	19	1.6	16.8	1.6

Again, the average of the light roof can reduce on average 7 times the cooling load (coastal) and 6 times (inland) compare to wall coating. The maximum reduction for the case of roof coating can reach up to 9 and 8 times for coastal and inland external environment, respectively. Overall, only in the case of the SD3 dwelling was the impact of wall coating more critical than the light roofs. This may also correlated with the effect of the story. Recalling, from roof insulation findings, the effectiveness of roof insulation was lower for the double story buildings. This is merely observed in the case of the roof coating, where the SD2, SD4 and SD5 are experiencing a substantial impact compared the rest of the buildings. For instance, comparing the SD4 (single story) to the SD6 (double story), having approximately the same roof coating, the percentage difference on heating and cooling impact is 76% and 80% (coastal) or 77% and 79% (inland), accordingly.

Now, in the context of default construction solar reflectivity, Figure 5-18 shows the outside and inside surface temperatures of roof element for SD4 and SD5 (0.4 and 0.8 absorptance, respectively), both single story buildings.

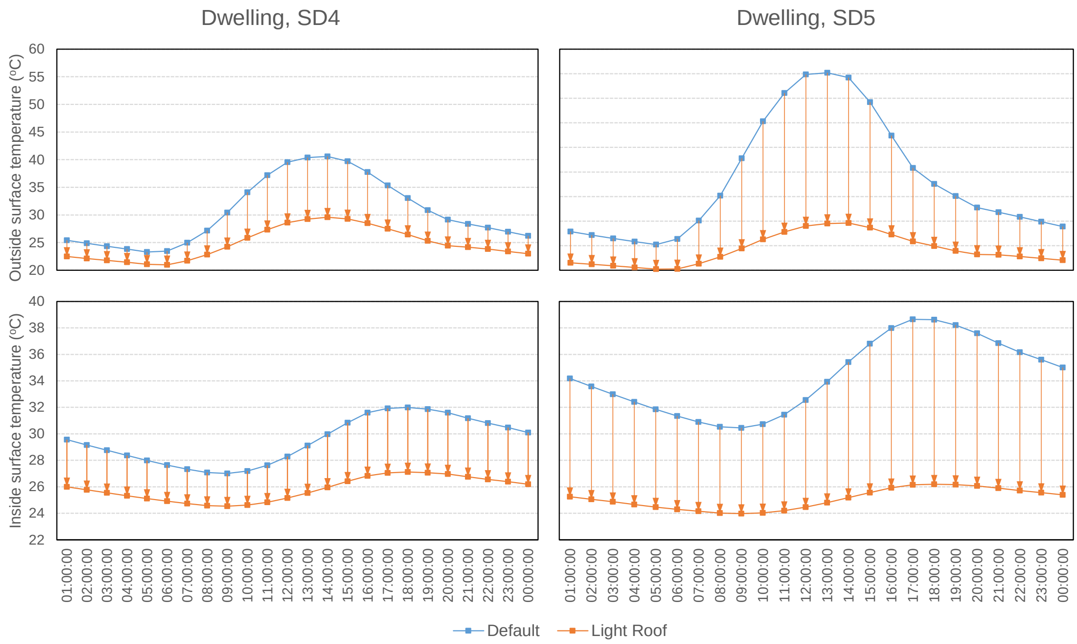


Figure 5-18 Comparison of SD4 and SD5 by the upgrade of high reflective coating (Coastal Weather-12/07)

Obviously, by the application of high reflectance material, the roof surface temperatures are dramatically decreased for the case of SD5 (see also the roof insulation section), improving the indoor thermal environment during the summer period and also, reducing the cooling demand. However, due to this fact, the winter performance of the building is compromised, as after the application of coating, the roof is unable to absorb the same amounts of solar insolation, causing a considerable increment of heating load, compromising also the indoor environment.

The same situation is also presented in the perspective of thermal comfort score. The application of coating enhances the indoor thermal environment that is experienced during the summer period. The structural surface temperatures are decreased due to a major proportion of solar gains been emitted back to the environment, so the elements are not charged with high heat gains. To this effect, the mean radiant temperature is lower, reducing the discomfort to the spaces. However, this counteracts on the absorption of heat gains during the winter period, where the building is unable to capture solar insolation and heat its thermal mass.

Overall, the application of this energy saving measure is critically based on the relative performance between winter and summer season.

5.2.4 Fenestration

The previous sections gives attention to altering the opaque elements either by the application of insulation (U-value) or by coating their outer surfaces with high solar reflective material (solar absorptance). Through section 4.4, the impact of upgrading the transparent elements of the building will be looked at. In particular, the study focuses on the investigation of the building's windows in the context of U-value and solar factor. In the latter category, a further analysis will be carried out on the effect of the external fixed shading devices. Table 5-10 shows the characteristics of building envelope in the perspective of window and wall areas, as these were estimated by the as-built drawings, collected during the site visits. The base case properties of windows for each individual case study are listed in Table 5-11.

Table 5-10 Windows to wall characteristics

DWELLING	TOTAL WALL GROSS AREA (m^2)	TOTAL WINDOWS AREA (m^2)	WINDOWS/EXTERNAL WALLS RATIO (%)				
			South	East	West	North	**Total**
SD1	422.84	82.47	1.5	4.2	7	6.8	**20**
SD2	422.25	55.06	2.4	5.7	0.5	4.4	**15**
SD3	594.75	89.07	2.3	3.3	4.9	4.5	**13**
SD4	227.63	42.5	5.9	3.8	3.9	5.1	**19**
SD5	183.33	37.22	7.9	0.4	6.8	5.1	**23**
SD6	357.95	83.1	8.6	5	5.7	3.9	**20**
SD7	351.82	68.79	5.9	6.2	3.8	3.6	**20**

Table 5-11 Base case windows characteristics

DWELLING	GLAZING SYSTEM	FRAME SYSTEM	U_W (W/m^2K)
SD1	Single 4mm	Aluminium	5.75
SD2	Single 3mm	Wood	4.94
SD3	Double 6-4 mm	Aluminium	3.55
SD4	Single 3mm	Aluminium	5.8
SD5	Double 4-3 mm	Aluminium	3.90
SD6	Double 4-3 mm	Aluminium	3.90
SD7	Double 6-4 mm	Aluminium with thermal break	2.9

Figure 5-19 depicts the various glazing systems that will be looked at throughout the study. In particular, the systems are categorized by their solar factor and number of glass panes.

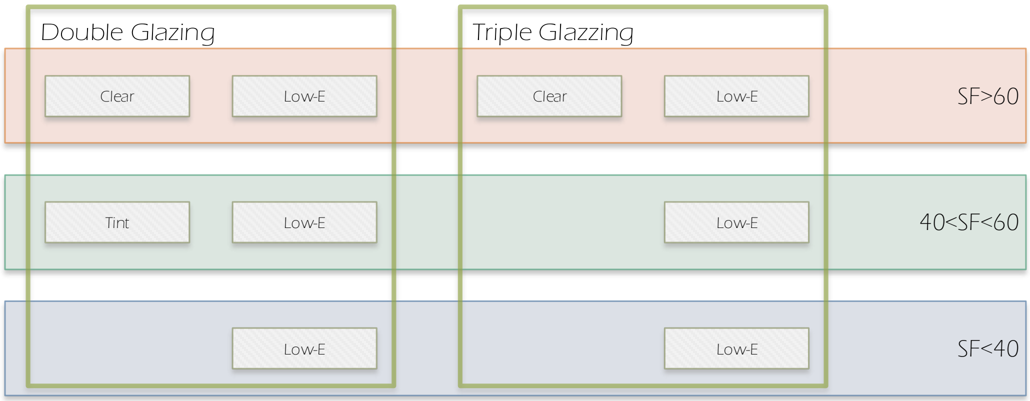


Figure 5-19 Categories of glazing under examination

In the case of Low-E systems, the investigation of low-e coating position was also considered critical, as the overall performance can be alternated by the position. As a guidance through the analysis, Figure 5-20 illustrates the indexed position for each glass surface for double or triple pane windows.

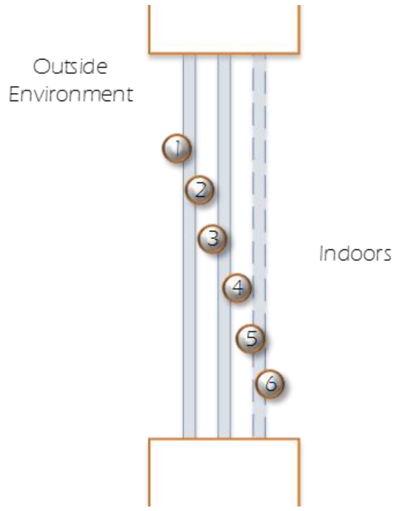


Figure 5-20 Numbering of surfaces on double and triple layer glazing

It was considered unsubstantial to examine the coating of surface 1 and 6, as in practise it is usually not applicable. The exposure to the external environment raises the possibility of corrosion and loss of its performance. Commercially, the coating can be found on surfaces 2-5, depending on the dominancy of the local climatic conditions (i.e., as a rule of thumb at cold climates, p3 (position 3) for double pane and p3 or p5 for triple pane are preferred).

IMPACT OF VARIOUS TYPES OF GLAZING SYSTEMS

For each dwelling, the results are presented in Figures (5-21, 5-22 (coastal)) and (L.5, L.6 (inland)) .Particularly, in Figures (5-21) and (L.5), the impact on seasonal primary energy is plotted for every glazing system, giving also attention to the different coating configuration for the case of the Low-E glazing. Tables 5-12 (and L.1-inland) summarize the average and range on thermal loads, for coastal and inland climates, respectively.

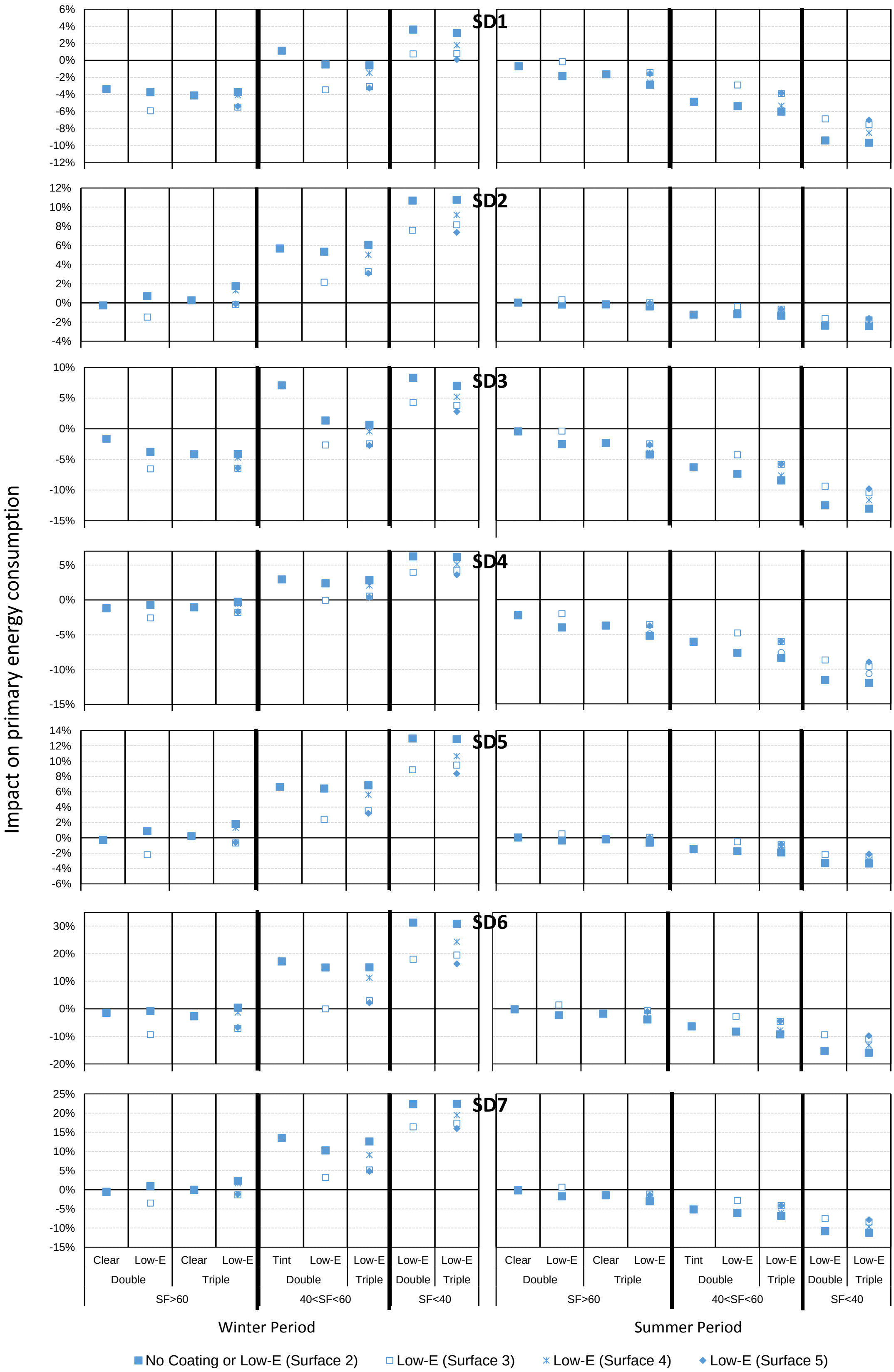


Figure 5-21 Impact of different glazing types-Coastal Weather

Table 5-12 Impact on thermal loads-Coastal weather (Average and Range)

GLASS TYPE				**THERMAL LOADS (%)**			
				Heating		Cooling	
				Average	Range	Average	Range
SF>60	Clear	Double		-1	-3 to 0	-1	-2 to 0
		Triple		-2	-4 to 0	-2	-4 to 0
	Low-E HSF	Double	p2	-1	-4 to 1	-2	-4 to 0
			p3	-5	-9 to -1	0	-2 to 1
		Triple	p2	0	-4 to 2	-3	-5 to 0
			p3	-3	-7 to 0	-1	-4 to 0
			p4	-1	-5 to 2	-3	-5 to 0
			p5	-3	-7 to 0	-1	-4 to 0
40<SF<60	Tint	Double		8	1 to 17	-4	-6 to -1
	Low-E MSF	Double	p2	6	0 to 15	-5	-8 to -1
			p3	0	-3 to 3	-3	-5 to 0
		Triple	p2	6	-1 to 15	-6	-9 to -1
			p3	1	-3 to 5	-4	-6 to -1
			p4	4	-1 to 11	-5	-8 to -1
			p5	1	-3 to 5	-4	-6 to -1
SF<40	Low-E LSF	Double	p2	14	4 to 31	-9	-15 to -2
			p3	9	1 to 18	-7	-9 to -2
		Triple	p2	13	3 to 31	-10	-16 to -2
			p3	9	1 to 20	-7	-11 to -2
			p4	11	2 to 24	-8	-13 to -2
			p5	8	0 to 16	-7	-10 to -2

From Figures (5-21) and (L.5), a variation on the performance is observed for each case building, due to the fact that the orientation and the layout of the dwellings are not similar. For instance, the SD6 has the greater ratio of window/wall fraction facing to the south, while all the conditioned spaces are located to the southern part of the house, increasing the effect of the solar penetration on the overall thermal performance. In essence, through the discussion on glazing systems, attention will be primarily given on each glazing system, to establish their global performance.

Evidently, looking at the winter energy performance, the impact of solar factor seems to be more critical compared the U-value of the glazing. On average, the glazing category with high solar factor (HSF) decreases the heating load up to 5% (coastal) and 4% (inland), while the medium (MSF) and low (LSF) solar factor categories are increasing the heating demand up to 14% (coastal) and 6% (inland), respectively. As an example of the impact of solar factor the case of double low-e glazing (p3) at coastal weather. For HSF the heating demand was reduced up to 5%, while for MSF the impact was neutral, followed by an increase up to 9% for LSF. On average, a difference of up to 14% is observed for glazing with approximately similar U-values, but different solar factor. This difference is mainly revealed from the characteristics of the Mediterranean climate, due to the excess solar insolation throughout a year. On the perspective of heat losses, while the U-value of fenestration is higher compare to other building elements, their exposed area is much smaller and thus, heat losses are lower.

Furthermore, from the results, it can be concluded that the impact of adding an additional layer (triple pane) is minor in the most cases and may also compromise the overall energy performance.

Now, in the perspective of Low-E glazing, the performance is shifted for different positions of coating. For double pane windows, p3 is considered as the ideal surface for coating. For each solar factor category, the performance of the window was increased about 4-6% (coastal) and 2-3% (inland), when the coating was placed on p3. The same situation is also presented for the case of triple pane glazing, with p3 and p5 showing better and similar performance, followed by p4. Table 5-13 shows the average reduction of heating load compare to p2 by solar factor category.

Table 5-13 Average improvement of energy performance compare to position 2

	AVERAGE IMPROVEMENT OF PERFORMANCE COMPARE TO POSITION 2 (%)								
Weather file	Position 3			Position 4			Position 5		
	HSF	MSF	LSF	HSF	MSF	LSF	HSF	MSF	LSF
Coastal	3	5	4	1	2	3	3	5	6
Inland	2	2	2	0	1	1	2	1	3

The background theory, describes the variation of energy performance due to different coating position, it is based on the inner gap thermal resistance. When the coating is applied at the inner surfaces, the glazing system is taking advantage of the thermal resistance of the gas fill (i.e., air) and thus, the heat losses are reduced resulting in lower heating demand.

Now, in the context of cooling demand, the overall situation can be described by a relatively good performance, as all types of glazing are reducing the thermal load. Again, the impact of U-value is minor with slightly better impact for lower units of U-value. For instance, Table 5-14 shows the percentage difference between Double clear, Low-E (p2), Triple clear and Low-e (p2 or p4) systems, on cooling load.

Table 5-14 Average improvement of performance compare to double clear glazing for HSF category

WEATHER FILE	**AVERAGE IMPROVEMENT OF PERFORMANCE COMPARE TO DOUBLE CLEAR (%)**		
	Double	Triple	
	Low-E	Clear	Low-E
Coastal	1.3	1.1	2.4
Inland	1.2	1	2.1

It can be clearly noticed that the difference between 2 or 3 glass panes is not critical, as the difference is about 1% for both climates.

In the perspective of Low-e coating, the performance scene is reversed during the summer period. In particular, the Low-e glazing presents higher impact when the coating is applied on surface 2 (double pane) or surfaces 2 and 4 (triple pane). On average, a difference of about 2% was observed between the surfaces. In this case, the coating keeps the unwanted heat out, preventing the rise of the indoor air temperature.

As in the case of winter season, a substantial impact on the cooling load is observed by the variation of the solar factor values. As it can be seen from Table 5-12, the average performance of a glazing system with high solar gains can improve by 3-4% (medium solar gains) and 6-7% (low solar gains). Following the energy performance of the glazing systems, the indoor thermal comfort is evaluated. Figures (5-22) and (L.6) present the variation of thermal comfort by glazing category.

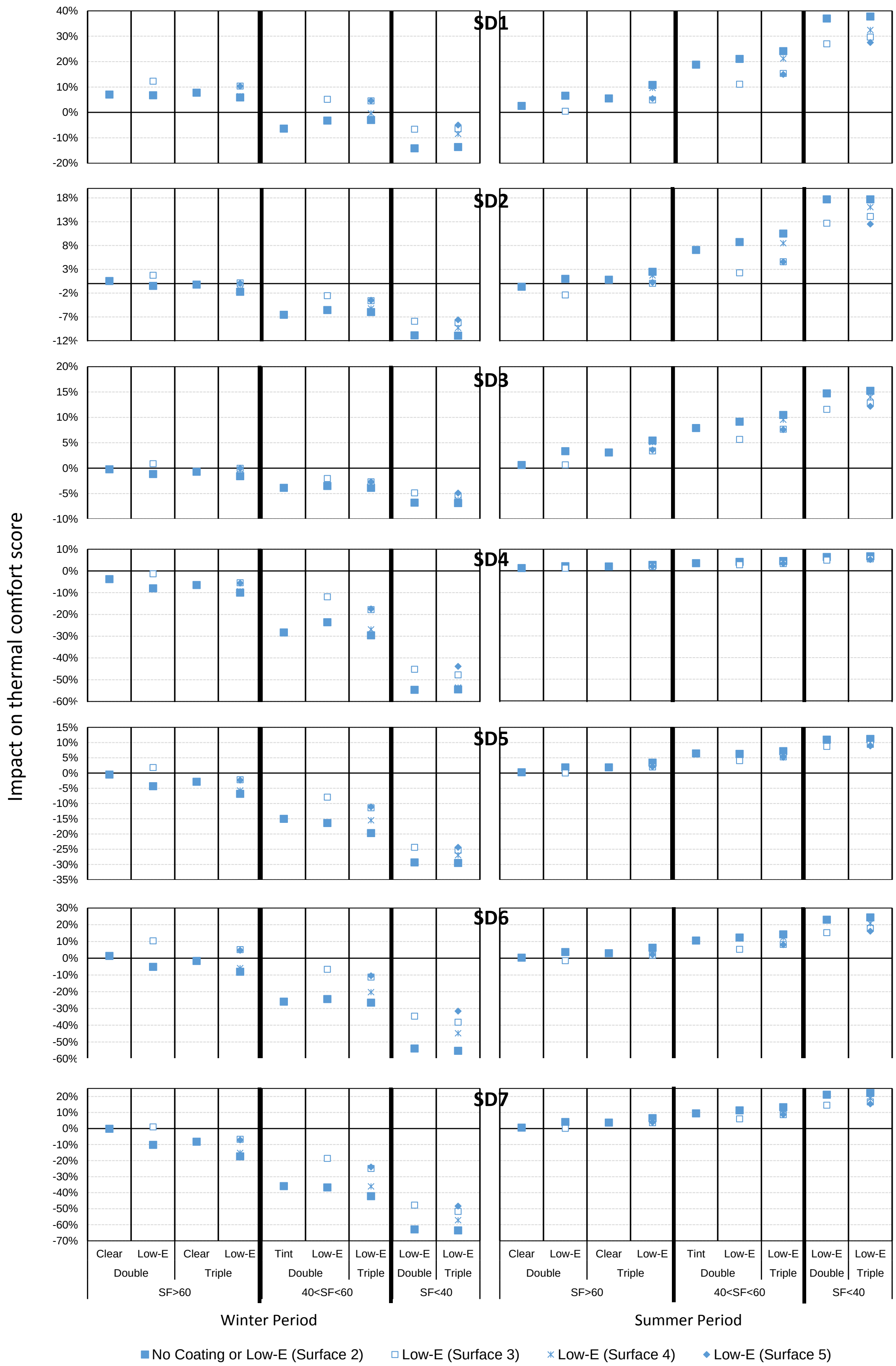


Figure 5-22 Impact on thermal comfort by window system-Coastal Weather

It can be clearly noticed that the solar factor of the glazing system is substantially important compare to the U-value. For the most cases in the winter period, the indoor environment is compromised by the application of MSF and LSF glazing, while the maximum positive effect on the summer comfort score equals to the low solar gains systems.

As in the case of primary energy, the position of coating in the Low-e glazing follows the same basis. The p3 (double or triple pane) and p5 (triple pane) have better performance during the winter period, which is reversed for the summer season.

Again, the integration of an additional pane (triple glazing) has no beneficial impact, compared with the double glazing to perform better during the winter and slightly worst during the summer period, without compromising the indoor environment.

An additional outcome from the analysis of the thermal comfort, is the effect of HVAC systems. For the dwellings SD4 to SD7, the winter comfort score presents higher reduction, compromising the indoor environment. These buildings are operating split units during the winter period. The main fact is that during the operation of split-units, only the air is conditioned (convection systems). The reduction of solar gains through the windows possess lower mean radiant temperature, resulting in uncomfortable indoor environment. On the contrary, the fraction of radiant heating on hydronic systems, maintains the radiant temperature and thus, the effect of low solar gains windows is lower.

In the energy and thermal comfort aspects, a general outcome from the analysis is, for the case of buildings with relatively small fenestration area in climates experiencing high solar gains throughout the year, the solar factor is considered as the most critical parameter, in order to control the annual thermal loads and provide a pleasant thermal environment.

IMPACT OF FRAME AND ARGON FILL

The thermal resistance of the fenestration system can be also increased either by the addition of a gas with higher thermal resistance or thermally improved frame.

In this study, the application of argon gas was examined in the perspective of gas fill, while for the frame system an aluminium thermally improved and UPVC frame with the same U-value were investigated. The main differences between aluminium and UPVC are described in Chapters 2 and 3. The application cost of aluminium and UPVC will be examined in the next chapter.

Figures 5-23 (and L.7) show the impact by upgrading the glazing system with argon fill (argon 90%-air 10%) and thermally improving the frame.

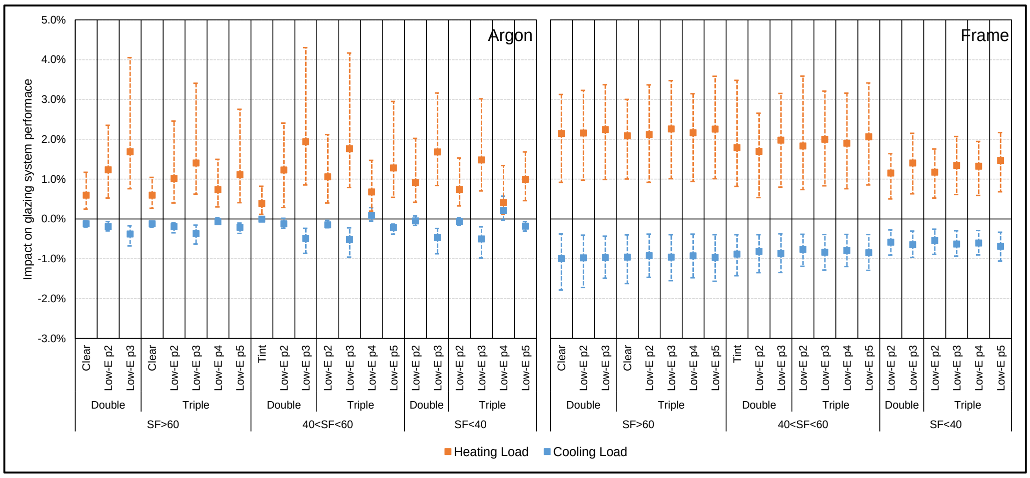


Figure 5-23 Integration of argon and improved thermal frame-Coastal Weather

With regards to argon fill, the winter performance of all glazing systems was improved, with enhancement from 0-4% for coastal weather and 0-2.5% for inland conditions. The average effect of argon fill is varied with regards to the case of glazing. The higher impact can be noticed on the Low-e glazing (p3). The heating load can be further reduced by upgrading a thermally improved frame. The average increment by the application of frame is estimated to 2% and 1.5% for coastal and inland, accordingly, varying between 1-3% (coastal) and 0.5-2.5% (inland). Apart from the thermal properties, the rational application of a frame system, will also reduce the sources of air infiltration and thus, the reduction of heating demand. In this study, the tightening of building envelope was only studied in the context of overall performance of building enclosure (see section (5.2.1)).

The application of argon and thermally improved frame seems to compromise the impact on cooling demand. The upgrade of argon gas has a minor negative effect, except in the cases of Low-e glazing systems (p2 and p4) which present slightly better performance than the air gas. The situation is burden in the case of frame, as on average the performance was reduced about 1% with a maximum impact up to 2%.

Figure 5-24 depicts the impact on indoor thermal environment by the use of argon and an improved thermal frame. Overall, the winter comfort score is increased by both upgrades (slightly better for the frame), while the summer comfort score is reduced.

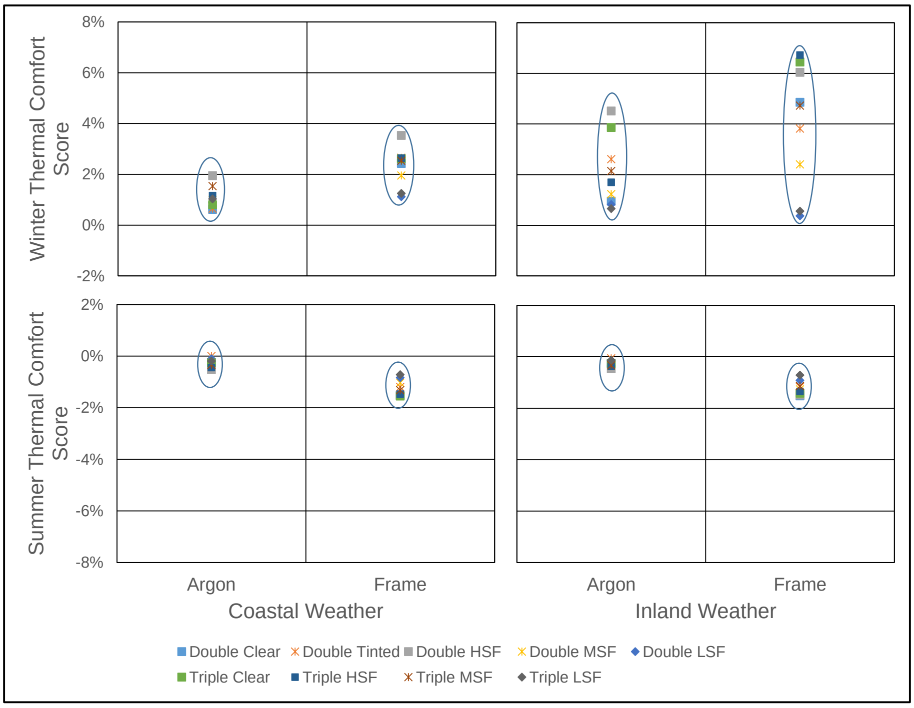


Figure 5-24 Impact on thermal comfort by argon and frame

In numbers, during the winter the performance of the glazing systems is improved by 0-2% (coastal) and 0-4% (inland) for an argon upgrade, while the frame upgrade enhances by 1-4% (coastal) and 0-6% (inland). The impact on summer comfort score is minor and negative, about 0.5% and 0.5-2% (coastal and inland).

In the perspective of the improved thermal frame, the effect of upgrade is varied with regards to the type of the glazing. This can be clearly observed on the winter comfort score for the case of the inland weather. The impact is higher for HSF glazing about 5-6% and lower for the LSF systems about 0-1%.

IMPACT OF SHADING DEVICES

To this effect, the study extends the investigation on the application of external shading devices. The upgrade of overhangs and fins on the external envelope will contribute to the control of the solar gains through the windows, founded on the dimensioning as presented in Chapter 3. The results by the upgrade of overhangs and fins on the south-east-west facing windows are presented by Figures 5-25 (and L.8).

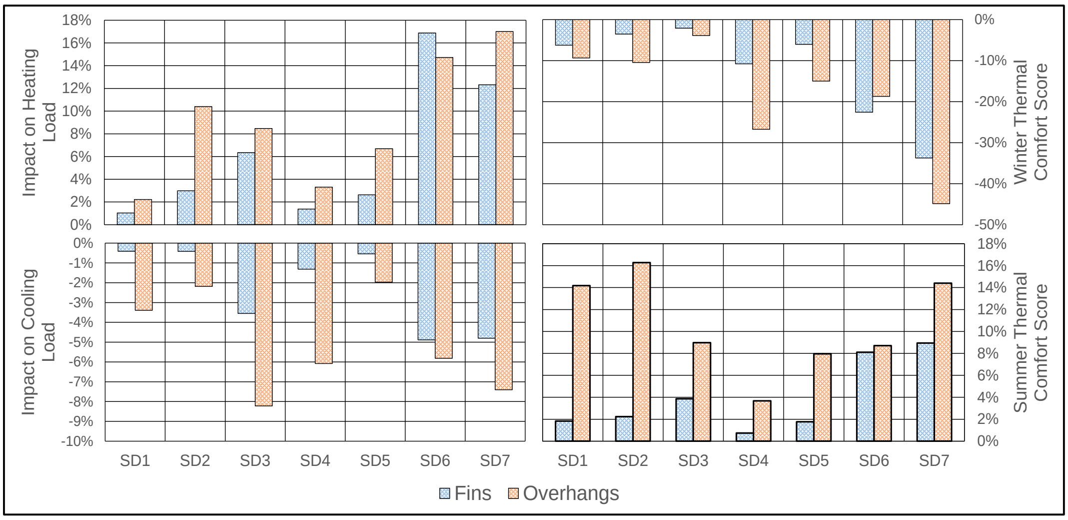


Figure 5-25 Impact of external fixed shading devices-Coastal Weather

As expected, the application of fixed shading devices has a seasonal effect on the overall performance of the dwelling. During the winter season, the thermal load is increased and indoor environment is compromised due to the fact that the solar insolation is not penetrating the transparent elements of the building, even the shading devices were based on solar geometry. On the contrary, the cooling load is reduced, while the comfort score is increased.

Overall, for the most cases the upgrade of overhangs (horizontal projection) seems to affect more the performance of the building in comparison with the fins (vertical projections). The variation of the effect of the fixed shading devices is primarily driven by the orientation of the dwelling, the exposed fenestration to the solar path and the indoor layout of the spaces. In the architectural point of view, the upgrade of fixed shading devices may not be always desirable, as the aesthetic view of the houses will be highly compromised.

From the analysis of the fenestration, it can be concluded that in climates with such characteristics (high annual solar gains and mild winters), the selection of appropriate glazing is primarily driven by the control of solar gains, as the performance of every type fluctuates between winter and summer season. Also, in the context of energy and thermal comfort, the application of fixed shading devices may also present a seasonal effect. Ideally, for this type of climate the best solution is to allow the solar gains to diffuse in the building during the winter period and block them at the summer period. In essence, this can be achieved by applying a HSF glazing system (i.e. double low-e with coating at position 3) and a movable shading device such as shutters, awnings (see Figure 5-26).

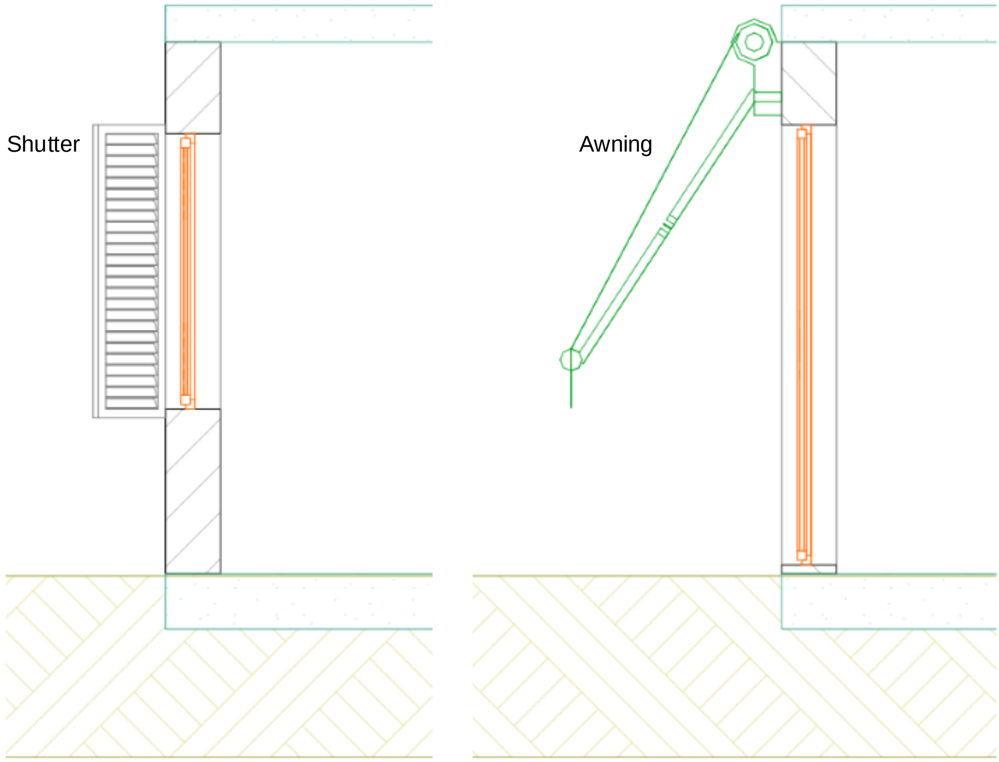


Figure 5-26 Example of external movable shading devices

Based on this concept, an additional simulation is included in the analysis, contacting the effect of the particular strategy. All buildings were upgraded with HSF glazing (p3) and a movable shading device that was fully opened during the winter season and fully closed during the summer season. The results are presented in Figure 5-27.

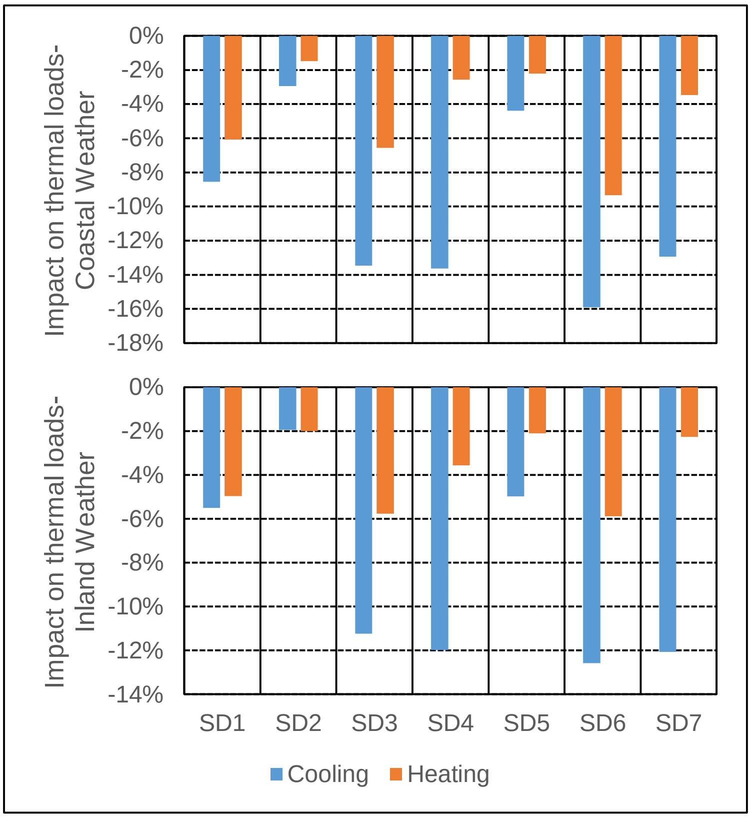


Figure 5-27 Impact on energy consumption by HSF glazing and movable shading device

It is evident that the upgrade of this strategy contributes on a positive impact on the annual energy performance of the buildings. The adoption of the particular strategy can be considerable, especially in residential buildings, where the occupants are directly interacting with the adaptive opportunities of the building, as an example raising or lowering, opening or closing the external device during any time of occupation.

5.3 Effect of Combined Interventions

5.3.1 Introduction

This part of the study deals with the investigation of the synergies between the measures. Recalling the parametric tree (see Figure 3-17), the resultant number of combinations reaches up to 7,056 for each weather file, which in total is 14,112 for every dwelling.

Due to the amount of data, the analysis of single interventions was considered impossible to be applied on the combined interventions. Consequently, a performance score was calculated, based on the simple additive weighting method (SAW), so-called SAW_{score}. The performance score is estimated for every single combination, driven by the assigned criteria described earlier in Chapter 3. The score indicates the performance of the intervention with regards to the primary energy consumption and the associated CO_2 emissions and also, the quality of the indoor thermal environment. Negative values of the SAW_{score} corresponds to lower performance than the base-case (default building characteristics), after normalization.

As in the case of single interventions, this section will give attention to the performance of the existing dwellings within the context of energy and thermal comfort and in Chapter 6 the discussion will be extended on the prioritization of the interventions, considering also the feasibility of the application (Net Present Value).

INTERVENTIONS AND INDEXING

In order to accommodate with the high amount of data, an indexing was developed for better guidance. Table 5-15 contains the short codes for the interventions that will be investigated through the rest of the section.

