Universidad de Valladolid

ESCUELA DE INGENIERÍAS INDUSTRIALES

UNIVERSIDAD DE VALLADOLID

ESCUELA DE INGENIERIAS INDUSTRIALES

Grado en Ingeniería en Organización Industrial

FEASIBILITY STUDY OF A SOCIAL HOUSING ENERGY RETROFIT PROJECT

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Valladolid, junio 2019.

TFG REALIZADO EN PROGRAMA DE INTERCAMBIO

TÍTULO: **FEASIBILITY STUDY OF A SOCIAL HOUSING ENERGY RETROFIT PROJECT**

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FECHA: 24/06/2019

CENTRO: **University of Malta**

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Resumen (Abstract)

El objetivo principal es identificar la combinación más adecuada de medidas pasivas de acondicionamiento para mejorar el confort térmico y el rendimiento energético en bloque de viviendas sociales (BVS) en Malta. Se modeló un BVS utilizando el software dinámico DesignBuilder-EnergyPlus. Se utilizaron los modelos de confort adaptativo EN 15251 y ASHRAE para evaluar el confort térmico en el piso superior del BVS, demostrando que tiene los peores niveles de comodidad. Los resultados mostraron que el confort térmico adaptativo no se cumple. Sin embargo, una vez que se introducen todas las medidas pasivas de acondicionamiento se alcanzan los niveles de confort térmico adaptativo. El análisis financiero y macroeconómico resultaron ser negativos. Otros beneficios sociales, como la reducción de la pobreza energética, la mejora de la comodidad y el bienestar de los ocupantes y la reducción de las cargas máximas en la central eléctrica, la viabilidad global de renovar los BVS se vuelve más atractiva.

Palabras claves (Keywords): EPBD; acondicionamiento; nZEB; DesignBuilder; adaptativo

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June 2019

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Leandro Filipe Teixeira Luciano

A dissertation presented at the

Institute for Sustainable Energy of the University of Malta, Malta

in partial fulfilment of the requirements for the degree of

Bachelor of Industrial Engineering

at the

Universidad de Valladolid, Spain,

under the Erasmus Plus Student Exchange Programme 2018/19.

Dedicated to my mother María, my father Manuel and my two sisters María and Daniela

Declaration

No portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Signature of Student Name of Student

June 2019

Date

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Abstract

Retrofitting of existing buildings have been given greater attention than new buildings in the new Energy Performance of Buildings Directive (EU) 2018/844 of July 2018. Moreover, all deep-renovated buildings have to reach nearly zero-energy status after the year 2020. Consequently, this dissertation has identified the renovation opportunity in existing social housing building stock. The main aim is therefore to identify the most suitable combination of retrofit passive measures to improve the thermal comfort and energy performance of the social housing building stock in Malta. For this scope, a typical social housing building block built in the 1990s, prior to the introduction of minimum energy performance requirement and synonymous with many existing social housing projects was modelled using DesignBuilder-EnergyPlus dynamic software. Once the EnergyPlus building model was calibrated with hourly on-site temperature measurements, the EN 15251 and ASHRAE adaptive comfort models were used to asses thermal comfort for the top-floor dwellings of the building block, which was shown to have worst comfort levels, based on occupants' questionnaire feedback and measured temperatures. Results showed that adaptive thermal comfort does not comply with EN 15251 Category II and ASHRAE 80% thermal acceptability requirements for both the summer and winter design weeks. However, once insulation is added to the envelope, external blinds are introduced and double glazing replace single glazing, the adaptive thermal comfort levels are attained. Thus, thermal comfort is achievable for the top-floor using passive measures alone without the need for air-conditioners. Furthermore, a sensitivity analysis showed that while all passive measures introduced are required for thermal comfort to be achieved, roof insulation and external blinds have the highest impact and should thus be prioritised. A life cycle financial analysis was also carried out. It was found that from the consumer's point of view, the most viable option would be to leave the building envelope as is and introduce air-conditioners to achieve thermal comfort, given that the cost of grid electricity is relatively low. The same results were achieved from a macroeconomic financial point of view, when accounting for the cost of carbon emissions. However, when other social benefits are considered, such as reducing energy poverty, improving the comfort and well-being of occupants and reducing the peak loads on the power station, the global viability of renovating social housing blocks becomes more attractive. This shows that future directives should also consider these social benefits in addition to the cost of carbon, to facilitate the introduction of such passive measures in Europe.

Acknowledgements

I would like to thank my supervisor, Dr. Ing. Charles Yousif and my co-supervisor Ing. Damien Gatt for their continuous help and support. Certainly, without their support, leadership and knowledge sharing, this dissertation would not have been possible. Their presence, advice and critical comments throughout this study enabled me to improve my work.

I would also like to thank my family; my mother María, my father Manuel and my two sisters, María and Daniela. Without their continuous encouragement throughout the last years I would not be the person that I am today.

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List of Abbreviations

A/C	Air Conditioner
AECD	Annual Electric Consumption per Dwelling
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BRB	Building Regulation Board
CBE	Center for the Built Environment
CBSA	Computer Based Simulation Audit
CIBSE	Chartered Institution of Building Services Engineers
CV(RMSE)	Coefficient of Variance of the Root Mean Square Error
DHW	Domestic Hot Water
DPP	Discount Payback Period
ECMs	Energy Conservation measures
EC	Energy Consumption
EE	Energy Efficient
EED	Energy Efficiency Directive
EI	Effectiveness Index
EPBD	Energy Performance of Buildings Directive
EPI	Energy Performance Indicator
EPS	Expanded Polystyrene Standard
ERDF	European Regional Development Fund
EU	European Union
GDPR	General Data Protection Regulation
HP	Heat Pumps
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IET	Indoor Thermal Environment
IRR	Internal Rate of Return
ISO	International Organization for Standardization
M&C	Maintenance and Verification

MEPRS	Minimum Energy Performance Requirements
MLR	Multiple Linear Regression
NCM	National Calculation Methodology
NEEAP	National Energy Efficiency Action Plan
NMBE	Normalized Mean Bias Error
NPV	Net Present Value
NREAP	National Renewable Energy Action Plan
NZEB	Nearly Zero Energy Building
nZEH	near Zero Energy Home
PB	Payback
PL	Plug Loads
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PV	Photovoltaic System
RE	Renewable Energy
RED	Renewable Energy Directive
RH	Relative Humidity
SA	Standard Audit
SPP	Simple Payback Method/Period
T&C	Test and Commissioning
VAT	Value Added Tax
WH	Water Heater
WTA	Walk Through Audit

Chapter 1. Introduction

The building sector is responsible for the 40% of EU's energy consumption. By 2050, the EU aims to reduce up to 90% of the greenhouse gas emissions in the building sector, but around 90% of EU's buildings were built before 1990 and the renovation rate is still very low (1 – 2% per year) [1][2]. However, the building sector is adopting the low-carbon economy roadmap [3]. The energy performance of building is covered by the Energy Performance of Building Directive (EPBD) [4] and the Energy Efficiency Directive (EED) [5]. According to the EPBD, all new buildings and buildings to undergo major renovation are to be nearly zero energy buildings by the end of 2020. By the end of 2020, the EED has established EU measures to achieve its 20% energy efficiency objective. Nonetheless, at present time, the EED from 2012 is been revised and the energy efficiency objective will increase from 20% in 2020 to 32.5% in 2030 [6].

The new EPBD of 2018 has shifted its focus from new buildings to deep renovation of existing buildings, together with energy use of appliances, lighting and healthy indoor climate, requiring EU member states to establish long-term renovation strategies, aiming at decarbonising the national building stocks by 2050 and reach the Nearly Zero Energy Building objective (NZEB).

On the other hand, Malta has its own specific strategies, encouraging the use of renewable energy, targeting a 10% of renewable energy, and improving energy efficiency in buildings by 2020 [7][8].

Technical Document F [9][10] stipulates the minimum energy performance for buildings in Malta, setting the minimum requirements for building services through a cost-optimal analysis. However, no guidelines have been specified to successfully energy retrofit housing buildings in practice.

This project aims to identify any barriers in renovating housing stocks. In this way, the project can be used by the housing sector in Malta when renovating housing stocks to improve both the energy performance of the building and thermal comfort inside the dwellings. The social housing buildings have been built prior to the existence of the actual energy performance regulations in buildings, so thermal comfort cannot be assured as the roofs are not insulated and many external walls are single file.

Thus, this project will also address a very important issue - energy poverty. Tackling energy poverty brings about multiple benefits, including less money spent by governments on health, reduced air pollution, better comfort and wellbeing, improved household budgets, and increased economic activity.

Once the lessons learned from this project are established and the most adequate retrofit measures established, this project can be replicated with relative ease to other housing building stocks. In addition, any schemes for the housing sector promoting energy efficiency can also be based on the most effective and practical measures learnt from this project.

Renovation of such buildings will set a best-practice example to other entities and will enhance the social corporate responsibility of the Housing Authority, by contributing towards the reduction of carbon emissions and enhancing the quality of life of social housing tenants. This dissertation answers the following research questions:

- Do typical social housing apartments in Malta, built prior to minimum energy performance regulations, comply with thermal comfort standard requirements?

- What are the best passive measures to improve the thermal comfort of such buildings?

Chapter 2. Literature Review

2.1 Energy consumption of buildings and relevant EU directives including Malta's national priorities

In 2016, the building sector was responsible for 40% of EU's energy consumption, 36% of EU's CO_2 emissions and 55% of EU's electricity consumption. Old buildings generally use more energy than new buildings. Currently, 90% of EU's buildings were built before 1990 and the renovation rate is still very low with the result that energy efficiency can still be improved [1]. By 2050, the EU aims to reduce up to 90% of the greenhouse gas emissions in the building sector, through the adoption of clean technologies (low-carbon economy roadmap) [3], when compared to the 1990 levels [2].

Energy performance in buildings is covered by two EU legislation: The Energy Performance of Buildings Directive (EPBD) [4] and the Energy Efficiency Directive (EED) [11]. According to the EPBD, every new building and those to undergo major renovation require to be Nearly Zero Energy Building (NZEB) as of January 2021. NZEB are those buildings where energy used by the building on an annual basis is approximately equal to the amount of renewable energy sources installed. The new (EU) 2018/844 EPBD has shifted its focus from new buildings to deep renovation of existing buildings, together with energy use of appliances, lighting and healthy indoor climate. On the other hand, the EED established EU measures to achieve its 20% energy efficiency objective (energy performance of buildings) by the end of 2020. At present time, the EED from 2012 is been revised and different targets have been announced: the energy efficiency objective for 2030 will increase from 20% in 2020 to 32.5%, as well as encourage countries to reduce energy consumption for households and businesses, increase investment and clearer information in household bills [6]. It has also been established that at least 3% of government's floor area must be renovated and energy efficient every year. *"Each Member State shall establish a long-term renovation strategy to support the renovation of the national stock of residential and non-residential buildings, both public and private, into a highly energy efficient and decarbonized building stock by 2050, facilitating the cost-effective transformation of existing buildings into nearly zero-energy buildings"*.

Malta has its own specific targets as required by both EPBD and EED, encouraging the use of renewable energy and improving energy efficiency in buildings by 2020:

- To comply with the EED, the National Energy Efficiency Action Plan developed for Malta (NEEAP for Malta) a target saving 1.032 GWh over the period 2014-2020 [12].
- To comply with the Renewable Energy Directive (RED) [13], Malta prepared the National Renewable Energy Action Plan (NREAP for Malta), targeting a 10% of renewable energy, as seen in Figure 1 [7].
- All new buildings and buildings undergoing major renovation must be NZEB by the end of 2020 as detailed in the Nearly Zero Building's Plan for Malta [8], which is in accordance with the EPBD.

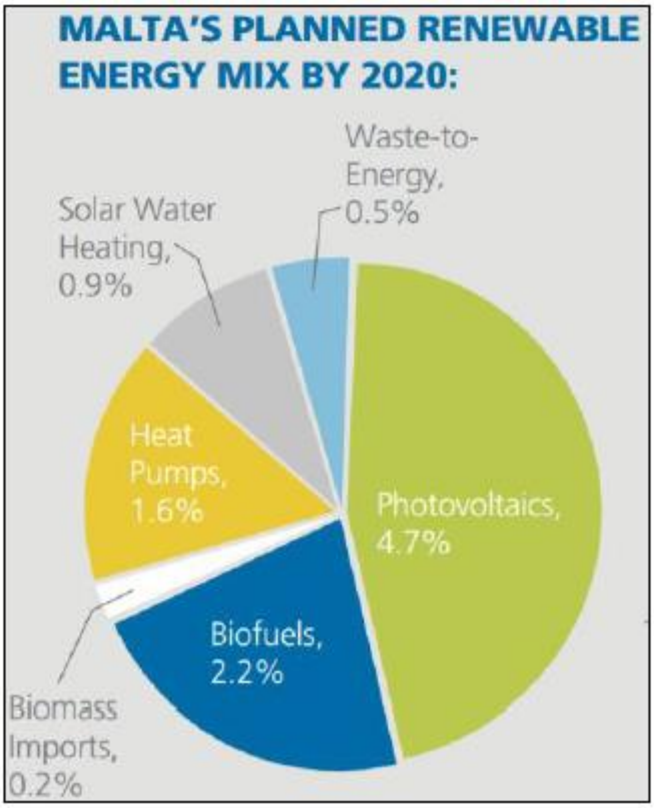


Figure 1: Malta's National Renewable Energy Action Plan [7]

The Building Regulation Board (BRB) of Malta stipulated the minimum energy performance requirements for buildings Technical Document F., which is divided into two parts. The EPBD requires member states to set cost-optimal and nearly zero energy performance requirements for buildings undergoing major renovation based on an asset rating approach, as seen in Technical Document F. Part 1 [9], [14]. On the other hand, Technical Document F, Part 2 [10] sets the minimum requirements for building services.

Despite the setting out of these requirements, actual guidelines to successfully energy retrofit housing buildings in practice and when based on operational energy performance have not yet been set. To enable such guidelines a typical housing block must be carefully studied in practice and evaluated via an energy auditing approach.

2.2 Energy auditing and retrofit methodologies

According to ISO 50002 [15], Energy Audit is defined as the *"Systematic analysis of energy use and energy consumption of audited objects, in order to identify, quantify and report on the opportunities for improved energy performance".*

Energy auditing as defined in ISO 50002, bases the analysis directly on the actual "operational" energy rating of the building.

2.2.1 Operational Rating energy auditing methodology

Operational Rating as an energy auditing methodology consists, as described in ISO 50002, of the following steps (Figure 2):

- **Energy audit planning:** Planning means defining the purpose of the audit choosing the relevant criteria to be gather from the building and dwellings.
- **Opening meeting:** Meeting similar to a Project Charter [16] where the different prospective parties are introduced to the audit aims and limits, while also reaching an agreement related to other important details.
- **Data collection:** The auditor analyses all the data to be gathered, organize and record according to the audit objectives.
- **Measurement plan:** The auditor and other parties must agree on different issues to gather on-site data, such as the measurement time and equipment used.
- **Conducting the site visit:** The person in charge of the facility/building/dwelling must give all necessary details to the auditor.
- **Analysis:** Once the data is collected, it will be analysed by the auditor evaluating the specific data (energy use and costs), highlighting any liabilities and stating any improvement before reporting (energy cost and consumption).

- **Energy audit reporting:** The auditor confirms that the energy auditing requests have been met and applicable measures have been identified.
- **Closing meeting:** Meeting realized once the auditing is finalized. The energy saving plans can be discussed from an economic point of view being able to quantify and rank all energy saving plans that can be adopted.

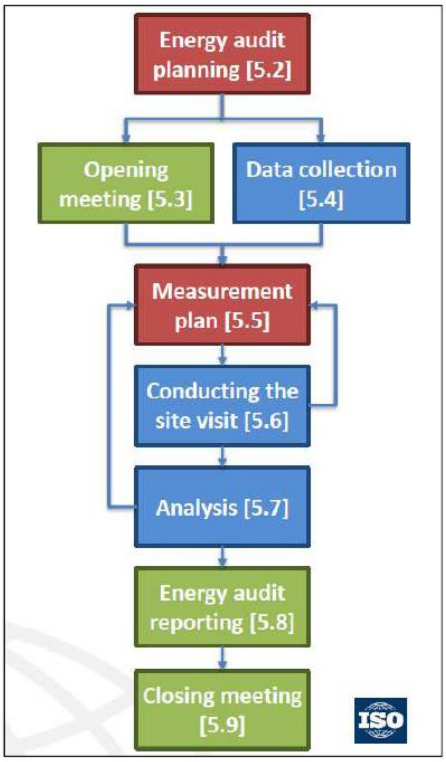


Figure 2: Operational rating energy auditing methodology [15]

It is important to say that ISO 50002 describes three more forms of auditing:

- Type 1: Auditing more suitable for small facilities
- Type 2: Auditing where technical specifications in detail are required.
- Type 3: Once Type 1 and Type 2 have been done, auditing requires prospects with excessive cost and risk.

2.2.2 Energy performance benchmarking

"A good place to begin an energy audit is to compare the use of the facility with similar facilities" [17]. Energy Performance Indicator (EPI) is a statistical meter, defined by ISO 50002 as a *"quantitative value or measure of energy performance"*, which

identifies the potential opportunities of energy savings once you compare the actual energy consumption. The most common used EPI is the kWh/m^2·year.

2.2.3 Retrofit methodologies

Retrofitting an existing building stock is not mandatory so far, even though only between 1.0% and 1.5% in the building sector are new buildings [18], [19]. This means, around 80% of the energy consumption by 2050 will be influenced by existing building stock and between one to over four centuries will be necessary to improve the building stock to the current new construction's energy level [20]. Thus, retrofitting existing buildings is necessary for achieving EU Energy and Climate Change Directive's targets. It is a considerable challenge in the energy building sector to reduce energy consumption meanwhile reducing/eliminating greenhouse gases and being cost effective for the building and occupants.

There are sundry techniques for an effective retrofit project. Cooper, Daly and Ledo's article [21] set retrofitting process of a building into five phases (Figure 3).

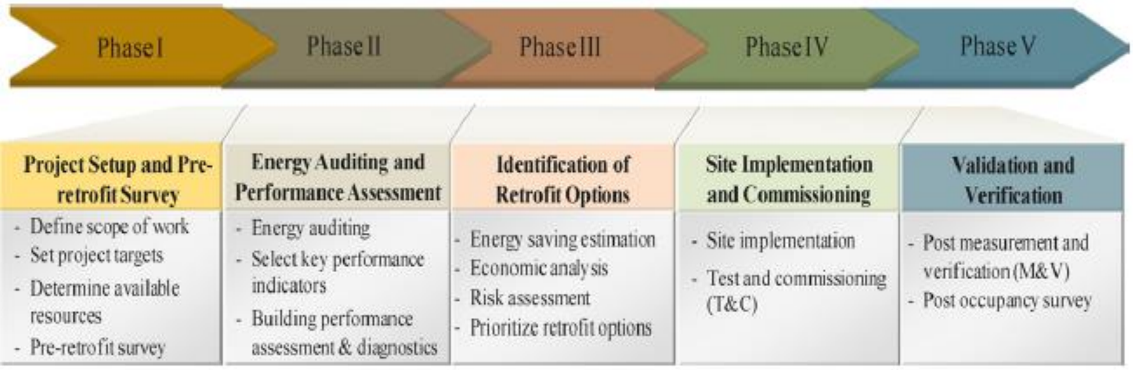


Figure 3: Key phases in a sustainable building retrofit programme [21]

- Phase I: *'Project Setup and Pre-retrofit Survey'*. The extension of the project and project's targets are defined. It is common to use a pre-retrofit survey to better understand the building operational problems and the main occupants' solicitudes. Frequently, the survey is assigned to Energy Service Companies, which are both responsible for planning and retrofitting the building.
- Phase II: *'Energy Auditing and Performance Assessment'*. As described before, energy auditing considers building energy data and building energy uses so that areas with energy wastage can be identified. Thus, no/low cost energy

conservation measures (ECMs) can be implemented. There are different energy audits, ranging from *'Walk Through Audit'* (WTA), *'Standard Audit'* (SA), and the *'Computer Based Simulation Audit'* (CBSA). For CBSA, the building is designed on a computer-based model, which replicates the energy consumption of the real building, considering the building physical condition and orientation for its calculation. The computer-based model is retrofitted with energy conservation measures for a simulation of what is expected on the renovated building energy consumption.

- Phase III: *'Identification of Retrofit Options'*. Thanks to CBSA, various retrofits can be simulated and synthesized into the ones who fit best the extension of the project, performing a compelling economic analysis and risk assessment.
- Phase IV: *'Site Implementation and Commissioning'*. The retrofitting measures considered will be implemented on-site and Test and Commissioning (T&C) is then employed, ensuring that the systems operate in an optimal manner.
- Phase V: 'Validation and Verification'. The last phase validates and verifies the expected energy savings. Maintenance and Verification (M&V) [22], [23] can be used to verify energy savings.

It is recommended to carry out a post occupancy survey to ascertain if the building occupants are satisfied with the overall retrofit results.

Achievement of successful retrofitting in buildings depends on different key elements that have a significant impact on building retrofit (Figure 4).

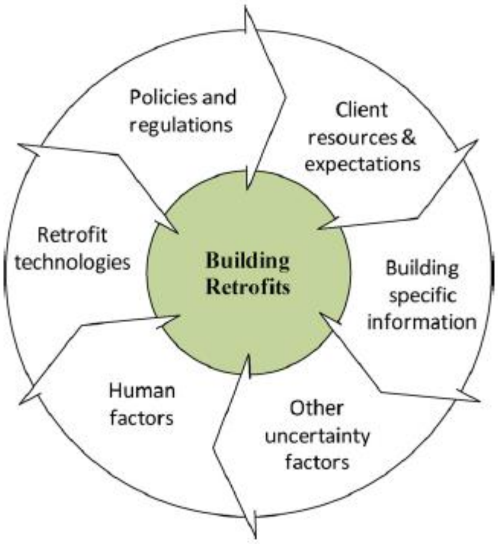


Figure 4: Key elements influencing building retrofits [21]

Building retrofit technologies can be classified into three groups (Figure 5):

- Supply side management: Use of renewable energy technologies, as photovoltaics or wind power systems, to generate green energy and the use of electrical systems retrofit.
- Energy consumption patterns: Management and change of human factors.
- Demand side management: Can be classified into two different strategies.
  - Heating and cooling demand reduction through retrofitting building fabric and other advanced technologies as windows shading.
  - Use of energy efficient equipment and low energy technologies as natural ventilation or thermal storage systems.

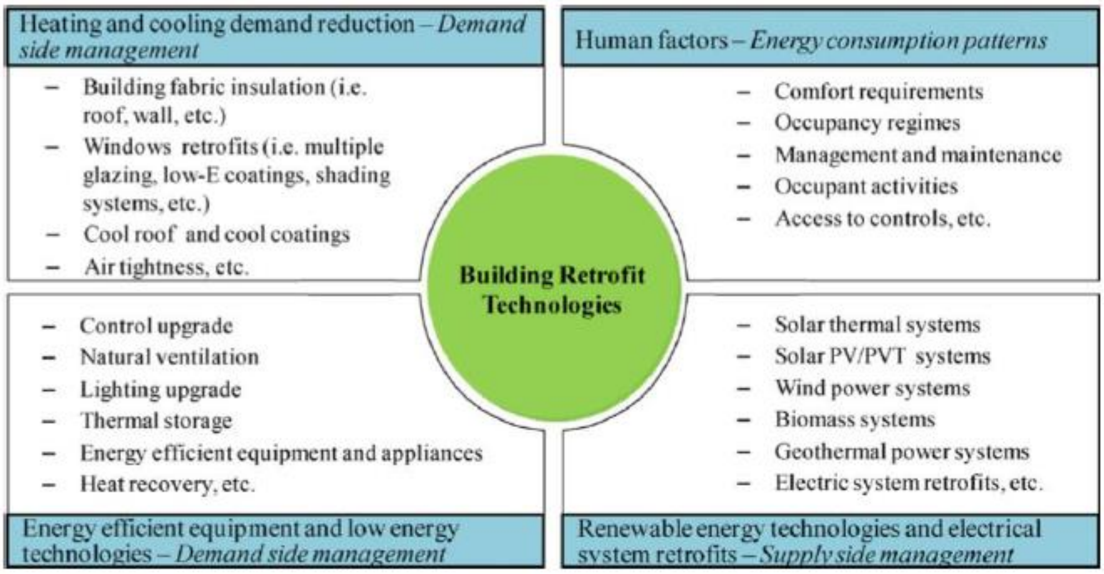


Figure 5: Main building retrofit technologies [21]

Different studies had been carried out for Malta on different building retrofit technologies, particularly on the supply side management and energy efficient equipment and low energy technologies due to its few energy resources and climate. Section 2.4 delves deeper into more detailed information about different retrofit technologies and energy efficiency measures used in Malta.

The project goal and the client’s environment concern have an important impact on the retrofit technologies’ selection. *“It can be found that retrofitting building fabric, building services systems and metering systems requires less cost investment, while providing much more environmental benefits, as compared to retrofit measures using renewable energy technologies”* [21] (Figure 6).

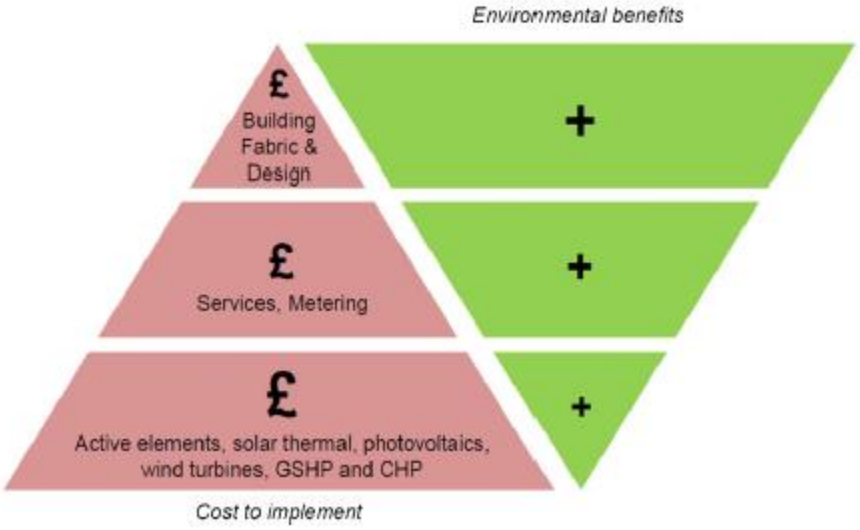


Figure 6: Cost versus environmental benefits (CO_2 emissions reduction) of the energy hierarchy [21]

Malta is a country with limited land and energy resources. That is why it is so important to consider the energy hierarchy of priorities, when improving the energy performance of buildings. The near Zero Energy Home (nZEH) strategies [24] shown in Figure 7 describe different strategies according to the type of energy resources and their use and cost.