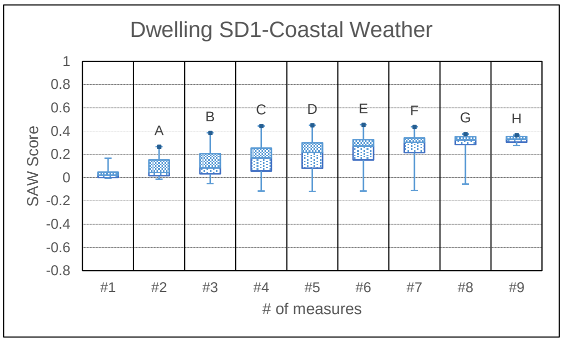
Table 5-15 Interventions indexing list

INTERVENTIONS		CODE	DETAILS
ROOF	External	RE	*3cm foam polyurethane*
	Internal	RI	*5cm (coastal)/6cm (inland) of EPS-polystyrene, XPS-polystyrene and Rock Wool*
EXTERNAL WALLS	External	WE	*3cm of EPS-polystyrene, XPS-polystyrene and Rock Wool*
	Internal	WI	
GROUND FLOOR		Gr	
COATING	Roof	CR	*0.15 absorptance*
	Walls	CW	
FIXED SHADING	Overhangs	SO	-
	Fins	SF	
MOVABLE SHADING		SM	
THERMALLY IMPROVED FRAME		Fr	
GLAZING[1]	Clear	GC	*Double pane*
	Tint	GT	
	Low-E HSF	GLH	
	Low-E MSF	GLM	
	Low-E LSF	GLL	

Notes:
[1]For each type, the simulation was repeated with argon fill, with index (Ar). i.e. GCAr

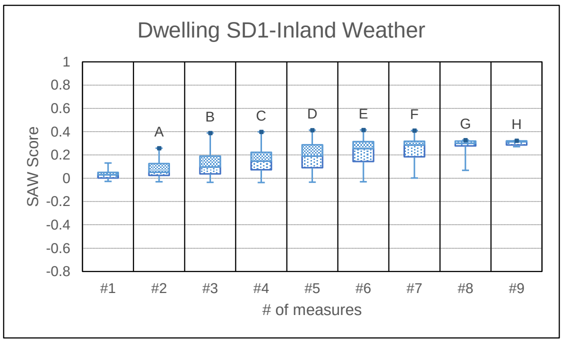
5.3.2 Combined Interventions and SAWscore

As described earlier, the synergies of the combined interventions will be assessed with the application of SAWscore. A filter is applied on the results, based on the number of intervention that occurred within a category. Figures (5-28) to (5-34) present the box-whisker plots for each individual dwelling, for both coastal and inland climate. Particularly, the plots show the median and the range of the impact by the category, presenting also the combinations with the highest performance.



	Interventions with highest possitive impact by # of measures
A	RE+WE
B	RE+WI+SMGLH
C	RE+WI+Gr+SMGLH
D	RE+WI+Gr+SMGLH+Fr
E	RE+WI+Gr+CR+SMGLH+Fr
F	RE+WI+Gr+CR+CW+SMGLH+Fr
G	RE+WE+Gr+CR+SO+SF+Fr+GLH
H	RE+WE+Gr+CR+CW+SO+SF+Fr+GLH

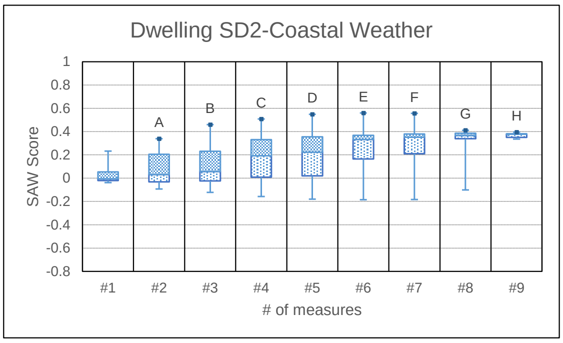
(a)



	Interventions with highest possitive impact by # of measures
A	RE+WE
B	RI+WI+SMGLH
C	RI+WI+Gr+SMGLH
D	RI+WI+Gr+SMGLH+Fr
E	RI+WI+Gr+CR+SMGLH+Fr
F	RI+WI+Gr+CR+CW+SMGLH+Fr
G	RE+WI+Gr+CR+SO+SF+Fr+GLL
H	RE+WE+Gr+CR+CW+SO+SF+Fr+GLM

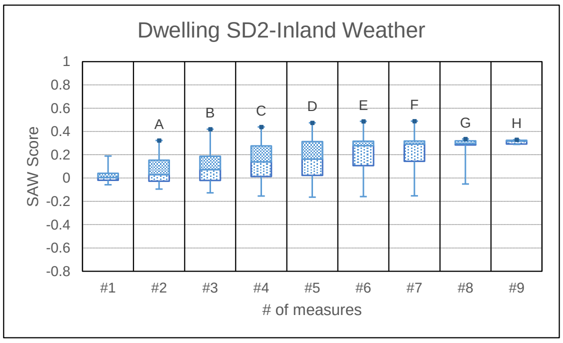
(b)

Figure 5-28 SAW$_{score}$ Dwelling SD1 (a) coastal weather and (b) inland weather



	Interventions with highest possitive impact by # of measures
A	RI+WI
B	RE+WI+SMGLH
C	RE+WI+Gr+SMGLH
D	RE+WI+Gr+CR+SMGLH
E	RI+WI+Gr+CR+SMGLH+Fr
F	RE+WE+Gr+CR+CW+SMGLH+Fr
G	RE+WE+Gr+CR+CW+SF+Fr+GLM
H	RE+WI+Gr+CR+CW+SO+SF+Fr+GLH

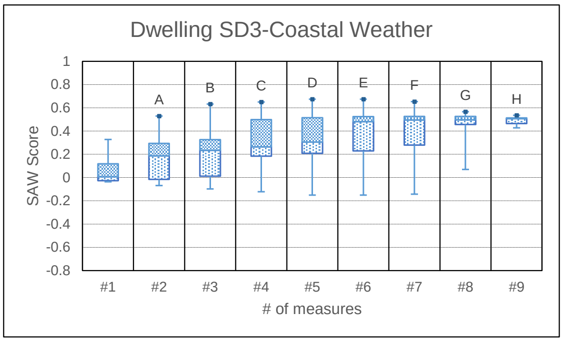
(a)



	Interventions with highest possitive impact by # of measures
A	RI+WI
B	RI+WI+SMGLH
C	RI+WI+CR+SMGLH
D	RI+WI+Gr+CR+SMGLH
E	RI+WI+Gr+CR+SMGLH+Fr
F	RI+WI+Gr+CR+CW+SMGLH+Fr
G	RI+WI+Gr+CR+CW+SF+Fr+GLH
H	RI+WI+Gr+CR+CW+SO+SF+Fr+GLM

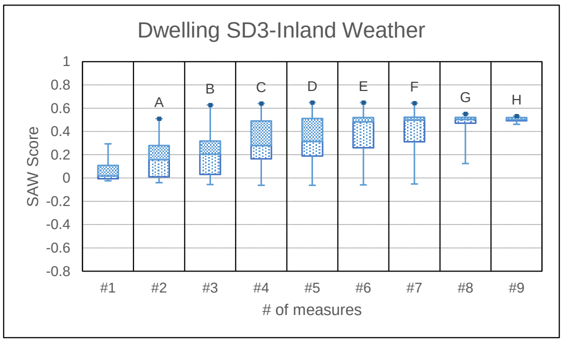
(b)

Figure 5-29 SAW$_{score}$ Dwelling SD2 (a) coastal weather and (b) inland weather



	Interventions with highest possitive impact by # of measures
A	RE+WE
B	RI+WI+SMGLH
C	RI+WI+CR+SMGLH
D	RI+WI+CR+SMGLH+Fr
E	RI+WI+Gr+CR+SMGLH+Fr
F	RI+WI+Gr+CR+CW+SMGLH+Fr
G	RE+WE+Gr+CR+CW+SF+Fr+GLH
H	RI+WI+Gr+CR+CW+SO+SF+Fr+GLH

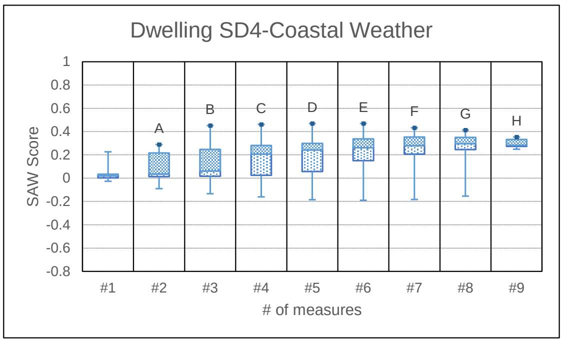
(a)



	Interventions with highest possitive impact by # of measures
A	RE+WE
B	RE+WE+SMGLH
C	RE+WE+SMGLH+Fr
D	RE+WI+CR+SMGLH+Fr
E	RE+WI+Gr+CR+SMGLH+Fr
F	RE+WE+Gr+CR+CW+SMGLH+Fr
G	RE+WI+Gr+CR+CW+SO+Fr+GLH
H	RI+WI+Gr+CR+CW+SO+SF+Fr+GLH

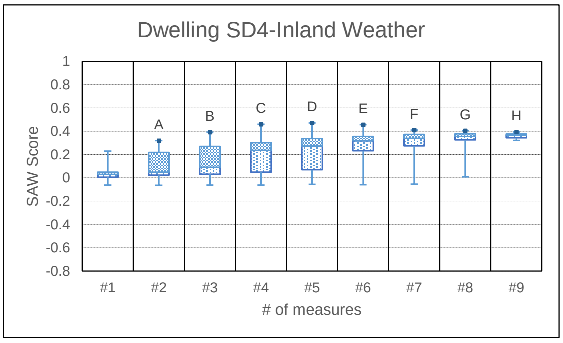
(b)

Figure 5-30 SAW$_{score}$ Dwelling SD3 (a) coastal weather and (b) inland weather



	Interventions with highest possitive impact by # of measures
A	RE+WI
B	RE+WI+SMGLH
C	RE+WI+CR+SMGLH
D	RI+WI+Gr+SMGLH+Fr
E	RE+WI+Gr+CR+SMGLH+Fr
F	RI+WI+Gr+CW+SF+Fr+GLH
G	RI+WI+Gr+CW+SO+SF+Fr+GLH
H	RI+WI+Gr+CR+CW+SO+SF+Fr+GC

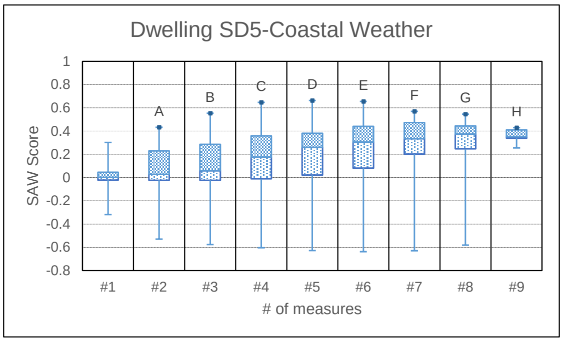
(a)



	Interventions with highest possitive impact by # of measures
A	RI+WI
B	RI+WI+SMGLH
C	RI+WI+Gr+SMGLH
D	RI+WI+Gr+SMGLH+Fr
E	RI+WI+Gr+CW+SMGLH+Fr
F	RI+WI+Gr+CW+SO+Fr+GLH
G	RI+WI+Gr+CW+SO+SF+Fr+GLH
H	RI+WI+Gr+CR+CW+SO+SF+Fr+GLH

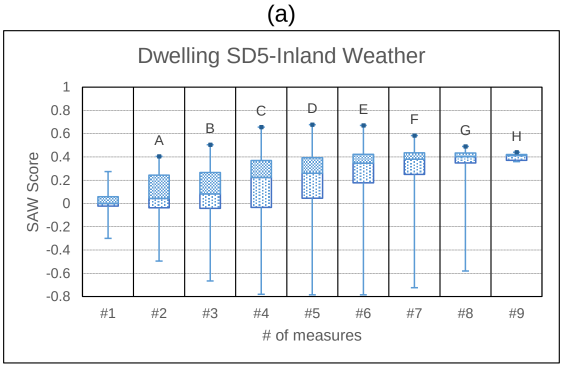
(b)

Figure 5-31 SAW$_{score}$ Dwelling SD4 (a) coastal weather and (b) inland weather



	Interventions with highest possitive impact by # of measures
A	RE+WE
B	RE+WE+Gr
C	RI+WI+Gr+SMGLH
D	RI+WI+Gr+SMGLH+Fr
E	RI+WI+Gr+CW+SMGLH+Fr
F	RE+WE+Gr+CW+SF+Fr+GLH
G	RE+WE+Gr+CW+SO+SF+Fr+GLH
H	RI+WI+Gr+CR+CW+SO+SF+Fr+GC

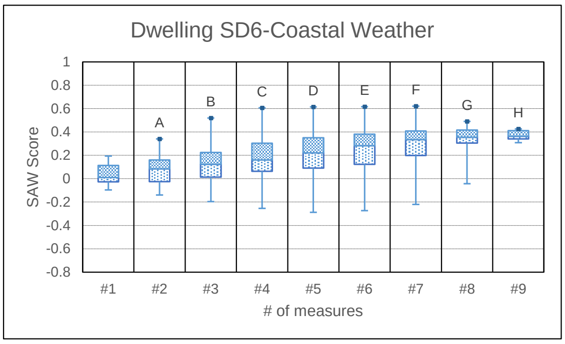
(a)



	Interventions with highest possitive impact by # of measures
A	RI+WI
B	RI+WI+SMGLH
C	RI+WI+Gr+SMGLH
D	RI+WI+Gr+SMGLH+Fr
E	RI+WI+Gr+CW+SMGLH+Fr
F	RI+WI+Gr+CR+CW+SMGLH+Fr
G	RI+WE+Gr+CR+CW+SF+Fr+GLH
H	RI+WI+Gr+CR+CW+SO+SF+Fr+GLH

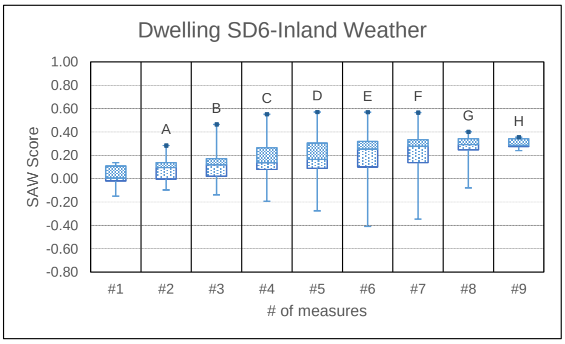
(b)

Figure 5-32 SAW$_{score}$ Dwelling SD5 (a) coastal weather and (b) inland weather



	Interventions with highest possitive impact by # of measures
A	RE+WI
B	RE+WI+SMGLH
C	RE+WE+Gr+SMGLH
D	RE+WE+Gr+SMGLH+Fr
E	RE+WE+Gr+CR+CW+SMGLH
F	RE+WE+Gr+CR+CW+SMGLH+Fr
G	RE+WI+Gr+CR+CW+SO+Fr+GLH
H	RE+WE+Gr+CR+CW+SO+SF+Fr+GLH

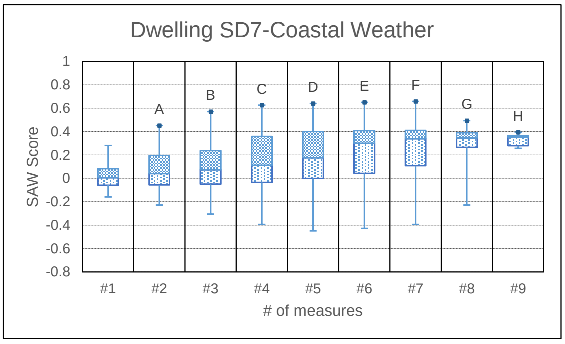
(a)



	Interventions with highest possitive impact by # of measures
A	RI+WI
B	RI+WI+SMGLH
C	RI+WI+Gr+SMGLH
D	RI+WI+Gr+SMGLH+Fr
E	RI+WI+Gr+CW+SMGLH+Fr
F	RI+WI+Gr+CR+CW+SMGLH+Fr
G	RI+WE+Gr+CR+CW+SO+Fr+GLH
H	RI+WI+Gr+CR+CW+SO+SF+Fr+GLH

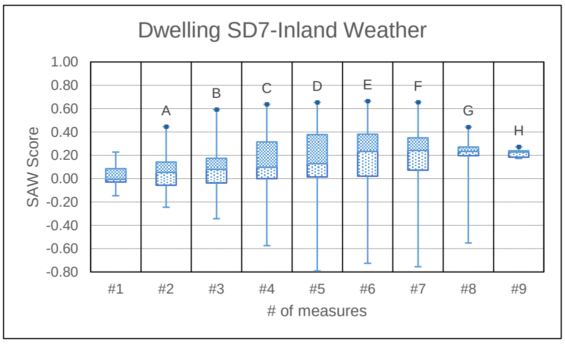
(b)

Figure 5-33 SAW$_{score}$ Dwelling SD6 (a) coastal weather and (b) inland weather



	Interventions with highest possitive impact by # of measures
A	RE+WE
B	RE+WI+SMGLH
C	RE+WI+Gr+SMGLH
D	RE+WI+Gr+CR+SMGLH
E	RE+WI+Gr+CR+SMGLH+Fr
F	RI+WI+Gr+CR+CW+SMGLH+Fr
G	RE+WE+Gr+CR+CW+SO+Fr+GLH
H	RE+WI+Gr+CR+CW+SO+SF+Fr+GLH

(a)



	Interventions with highest possitive impact by # of measures
A	RE+WE
B	RI+WI+SMGLH
C	RI+WE+Gr+SMGLH
D	RI+WE+Gr+SMGLH+Fr
E	RI+WE+Gr+CR+SMGLH+Fr
F	RI+WE+Gr+CR+CW+SMGLH+Fr
G	RI+WE+Gr+CR+CW+SF+Fr+GLH
H	RI+WI+Gr+CR+CW+SO+SF+Fr+GLH

(b)

Figure 5-34 SAW$_{score}$ Dwelling SD7 (a) coastal weather and (b) inland weather

The results initially show that the impact on the performance score is dramatically increased in both directions (negative or positive) by the number of interventions. For all cases, the performance of single intervention is lower with regards to the median and maximum values, compared to the combined interventions.

The optimum SAW_{score} is presented in the categories where 5 or 6 measures are applied, indicating that is not always necessary to adopt a high number of interventions to achieve the maximum performance. However, as will be described in Chapter 6, the final selection of the optimum measure or optimum combination will be founded on the cost analysis of the measures, as the cost effectiveness is defined as a substantial factor on the application of energy saving measures.

In numbers, 16 combinations for each house are presented in Figures (5-28) to (5-34), resulting in 56 combinations for each climatic condition. In essence, the aim is to identify the occurrence of each individual measure in the combinations and draw a general picture on the importance of the measures on the overall annual performance. To this effect, Figure 5-35 present the frequency of occurrence for each measure by the 56 combinations for the two weather files. In more depth, Figure 5-36 presents the frequency of occurrence for each measure, with regards to the optimum combinations by dwelling (7 for each climatic condition).

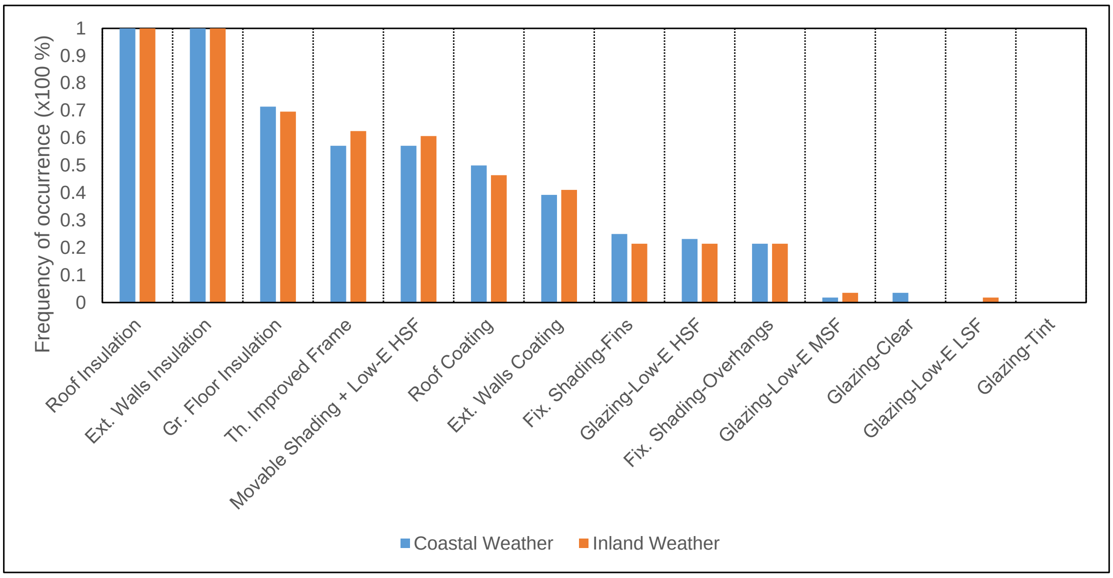


Figure 5-35 Frequency of occurrence for all combinations by climatic condition

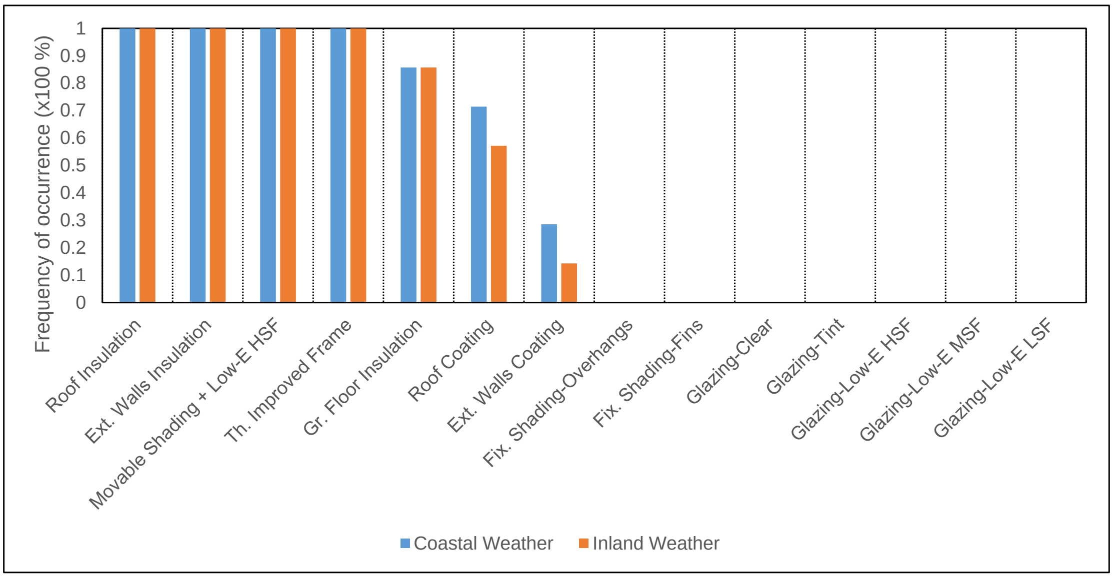


Figure 5-36 Frequency of occurrence for optimum combinations by climatic condition

As it can be observed by Figure 5-35, the results for both climatic conditions are expressing a similar performance. In particular, the roof and external wall thermal insulation were the only measures that were applied in all combinations, followed by ground floor insulation (70%), thermally improved frame (57% coastal and 63% inland) and the strategy of movable shading with high solar factor Low-E glazing (57% coastal and 61% inland). Reflective coating was frequently used, with roof coating slightly more important than wall coating. Fixed shading and Low-E HSF glazing were also applied but in less significance, while the rest of the measures were occasionally adopted.

Now, looking at Figure 5-36, the highest performance seems to be achieved when thermal insulation is applied to the roof, external walls and to a slightly less extent (80%) on ground floor. Movable shading with Low-E HSF glazing and thermally improved frame are also presented in all buildings. The application of these measures are providing a considerable improvement on the overall performance of the dwelling. The roof coating may also enhance the performance of the envelope, as a considerable proportion of houses (70% coastal and 60% inland), utilized this measure. Less significant seems to be the wall coating with (30% coastal and 15 % inland) of application.

Overall, in the perspective of performance, the addition of multiple measures may increase the maximum impact SAW_{score} up to 1.2 to 3 times for coastal and 1.2 to 4 times for inland, compared single interventions. However, increasing the number of measures, leads to a rise in the capital cost of the investment, which is not always desirable from the consumer's point of view. The trade-offs between performance and cost will be further discussed in Chapter 6.

It can be concluded that in the context of envelope performance, the insulation of opaque elements with roof coating, thermally improved frame, movable shading and HSF Low-E glazing can achieve the highest performance, while balancing the effect of energy consumption, CO_2 emission and thermal indoor environment.

5.4 SUMMARY

This chapter presented the analysis of the results by the integration of energy saving measures on existing residential envelopes. In particular, the analysis was focused on the effect of seasonal energy consumption and thermal indoor conditions. The results were based on the analysis of 7 detached dwellings that were previously calibrated (see Chapter 4).

Generally, the results indicated that the implication of envelope measures are directly coherent with the seasonality of the outdoor conditions, especially in climates with equal dominant seasons. The only measure that is incoherent with the fluctuation of seasons, is the roof insulation.

Initially, four categories of measures were investigated, contacting a plethora of parameters coherent with their characteristics. The second part of this chapter investigated the synergies between the interventions. A discussion will be developed in Chapter 6, comparing the performance and prioritizing the measures. To this effect, a feasibility study will also be presented, in order to ensure the future rationalistic application of the measures.

Chapter 6. FURTHER ANALYSIS AND PRIORITIZATION

6.1 INTRODUCTION

In Chapter 5, the interventions were assessed with regards to their impact on the primary energy consumption and indoor thermal environment. A further analysis has been undertaken to evaluate the measures from a feasibility perspective, as in practise cost is a substantial factor. To this effect, this chapter seeks to determine the optimum solutions for retrofitting existing domestic buildings, considering primarily the impact on cost effectiveness, while complying with the trade-offs between energy reduction and thermal comfort.

The prioritization of solutions will be based on the estimation of NPV, a financial indicator that expresses the feasibility of investment. According to the literature, the period of 30 years is considered as the period of financial evaluation, for ESM coherent with residential building envelopes. Due to the long investment horizon, the estimation of NPV is subjective to uncertainties associated with the values of the input parameters. Consequently, in order to mitigate with the uncertainty, a risk analysis was adopted based on the statistical distribution of parameters (see section 3.6.3).

Initially, the chapter presents the evaluation of the single interventions, based on their parameters and properties that were discussed in Chapter 5. In the single intervention assessment, the air-tightness was not evaluated, due to the absence of economic data regarding its application. The latter section of this chapter describes the prioritization of combined interventions, comparing also the performance of the single interventions over the synergies of the combined measures.

6.2 Single Interventions

This section presents the economic assessment of envelope interventions under two climate scenarios (coastal and inland). Through the financial evaluation of the measures, a general guidance will be drawn, in order to define the most cost effective retrofitting solution.

As a matter of normalization, an assessment scale (0-9) was developed, in order to accommodate with the differences between the case studies. In particular, the buildings under investigation were actual dwellings, differing substantially on the layout, orientation and HVAC systems. In essence, the scale was applied to normalize the effect of individual properties, contributing on the prioritization of the measures. The scale is based on the classification of the measures based on the maximum performance and the range between the highest and lowest value, observed for the category of the measures. For instance, the number 9 of the scale corresponds to the highest value, occurred for every case study. The rest of the measures are classified with regards to the highest value.

In order to draw a clear picture about the performance and selection of the optimum measures, the evaluation procedure also considers the annual energy impact and the thermal comfort score. The measures that will be financially assessed, must comply with the following constraints:

a. Have positive impact on the annual primary energy consumption.
b. The thermal comfort score does not exist below -2% during either winter or summer periods.

Driven by the constraints set for the optimization of the alternative solutions, Figures (6-1) and (6-2) are graphically summarizing the variation of NPV_{mean} over the positive impact on the annual primary energy. Additionally, the measures are classified according to their annual thermal comfort performance.

In general, the Figures (6-1) and (6-2) can be divided into 4 regions of performance; a) lower left region-high NPV and high energy impact, b) lower right region-high NPV and low energy impact, c) upper left region-low NPV and high energy impact and d) upper right region-low NPV and low energy impact. In essence, the solutions appeared in the regions (a) and (b) are suitable in the perspective of retrofitting, with the region (a) to be considered as the most attractive due to the cost and energy effectiveness. However, the classification of the solutions was also based on the impact on the indoor thermal environment. As it can be noticed from the graphs, there are measures where the thermal comfort is seasonally affected, with reverse performance between winter and summer seasons. Therefore, a measure was considered as a suitable retrofitting option only when the thermal comfort was not compromised throughout the year.

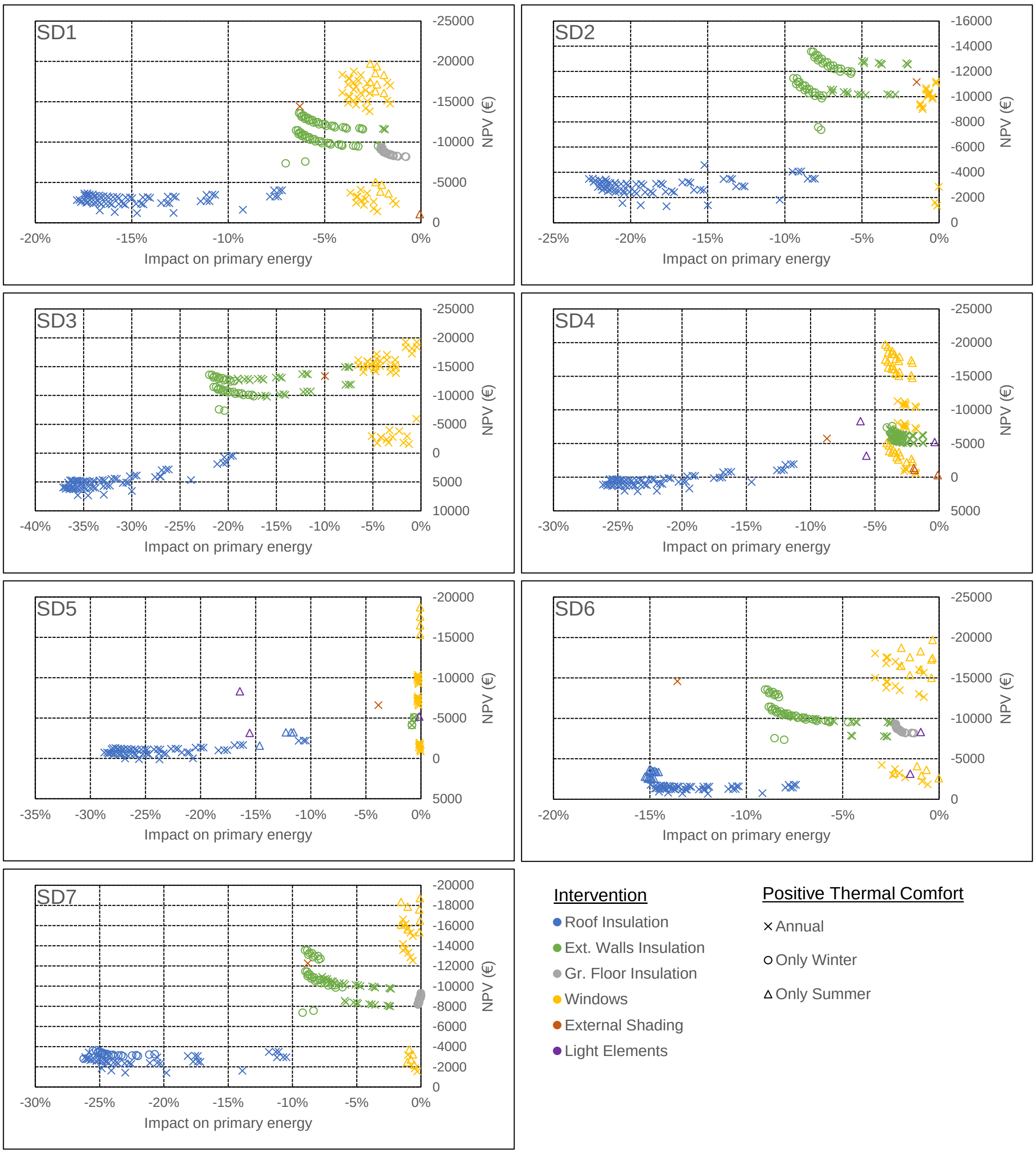


Figure 6-1 NPV-Impact on primary energy consumption-Coastal Weather

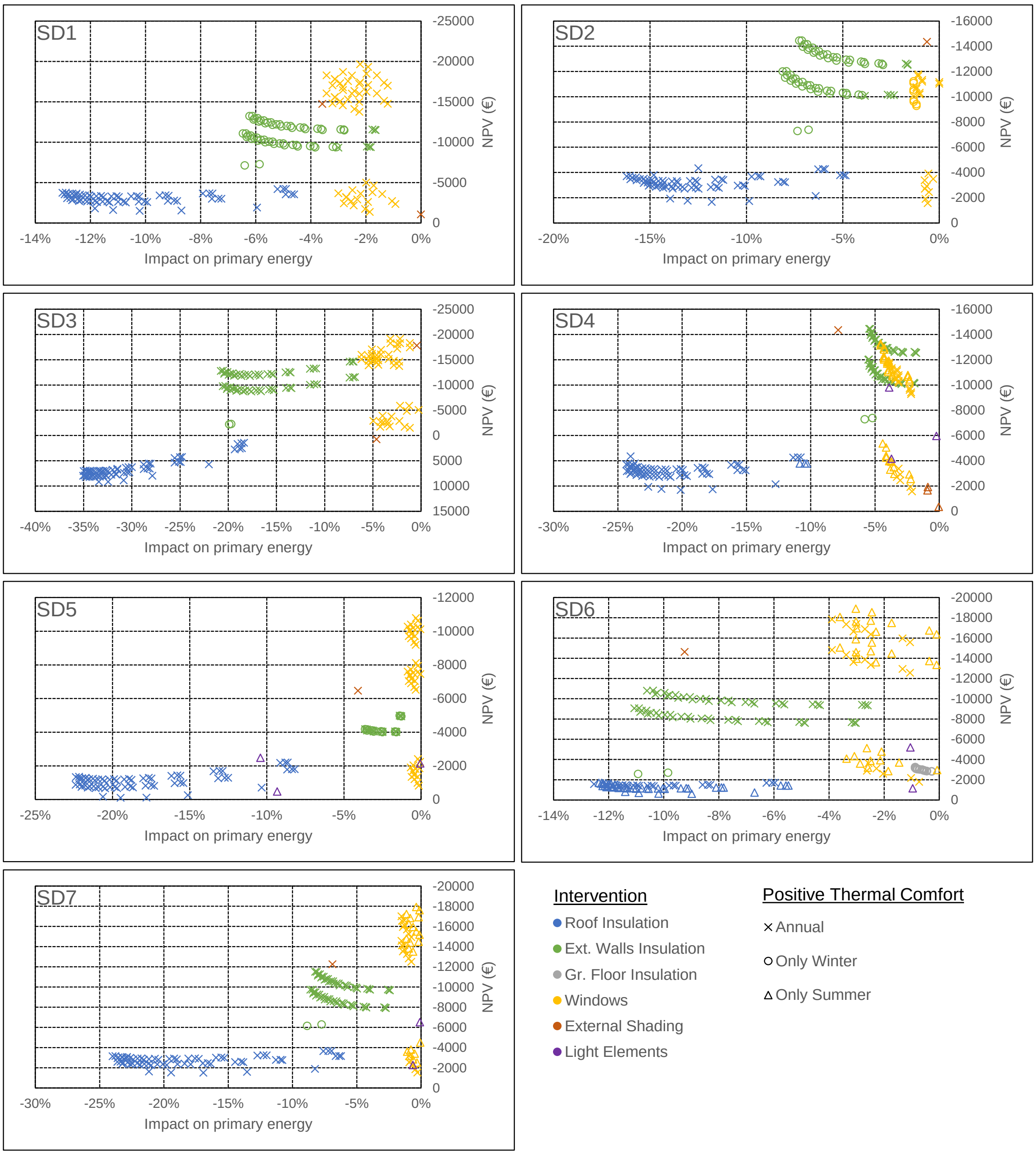


Figure 6-2 NPV-Impact on primary energy consumption-Inland Weather

The primary outcome from the Figures (6-1) and (6-2) is the advantageous performance of the roof insulation. As a solution may be considered as the most energy and cost efficient measure for climates with hot-dry summers and mild-wet winters, with also a positive annual impact on thermal comfort.

Following the concept of the 9-point assessment scale, the impact of material and thickness on the NPV_{mean} is depicted in the Figure 6-3.

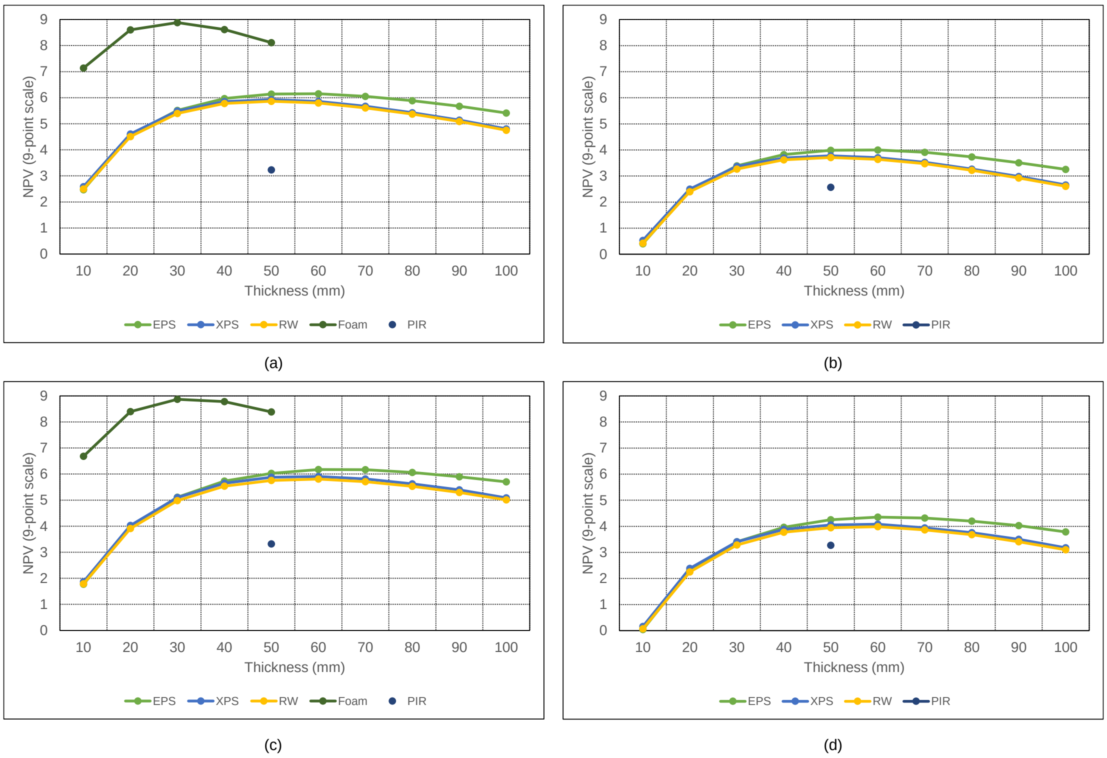


Figure 6-3 Roof thermal insulation-NPV (a) coastal-external, (b) coastal-internal, (c) inland external and (d) inland-internal

It can be clearly noticed that the foam polyurethane has the highest NPV score, with an optimum thickness of 30mm for both climate scenarios. Now, on the rest materials the EPS polystyrene presents slightly better performance with optimum thickness at 60mm. On the case of the XPS polystyrene and Rockwool, the thickness varies between 50mm (coastal) and 60mm (inland). The lowest NPV occurs for the case of the PIR material due to the high capital cost. In general, the NPV is reduced for thicker materials, underlying that in practise “the more, the better” is not always desirable. The same scene is repeated for the internal insulation, however with lower scores of NPV.

On the external wall insulation, the applicability of this intervention is not always considerable, as in some cases it is compromising the overall performance of the building enclosure. In particular, for materials higher than

40mm the summer thermal environment is compromised, violating the trade-offs between energy and thermal comfort. Figure 6-4 presents the findings from the application of wall insulation.

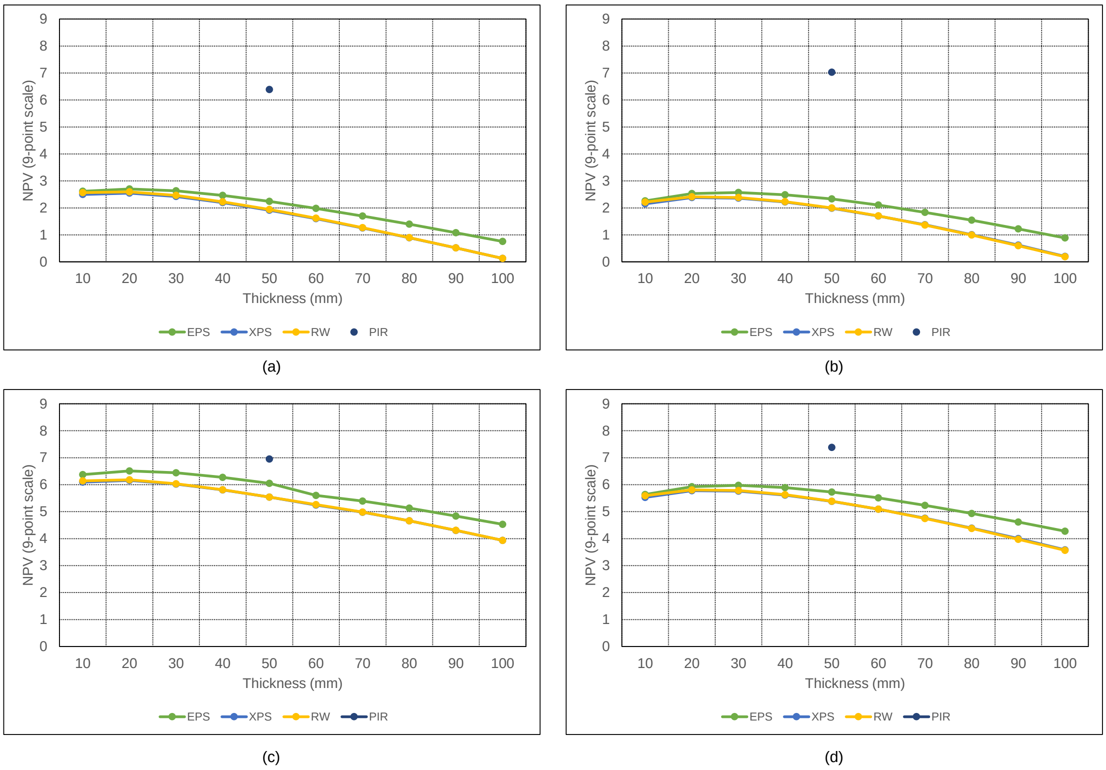


Figure 6-4 External wall thermal insulation-NPV (a) coastal-external, (b) coastal-internal, (c) inland external and (d) inland-internal

For the case of wall insulation, due to the capital cost of internal application the arrangement of the element is opposed in relation to the roof insulation. The internal insulation presents higher values of NPV, making the particular arrangement more attractive for adoption. Regarding to the optimum thickness, the 20mm (coastal) and 30mm (inland) have the higher NPV, for all materials. However, in the case of coastal climate, the 20mm does not complying with the minimum standard of U-value of the current building regulations and consequently, the closest thickness for selection is the 30mm.

On the ground floor insulation, the impact on energy consumption and thermal comfort is seasonally affecting the performance of the buildings and as a result, may not be considered a single alternative solution.

On reflective coating, the same scene is presented as in the case of ground floor insulation, where the summer performance cannot compensate the negative impact during the winter season. In spite the fact of the high amount of solar insolation and the benefits during the summer season, the winter performance is compromised, resulting in poor annual performance.

On the window system, the double clear glazing (6mm-12mm-4mm) seems to be adequate for such weather conditions, as only the SD3 and SD4 houses perform better with a Low-e HSF glazing. A considerable performance is also presented by the application of argon fill on the double clear glazing, with slightly lower NPV. The application of frame seems to improve slightly the annual energy impact, however due to the high cost of installation, the frame is not considered as feasible solution for retrofitting. However, it is important to mention the synergies when replacing the frame system in an existing building envelope. For instance, the application of a frame system may significantly contribute on the tightening of the house and thus, the reduction of air infiltration. In this study, this effect was not studied, as only the U-value of a thermally improved frame was examined. Nevertheless, the application of 6mm-12mm-4mm clear double glazing is considered adequate for Mediterranean conditions.

On the shading system, in spite the higher capital cost of the movable shading compare to the fixed, the performance of the buildings was enhanced due to the adaptivity of the intervention on the seasonality of the weather conditions. The performance of fixed external shading is subjective to the seasonal loads, varying between summer and winter seasons.

6.2.1 Prioritization of Single Interventions

In this section, the outcome will be summarized, contributing to the development of a general guidance for the application of single interventions on existing domestic buildings. The results by the application of the 9-point assessment scale are presented in Figures (6-5) and (6-6), with the impact on the primary energy consumption for coastal and inland weather conditions, accordingly.

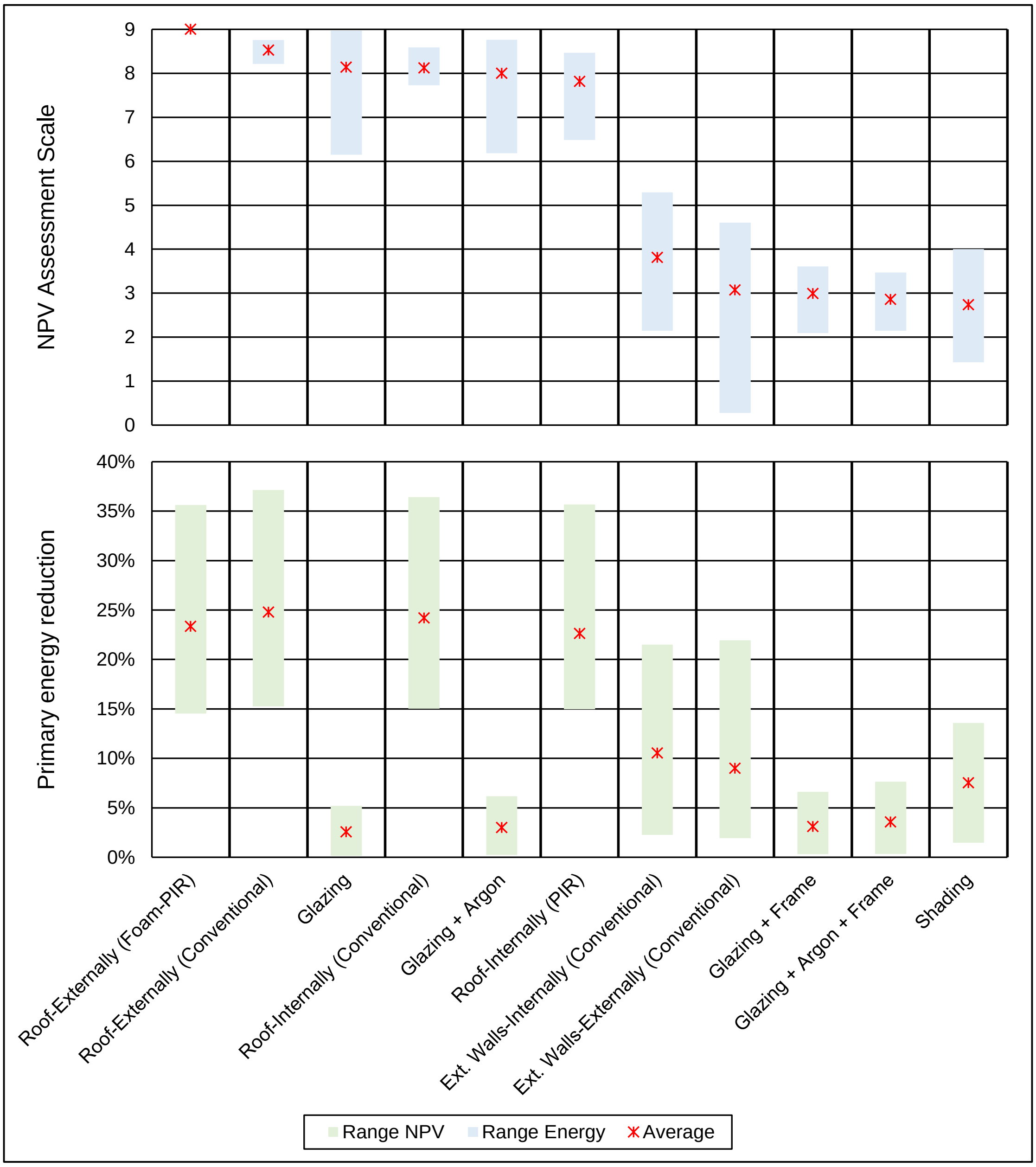


Figure 6-5 Average NPV score and primary energy reduction-Coastal Weather

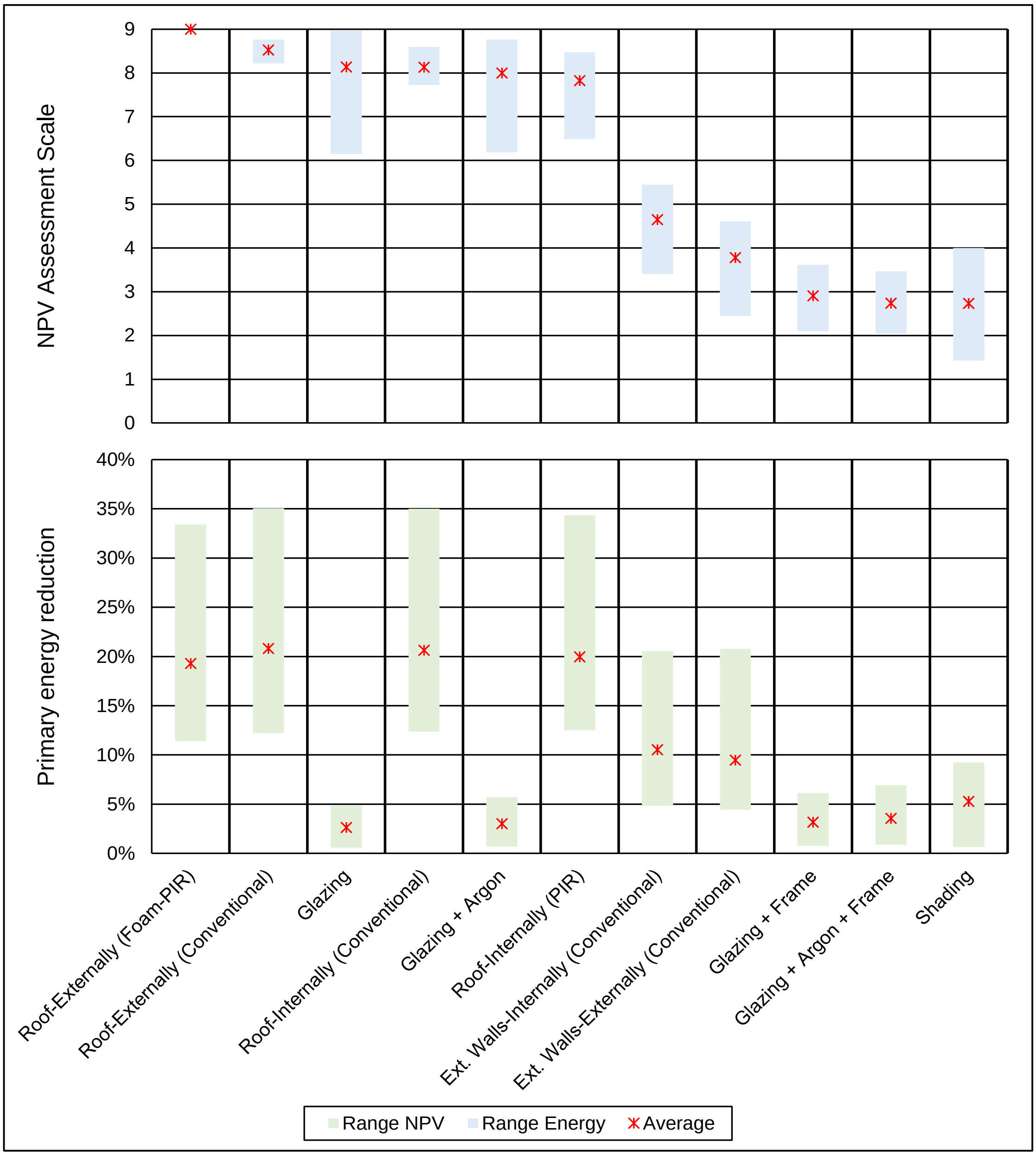


Figure 6-6 Average NPV score and primary energy reduction-Inland Weather

Initially, from Figures (6-5) and (6-6), it can be noticed that the measures are classified into two categories; (a) high NPV and (b) low NPV, regardless to the annual primary energy reduction. Overall, the scene occurs in both climate conditions. The first category comprises the measures coherent with the roof insulation and upgrade of glazing system. The latter category consists of the insulation of external walls, upgrade of frame system and the external shading devices.

The application of external roof insulation seems to be the most cost effective measure for the retrofitting of existing dwellings, with the foam polyurethane (30mm) ranked highest for both climates. This is followed by the external application of EPS-polystyrene, XPS-polystyrene and Rock Wool (50-60mm) on the roof. A remarkable outcome is the performance of glazing system. It is ranked 3rd (double clear glazing) and 5th (double clear glazing + argon fill) measure with the highest NPV. In the case of the glazing upgrade, looking at the impact on energy consumption, as a solution contributes to the lower on average reduction. This is primarily resulted by the capital cost of the application. In 4th and 6th place, the internal insulation of the roof with polystyrene, rock wool and PIR is presented, respectively.

As aforementioned, the range of annual energy consumed is dependent on the default construction, layout, orientation and HVAC systems. However, the importance of single interventions is described by the application of the 9-scale assessment, as the results are normalized in order to compare the optimum solutions from the categories of interventions.

In conclusion, Table 6-1 summarizes the results by the investigation of the single interventions with regards to cost effectiveness evaluation, referring also the average impact on the primary energy consumption.

Table 6-1 Prioritization of single interventions

RANK	CATEGORY	ENERGY SAVING MEASURE	AVERAGE NPV (ON ASSESSMENT SCALE)		AVERAGE ENERGY REDUCTION (%)	
			COASTAL	INLAND	COASTAL	INLAND
1	Roof thermal insulation	*30mm Foam Polyurethane, Externally*	9.0	9.0	23	19
2	Roof thermal insulation	*50mm (coastal)-60mm (inland) of EPS-polystyrene, XPS-polystyrene and Rock Wool [+], Externally*	8.5	8.5	25	21
3	Fenestration	*Double Clear Glazing (6mm-12mm-4mm)***	8.1	8.1	3	3
4	Roof thermal insulation	*50mm (coastal)-60 mm (inland) of EPS-polystyrene, XPS-polystyrene and Rock Wool, Internally*	8.1	8.1	24	21
5	Fenestration	*Double Clear Glazing (6mm-12mm-4mm)** + Argon fill*	8.0	8.0	3	3
6	Roof thermal insulation	*50mm PIR material, Internally*	7.8	7.8	23	20
7	Ext. walls thermal insulation	*30mm of EPS-polystyrene, XPS-polystyrene and Rock Wool, Internally*	3.8	4.6	11	11
8	Ext. walls thermal insulation	*30mm of EPS-polystyrene, XPS-polystyrene and Rock Wool, Externally*	3.1	3.8	9	9
9	Fenestration	*Double Clear Glazing (6mm-12mm-4mm)** + UPVC Frame*	3.0	2.9	3	3
10	Fenestration	*Double Clear Glazing (6mm-12mm-4mm)**+Argon+ UPVC Frame*	2.9	2.7	4	4
11	Shading Device	*Movable Shading*	2.7	2.7	8	5

Notes:

***The case of SD3 and SD4 building presented better performance with Low-E HSF (p3) glazing*

[+] In general, EPS polystyrene shows better performance than the rest materials

Overall, the outcome from the analysis of single interventions agrees with previous studies that have been carried out in Cyprus. In spite the fact that the authors were investigated the impact of measures on new dwellings, the importance of roof insulation was mentioned (Florides et al., 2000; Kalogirou et al., 2002; Panayi, 2004).

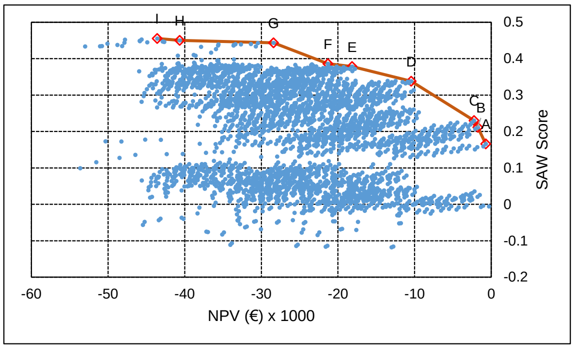
6.3 Single or Combined Interventions

In the previous section, the application of single interventions was assessed with regards to the viability as an investment under a 30 year horizon. This section extends the assessment by the evaluation of measures either as single interventions or as a combination of the alternatives. The outcome will finally contribute on the establishment of the optimum measures for two climate scenarios that are experienced in the wider area of Cyprus.

Due to the amount of the data, the results will be initially based on the adoption of NPV and SAW_{score}, following the concept of multi-objective optimization. However, in this manner of optimization, there is not a single solution that satisfies the constraints of the problem. To this effect, the approach of selection of optimum solutions from the case studies will be based on the selection of representative solutions, so-called Pareto Frontiers or Pareto Optimal (see section (3.6.3)). By the establishment of the Pareto Frontiers, the 9-point assessment procedure will be applied to normalize the results and draw a general picture on the optimum measures for each climate scenario (coastal and inland weather files).

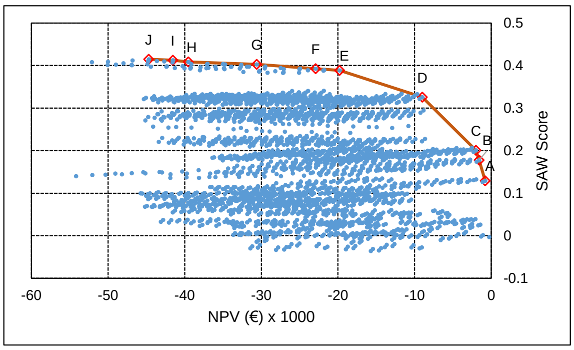
6.3.1 Performance of Interventions

Following, the concept of the Pareto multi-objective method, the optimization is based on the NPV and SAW_{score}. Figures (6-7) to (6-13) show the distribution of the results based on the optimization criteria. Based on the aim of the study, the solutions close to the upper right region (high SAW_{score} and high NPV) are the most attractive options for retrofitting. However, as a multi-objective problem, there is not a single solution. In essence, for every building a set of solutions (frontiers-red points) was selected, driven by the Pareto method, described earlier. The Pareto frontiers declared that there was not better solution to the optimization region. On the following graphs, a red line connects all the Pareto frontiers, highlighting the limits of the optimum region (top-right corner).



	Pareto Frontiers
A	RE
B	RE+GC
C	RE+GLH
D	RE+WI+GLH
E	RE+WI+Gr+GLM
F	RE+WI+SM+GLH
G	RE+WI+Gr+SM+GLH
H	RE+WI+Gr+SM+Fr+GLH
I	RE+WI+Gr+CR+SM+Fr+GLH

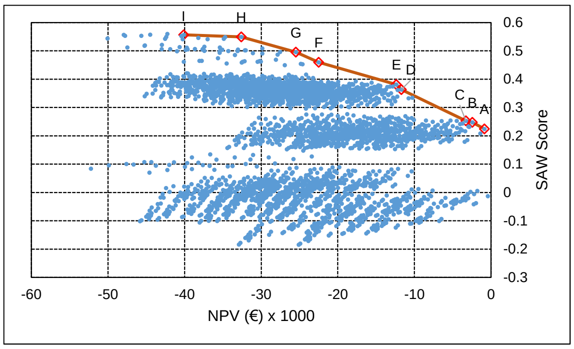
(a)



	Pareto Frontiers
A	RE
B	RE+GC
C	RE+GLH
D	RE+WI+GLH
E	RE+WI+SM+GLH
F	RE+WI+CR+SM+GLH
G	RE+WI+Gr+CR+SM+GLH
H	RE+WI+Gr+SM+Fr+GLH
I	RE+WI+Gr+SM+Fr+GLH
J	RE+WI+Gr+CR+SM+Fr+GLH

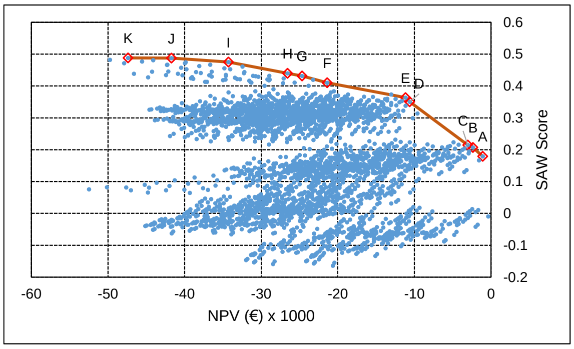
(b)

Figure 6-7 Pareto frontiers Dwelling SD1 (a) coastal weather and (b) inland weather



	Pareto Frontiers
A	RE
B	RE+GC
C	RE+GLH
D	RE+WI+GC
E	RE+WI+GLH
F	RE+WI+SM+GLH
G	RE+WI+CR+SM+GLH
H	RE+WI+Gr+CR+SM+GLH
I	RE+WI+Gr+CR+SM+Fr+GLH

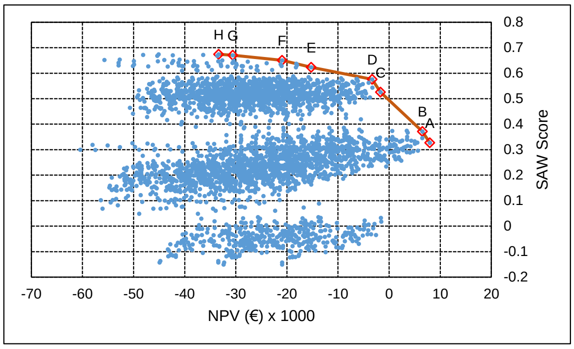
(a)



	Pareto Frontiers
A	RE
B	RE+GC
C	RE+GLH
D	RE+WI+GC
E	RE+WI+GLH
F	RE+WI+SM+GLH
G	RE+WI+CR+SM+GLH
H	RE+WI+CR+SM+GLH
I	RE+WI+Gr+CR+SM+GLH
J	RE+WI+Gr+CR+SM+Fr+GLH
K	RE+WI+Gr+CR+CW+SM+Fr+GLH

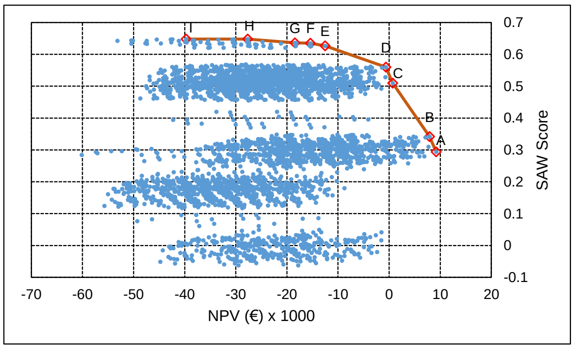
(b)

Figure 6-8 Pareto frontiers Dwelling SD2 (a) coastal weather and (b) inland weather



	Pareto Frontiers
A	RE
B	RE+GLH
C	RE+WI
D	RE+WI+GLH
E	RE+WI+SM+GLH
F	RE+WI+CR+SM+GLH
G	RE+WI+CR+SM+Fr+GLH
H	RE+WI+CR+SM+Fr+GLH

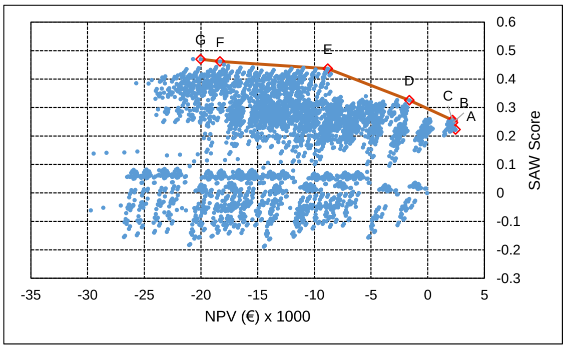
(a)



	Pareto Frontiers
A	RE
B	RE+GLH
C	RE+WI
D	RE+WI+GLH
E	RE+WI+SM+GLH
F	RE+WI+CR+SM+GLH
G	RE+WE+CR+SM+GLH
H	RE+WI+CR+SM+Fr+GLH
I	RE+WI+Gr+CR+SM+Fr+GLH

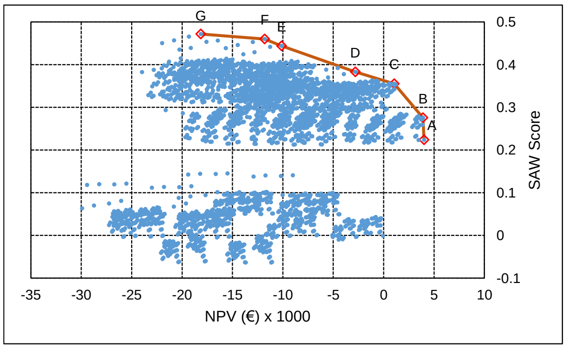
(b)

Figure 6-9 Pareto frontiers Dwelling SD3 (a) coastal weather and (b) inland weather



	Pareto Frontiers
A	RE
B	RE+GC
C	RE+GLH
D	RE+WI+GLH
E	RE+WI+Gr+GLH
F	RE+WI+CR+SM+GLH
G	RE+WI+Gr+CR+SM+Fr+GLH

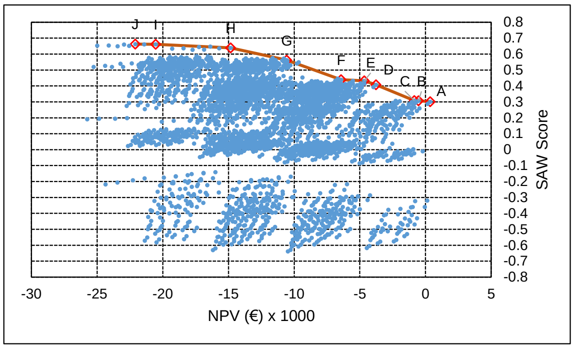
(a)



	Pareto Frontiers
A	RE
B	RE+GLH
C	RE+WI+GLH
D	RE+WI+SM+GLH
E	RE+WI+Gr+SM+GLH
F	RE+WI+Gr+SM+GLH
G	RE+WI+Gr+SM+Fr+GLH

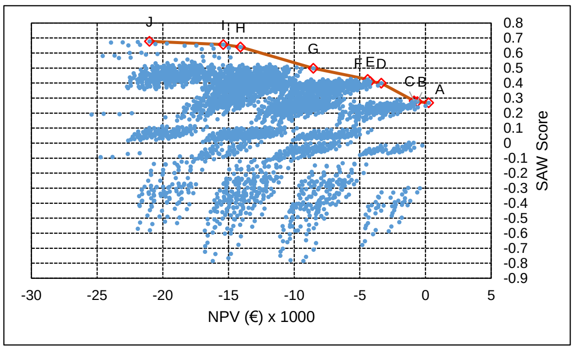
(b)

Figure 6-10 Pareto frontiers Dwelling SD4 (a) coastal weather and (b) inland weather



	Pareto Frontiers
A	RE
B	RE+GC
C	RE+GLH
D	RE+WI
E	RE+WE
F	RE+Gr+GC
G	RE+WI+Gr+GC
H	RE+WI+Gr+SM+GLH
I	RE+WI+Gr+SM+Fr+GLH
J	RE+WI+Gr+SM+Fr+GLH

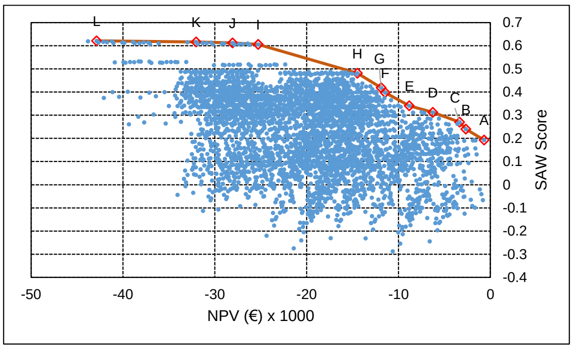
(a)



	Pareto Frontiers
A	RE
B	RE+GC
C	RE+GLH
D	RE+WI
E	RE+WI+GC
F	RE+WI+GLH
G	RE+WI+SM+GLH
H	RE+WI+Gr+SM+GLH
I	RE+WI+Gr+SM+GLH
J	RE+WI+Gr+SM+Fr+GLH

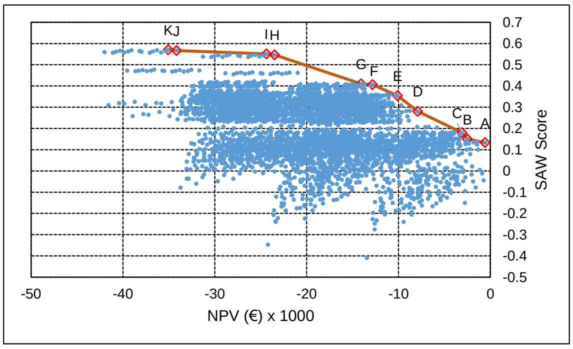
(b)

Figure 6-11 Pareto frontiers Dwelling SD5 (a) coastal weather and (b) inland weather



	Pareto Frontiers
A	RE
B	RE+GC
C	RE+GLH
D	RE+Gr+GLH
E	RE+WI
F	RE+WI+GLH
G	RE+WI+Gr
H	RE+WI+Gr+GLM
I	RE+WI+Gr+SM+GLH
J	RE+WE+Gr+CR+SM+GLH
K	RE+WE+Gr+CR+CW+SM+GLH
L	RE+WE+Gr+CR+CW+SM+Fr+GLH

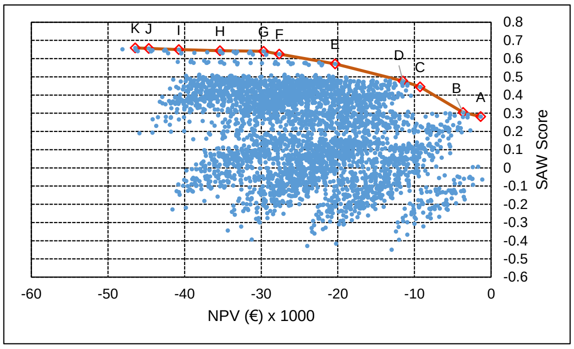
(a)



	Pareto Frontiers
A	RE
B	RE+GC
C	RE+GLH
D	RE+WI
E	RE+WI+GLH
F	RE+WI+Gr+GLH
G	RE+WI+Gr+CR+GLH
H	RE+WI+Gr+SM+GLH
I	RE+WI+Gr+SM+GLH
J	RE+WI+Gr+SM+Fr+GLH
K	RE+WI+Gr+SM+Fr+GLH

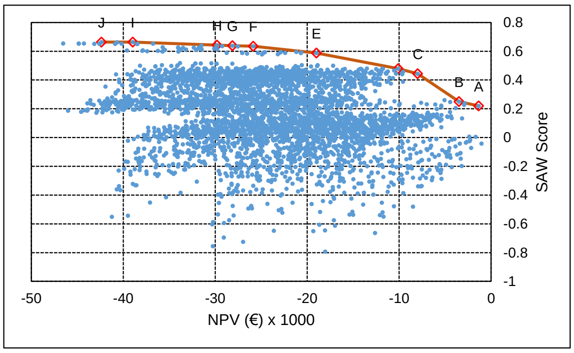
(b)

Figure 6-12 Pareto frontiers Dwelling SD6 (a) coastal weather and (b) inland weather



	Pareto Frontiers
A	RE
B	RE+GLH
C	RE+WI
D	RE+WI+GLH
E	RE+WI+SM+GLH
F	RE+WI+Gr+SM+GLH
G	RE+WI+Gr+CR+SM+GLH
H	RE+WI+Gr+CR+CW+SM+GLH
I	RE+WI+Gr+CR+SM+Fr+GLH
J	RE+WI+Gr+CR+CW+SM+Fr+GLH
K	RE+WI+Gr+CR+CW+SM+Fr+GLH

(a)



	Pareto Frontiers
A	RE
B	RE+GLH
C	RE+WI
D	RE+WI+GLH
E	RE+WI+SM+GLH
F	RE+WI+Gr+SM+GLH
G	RE+WI+Gr+CR+SM+GLH
H	RE+WI+Gr+CR+SM+GLH
I	RE+WI+Gr+CR+SM+Fr+GLH
J	RE+WE+Gr+CR+SM+Fr+GLH

(b)

Figure 6-13 Pareto frontiers Dwelling SD7 (a) coastal weather and (b) inland weather

Overall, it can be noticed that the upgrade of roof insulation appears in every combination, proving the importance of roof as a building element and the impact of its thermal insulation. This is followed by upgrade of external wall insulation and the replacement of glazing system either by a double clear or a Low-E (HSF) glazing.

Ideally, the top-right direction in the graphs is associated with the optimum solutions. In essence, the interventions yield to this direction without dominating by any other point are selected as the optimum solutions. It can be clearly observed that the SAW_{score} is relatively improved, as the number of the measures is increased, presenting the impact of the synergies between the measures. However, this corresponds to higher capital cost and thus, lower NPV value.

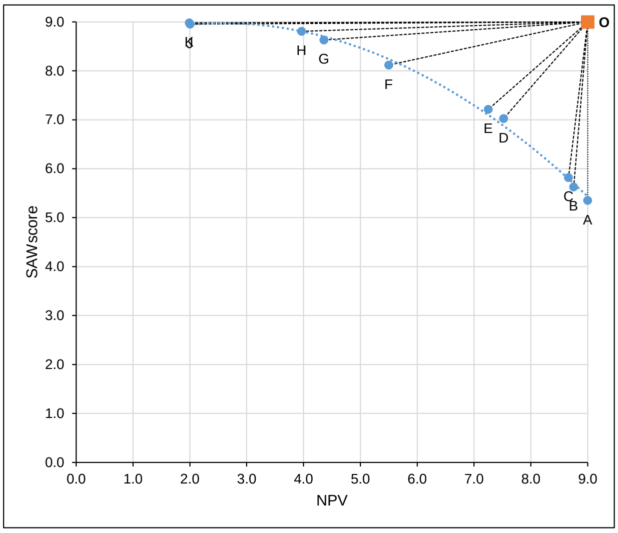
In essence, the results can be primarily analysed by two perspectives; a) high NPV and b) high SAW_{score}. For every case, it was noticed that the upgrade of external roof insulation seems to be adequate, as the performance of the building was improved, while the NPV is maintained at high levels. This is in the same line of thought as the consumer's perspective, as the NPV is the most critical factor on a retrofitting investment. A relatively similar performance is also presented by the combination of roof insulation with double clear (initially presented for cases with single or inefficient double glazing on the default construction) or Low-E HSF glazing, where NPV is slightly decreased and SAW_{score} is increased.

Higher levels of SAW_{score}, can be achieved by applying thermal insulation on external walls, maintaining the upgrade of roof insulation. Again, similar performance is presented when the existing glazing system is replaced by double clear, Low-E HSF or Low-E MSF glazing. These combinations define the medium-performance category where the SAW_{score} is relatively increased compared the low-category. However, in this category the improved performance is associated with lower NPV values, due to the higher capital cost.

The last category of combinations is determined by the highest performance score and a substantial capital cost. Neglecting the capital cost (and thus, the NPV), this category of interventions can substantially contribute on the reduction of the primary energy and associated CO_2 emissions, by the existing housing inventory (tracing back to national level), while the indoor thermal environment is not compromised.

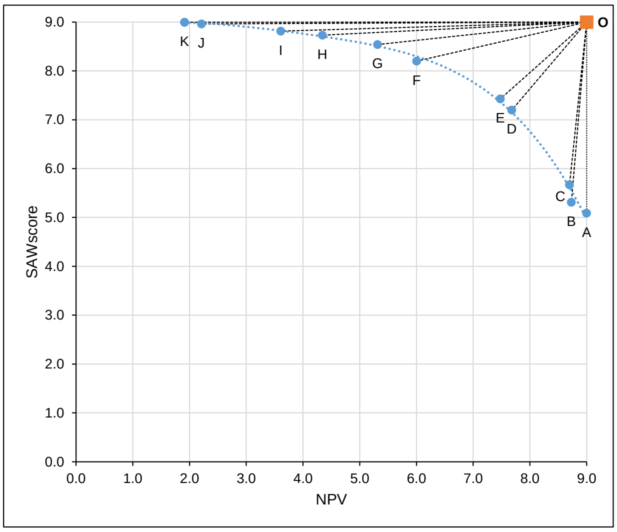
6.3.2 PRIORITIZATION OF INTERVENTIONS

In the previous section, the Pareto Frontiers were established for every case study, classifying their performance in three categories (low, medium and high performance). Under the scope of optimization, at this point the analysis gives an attention only on the Pareto Frontiers, in order to globalize the prioritization of the measures. To this effect, the Pareto optimals for each individual case study is normalized on the 9-point assessment scale with regards to the NPV and SAW_{score}. The analysis comprises the Pareto solutions that occurred in more than 3 houses. Subsequently, the average value, for each assessment factor, was estimated. Figures (6-14) and (6-15) depict the results, for coastal and inland weather conditions, respectively.



	Intervention
A	RE
B	RE+GC
C	RE+GLH
D	RE+WI
E	RE+WI+GLH
F	RE+WI+SM+GLH
G	RE+WI+CR+SM+GLH
H	RE+WI+Gr+SM+GLH
I	RE+WI+Gr+SM+Fr+GLH
J	RE+WI+Gr+CR+SM+Fr+GLH

Figure 6-14 Average performance of Pareto Frontiers-coastal weather



	Interventions
A	RE
B	RE+GC
C	RE+GLH
D	RE+WI
E	RE+WI+GLH
F	RE+WI+SM+GLH
G	RE+WI+CR+SM+GLH
H	RE+WI+Gr+SM+GLH
I	RE+WI+Gr+CR+SM+GLH
J	RE+WI+Gr+SM+Fr+GLH
K	RE+WI+Gr+CR+SM+Fr+GLH

Figure 6-15 Average performance of Pareto Frontiers-inland weather

In order to rank the measures, the perpendicular distance of each measure to the optimum point O (NPV=9, SAWscore=9) is calculated. The size of the perpendicular distance defines the performance of the measure, establishing the optimal solution of the multi-objective assessment.