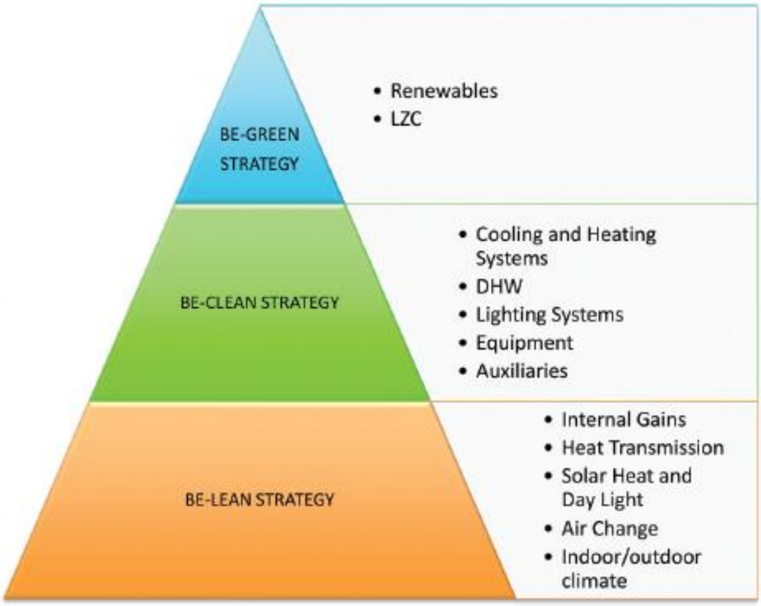


Figure 7: The nZEH strategies [24]

- First stage: *'Be Lean'* strategy focuses on reducing energy demand as result of an effective and efficient building design and retrofit (energy efficient equipment and low energy technologies).
- Second stage: *'Be Clean'* strategy focuses on using efficiently energy systems to reduce the energy consumption, when the measures taken in *'Be Lean'* are not enough.
- Third stage: *'Be Green'* strategy focuses on using renewable energies fulfilling the prior stage.

Renewable energies depend on location, land and natural resources. That is why Malta should only follow *'Be Green'* strategies when the two prior stages are carried out, evaluated and implemented; that means, assuring energy efficiency and thermal comfort for occupants.

2.3 Comfort analysis for naturally ventilated buildings and ways to avoid overheating in buildings

2.3.1 Introduction

Thermal comfort, indoor air quality (IAQ), visual and acoustic comfort are the four main indoor environmental parameters (Figure 8) for design and assessment of energy performance of building addressing. The comfort criteria for these parameters are developed in EN 15251 [25].

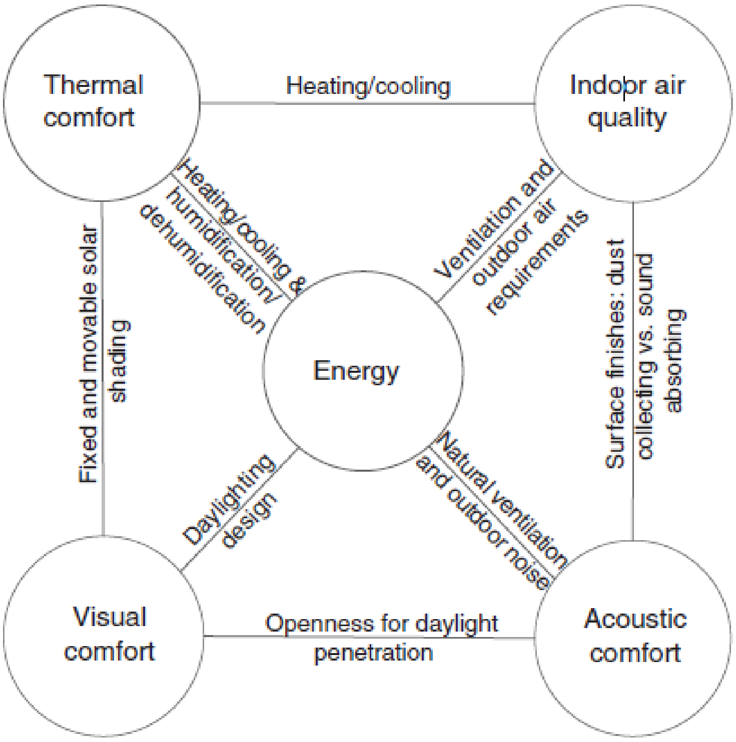


Figure 8: Different indoor environmental parameters [26]

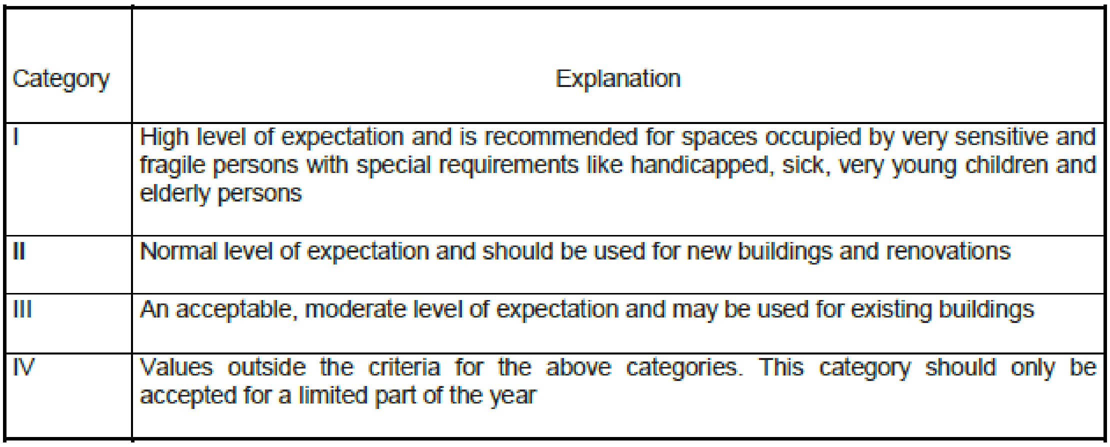
The Standard EN 15251 states: *"An energy declaration without a declaration related to the indoor environment makes no sense. Therefore, there is a need for specifying criteria for the indoor environment for design, energy calculations, performance and operation of buildings"*.

Besides environmental conditions and the build-up of the building, there are individual conditions affecting comfort, such as individual metabolic rate and the type of clothing used [27]. In order to evaluate thermal comfort, the EN ISO 7730 [28] and the CEN CR 1752 [29] form the backbone. These norms define the process to be followed to determine and interpret thermal comfort using the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) indices, as determined by Fanger [30]. EN 15251 helps defining and establishing the main parameters to be used in building energy calculation and long-term evaluation of the indoor thermal environment (IET).

When dimensioning room conditioning systems, the thermal comfort criteria shall be used as input for heating and cooling load (EN 12831, prEN 15255) calculations, thus, the minimum room temperature in winter and the maximum room temperature in summer are key factors for the thermal comfort criteria.

The recommended input values differ according to four different categories, shown in Table 1:

Table 1: Description of the applicability of the categories used [25]



Category	Explanation
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
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

2.3.2 Thermal Comfort

Thermal Comfort has been defined as *“that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation”* [31].

Reaching NZEB targets is an urgency. Half of the energy used in buildings is due to heating, ventilation and air conditioning (HVAC) energy consumption [32].

For Thermal comfort EN 15251 defines two models which are the PMV/PPD model and the adaptive comfort model. The PMV/PPD model is applicable to mechanically heated and cooled spaces, while the adaptive comfort model should be used to assess comfort in buildings without mechanical cooling, that is naturally ventilated.

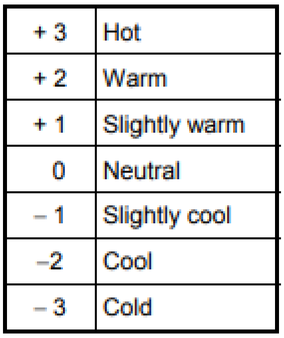
2.3.2.1 Mechanically cooled and heated buildings – PMV/PPD model

The PMV/PDD model depends on the operative temperature, the local air speed, humidity, metabolic rate and clothing level.

The criteria for the ITE shall be based on the thermal comfort indices:

- PMV: *"Predicted Mean Vote is and index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale given in Table 2, based on the heat balance of the human body"* [28]
- PPD: *"Predicted Percentage Dissatisfied is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people who feel too cool or too warm. Thermally dissatisfied people are those who will vote hot, warm, cool or cold on the 7-point thermal sensation scale given in Table 2."* [28]

Table 2: 7-Point thermal sensation scale [25]



+ 3	Hot
+ 2	Warm
+ 1	Slightly warm
0	Neutral
− 1	Slightly cool
−2	Cool
− 3	Cold

Both criteria were proposed by Povl Ole Fanger [30], by which he succeeded in explaining that the sensation experienced by a person was a function of the physiological strain imposed on him/her by the environment. Relating both criteria he was able to predict what comfort vote would arise for different environmental conditions.

Having the PMV value, we can calculate PPD using the equation (1) below.

$$PPD = 100 - 95 * \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2) \qquad (1)$$

We can see PPD as function of PMV in Figure 9.

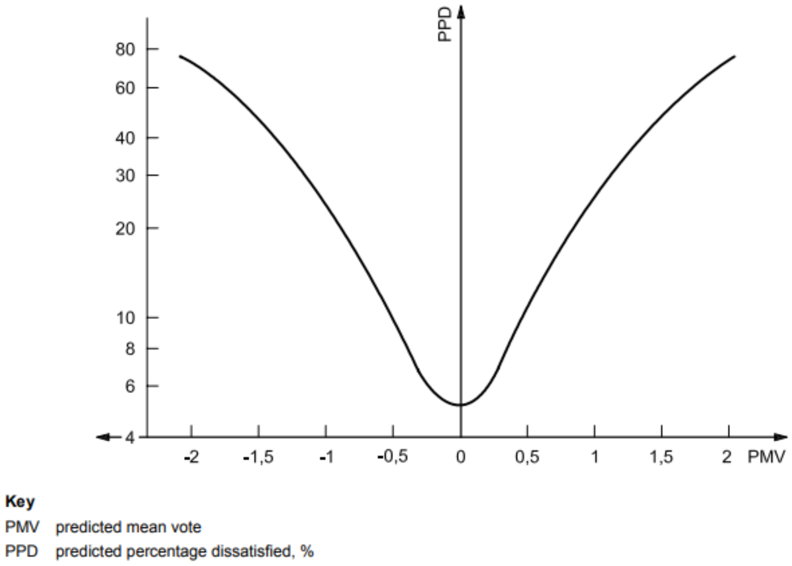
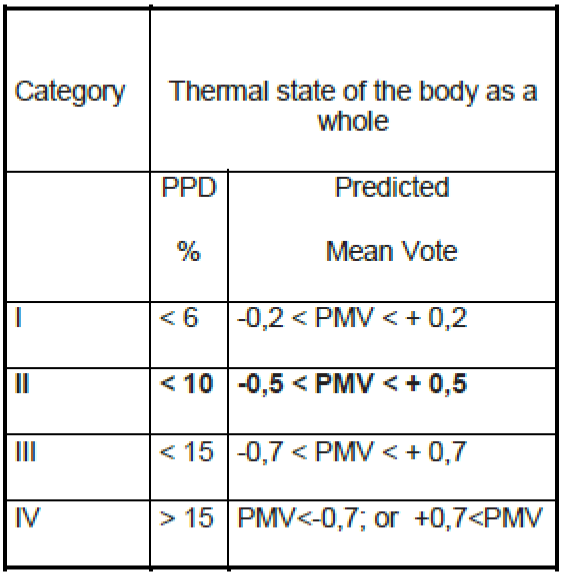


Figure 9: PPD/PMV Thermal Comfort Graph [28]

According to the different categories we can table (Table 3) the different ranges for the PMV which complies with EN 15251.

Table 3: Recommended categories for design of mechanical heated and cooled buildings [25]



Category	Thermal state of the body as a whole	
	PPD %	Predicted Mean Vote
I	< 6	-0,2 < PMV < + 0,2
II	**< 10**	**-0,5 < PMV < + 0,5**
III	< 15	-0,7 < PMV < + 0,7
IV	> 15	PMV<-0,7; or +0,7<PMV

The PMV/PPD method provides a range of temperatures according to environmental and individual conditions and the building’s build-up. A few examples can be seen in Table 4. These temperatures can be calculated with the tool presented in Section 2.3.5.

Table 4: Examples of recommended design values of the indoor temperature for design of buildings and HVAC systems [25]

Type of building/ space	Category	Operative temperature °C	
		Minimum for heating (winter season), ~ 1,0 clo	Maximum for cooling (summer season), ~ 0,5 clo
Residential buildings: living spaces (bed rooms, drawing room, kitchen etc) Sedentary ~ 1,2 met	I	21,0	25,5
	II	20,0	26,0
	III	18,0	27,0
Residential buildings: other spaces: storages, halls, etc) Standing-walking ~ 1,6 met	I	18,0	
	II	16,0	
	III	14,0	

The comfort range of a building for both summer and winter based on the PMV/PPD method can be visualised via a psychometric chart. Tools such as Climate consultant can be used to show both the comfort range hourly values of climate data for a typical year on the same psychometric chart. This plot will enable architects and engineers to identify the most suitable passive and active measures to satisfy comfort for a specific climate. Figure 10 shows a psychometric climate plot for Malta and the best measures identified by Climate consultant [33] to achieve comfort.

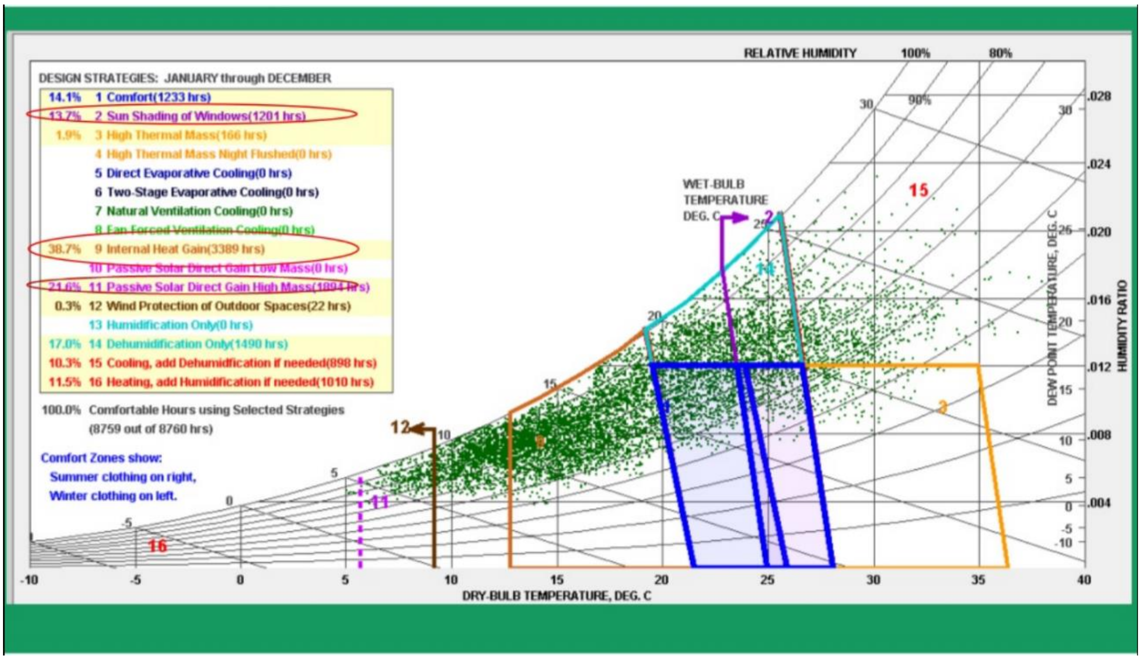


Figure 10: Psychometric chart comfort analysis (PMV/PPD Model) for Malta [34]

2.3.2.2 Buildings without mechanical cooling – EN 15251 Adaptive Comfort Model

“Adaptive thermal comfort models have become widely accepted and have been increasingly used in recent years despite the fact that model differences in regulatory documents and minor uncertainties in applications still do exist” [35]. The Adaptive Comfort Model of the European Standard EN 15251 is employed for estimating thermal comfort in buildings without mechanical cooling. EN 15251 adaptive comfort model is not influenced by humidity or occupants’ metabolic rate and clothing. The comfort temperature according to this model is a function of the outdoor running mean temperature.

Thermal adaptation and prediction are strongly related to outdoor climatic conditions and human beings’ tendency to adapt to changes in climate.

Due to the nature of this study, it is appropriate to state that all apartments do not have constant mechanical cooling conditions. In this case, summer temperatures are chiefly used for the provision of passive thermal controls (e.g. solar shading, opening windows, etc) avoiding overheating of the building when needed.

In Figure 11 one can see the relation between the indoor comfort temperature and the outdoor running mean temperatures for buildings with human occupancy with primarily sedentary activities and easy access to workable windows. Occupants are freely able to adapt their clothing to indoor and/or outdoor thermal environment.

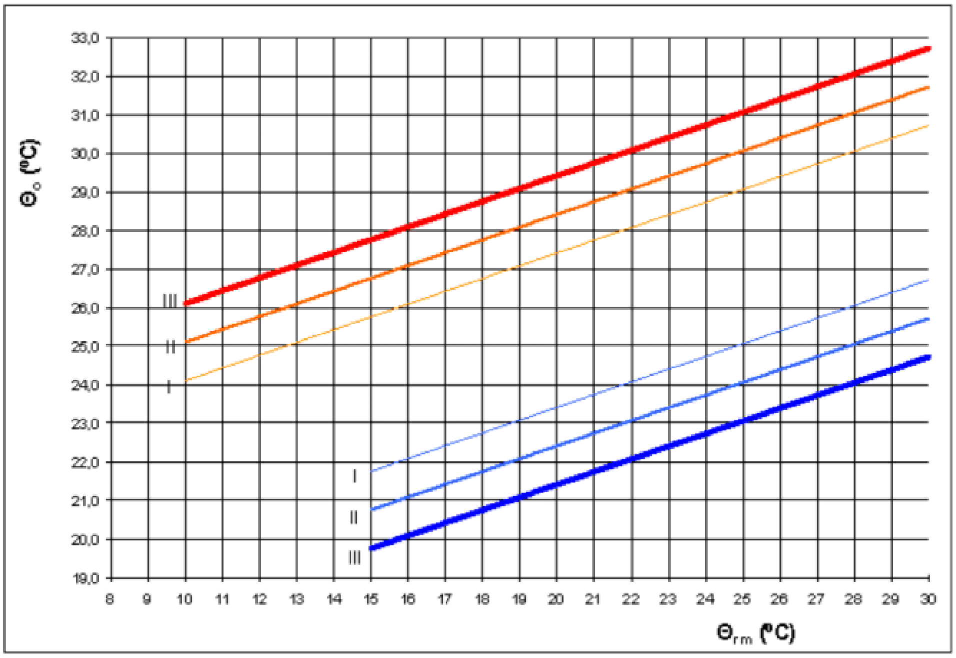


Figure 11: Design Values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially weighted running mean of the outdoor temperature [25]

$$\Theta_{rm} = Outdoor\ Running\ mean\ Temperature\ ℃$$

$$\Theta_o = Indoor\ comfort\ temperature\ ℃$$

The equations representing the lines for Category I, Category II and Category III in Figure 11 are:

Category I $\quad Upper\ limit: \Theta_{i\,max} = 0.33 \cdot \theta_{rm} + 18.8 + 2$ (2)

$Lower\ limit: \Theta_{i\,min} = 0.33 \cdot \theta_{rm} + 18.8 - 2$ (3)

Category II $\quad Upper\ limit: \Theta_{i\,max} = 0.33 \cdot \theta_{rm} + 18.8 + 3$ (4)

$Lower\ limit: \Theta_{i\,min} = 0.33 \cdot \theta_{rm} + 18.8 - 3$ (5)

Category III $\quad Upper\ limit: \Theta_{i\,max} = 0.33 \cdot \theta_{rm} + 18.8 + 4$ (6)

$Lower\ limit: \Theta_{i\,min} = 0.33 \cdot \theta_{rm} + 18.8 - 4$ (7)

Where $\quad \Theta_i = limit\ value\ of\ indoor\ operative\ temperature, ℃$

2.3.2.3 Buildings without mechanical cooling – ASHRAE Adaptive Comfort Model

ASHRAE also defines an adaptive comfort model. Like the EN 15251 model, for the ASHRAE model, the operative comfort temperature (t_{oc}) is a function of the outdoor running mean temperature (t_{out}). Two comfort categories are defined as follows:

90% Thermal acceptability:

$$Upper\ limit: t_{oc} = 0.31 \cdot t_{out} + 17.8 + 2.5 \tag{8}$$

$$Lower\ limit: t_{oc} = 0.31 \cdot t_{out} + 17.8 - 2.2 \tag{9}$$

80% Thermal acceptability:

$$Upper\ limit: t_{oc} = 0.31 \cdot t_{out} + 17.8 + 3.5 \tag{10}$$

$$Lower\ limit: t_{oc} = 0.31 \cdot t_{out} + 17.8 - 3.5 \tag{11}$$

2.3.2.4 Buildings without mechanical cooling – ASHRAE Adaptive Comfort Model considering RH impact

The actual adaptive thermal comfort models are derived using a simple linear regression of the indoor operative temperature against the corresponding outdoor running mean temperature. M. Vellei et al. [36] proposed an improved ASHRAE adaptive comfort model that also consider relative humidity (RH) in addition to the running mean outdoor temperature. According to Sterling's criteria [37] the optimal conditions to minimize human health risks occur between the range of 40 and 60% RH. M. Vellei et al. [36] therefore provides three different linear models describing operative comfort temperature (t_{oc}) as a function of the outdoor running mean temperature (t_{out}) for three different RH categories as follows:

$T_{oc\ RH > 60\%}$:

$$Upper\ limit: t_{oc\ RH>60\%} = 0.53 \cdot t_{out} + 12.85 + 2.84 \quad (12)$$

$$Lower\ limit: t_{oc\ RH>60\%} = 0.53 \cdot t_{out} + 12.85 - 2.84 \quad (13)$$

$T_{oc\ 40\% < RH \leq 60\%}$:

$$Upper\ limit: t_{oc\ 40\%< RH\leq 60\%} = 0.53 \cdot t_{out} + 14.16 + 3.7 \quad (14)$$

$$Lower\ limit: t_{oc\ 40\%< RH\leq 60\%} = 0.53 \cdot t_{out} + 14.16 - 3.7 \quad (15)$$

$T_{oc\ RH \leq 40\%}$:

$$Upper\ limit: t_{oc\ RH\leq 40\%} = 0.52 \cdot t_{out} + 15.23 + 4.40 \quad (16)$$

$$Lower\ limit: t_{oc\ RH\leq 40\%} = 0.52 \cdot t_{out} + 15.23 - 4.40 \quad (17)$$

As seen in Figure 12, the operative comfort temperatures are higher and steeper than those predicted by the ASHRAE 80% thermal acceptability adaptive comfort model. The operative comfort temperatures are lower when the RH is high and higher when the RH is low. The smallest temperature acceptability range for the impact of RH corresponds to the high RH, meanwhile, the acceptability range for medium RH is equal to the ASHRAE 80% acceptability range.

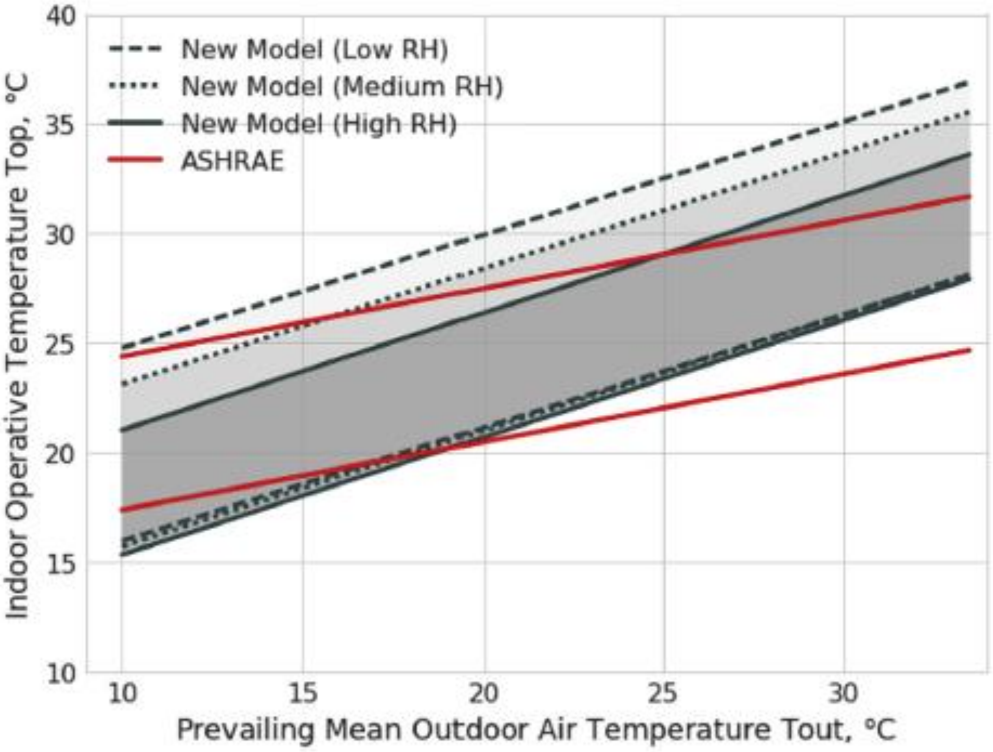
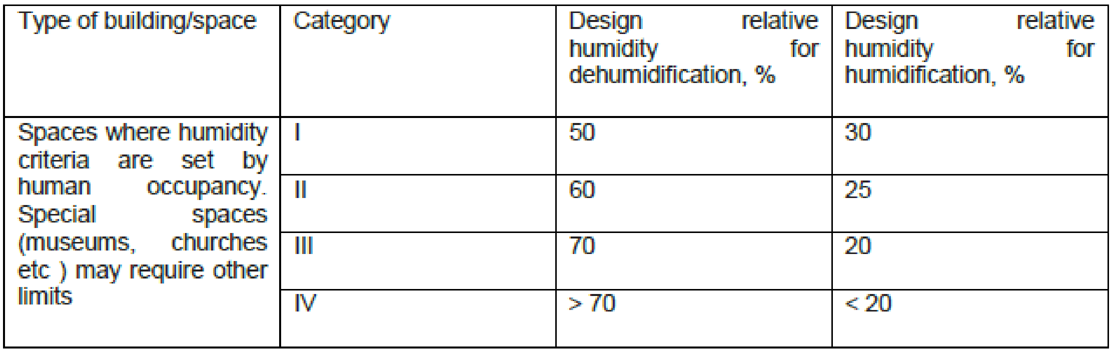


***Figure** 12: ASHRAE 80% thermal acceptability adaptive comfort model and M. Vellei et al. model for RH impact on the ASHRAE Adaptive Comfort Model* [36]

2.3.3 Humidity

Humidity does not factor in the ASHRAE and EN 15251 adaptive comfort models, which is a main limitation of this model, given that the role of humidity on comfort is well documented [36]. Besides, long term high indoor humidity could cause microbial growth. On the other hand, very low humidity causes irritation and dryness of air ways and eyes. Thus, humidification and dehumidification are needed for long periods of time and when needed according to Table 5.

Table 5: Recommended design criteria for the humidity on occupied spaces[25]



Type of building/space	Category	Design relative humidity for dehumidification, %	Design relative humidity for humidification, %
Spaces where humidity criteria are set by human occupancy. Special spaces (museums, churches etc) may require other limits	I	50	30
	II	60	25
	III	70	20
	IV	> 70	< 20

2.3.4 Indoor Air Quality and ventilation

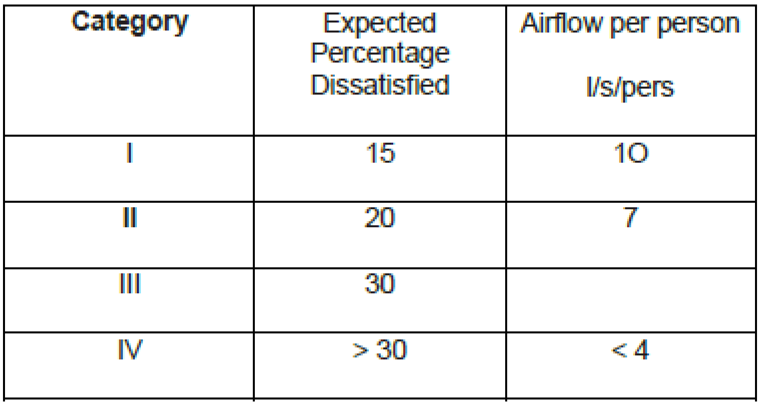
One important factor is the IAQ expressed as CO_2 concentration and the appropriate level of ventilation. The required ventilation is based on comfort and health criteria, where humidity and thermal comfort gain importance.

In design of buildings, one requires to take into consideration two flow rates (l/s, pers):

- Ventilation for pollution caused by occupants, q_A
- Ventilation for pollution caused by the building and systems, q_B

The ventilation rate for pollution, q_A, can be seen in Table 6.

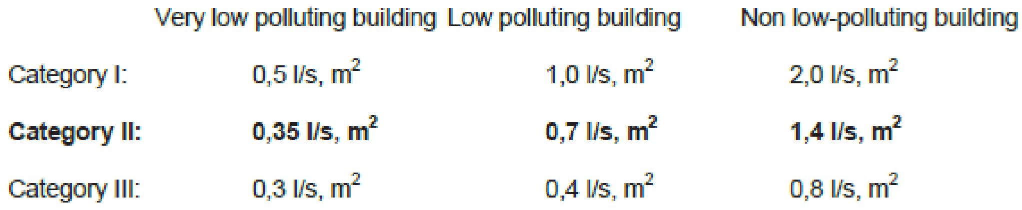
Table 6: Basic required ventilation rates for diluting emissions from people for different categories [25]



Category	Expected Percentage Dissatisfied	Airflow per person l/s/pers
I	15	10
II	20	7
III	30	
IV	> 30	< 4

The ventilation rate for the building emissions, q_B, can be seen in Table 7.

Table 7: Basic required ventilation rates for building emissions [25]



	Very low polluting building	Low polluting building	Non low-polluting building
Category I:	0,5 l/s, m^2	1,0 l/s, m^2	2,0 l/s, m^2
Category II:	**0,35 l/s, m^2**	**0,7 l/s, m^2**	**1,4 l/s, m^2**
Category III:	0,3 l/s, m^2	0,4 l/s, m^2	0,8 l/s, m^2

Total Ventilation rate needed for a room is calculated according to:

$$q_{tot} = n \cdot q_A + A \cdot q_B \tag{18}$$

$q_{tot} = total\ ventilation\ rate\ of\ the\ room, l/s$

$n = design\ value\ for\ the\ number\ of\ the\ persons\ in\ the\ room$

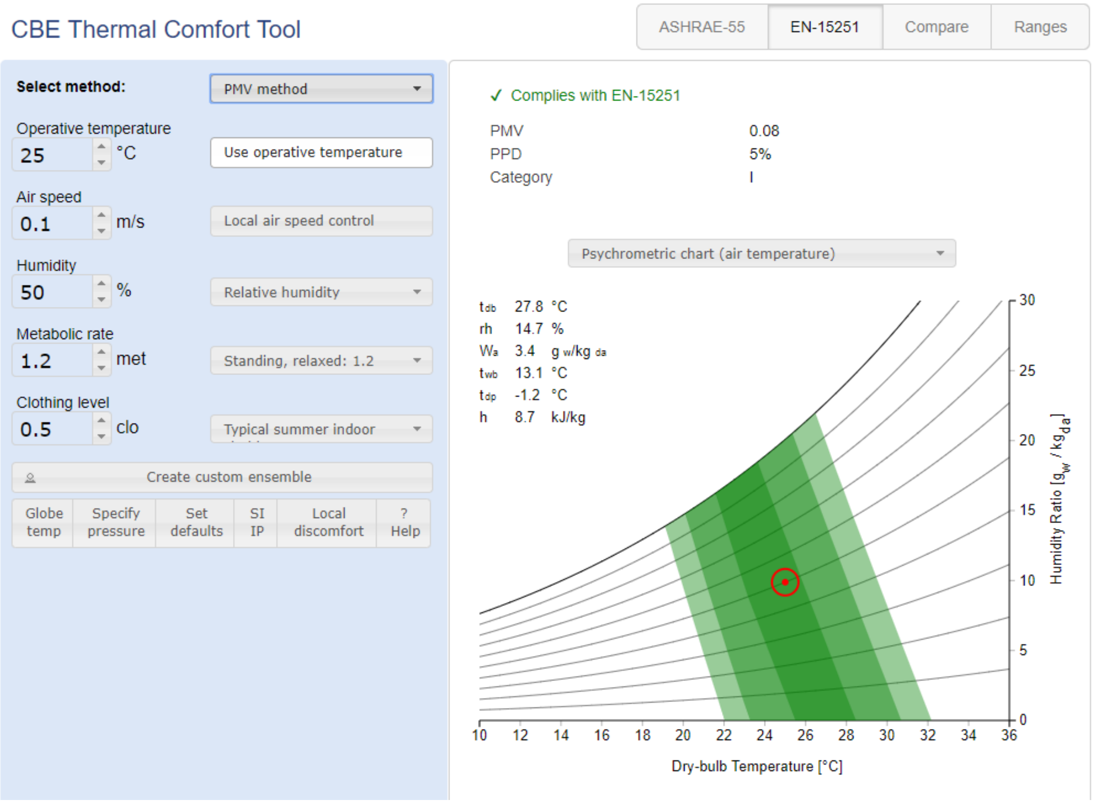
$q_A = \text{ventilation rate for occupancy per person}, \frac{l}{s}.\text{pers}$

$A = room\ floor\ area, m^2$

$q_B = ventilation\ rate\ for\ emissions\ from\ building, \frac{l}{s}.m^2$

2.3.5 CBE Thermal Comfort Tool

The Center for the Built Environment (CBE) offers a tool (http://comfort.cbe.berkeley.edu/EN) to ascertain if a given operative temperature complies with both EN 15251 and ASHRAE adaptive comfort models. For the EN 15251 with this tool one can select one of the methods mentioned; for PMV Method, one just needs to know the operative temperature, the local air speed, humidity, metabolic rate and clothing level (Figure 13), in the other hand, for the EN 15251 adaptive comfort model, one will need to know the operative temperature, the outdoor running mean temperature and the air speed (Figure 14). For the ASHRAE adaptive comfort model one will need to know the operative temperature and the prevailing mean outdoor temperature (Figure 15).



Select method: PMV method

Operative temperature 25 °C — Use operative temperature

Air speed 0.1 m/s — Local air speed control

Humidity 50 % — Relative humidity

Metabolic rate 1.2 met — Standing, relaxed: 1.2

Clothing level 0.5 clo — Typical summer indoor

✓ Complies with EN-15251

PMV	0.08
PPD	5%
Category	I

t_{db} 27.8 °C
rh 14.7 %
W_a 3.4 g $_w$/kg $_{da}$
t_{wb} 13.1 °C
t_{dp} -1.2 °C
h 8.7 kJ/kg

Figure 13: CBE Thermal Comfort Tool - EN 15251 PMV method [38]

Select method: Adaptive method

Operative temperature 25 °C

Outdoor running mean temperature 24 °C

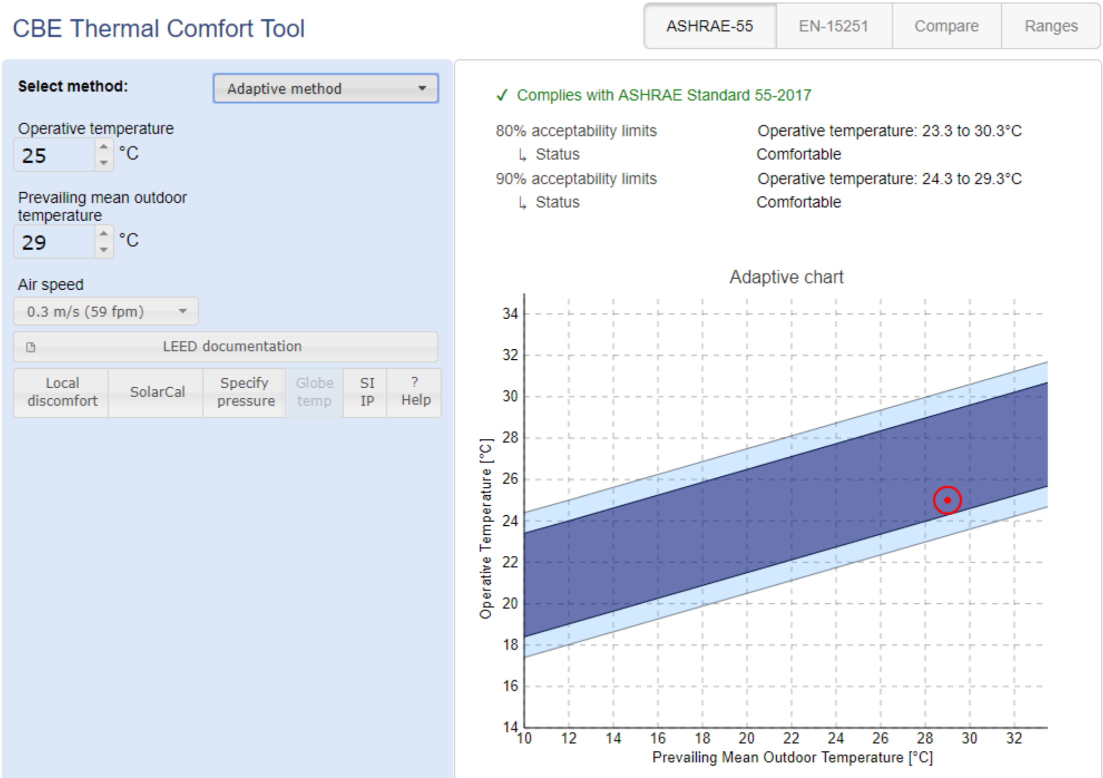
Air speed 0.2 m/s

Local air speed control required

✓ Complies with EN-15251

Class III acceptability limits	Operative temperature: 22.7 to 30.7°C
↳ Status	Comfortable
Class II acceptability limits	Operative temperature: 23.7 to 29.7°C
↳ Status	Comfortable
Class I acceptability limits	Operative temperature: 24.7 to 28.7°C
↳ Status	Comfortable

Figure 14: CBE Thermal Comfort Tool – EN 15251 adaptive comfort method [38]



Select method: Adaptive method

Operative temperature 25 °C

Prevailing mean outdoor temperature 29 °C

Air speed 0.3 m/s (59 fpm)

✓ Complies with ASHRAE Standard 55-2017

80% acceptability limits	Operative temperature: 23.3 to 30.3°C
↳ Status	Comfortable
90% acceptability limits	Operative temperature: 24.3 to 29.3°C
↳ Status	Comfortable

Figure 15: CBE Thermal Comfort Tool - ASHRAE adaptive comfort method [38]

2.3.6 Ways to avoid overheating in a building

Mediterranean regions can lead to uncomfortable conditions, especially during spring and summer time, if suitable measures are not taken to improve comfort. This condition is known *“as ‘overheating’, i.e. the indoor environment would become hotter than is desirable, comfortable or sometimes even tolerable”* [39].

Generally, occupants want to satisfy their thermal comfort in the building establishing the optimum conditions without using any mechanical device or active energy systems. Discomfort can be understood in two ways:

- Discomfort due to high thermal conditions – Overheating.
- Discomfort due to air freshness – Ventilation systems.

Reducing the occupants’ discomfort can be done by designing or retrofitting energy efficient buildings.

The main sources of heat come from internal gains but more importantly from solar gains through the building’s fabric envelope and glazing, which increases the indoor temperature. Nevertheless, dwelling characteristics are also important. Location, orientation, ventilation, design and construction are five different factors considered when analysing thermal comfort, placing the sensors and deciding what solutions can be made to reduce discomfort or better to attain comfort.

Preventive measures to existing buildings (Figures 16, 17) rather than the design of new ones [40] are:

- Thermal insulation to the walls and loft.
- Shading, reflection and protection.
- Ventilation
    - Mechanical systems: fans, air conditioning, etc.
    - Natural ventilation (opening windows).

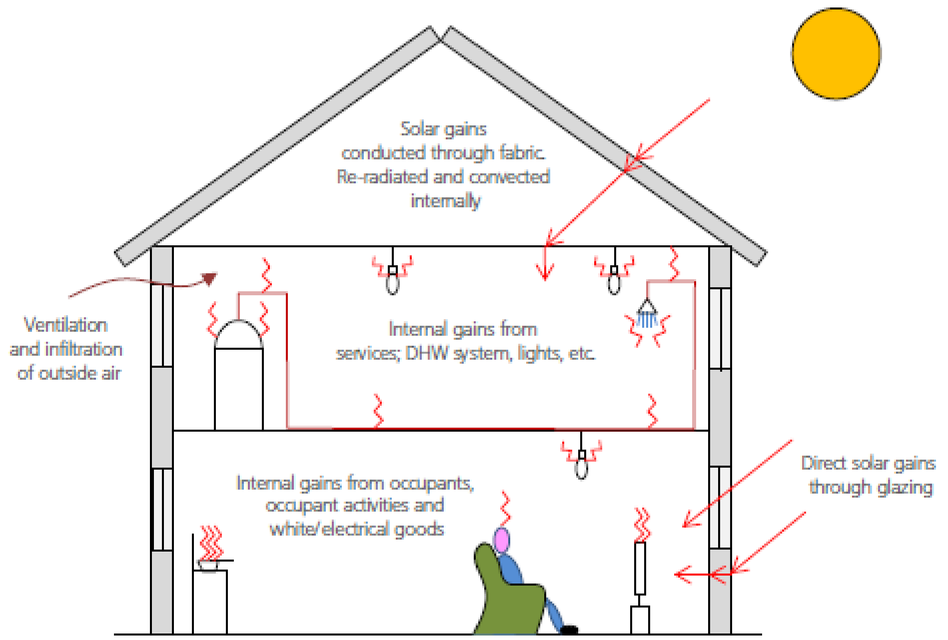


Figure 16: Sources of heat gain [40]

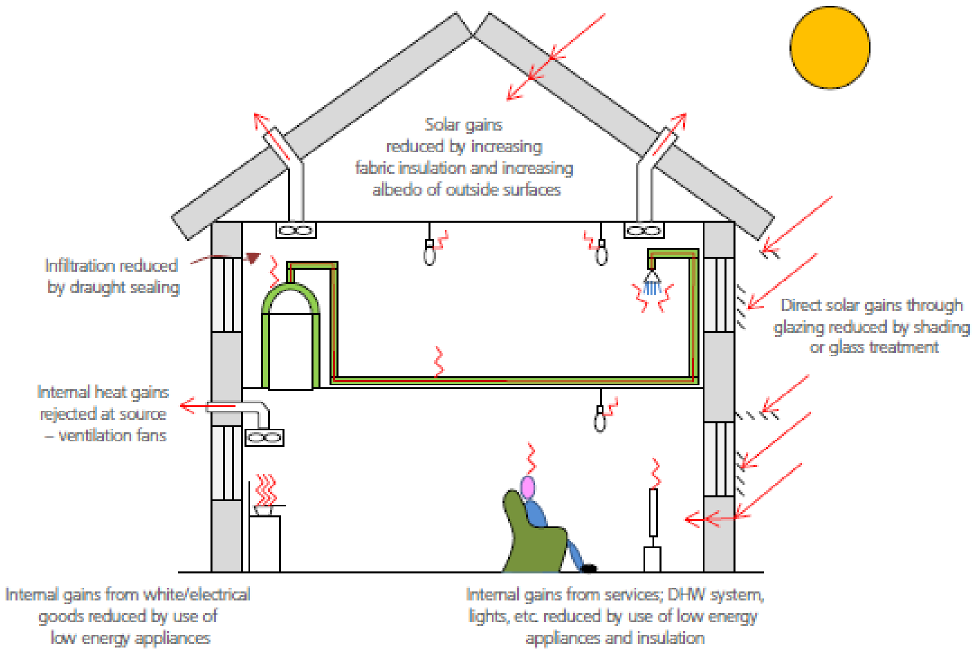


Figure 17: Potential measures to minimise heat gains [40]

2.3.7 Assessing overheating

"In order to assess whether an existing building is overheating or uncomfortable, the upper limit of the indoor comfort temperature needs to be known for that day" [39]. It is recognised that noticeable variations of outdoor temperatures can occur in periods of times shorter than a month. The adaptive method suggests that comfort depends on very recent thermal experience, i.e. comfort temperature depends on the daily running mean outdoor temperature (weighted average outdoor temperature over the past few days) in relation to today's running mean outdoor temperature. According to this, a sudden warm spell is more uncomfortable when there is not a steady build-up of warmer condition. When the running mean outdoor temperature has been low for several days and a sudden warm spell occurs, the odds of feeling uncomfortable are higher (Figure 18) than when the running mean outdoor temperature has been high (Figure 19).

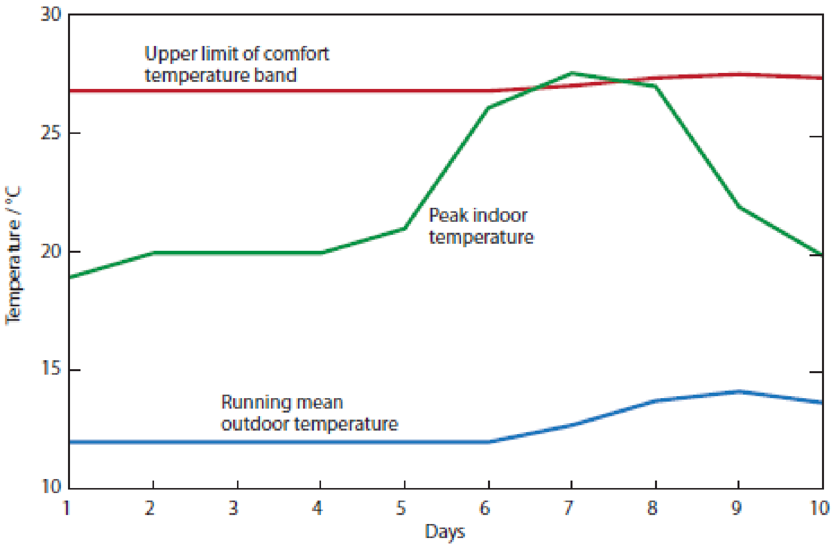


Figure 18: Hot spell in April [39]

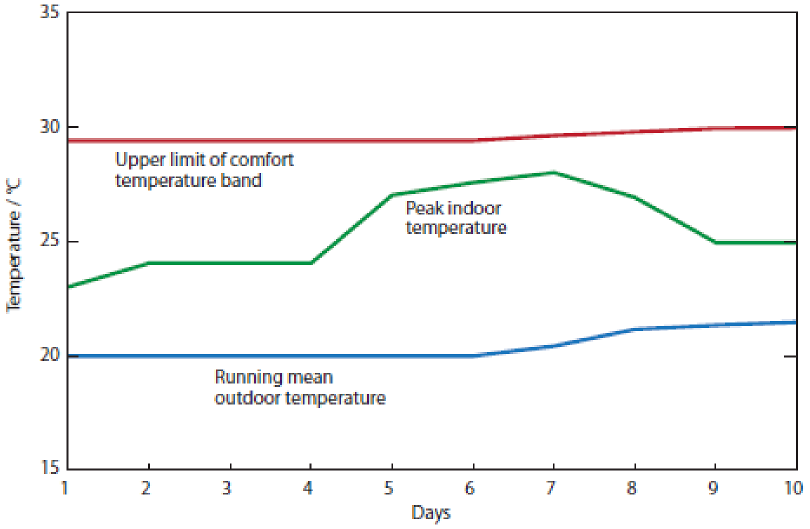


Figure 19: Hot spell in July [39]

Therefore, we can plot, for an existing building, the indoor comfort temperature versus the running mean outdoor temperature with the upper limit of comfort temperature band, as we can see in Figure 14.

When the indoor comfort temperature of the day exceeds the upper limit of comfort temperature band, we could say that the existing building is overheated; hence the temperatures are *'too hot'* for most people, i.e. uncomfortable.

2.4 Housing authority buildings retrofit measures and case studies

2.4.1 Similar local study

Yousif et al. [41] analysed the economic viability of the different energy efficient (EE) and renewable energy (RE) installations proposed on the first energy efficient housing project in Malta, base year 2010. The different measures proposed were double-glazing, louvered windows and door, roof insulation, solar water heating, solar photovoltaic systems, shading features and underground second-class rainwater reservoir. An average price for energy efficient options was calculated based on quotations from local suppliers. The study was able to evaluate the carbon footprint, the Net Present Value (NPV) and the Discounted Payback Period (DPP). Three energy efficiency measures stood out from the others; the solar water heating resulted to have the best NPV (42,920 €) and a payback period of 4 years; the second best NPV rated (33,593 €) was the roof insulation with a payback period of 2 years and the third best NPV rated (19,637 €) was the double glazing with a payback period of 3 years. It is important to mention that a photovoltaic system (PV) had the fourth best NPV but the payback (PB) period is 20 years in 2010. Naturally, for this last measure, the prices of solar photovoltaics have dropped significantly, and this implies that installing solar photovoltaics could have a very attractive rate of return in 2019/2020, when compared to 10 years ago. There were also different measures with a negative NPV after 20 years, such as louvred windows, due to the high cost of the louvred window itself.

In this study, the energy saving of the new building block was estimated, given that no energy consumption data existed. Nevertheless, given that the electricity tariffs today are much cheaper than those in 2010 (by a factor of 1.5), it is imperative that the payback periods for all energy efficiency measures could be different from those in 2010.

2.4.2 Housing retrofit studies in Mediterranean climate

Lizana et al. [42] performed a multi-criteria assessment to derive on an energy Effectiveness Index (EI) for each measure or package of measures that considers the environmental, economic and social variables for all the stakeholders, which include the user, the public promotor and the private promotor. Therefore, this assessment considers more criteria for decision making than the EPBD cost-optimal method, which is only concerned with primary energy savings and life-cycle costings. The different measures were applied on a southern Spanish building from the 1950s. It was found that heat pumps have the potential of reducing up to 45% of the building's CO_2 emissions with a payback period of 6 years. Most passive retrofit measures, including shading elements and installation of high efficiency windows, were found to have a resulting high payback period of 15 years or more .The paper also provides a detailed literature review of the different assessment measures adopted by other studies, to identify the effectiveness of the other energy efficiency retrofit measures.

Suárez et al. [43], performed an energy assessment using DesignBuilder [44], whose simulation engine is Energy Plus [45]. The different retrofit measures analysed were natural ventilation at night during the summer period, energy conservation measures improving insulation on external framework and double glazing, solar radiation and solar control using sliding, folding and fixed slat systems, movable shading devices and thermal envelope insulation with ceramic or metal finish. Not only energy consumption and savings were analysed, but thermal comfort was also taken into account using the adaptive models defined by Auliciems and Szokolay [46]. Thermal comfort was improved by reducing the gap between the indoor temperature and the comfort temperature band, mainly through the improvement in U-values of each building envelope element.

Santamaría et al. [47], performed an energy and economic assessment of dwellings in Mediterranean climates also using Design Builder. The different retrofit measures studied included a façade restored by inner cladding, internal roof and ground insulation, double-glazed windows and insulated aluminium frames and an efficient use of terraces as solar collectors. As in Yousif et al. [41], NPV is also analysed for each measure. Finally, the best comparative results were found to be an insulation system on the external envelope with a payback period of 19 years and an insulation system for the internal side of the building with a payback period of 15 years. These settings get the highest energy and economic savings and when giving a more detailed analysis, the inner insulation is more profitable than those on the external side of the envelope due to the lower cost that this entails. This study also highlights that installation of solar protection in that specific building is not profitable due to the lower percentage of façades with south and west components.

Escandón et al. [48], also featured an energy assessment of three different case studies in South Spain using DesignBuilder. Escandón distinguished between real and estimated consumption in the housing stock and behaviour. Thus, monitoring the case studies with long-term measurements was the method used to evaluate energy efficiency and thermal behaviour of the building and its comfort levels following the adaptive model established by standard EN 15251. Specific retrofit measures are not mentioned, although general insulation is named. This study highlights the importance of different user profiles and location for retrofitting decisions and how important the financial constraints are for users when using their heating systems. Therefore, improving thermal comfort must be done with efficient heating systems that do not affect users economically and with passive retrofit measures as much as possible.

Desogus et al. [49], studied the feasibility of heavy thermal upgrades on different buildings in the Mediterranean climate, proving that different energy efficiency retrofit measures are not completely cost-effective as far as payback time is concerned, unless national subsidy policies are implemented to improve the economic return on the investment. For this, Desogus et al. propounded two different scenarios and assessed the different NPV obtained with and without national subsidy policies.

Blázquez et al. [50], focused their study on how important calibration is on simulations of building energy models, to allow a better approach to the current environmental conditions and to predict and optimise the different energy retrofit measures to implement. In order to implement the information recorded *in situ*, software such as DesignBuilder allows the energy model to be supplemented with a complete description of the internal loads and user's profile. For this, reducing the number of uncertain parameters improves the precision of the calibration. More information is developed in Section 2.6.

2.4.3 More local studies

Manz et al. [35], performed an energy simulation with the computer program WUFI®Plus. The study analysed the thermal comfort of different passive energy retrofit measures in the Maltese archipelago following the adaptive thermal comfort model from the European standard EN 15251. The U-value of different building elements was considered. The study concluded that in an energy efficient well-designed building, that is equipped with double glazing, decent insulation, different shading devices and natural night ventilation, natural night ventilation in summer could be the most effective strategy, although it has its limitations such as the low temperature difference between outdoor temperatures and indoor temperature, as well as the low speed of wind in summer and the level of humidity, which depends on the wind direction. For the case of low wind speed, the paper proposes to assist natural ventilation by adding mechanical ventilation

Damien Gatt and Charles Yousif [51] studied a new boutique hotel building in Malta to reduce its CO_2 emissions approaching the NZEB objectives from the EPBD. The modelling was carried out using EnergyPlus modelling in the computer program DesignBuilder. The analysis highlighted that it was possible to reduce more than 75%

of CO_2 emissions with a payback period of approximately 9 years. Most of the CO_2 savings were achieved from the main energy consumer, Domestic Hot Water. Therefore, using renewable energies for producing hot water should be considered such as solar heating, heat pumps or ground source heat pumps. The study also noted that using liquified petroleum gas for cooking instead of electricity can already result in a significant reduction in CO_2 emissions, despite no reduction in site energy demand.