Table 6-2 Prioritization of Pareto Frontiers

<table>
<tr><th rowspan="3">INDEX ON GRAPHS</th><th rowspan="3">STRATEGY</th><th colspan="2" rowspan="2">PERPENDICULAR DISTANCE</th><th colspan="2" rowspan="2">RANK</th><th colspan="8">DETAILS</th></tr>
<tr><th colspan="3">Thermal Insulation</th><th colspan="2">Reflective Coating*</th><th rowspan="2">Shading</th><th rowspan="2">Frame</th><th rowspan="2">Fenestration</th></tr>
<tr><th>Coastal</th><th>Inland</th><th>Coastal</th><th>Inland</th><th>Roof</th><th>Ext. Walls</th><th>Gr. Floor</th><th>Roof</th><th>Ext. Walls</th></tr>
<tr><td>A</td><td>RE</td><td>3.65</td><td>3.91</td><td>6</td><td>7</td><td rowspan="11">Externally, Foam polyurethane 30mm or Externally, EPS-polystyrene, XPS-polystyrene and Rock Wool 50-60mm</td><td rowspan="3">-</td><td rowspan="7">-</td><td rowspan="6">-</td><td rowspan="11">-</td><td rowspan="5">-</td><td rowspan="9">-</td><td>-</td></tr>
<tr><td>B</td><td>RE+GC</td><td>3.38</td><td>3.70</td><td>4</td><td>5</td><td>Double Clear</td></tr>
<tr><td>C</td><td>RE+GLH</td><td>3.20</td><td>3.35</td><td>3</td><td>4</td><td>Double Low-E HSF</td></tr>
<tr><td>D</td><td>RE+WI</td><td>2.47</td><td>2.23</td><td>1</td><td>2</td><td rowspan="8">Internally, EPS-polystyrene, XPS-polystyrene and Rock Wool 30mm</td><td>-</td></tr>
<tr><td>E</td><td>RE+WI+GLH</td><td>2.50</td><td>2.19</td><td>2</td><td>1</td><td rowspan="7">Double Low-E HSF</td></tr>
<tr><td>F</td><td>RE+WI+SM+GLH</td><td>3.61</td><td>3.10</td><td>5</td><td>3</td><td rowspan="6">Movable</td></tr>
<tr><td>G</td><td>RE+WI+CR+SM+GLH</td><td>4.66</td><td>3.71</td><td>7</td><td>6</td><td>√</td></tr>
<tr><td>H</td><td>RE+WI+Gr+SM+GLH</td><td>5.04</td><td>4.66</td><td>8</td><td>8</td><td rowspan="4">EPS-polystyrene, XPS-polystyrene and Rock Wool 30mm</td><td>-</td></tr>
<tr><td>I</td><td>RE+WI+Gr+CR+SM+GLH</td><td>-</td><td>5.39</td><td>-</td><td>9</td><td>√</td></tr>
<tr><td>J</td><td>RE+WI+Gr+SM+Fr+GLH</td><td>7.00</td><td>6.79</td><td>9</td><td>10</td><td>-</td><td rowspan="2">√</td></tr>
<tr><td>K</td><td>RE+WI+Gr+CR+SM+Fr+GLH</td><td>7.01</td><td>7.09</td><td>10</td><td>11</td><td>√</td></tr>
</table>

Notes:

**Applying reflective coating with absorptance 0.15*

Generally, it can be concluded that the most predominant intervention during retrofitting domestic envelopes is the application of roof insulation. As a single intervention, compare to the other measures (single or combined), presents the higher NPV with the highest frequency of implementation in any combination for all case studies, under two climate scenarios. The second most frequent intervention seems to be the upgrade of glazing system primarily with Low-E HSF glazing, followed by the insulation of external walls.

However, the analysis deduces that the medium category measures (see section 6.3.2) satisfy the criteria (NPV and SAW_{score}) of the optimization. At the coastal weather conditions the strategy coherent with the optimum performance is the application of roof (externally) and external wall insulation (internally), while for the inland conditions the analysis indicates also the addition of a Low-E HSF glazing. In general, the measures ranked at the highest levels of performance are presented in both climate scenarios. Table 6-3 demonstrates the top 5 ranked strategies/measures for each climate conditions.

Table 6-3 Top 5 measures by climatic condition

RANK	COASTAL			INLAND		
	Measure	Annual Energy Reduction-Average (%)	NPV-Average (€)	Measure	Annual Energy Reduction-Average (%)	NPV-Average (€)
1	RE+WI	34	-6449	RE+WI+GLH	38	-6338
2	RE+WI+GLH	38	-7953	RE+WI	33	-5220
3	RE+GLH	27	-673	RE+WI+SM+GLH	45	-15011
4	RE+GC	25	-253	RE+GLH	23	-106
5	RE+WI+SM+GLH	47	-16659	RE+GC	22	206

It can be realized that the strategies comprising of 2 to 4 measures are ranked at the 5 highest positions, indicating that the substantial performance is not always coherent with the number of interventions.

A further reduction on the capital cost of the optimum solution will enhance the viability over the long term horizon. Subsidizing the capital cost of the optimum strategy by 40-70% (coastal) and 30-60% (inland), its NPV will reach the highest NPV occurred in the analysis (in particular the NPV the roof insulation).

6.4 SUMMARY

This chapter discusses the prioritization of the measures, giving an attention initially on the parameters of single interventions and then, on the evaluation of single interventions and combined strategies. The prioritization was based on the application of the NPV and the performance SAW_{score}.

In the perspective of single ESM, it can be concluded that the application of roof insulation is a substantial strategy towards the reduction of the annual energy consumption while the indoor thermal environment is maintained or improved. This is followed by the upgrade of double glazing clear or Low-E HSF.

In the context of retrofitting, the outcome that ranked at the highest place was the application of insulation on roof and external walls (coastal) and insulation of roof and external walls with Low-E HSF (inland).

Chapter 7. CONCLUSIONS AND FUTURE WORK

7.1 RESEARCH SUMMARY

On the global level, buildings are responsible for nearly 40% of energy consumption, the highest among the end-use energy sectors. Acknowledging the great potential of building sector for energy reduction and a decarbonized future, the study examined the impact of envelope retrofitting measures in the housing inventory of Cyprus, in order to offer the opportunity of the existing inefficient Mediterranean residential stock to get in line with the rest of the European inventory.

The aim of this research was to prioritize the retrofitting measures with regards to the trade-offs between energy consumption and thermal comfort. In essence, the guidelines provided by this study will ensure a perceptual retrofitting, governed by the targets of the European Council for 2020. In order to accomplish the aim of the study, 8 objectives were formed, completing consecutive tasks.

Initially, a literature review has been undertaken, exploring the energy and the residential buildings in terms of retrofitting and available retrofitting solutions. An attention was also given on the implementation of building simulation during the investigation of the effectiveness of ESM, highlighting the importance of thermal comfort during the post evaluation assessment of envelope interventions. A wider picture of Cyprus was also presented

(***Objectives 1 & 2***). Through stratified sampling, 7 detached houses were selected to represent the sample of the study. The houses were permanent residences, located at the south-west coastal area of Cyprus, covering a range of floor area between 117-384 m^2 (***Objective 3***). The 7 dwellings were monitored for one year period, collecting data (i.e., as-built drawings, indoor air temperature, energy records, weather conditions, etc.). The data formulated the basis of calibration and validation during building simulation (***Objective 4***). Following the Objective 4, the data was updated in a simulation engine, generating building models. Through this stage, the concept of the back-ward stepwise approach (mid-season calibration) was adopted to develop reliable models that were later used to investigate the impact of retrofitting interventions (***Objective 5***). Under two climate scenarios (coastal and inland), 253 parameters of single interventions and 7,056 synergies of interventions for each house were analysed, assessing the performance of the building envelopes regarding to energy savings, indoor thermal environment and also, the feasibility of investment under a horizon of 30 years (***Objectives 6 & 7***). Finally, guidelines and recommendations were drawn, based on the analysis of the outcome by the parametric analysis, giving attention on the trade-offs between energy and thermal comfort (***Objective 8***).

7.2 Contribution to Knowledge and Guidelines

This thesis focused on the investigation of retrofitting interventions on existing residential buildings, in order to reduce the energy consumption coherent with the thermal loads without sacrificing the indoor thermal environment. In particular, the interventions comprise 4 categories, addressing in total 253 parameters under two micro-climate scenarios (coastal and low-lands), for 7 cases of dwellings. Extending the study, the synergies of combined interventions (7,056 for each building) were studied. The outcome of the study was based on the calibration and validation simulation models, by data collected during an annual monitoring of actual residential buildings.

The results provide compelling evidence for government bodies to adopt the renovation strategies to achieve the European targets of 2020. Recalling the analysis from Chapters (5) and (6), the following valuable guidelines can be drawn:

1. **Environmental Performance**
    - Tightening building envelope can enhance the impact of other interventions, especially during heating period (up to 12 %). However, the building must “breathe” (built tight, ventilate right), as the ventilation relied on the leakiness of the envelope.
    - In terms of environmental performance, thicknesses above 7cm (roof and external walls) and 3cm (ground floor) of insulation materials demonstrated minor effect on energy and thermal comfort.
    - An opposed seasonal impact was observed for the interventions related with external wall and ground floor insulation, reflective coating, glazing systems and external fixed shading devices.
    - The highest heating reduction was achieved by the integration of roof insulation (on average 33%-coastal and 25%-inland). The

premier cooling reduction occurred with the application of roof reflective coating (on average 19%-coastal and 15%-inland).

- In the case of fenestration systems, the solar factor seems to be the most critical factor for climates described by hot-dry summers and mild-wet winters, with excess winter solar radiation.
- On the Low-E glazing systems, the position of the coating shows better performance with regards to the season p2, p4 (summer) and p3, p5 (winter) (for indexing see Figure 5-20).
- The synergies between the various interventions can dramatically increase the performance of the envelope compared to single interventions, with the most dominant measures to be the insulation of opaque elements with a Low-E HSF, thermally improved frame and movable external shading device.

Figure 7-1 summarizes the average maximum energy impact by the application of single interventions.

Roof Reflective Coating
- Heating Load[2]: +24%(Coastal), +14%(Inland)
- Cooling Load[3]: -19%(Coastal), -15%(Inland)

Roof Thermal Insulation
- Heating Load: -33%(Coastal), -25%(Inland)
- Cooling Load[1]: -8%(Coastal), -6%(Inland)

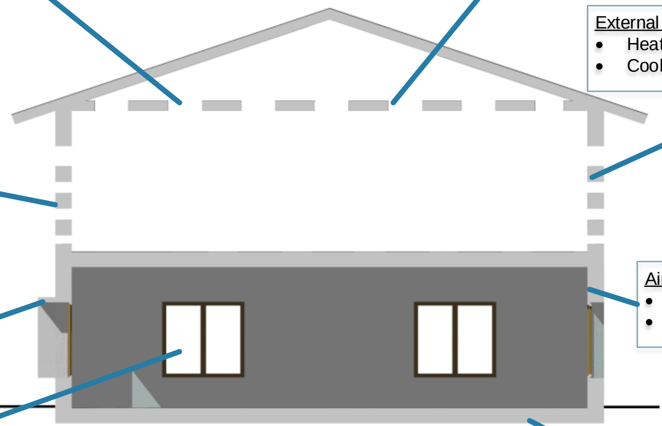
External Walls Thermal Insulation
- Heating Load: -15%(Coastal), -13%(Inland)
- Cooling Load: +1%(Coastal), +0.2%(Inland)

External Walls Reflective Coating
- Heating Load: +6%(Coastal), +4%(Inland)
- Cooling Load: -3%(Coastal), -3%(Inland)

Fenestration-Shading

Overhangs
- Heating Load: +9%(Coastal), +5%(Inland)
- Cooling Load: -5%(Coastal), -4%(Inland)

Fins
- Heating Load: +6%(Coastal), +3%(Inland)
- Cooling Load: -2%(Coastal), -2%(Inland)



Air-Tightness
- Heating Load: -4%(Coastal), -4%(Inland)
- Cooling Load: +1%(Coastal), -2%(Inland)

Ground Floor Thermal Insulation
- Heating Load: -7%(Coastal), -2%(Inland)
- Cooling Load: +4%(Coastal), +5%(Inland)

Fenestration-Glazing[4]

Glazing		Coastal/Inland	
		Heating	Cooling
Clear		-2%/-2%	-2%/-1%
Tint		+8%/3%	-4%/-4%
HSF	p2, p4	-1%/-2%	-3%/-2%
	p3, p5	-5%/-4%	-1%/-1%
MSF	p2, p4	+6%/+2%	-5%/-5%
	p3, p5	+1%/-1%	-4%/-3%
LSF	p2, p4	+14%/+6%	-10%/-8%
	p3, p5	+9%/+3%	-7%/-6%

Notes

[1]The cooling load in the case of single story buildings is reduced up to 2-3 times than double story houses.

[2]In the case of single story buildings, the impact is increased by 4 to 8 times compare to double story, regarding to the default roof coating.

[3]As the heating load, the reduction on cooling load is higher by 1.5 to 3 times for single story dwellings.

[4]Adding argon fill, the heating load may be reduced on average by 2% (coastal) and 1.25% (inland), where the frame can enhance the heating reduction by 1.5% (coastal) and 1.25 (inland). During cooling period, the impact of the upgrades is negligible <1% (average).

Figure 7-1 Average energy impact by single interventions

2. Feasibility and Prioritization

The feasibility of the investment and thus, the prioritization of the alternative solutions were based on the economic indicator, NPV and the annual performance of each intervention. The main findings are summarized in Tables (6-1) and (6-2) for single and combined interventions, respectively. Here, the 2 top ranked interventions are listed for each category:

- Top ranked single interventions

  1st External roof insulation: 3cm foam polyurethane *(Average annual energy reduction 23% (coastal)/19% (inland))*

  2nd External roof insulation: 5cm (coastal) and 6cm (inland) of polystyrene or rock wool *(Average annual energy reduction 25% (coastal)/21% (inland))*

- Top ranked combined interventions (Coastal)

  1st External Roof + Internal Wall Insulation: 3cm foam polyurethane/5cm of polystyrene or rock wool + 3cm of polystyrene or rock wool *(Average annual energy reduction 34%)*

  2nd External Roof + Internal Wall Insulation + Double glazing: 3cm foam polyurethane/5cm of polystyrene or rock wool + 3cm of polystyrene or rock wool + Low-E HSF (p3) *(Average annual energy reduction 38%)*

- Top ranked combined interventions (Inland)

  1st External Roof + Internal Wall Insulation + Double glazing: 3cm foam polyurethane/5cm of polystyrene or rock wool + 3cm of polystyrene or rock wool + Low-E HSF (p3) *(Average annual energy reduction 38%)*

  2nd External Roof + Internal Wall Insulation: 3cm foam polyurethane/5cm of polystyrene or rock wool + 3cm of polystyrene or rock wool *(Average annual energy reduction 33%)*

In addition to the main goal of the study:

- An updated TMY weather file was developed, for the south-west coastal area, based on the data collected from the national weather station (Paphos Airport).
- On a national level, the first air-infiltration test has been carried out during the study, providing an abstraction of the current air-tightness scene for single detached houses.

7.3 LIMITATIONS

Although this research has examined the impact of ESM during retrofitting existing residential envelopes in the Mediterranean region, there are some limitations. The limitations of this study are mainly coherent with the generation of the simulation models, resulted by the privacy of residential buildings and the criticality of any damage during monitoring:

- Plug-loads metering: The equipment and devices (plug-load) were not monitored by plug-meters. This was addressed by the adoption of operation profiles by previous studies, interviews and the nameplate power of devices (see section 4.2.3).
- Monthly/hourly energy consumption: While the indoor air temperature was monitored hourly, the energy consumption was recorded during the en-situ visits on monthly basis, as the utilization of energy meters on the private properties was inaccessible (see section 4.3.1).
- Occupancy behaviour: During the calibration procedure, a strategy was developed to emulate the occupancy behaviour, related to natural ventilation, shading devices and local heating systems (see section 4.2.2).

7.4 Suggestions for Future Work

- Adopting the methodology for the assessment of retrofitting measures in other types of residential envelopes (i.e., apartment, terraced houses etc.)
- Extending the research on the investigation of the additional tiers of the Kyoto pyramid, improving the passive design of dwellings. In the case of Cyprus, most attention has previously focused on the application of solar systems, contributing to a significant number of studies.

- Examining the performance of dynamic interventions, driven by the seasonality of weather conditions. It seems that in climate conditions, experience along the Mediterranean region, the buildings must be constructed, based on the seasonal variations of the outdoor weather. For instance, the application of a coating that will absorb solar radiation (electrochromic) during winter period and reflect it during summer period.
- Currently, based on the author’s knowledge, limited literature exists for domestic buildings, on aspects related with the occupancy behaviour such as natural ventilation and shading devices. Addressing this gap in the literature will reduce the sources of uncertainty by simulation studies.
- On a national level, there seems to be a gap on standards related to the built environment. For instance, there is no reference regarding the air-tightness of buildings in Cyprus. Therefore, fostering the studies coherent with building sector will contribute towards achieving the targets of the EU for 2020.

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APPENDICES

A. INSULATION OF OPAQUE ELEMENTS

In this Appendix, the methods of application techniques will be described for each individual opaque element of a building envelope.

A.1. External Walls

Critical elements of the building envelope (especially for detached dwellings) are the external walls which are entirely exposed to environmental conditions. In the context of thermal insulation, three methods are primarily available; internal, external and cavity. Particularly, the latter method is merely used on the construction of new buildings, whereas the other two approaches are recommended for retrofitting of houses with solid walls. Therefore, the internal and external insulation will be extensively described throughout this section. Figure A. 1 represents a simple layout of the methods.

Generally, the adoption of an insulation method is governed by the cost, the material and parameters relative to the structure of the building. For example, in cases were the external façade of the property must not be changed, the internal insulation may be selected, while in cases with limited internal space, the external insulation is recommended.

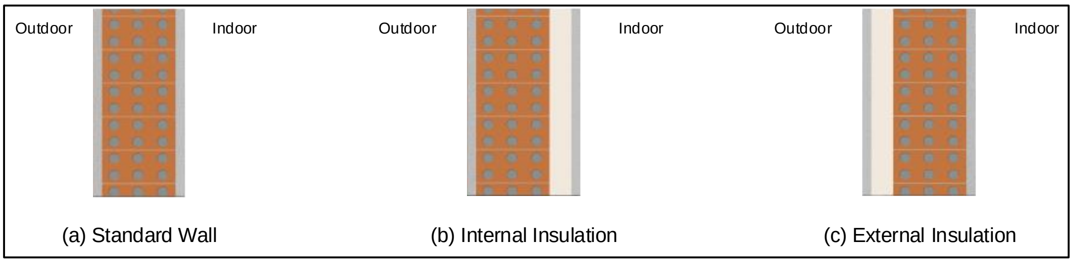


Figure A. 1 Layout of (a) Standard Wall, (b) Internally Insulated and (c) Externally Insulated

For both methods, different approaches of application are available. For external insulation usually wet rendering and dry cladding are adopted. While the wet rendering is cheaper than dry cladding, the latter is preferred for occasions where planning permission and external appearance are critical issues. Now, in the internal insulation case, there are three available methods; (a) laminated insulation board fixed directly to the wall, (b) rigid insulation between battens fixed to the wall and (c) a frame with insulation leaving an air gap between the building element and the insulation (Burton, 2012).

Insulation techniques are contributing on the improvement of thermal resistance of the walls, however the selection of which is the best solution is governed by other critical factors. Some factors are the cost, the condensation, the thermal bridges, thermal mass, etc. For instance, the cost of internal insulation is lower but the internal space is “shrunk” and also causes disruption to the occupants during its application. Additionally, when internal insulation is applied, the functionality of the space will be limited, as heavy items cannot mount on the walls. An advantage of the internal insulation system is the reduction of the thermal response of the fabric and thus, the faster warm up of the space (Griffiths, 2012). On the contrary, an advantage of the external insulation is that it retains the usability of thermal mass of the building, resulting on the maintenance of the internal environment. An experiment by Jankovic (2012) shows that the wall with external insulation presents higher heat capacity and the slope of the cooling curve was smoother than the internal system. Further to this, by retaining the thermal mass and controlling ventilation and solar gain, the overheating will be prevented (Burberry, 1997).

In terms of condensation risk, it must be mentioned that both methods are subjective to condensation, especially by their misapplication. However, the external insulation may contribute to the reduction or even elimination of thermal or cold bridges (high risk areas of condensation), as its application is ideally described by a continuous and contiguous wrapping of the building's façades ('warm-overcoat' (Cook, 2011)). On the contrary due to the discontinuities of internal insulation, the thermal bridges may sometimes be difficult to be addressed, i.e., element joints which are inaccessible. In both cases, vapour resistance layers may be applied to prevent the diffusion of the moisture through the structure, as an example rain penetration

A.2. Roof

Roof is a horizontal element, exposed to the external conditions. Like the external walls, the roof is a critical component towards the reduction of the transition losses, as well as offering protection from the elements (rain and wind). Additionally, in climates with excessive insolation, the roof receives huge amounts of solar radiation for most of the year. Typically, there are two types of roof; (a) flat and (b) pitched roofs (with or without attic).

In the context of insulation, different systems are currently available, principally defined by the layout of the layers and the position of the insulation material. A typical layout of that system is depicted in Figure A. 2.

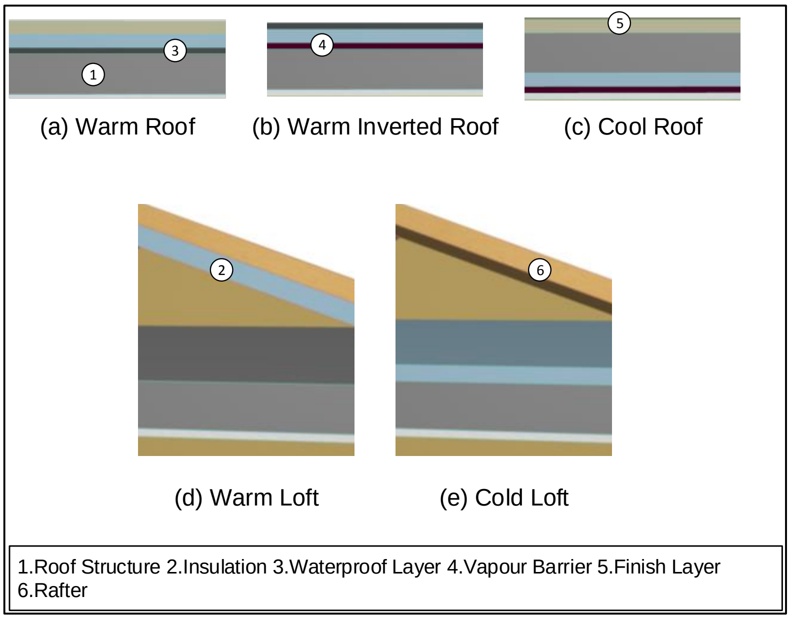


Figure A. 2 Typical insulation layouts. (a)-(c) flat roofs, (d) and (e) pitched roofs (Burton, 2012)

For pitched roofs with attics, the warm and cold loft system may be applied. The difference of the systems is governed by the level on which the insulation is applied. In the case of a cold system, the insulation is placed on the level of the ceiling, leaving the loft space uninsulated. On the contrary, when the insulation is applied on the rafter level, the system is defined as warm loft.

Similarly, when the insulation is placed above the roof deck (thermal mass faces the internal space) it is the warm system and regarding to the location of the waterproof membrane the warm flat roof is split into warm and warm inverted ((a) and (b) respectively), whilst the application of internal insulation is defined as cold roof, exposing the thermal mass to the external environment.

As also mentioned in the external wall section, the condensation must be addressed in order to avoid the growth of mould and other issues that may affect the construction element. The cold deck system is susceptible to internal condensation and thus, critical attention must be given to the application of a vapour barrier layer and sealing of the junctions and penetrations (Burton, 2012).

Furthermore, in the context of investment cost, the adaptation of thermal insulation systems for roofing elements is lower than external walls, making its application attractive throughout a thermal upgrading renovation.

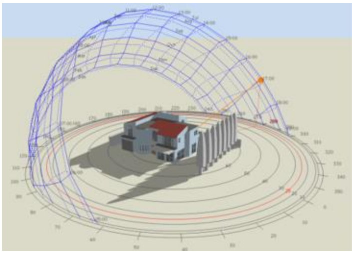
A.3. Floor

Another element where renovation may take place is the floor in contact with the ground. The transition losses to the ground are primarily affected by the structure of the ground floor. For example, in a suspended timber frame floor, the cold air that is circulated causing convection and transfer of the heat. In the presence of solid concrete slab, the conduction removes heat directly into the ground.

A common floor construction along the Mediterranean region is the solid floor, built by reinforced concrete (Andeweg et al., 2007, p.16). In the context of refurbishment, it is considered as one of the most difficult structures to be thermally improved. The insulation material, for this case, is usually placed on the top of the concrete slab, as it may be technically impossible to brake the slab in order to place the insulation below the existing concrete (Griffiths, 2012). An excavation removes the existing tiles reaching on the level of the slab, where the insulation can be added, covered by screed and finally, a finish layer (tiles, wood etc.). In the presence of a basement, the insulation can be placed at the underside of the floor. As with other opaque elements, technically issues may arise such as condensation and space reduction. Caution must be taken on the junctions with the walls due to the possibility of thermal bridges. “Head-height” is another critical issue, especially for the door openings. However, as Griffiths (2012) claimed rather than no insulation, a little insulation is better.

B. CASE STUDIES

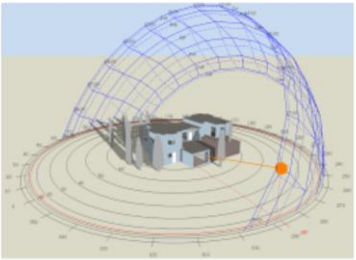
Appendix B presents important information about the dwellings that are investigated. The buildings are divided into 2 categories: Category A represents the houses that are using heating oil as a primary fuel for heating, Category B consist of buildings that rely entirely on grid electricity for heating and cooling. The subsequent tables summarize the following information: Construction period, Occupancy, Envelope details, Building Services and Annual heating-cooling consumption.

Category A	House SD1
	
	
Construction Year	1995
Occupants	3-4 

Envelope Details									
Volume (m^3)	Envelope Area(m^2)	Floor Area (m^2)	Conditioned Area (m^2)		Conditioned Volume (m^3)		Wall Gross Area (m^2)	Windows Area (m^2)	% of windows to wall area
			Heat	Cool	Heat	Cool			
1091	788	290	252	53.8	1028	196	422	83	20

Building Services			Thermal Loads Consumption			
			Actual Weather	Coastal TMY	Inland TMY	Units
HVAC	Heating	Oil fired boiler (Radiators) & auxiliary local heater	6603.91	13113	17285	kWh
			22	48.34	65.9	$kWh_p/m^2_{heatcon}$
	Cooling	Split Units	111	107.5	54.5	$kWh_p/m^2_{coolcon}$
DHW		Solar collectors & auxiliary electrical heater 3 kW	5.5	11.8	16.2	$kWh_p/m^3_{heatcon}$
			30.6	29.4	34.7	$kWh_p/m^3_{coolcon}$

Table B. 1 Details SD1

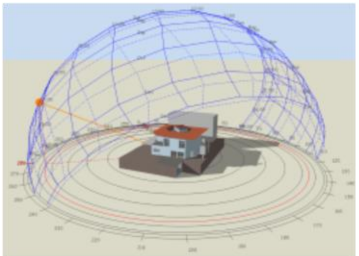
Category A	House SD2
	
	
Construction Year	1987
Occupants	3

Envelope Details									
Volume (m^3)	Envelope Area(m^2)	Floor Area (m^2)	Conditioned Area (m^2)		Conditioned Volume (m^3)		Wall Gross Area (m^2)	Windows Area (m^2)	% of windows to wall area
			Heat	Cool	Heat	Cool			
606	780	188	116	33	380	104	422	55	13

Building Services		
HVAC	Heating	Oil fired boiler (Radiators)
HVAC	Cooling	Split Units
DHW		Solar collectors & auxiliary electrical heater 3 kW

Thermal Loads Consumption			
Actual Weather	Coastal TMY	Inland TMY	Units
6992	11030	15566	kWh
69.7	88	129.5	$kWh_p/m^2_{heatcon}$
54.6	53.7	159.5	$kWh_p/m^2_{coolcon}$
21.3	26.9	39.7	$kWh_p/m^3_{heatcon}$
17.3	46.07	50.5	$kWh_p/m^3_{coolcon}$

Table B. 2 Details SD2

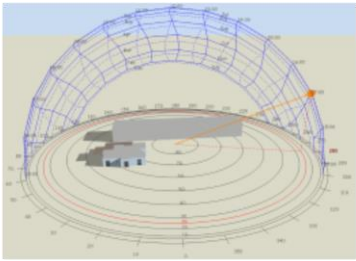
Category A	House SD3
	
	
Construction Year	1996
Occupants	2-3

Envelope Details									
Volume (m^3)	Envelope Area(m^2)	Floor Area (m^2)	Conditioned Area (m^2)		Conditioned Volume (m^3)		Wall Gross Area (m^2)	Windows Area (m^2)	% of windows to wall area
			Heat	Cool	Heat	Cool			
1333	1040	384	332	109	1239	459	594	89	15

Building Services		
HVAC	Heating	Oil fired boiler (Underfloor)
	Cooling	Split Units
DHW		Central heating

Thermal Loads Consumption			
Actual Weather	Coastal TMY	Inland TMY	Units
22176	26169.6	30306	kWh
70.7	76.9	89	$kWh_p/m^2_{heatcon}$
38.4	73.7	86.8	$kWh_p/m^2_{coolcon}$
19	20.6	23.84	$kWh_p/m^3_{heatcon}$
9.1	17.5	20.6	$kWh_p/m^3_{coolcon}$

Table B. 3 Details SD3

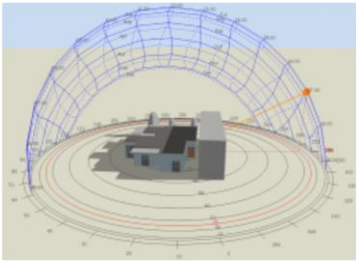
Category B	House SD4
	
	
Construction Year	1994
Occupants	2-3

Envelope Details									
Volume (m^3)	Envelope Area(m^2)	Floor Area (m^2)	Conditioned Area (m^2)		Conditioned Volume (m^3)		Wall Gross Area (m^2)	Windows Area (m^2)	% of windows to wall area
			Heat	Cool	Heat	Cool			
591	580	176	94	94	315	315	277	43	19

Building Services		
HVAC	Heating	Splir Units
	Cooling	Split Units
DHW		Solar collectors & auxiliary electrical heater 3 kW

Thermal Loads Consumption			
Actual Weather	Coastal TMY	Inland TMY	Units
4028	7895.6	10187.5	kWh
28	100.7	142.9	$kWh_p/m^2_{heatcon}$
87.5	125.7	149.2	$kWh_p/m^2_{coolcon}$
8.4	30	42.6	$kWh_p/m^3_{heatcon}$
26.1	37.5	44.5	$kWh_p/m^3_{coolcon}$

Table B. 4 Details SD4

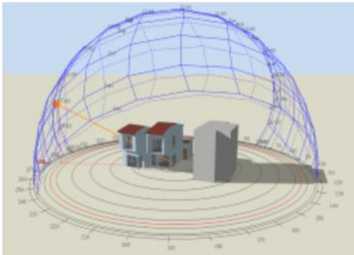
Category B	House SD5
	
	
Construction Year	1987
Occupants	3

Envelope Details									
Volume (m^3)	Envelope Area(m^2)	Floor Area (m^2)	Conditioned Area (m^2)		Conditioned Volume (m^3)		Wall Gross Area (m^2)	Windows Area (m^2)	% of windows to wall area
			Heat	Cool	Heat	Cool			
365	423	117	54	54	54	54	183	37	20

Building Services		
HVAC	Heating	Splir Units & auxiliary halogen heater
	Cooling	Split Units
DHW		Solar collectors & auxiliary electrical heater 3 kW

Thermal Loads Consumption			
Actual Weather	Coastal TMY	Inland TMY	Units
1887	3420	4207	kWh
61.6	40	65	$kWh_p/m^2_{heatcon}$
32.3	130	144.2	$kWh_p/m^2_{coolcon}$
19.9	12.9	20.9	$kWh_p/m^3_{heatcon}$
10.4	42	26.2	$kWh_p/m^3_{coolcon}$

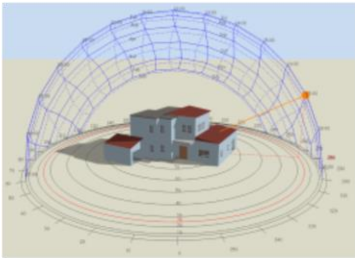
Table B. 5 Details SD5

Category B	House SD6
	
	
Construction Year	2007
Occupants	3

Envelope Details									
Volume (m^3)	Envelope Area(m^2)	Floor Area (m^2)	Conditioned Area (m^2)		Conditioned Volume (m^3)		Wall Gross Area (m^2)	Windows Area (m^2)	% of windows to wall area
			Heat	Cool	Heat	Cool			
473	501	120	62	62	62	62	357	83	23

Building Services			Thermal Loads Consumption			
			Actual Weather	Coastal TMY	Inland TMY	Units
HVAC	Heating	Splir Units & auxiliary halogen heater	1946.2	2531	3564	kWh
			19.4	49.5	98	$kWh_p/m^2_{heatcon}$
	Cooling	Split Units	88.2	90.5	99	$kWh_p/m^2_{coolcon}$
DHW		Solar collectors & auxiliary electrical heater 3 kW	5.1	13.1	25.9	$kWh_p/m^3_{heatcon}$
			23.3	23.9	26.2	$kWh_p/m^3_{coolcon}$

Table B. 6 Details SD6

Category B	House SD6
	
	
Construction Year	2006
Occupants	3

Envelope Details									
Volume (m^3)	Envelope Area(m^2)	Floor Area (m^2)	Conditioned Area (m^2)		Conditioned Volume (m^3)		Wall Gross Area (m^2)	Windows Area (m^2)	% of windows to wall area
			Heat	Cool	Heat	Cool			
67	644	208	50	50	50	50	351	68	20

Building Services			Thermal Loads Consumption			
			Actual Weather	Coastal TMY	Inland TMY	Units
HVAC	Heating	Splir Units & auxiliary halogen heater	2858	2580	3349.3	kWh
			83.9	59.6	93.7	$kWh_p/m^2_{heatcon}$
	Cooling	Split Units	67.7	77.3	84	$kWh_p/m^2_{coolcon}$
DHW		Solar collectors & auxiliary electrical heater 3 kW	26.2	18.6	29.3	$kWh_p/m^3_{heatcon}$
			21.2	24.2	26.3	$kWh_p/m^3_{coolcon}$

Table B. 7 Details SD7

B.1. Building Envelope construction materials

Where the properties of materials were not mentioned in the National Thermal Insulation Guidance, the values were adopted by the databases of ASHRAE and CIBSE (ASHRAE, 2009; CIBSE, 2006b).

Table B. 8 Roof construction

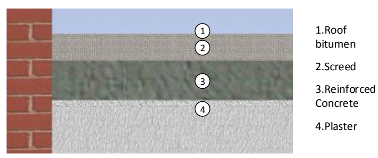
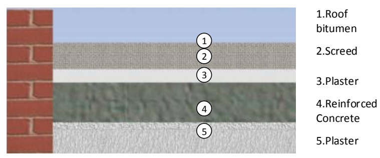
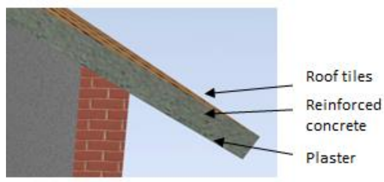
<table>
<tr><th>ROOF</th><th>U-VALUE (W/m².K)</th><th>INDEX</th><th colspan="2">DETAILS</th></tr>
<tr><td rowspan="4">Flat</td><td>3.458</td><td>RF1</td><td>Slab of 15-20 cm reinforced concrete (2 % steel) covered by 2.5 cm plaster on the inner surface. Additional layers are a 6-10 cm screed and a finishing of 0.4 cm roof bitumen</td><td>
</td></tr>
<tr><td>0.516 (Only Screed)</td><td>RF2</td><td rowspan="3">As the previous structure, with an additional 5 cm insulation layer between reinforced concrete and screed</td><td rowspan="3">
</td></tr>
<tr><td>0.521 (Only Bitumen)</td><td>RF3</td></tr>
<tr><td>0.511 (Screed & Bitumen)</td><td>RF4</td></tr>
<tr><td rowspan="3">Pitched</td><td>3.014 (Only Screed)</td><td>RP1</td><td rowspan="3">Incline slab of 15 cm reinforced concrete covered by roof tiles (outer leaf) and plaster (inner leaf). In some case bitumen, screed and insulation are added as the flat roof</td><td rowspan="3">
</td></tr>
<tr><td>3.204 (Only Bitumen)</td><td>RP2</td></tr>
<tr><td>2.864 (Screed & Bitumen)</td><td>RP3</td></tr>
</table>

Table B. 9 Floor construction

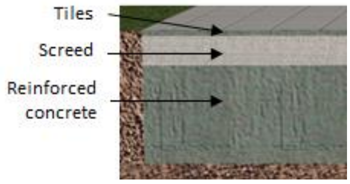
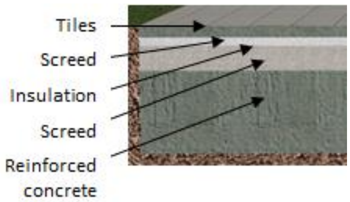
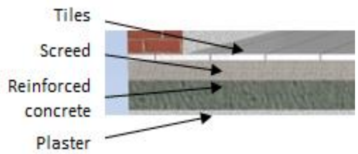
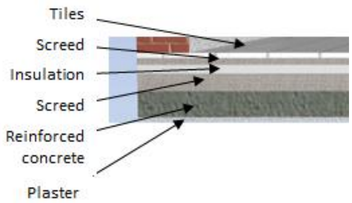
FLOOR	U-VALUE (W/m².K)	INDEX	DETAILS	
Ground	1.831 ***(Ceramic Tiles)***	FG1	*Foundation of 50cm reinforced concrete (2 % steel), 10-15cm screed (medium density) for the services and 3 cm floor tiles*	
	1.888 ***(Marble Tiles)***	FG2		
	1.88 ***(Granite Tiles)***	FG3		
	0.405 ***(Ceramic Tiles)***	FG4	*Foundation of 50cm reinforced concrete (2 % steel), 10-15cm screed (medium density), insulation material for the hydronic piping, additional screed layer of 4cm for the services and 3 cm floor tiles*	
	0.408 ***(Marble Tiles)***	FG5		
	0.407 ***(Granite Tiles)***	FG6		
Internal	1.752 ***(Ceramic Tiles)***	FI1	*Slab of 15 cm reinforced concrete (2 % steel) covered by 2.5 cm plaster on the outermost surface, 10-15 screed (medium density) for services and 3 cm floor tiles*	
	1.804 ***(Marble Tiles)***	FI2		
	1.797 ***(Granite Tiles)***	FI3		
	0.395 ***(Ceramic Tiles)***	FI4	*Slab of 15 cm reinforced concrete (2 % steel) covered by 2.5 cm plaster on the outermost surface, 10-15 screed (medium density), 5 cm insulation material, an additional 4 cm screed layer for services and 3 cm floor tiles*	
	0.397 ***(Marble Tiles)***	FI5		
	0.397 ***(Granite Tiles)***	FI6		

Table B. 10 Walls construction

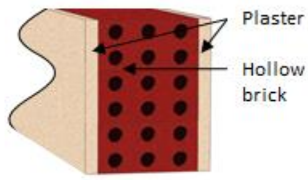
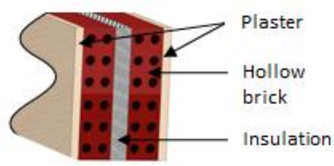
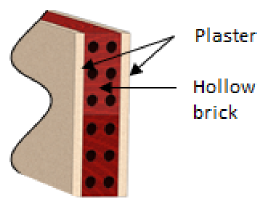
WALLS	**U-VALUE (W/m².K)**	**INDEX**	**DETAILS**	
External	1.389	WE1	*A hollow clay brick (20 x 30 x 10 cm) placed horizontal and covered by 2.5 cm plaster at both sides*	
	0.447	WE2	*Two hollow clay bricks (20 x 30 x 10 cm) placed horizontal with a cavity filled with 5 cm insulation and covered by 2.5 cm plaster at both sides*	
Internal	2.128	WI1	*A hollow clay brick (20 x 30 x 10 cm) placed vertical and covered by 2.5 cm plaster at both sides*	

Table B. 11 Fenestration construction

TYPE		**INDEX**	**Uw-VALUE (W/m².K)**	**DETAILS**
Window	Single	Win1	≈4.9-6	*4mm or 3mm single leaf glazing*
	Double	Win2	≈2.9-3.6	*4mm or 6mm double leaf glazing with air gap (12-16 mm)*
Door	Aluminium	Door 1	*Two 0.03 layers of aluminium separated by 0.1 cm air gap*	
	Wooden	Door 2	*4 cm opaque single oak leaf*	

Table B. 12 Default constructions, indexed by Table B. 8 and Table B. 11

HOUSE	**INDEX**						
	Roof		Floor		Walls		Windows
	Flat	Pitched	Ground	First Floor	External	Internal	
SD1	RF3	RP1	FG1,FG3	FI1,FI3	WE1	WI1	Win1
SD2	RF2	-	FG1,FG4	-	WE1	WI1	Win1
SD3	RF4	RP1	FG4, FG5	FI4,FI5	WE1	WI1	Win2
SD4	RF2	-	FG1,FG3	-	WE1	WI1	Win1
SD5	RF4	-	FG1, FG3	-	WE1	WI1	Win2
SD6	RF4	RP3	FG1,FG3	FI1,FI3	WE1	WI1	Win2
SD7	RF4	RP2	FG1,FG3	FI1,FI3	WE1	WI1	Win2

C. BLOWER DOOR TEST

The blower door test has been primarily carried out to estimate the air infiltration of the building enclosure, following the guidelines set by ATTMA and EN 13829:2001 (CEN, 2001; ATTMA, 2010). Referring to the current national literature, this blower door test may be determined as the first experiment undertaken to establish the air tightness of residential buildings along the country.

The whole procedure consists of three subsequent steps guided by the standards mentioned earlier. Initially, the first part is the preparation of the building, followed by the experimentation and finally, the acquisition of reliable data.

C.1. Experimental procedure and equipment

HOUSE PREPARATION

Before applying the experimental equipment on the sample building, ATTMA indicate the following steps, prior the test (ATTMA, 2010):

- All the drainage taps should be filled by water.
- Any external opening (e.g. doors, windows) should be closed, apart from the main entrance door, where the equipment will be attached.
- Any internal openings must remain open.
- Any holes (chimney) must be temporarily sealed, at both sides to ensure zero air flow (Figure C. 1).

- External and indoor temperatures should be recorded during the experiment.

During the experimentation, ensure that any gas equipment is turned-off, as there is a possibility that the device can be blown during the Blower Door test (The Energy Conservatory, 2012). Additionally, it is pointed that the pressure difference of the enclosure and the environment must not exceed 100 Pa, as this may result on the deformation of the envelope elements.

Figure C. 1 Sealing fireplace's chimney

Finally, two HOBO data loggers were placed in the indoor and outdoor environment of the building to monitor the air temperature.

EXPERIMENT

By the preparation of the building, the blower door equipment (Minneapolis Blower Door-Model 4) is mounted on the entrance door of the house. The equipment consisted of (Figure C. 2):

- Blower Door Fan

- Test Instrumentation (Pressure and Fan Flow Gauges)
- Fan Speed Controllers
- Adjustable Blower Door Frame
- TECTITE Blower Door Test Software

Figure C. 2 Equipment set up (SD7)

Furthermore, a pressure tube is extended outside of the building, and away from fan exhaust. The equipment is connected with the software, which enables the user to control the operation of the fan. Prior to the experiment, the software requires some input parameters that describe the building and the mode that the experiment will follow. Particularly, the parameters are:

-Temperatures (Indoor and Outdoor).

-Building Dimensions (Volume, Floor Area and Surface Area).

-Test Settings (the mode can be selected [e.g. pressurization and depressurization])

An example, of the software's environment, is illustrated in Figure C. 3. The parameters can be defined either before or after the experiment.

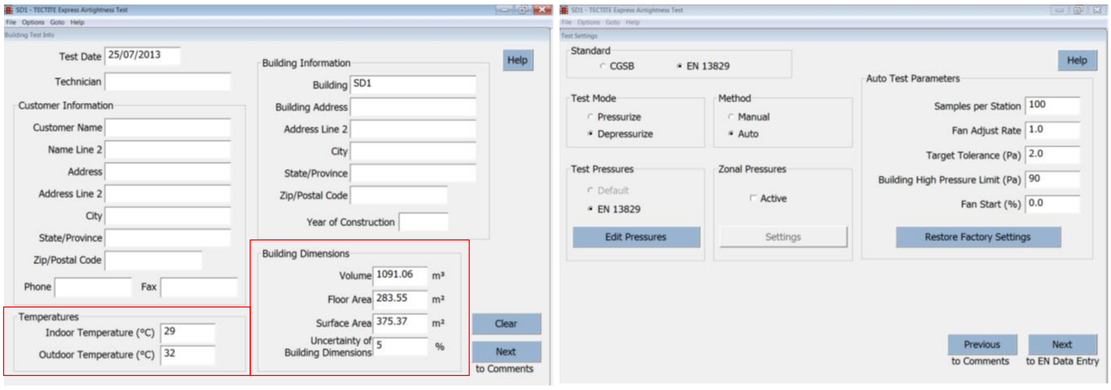


Figure C. 3 TECTITE Blower Door Test software-TABS

Initially the baseline pressure of the building is estimated, while the fan is off. Then, by choosing the appropriate ring which is mounted on the fan (the software recommends a certain ring for the current situation), the experiment starts, raising the pressure difference between building and environment up to 70 Pa. When the equipment establishes the target pressure difference, the leakage by the building envelope is recorded. The target pressures for the whole experiment are 70, 65, 60, 55, 50, 45, 40, 35, 30, 25 Pa. The whole procedure requires about 20 minutes.

RESULTS

The results from the blower door test are automatically produced by the TECTITE software. The accuracy of the results is revealed by the correlation coefficient (a variable that measures how well the collected data fits the "best-fit" Building leakage curve) (The Energy Conservatory, 2007).

Figure C. 4 presents the air-tightness characteristics of each house. In terms of accuracy, Table C. 1 lists the correlation coefficient for each dwelling, proving the reliability of results, as all of the buildings' results are fitting the curve with an accuracy higher than 0.99.

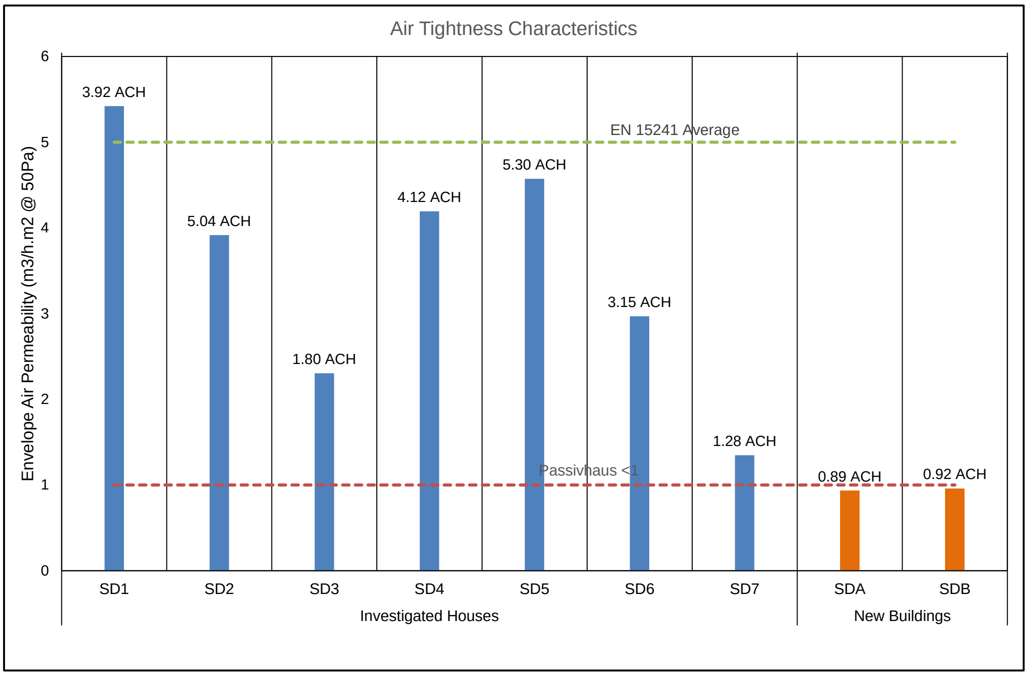


Figure C. 4 Air-tightness characteristics of the houses

Table C. 1 Accuracy of the blower-door test results

HOUSE	CORRELATION COEFFICIENT
SD1	0.99948
SD2	0.99835
SD3	0.99991
SD4	0.99928
SD5	0.99217
SD6	0.99056
SD7	0.99279
SDA	0.99230
SDB	0.99345

The values from the experiment were initially used to assign the air-tightness of the buildings throughout the simulation procedure, minimizing the source of uncertainty. Additionally, an important outcome is revealed from this particular experiment. Figure C. 5 illustrates the impact of the construction year on the air-tightness of the building.

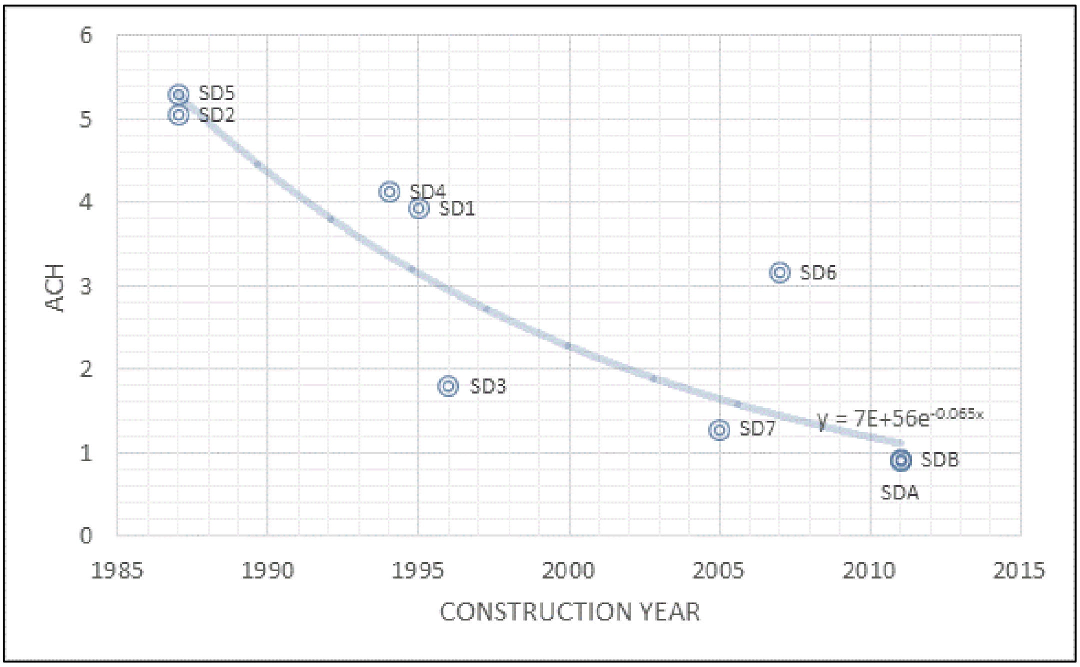


Figure C. 5 ACH against construction year

A decreasing trend is presented through the years, due to tightened envelopes. As the constructors are immune to any building regulation in terms of building air-tightness, possible facts for the decreased trend are the high quality materials, the construction techniques or even the bearing structure of the building. The latter may be explained by the fact that there are not timber frames or suspended floors, and the primary air paths are the external openings. Therefore, as shown in Figure C. 5, the houses SDA and SDB, under no regulation on building air-tightness achieve high levels of air-tightness.

D. Site Assessment-Surveys (Questionnaire)

My name is Georgios Georgiou and I am a PhD candidate at the school of Civil & Building Engineering, Loughborough University. I am supervised by Dr. Mahroo Eftekhari and Prof. Phil C Eames. My research is to investigate the domestic building in the Mediterranean region in the perspective of energy consumption and thermal comfort.

Information for Participant

- I understand that I am under no obligation to take part in the study.
- I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.
- I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

If you have any queries or questions you can contact me on my university email:

G.Georgiou@lboro.ac.uk

Many thanks for your cooperation.

Building (#): ………………………………………………….

Householder: …………………………………………………

Building Details

Construction Year	
Number of Occupants	

Envelope Characteristics

Name the structural materials from inside to outside for each element of the building:

ROOF

	Flat	Pitched
1.		
2.		
3.		
4.		
5.		

6.		
7.		
8.		

WALLS

	Internal	External
1.		
2.		
3.		
4.		
5.		
6.		

FLOOR

	Ground	Internal
1.		
2.		
3.		
4.		
5.		
6.		
7.		

Q2. Name the type of the windows and any further details

Type	Details

HVAC Systems

Q1.Indicate the systems that utilizing through heating season

Primary	
Secondary	

Q2. During heating season, name the set-points, type of operation and any other detail related for each room

Room Name	

	Primary System	Secondary System	DETAILS
On/Off or electrical			
# Thermostats/ Controller			
Programmed or not			
Set Point			
Interaction			

Room Name			
	Primary System	Secondary System	DETAILS
On/Off or electrical			
# Thermostats/ Controller			

Programmed or not			
Set Point			
Interaction			

Room Name			
	Primary System	Secondary System	DETAILS
On/Off or electrical			
# Thermostats/ Controller			
Programmed or not			
Set Point			
Interaction			

Room Name			
	Primary System	Secondary System	DETAILS
On/Off or electrical			
# Thermostats/ Controller			
Programmed or not			
Set Point			
Interaction			

Room Name			
	Primary System	Secondary System	DETAILS
On/Off or electrical			

# Thermostats/ Controller			
Programmed or not			
Set Point			
Interaction			

Room Name			
	Primary System	Secondary System	DETAILS
On/Off or electrical			
# Thermostats/ Controller			
Programmed or not			
Set Point			

Interaction			

Q3.Indicate the systems that utilizing through cooling season

Primary	
Secondary	

Q4. During cooling season, name the set-points, type of operation and any other detail related for each room

Room Name			
	Primary System	Secondary System	DETAILS
On/Off or electrical			
# Thermostats/ Controller			
Programmed or			

not			
Set Point			
Interaction			

Room Name			
	Primary System	Secondary System	DETAILS
On/Off or electrical			
# Thermostats/ Controller			
Programmed or not			
Set Point			
Interaction			

Room Name			
	Primary System	Secondary System	DETAILS
On/Off or electrical			
# Thermostats/ Controller			
Programmed or not			
Set Point			
Interaction			

Room Name			
	Primary System	Secondary System	DETAILS
On/Off or electrical			
# Thermostats/ Controller			

Programmed or not			
Set Point			
Interaction			

Room Name			
	Primary System	Secondary System	DETAILS
On/Off or electrical			
# Thermostats/ Controller			
Programmed or not			
Set Point			
Interaction			

Room Name			
	Primary System	Secondary System	DETAILS
On/Off or electrical			
# Thermostats/ Controller			
Programmed or not			
Set Point			
Interaction			

Domestic Hot Water System/s

Q1.Indicate the system/s for hot water

Primary	

Secondary	

Nameplate power of electrical devices

Device Name	Room (Location)	Power (Watts)

Lighting Fixtures

Room	Number of bulbs	Power (Watts)	Total Power (Watts)

Occupancy Pattern

Draw a picture for a typical day:

Weekdays Pattern

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00
In House												
# Occup.												
	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
In House												
# Occup.												

Weekends Pattern

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00
In House												
# Occup.												
	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
In House												
# Occup.												

CHECKLIST

□ Building Details

□ Envelope Characteristics

□ HVAC Systems

□ DHW systems

□ Occupancy Pattern

□ As-built drawing

□ Nameplate power of electrical devices

□ Lighting Fixtures

□ Monthly Electricity Consumption record

□ Monthly Oil Consumption record

E. WEATHER DATA-TMY GENERATION AND EPW FILE

In Appendix E, the generation of the weather databases will be described giving initial attention on the Sandia Method and the generation of a TMY database. Later, the transition from a database to an EPW file (EnergyPlus weather file extension) will be presented and finally, a study will be carried out to select the appropriate TMY file for the application on the main simulation procedure.

E.1. Sandia Method-TMY Generation

The Sandia method is an empirical approach where a TMY consists of 12 calendar months (Ebrahimpour and Maerefat, 2010). The generation of the meteorological data file lies upon the statistical analysis of several weather parameters and their weighting factors. At the initial state, Hall et al. (1978) used 13 parameters from a 23 years period. These were the maximum, minimum, mean and ranges of dry bulb and dew point temperature, wind velocity and total daily solar radiation.

Thereafter, several studies mentioned the generation of a TMY database, based on different climatic variables and weighting factors, as shown in the Table E. 1.

Table E. 1 Weather Parameters and assigned weather indices

INDICES		**STUDIES**				
		Gr.1	**Gr.2**	**Gr.3**	**Gr.4**	**Gr.5**
Air Temperature	Max	1/24	1/22	1/32	1/20	1/20
	Min	1/24	1/22	1/32	1/20	1/20
	Mean	1/12	1/22	1/16	1/10	3/10
	Range	-	1/22	1/32	-	-
Humidity/Dew-Point Temp.	Max	1/24	1/22	1/32	1/20	2.5/100
	Min	1/24	1/22	1/32	1/20	2.5/100
	Mean	1/12	1/22	1/16	1/10	1/20
	Range	-	1/22	1/32	-	-
Wind velocity	Max	1/12	1/22	1/32	1/20	1/20
	Min	-	-	1/32	-	-
	Mean	1/12	1/22	1/16	1/20	1/20
	Range	-	1/22	1/32	-	-
Wind direction	Mean	-	-	1/32	-	-
Solar Radiation	Global	1/2	1/2	1/4	1/4	2/5
	Direct beam	-	-	1/4	1/4	-

Notes:

Group 1 (Hall et al., 1978; Skeiker and Ghani, 2008; Skeiker and Ghani, 2009; Skeiker, 2004)

Group 2 (Sawaqed et al., 2005)

Group 3 (Petrakis et al., 1998; Kalogirou, 2003)

Group 4 (Marion and Urban, 1995)

Group 5 (Chan et al., 2006)

In this study, the generation of the TMY will depend upon the maximum, minimum and mean of dry bulb temperature, relative humidity, maximum and mean wind velocity and the total daily solar radiation (9 weather indices).

The procedure generally consists of two sub-processes. The first is the selection of the five candidate years, founded on the FS statistics. This approach is adopted by the majority of the studies based on the Sandia method. The latter is the final selection of TMM, driven by the persistence structure of the five candidate months. At the default Sandia version, Hall et al. (1978) evaluated the persistence of weather parameters by determining the frequency and run length above and below of fixed percentiles.

However, given the significant number of studies that have adopted the Pissimanis method (Argiriou et al., 1999; Janjai and Deeyai, 2009; De Miguel and Bilbao, 2005; Skeiker, 2007; Skeiker and Ghani, 2009), the current study will be based on its application. The method is based on simpler and intuitive formulas for the selection of TMM (Skeiker, 2007).

It is also critical to highlight the presence of erroneous and missing data. According to Levermore and Parkinson (2006), a fraction of 15% of erroneous data is acceptable for the generation of TMY. In addition, if there are gaps in data for a period of 1 to 6 hours, the linear and polynomial interpolation will be applied, as proposed by Chen and Claridge (2000). Essentially, twelve typical months will concatenate to form a typical meteorological year. The transition from one month to the next has been smoothed, using the linear interpolation of the real values for ± 5 hours.

SELECTION OF FIVE CANDIDATE YEARS

The selection of the five candidate years involves the examination of the closeness to the long-term database. The procedure is repeated in a similar manner for all calendar months. For this study, the long-term database comprises of data from the recent decade of 2001-2011.

The closeness of each year to the long term is examined by the comparison of the short and long-term cumulative distribution function (CDF) through the Filkenstein-Schafer (FS) statistics. In a given month, the daily averages are referred to as *"short term"*. When these are averaged for the whole period of database then they called *"long term"*. The short and long term cumulative distribution function (CDF) of weather index (i.e. temperature) is determined by a monotonic increasing function $CDF_{(x)}$, when a number n, of observations of the weather variable x are available and have been sorted into an ascending order $x_1, x_2, \ldots, x_n$. Eq. E 1 expresses the CDF.

$$CFD\ (x) = \begin{cases} 0 & for\ x < x_1 \\ \dfrac{(i-0.5)}{n} & for\ x_i \leq x < x_{i+1} \\ 1 & for\ x \geq x_n \end{cases}$$ ***Eq. E 1***

Eq. E 2 calculates the FS statistics between the short and long term CDF for a given month:

$$FS_x(y,m) = \frac{1}{N}\sum_{i=1}^{N}\left|CDF_m(x_i) - CDF_{y,m}(x_i)\right|$$ ***Eq. E 2***

,where $FS_x(y, m)$ is FS (y, m) statistics for each weather index x (y-year and m-month); CDF_m is the long-term and $CDF_{y,m}$ is the short term (for the year y) cumulative distribution function of the weather index x for month m and N is the number of daily reading of the month (i.e. February N=28).

Finally, the five candidate years for each month selected with respect to the smallest score of the Weighted Sum (WS). The WS is the aggregation of FS statistics of the nine climatic indices that is multiplied by their assigned weighting factor.

$$WS(y,m) = \frac{1}{M}\sum_{x=1}^{M} WF_x FS_x(y,m)$$ ***Eq. E 3***

, where WS(y, m) is the weighted sum for the month m in the year y, WF_x is the weighting factor for the x_{th} weather index and M is the number of the meteorological indices.

FINAL SELECTION OF TMM

The final selection of the typical meteorological months (TMM) carried out by the examination of the persistence structure of the five candidate years.

According to the aforementioned, the Pissimanis method applied, which is founded on a simpler method to examine the persistence of mean daily values of weather variables by the utilization of RMSD (Pissimanis et al., 1988):

$$RMSD = \left(\frac{1}{n}\sum_{i=1}^{n} d_i^2\right)^{0.5}$$ ***Eq. E 4***

, where n is the total number of data (i.e. 8,760 for a year) and d_i is the difference between the hourly values and the hourly long-term average values of global radiation. Afterwards, a variation of this method was introduced, where a composite score S is calculated by Eq. E 5 and the month with the highest score is selected.

$$S_x(y,m) = \frac{\min_{i=1,\ldots,20}(RMSD_x(i,m))}{RMSD_x(y,m)}$$ ***Eq. E 5***

According to Levermore and Parkinson (2006), a fraction of 15% of erroneous data is allowed for the generation of a weather file. In addition, if gaps of missing data are presented for a period of 1 to 6 hours, the linear and polynomial interpolation will be applied, which are proposed by Chen and Claridge (2000).

E.2. Generation of EPW file

In order to run a dynamic simulation in EnergyPlus, the software requires the use of a special weather format (EPW) (USDOE, 2012a). Through the weather pre-processor, the user can develop a custom EPW file, as it is illustrated in Figure E. 1

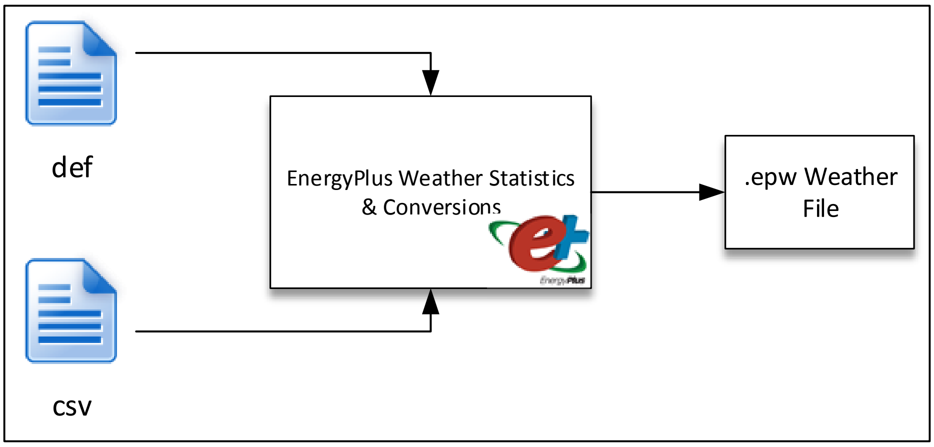


Figure E. 1 Procedure to create an EPW file

Two files must be uploaded in the pre-processor; a) a definition file (def) and b) a text file (txt or csv). The definition file specifies the characteristics of the incoming data, while the text file contains the weather parameters that will finally describe the EPW weather file (USDOE, 2012a). The Table E. 2 lists only the parameters that are currently used in EnergyPlus and their availability from the local weather station.

Table E. 2 Weather parameters for EPW generation, reproduced by (USDOE, 2012a)

WEATHER ELEMENTS	**USED IN ENERGYPLUS**	**UNITS**	**AVAILABLE FROM PAPHOS WEATHER STATION**
Dry bulb temperature	Y	ºC	Y
Dew point temperature[1]	Y	ºC	N
Relative humidity[1]	Y	%	Y
Atmospheric Pressure	Y	Pa	Y
Horizontal Infrared radiation intensity from sky[2]	Y	Wh/m^2	N
Global horizontal radiation[3]	N	Wh/m^2	Y
Direct normal radiation[3]	Y	Wh/m^2	N
Diffuse horizontal radiation[3]	Y	Wh/m^2	N
Wind direction	Y	Degrees	Y
Wind speed	Y	m/s	Y
Total sky cover	N	Tenths	N
Opaque sky cover[2]	N	Tenths	N
Present weather observation	Y	-	N
Present weather codes	Y	-	N
Snow depth	Y	cm	N
Liquid precipitation depth	Y	mm	N

Notes:
[1] *The dew point temperature can be estimated by relative humidity (see Eq. E 6, Eq. E 7 and Eq. E 8)*
[2] *When the Horizontal Infrared Radiation Intensity is missing, it is calculated by the Opaque sky cover* (USDOE, 2012a)

As the dew point temperature was missing from the data collected from the weather station, an alternative method was applied to estimate it. Relative humidity is defined as the ratio of the actual water vapour pressure (e) to the equilibrium vapour pressure over a plane of water (e_s), given by the equation (Lawrence, 2005):

Eq. E 6

$$RH = 100.\frac{e}{e_s}$$

The actual water vapour pressure and the equilibrium vapour pressure over a plane of water can be calculated by the empirical equation, so-called Magnus formula (Eq. E 7, Eq. E 8), which is commonly applied.

Eq. E 7

$$e = C.e^{\left(\frac{A.T_d}{B+T_d}\right)}$$

T_d= dew point temperature, ^oC

Eq. E 8

$$e_s = C.e^{\left(\frac{A.T}{B+T}\right)}$$

T=dry bulb temperature, ^oC

The coefficients in Eq. E 7 and Eq. E 8 have been calculated by Alduchov and Eskridge (1996), claiming less than 0.4% error for the temperature range of -40^{o}C $\leq$ t $\leq$ 50^{o}C. The values are as follows: A=17.625 ^{o}C, B=243.04 ^{o}C and C=610.94 Pa (Alduchov and Eskridge, 1996). Solving the equations Eq. E 7 and Eq. E 8, the dew-point temperature was calculated and used in the generation of the EPW file.

For the generation of the weather file, the values of hourly extraterrestrial (I_o), direct normal (I_{bn}) and diffuse horizontal (I_d) radiation were estimated according to the Duffie and Beckman method (Duffie and Beckman, 1982). The method is presented below:

Initially, the procedure requires some mandatory parameters of the solar geometry. Thus, the declination angle of the sun, δ, (degrees) is defined by:

$$\delta = 23{,}45.\sin\left(360.\frac{284+D}{365}\right)$$

Eq. E 9

where,

D is the calendar day of the year (1-365)

Here, φ is the latitude of the location (degrees) and ω is the hourly angle of the sun (degrees). At 12:00 midday the value of ω is zero, with the morning being negative and afternoon being positive, where for each hour the value is changed by 15^o (i.e. at 10:00 ω=-30^o). Moreover, the θ_z is the solar zenith angle calculated by Duffie and Beckman (1982):

$$\cos\theta_z = \cos\varphi\,.\cos\delta\,.\cos\omega + \sin\varphi\,.\sin\delta$$

Eq. E 10

The radiation variables can be estimated by the following equations. The extraterrestrial horizontal radiation (kJ/m^2) is given by as:

$$I_o = \left({}^{12.3600.I_{sc}}/_{\pi}\right).E_o.[\cos\varphi\,.\cos\delta\,.(\sin\omega_2 - \sin\omega_1)] + \left({}^{2\pi(\omega_2-\omega_1).\sin\varphi\,.\sin\delta}/_{360}\right)$$

Eq. E 11

where,

the solar constant, I_{sc}=1367 Wm^{-2}, E_O=1+0,033.cos (360.D/365)

The hourly clearness index (k_t) defined as the ratio of the hourly horizontal radiation on the horizontal surface to the hourly horizontal extra-terrestrial radiation,

$$k_t = {}^{I}/_{I_o}$$ ***Eq. E 12***

The hourly diffuse solar radiation, I_d, is estimated by (Orgill and Hollands, 1977) as:

$$k_d = {}^{I_d}/_{I} = \begin{array}{ll} 1 - 0.249k_t & k_t < 0.35 \\ 1.557 - 1.84k_t & 0.35 < k_t < 0.75 \\ 0.17 & k_t > 0.75 \end{array}$$ ***Eq. E 13***

, while the direct normal radiation is calculated as follows:

$$I_{bn} = \frac{I - I_d}{\cos\theta_z}$$ ***Eq. E 14***

During the generation of the EPW file, EnergyPlus also provides the user with the option to calculate the cloud cover index through randomisation. However, in order to minimize the source of uncertainty an empirical method was applied, implementing the atmospheric transmittance for beam radiation (k_b). The atmospheric transmittance for beam radiation is defined as the ratio of direct normal to hourly extraterrestrial radiation, indicating the clearness of the sky, with values closer to 1.0, representing clear sky (Wong and Chow, 2001; Sen, 2008).

$$k_b = {}^{I_{bn}}/_{I_{on}}$$ ***Eq. E 15***

I_{on}=extraterrestrial direct normal radiation (Wh/m^2)

Thereafter, data from neighbouring weather stations were used to develop a correlation for the different hours of the day between the atmospheric transmittance for beam radiation and the cloud cover index. Figure E. 2 illustrates the correlation between the average values of k_b and cloud cover index for Larnaca and Jerusalem weather stations.

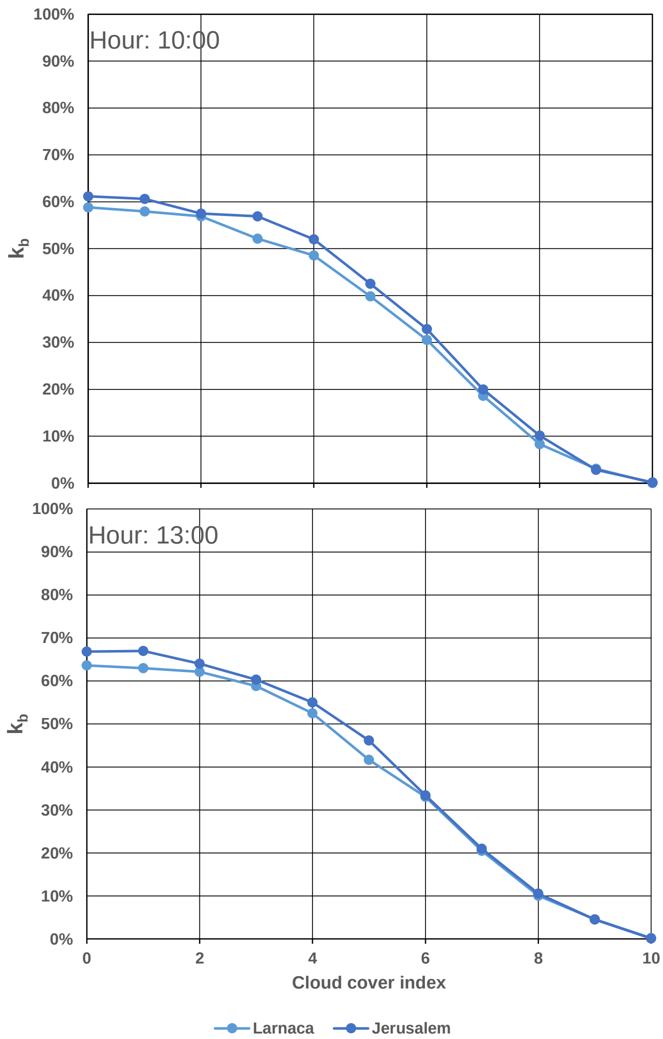


Figure E. 2 Atmospheric transmittance for beam radiation against cloud cover index

Applying the average values for each hour of the year when the sun is above the horizon, the cloud cover index was estimated and used to calculate the effective sky temperature of the EPW file.

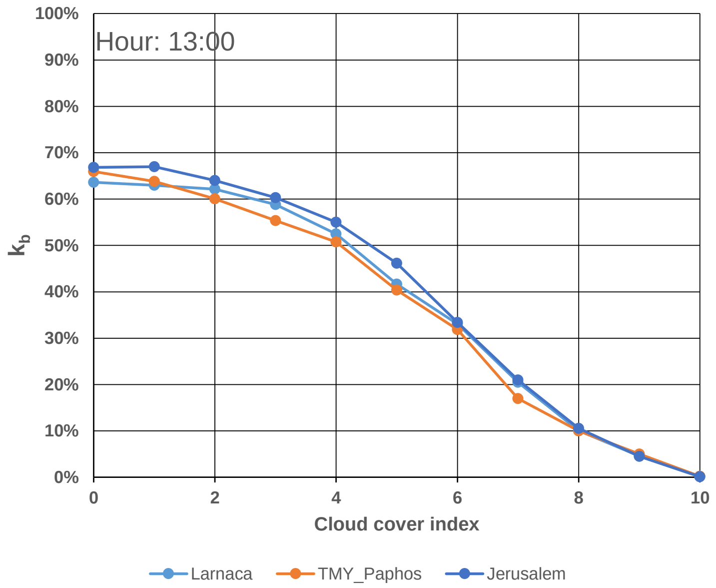


Figure E. 3 Atmospheric transmittance for beam radiation against cloud cover index (TMY-Paphos)

The same procedure for the generation of an EnergyPlus weather file was repeated for both TMY data set and actual weather data (of 2012).

E.3. Study on the weighting indices

Through this section, a study will be presented which seeks to investigate the impact of weighting index for the different climatological parameters and finally, the selection of the appropriate weather file that will be used on the main simulation procedure. In this scope, four TMY sets were generated, focusing on the different weather parameters.

Particularly, the weighting index for all parameters was nullified, except the one that will describe the selection of the TMY. The indexing is presented in Table E. 3. Moreover, the TMY_d is constructed with regards to the default weather indices by Hall et al., (1978), acting as a reference database to the study.

Table E. 3 Weighting factor of environmental parameters

PARAMETER		**WEIGHTING INDICES**				
		Default (TMY_d)	TMY_g	TMY_{db}	TMY_{rh}	TMY_{ws}
Temperature	Mean	0.08	0	0.5	0	0
	Max	0.04	0	0.25	0	0
	Min	0.04	0	0.25	0	0
Relative Humidity	Mean	0.08	0	0	0.5	0
	Max	0.04	0	0	0.25	0
	Min	0.04	0	0	0.25	0
Wind Speed	Mean	0.08	0	0	0	0.5
	Max	0.08	0	0	0	0.25
	Min	0	0	0	0	0.25
Global Radiation		**0.50**	1	0	0	0
Focus on			Global Radiation	Dry bulb temperature	Relative humidity	Wind Speed

As a result, the impact of each meteorological parameter will be examined in comparison to the Long Term (LT) and Actual Data (AD) year databases. Through the analysis, the impact of weighting index is determined in the perspective of typicality for the period (i.e. 2001-2011 periods) and the capability to predict future years.

The evaluation assessment is developed through a statistical analysis, based on the modified Pearson coefficient of determination, so-called adjusted-R^2 and the root mean square error (RMSE). The application of each coefficient is mainly based on the extent of impact by the presence of outliers.

In the case of cooling mode and solar collector, the adjusted-R^2 was employed, with a confidence level of 95%. The adjusted-R^2 compensates for the additional variables in the model, enhancing the accuracy of the analysis, on the contrary to the simple R^2 (Mark and Jolley 2010). A closer value to 1.0 indicates a strong correlation between the compared data sets.

However, for the heating mode case, the simple regression analysis is not sufficient to describe the model. Due to this fact, the robust regression was applied to estimate the adjusted-R^2 to eliminate the impact of outliers (Witten and Frank 2000).

Furthermore, the unpredictable seasonal wind profile contributes to the implementation of the root mean square error (RMSE) for the assessment of turbine performance. Lower values of RMSE indicate a smaller offset between the compared data set.

SIMULATION APPLICATIONS

The investigation of TMY's performance was examined by the implementation of three particular scenarios; a) a residential solar thermal system, b) a wind turbine generator and c) heating/cooling mode analysis of a typical dwelling in Cyprus. The same parameters of each simulation was used for all weather data sets.

SOLAR THERMAL SYSTEM

A domestic flat plate solar collector designed to serve the residential demands for domestic hot water, in conjunction with an electrical heater. The collector consisted of two solar plates with a gross area 2.96 m^2. In Figure E. 4, the daily heat production is presented for 3 arbitrary days in January, April and July.

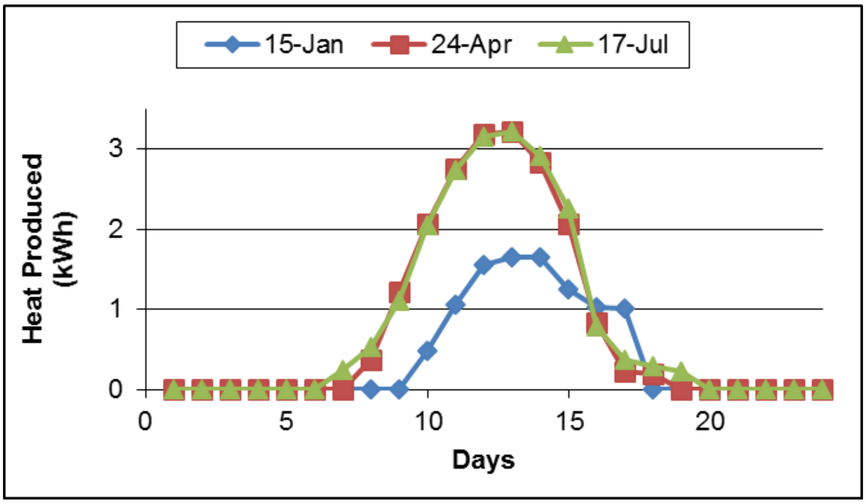


Figure E. 4 Daily heat production (Long term data set)

WIND TURBINE GENERATOR

Similarly, a wind turbine was examined in the perspective of energy production. For the particular simulation case, the result will be the electricity generation (kWh) and will be assessed in a similar manner as the solar collector case study. In Table E. 4, the characteristics of a horizontal axis turbine are shown, as described by (Bergey, 2012).

Table E. 4 Wind turbine characteristics

CHARACTERISTIC		UNITS
Rated rotor speed	84.07	rev/min
Rotor diameter	2.5	m
Overall height	5	m
Number of blades	3	-
Rated power	1.0	kW
Rated wind speed	11.6	m/s

Cut in wind speed	2.5	m/s
Cut out wind speed	30	m/s
Maximum tip speed ratio	5	-

THERMAL LOAD ANALYSIS

The last scenario is coherent with the analysis of thermal loads of a typical residential building. A single zone dwelling was designed with a total floor area of 200 m^2, in accordance with the parameters by (CYSTAT, 2010). Table E. 5 presents the properties of the building elements.