Another study from Gatt and Yousif [52] on a primary school building in Malta was modelled in DesignBuilder in order to meet the Minimum Energy Performance Requirements (MEPRS) defined by the EPBD, using the Net Present Value point of view. Achieving comfort using the EN 15251 adaptive thermal comfort was also considered in their conclusions. Different retrofit technologies were carried out; convective heaters were replaced with infra-red radiative panel heaters, photovoltaic solar modules were installed, the swimming pool's energy was reduced with an automated pool cover and air to water heat pumps coupled with a solar thermal heating system, while electrical storage water heaters were replaced by instant water heaters in the bathrooms. Other measures such as wall insulation and light dimming using photocells were installed although they had lower economic impact, as reflected in their NPV results but these were applied to compare their actual performance with the Energy Plus simulation results.

2.5 Housing authority and ERDF priority axis 4

Malta's Priority Axis 4 section 4c, which sources its funding from the European Regional Development Fund (ERDF) and Cohesion Fund, promotes the use of renewable energy sources and energy efficient systems through financial incentives in the housing sector. *"Moving towards resource-efficiency, low-carbon economy and sustainable growth is one of the central objectives of the Europe 2020 Strategy and remains one of Malta's top priorities for the 2014-2020 period"* [53]. To meet the objectives, it is important to invest in more environmentally friendly measures and exploit natural resources in a sustainable way. Malta is carrying out different national strategies such as the National Renewable Energy Action Plan and the National Energy Efficiency Action Plan. Malta has also published the draft National Energy and Climate Plan for 2030, which proposes the way forward with regards to Malta's commitments towards climate change and renewable energy [54]. Households, enterprises and the public sector are encouraged to increase the share of renewable energy sources, energy saving, energy efficiency systems and buildings thanks to the measures seen in priority axis 4 to contribute towards EU 2020 and national targets. Under the Investment Priority, Government will aid with retrofitting measures for renewable energy and energy efficient systems for retrofitting to minimize energy demand, and hence carbon emissions.

2.6 Energy simulation

Energy modelling has become an important tool for building design. Different energy calculation methods can range from simple benchmarking models to dynamic models as shown in Figure 21.

Benchmarking methods use the building area and tabulated data to carry out a basic analysis. Degree-day methods assume heat load to be linearly related to external air temperature. The bin method uses frequency distribution for different discrete temperature classes. Quasi-steady state determines useful heat gains for each period of calculation. Lumped parameter models simplify a room to a small network of resistances and capacitances, to evaluate the different temperature nodes of the room. The last method, dynamic thermal simulation is an hourly/sub-hourly time step method applied via commercially available software tools. It is the most complex method due to the number of influencing variables in the simulation such as the heating and cooling loads, internal gains and heat transmissions, the structure and occupancy of the building.

DesignBuilder is a dynamic software [55] that facilitates graphical inputs into the interface energy simulation engine of EnergyPlus. EnergyPlus is a whole building energy simulation tool used to model energy consumption for heating, cooling, ventilation, lightning and plug and process loads. This program enables simultaneous interaction of the geometric model of the building, with the outdoor conditions, occupancy and usage of building systems in order to predict heating and cooling loads arising in the building on an hourly basis. Therefore, thermophysical properties of materials, occupancy and subjective data and the performance of systems influenced by the internal and external environmental conditions can be considered to evaluate the energy performance of a building provided in DesignBuilder.

CIBSE Guide A [56] and CIBSE Guide L [57] recommends using dynamic thermal modelling to predict energy demand to ensure suitable design strategies for the most effective solution to satisfy differing needs. Such needs include complying with national and regional standards, minimizing greenhouse gas emissions and minimizing cost in use. Dynamic modelling is however more time consuming and computationally expensive than simpler modelling tools.

Despite their benefits in sustainable building design, energy modelling tools have their limitations; all models are always a simplified view of the reality, occupants never operate as expected, weather conditions are assumed when there is no approach or data collected, calculation software packages use different algorithms providing different results [58]. It is therefore important and useful to subdivide models depending on the focus, namely, determine zone energy demands, determine fuel demand and determine carbon emissions as seen in Figure 20.

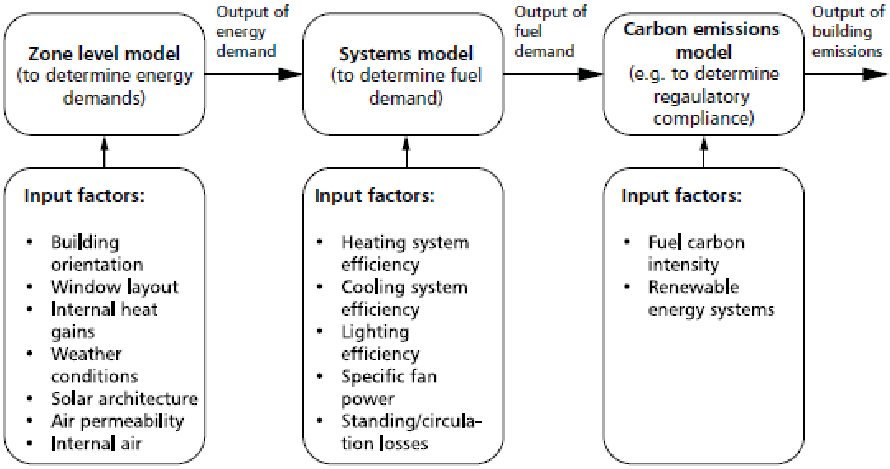


Figure 20: Relationship between different energy models [58]

Once the focus is established different alternative methodologies can be applied for energy calculation depending on the time step applied (annual/seasonal, monthly/daily, hourly/sub-hourly) as seen in Figure 21.

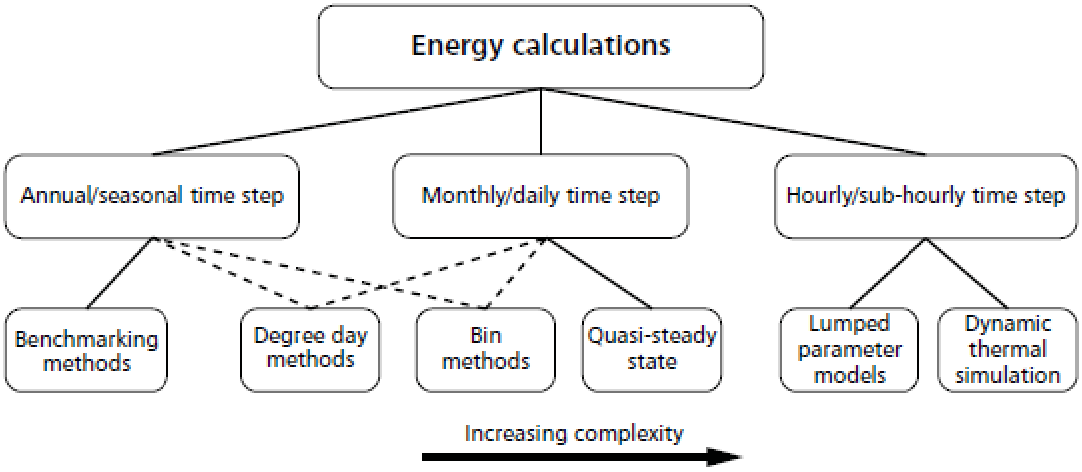


Figure 21: Building energy model methodologies [58]

In order to gain confidence of the suitability in the analysis method proposed when undertaking an energy retrofit project, the building energy model under study should be calibrated with actual measured energy consumption data. Calibration involves observation of changes in simulation output when simulation input is modified, in order to identify the set of inputs leading to simulation outputs that match measured building performance. Calibrating a model can be a complex and time-consuming endeavor, because of its uncertain nature. In fact, the approach in identifying the discrepancy between the results of model and the actual data are not always possible and database used from the software can sometimes be farfetched or poorly implemented. According to the ASHRAE Handbook [59], the quality of a calibration is often evaluated in terms of statistical indicators, the normalized mean bias error (NMBE) and the coefficient of variance of the root mean square error (CV(RMSE)).

$$NMBE = \frac{\Sigma(V_{actual} - V_{modeled})}{(N-1)\cdot Mean(V_{actual})} \cdot 100\% \qquad (19)$$

$$CV(RMSE) = \frac{\sqrt{\frac{\Sigma(V_{actual} - V_{modeled})^2}{N-1}}}{Mean(V_{actual})} \cdot 100\% \qquad (20)$$

$V_{actual} = parameter's\ measured\ or\ metered\ value\ for\ each\ time\ step$

$V_{modeled} = \text{parameter}'s\ estimated\ or\ modeled\ value\ for\ each\ time\ step$

$N = number\ of\ time\ steps\ being\ analyzed\ during\ period\ of\ evaluation$

The model can be considered calibrated if NMBE < 10% and CV(RMSE) < 30% for hourly data and if NMBE < 5% and CV(RMSE) < 15% when monthly data are used.

2.7 Gaps in literature

From the literature review, studies on energy retrofit projects for the housing sector have never been performed using state of the art dynamic simulation tools for the Maltese climate. While one study [41] performed research on different measures that can be implemented in new rather than retrofitted housing stock buildings, the study lacks the use of simulation tools for accurately estimating energy savings from the proposed energy efficiency measures. The study also did not delve into internal thermal comfort improvements, once the different measures were applied. Most studies for overseas Mediterranean buildings also focus on the sustainable design of new buildings, instead of energy performance and thermal comfort improvement in existing housing buildings. Furthermore, the previous study is more than 10 years old and the financial estimates do not reflect the current energy prices and capital cost of the different retrofit measures.

Therefore, the proposed study will bridge this gap by undertaking the first project for energy retrofit of the housing sector versus new housing stocks via calibrated building energy simulation tools. Such a study is critical for Malta to establish and promote the optimal retrofit measures to reach NZEB, while tackling social poverty by reducing operational energy cost and improving health and well-being of occupants via better thermal comfort.

Chapter 3. Methodology

3.1 Description and choice of building under study

3.1.1 Why the building was chosen

The social housing building is located in the locality of Żabbar, Malta; more specifically, at Fewdu street (Figure 22). The building consists of four blocks of houses (A, B, C, D), with a total of five floors for each block and two apartments on each floor, which makes up a total of 40 dwellings (10 dwellings per block). Different reasons this building was chosen for analysis is because of the following:

- This is a typical housing stock block built in the 1990s prior to establishment of energy performance guidelines or regulations. There are many such housing blocks that were built during that period. Thus, this building can serve as pilot project with respect to energy retrofitting, which can be replicated for the other buildings.
- The building is symmetrically constructed (Figure 23), in all cardinal directions within an angle of ±65°; this enables a full study of each dwelling depending on which direction it is facing.
- Due to favourable configuration, one can compare the impact of energy performance and comfort for each combination of orientation and floor level (ground floor, middle floor and top floor), using occupants' feedback from questionnaires, operational energy performance data, on-site measurements and simulated data. On site measurements for 15 dwellings in total were also carried out[1] to gather relative humidity and dry bulb temperature every 10 minutes.

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[1] For the following dwelling, the on-site temperature and relative humidity was recorded on a sub-hourly basis: dwellings nº 1 and 2 belonging to the ground floor, dwellings nº 3, 4, 5, 6, 7 and 8 belonging to the Middle floor and dwellings nº 9 and 10 belongs to the top floor. For this study, only 1-month of data was analysed, due to time constraints.

Figure 22: Żabbar location and 3D case study building

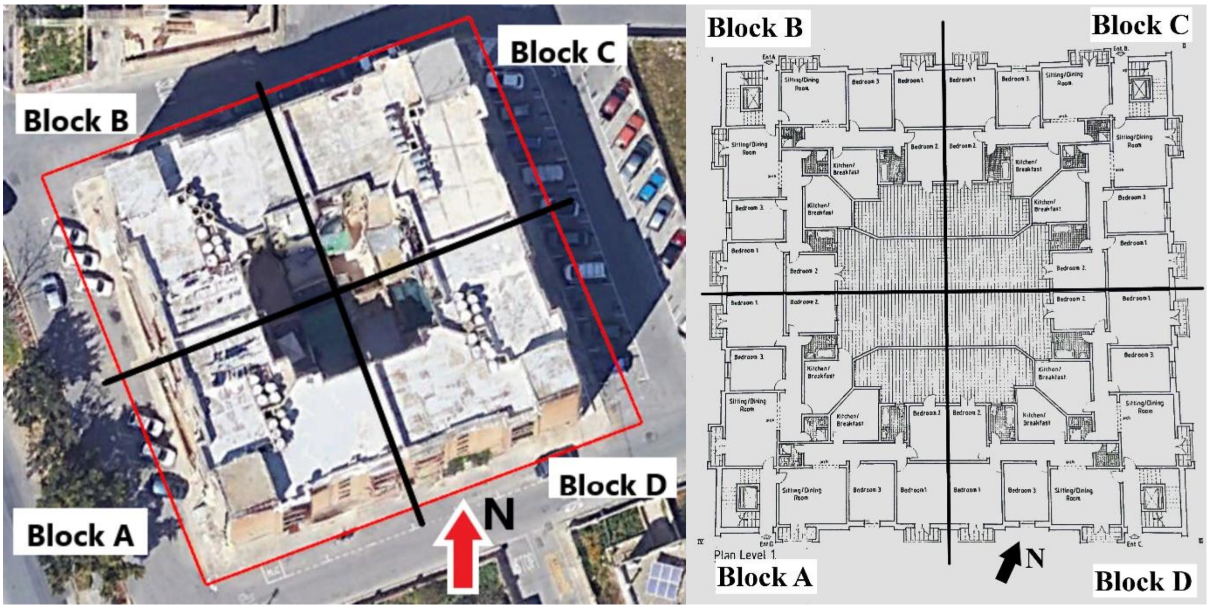

Figure 23: Building distribution and building blueprint

3.1.2 Building fabric (U-Values)

The building has the following envelope properties (table 8). The U-values were calculated using the standard methodology of ISO 6946:2017 [60]

Table 8: Building envelope properties and materials

Original building envelope	U-Value (W/m^{2}K)
External Wall (façade), made up of double limestone block with an air gap	1.58
External Wall (interior courtyard), made up of single limestone block	2.8
Interior Walls, made up of single limestone	2.1
Glazing, single clear glazing with aluminium frame (6mm)	5.78
Roof (uninsulated)	2.0
Floor (uninsulated)	1.57

3.2 Data Collection

3.2.1 Questionnaires

In order to know the occupants and their actual electricity consumption and comfort, information was collected from a total of 31 dwellings (out of 40 dwellings). Nine dwellings could not be reached to conduct the questionnaires. Data validation and analysis was performed to identify which variables showed the biggest impact on the energy performance of the building. Twelve variables (floor level, orientation, number of occupants, number of heat pumps, type of heater, water heater continuously being used, age of the fridge-freeze, age of the freezer, type of oven, number of electric equipment in the kitchen, age of the washing machine and other plug loads) were determined, to analyse energy performance in terms of equipment and building operation. It must be noted that only 26 dwellings had valid electricity and water bills (based on actual figures) data for research purposes (out of the 31 dwellings visited).

3.2.2 Electricity and water bills

The data collected from the electricity and water bills were inputted on a spreadsheet for analysis. The collection of raw data is shown in Appendix 1.

3.2.3 Installation of Sensors

A total of 15 HOBO MX Temp/RH Data Loggers (MX1101) [61] (Figure 24),were used to gather relative humidity and temperature every 10 minutes. These sensors were primarily located in the bedrooms of the dwellings under study.

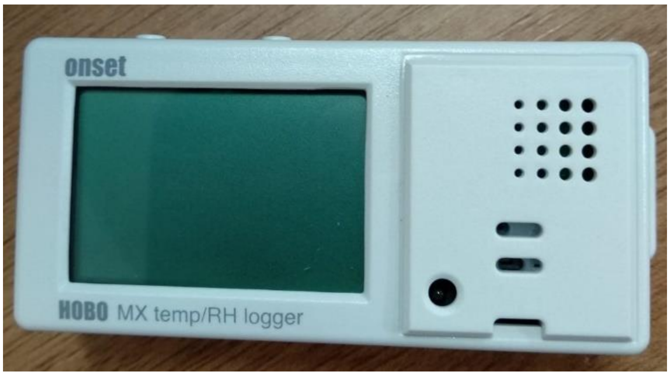

Figure 24: HOBO MX Temp/RH Data Logger (MX1101)

Due to the limitation of time, only one month of data was used to calibrate the software DesignBuilder simulation software based on hourly temperature readings (see Section 2.6). However, this was enough to attain an acceptable level of confidence in the modelling results.

3.2.4 Statistical analysis and identification of the baseline energy consumption

The annual energy consumption can be divided into three main sources of significant energy consumption: heating and cooling energy consumption, domestic hot water (DHW) energy consumption and others (lighting, plug loads, appliances).

The annual energy consumption was calculated by adding the energy consumption of each dwelling for one year. For missing data, an average energy consumption per occupant was calculated. The DHW energy consumption is calculated in the same way as the annual energy consumption, with a 20 litres/day per occupant [62]. For the heating and cooling energy consumption, questionnaire data is used to quantify the number of dwellings using air-conditioners and therefore estimate their energy consumption. The *"others"* (lighting, plug loads and appliance) energy consumption were automatically derived by subtracting the space heating, cooling and DHW energy consumption from the total consumption.

The annual DHW energy consumption (EC) was calculated following the equation:

$$DHW\ EC = \frac{Nº Occupants \cdot DHW\ consumed\ per\ occupant \cdot (T_f - T_i) \cdot Nº\ days \cdot \mathrm{C} \cdot \alpha}{DHW\ system\ efficiency} \quad (21)$$

$T_f = Average\ Temperature\ after\ heating\ \approx 60°C$

$T_i = Average\ Temperature\ before\ heating\ \approx 20°C$

$\mathrm{C} = Water\ heat\ Capacity\ (Joules/kg)$

$\alpha = conversion\ factor\ from\ Joules\ to\ kWh = 2{,}77778 \cdot 10^{-7}$

3.3 Building Energy modelling of base (actual building) scenario

3.3.1 Use of software and why it was chosen

The software used for the simulation was DesignBuilder version 6.1.0.006. DesignBuilder is a dynamic software [55] that facilitates graphical inputs into the interface energy simulation engine of EnergyPlus. EnergyPlus is a simulation program based on Building Loads Analysis and Systems Thermodynamics. This program allows a whole building energy simulation used to model energy consumption for heating, cooling, ventilation, lightning and plug and process loads. It enables simultaneous interaction of the geometric model of the building with the outdoor conditions, occupancy and usage of building systems in order to predict heating and cooling loads arising in the building on an hourly basis. Therefore, being able to evaluate the energy performance on an hourly basis makes this program the ideal tool for the objectives of this dissertation. This is complimented by the fact that the engine also considers the thermophysical properties of materials, occupancy, subjective data and the performance of systems influenced by the internal and external environmental conditions.

3.3.2 Use of questionnaires to understand typical equipment inside building

Questionnaires were used to understand which variables tend to be similar or different between dwellings. Twelve variables were determined to analyse energy performance in terms of equipment and building operation. Questionnaires were also used to see how comfortable the occupants were during summer and winter periods.

Questionnaires led to the conclusion that approximately half of the dwellings have an air conditioner (A/C) that could only improve comfort in the room where it is located.

3.3.3 Questionnaire analysis

In order to assess the questionnaires and see what variables are the most significant, a Multiple Linear Regression (MLR) with the annual consumption as dependent variable was analysed in the program STATGRAPHICS Centurion 18 (Version 18.1.06, 64-bits). The Homogeneity of Variance Hypothesis, the Normality Hypothesis and the Independence Hypothesis were tested.

3.3.4 Floor choice level for analysis

The comfort feedback from the questionnaires was analysed to determine which floor (top, middle, or ground/bottom) has the highest discomfort among the occupants and which requires to be prioritised for this study. Top floor resulted to have a 100% of discomfort among the occupants. Thus, this floor was given priority and analysed for this study.

3.3.5 Hourly calibration of simulated temperatures with actual logged data

From the data loggers, relative humidity and dry-bulb room temperature were gathered for a period of at least 1 month. Ideally data would have been gathered for at least one year. However, this was one of the main limitations of this study, given that the project was initiated in March 2019, and therefore only one month of actual measured comfort data was available for the study. According to Section 2.6, to gain confidence of the suitability in the analysis method proposed when undertaking an energy retrofit project, the building energy model should be calibrated with actual measured data. The measured temperature data was compared to hourly simulated data. Calibration was validated on an hourly resolution using NMBE and CV(RMSE) criteria explained in the ASHRAE Handbook [59]. According to ASHRAE when undertaking hourly calibration if the resulting NMBE < 10% and CV(RMSE) < 30%, the model can be considered calibrated. For calibration, the actual outdoor weather data for the period analyzed was considered.

3.3.6 Comfort analysis and comfort analysis approaches

The comfort assessment is divided in two general scenarios, according to the seasons simulated. The assessment was carried out for the most extreme typical week of winter and summer, called design week[2]. These weeks were automatically determined by EnergyPlus for a typical meteorological year for Malta. It is assumed, that if comfort is satisfied during these weeks, the building will also be comfortable throughout the whole year.

As reviewed in the literature, the adaptive comfort versus the PMV/PPD comfort model was used for analysis, as the aim of this study was achieving thermal comfort using no mechanical means for heating, cooling or ventilation.

In order to assess thermal comfort with the considered adaptive model standards (EN 15251, ASHRAE and M. Vellei et al. [36] model) simulations were carried out using no mechanical means for heating, cooling or ventilation both for the summer and winter design weeks.

In the Summer period, occupants tend to open windows in order to improve their comfort. When running the building simulation for Summer design week, two approaches were considered, to identify the sensitivity of opening windows in summer. For the first approach, the *"Summer design week with Windows Closed"* considered that all windows remain closed independent of the temperatures outside and inside the dwelling. In the second approach, the "*Summer design week with Windows Open"*,

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[2] Simulated summer design week: 13/07/2002 - 20/07/2002.
Simulated winter design week: 20/01/2002 - 27/02/2002.

windows were opened when the temperature outside is lower than the temperature inside the dwelling´s room and the operation schedule of the room allows it. For winter, only the approach with windows closed was considered given that occupants ensure that heat losses to the outside air is minimised.

3.3.7 Comfort assessment of the base (as is) building

The building has been modelled in DesignBuilder (Figure 25).

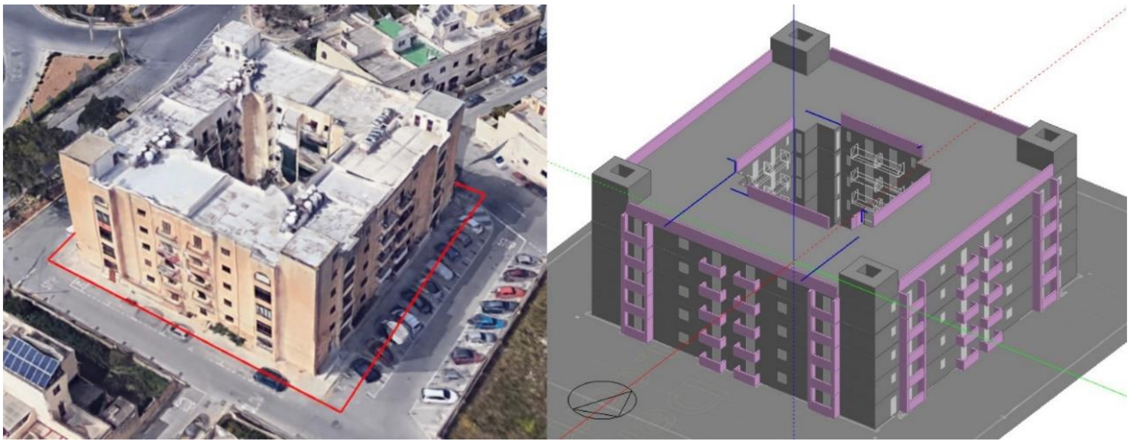

Figure 25: Building model on DesignBuilder

As mentioned, in Section 3.3.4, the simulation analysis is done for the top floor (Figure 26). In order to perform a quicker and more specific analysis and thanks to the fact that the building is symmetrical, one dwelling per cardinal orientation was simulated for the top floor. Thus, the comfort study considered each orientation for the top floor.

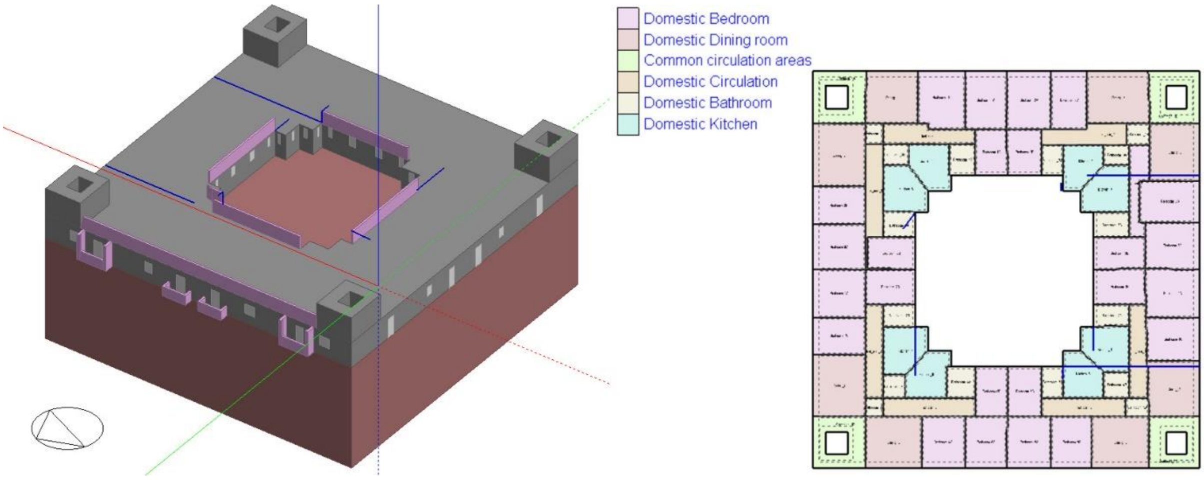

Figure 26: Simplified top floor model on DesignBuilder and top floor plan showing dwellings' configuration

All dwellings have 3 bedrooms, 2 bathrooms, 1 dining room, 1 kitchen and 1 indoor corridor as seen in Figure 27.

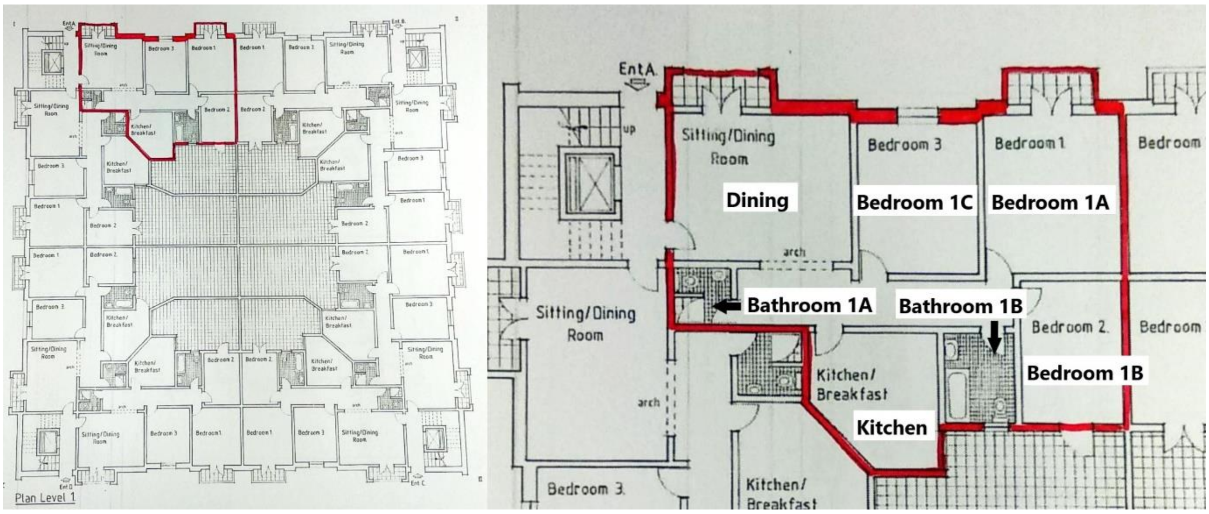

Figure 27: Dwellings and zones for each orientation

For the simulations carried out, different aspects have been considered: the occupancy schedule per room is based on the default setting by DesignBuilder that utilises the UK national calculation methodology (NCM).

For the summer period, for the simulations with windows opened, the windows were scheduled to open 50 % of the glazing area when the temperature inside the room is higher than the outside and when the room is occupied. The building does not make use of mechanical ventilation for air changes.

The dwelling floor is considered adiabatic, to improve simulation computation time. This assumption was validated given that the floor is internal and therefore the heat gains and heat losses from the apartments below operating with the same schedule can be neglected.

When collecting the simulated data, all rooms were analysed except for the indoor corridor, as displayed in Figure 27. The rooms analysed are Bedroom 1A, Bedroom 1B, Bedroom 1C, Bathroom 1A, Bathroom 1B, Kitchen and Dining.

Hourly data is collected for each design week. The data collected is the zone operative temperature, the zone air relative humidity, the zone thermal comfort ASHRAE 55 adaptive model, running average outdoor air temperature and the zone thermal comfort EN 15251 adaptive model temperature. This data was plotted to analyse comfort for both the EN 15251 and ASHRAE adaptive comfort models. All EN 15251 categories were considered while ASHRAE 80% acceptability model was used.

Another model, M. Vellei et al. [36], that also considers the impact of relative humidity on ASHRAE adaptive comfort was also used, given the high relative humidity levels found in Malta.

Once the comfort analysis was done, potential retrofit measures were considered to improve comfort.

3.4 Identification of retrofit measures

3.4.1 Identification of potential retrofit measures

In order to improve comfort and reduce energy consumption, different retrofit measures were considered for analysis. In order to identify potential measures, previous energy retrofit studies of Maltese buildings were first consulted. Furthermore, EnergyPlus was used to show and quantify the main sources of heat loss and heat gain on a monthly resolution for each part the building envelope (roof, glazing, walls) allowing one to identify potential measures to be prioritised (see Table 9).

Table 9: Retrofit measures considered and their properties

Retrofit measure number	Details
1	Addition of 5 cm of Expanded Polystyrene Standard (EPS) (Figure 28) to improve U-Value of the external wall façade from U=1.57 W/m^{2}K to U=0.57 W/m^{2}K
2	Addition of 5 cm of Expanded Polystyrene Standard (EPS) to improve U-Value of the external wall from the interior courtyard from U=2.81 W/m^{2}K to U=0.62 W/m^{2}K
3 (Figures 29,30)	Blinds as specified in Table 10
4	Double glazing (6mm/6mm) use instead of single glazing (6mm) with aluminium frame to improve U-Value from U=5.58 W/m^{2}K to U=3.1 W/m^{2}K
5	Addition of 8 cm of Expanded Polystyrene Standard (EPS) to improve roof U-Value from U=2 W/m^{2}K to U=0.41 W/m^{2}K

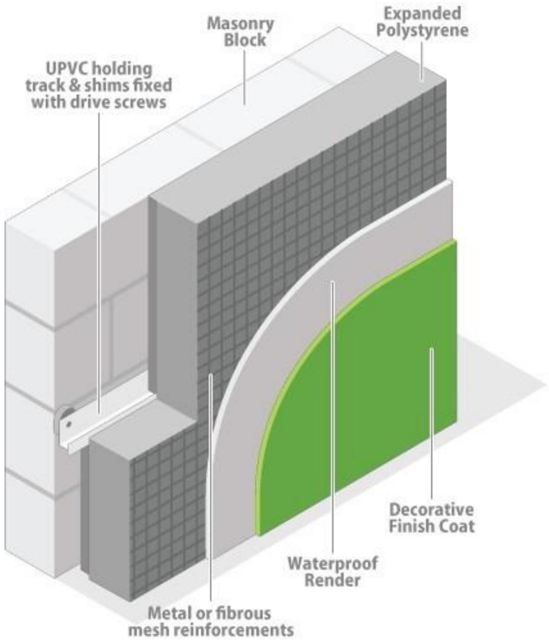

Figure 28: EPS Insulation proposed

Table 10: Blind/slat properties

Blind-to-glass distance (m)	0.05
Slat orientation	Horizontal
Slat width (m)	0.025
Slat separation (m)	0.01875
Slat thickness (m)	0.001
Slat conductivity (W/m·K)	0.9
Slat angle (°)	45
Minimum slat angle (°)	0
Maximum slat angle (°)	180

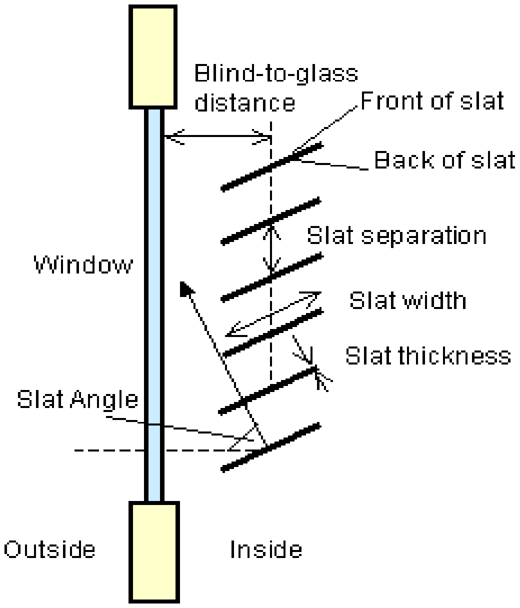

Figure 29: Slat/blind used in DesignBuilder

Figure 30: Blind type proposed

3.4.2 Comfort analysis with all measures

All measures considered in Table 10 were added to the building model to identify the adaptive comfort improvement for the summer and winter design weeks versus the base scenario when the retrofit measures were applied.

3.4.3 Global sensitivity analysis using standardised beta coefficient to rank retrofit measures based on discomfort hours on summer and winter design weeks

A global sensitivity analysis was carried out to study the impact of each potential retrofit measure individually and in combination. This helps to identify whether there are any measures (measure 1 to measure 5) in Table 9 which are not contributing significantly to comfort. The analysis was carried out to rank the measures in terms of impact on the number of discomfort hours during the design weeks.

A total of 500 runs for the global sensitivity analysis was carried out for the summer and winter design week. The results obtained were analysed with the statistical software SPSS version 24 doing a regression analysis and checking out the beta coefficient, which compares the strength of the effect of each individual independent variable (the retrofit measures and orientation) to the dependent variable (discomfort hours in summer for the adaptive comfort models and space heating energy demand for winter[3]).

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[3] For summer design week both, EN 15251 adaptive comfort model and ASHRAE adaptive comfort model discomfort hours, were used as dependent variables in the global sensitivity analysis. However, for winter design week these dependent variables are not available in DesignBuilder version 6.1.0.006. Instead, to be able to analyse how comfortable a dwelling can be, the dependent variable taken was the heat loads from the dwelling. But to improve comfort in winter, one must increase the actual temperature

An MLR is carried out doing a Backward Stepwise selection leading to eliminate any non-significant or highly correlated variables from the analysis.

3.5 Re-evaluation of thermal comfort based on the results of the sensitivity analysis

The adaptive comfort for the summer and winter design week was re-evaluated multiple times, each time removing the parameter having the least impact on the summer discomfort hours/ winter heating loads. This was carried out to check whether any retrofit parameters are redundant.

3.6 Financial analysis

In order to assess the economic viability for the identified retrofit measures, a financial feasibility and a macroeconomic financial analysis were carried out for each retrofit combination scenario proposed.

A 30-year-period was considered as performed for the 2013 EPBD cost-optimal studies for domestic building in Malta [63] and as recommended in the EPBD for residential buildings.

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of the room and maintain it. Therefore, using heat loads is a good analysis approach to see what potential retrofit measures are the best fitted.

3.6.1 Financial calculation using NPV, Payback period and financial global cost

An investment appraisal technique is applied in order to determine the financial feasibility of each retrofitted scenario proposed. The Simple Payback Method/Period (SPP) measures the number of years it is expected to take for the future net cash flows from the retrofitted scenarios. The simple payback period method ignores the time value of money, which means that the number of years given is just an approach of the actual money value.

$$SPP = \frac{Initial\ Investment}{Net\ Cash\ Flow\ per\ Period} \tag{22}$$

The Net Present Value (NPV) method is used to calculate net present value of the retrofitted scenarios by comparing cash outflows with cash inflows at the same point in time.

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \tag{23}$$

$R_t = net\ cash\ inflow - outflow\ during\ a\ single\ period\ t$

$i = discount\ rate\ or\ return\ that\ could\ be\ earned\ in\ alternative\ investments$

$t = number\ of\ periods$

The discount used is 3% as seen in the 2018 Malta cost-optimal reports [64]. The price used per kWh consumed in a domestic property in Malta has been rounded to 0.15€ per kWh as can be seen in regulated electricity tariffs for Malta approved in 2014 and that is today still in force [65]. The VAT rates in Malta used is 18% for the general taxes and 5% for the supply of electricity [66].

The prices per retrofit measures can be seen in Table 11.

Table 11: Prices of each potential retrofit measure [64]

Roof Insulation (€/m^2)	42.80
External Wall façade insulation (€/m^2)	45.00
External Wall façade insulation (€/m^2)	45.00
Glazing insulation (€/m^2)	187.00
Blinds (€/m^2)	240.00

The financial global energy cost was calculated for both the base and proposed retrofit scenarios.

In order to be able to compare the financial and macroeconomic energy savings, the base scenario simulation included a total of 5 split unit reversible heat pumps (one per bedroom, another one for the kitchen and the last one for the dining), whose expected price was 720€ per unit, was used to calculate the average energy consumption for cooling and heating per year.

3.6.2 Macroeconomic global cost calculation

For this purpose, a macroeconomic analysis of each retrofitted scenario is carried out and a macroeconomic global cost comparison is done between the building without any cooling and/or heating system and each retrofitted scenario. Macroeconomic analysis takes also into account the cost of carbon.

In Malta, a total of 0.452 kgCO_2 per kWh is produced [67] and the cost of greenhouse gas emissions is estimated to increase drastically over the years as per [64].

Chapter 4. Results and Discussion

4.1 Questionnaires and data collected from the dwellings

As mentioned in the Methodology, a questionnaire was prepared with the aim of collecting the qualitative feedback of people living in the housing block, on their comfort levels, the type of energy systems in their apartments and the general trend of usage. All data protection procedures and forms have been filled up and approval was sought from the Housing Authority and the University of Malta to process the data in accordance with the Data Protection Act and the EU General Data Protection Regulation (GDPR).

The questionnaire, the summary of the questionnaires and a summary of the data collected from the dwellings can be seen in Appendix 1. Here below, the main results of the questionnaire are presented.

4.2 Baseline scenario energy consumption pie-chart

Figure 31 provides a breakdown of the annual energy consumption divided by end use into three main sources of energy consumption: heating and cooling energy consumption, domestic hot water (DHW) energy consumption and others (lighting, plugs loads and appliances). It is shown that DHW is the major consumer contributing to around 39 % of the total energy consumption.

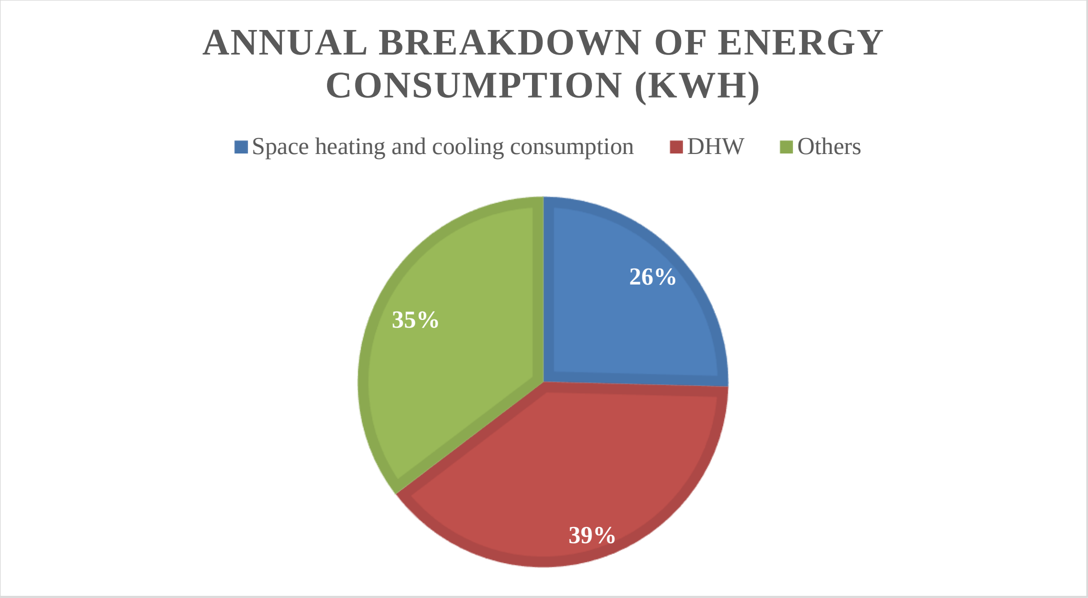


Figure 31: Annual Breakdown of energy consumption (kWh)

4.3 Questionnaires statistical analysis and calibration

4.3.1 Questionnaires statistical analysis

An MLR analysis was used to assess the questionnaires answers using the annual consumption per dwelling as the dependent variable. The Homogeneity of Variance Hypothesis, the Normality Hypothesis and the Independence Hypothesis were tested and met. Three variables out of twelve proved to have a significant impact on energy consumption ($p<0.05$), namely the number of air-to-air reversible heat pumps (N° HP), if the water heater is continuously switched on (WH Cont. ON) and the number of plug loads and appliances being used (N° PL), as seen in Table 12.. The backward MLR equation obtained for annual electric consumption per dwelling (AECD) is:

$$AECD = 1501.76 + 610.284 \cdot Nº\,HP + 1126.34 \cdot WH\,Cont.ON + 431.665 \cdot\ Nº\,PL \quad (24)$$

The derived MLR equation was able to explain 54% of the variability in annual electric energy consumption (R-squared = 54%). This means that there are also other latent variables that influence the annual consumption per dwelling, but these could not be determined due to the limitation of the questionnaires (e.g. tenants' financial situation, time of use of the dwelling). Even though some dwellings just have one, two, three or no air to air heat pumps (air-conditioners), these significantly impact the annual energy consumption.

Table 12: MLR Significant variables out of 26 observations

Parameter	Estimate	Standard Error	T Statistic	P-Value
CONSTANT	1501.76	536.698	2.79814	0.0105
Nº of Heat Pumps	610.284	272.392	2.24046	0.0355
WH Continuously ON	1126.34	479.744	2.34779	0.0283
Nº of Other Plug Loads	431.665	137.029	3.15018	0.0046

From the questionnaires, it can be seen (Table 13) that the occupants of the Top floor have 100% of discomfort during both summer and winter period.

Table 13: Discomfort - Comfort answers percentages per floor level

		Winter	Summer
Bottom Floor	Discomfort	60%	40%
	Comfort	40%	60%
Middle Floor	Discomfort	26%	32%
	Comfort	74%	68%
Top Floor	Discomfort	100%	100%
	Comfort	0%	0%

Therefore, the top floor was chosen to be the specific case study for this dissertation. Furthermore, from the actual temperature data logger metering it was shown that the top floor had a more variable temperature, which follows the variations with the external air temperatures, as shown in Figure 32.

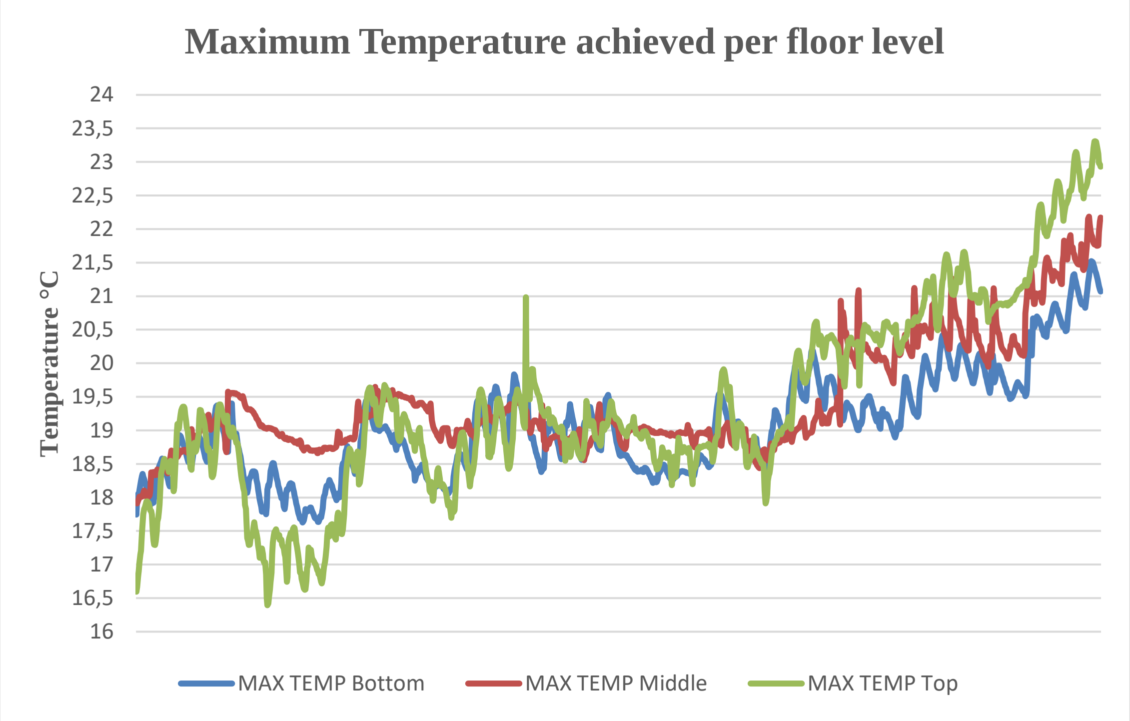


Figure 32: Maximum temperature achieved with the data loggers per floor level

The main aim of the dissertation is to identify the best retrofit measures for a typical housing block in Malta to improve the energy performance of such buildings while improving the thermal comfort of the occupants. The focus of this study was carried out for the top floor level of the building given that it was identified via feedback from occupants' questionnaires that the highest level of discomfort is on this floor. Furthermore, sub-hourly temperature monitoring in the housing block confirmed that the indoor temperature in this level has the most variability when compared to the other floors, according to changes in outside temperatures.

The MLR analysis that was used to assess the questionnaires, highlighted that the air-to-air reversible heat pumps, the number of plug loads being used and the management of the electric water heater are the variables having the biggest impact on electrical energy consumption. Thus, more education is required to inform occupants to switch on the electric water heaters only prior to being used. Furthermore, these findings suggest that reducing or eliminating the use of air-to-air heat pumps via passive solutions to improve thermal comfort can play an important role to improve the energy performance of such building stocks.

4.3.2 Hourly temperature Calibration

Calibration between simulated inside temperatures and actual metered temperature was validated on an hourly resolution using NMBE and CV(RMSE) criteria explained in ASHRAE Handbook [59]. According to ASHRAE when undertaking hourly calibration, if the resulting NMBE < 10% and CV(RMSE) < 30%, then the model can be considered calibrated. For calibration, the actual outdoor weather data for the period analyzed was considered for the simulations.

Table 14: Temperature statistical calibration indicators for the bedroom in which the data logger was installed (Bedroom 1B)

NMBE	7.79%
CV(RMSE)	6.25%

Table 15: Humidity statistical calibration indicators for Bedroom 1B

NMBE	7.19%
CV(RMSE)	3.36%

As NMBE < 10% and CV(RMSE) < 30% the model was considered calibrated for hourly data.

4.4 Comfort plots for the current building envelope with no mechanical heating and cooling

The comfort assessment is divided in two general scenarios, according to the seasons simulated. The assessment was carried out for the most extreme week of winter and summer, known ss the design week. These weeks were automatically determined by EnergyPlus for the weather file for Malta. It is assumed, that if comfort is satisfied during these weeks, the building will also be comfortable throughout the whole year. The coding used to analyse the base building can be seen in Table 13.

Table 16: Base Comfort analysis codification

Nomenclature	Abbreviation
Summer design week with **W**indows **C**losed	S + WC
Summer design week with **W**indows **O**pen	S + WO
Winter design week	W

In order to assess thermal comfort with the considered adaptive model standards (EN 15251, ASHRAE and M. Vellei et al. [36] model) simulations were carried out using no mechanical means for heating, cooling or ventilation both for the summer and winter design weeks.

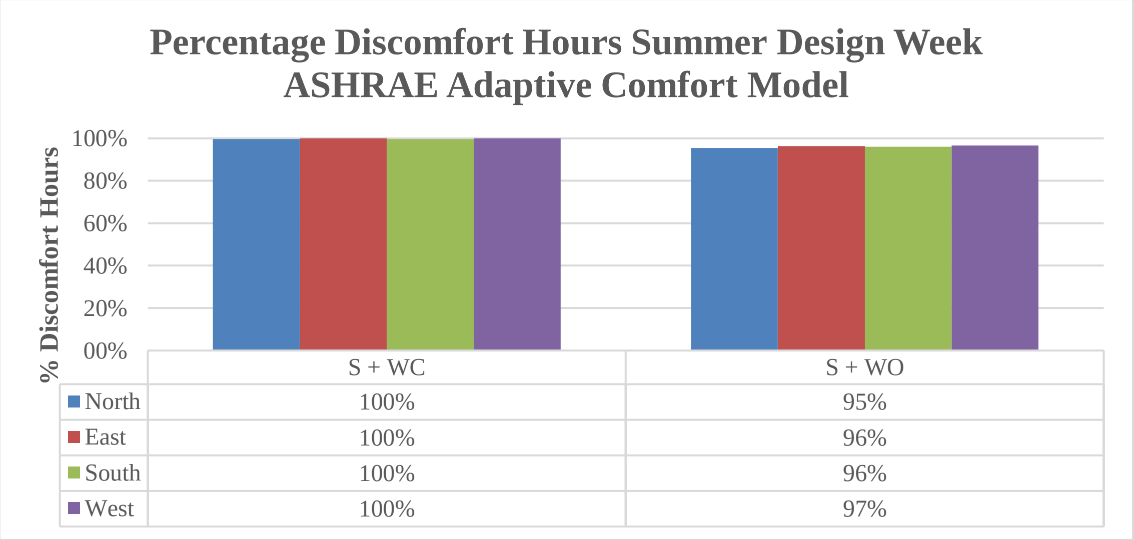
The rooms analysed are Bedroom 1A, Bedroom 1B, Bedroom 1C, Bathroom 1A, Bathroom 1B, Kitchen and Dining.

Simulated hourly data were collected for each design week and plotted for the three adaptive comfort models used in these studies:

- ASHRAE adaptive comfort model with an 80% of acceptability range.
- M. Vellei et al. [36] model.
- EN 15251 adaptive comfort model Category I, II and III.

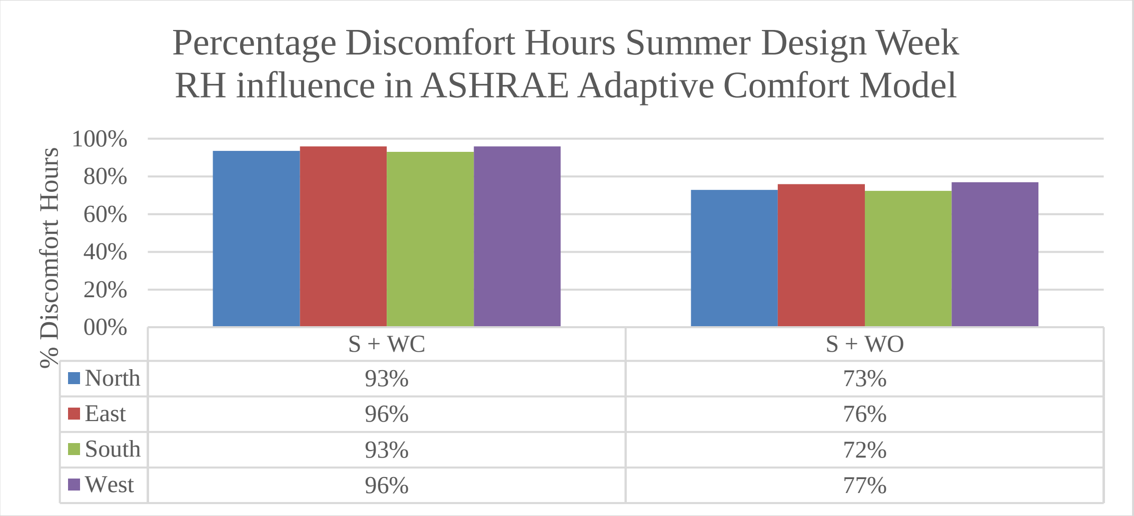
and plotted as seen in Appendix 2

One can see that the amount of discomfort hours drops when windows are opened. Therefore, all subsequent analysis for summer period was considered for *"windows open"* status (see Figures 33, 34, 35).



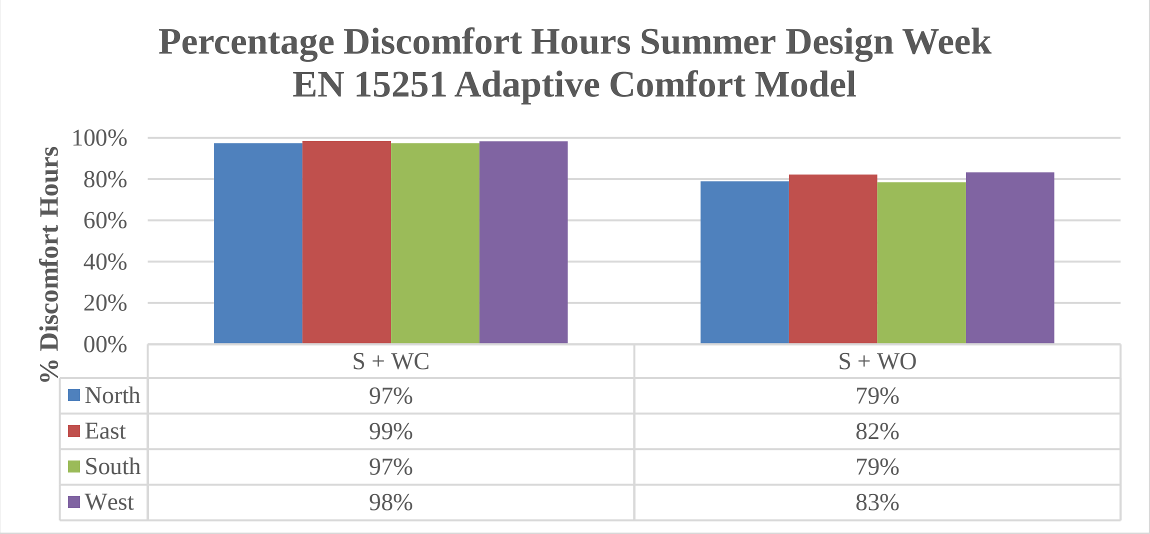
	S + WC	S + WO
🟦 North	100%	95%
🟥 East	100%	96%
🟩 South	100%	96%
🟪 West	100%	97%

Figure 33: Discomfort hours percentages for ASHRAE adaptive comfort model in Summer per orientation for the base scenario



	S + WC	S + WO
🟦 North	93%	73%
🟥 East	96%	76%
🟩 South	93%	72%
🟪 West	96%	77%

Figure* 34*: Discomfort hours percentage for M. Vellei et al.* [36] *adaptive comfort model in Summer per orientation



	S + WC	S + WO
🟦 North	97%	79%
🟥 East	99%	82%
🟩 South	97%	79%
🟪 West	98%	83%

Figure 35: Discomfort hours percentages for EN 15251 adaptive comfort model in Summer per orientation

The plotted comfort results, per orientation and room, for summer and winter design weeks, can be seen in the Appendix 2 Section A2.2; these plotted comfort results follow the same trend. Thus, Bedroom 1B was chosen to represent the rest of the rooms in this Section.