Table E. 5 Properties of building envelope

STRUCTURAL ELEMENT	**U VALUE (W/m^2K)**
Exterior Walls	1.389
Floor	2.47
Roof	1.8
Glazing	1.960

The parameters that are investigated through the study are the energy required by the heating and cooling loads, to maintain the indoor temperature at 21 ^oC and 25 ^oC, for the period of November-March and April-October, respectively.

RESULTS AND DISCUSSION

In this section, the results from the evaluation of the TMYs performance against the LT and AD databases are presented. The outcome is based on the aforementioned simulation cases. As can be seen from the Figure E. 5 and Figure E. 7, the cooling mode and solar collector cases are following a linear trend. The application of simple linear regression will be sufficient to evaluate the TMYs.

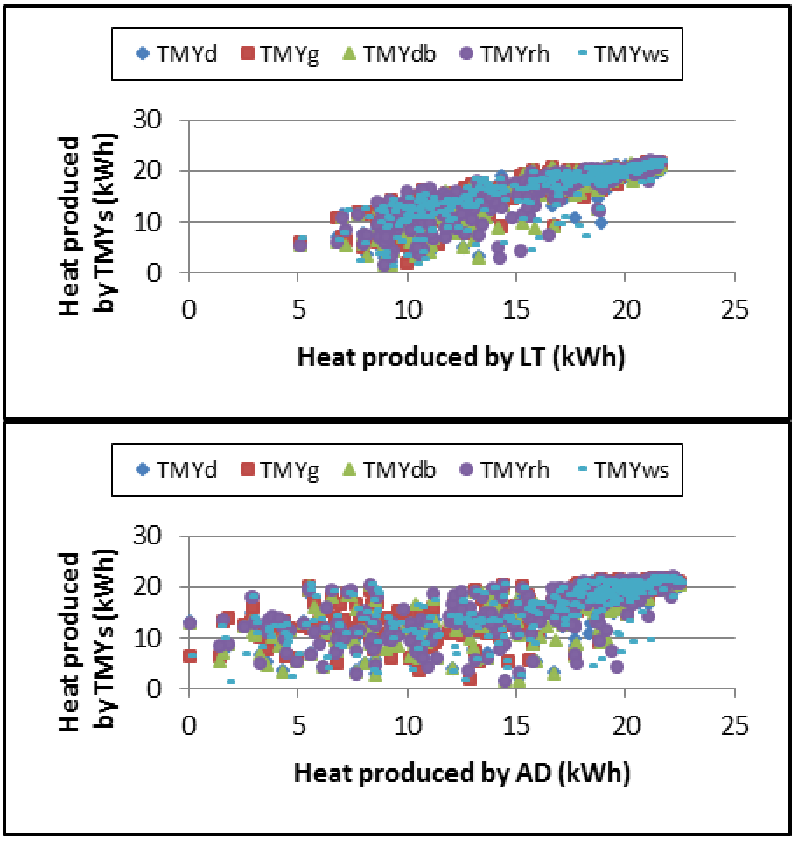


Figure E. 5 Heat production against LT and AD (Solar Collector)

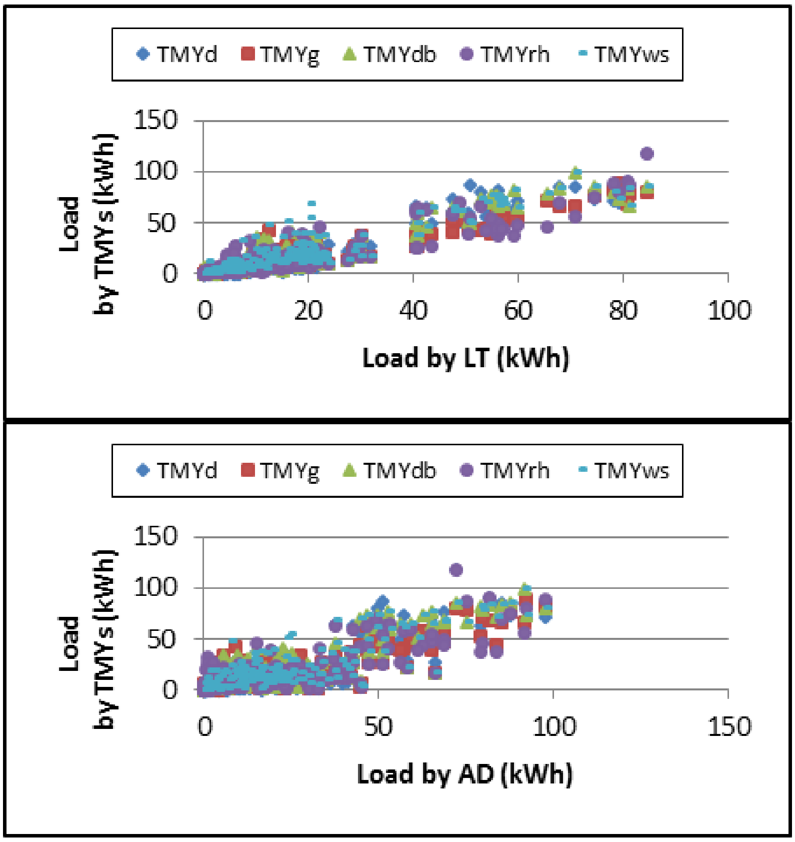


Figure E. 6 Cooling load against LT and AD

In contradiction, for the heating mode and wind turbine simulation the adoption of an alternative approach is mandatory, due to the existence of outliers that distort the linearity of the model. A possible cause is the lack of seasonality of the winter period and the difficulty to forecast the wind profile.

The climate in Cyprus is characterized as summer dominant. In essence, the winter period is not as constant as summer season. This is shown in Table E. 6, where the frequency of standard deviation for the dry bulb temperature hourly values is estimated for winter and summer period during 2001-2011.

Table E. 6 Frequency of standard deviation in winter and summer period in Cyprus

STANDARD DEVIATION	SUMMER	WINTER
0-1	538	4
1.01-2	1478	215
2.01-3	142	722
3.01-4	2	593
4.01-5	0	495
5.01-8	0	131

As it can be seen, the standard deviation during the winter period reaches up to 8, whereas during the summer goes up to 4 with the frequency lies within 1-3. As a result, the presence of outliers leads to the distortion of the results. In essence, the adjusted-R^2 calculated by robust fitting using the case of the heating mode. Figure E. 7 shows the results for the heating mode.

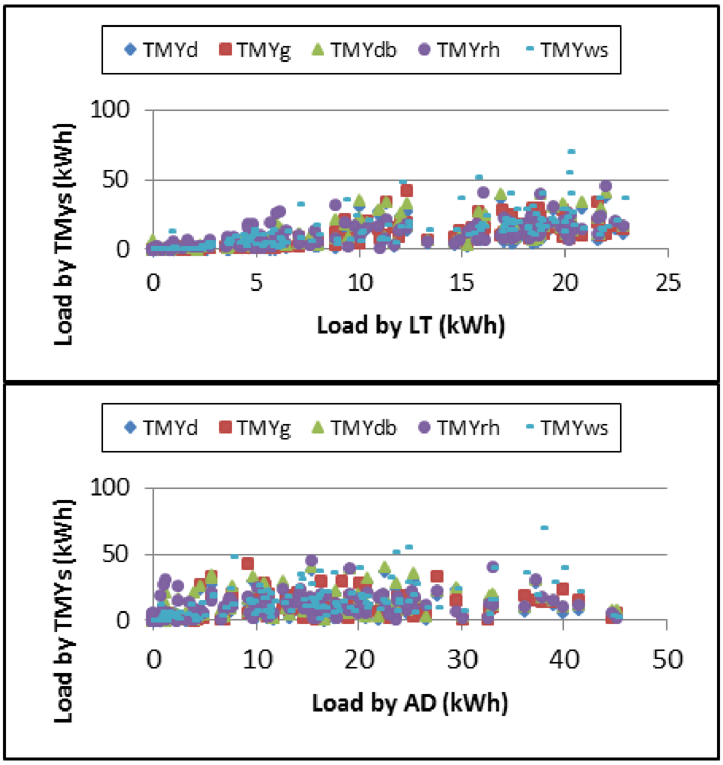


Figure E. 7 Heating load against LT and AD

Analogously, the effect of large-scale mechanisms such as the difference of temperature, pressure and local surface characteristics contribute to the difficulty of estimating wind profile between years (Sfetsos, 2000). The TMYs present similar seasonal profile, but the hourly magnitude and direction of wind varies considerably. Thereby, the deviation from the long term and actual data of 2012 estimated by the RMSE.

Table E. 7 Performance of TMYs with regards to LT

DATA SET	**SOLAR COLLECTOR**	**COOLING MODE**	**HEATING MODE**	**WIND TURBINE**
	Adjusted-R^2			RMSE
TMY_d	0.7692	**0.9265**	**0.8878**	0.455
TMY_g	**0.8132**	0.902	0.87	0.464
TMY_{db}	0.7831	0.923	0.83	0.427
TMY_{rh}	0.7456	0.9156	0.69	0.447
TMY_{ws}	0.7183	0.914	0.85	**0.401**

Table E. 8 Performance of TMYs with regards to AD

DATA SET	SOLAR COLLECTOR	COOLING MODE	HEATING MODE	WIND TURBINE
	Adjusted-R^2			RMSE
TMY_d	0.51	**0.9886**	**0.747**	0.83
TMY_g	**0.526**	0.809	0.722	0.86
TMY_{db}	0.5212	0.88	0.5745	0.831
TMY_{rh}	0.446	0.862	0.3558	0.857
TMY_{ws}	0.4607	0.87	0.7102	**0.795**

It is noticed that the performance of all TMYs data series are relatively similar, which is revealed by the composition method. During the concatenation of the months to form the data sets, the selected months are the most typical, resulting in approximately similar performance.

However, distinction can be made with the cases that have the best fit with the long term. The TMYs driven mainly by global radiation and wind speed have the best performance, for the solar collector and wind turbine, accordingly. Now, in the perspective of the heating and cooling mode of a residential building, the TMY_d presents the best performance. As it is aforementioned, the generation of TMY_d is mainly driven by global radiation, but it is also influenced by the rest of the meteorological parameters, resulting in the expected performance on the calculation of building loads.

As it can be seen in Table E. 8, the scene remains the same through the comparison of the TMYs against the AD. The best performance is also presented by the same TMYs, as described before.

According to the aforementioned, the impact of weighting factor in the generation of TMY data series is driven by the simulation case that the TMY will be applied as a weather input. For the investigation of specific renewable applications such as solar collector and wind turbine, an attention must be given to the weather parameters that are directly related to the applications, i.e., global radiation and wind profile.

On the contrary, when the simulations examine the performance of a building under the heating and cooling mode, the emphasis must be given to all meteorological variables, as the demand for heating or cooling is driven by the conjunction of numerous weather parameters.

Moreover, the application of a TMY for a given location must be examined within the perspective of the climate characteristics. As highlighted in the study, the cooling load evaluated by the use of the linear regression, while the heating load and the wind turbine require the implementation of the robust regression and RMSE to estimate the performance of TMYs against the long term and actual future data.

F. ENERGY SAVING MEASURES ASSESSMENT

The Appendix F contains the questionnaires that were distributed to the relevant companies to estimate the current prices for the application of measures during the retrofitting of existing houses. The Appendix F is divided as follows:

F.1 Thermal Insulation Materials

F.2 Glazing System

F.3 Frame and Window Installation Cost

F.4 Labour during retrofitting-Cost

F.1. Thermal Insulation Materials

My name is George Georgiou and I am a PhD candidate at the school of Civil & Building Engineering, Loughborough University. I am supervised by Dr. Mahroo Eftekhari and Prof. Phil C Eames. My research is to investigate the domestic building in the Mediterranean region in the perspective of energy consumption and thermal comfort. As part of my research, I am assessing the characteristics of thermal insulation materials for refurbishment of existing dwellings. Therefore I would really appreciate your help by filling out the short questionnaire below.

Information for Participant

- I understand that I am under no obligation to take part in the study.
- I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.
- I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

If you have any queries or questions you can contact me on my university email:

G.Georgiou@lboro.ac.uk

Many thanks for your cooperation.

Company: ……………………………………………………..

Position: ……………………………………………………..

Q1. Name at least 5 materials and their properties for the integration on EXISTING DWELLINGS for refurbishment. The thermal material will be INTERNALLY or EXTERNALLY applied on the building enclosure.

	Material	**Thermal Conductivity, λ (W/mK)**	**Application *(Mark with √)*** Building Element	Location	**1**	**2**	**3**	**4**	**5**	**6**	**Details**
1			□External Walls □Roof □Floor	□Internal □External							Thickness (mm)
											Cost (€/m^2)
2			□External Walls	□Internal							Thickness (mm)

			□Roof □Floor	□External							Cost (€/m²)

3			□External Walls □Roof □Floor	□Internal □External							Thickness (mm)
											Cost (€/m²)

4			□External Walls □Roof □Floor	□Internal □External							Thickness (mm)
											Cost (€/m²)

5			□External Walls	□Internal							Thickness (mm)

			□Roof □Floor	□External							Cost (€/m^2)

6			□External Walls □Roof □Floor	□Internal □External							Thickness (mm)
											Cost (€/m^2)

7			□External Walls	□Internal							Thickness (mm)

			□Roof □Floor	□External								Cost (€/m^2)

8			□External Walls □Roof □Floor	□Internal □External								Thickness (mm)
												Cost (€/m^2)

9			□External Walls □Roof □Floor	□Internal □External								Thickness (mm)
												Cost (€/m^2)

Any other information about thermal materials (Please comment):

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Q2. If it is available, please specify the average number per year of applications, for the materials mentioned at the previous question?

Material Number	New Houses					Existing Houses				
	2009	2010	2011	2012	2013	2009	2010	2011	2012	2013
1										
2										
3										

4										
5										
6										
7										
8										
9										
10										

Any other information (Please comment):

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Q3. Specify the total capital cost for the application of thermal material:

Location	Structural Element	Cost (€/m^2)
Outside of	External Walls	
	Roof	
Inside of	External Walls	
	Roof	
	Floor	

Any other information (Please comment):

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Loughborough University

F.2. Glazing System

My name is George Georgiou and I am a PhD candidate at the school of Civil & Building Engineering, Loughborough University. I am supervised by Dr. Mahroo Eftekhari and Prof. Phil C Eames. My research is to investigate the domestic building in the Mediterranean region in the perspective of energy consumption and thermal comfort. As part of my research, I am assessing the characteristics of glazing systems for refurbishment of existing dwellings. Therefore, I would really appreciate your help by filling out the short questionnaire below.

Information for Participant

- I understand that I am under no obligation to take part in the study.
- I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.
- I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

If you have any queries or questions you can contact me on my university email:

G.Georgiou@lboro.ac.uk

Many thanks for your cooperation.

Company: …………………………………………………

Position: …………………………………………………..

Q1. Specify the U_g and cost for the following glazing systems, based on your company's standard spacer and with visible transmittance (VT) within the range of 25% to 80%:

Glazing Type	Dimensions	Glass	Gas Fill	U_g (W/K.m^2)	Solar Factor, g (%)	Cost (€/m^2)
Double Pane	$\frac{Glass}{6mm} - \frac{Gap}{12\sim16mm} - \frac{Glass}{4mm}$	1.Clear	Air			
		2.Tinted				
		3.Low-E-**HSF**				
		4.Low-E-**MSF**				
		5.Low-E-**LSF**				

, if your company is manufacturing triple pane glazing, please fill the table as in the case of double glazing (add also the typical thickness of each component)

Triple Pane	6mm-**6mm**-4mm(clear)-**6mm**-4mm(clear)	6.Clear				
		7.Low-E-**HSF**				
		8.Low-E-**MSF**				
		9.Low-E-**LSF**				

HSF=High Solar Factor (>60%), MSF=Medium Solar Factor (60%-40%), LSF=Low Solar Factor (40%>)

Q2. Instate of Air, which gas is commonly used for gap filling?

Gas: …………………………………………………………………

, indicate also the changes on the Ug and cost on the glazing system mentioned in Q1.

Glazing Type	Glass	U-value Reduction ($W/K.m^2$)	Additional Cost (€/m^2)
Double Pane	1.Clear		
	2.Tinted		
	3.Low-E-**HSF**		
	4.Low-E-**MSF**		
	5.Low-E-**LSF**		

Triple Pane	6.Clear		
	7.Low-E-**HSF**		
	8.Low-E-**MSF**		
	9.Low-E-**LSF**		

Q3. In the case of using an alternative thermal spacer, please name the type and the impact on the cost and Ug:

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Loughborough University

F.3. Frame and Window Installation Cost

My name is George Georgiou and I am a PhD candidate at the school of Civil & Building Engineering, Loughborough University. I am supervised by Dr. Mahroo Eftekhari and Prof. Phil C Eames. My research is to investigate the domestic building in the Mediterranean region in the perspective of energy consumption and thermal comfort. As part of my research, I am assessing the characteristics of glazing systems for refurbishment of existing dwellings. Therefore, I would really appreciate your help by filling out the short questionnaire below.

Information for Participant

- I understand that I am under no obligation to take part in the study.
- I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.
- I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

If you have any queries or questions you can contact me on my university email:

G.Georgiou@lboro.ac.uk

Many thanks for your cooperation.

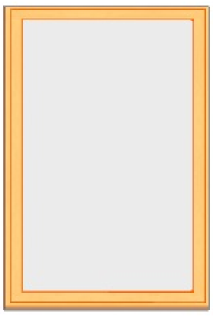
Company: ……………………………………………………

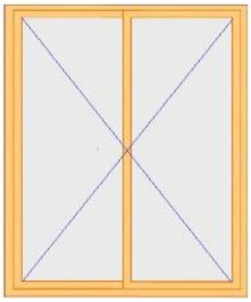
Position: ……………………………………………………..

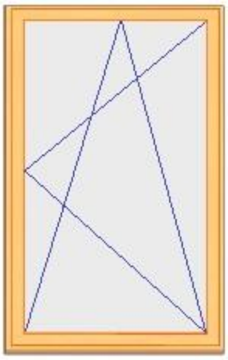
Q1. Name the properties of your company's THERMAL frame.

Window System	Material	U_f (W/m^{2}K)
1.Fix		
2.Opening		
3. Sliding		
4. Curtain Walls		

Q2. Indicate the estimated cost for the following window systems WITHOUT the cost of the glass (€/unit).

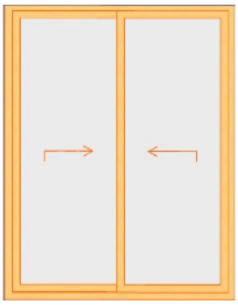
FIX WINDOW		
		
Details		
Length (cm)	Height (cm)	Cost (€/unit)
30	240	

40	150	
70	100	
OPENING WINDOW		
		
Details		
Length (cm)	Height (cm)	Cost (€/unit)
100	100	
120	120	
150	150	
200	100	
OPENING AND TURN & TILT WINDOW		



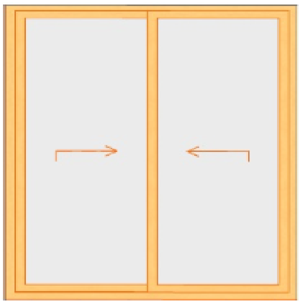
Details		
Length (cm)	Height (cm)	Cost (€/unit)
40	150	
80	80	
80	120	
100	100	
100	160	

SLIDE WINDOWS (2 PANES)



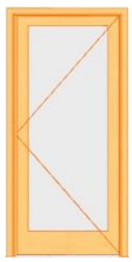
Details		
Length (cm)	Height (cm)	Cost (€/unit)
120	250	
140	200	
170	220	
190	250	
200	200	
200	270	
250	150	
250	240	

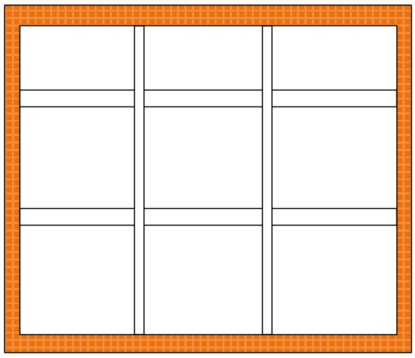
LIFT AND SLIDE WINDOWS (2 PANES)



Details

Loughborough University

Length (cm)	Height (cm)	Cost (€/unit)
300	250	
320	240	
350	220	
370	240	
400	220	
KITCHEN DOOR		
		
Details		
Length (cm)	Height (cm)	Cost (€/unit)
100	220	
CURTAIN WALL		



Details		
Length (cm)	Height (cm)	Cost (€/unit)
120	570	

Loughborough University

F.4. Labour during retrofitting-Cost

My name is George Georgiou and I am a PhD candidate at the school of Civil & Building Engineering, Loughborough University. I am supervised by Dr. Mahroo Eftekhari and Prof. Phil C Eames. My research is to investigate the domestic building in the Mediterranean region in the perspective of energy consumption and thermal comfort. As part of my research, I am assessing the retrofitting existing residential buildings. Therefore, I would really appreciate your help by filling out the short questionnaire below.

Information for Participant

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

If you have any queries or questions you can contact me on my university email:

G.Georgiou@lboro.ac.uk

Many thanks for your cooperation.

Company: ………………………………………………………

Position: ……………………………………………………..

Please, give the indicative cost (€/m^2) for labour and material during retrofitting a house:

A. Thermal Insulation:

- **Assume an insulant with thickness of 5 cm and cost of € 5, 00/m^2.**
- **If your company installs internal insulation, give the cost for the application of internal insulation finished with gypsum board**
- **In the cost, include the price of all materials as well as the cost of the thermal insulation material.**

A1. Insulation of external walls.

Location of insulation material	Cost (€/m^2)	
	Labour	Materials
A. Internally		
B.Externally		

A2. Insulation of flat roof.

Location of insulation material	Cost (€/m^2)	
	Labour	Materials
A. Internally		
B. Externally		

A3. Insulation of pitched roof (application on the loft).

Location of insulation material	Cost (€/m^2)	
	Labour	Materials
A. Internally		
B. Externally		

A4. Insulation of pitched roof (application on the inclined roof slab).

Location of insulation material	Cost (€/m^2)	
	Labour	Materials
A. Internally		
B. Externally		

A5. Insulation of the ground floor (Include also the cost of removing the existing floor, for the placement of the insulant at the top of slab).

Cost (€/m^2)	
Labour	Materials

B. External Shading:

B1. Construction of a concrete projection of 10 cm (Overhang or Fins).

Location of the projection	Cost (€/m²)	
	Labour	Materials
A. Vertical		
B. Horizontal		

C. Coating of surfaces

C1. For the coating of roof or external walls (white paint).

Element	Cost (€/m²)	
	Labour	Materials
A. Roof (Flat)		
B. Roof (Pitched-below tiles)		
C. External Walls		

Any other information (Refer to the number of the question i.e. A2. Flat roof):

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G. ENERGY MANAGEMENT SYSTEM (EMS)

An advantage of the latest versions of the E+ is the implementation of Energy Management System (EMS). It is based on the use of EPlus Runtime Language (Erl) to supervisory control the components and systems in E+. The principle of its function is governed by the use of "sensors" and "actuators" and through a Program Manager which manipulates them, triggers the function or overrides the control of components (e.g. shading, windows, coils, ideal systems etc.) (USDOE, 2012c). For instance, the user can trigger the use of a heating system when the $T_{rm} < 15^oC$, while combining the presence of occupancy and low levels of CO_2.

In essence, the user is able to describe, control or simulate the actions in buildings, rather than setting typical control schedules which may lead to inaccurate performance of the building's system.

G.1. Natural Ventilation

The following EMS reproduces the natural ventilation rules of Figure 4-4. The same coding was repeated for all the rooms of the house. Here, is an example for the case of living room.

```
!-   =========== ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM: SENSOR ===========
EnergyManagementSystem:Sensor,
    OTemp,                  !- Name
    *,                      !- Output:Variable or Output:Meter Index Key Name
    Site Outdoor Air Drybulb Temperature;  !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
```

```
    Rm,                      !- Name
    RunningMeanTemp,         !- Output:Variable or Output:Meter Index Key Name
    Schedule Value;          !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    LR_CO2,                  !- Name
    Ground%Floor:LivingRoom, !- Output:Variable or Output:Meter Index Key Name
    Zone Air CO2 Concentration;  !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    LR_Occ,                  !- Name
    Occupancy_LR,            !- Output:Variable or Output:Meter Index Key Name
    Schedule Value;          !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    LR_HVAC,                 !- Name
    Heating_LR,              !- Output:Variable or Output:Meter Index Key Name
    Schedule Value;          !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    LR_OperTem,              !- Name
    Ground%Floor:LivingRoom, !- Output:Variable or Output:Meter Index Key Name
    Zone Operative Temperature;  !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    LR_Temp,                 !- Name
    Ground%Floor:LivingRoom, !- Output:Variable or Output:Meter Index Key Name
    Zone Air Temperature;    !- Output:Variable or Output:Meter Name
!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:ACTUATOR ===========
EnergyManagementSystem:Actuator,
    LR_Sw1,                  !- Name
    LR_Vent,                 !- Actuated Component Unique Name
    Zone Ventilation,        !- Actuated Component Type
    Air Exchange Flow Rate;  !- Actuated Component Control Type
!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAMCALLINGMANAGER
===========
```

```
EnergyManagementSystem:ProgramCallingManager,
   NaturalVent,            !- Name
   BeginTimestepBeforePredictor,  !- EnergyPlus Model Calling Point
   NaturalVent_LR;,         !- Program Name 1
!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAM
===========
EnergyManagementSystem:Program,
   NaturalVent_LR,         !- Name
   IF LR_Occ==0.0,         !- Program Line 1
   Run Fully_Close_LR,      !- Program Line 2
   ELSEIF LR_Occ<>0.0  && LR_CO2>=800,  !- A4
   Run Fully_Open_LR,       !- A5
   ELSEIF LR_Occ<>0.0 && LR_CO2<800 && LR_HVAC==0.0,  !- A6
   Run TempControl_LR,      !- A7
   ELSEIF LR_Occ<>0.0 && LR_CO2<800 && LR_HVAC==1.0,  !- A8
   Run Fully_Close_LR,      !- A9
   ENDIF;                 !- A10
!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:SUBROUTINE
===========
EnergyManagementSystem:Subroutine,
   Fully_Open_LR,          !- Name
   SET LR_Sw1=0.1154;      !- Program Line 1
EnergyManagementSystem:Subroutine,
   TempControl_LR,         !- Name
   IF RM<28.1 && OTemp<32 && LR_Temp>OTemp && RM>=15 && LR_OperTem>=24.6 &&
LR_OperTem<=30.6,  !- Program Line 1
   SET LR_Sw1=0.1154*((LR_OperTem-24.6)/(30.6-24.6)),  !- Program Line 2
   ELSEIF RM>=28.1 && OTemp>=32 && OTemp<LR_Temp+5,  !- A4
   SET LR_Sw1=0.1154,      !- A5
   ELSE,                 !- A6
   SET LR_Sw1=0.0,         !- A7
   ENDIF;                !- A8
```

```
EnergyManagementSystem:Subroutine,
    Fully_Close_LR,          !- Name
    SET LR_Sw1=0.0;          !- Program Line 1
```

G.2. Halogen Heater

As the natural ventilation strategy, the halogen heater was simulated by the EMS. The following example emulates the operation of a halogen heater in a living room.

```
!-   =========== ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM: SENSOR ===========
EnergyManagementSystem:Sensor,
    LR_Occc,                 !- Name
    Occupancy_LR,            !- Output:Variable or Output:Meter Index Key Name
    Schedule Value;          !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    LocHeatAvai,             !- Name
    LocalHeaterAvailability, !- Output:Variable or Output:Meter Index Key Name
    Schedule Value;          !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    OTemp,                   !- Name
    *,                       !- Output:Variable or Output:Meter Index Key Name
    Site Outdoor Air Drybulb Temperature;  !- Output:Variable or Output:Meter Name
EnergyManagementSystem:Sensor,
    Rm,                      !- Name
    RunningMeanTemp,         !- Output:Variable or Output:Meter Index Key Name
    Schedule Value;          !- Output:Variable or Output:Meter Name
!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:ACTUATOR ===========
EnergyManagementSystem:Actuator,
    HeaterLR,                !- Name
```

```
   HeaterSchedule,          !- Actuated Component Unique Name

   Schedule:Compact,        !- Actuated Component Type

   Schedule Value;          !- Actuated Component Control Type

!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAMCALLINGMANAGER
===========

EnergyManagementSystem:ProgramCallingManager,

   Local_Heater,            !- Name

   BeginTimestepBeforePredictor,  !- EnergyPlus Model Calling Point

   Local_Heater_LR;         !- Program Name 1

!-   ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAM
===========

EnergyManagementSystem:Program,

   Local_Heater_LR,         !- Name

   IF LR_Occ<>0.0 && LocHeatAvai==1.0 && Rm<=15.0 && LR_OperTem<=18.8,  !- Program Line 1

   SET HeaterLR=1.0,        !- Program Line 2

   ELSE,                    !- A4

   SET HeaterLR=0,          !- A5

   ENDIF;                   !- A6
```

H. Validation Results

As it is mentioned, the calibration and validation procedure was applied in every case study that is examined in this study. This Appendix presents the results for all dwellings.

1. Dwelling-SD1

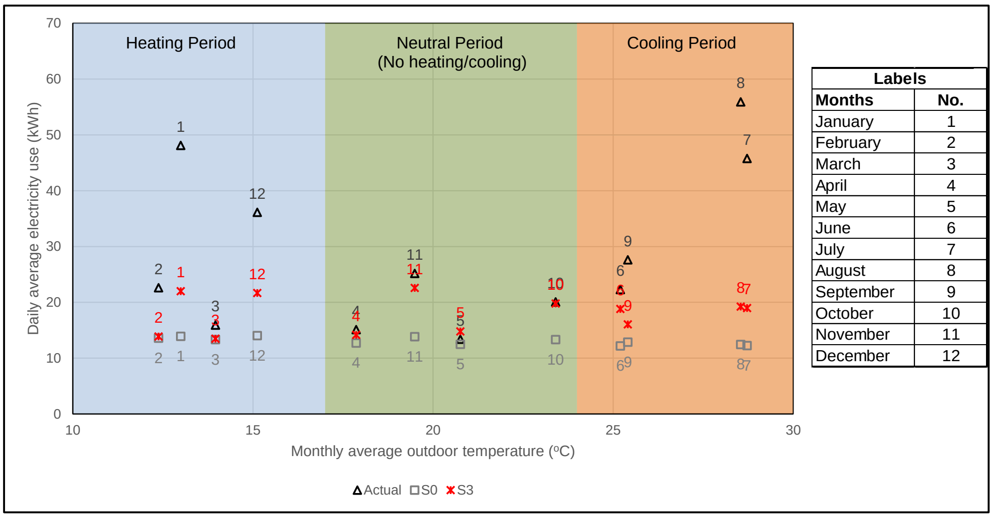


Figure H. 1 Daily average electricity against average monthly outdoor temperature, SD1

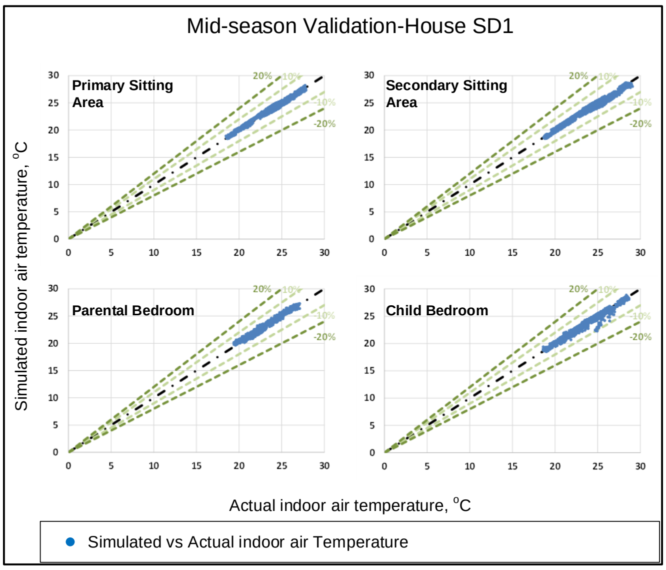


Figure H. 2 Simulated and actual indoor temperature, SD1

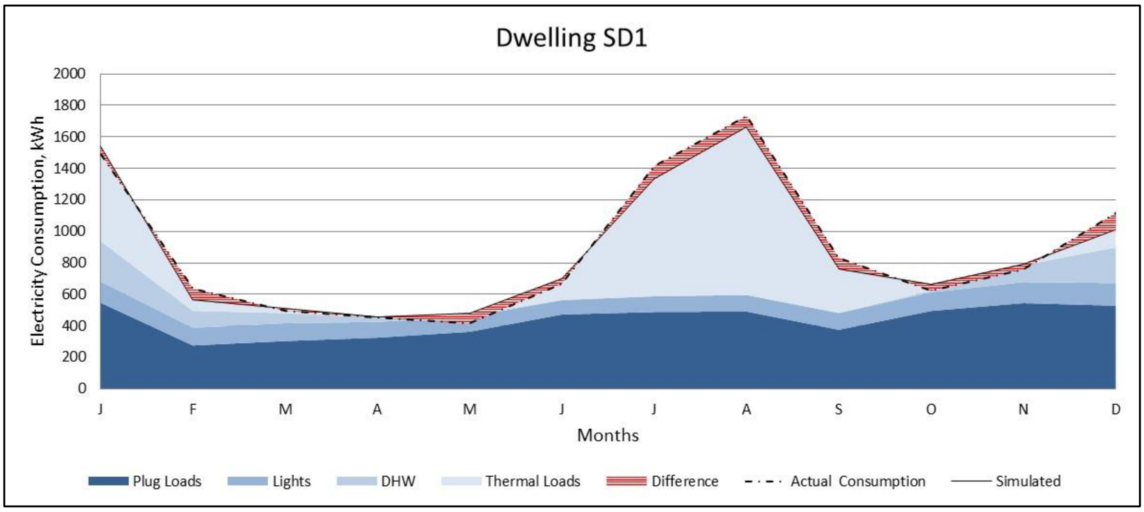


Figure H. 3 Actual and simulated electricity consumption-case study SD1

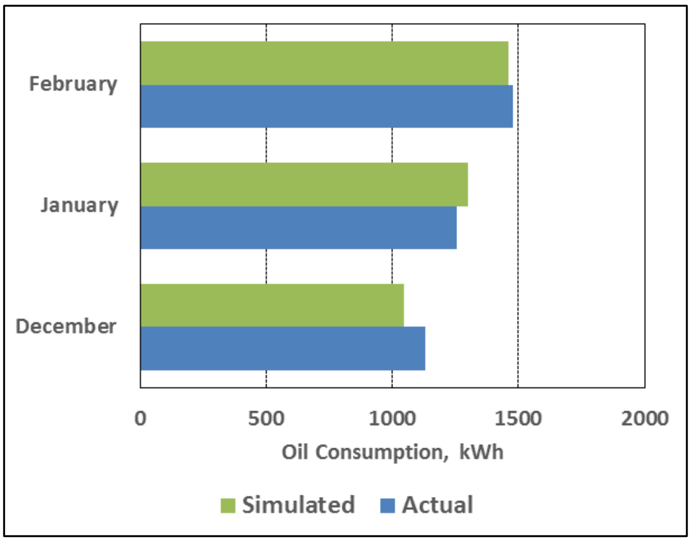
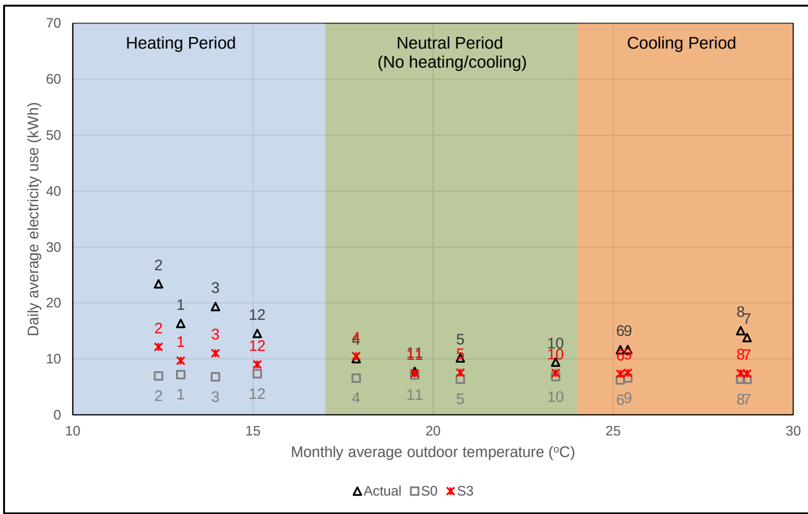


Figure H. 4 Actual and simulated heating oil consumption-case study SD1

2. Dwelling-SD2



Labels	
Months	No.
January	1
February	2
March	3
April	4
May	5
June	6
July	7
August	8
September	9
October	10
November	11
December	12

Figure H. 5 Daily average electricity against average monthly outdoor temperature, SD2