In Figure 36, for Bedroom 1B facing North orientation, the plotted ASHRAE adaptive comfort model results are compared with the M. Vellei et al. [36] adaptive comfort model results for the summer design week.

In addition, in Figure 37, the results for the EN 15251 adaptive comfort model are also plotted for the same bedroom for the summer design week.

For the same room, Figure 38 summarises the number of discomfort hours resulting from the different comfort models under analysis for the summer design week.

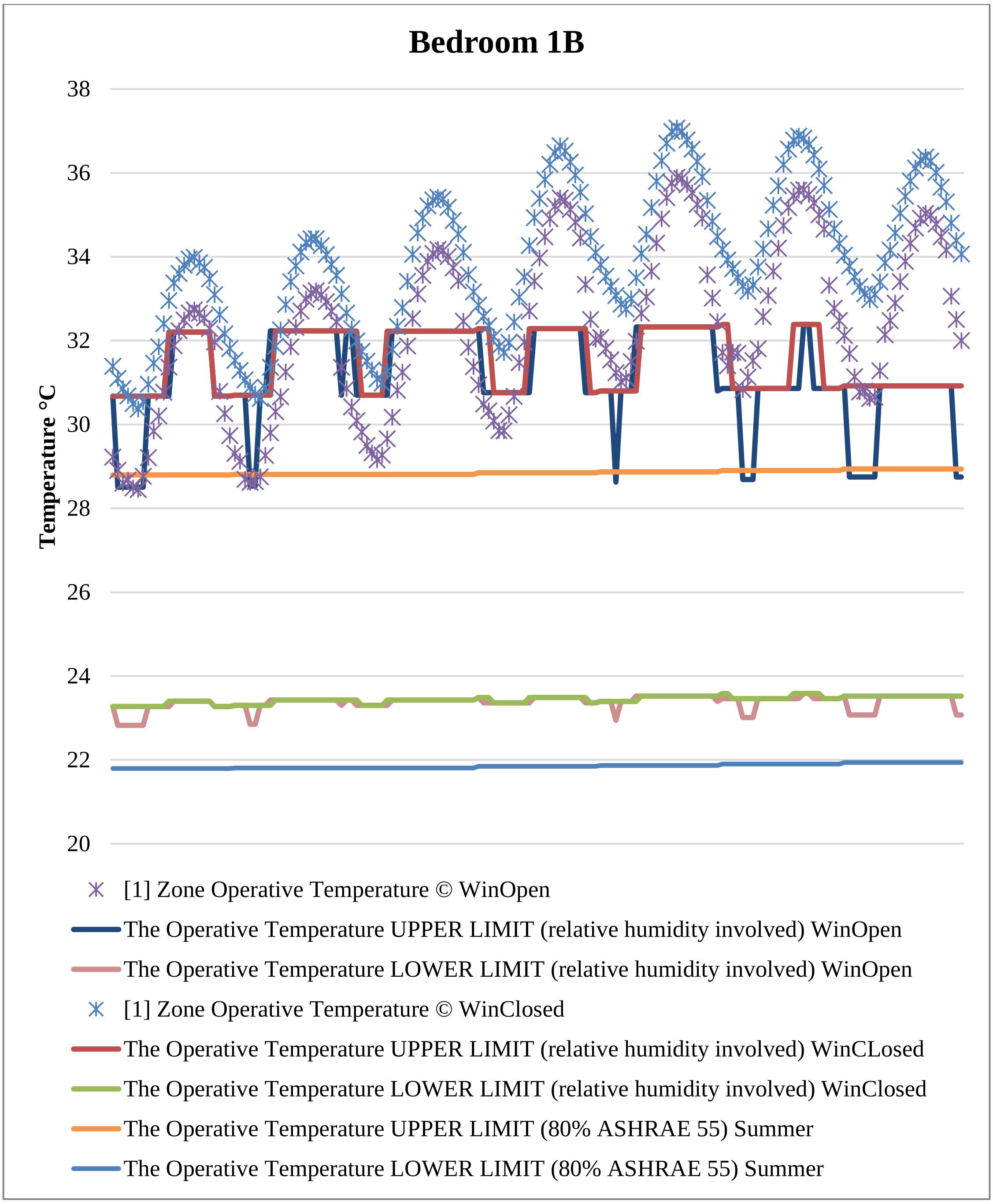


Figure 36: Summer design week ASHRAE and M. Vellei et al. [36] ***comfort analysis for Bedroom 1B using different windows opening configurations facing North orientation***

The RH is influenced by the windows opening configuration, this is, RH will change if windows are open or closed.

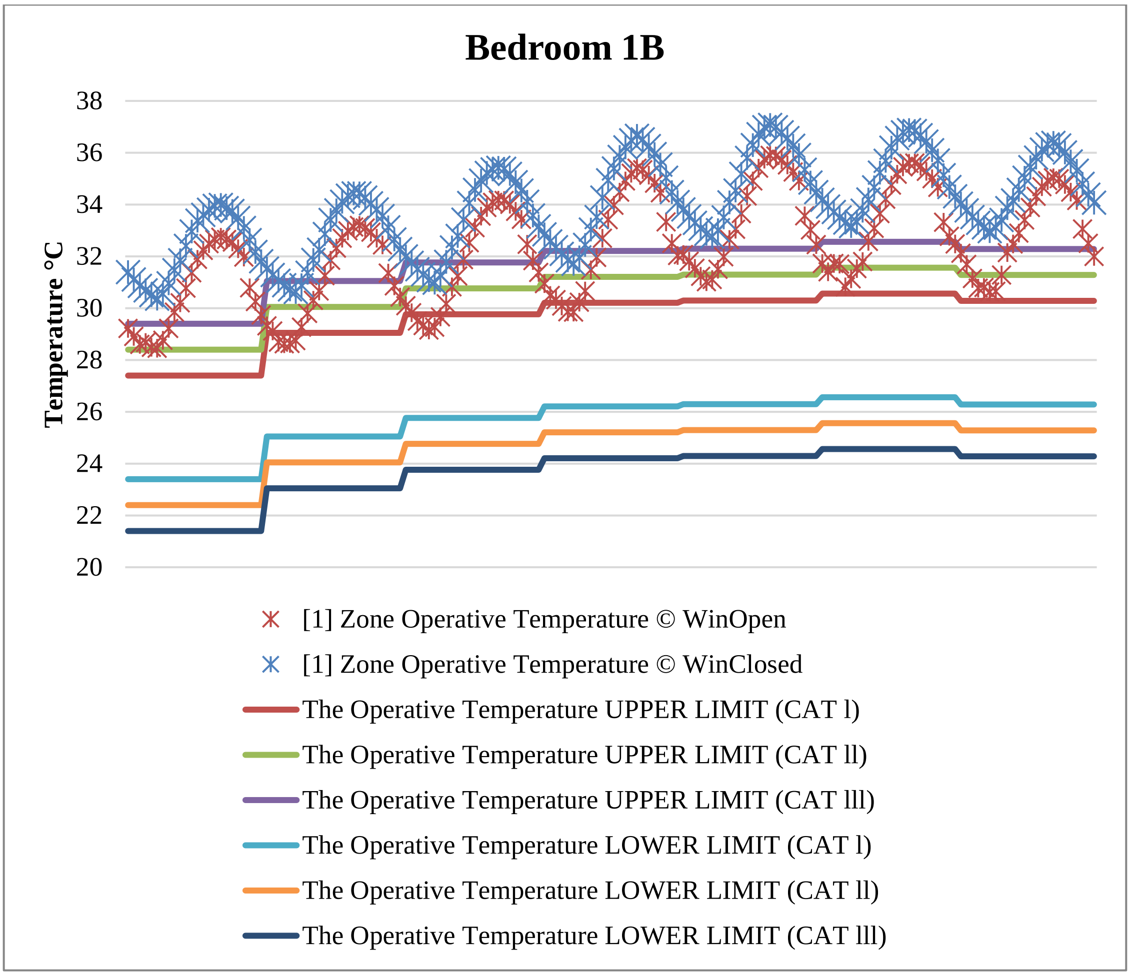


Figure 37: Summer design week EN 15251 comfort analysis for Bedroom 1B using different windows opening configurations facing North orientation

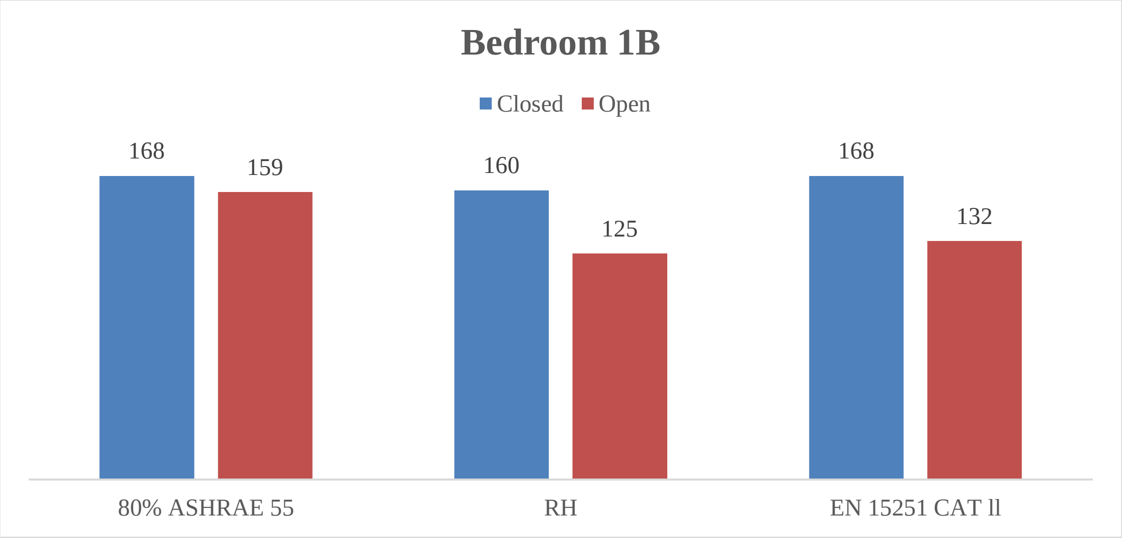


Figure 38: Summer design week number of discomfort hours for Bedroom 1B using different windows opening configurations and adaptive comfort models facing North orientation

From Figures 33, 34, 35 it was observed for each orientation on the top floor, that natural ventilation via the opening of windows showed an improvement in comfort via a reduction of indoor temperature by up to 2 °C during the summer design week. Relative humidity also falls when fresh air enters the building, thus allowing a further improvement in thermal comfort during the summer months. Thus, natural ventilation in summer could prove to be an effective measure to improve occupants' thermal comfort, even if the windows are only opened during the occupancy schedule. However, with the building envelope as is, natural ventilation alone (irrespective of building orientation) is insufficient to allow the building to achieve thermal comfort that complies with EN 15251 Category II or ASHRAE 80% thermal acceptability criteria. Therefore, other passive measures are required to be added to improve thermal comfort during a summer design week.

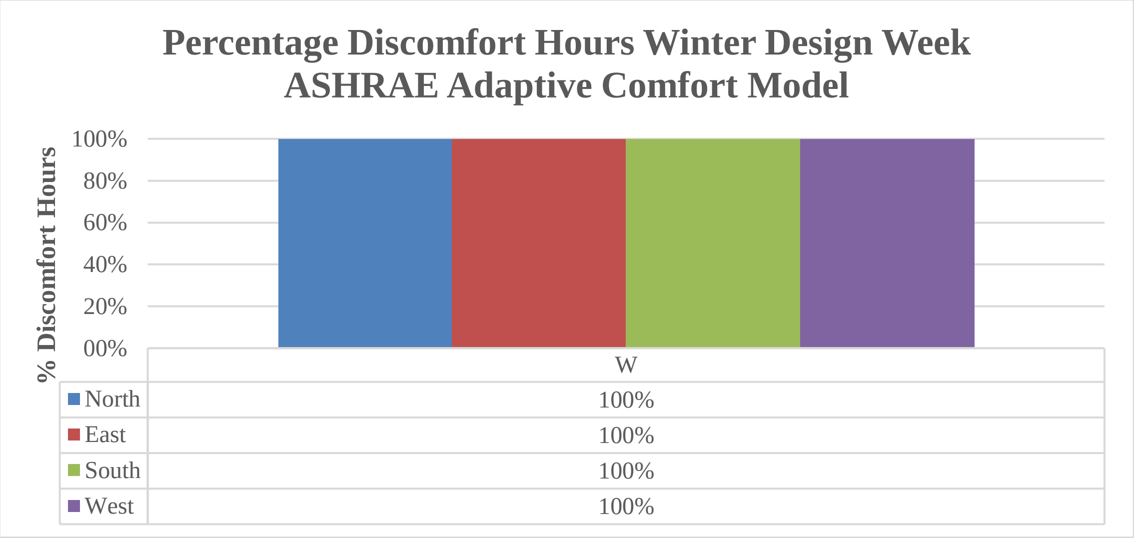


Figure 39*: Discomfort hours percentages for ASHRAE adaptive comfort model in Winter per orientation*

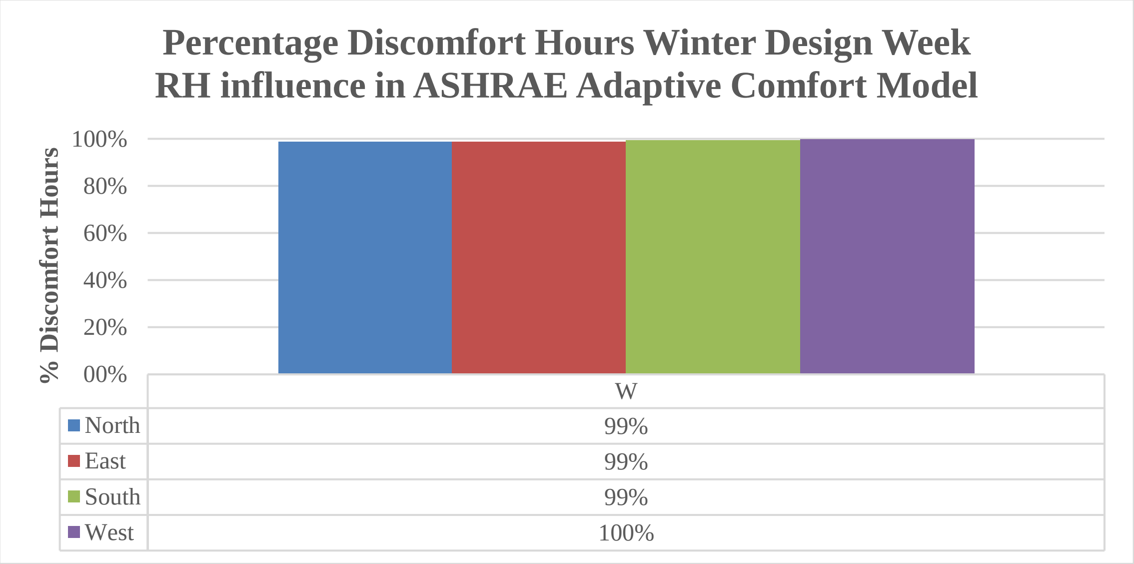


Figure 40*: Discomfort hours percentage for M. Vellei et al.* [36] *adaptive comfort model in Winter per orientation*

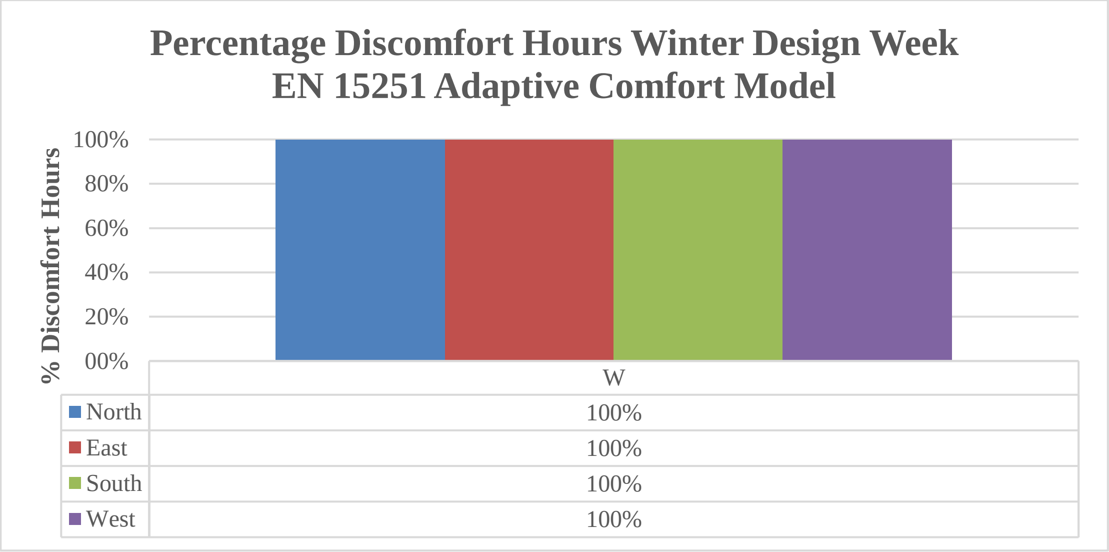


Figure 41: Discomfort hours percentages for EN 15251 adaptive comfort model in Winter per orientation

In the winter period, it was shown that for most hours in the design week for each orientation, the hourly indoor temperatures are below the comfort temperature limits. Thus, with the building envelope as is, adaptive comfort cannot be met for the top floor buildings. Retrofit measures are therefore required to improve adaptive comfort.

In Figure 42, for Bedroom 1B facing North orientation, the plotted ASHRAE adaptive comfort model comfort results are compared with the M. Vellei et al. [36] adaptive comfort model results for the winter design week.

In addition, in Figure 43, the results for the EN 15251 adaptive comfort model are also plotted for the same bedroom for the winter design week.

For the same room, Figure 44 summarises the number of discomfort hours resulting from the different comfort models under analysis for the winter design week.

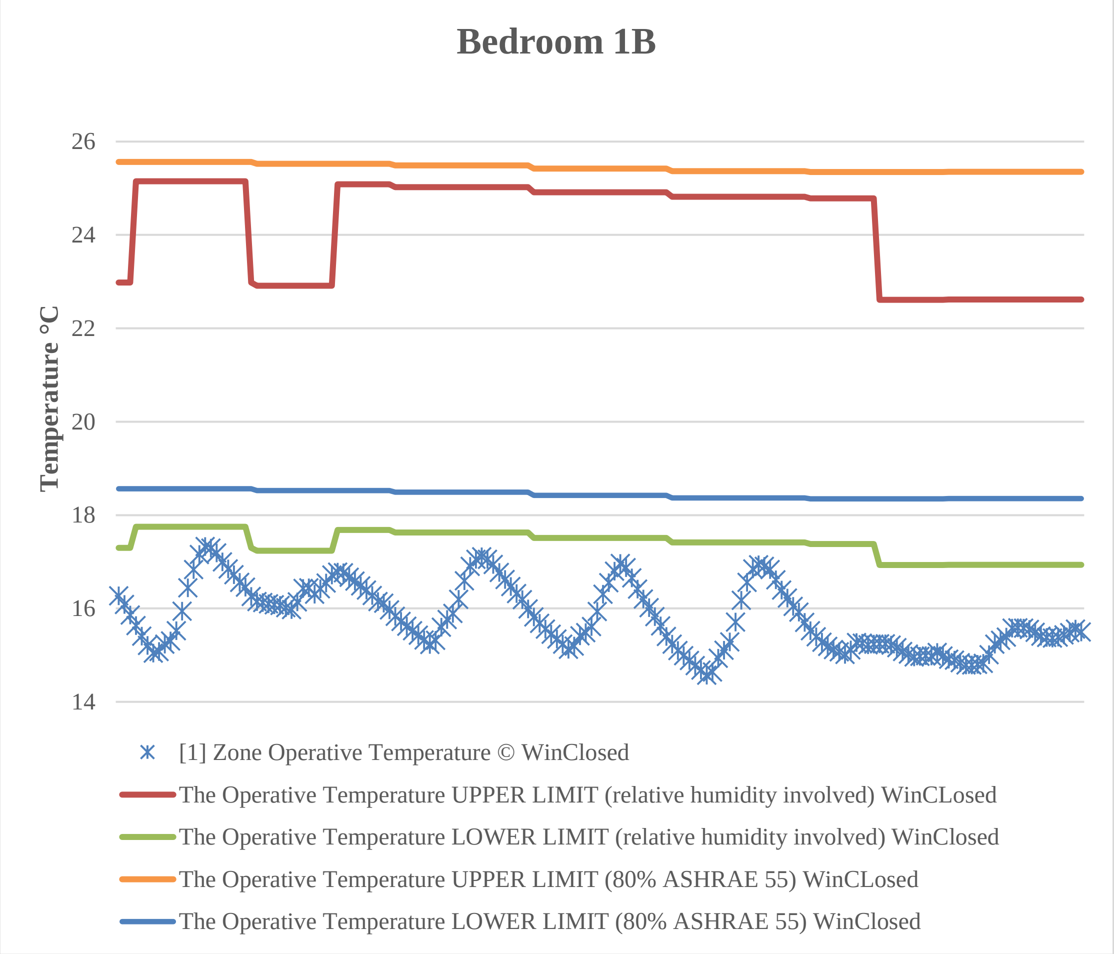


Figure 42: Winter design week ASHRAE and M. Vellei et al. [36] ***comfort analysis for Bedroom 1B using windows close configuration facing North orientation***

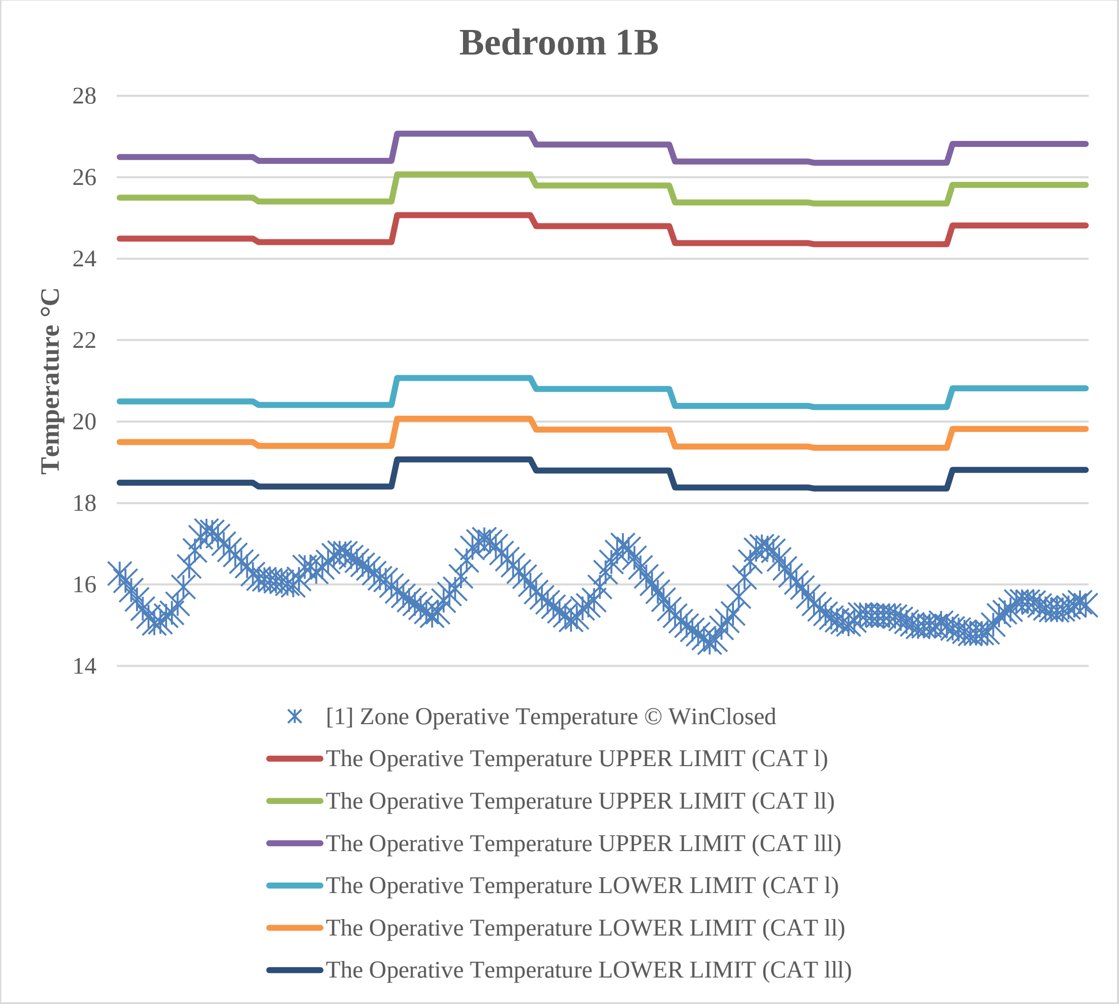


Figure 43: Winter design week EN 15251 comfort analysis for Bedroom 1B using windows close configuration facing North orientation

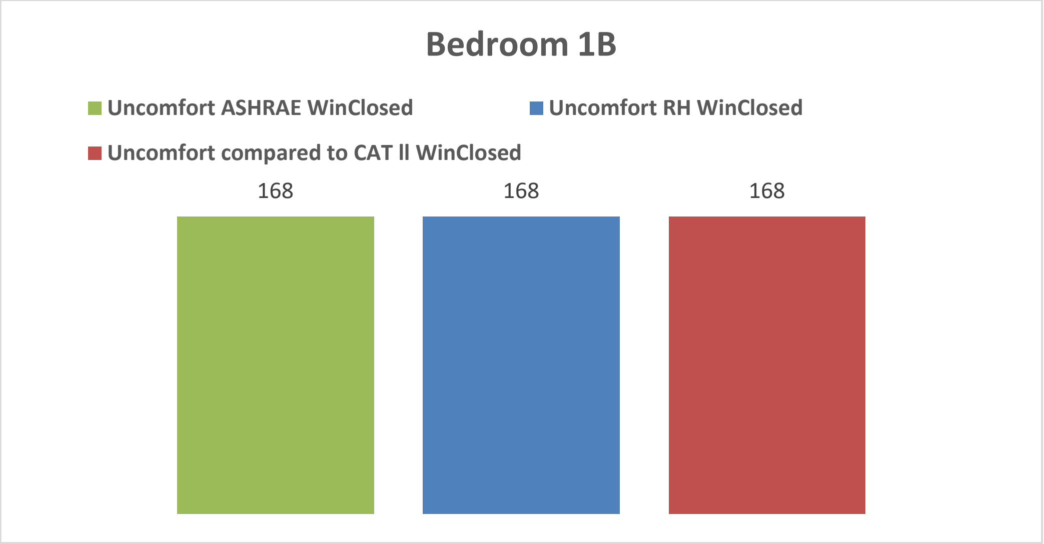


Figure 44: Winter design week number of discomfort hours for Bedroom 1B using windows close configuration and adaptive comfort models facing North orientation

Similarly, for winter, with the current building construction, it is not possible to comply with EN 15251 Category II or ASHRAE 80% thermal acceptability criteria for the winter design weeks for all orientations. This low thermal comfort results are achieved even when the windows are kept closed as to retain the heat gain inside the building as observed in Figures 39, 40, 41.

4.4.1 Discussion for the current building envelope with no mechanical heating and cooling

All EN 15251 standard[4] adaptive comfort categories were considered for the hourly indoor temperature plots. However, for the purpose of quantifying the discomfort hours, Category II instead of Category III was applied to allow a more rigorous approach to discomfort hour analysis for the EN 15251 adaptive comfort model.

During the summer design week, for the base scenario, both ASHRAE 80% thermal acceptability and EN 15251 Category II adaptive comfort models showed almost 100% of discomfort hours for all zones and orientations when the windows were kept closed. However, when windows were kept open, despite the decrease in indoor temperatures, the number of discomfort hours was still almost 100% for both the ASHRAE 80% thermal acceptability model and the EN 15251 Category II adaptive comfort model.

However, the M. Vellei et al. [36] modified ASHRAE adaptive comfort model (that takes into account the impact of RH on thermal comfort), shows less number of discomfort hours for the base scenario when compared to the other models for the Summer design week. This given that the M. Vellei et al. [36] model, when compared to the standard ASHRAE adaptive comfort model, has a higher upper comfort temperature limit at running outdoor mean temperatures of 25 °C or above and therefore predicts better comfort during the summer design week. This is true even when high indoor relative humidity levels are considered.

On the other hand, for the winter design week, for the base scenario, comfort was not achieved for any of the three models as shown in Figures 51, 52, 53. The M. Vellei et al. [36] model shows fewer discomfort hours when compared to the standard ASHRAE

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[4] Category 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), Category II (normal level of expectation, used for new buildings and renovations) and Category III (a moderate level of expectation, used for existing buildings)

adaptive comfort model given a lower comfort temperature limit at running mean outdoor temperatures of 18 °C or below.

Once the base scenario was carefully analysed, potential passive retrofit measures were identified and studied. Given that the simulations showed the highest heat losses result from the envelope during winter, while solar radiation penetration from glazing accounts for the highest heat gains during the summer, the following potential measures were considered : i) insulation of the external walls and roof , ii) replacement of single glazed windows with double glazing and iii) blinds that can be retracted to block heat gain by solar radiation during summer, while allowing radiation to pass through the glazing during winter.

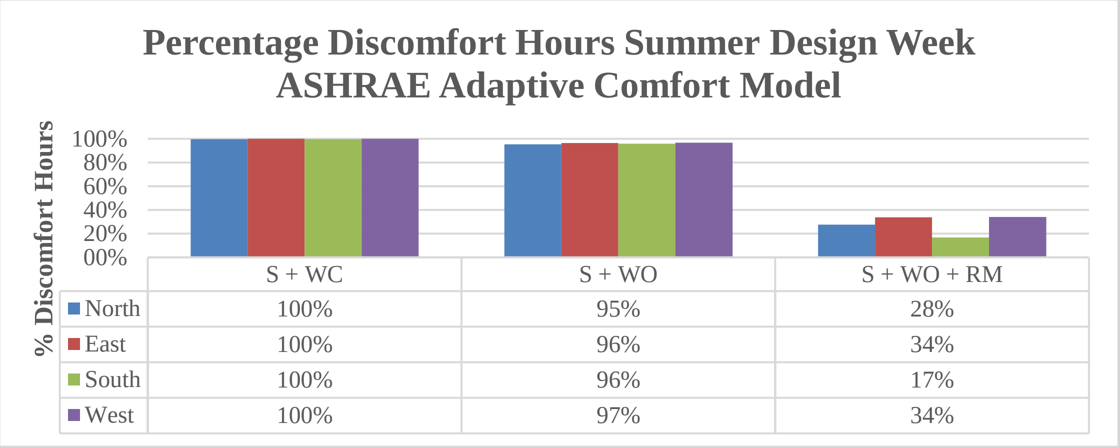
4.5 Comfort analysis for the scenario with all passive retrofit measures implemented

The building is simulated without the use of any mechanical ventilation and with all potential retrofit measures implemented for each season design week following the codification seen in Table 17.

Table 17: Base Comfort analysis and implementation of potential retrofit measures codification

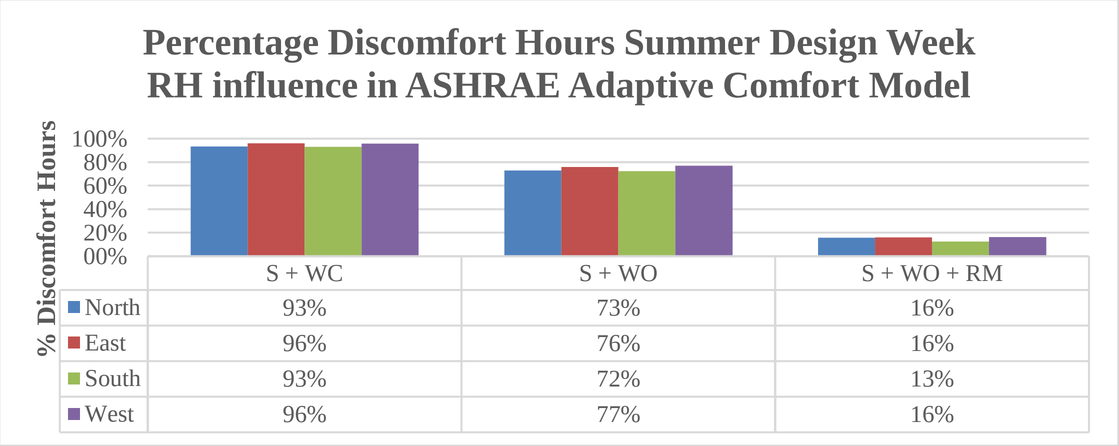
Nomenclature	**Abbreviation**
Summer design week with **W**indows **O**pen	S + WO
Winter design week	W
Summer design week with **W**indows **O**pen with all potential **R**etrofit **M**easures implemented	S + WO + RM
Winter design week with all potential **R**etrofit **M**easures implemented	W + RM

For the summer design week, the number of discomfort hours were reduced once the potential retrofit measures were implemented (see Figures 45, 46, 47).



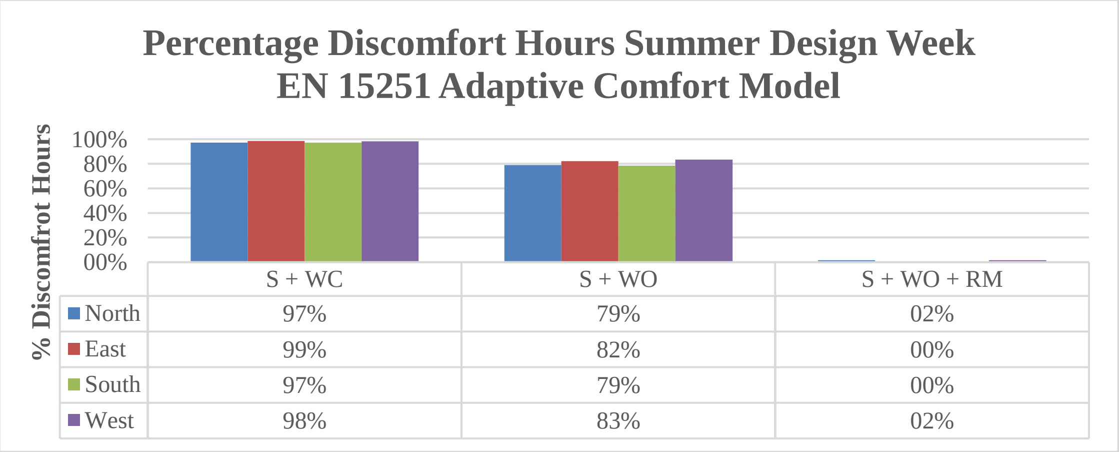
	S + WC	S + WO	S + WO + RM
North	100%	95%	28%
East	100%	96%	34%
South	100%	96%	17%
West	100%	97%	34%

***Figure** 45**: Discomfort hours percentages for ASHRAE adaptive comfort model in Summer with measures per orientation*



	S + WC	S + WO	S + WO + RM
North	93%	73%	16%
East	96%	76%	16%
South	93%	72%	13%
West	96%	77%	16%

***Figure** 46**: Discomfort hours percentage for M. Vellei et al.** [36] **adaptive comfort model in Summer with measures per orientation*



	S + WC	S + WO	S + WO + RM
North	97%	79%	02%
East	99%	82%	00%
South	97%	79%	00%
West	98%	83%	02%

Figure 47: Discomfort hours percentage for EN 15251 adaptive comfort model in Summer with measures per orientation

More plotted comfort results, per orientation and room, can be seen in the Appendix 2 Section A2.2; these plotted comfort results follow the same trend, thus, Bedroom 1B was chosen to represent the rest of the rooms in this Section.

In Figure 48, for Bedroom 1B facing North orientation, the plotted ASHRAE adaptive comfort model comfort results are compared with the M. Vellei et al. [36] adaptive comfort model results for the winter design week when all retrofit measures are implemented.

In addition, in Figure 49, the results for the EN 15251 adaptive comfort model are also plotted for the same bedroom for the summer design week.

For the same room, Figure 50 summarises the number of discomfort hours resulting from the different comfort models under analysis for the summer design week.

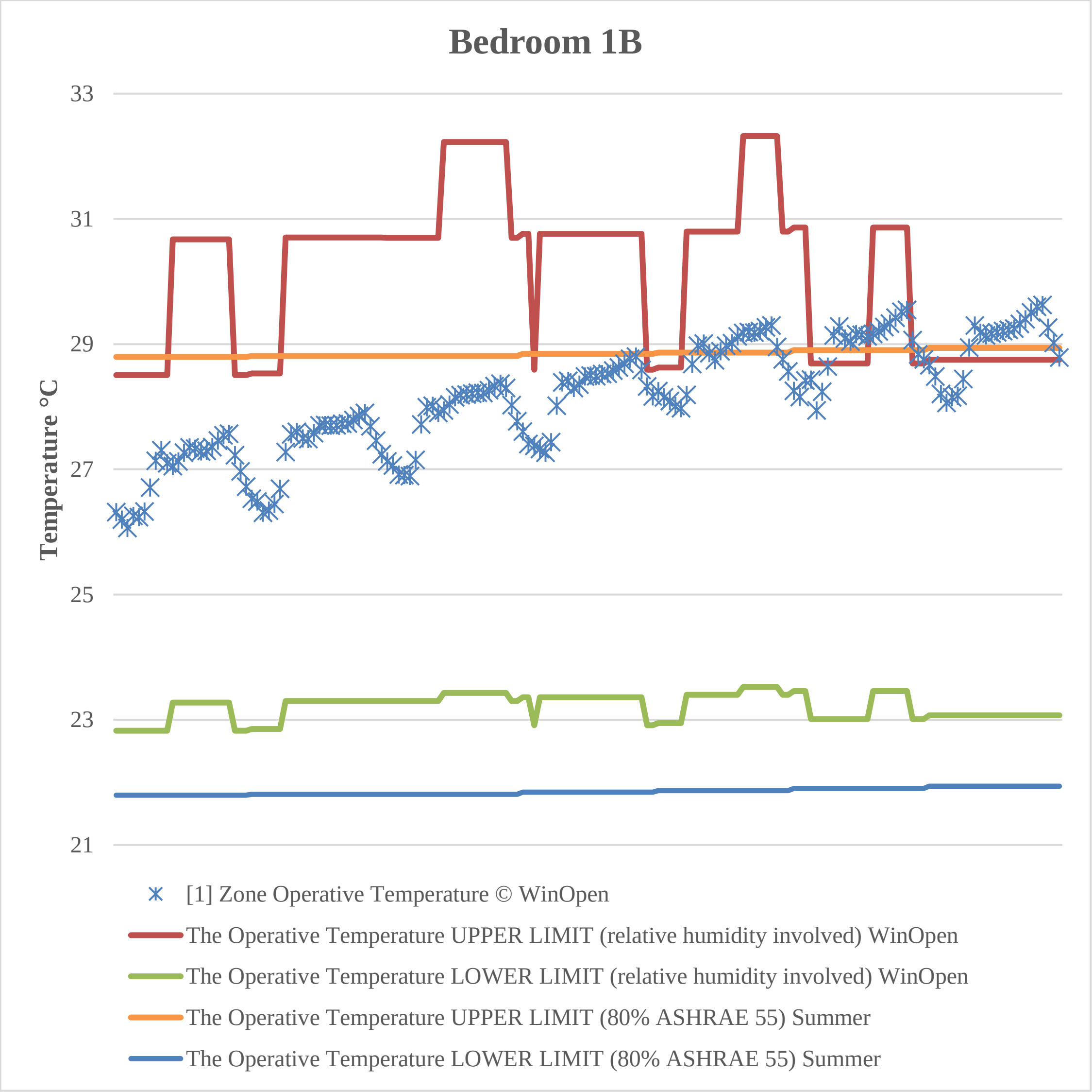


Figure 48: Summer design week ASHRAE and M. Vellei et al. [36] ***comfort analysis for Bedroom 1B when all measures are implemented facing North orientation***

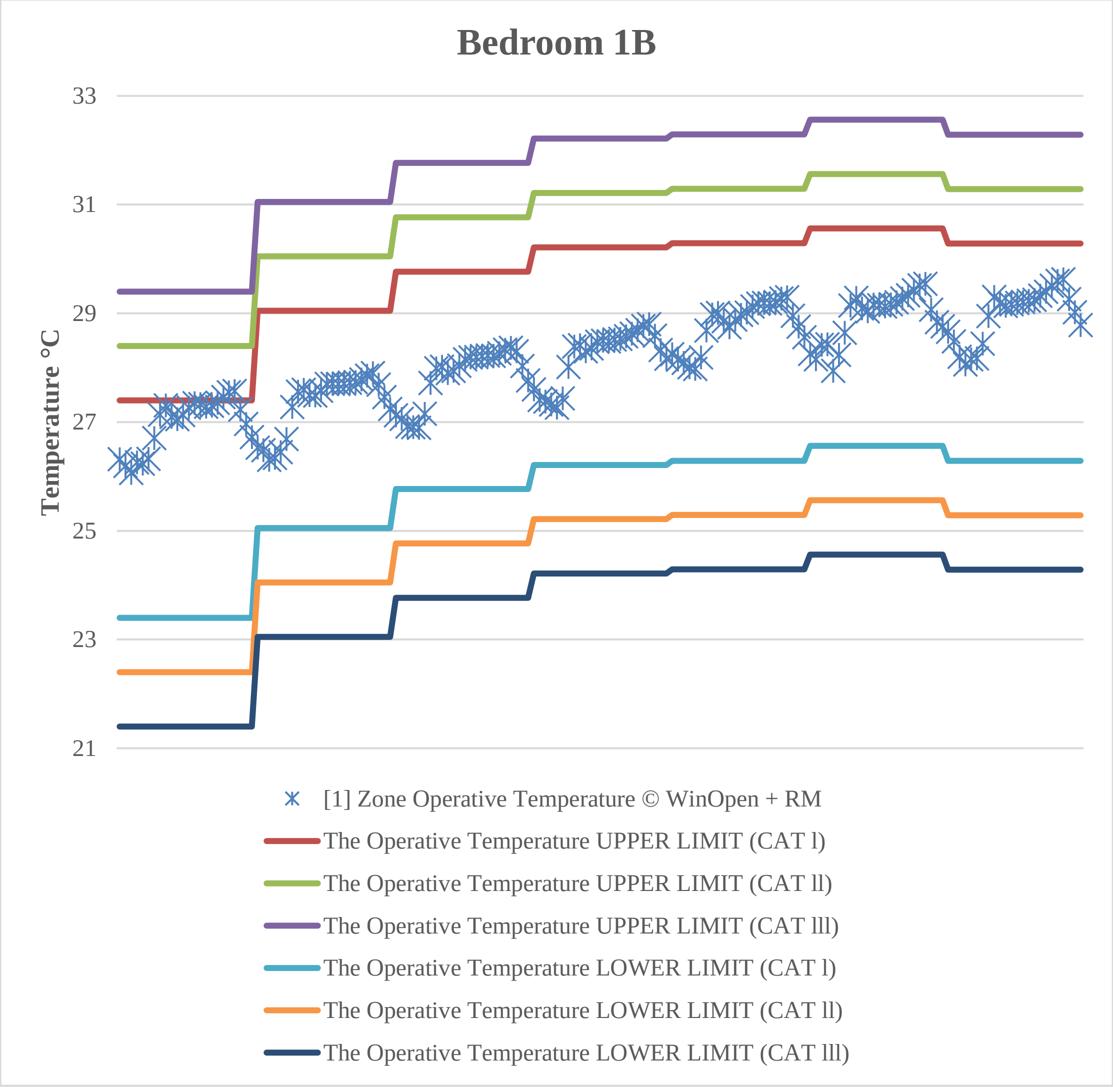


Figure 49: Summer design week EN 15251 comfort analysis for Bedroom 1B when all measures are implemented facing North orientation

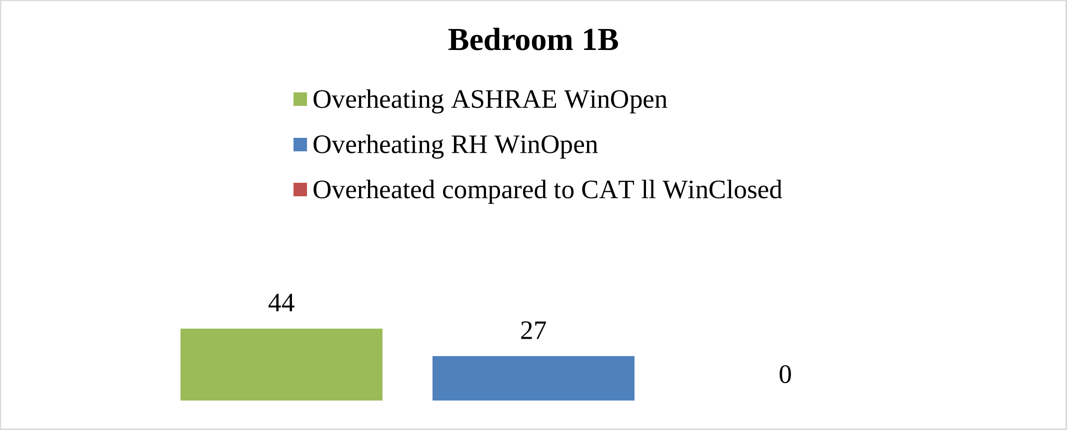
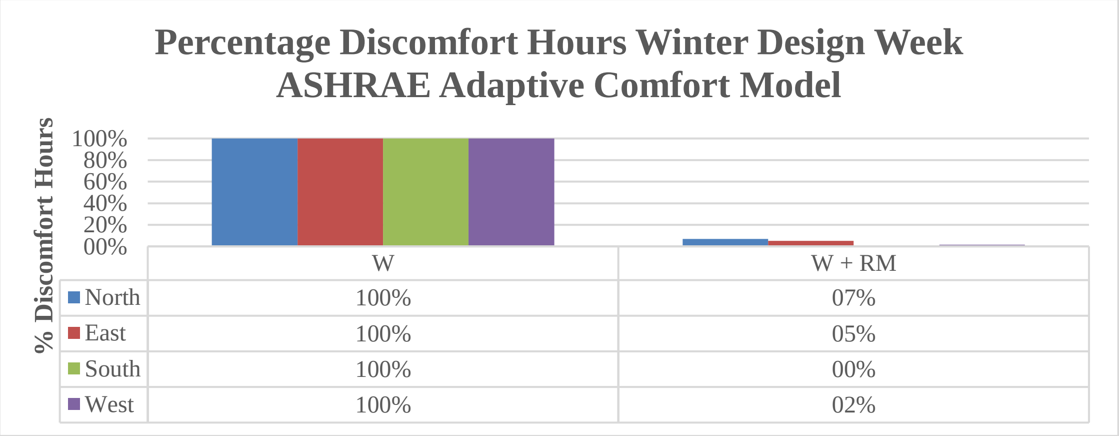


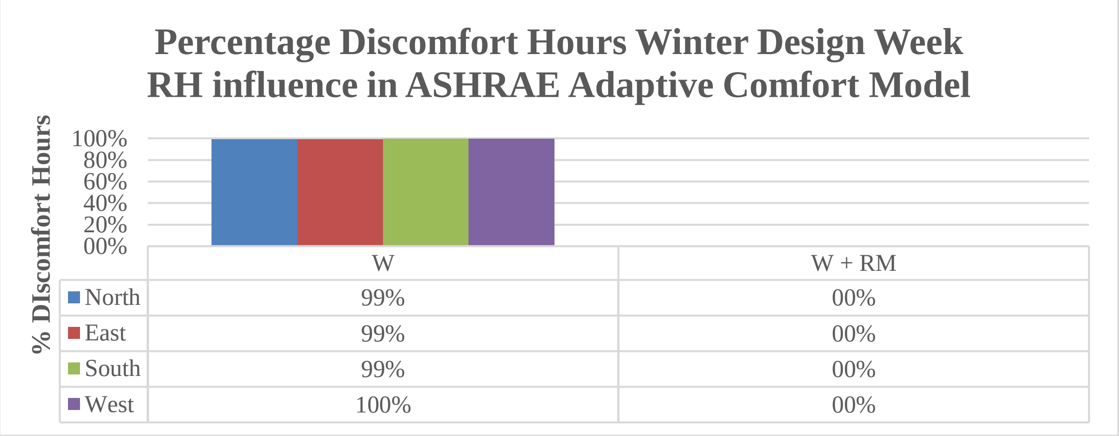
Figure 50: Summer design week number of discomfort hours for Bedroom 1B when all measures are implemented facing North orientation

For winter design week, the number of discomfort hours were reduced once the potential retrofit measures were implemented (Figures 51, 52, 53). One can see the percentage of discomfort hours is slightly high for the EN 15251 Adaptive Comfort model (Figure 53). This is because the Category II comfort limits were used to derive the discomfort hours. If Category III comfort criteria (suitable for an existing building) are considered, one can see in Appendix 2 Section A2.2.3 and in Figure 110, that the number of discomfort hours plotted are reduced. Thus, the building can be seen to comply with Category III adaptive comfort limits. EN 15251 Category III comfort level should be enough for the building under study.



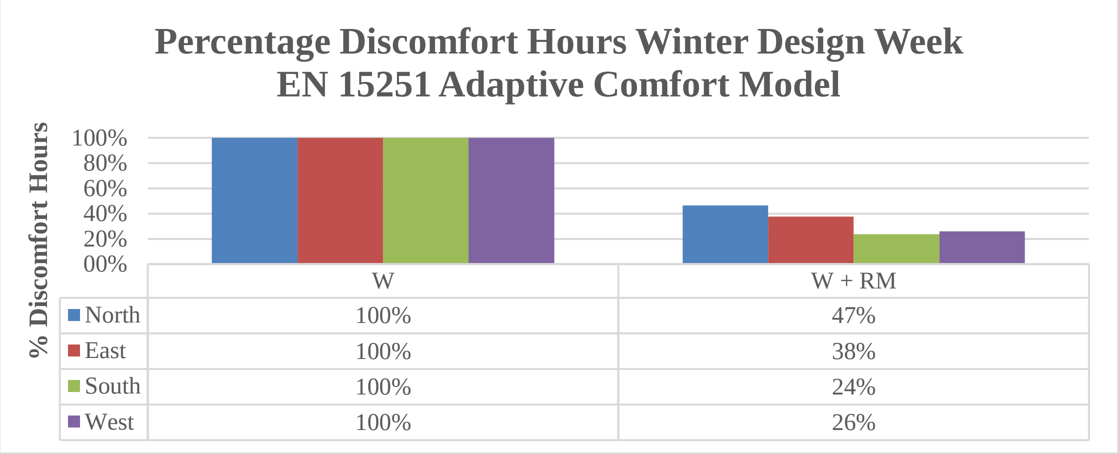
	W	W + RM
🟦 North	100%	07%
🟥 East	100%	05%
🟩 South	100%	00%
🟪 West	100%	02%

Figure 51: Discomfort hours percentages for ASHRAE adaptive comfort model in Winter with measures per orientation



	W	W + RM
🟦 North	99%	00%
🟥 East	99%	00%
🟩 South	99%	00%
🟪 West	100%	00%

Figure 52: Discomfort hours percentage for M. Vellei et al. [36] ***adaptive comfort model in Winter with measures per orientation***



	W	W + RM
🟦 North	100%	47%
🟥 East	100%	38%
🟩 South	100%	24%
🟪 West	100%	26%

Figure 53: Discomfort hours percentage for EN 15251 adaptive comfort model in Winter with measures per orientation

In Figure 54, for Bedroom 1B facing North orientation, the plotted ASHRAE adaptive comfort model comfort results are compared with the M. Vellei et al. [36] adaptive comfort model results for the winter design week when all measures are implemented.

In addition, in Figure 55, the results for the EN 15251 adaptive comfort model are also plotted for the same bedroom for the winter design week.

For the same room, Figure 56 summarises the number of discomfort hours resulting from the different comfort models under analysis for the winter design week.