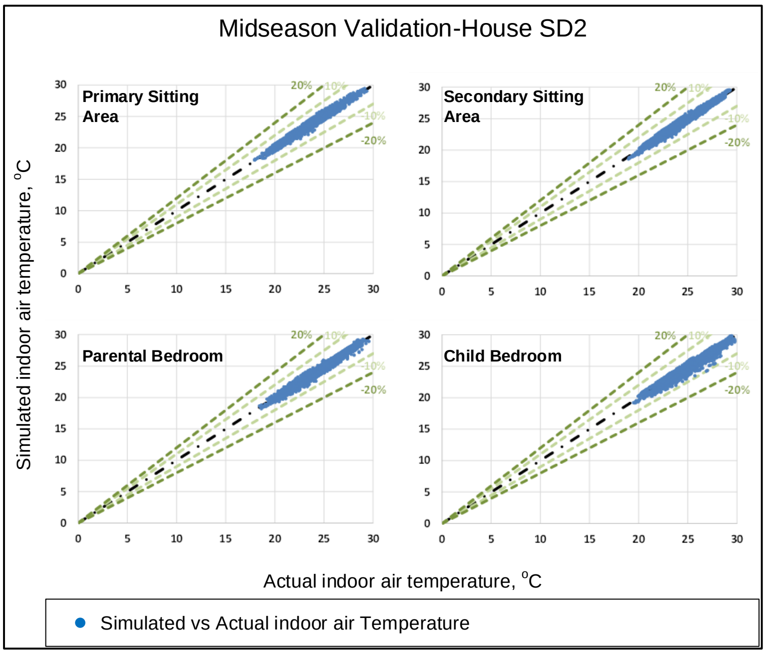


Figure H. 6 Simulated and actual indoor temperature, SD2

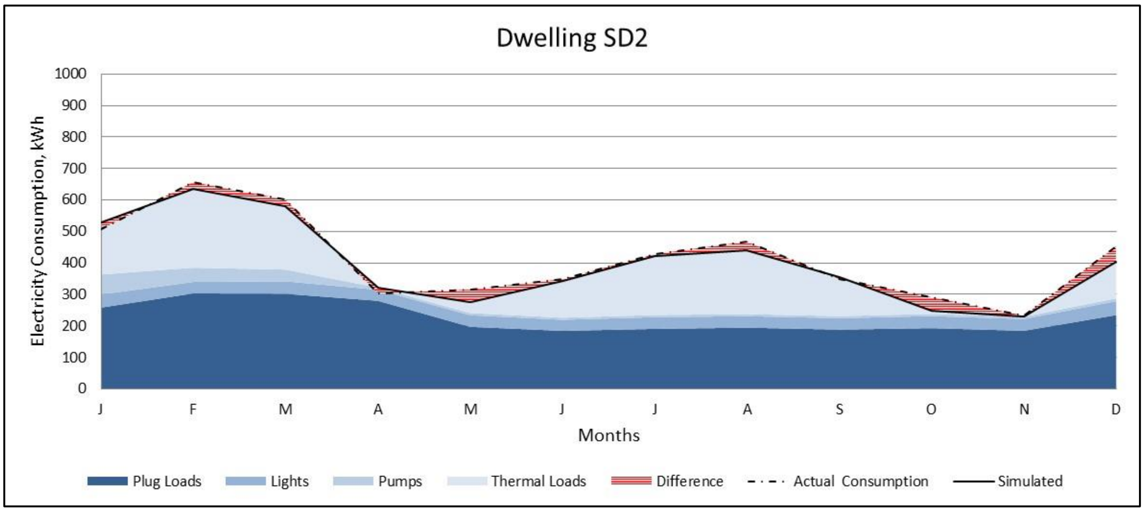


Figure H. 7 Actual and simulated electricity consumption-case study SD2

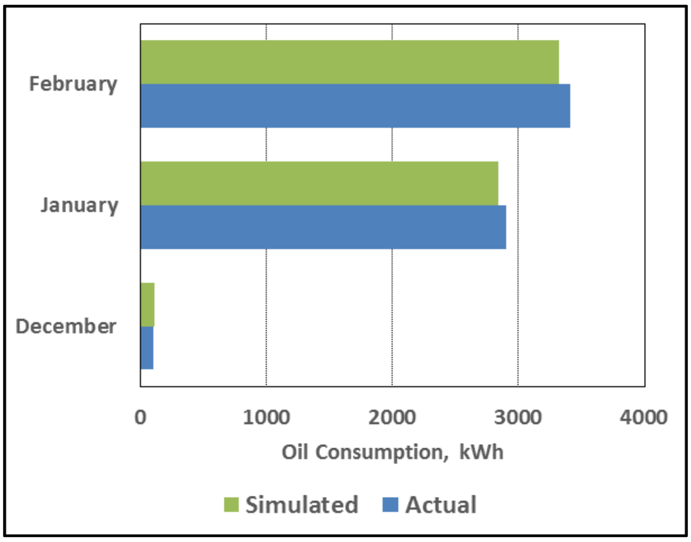
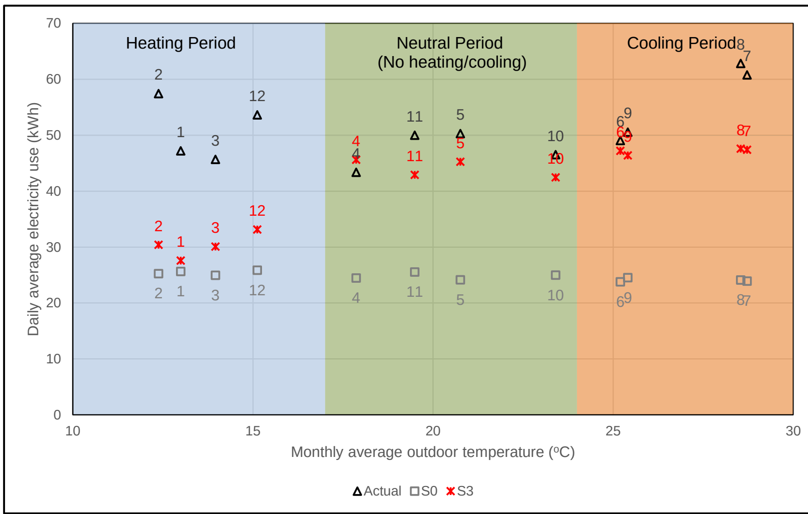


Figure H. 8 Actual and simulated heating oil consumption-case study SD2

3. Dwelling-SD3



Labels	
Months	No.
January	1
February	2
March	3
April	4
May	5
June	6
July	7
August	8
September	9
October	10
November	11
December	12

Figure H. 9 Daily average electricity against average monthly outdoor temperature, SD3

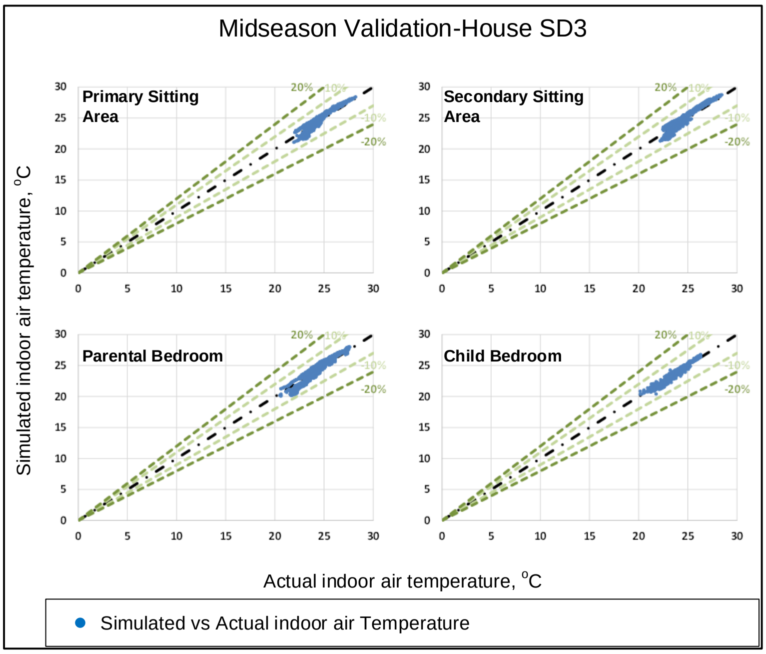


Figure H. 10 Simulated and actual indoor temperature, SD3

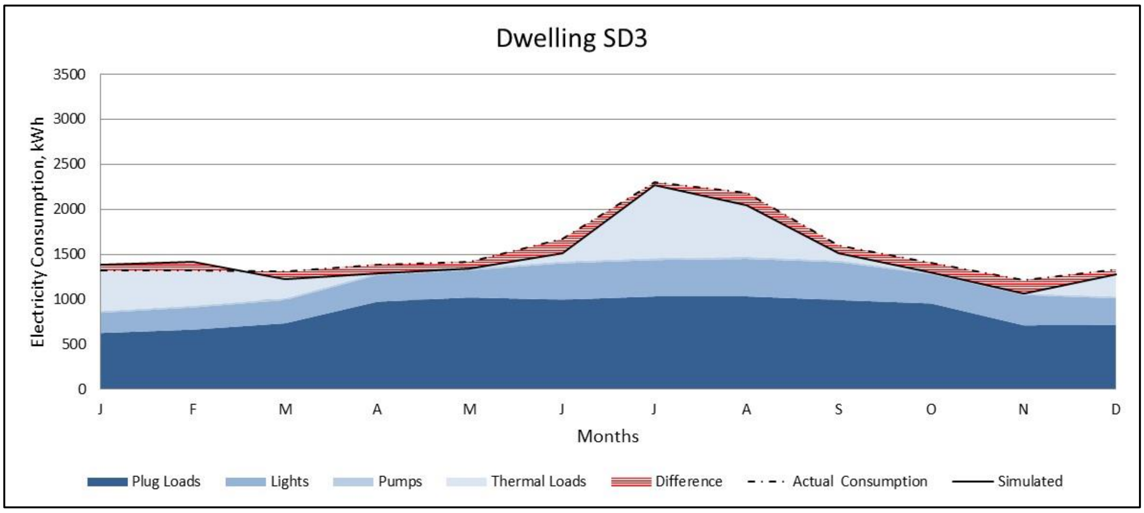


Figure H. 11 Actual and simulated electricity consumption-case study SD3

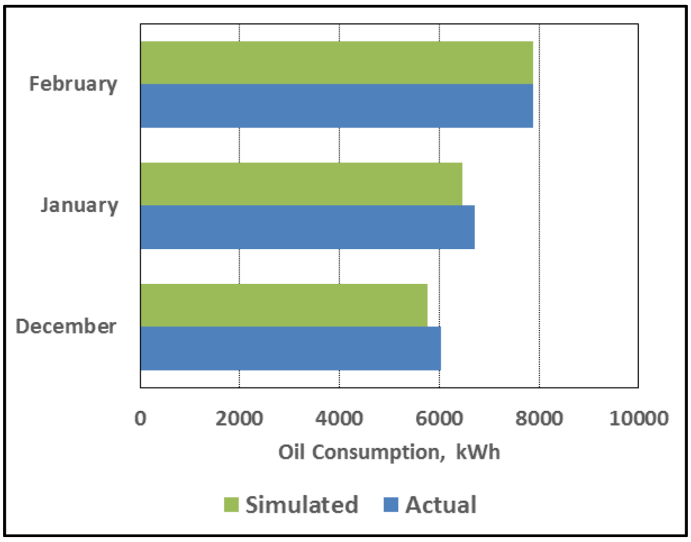


Figure H. 12 Actual and simulated heating oil consumption-case study SD3

4. Dwelling-SD4

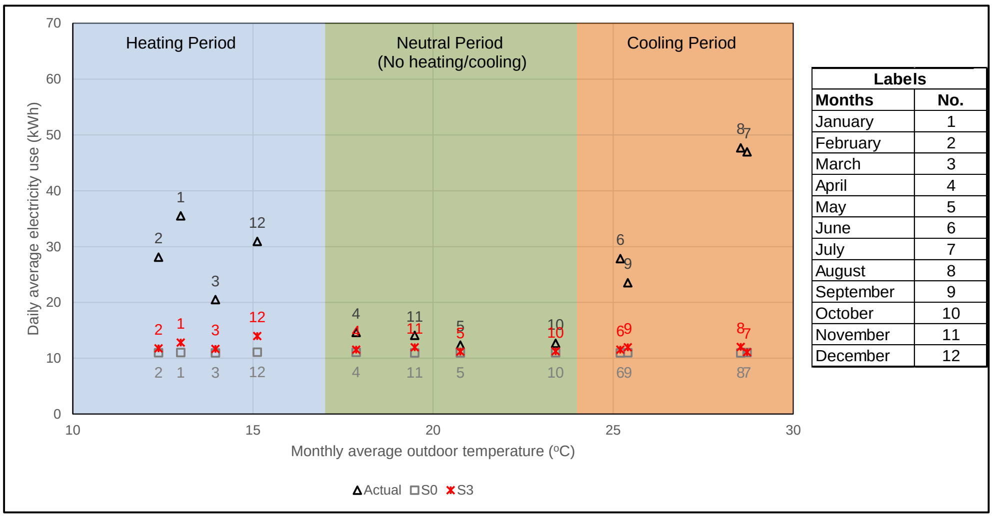


Figure H. 13 Daily average electricity against average monthly outdoor temperature, SD4

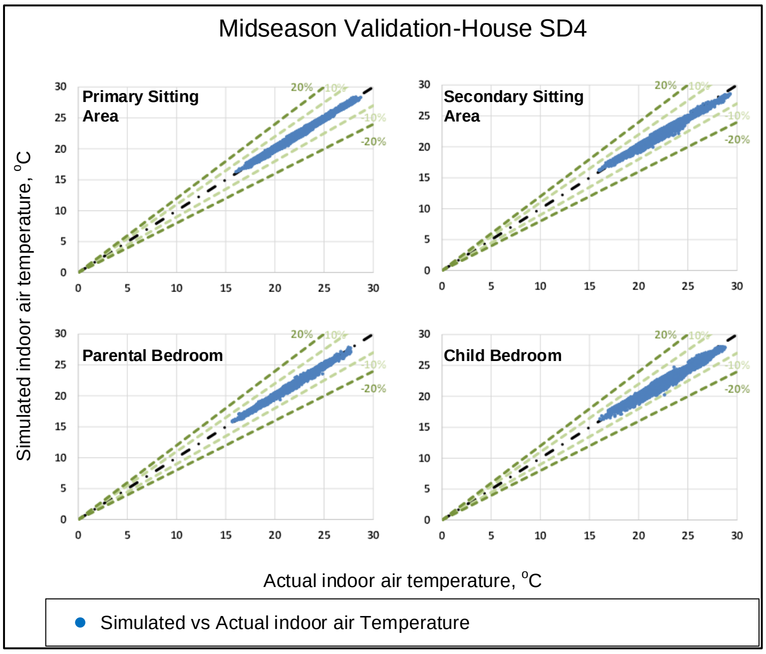


Figure H. 14 Simulated and actual indoor temperature, SD4

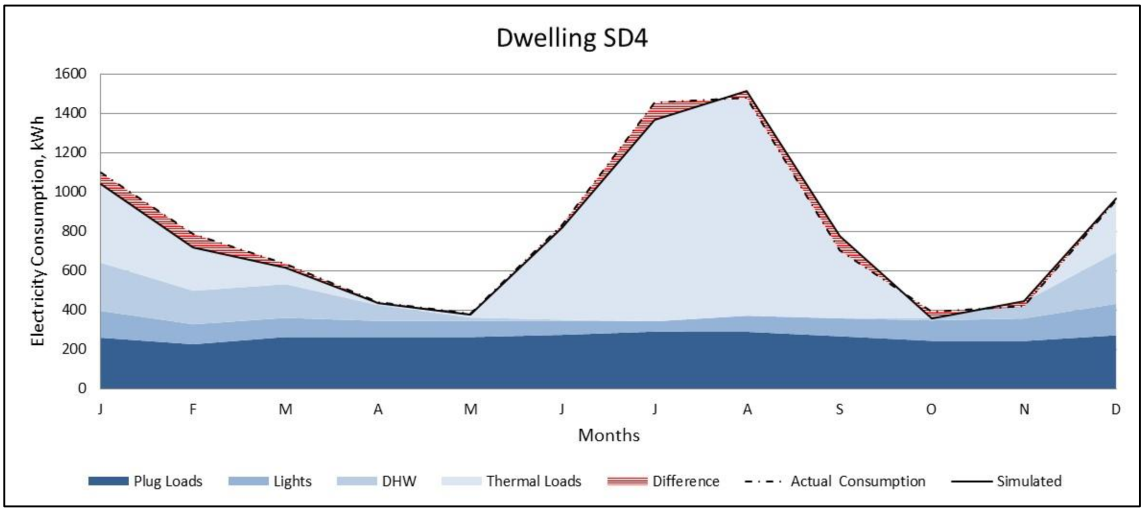


Figure H. 15 Actual and simulated electricity consumption-case study SD4

5. Dwelling-SD5

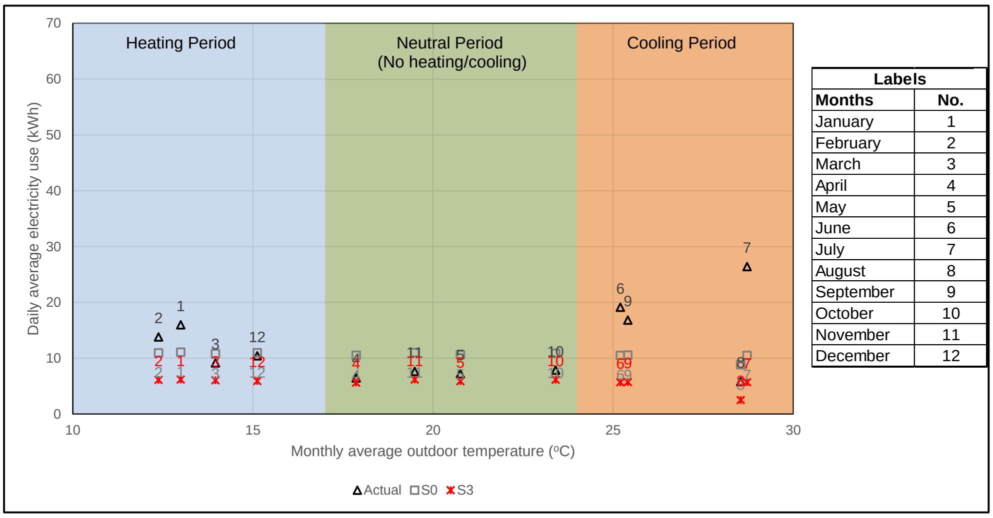


Figure H. 16 Daily average electricity against average monthly outdoor temperature, SD5

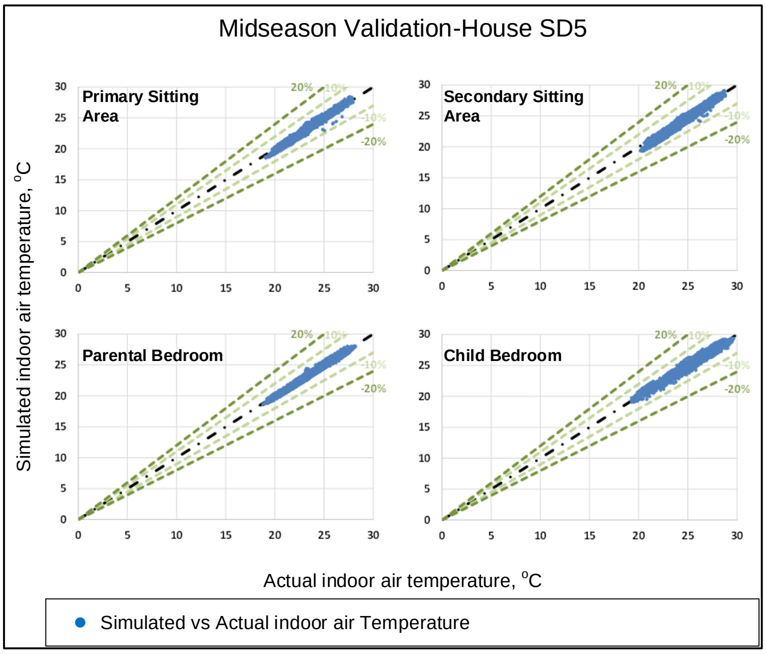


Figure H. 17 Simulated and actual indoor temperature, SD5

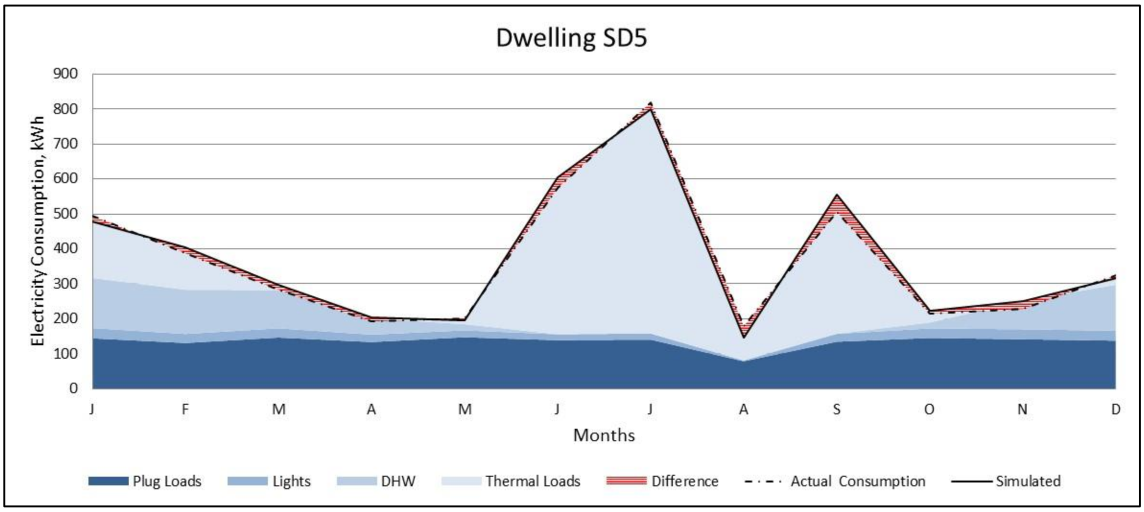


Figure H. 18 Actual and simulated electricity consumption-case study SD5

6. Dwelling-SD6

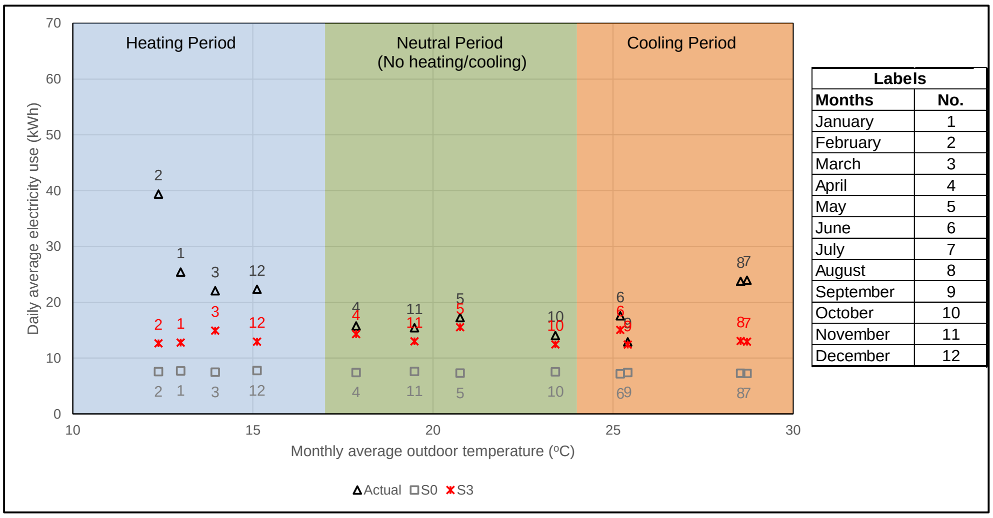


Figure H. 19 Daily average electricity against average monthly outdoor temperature, SD6

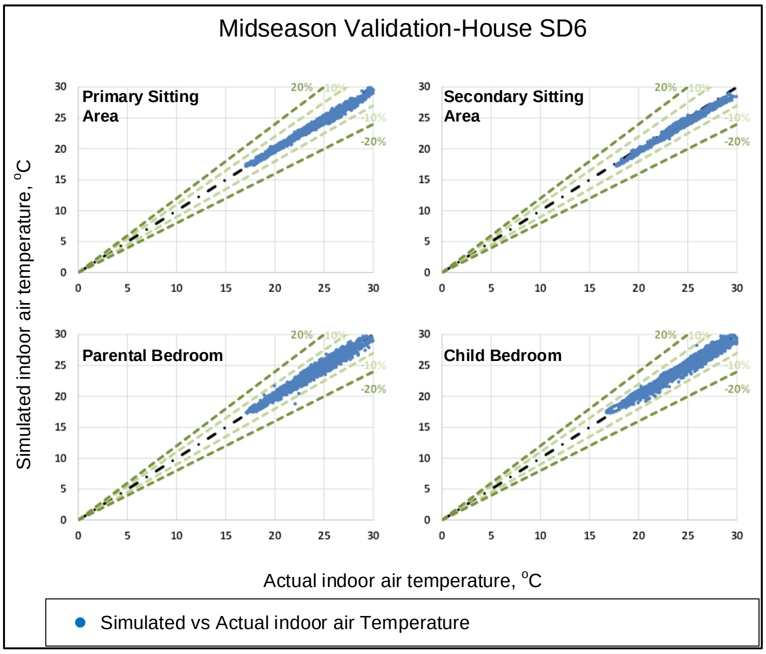


Figure H. 20 Simulated and actual indoor temperature, SD6

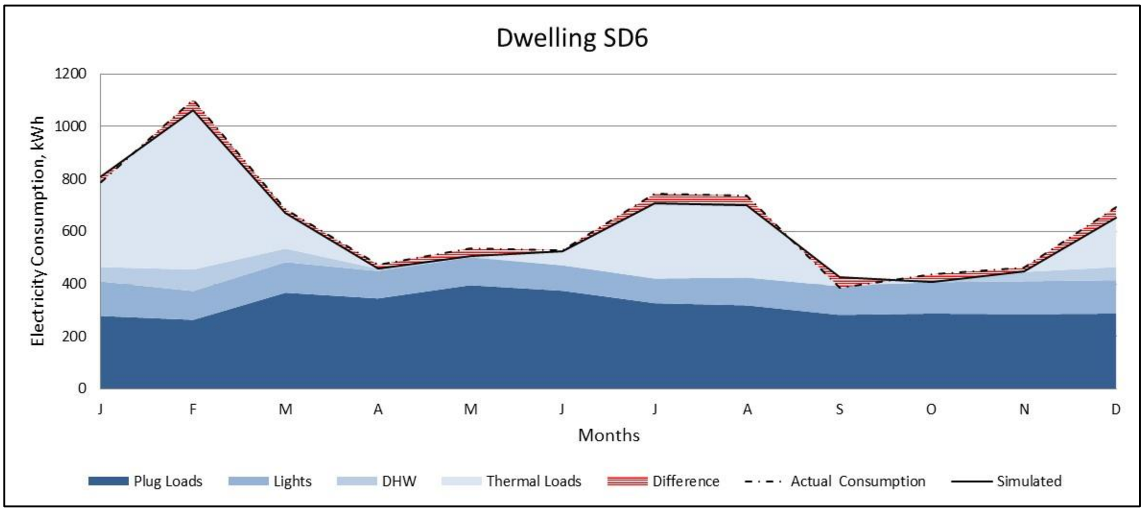


Figure H. 21 Actual and simulated electricity consumption-case study SD6

7. Dwelling-SD7

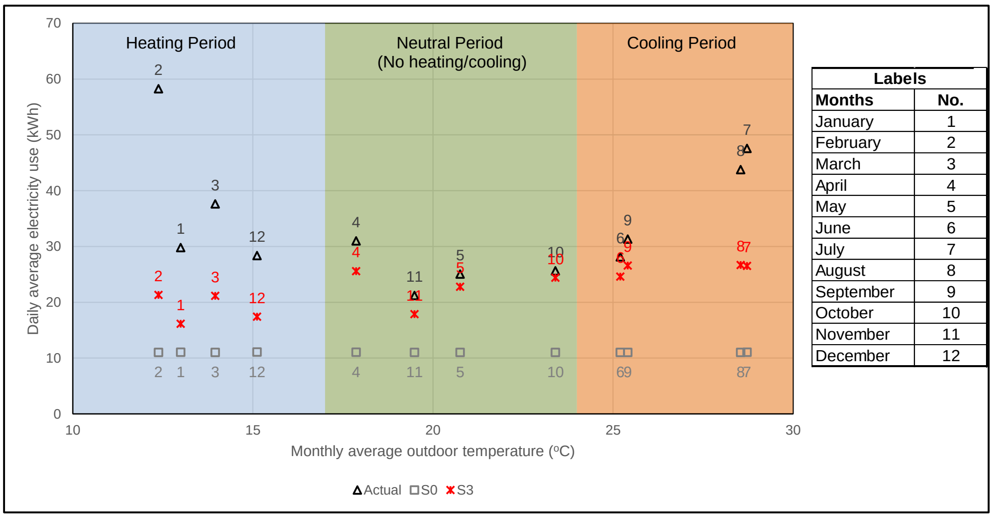


Figure H. 22 Daily average electricity against average monthly outdoor temperature, SD7

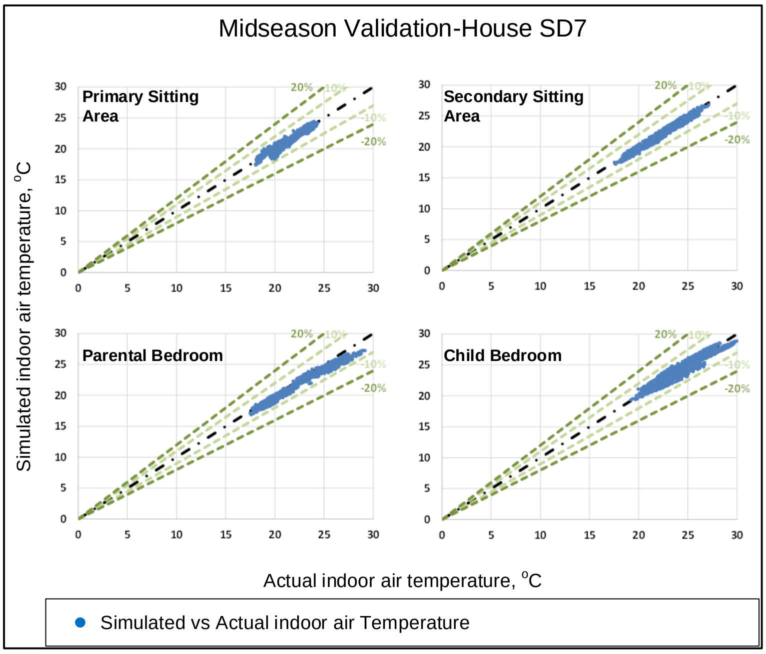


Figure H. 23 Simulated and actual indoor temperature, SD7

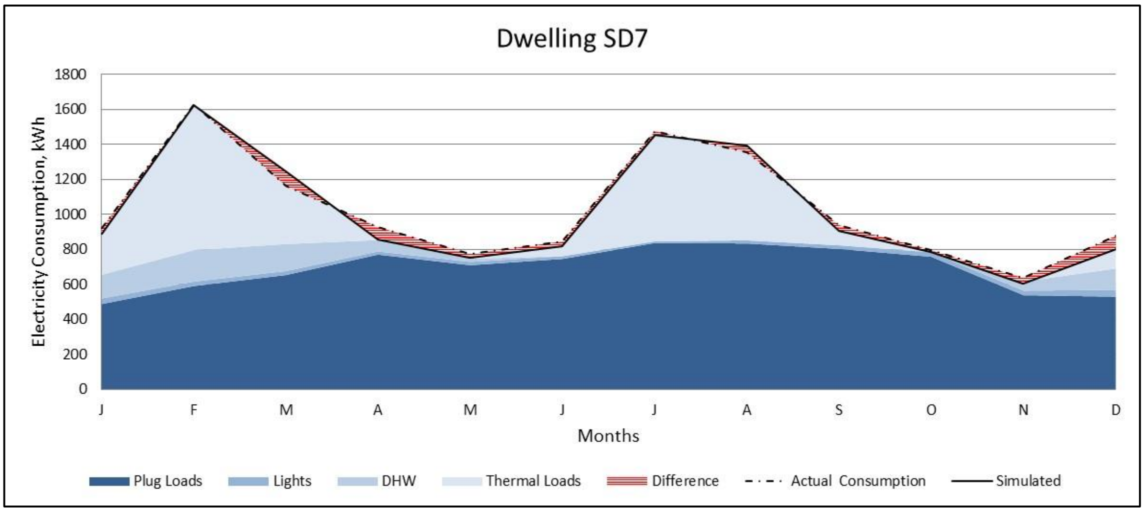
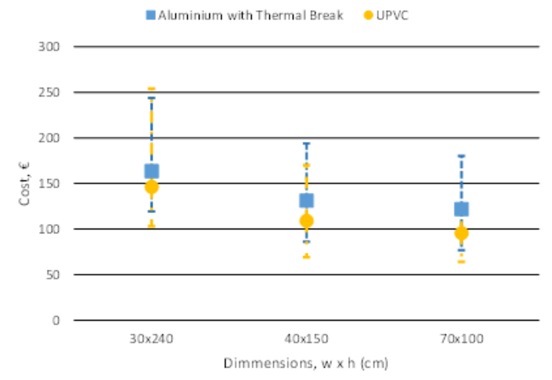


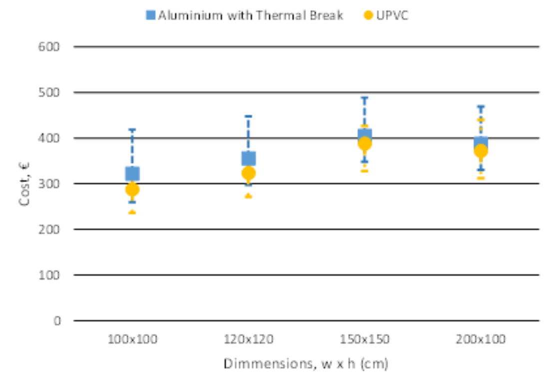
Figure H. 24 Actual and simulated electricity consumption-case study SD7

I. FRAME COST

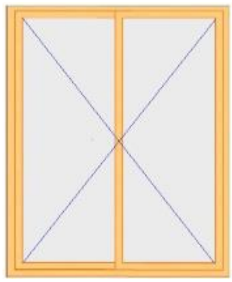
The following figures present the variation of the installation cost for the application during retrofitting of aluminium with thermal break or UPVC frame system, for different type of windows.

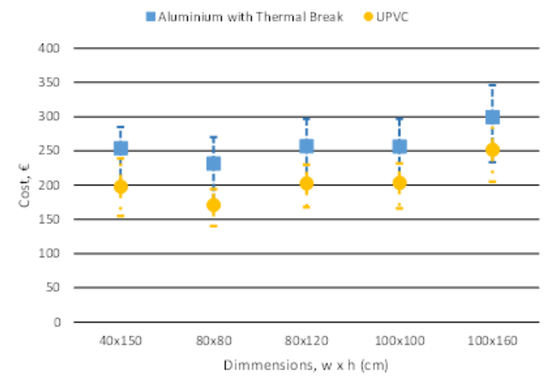


Type: Fixed

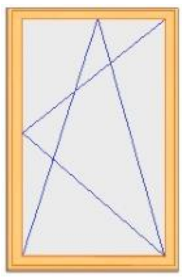


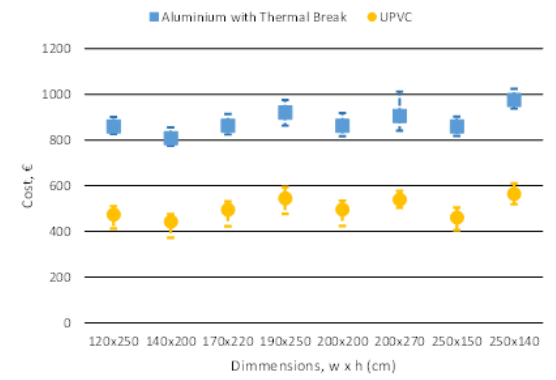
Type: Opening



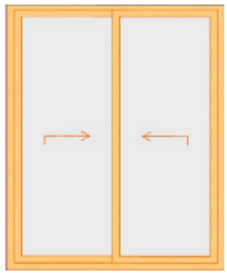


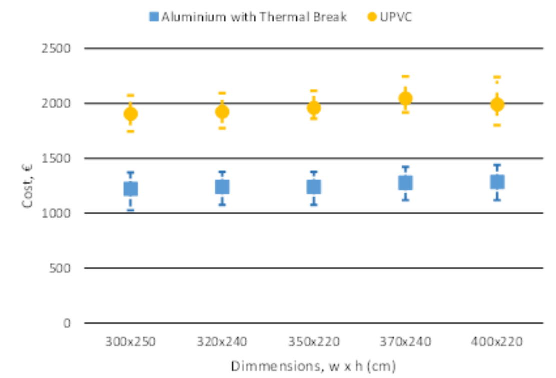
Type: Opening and Turn & Tilt



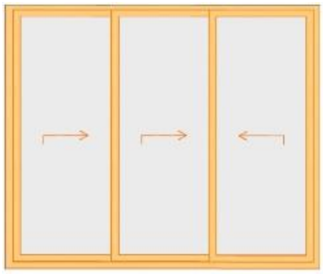


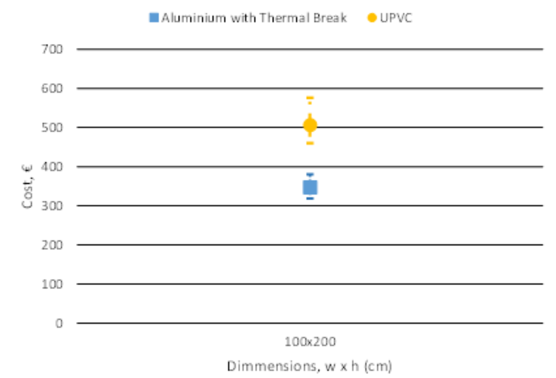
Type: Slide



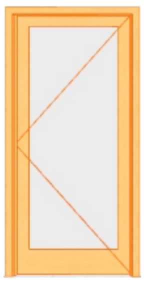


Type: Lift & Slide





Type: Kitchen Door



J. SOLAR SHADING CALCULATIONS

Through the Appendix J, the calculation of the projection's depth, referring to overhangs and fins will be presented. The layout of the external fixed shading devices is depicted in Figure J. 1, with d_f and d_o to represent the depths of the fin and overhang, accordingly.

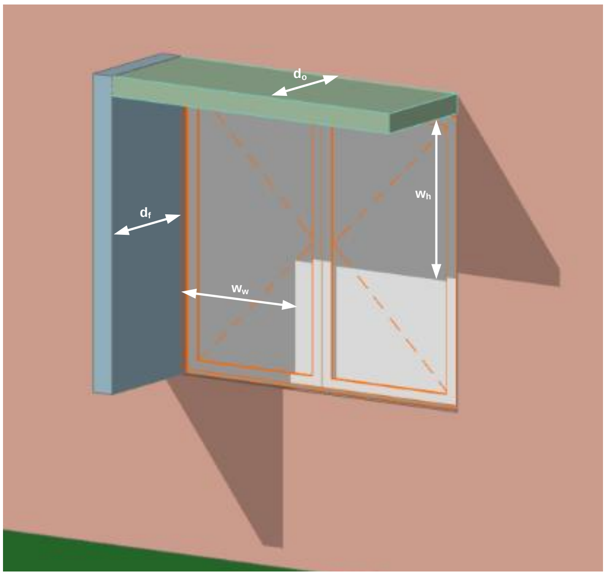


Figure J. 1 Layout of the overhang (green) and fin (blue)

The relationship of the dimensions with the solar position is given by the equations (Athienitis and Santamouris, 2002; Duffie and Beckman, 1982):

Overhangs:

$$\tan \alpha_p = \frac{\tan \alpha_s}{\cos(\gamma_s - \gamma)} = \frac{w_h}{d_o}$$ **Eq. J 1**

a_p=profile angle, degrees
a_s=Solar altitude angle, degrees
γ_s=Azimuth solar angle, degrees
γ=Surface azimuth angle, degrees
w_h=height of window, cm
d_o=depth of overhang, cm

Fins:

$$\frac{w_w}{d_f} = \tan(\gamma_s - \gamma)$$ ***Eq. J 2***

w_w=width of window (cm)
d_f=depth of fin (cm)

The azimuth solar angle (γ_S) is defined as the angular displacement from the south of the projection of beam radiation on horizontal plane, with negative values for east of the south and positive for west of the south (Duffie and Beckman, 1982). The azimuth solar angle can be estimated by the equation (Eq. J 3).

$$\gamma_s = sign(\omega)\left|\cos^{-1}\left(\frac{\cos\theta_z \sin\varphi - \sin\delta}{\sin\theta_z \cos\varphi}\right)\right|$$ ***Eq. J 3***

In the Appendix E, the zenith angle (θ_Z), hourly angle (ω) and declination angle (δ) were presented. Now, the surface azimuth angle (γ) describes the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due to south, east negative and west positive; $0^o \leq \gamma \leq 180^o$ (Duffie and Beckman, 1982). The solar geometry is depicted in the Figure J. 2, giving also the angle between the surface and the horizontal (β).

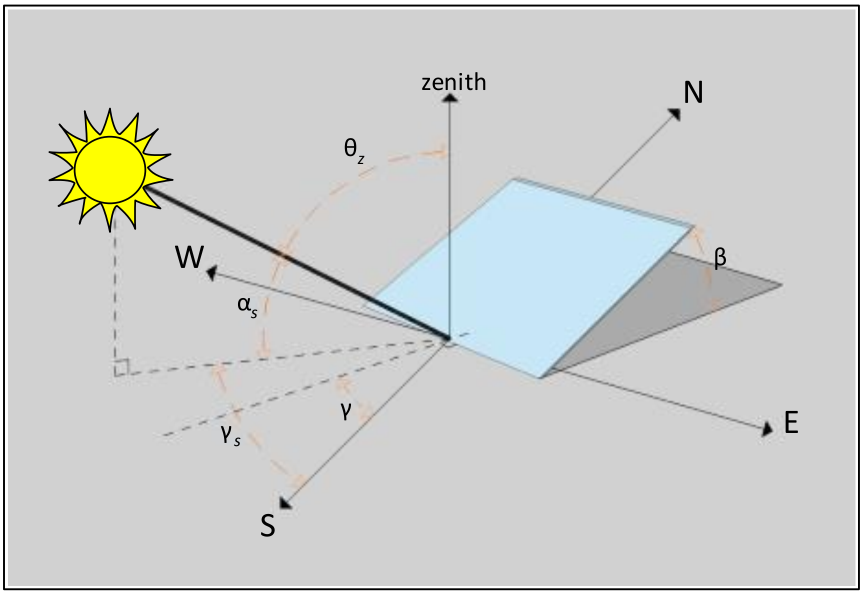


Figure J. 2 Solar angles (reproduced by (Duffie and Beckman, 1982))

From Eq. J 2 and Eq. J 3, the depth of the fins can be calculated, based on the hour of the day and the orientation of the window in question. In the case of the overhang, the solar altitude angle (a_S) is also required. This was estimated through the adoption of the degree days and the position of the sun during the summer season. The cooling and heating degree days are estimated using the method described by (CIBSE, 2006a), using the base temperatures of 15°C and 25°C, for HDD and CDD, respectively (Giannakopoulos, Le Sager, et al., 2009; Giannakopoulos, Hadjinicolaou, et al., 2009). In Figure J. 3, the degree days and the solar altitude angle (12:00 mid-day hour) for all the days of the year are plotted. Considering the longitude and latitude of Cyprus, at 12:00 the sun is at the highest altitude above the horizon.

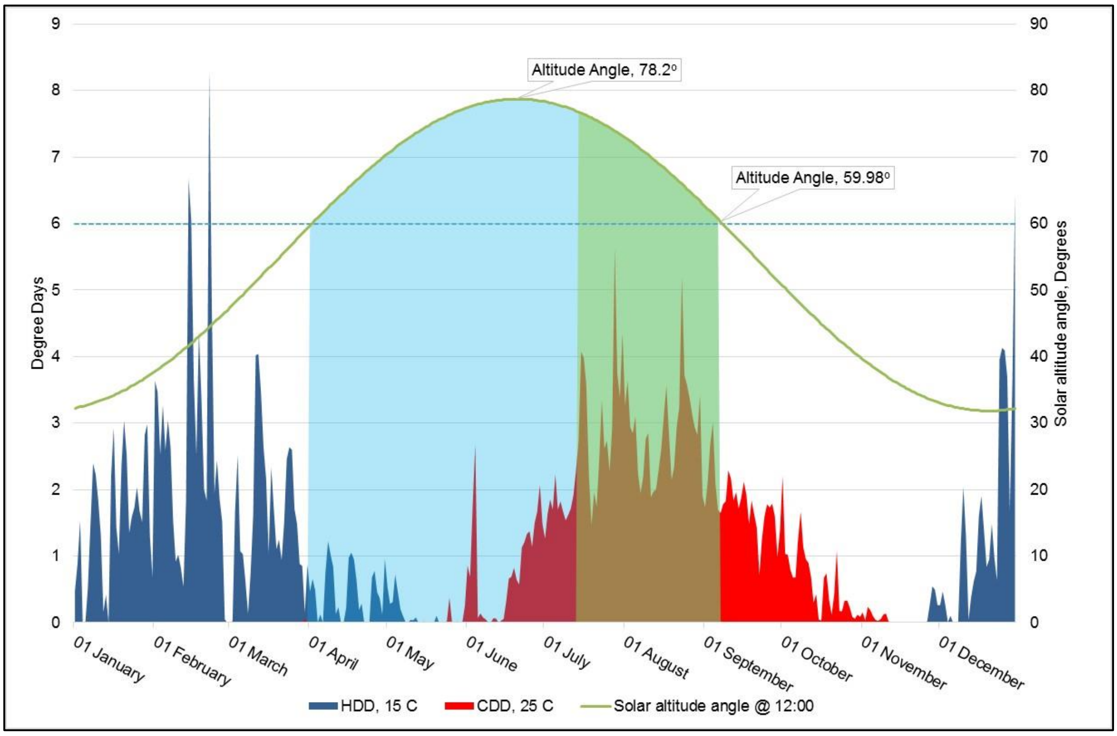


Figure J. 3 Estimation of the reference solar altitude angle

The altitude angle of 60º was selected as the reference angle for the calculations, driven by the limitation to minimize the impact of the overhang during the winter season. Apparently, by selecting a retractable external device this will be more suitable as the position of the projection will be alternated, according to the position of the sun, enhancing the effect of the solar penetration during the winter and preventing the solar insolation during the summer.

K. NET PRESENT VALUE-RISK ANALYSIS

A quantitative risk analysis was adopted to estimate the value of the NPV. In particular, the method is based on the Monte Carlo simulation, where for every possible value of parameters, a number of possible scenarios were generated (Vose, 2008). By the risk analysis, the uncertainties by using deterministic values is accommodated, improving the reliability and accuracy of results. In general, the value of the NPV for each individual intervention can be estimated by Eq. K 3, as follows:

$$NPV = -CCI + \sum_{n=1}^{30} \frac{(El \times EP_n) + (Ol \times OP_n)}{(1 + I_r)^n}$$ ***Eq. K 1***

$$EP_n = EP_{n-1} + (EP_{n-1} \times P_a)$$ ***Eq. K 2***

$$OP_n = OP_{n-1} + (OP_{n-1} \times P_a)$$ ***Eq. K 3***

CCI=Capital cost of investment (€)

El= Annual electricity consumption (kWh)

Ol=Annual oil consumption (litres)

EP_n=Annual electricity price (€/kWh)

OP_n=Annual oil price (€/litres)

P_a=Annual increase on energy prices-inflation rate (%)

I_r=Interest rate (%)

From the formula, 7 parameters can be identified that are affecting the output of the NPV. Based on historical data, the stochastic distributions of the parameters were estimated. For the whole procedure, 2013 was adopted as a baseline year.

The calculations were performed in the Excel Software, by the application of the add-on tool @Risk (Palisade, 2014). The tool uses random values of inputs, based on a Monte Carlo simulation to develop several scenarios for an output, running 5,000 iterations.

At this point, the assumptions adopted for every parameter and its distribution are summarized.

1. Capital Cost of Investment (CCI)

In this case, the values collected during the market survey were evaluated and the maximum and minimum cost for each alternative solution was applied to form an equal probability of distribution between them.

$$CCI_{min} \leq CCI_i \leq CCI_{max}$$

2. Annual Consumption
    a. Electricity (El)
    b. Heating Oil (Ol)

These parameters are directly related with the outcome of the simulation procedure. As it was aforementioned, the simulation outcome was based on a calibration and validation procedure. However, the normalization of the outcome based on typical conditions may introduce uncertainty due to the typical weather conditions or other unquantifiable variables. Therefore, based on the theory of sensitivity analysis, a uniform distribution between the 10% of the output was adopted.

Variation between ± 10% of the $\text{Simulation}_{output}$

3. Annual Prices
    a. Electricity (EP_n)
    b. Oil (OP_n)

Referring to Eurostat (2014), at the baseline year the prices for electricity and oil are 0.227 €/kWh and 1.035 €/litres, respectively (Eurostat, 2014). Therefore, a triangular distribution was adopted, giving the most likely occurrence of the price at the baseline year with a distribution between the ± 10%.

4. Inflation Rate (P_a)

For every individual year contained within the 30 of horizon investment, the annual increase (inflation rate) on energy prices is based on the guidelines of (EC, 2010b; MCIT, 2013b), and the recent forecasting prices published by (Zachariadis, 2014). An equal probability of distribution was also applied for this parameter, with values varying between ± 10% of the estimated annual inflation rate.

5. Interest Rate (I_r)

This is the last parameter in the formula for the calculation of the NPV and may be considered critical, due to the uncertain factors that are affecting the economic scene on national level. On the evaluation of data obtained from the database of the National Central Bank (CBC, 2014), the gamma-distribution presented the best-fit on the data. Figure K.1 presents the best-fitted distributions, on the probability density of the historical data.

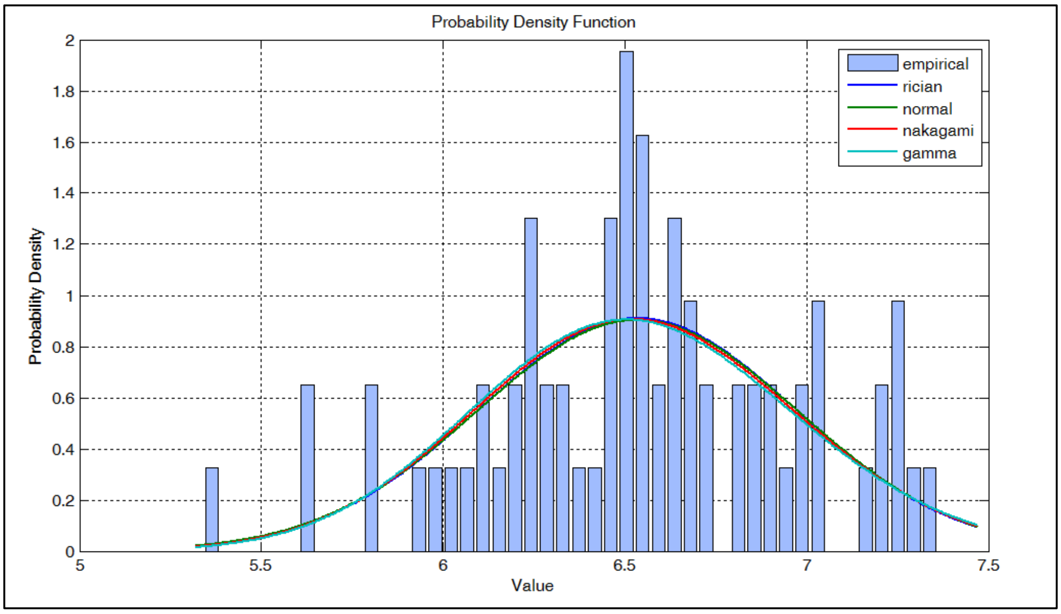


Figure K. 1 Best-fit distributions on historical data of interest rate

Following the guidelines of the @Risk Tool, the parameters associated with the simulation of the gamma distribution are a=2.18 and b=0.029866.

L. Inland Weather Scenario-Results

L.1. Thermal Insulation of opaque elements

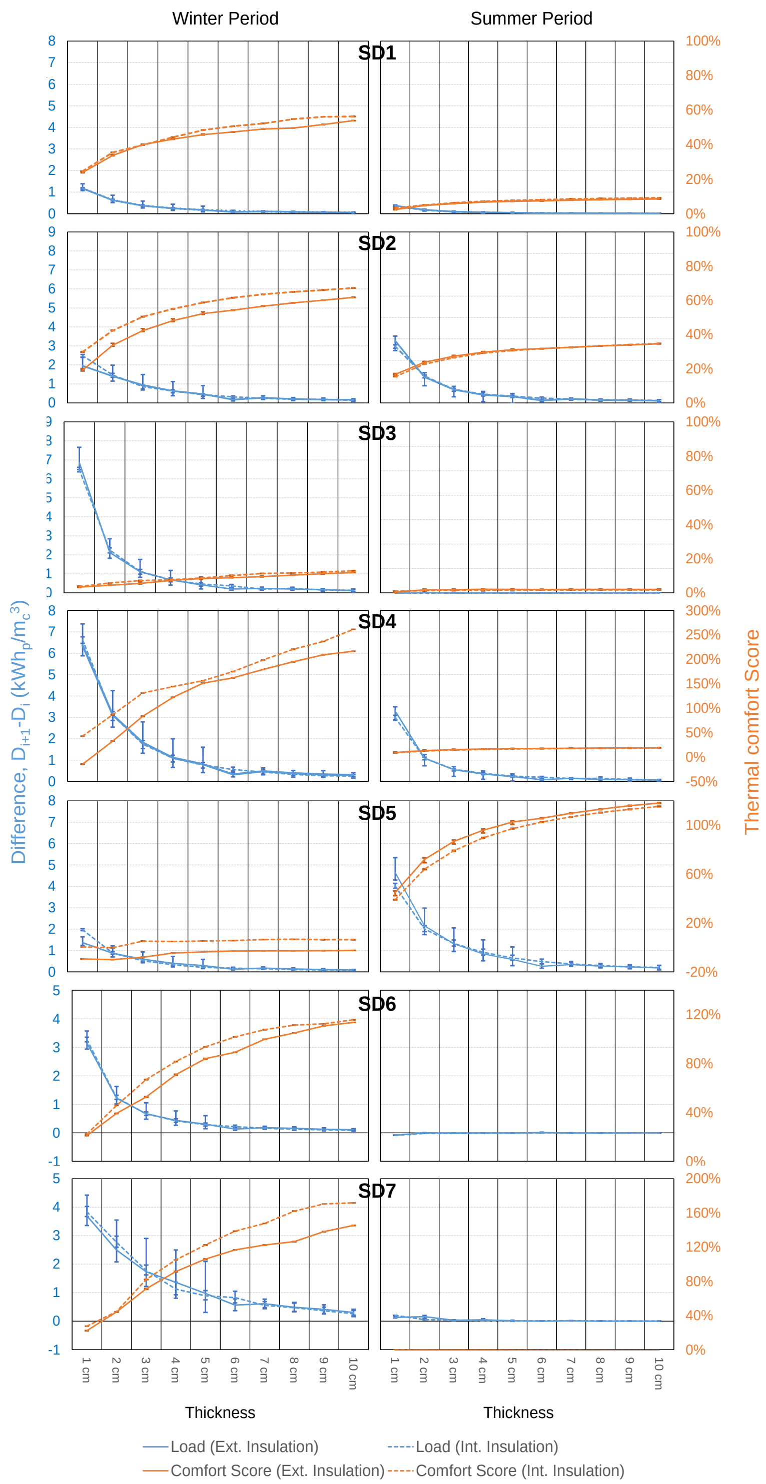


__Figure L. 1 Effect of roof insulation-Inland Weather__

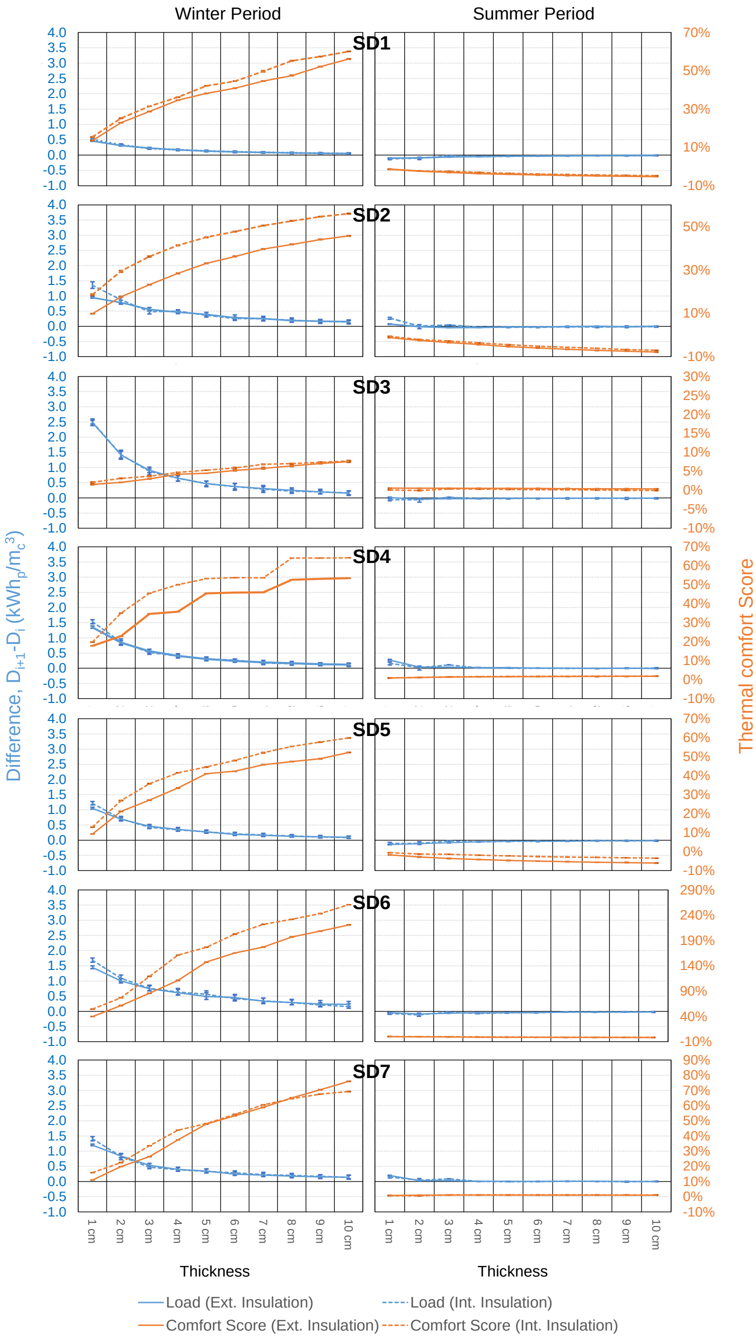


__Figure L. 2 Effect of external wall insulation-Inland Weather__

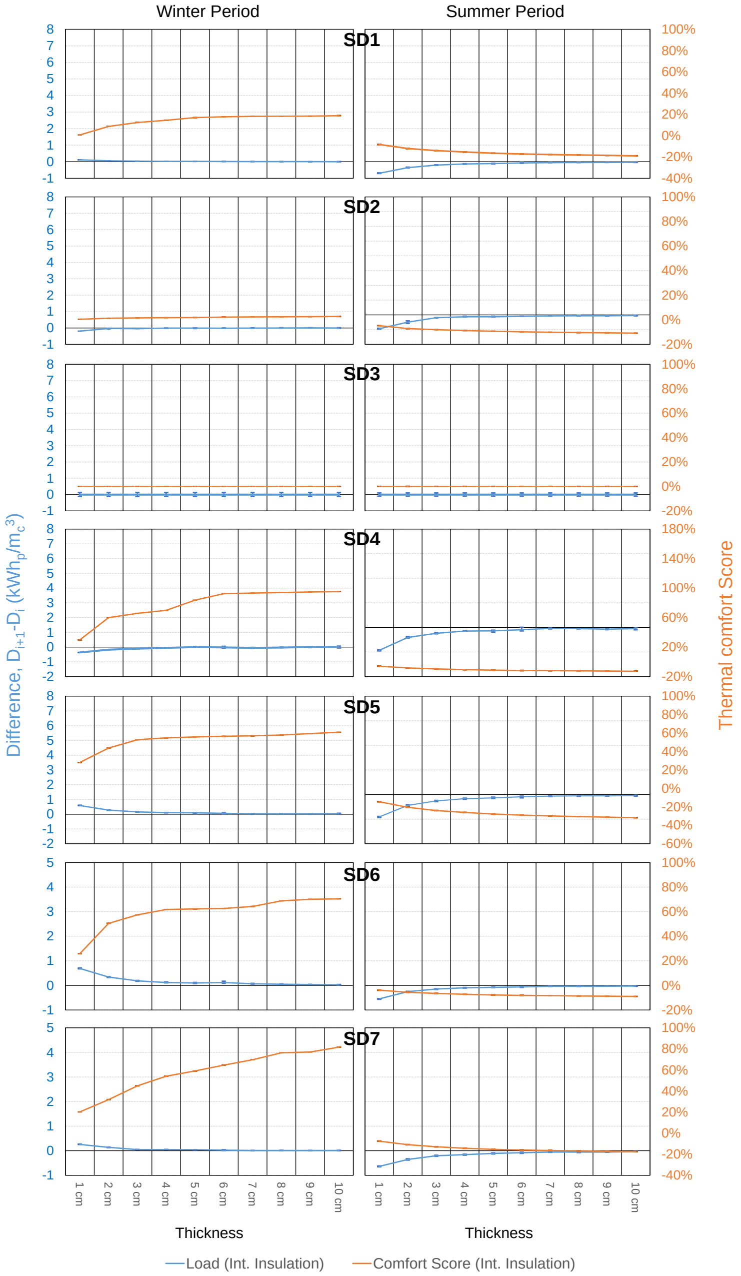


Figure L. 3 Effect of ground floor insulation-Inland Weather

L.2. Light opaque elements

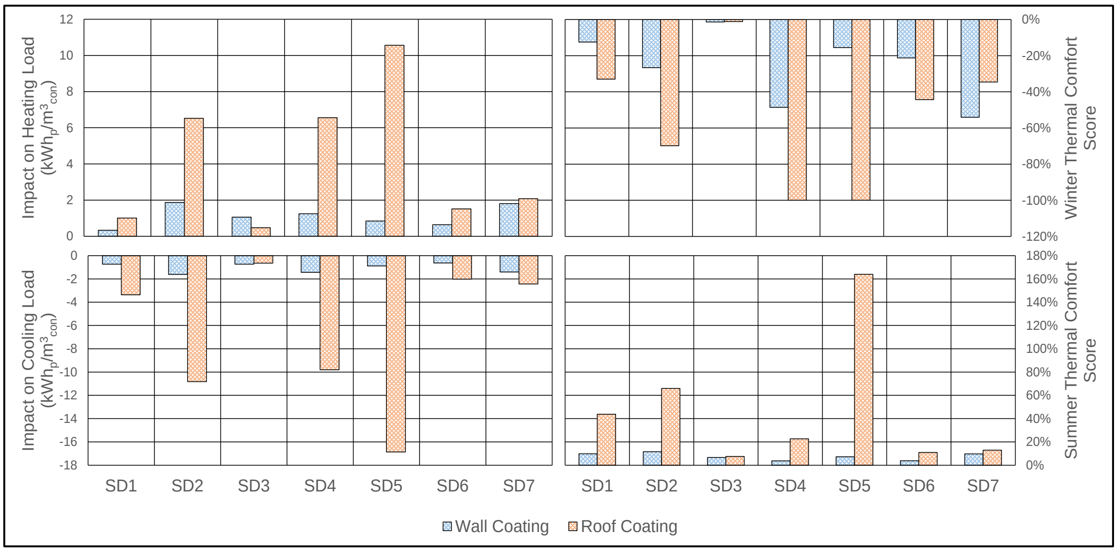


Figure L. 4 Low reflectance impact-Inland Weather

L.3. Fenestration

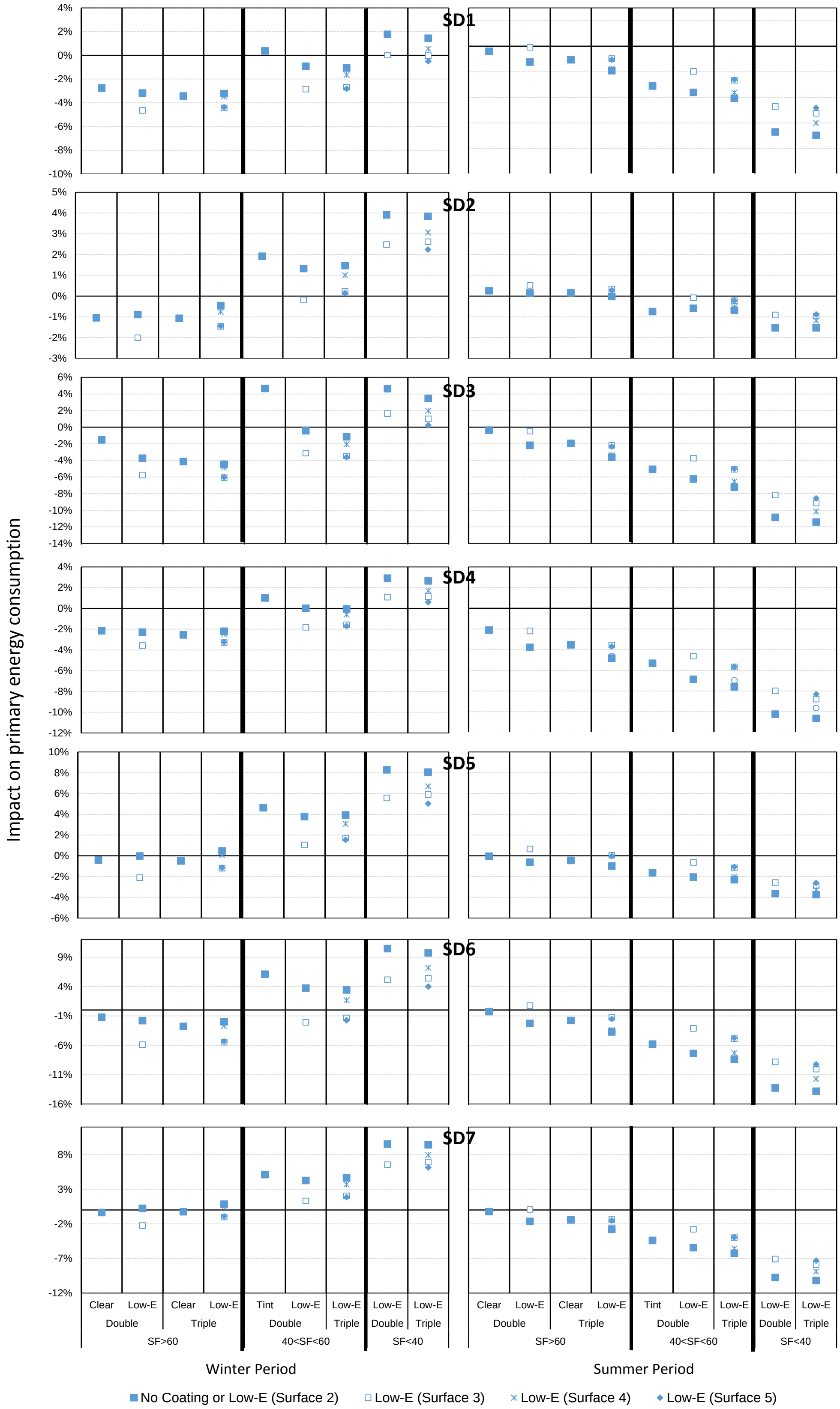


Figure L. 5 Impact of different glazing types-Inland Weather

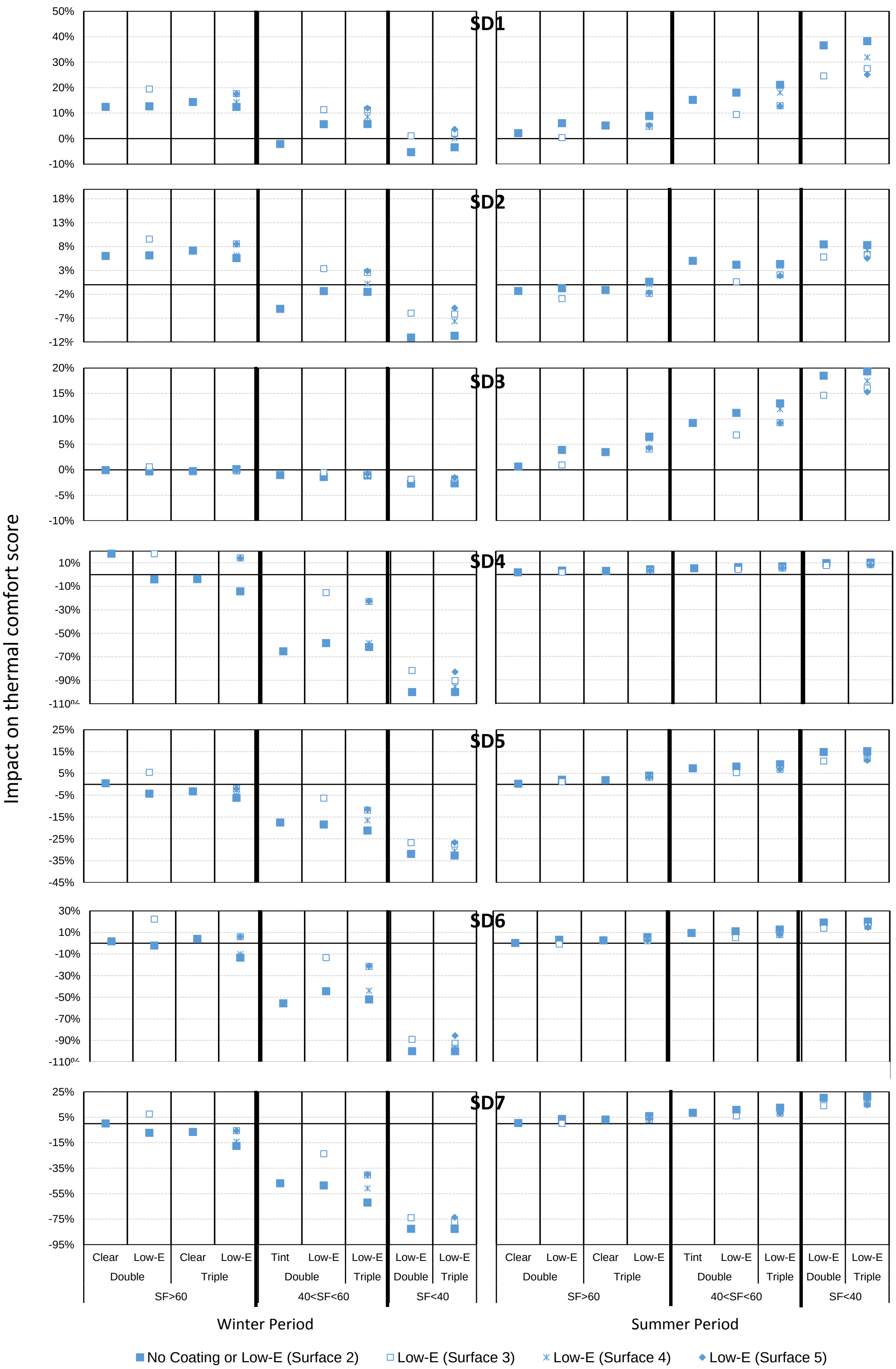


Figure L. 6 Impact on thermal comfort by window system-Inland Weather

Table L. 1 Impact on thermal loads-Inland weather (Average and Range)

<table>
<tr><th colspan="4" rowspan="3">GLASS TYPE</th><th colspan="4">THERMAL LOADS (%)</th></tr>
<tr><th colspan="2">Heating</th><th colspan="2">Cooling</th></tr>
<tr><th>Average</th><th>Range</th><th>Average</th><th>Range</th></tr>
<tr><td rowspan="8">SF>60</td><td rowspan="2">Clear</td><td colspan="2">Double</td><td>-1</td><td>-3 to 0</td><td>0</td><td>-2 to 0</td></tr>
<tr><td colspan="2">Triple</td><td>-2</td><td>-4 to 0</td><td>-1</td><td>-4 to 0</td></tr>
<tr><td rowspan="6">Low-E HSF</td><td rowspan="2">Double</td><td>p2</td><td>-2</td><td>-4 to 0</td><td>-2</td><td>-4 to 0</td></tr>
<tr><td>p3</td><td>-4</td><td>-6 to -2</td><td>0</td><td>-2 to 1</td></tr>
<tr><td rowspan="4">Triple</td><td>p2</td><td>-2</td><td>-4 to1</td><td>-3</td><td>-5 to 0</td></tr>
<tr><td>p3</td><td>-3</td><td>-6 to -1</td><td>-1</td><td>-4 to 0</td></tr>
<tr><td>p4</td><td>-2</td><td>-5 to 0</td><td>-2</td><td>-5 to 0</td></tr>
<tr><td>p5</td><td>-3</td><td>-6 to -1</td><td>-1</td><td>-4 to 0</td></tr>
<tr><td rowspan="7">40<SF<60</td><td>Tint</td><td colspan="2">Double</td><td>3</td><td>0 to 6</td><td>-4</td><td>-6 to -1</td></tr>
<tr><td rowspan="6">Low-E MSF</td><td rowspan="2">Double</td><td>p2</td><td>2</td><td>-1 to 4</td><td>-5</td><td>-7 to -1</td></tr>
<tr><td>p3</td><td>-1</td><td>-3 to 1</td><td>-2</td><td>-5 to 0</td></tr>
<tr><td rowspan="4">Triple</td><td>p2</td><td>2</td><td>-1 to 5</td><td>-5</td><td>-8 to -2</td></tr>
<tr><td>p3</td><td>-1</td><td>-3 to 2</td><td>-3</td><td>-6 to 0</td></tr>
<tr><td>p4</td><td>1</td><td>-2 to 4</td><td>-5</td><td>-7 to -1</td></tr>
<tr><td>p5</td><td>-1</td><td>-4 to 2</td><td>-3</td><td>-6 to 0</td></tr>
<tr><td rowspan="6">SF<40</td><td rowspan="6">Low-E LSF</td><td rowspan="2">Double</td><td>p2</td><td>6</td><td>2 to 10</td><td>-8</td><td>-13 to -2</td></tr>
<tr><td>p3</td><td>3</td><td>0 to 7</td><td>-6</td><td>-9 to -1</td></tr>
<tr><td rowspan="4">Triple</td><td>p2</td><td>6</td><td>1 to 10</td><td>-8</td><td>-14 to -2</td></tr>
<tr><td>p3</td><td>3</td><td>0 to 7</td><td>-6</td><td>-10 to -1</td></tr>
<tr><td>p4</td><td>4</td><td>1 to 8</td><td>-7</td><td>-12 to -1</td></tr>
<tr><td>p5</td><td>3</td><td>-1 to 6</td><td>-6</td><td>-9 to -1</td></tr>
</table>

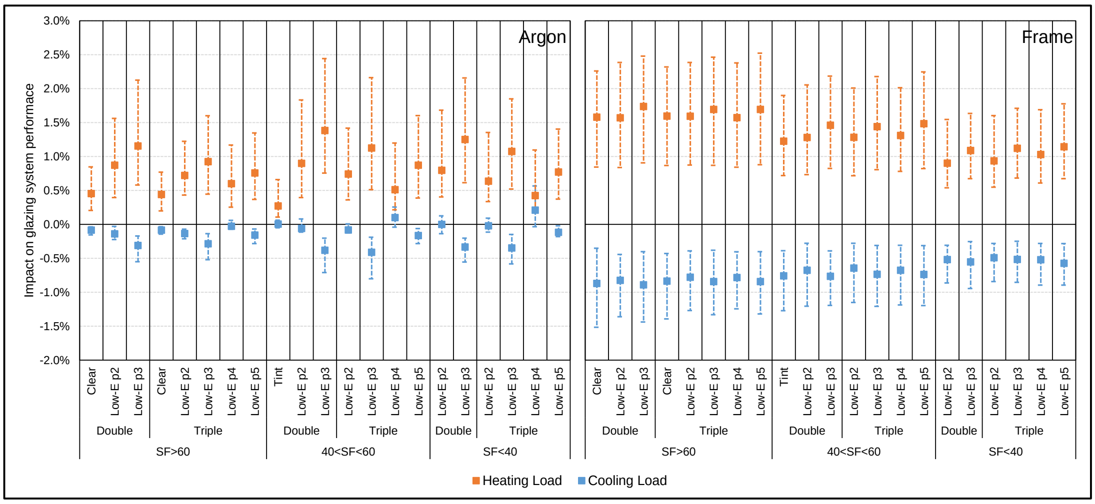


Figure L. 7 Integration of argon and improved thermal frame-Inland Weather

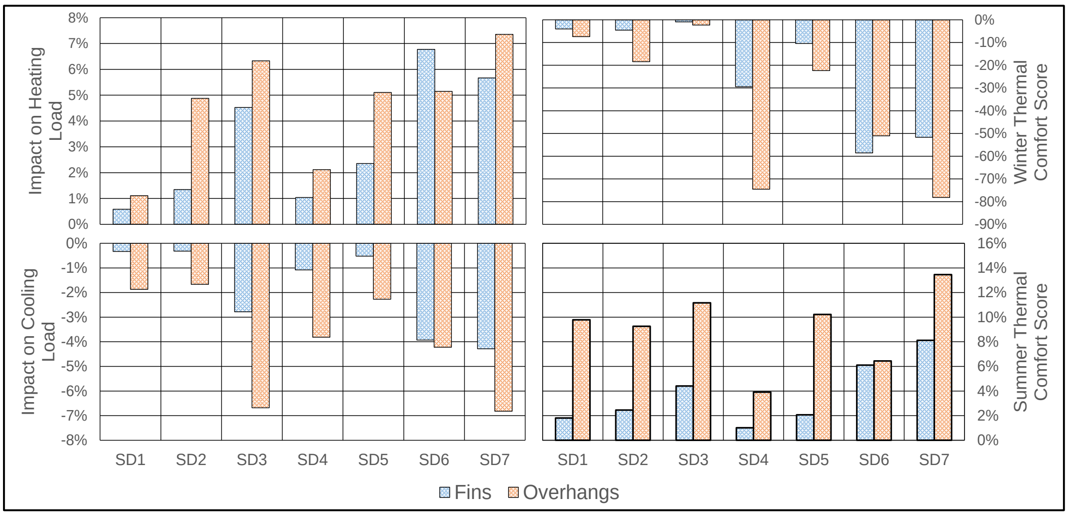


Figure L. 8 Impact of external fixed shading devices-Inland Weather

Staff Development

Running Year	Date	Title	Period (Days)
1st Year (October 2011-October 2012)	13th October 2011	Ethical Thinking in Research	0.5
	18th October 2011	Postgraduate Research Students Induction	1
	19th October 2011	Time and Self-management	0.5
	25th October 2011	Finding Resources for your Literature Review and Beyond-Theory	0.5
		Finding Resources for your Literature Review and Beyond-Practice	0.5
	14th December 2011	Introduction to the Design of Multifactor Experiments	0.5
	3rd May 2012	VIVA-What Happens?	0.5
	8th May 2012	Teaching skills for those working in small groups	1.5
	9th May 2012	Copyright and your Thesis	0.5
	16th May 2012	OneNote 2012: Taking notes and research tool	0.5
	17th May 2012	Keeping alert to new information	0.5
	23rd May 2012	Designing and producing conference posters	0.5
		Introduction to PowerPoint 2010	0.5
	30th May 2012	Writing up your Thesis	0.5
	2nd&4th November 2011	Energy performance of buildings (KTEE/Cyprus)	2
	3rd November 2011	Analysis of Photovoltaic and solar thermal power systems (ETEK/Cyprus)	1
	18th&19th April 2012	CIBSE ASHRAE Technical Symposium 2012 (London)[1]	2
2nd Year (October 2012-October 2013)	12th December 2012	CIBSE ASHRAE Group-Towards Net Zero Energy Buildings (Webinar)	0.5
	29th -30th May & 12th-13th June 2013	Mitsubishi Project[3]	2.5

	8th-12th July 2013	NATCOR course: Simulation	5
	25th-28th August 2013	13th International Conference of the International Building Performance Simulation Association[2](France)	4
3rd Year (October 2013-October 2014)	18th & 22nd-24th October 2013	Assign Tutorials for IES & DesignBuilder for CVP310 module	4
	23rd-24th June 2014	2nd IBPSA-England conference in association with CIBSE (UK)	3
First Year Total			**13.5**
Second Year Total			**12**
Third Year Total			**7**
		Total=	**31.5**

Details:

[1] *At the Technical Symposium, the first day at the 3rd session, I presented the paper "Measurements of CO_2 levels in a classroom and its effect on the performance of the students".*

[2] *Presentation of the paper entitled "A study of the effect of the weighting indices for the development of TMY used for building simulation"*

[3]*Working as assistant for the Mitsubishi-Loughborough University project, completing one of the objectives related to the weather data of main European cities. In addition, I developed web-based questionnaires for the collection of data.*

PUBLICATIONS

1. Conference Papers

- Georgiou, G., Eftekhari, M., Eames, P., Mourshed, M., (2013), *"A study of the effect of weighting indices for the development of TMY used for building simulation"*, 13th International Conference of the Internal Building Performance Simulation Association, INES, INSA, Chambery, France.
- Georgiou, G., Eftekhari, M., Eames, P., (2014), *"Calibration and validation of residential buildings: 8 case studies of detached houses"*, Building Simulation and Optimization, 2nd IBPSA-England conference in association with CIBSE, UCL, London, UK.
- Georgiou, G., Eftekhari, M., Lupton, T., (2015), *"Investigating the effect of tightening residential envelopes in the Mediterranean region"*, 14th International Conference on Sustainable Energy Technologies, Nottingham, UK.