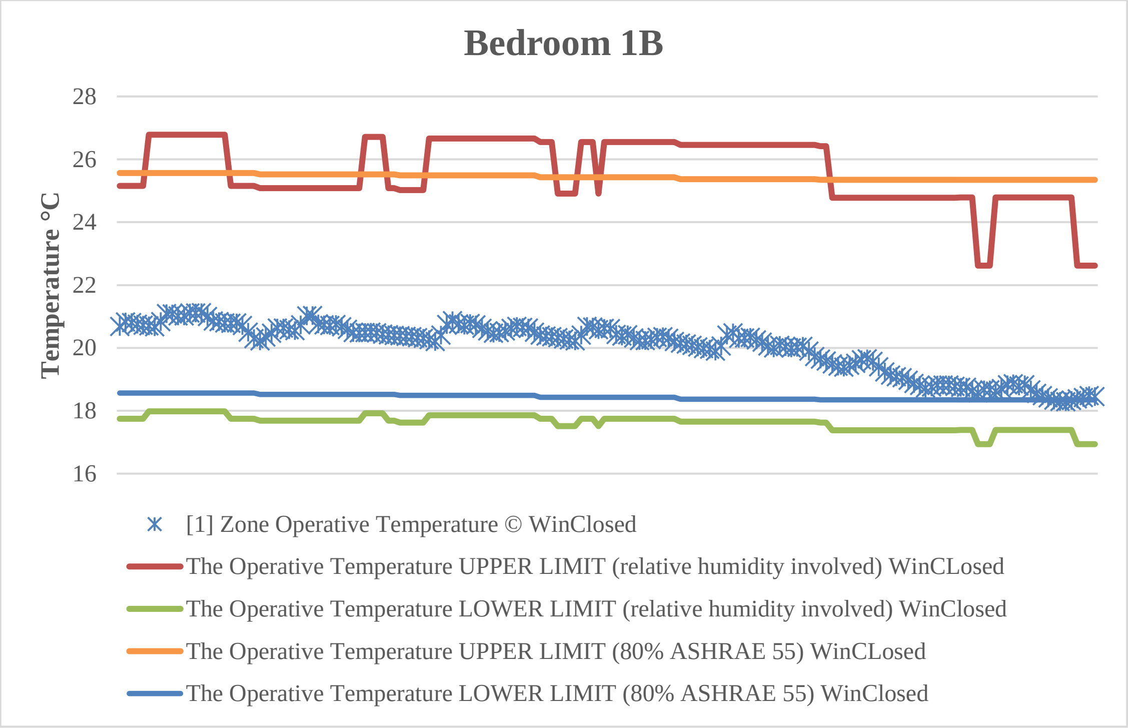


Figure 54: Winter design week ASHRAE and M. Vellei et al. [36] ***comfort analysis for Bedroom 1B when all measures are implemented facing North orientation***

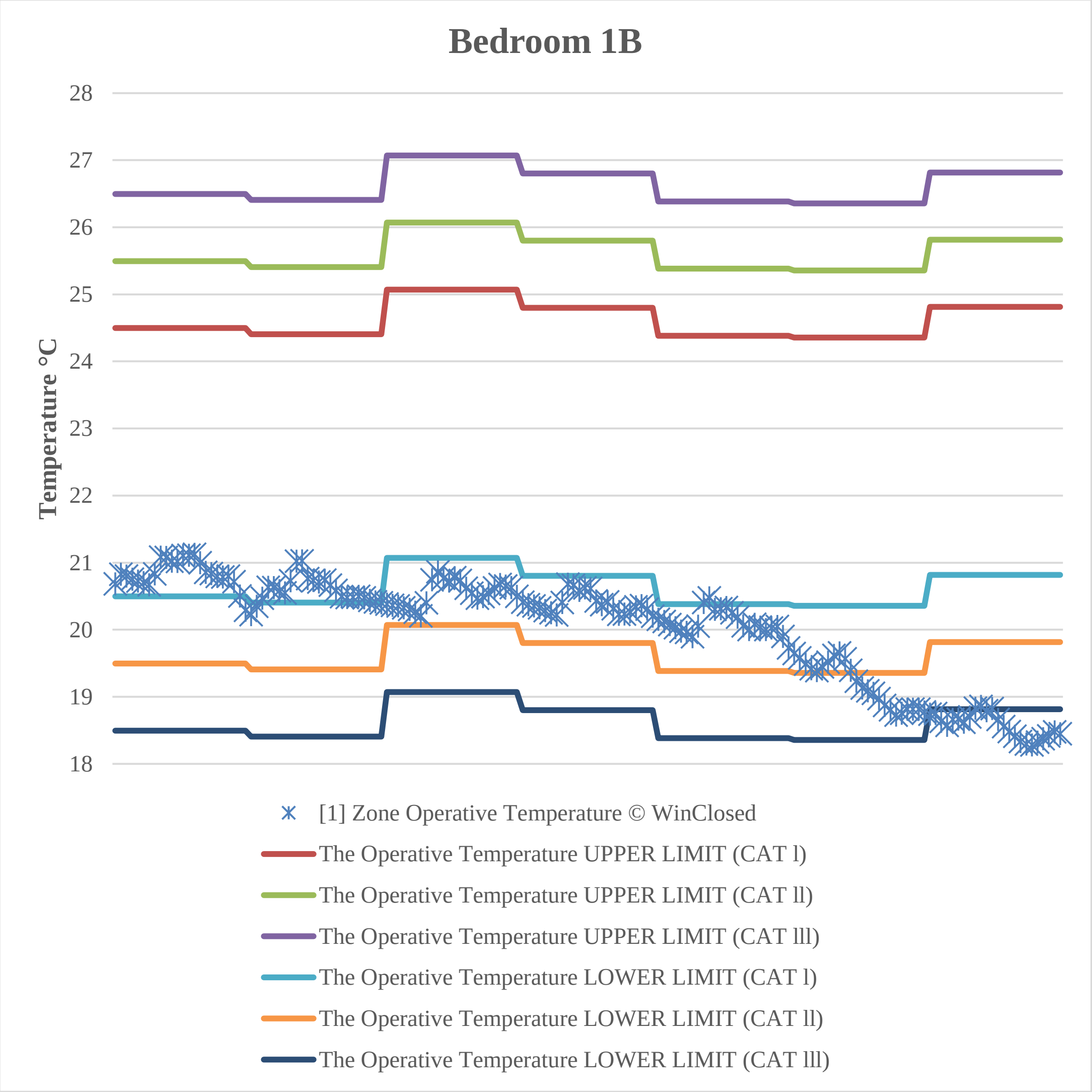


Figure 55: Winter design week EN 15251 comfort analysis for Bedroom 1B when all measures are implemented facing North orientation

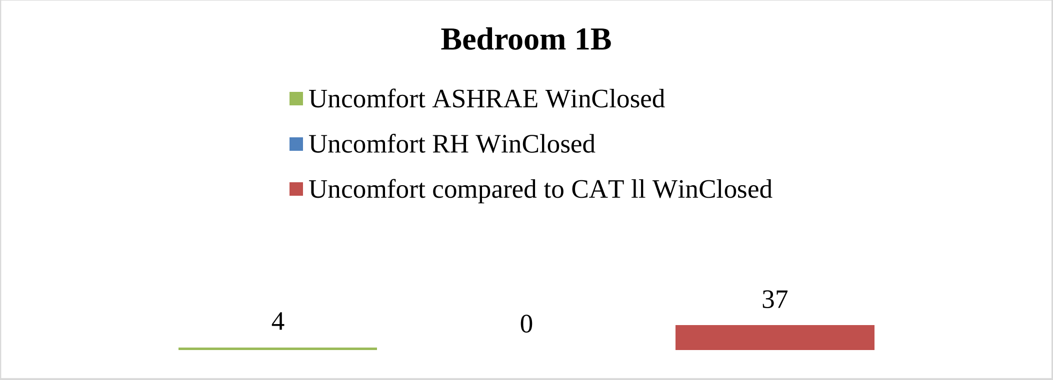


Figure 56: Winter design week number of discomfort hours for Bedroom 1B when all measures are implemented facing North orientation

4.5.1 Discussion for the scenario with all passive retrofit measures implemented

For the summer design week, with all the above measures implemented, thermal comfort was achieved for the EN 15251 Category II adaptive comfort model for all orientations and zones. In contrast, for the standard ASHRAE 80% thermal acceptability adaptive comfort model, while the discomfort hours were reduced when compared to the base scenario, some hourly indoor temperatures exceeded the upper comfort limit, especially for the kitchen that has high heat gains. The M. Vellei et al. [36] model provides a balance between the comfort performance of the EN 15251 Category II and the standard ASHRAE 80% thermal acceptability adaptive comfort models. Thus, the standard ASHRAE 80% thermal acceptability is the most difficult model to comply to for Summer, while the EN 15251 Category II model is the least strict model.

In contrast, for the winter design week, when all the passive retrofit measures were introduced, comfort was only achieved for the ASHRAE 80% thermal acceptability adaptive comfort model and the M. Vellei et al. [36] model, but not for the EN 15251 Category II model. Thus, for summer comfort, the EN 15251 Category II is the most difficult model to comply to for winter thermal comfort. In addition, unlike the summer design week, the kitchen was the zone with lowest number of discomfort hours due to the high internal heat gains in winter. One can also see that the North and East orientations show the highest number of discomfort hours, when compared to the dwellings facing the South and West orientations due to higher solar radiation penetrating the glazing at lower solar elevations. This contrasts with the summer design week, where similar peak temperatures result in dwellings having different orientations. Given that no dwelling is perfectly south oriented, the shading offered by the balconies has the same impact on the orientations studied.

4.6 Global sensitivity analysis

A global sensitivity analysis was carried out analysing each potential retrofit measure and orientation in order to see which affect the most in the ASHRAE adaptive comfort model and in the EN 15251 adaptive comfort model on a summer and winter design week. This was carried out to identify whether all considered potential measures require to be implemented to satisfy the required comfort levels.

An MLR was carried out for both seasons. This allowed one to identify the variables with most significant impact on comfort. For summer, doing a Backward Stepwise selection (this is, step by step elimination of the non-significant parameters) ranked the parameters in terms of impact on the EN 15251 adaptive comfort hours as follows (starting from the parameter having most impact): roof insulation, external blinds, external wall insulation (interior courtyard) and the orientation of the building. The resulting variables with no significant impact are the external wall façade insulation and the glazing type as seen in Table 18.

Table 18: Standardized Coefficients Beta for the Summer design week for the EN 15251 Category II discomfort hours

Backward Stepwise Selection	
Step 0	**Standardized Coefficient Beta**
External Wall Insulation (façade)	-0.034
External Wall Insulation (courtyard)	-0.139
Roof Insulation	-0.655
Double Glazing	-0.104
External Blinds	-0.203
Orientation	-0.123
Step 1	**Standardized Coefficient Beta**
External Wall Insulation (courtyard)	-0.138
Roof Insulation	-0.654
Double Glazing	-0.103
External Blinds	-0.203
Orientation	-0.125
Step 2	**Standardized Coefficient Beta**
External Wall Insulation (courtyard)	-0.138
Roof Insulation	-0.655
External Blinds	-0.201
Orientation	-0.129

All parameters are negatively correlated with number of summer discomfort hours. This means that the application of all measures acts favourable in reducing the number of discomfort hours.

For the ASHRAE adaptive comfort model, in terms of impact, the most important parameters can be ranked as follows (starting from the one having the largest impact): roof insulation, external blinds, the orientation of the building, the glazing type and the external wall insulation (interior courtyard). The only parameter that resulted statistically not significant is the external wall insulation (façade) as can be seen in Table 19. One is to note that the façade is a double walled faced and no single wall.

Table 19: Standardized Coefficients Beta for Summer design week for the ASHRAE 80% acceptability adaptive comfort model

Backward Stepwise Selection	
Step 0	**Standardized Coefficient Beta**
External Wall Insulation (façade)	-0.009
External Wall Insulation (courtyard)	-0.042
Roof Insulation	-0.927
Double Glazing	-0.046
External Blinds	-0.236
Orientation	-0.092
Step 1	**Standardized Coefficient Beta**
External Wall Insulation (courtyard)	-0.042
Roof Insulation	-0.927
Double Glazing	-0.046
External Blinds	-0.236
Orientation	-0.093

An MLR analysis was used to identify the impact of the different retrofit measures on the space heating demand for the building in winter design week. The sensitivity analysis results are shown in Table 20.

Table 20: Standardized Coefficients Beta for Winter design week for heat loads

Backward Stepwise Selection	
Step 0	**Standardized Coefficient Beta**
External Wall Insulation (façade)	-0.122
External Wall Insulation (courtyard)	-0.152
Roof Insulation	-0.958
Double Glazing	-0.046
Orientation	0.107

All retrofit measures are negatively correlated with the space heating demand. This means that the application of all measures acts favourably in reducing the space heating demand. For winter, a Backward Stepwise selection has been also used showing to identify the parameters having the highest impact on space heating. The parameters can be ranked as follows (starting from the parameter having the highest impact on space heating demand): roof insulation, external wall insulation (courtyard), external wall façade insulation, the orientation of the building and double glazing. Blinds were assumed to not be activated during the winter period to maximise heat gains to achieve comfort.

For winter comfort, unlike for summer comfort, double glazing and external wall insulation (façade) have a statistically significant impact on comfort.

Thus, it was concluded that all measures (roof insulation, external wall insulation (courtyard), external wall insulation (façade), the orientation of the building, double glazing and blinds should be considered further for analysis.

4.6.1 Discussion for the Global sensitivity analysis

The sensitivity analysis was also carried out in order to reduce what retrofit measures had the most and least significance on ASHRAE and EN 15251 adaptive thermal comfort models.

From the sensitivity analysis carried out in Section 4.6, the measures having the largest impact on summer discomfort hours are the roof insulation and the use of external blinds. This given that the roof is not insulated and does not satisfy the cost-optimal U-value minimum requirements of 0.4 W/m^{2}K [9]. Given that the roof is horizontal and receives the most solar radiation throughout summer period when compared to vertical walls, a lot of solar heat gains result from conduction and convection via the roof. In addition, as demonstrated in previous studies for Malta [68], external shading (via blinds) to reduce the penetration of solar radiation into the building, is essential to achieve adaptive thermal comfort during the summer period.

For Malta, the use of shading to prevent solar radiation penetration from glazing is more important than improving the insulation of fenestration via double glazing. This is because Malta has a temperate climate, meaning that the use of double versus single glazing to reduce heat gains by convection and conduction is less important when compared to colder northern countries, that have a high temperature difference between the interior and exterior. Furthermore, given that the external wall already complies to Technical Document F [9], additional insulation does not have a lot of significance on thermal comfort. This is because Technical Document F [9] has derived U-Values for the envelope based on cost-optimal requirements for Malta. Various studies including [69][51][70] showed that it is not cost-optimal to reduce the limits as set in Technical Document F for Malta.

In contrast, during winter double glazing provided a small but statistically significant impact on heat loads given the greenhouse effect, where the long wave solar radiation gets trapped inside the building. Double glazing also contributes to improved acoustic comfort. Furthermore, insulating the external wall façade also showed a significant effect in reducing the heat loads during winter.

Given the requirement to improve and comply with EN 15251 Category II adaptive comfort requirements (Section 4.7), all measures (external wall façade insulation, external wall courtyard insulation, double glazing, use of blinds and roof insulation), considered were deemed important for implementation.

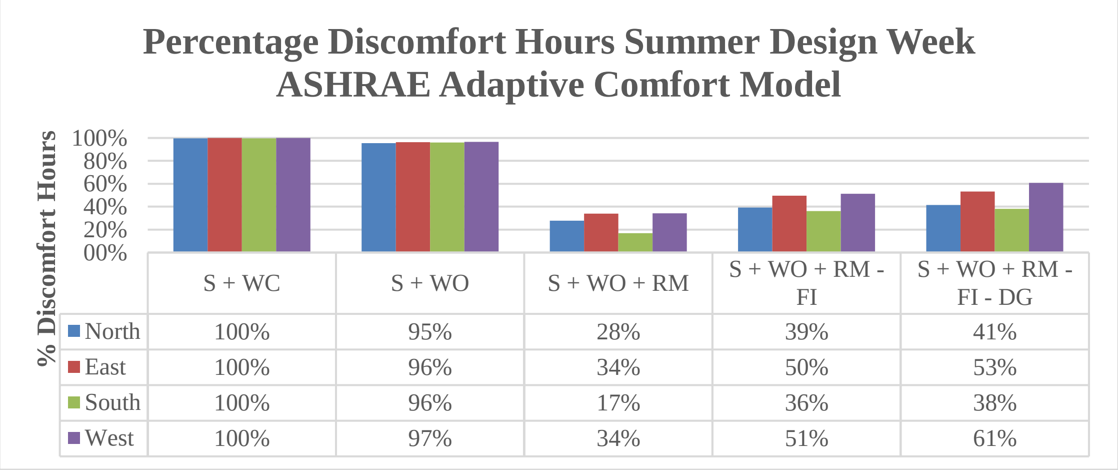
4.7 Comfort analysis plots performed removing the least important measures one by one

The impact of comfort on parameters having a low Standardized Coefficient Beta were also analysed using hourly temperature adaptive model plots for summer and winter design weeks. For each analysis one measure was eliminated each time starting from the measure having least impact. The results are summarised in Appendix 2. This analysis enabled one to have a better visual depiction of the influence on comfort for each of these parameters. When observing the plots and results shown below, this analysis reinforced the statistical analysis that all measures should be considered further.

Table 21: Base Comfort analysis and implementation of potential retrofit measures, all retrofit measures without façade insulation and all retrofit measures without double glazing codification

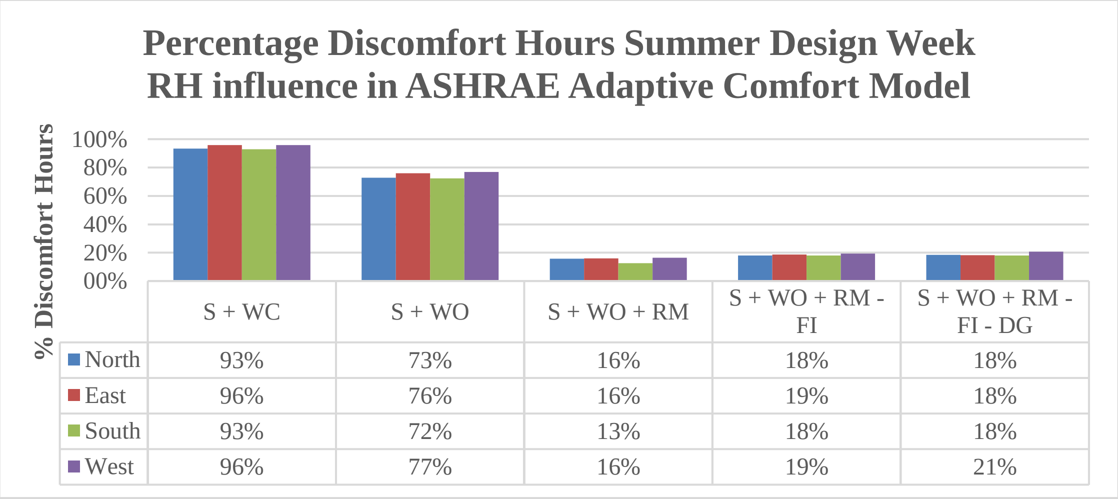
Nomenclature	**Abbreviation**
Summer design week with **W**indows **C**losed	S + WC
Summer design week with **W**indows **O**pen	S + WO
Winter design week	W
Summer design week with **W**indows **O**pen with all potential **R**etrofit **M**easures implemented	S + WO + RM
Winter design week with all potential **R**etrofit **M**easures implemented	W + RM
Summer design week with **W**indows **O**pen with all potential **R**etrofit **M**easures implemented except for the External wall **F**açade **I**nsulation	S + WO + RM - FI
Winter design week with all potential **R**etrofit **M**easures implemented except for the External wall **F**açade **I**nsulation	W + RM - FI
Summer design week with **W**indows **O**pen with all potential **R**etrofit **M**easures implemented except for the External wall **F**açade **I**nsulation and **D**ouble **G**lazing	S + WO + RM - FI - DG
Winter design week with all potential **R**etrofit **M**easures implemented except for the External wall **F**açade **I**nsulation and **D**ouble **G**lazing	W + RM - FI - DG

The number of discomfort hours were first simulated with the external wall façade insulation not implemented. In the second simulation both the external wall façade insulation and double glazing were not implemented. Refer to Tables 57, 58, 59.



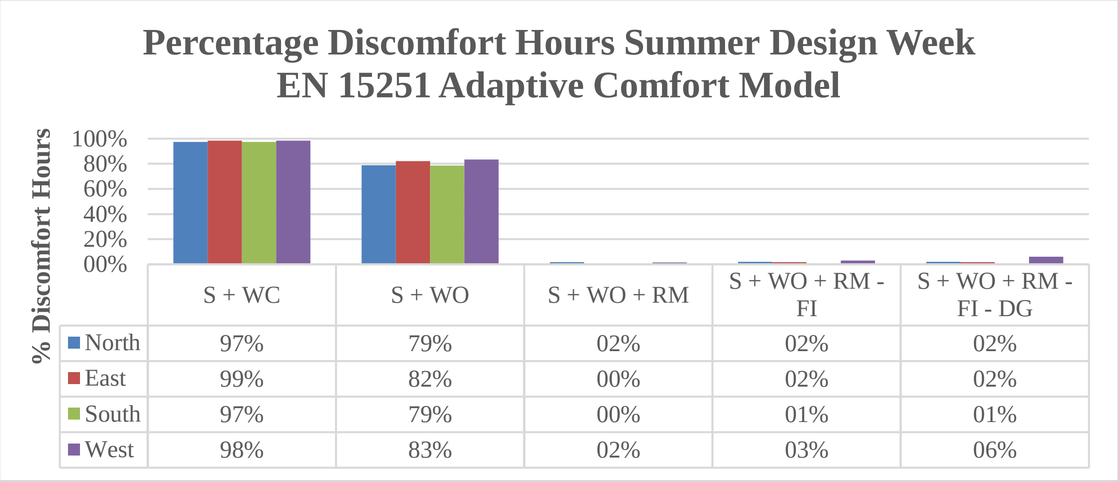
	S + WC	S + WO	S + WO + RM	S + WO + RM - FI	S + WO + RM - FI - DG
🟦 North	100%	95%	28%	39%	41%
🟥 East	100%	96%	34%	50%	53%
🟩 South	100%	96%	17%	36%	38%
🟪 West	100%	97%	34%	51%	61%

Figure 57: Discomfort hours percentages for ASHRAE adaptive comfort model in Summer with measures without façade insulation and double glazing per orientation



	S + WC	S + WO	S + WO + RM	S + WO + RM - FI	S + WO + RM - FI - DG
🟦 North	93%	73%	16%	18%	18%
🟥 East	96%	76%	16%	19%	18%
🟩 South	93%	72%	13%	18%	18%
🟪 West	96%	77%	16%	19%	21%

Figure 58: Discomfort hours percentage for M. Vellei et al. [36] *adaptive comfort model in Summer with measures without façade insulation and double glazing per orientation*



	S + WC	S + WO	S + WO + RM	S + WO + RM - FI	S + WO + RM - FI - DG
🟦 North	97%	79%	02%	02%	02%
🟥 East	99%	82%	00%	02%	02%
🟩 South	97%	79%	00%	01%	01%
🟪 West	98%	83%	02%	03%	06%

Figure 59: Discomfort hours percentage for EN 15251 adaptive comfort model in Summer with measures without façade insulation and double glazing per orientation

More plotted comfort results per orientation and room, can be seen in the Appendix 2 Section A2.2; The plotted comfort results for the different rooms follow the same trend, thus, Bedroom 1A was chosen to represent the rest of the rooms in this Section. Bedroom 1A was chosen for this analysis, given that it has a façade external wall envelope, allowing one to appreciate the impact of comfort by adding external insulation to the façade.

In Figure 60, for Bedroom 1A facing North orientation, the plotted ASHRAE adaptive comfort model comfort results are compared with the M. Vellei et al. [36] adaptive comfort model results for the summer design week when all retrofit measures are implemented, when all retrofit measures are implemented except for the external wall façade insulation and when all retrofit measures are implemented except for the external wall façade insulation and double glazing.

In addition, in Figure 61, the results for the EN 15251 adaptive comfort model are also plotted for the same bedroom for the summer design week.

For the same room, Figure 62 summarises the number of discomfort hours resulting from the different comfort models under analysis for the summer design week.

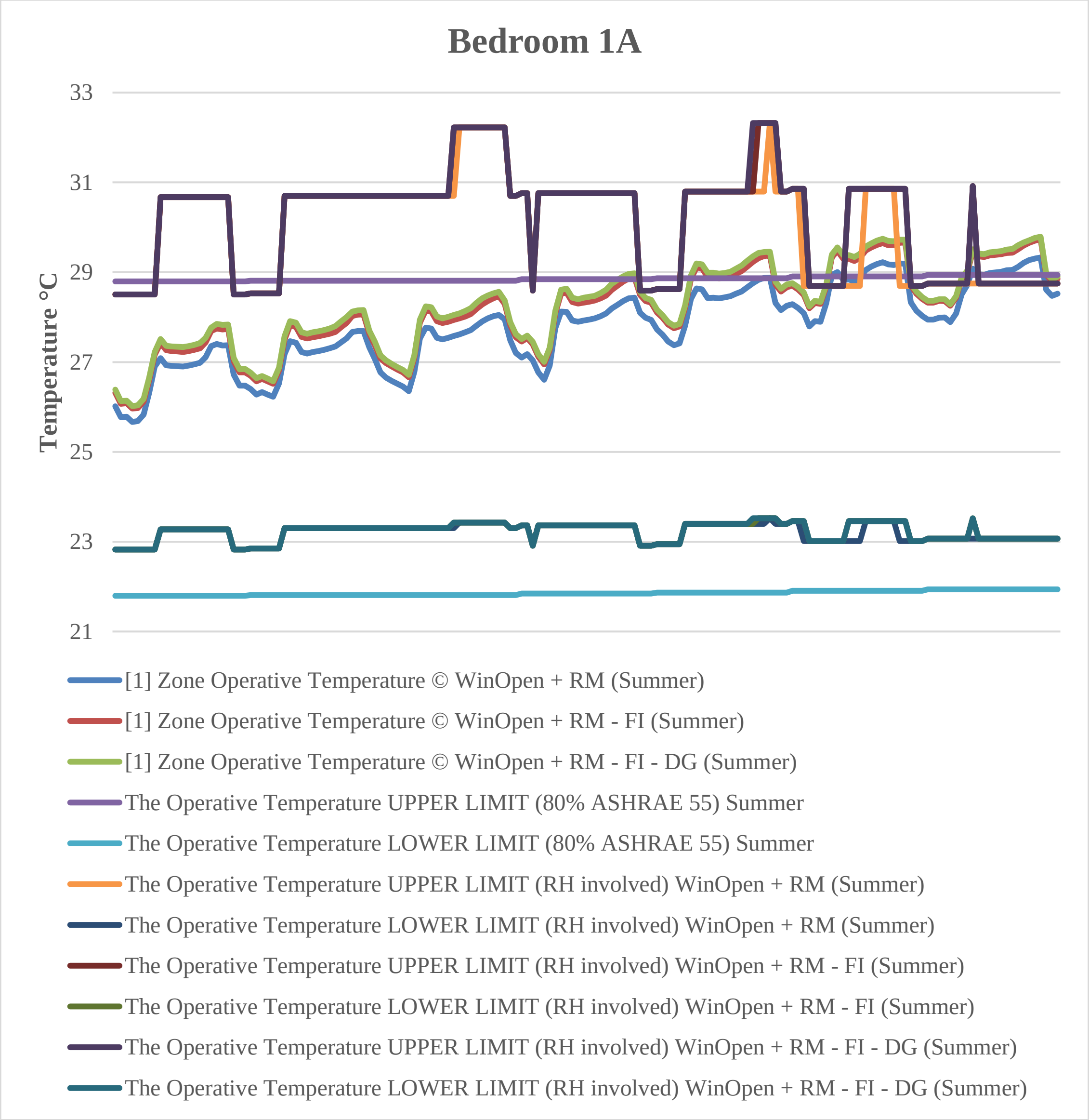


Figure 60: Summer design week ASHRAE and M. Vellei et al. [35] ***comfort analysis for Bedroom 1A facing North orientation using windows open configuration and using different combination of measures***

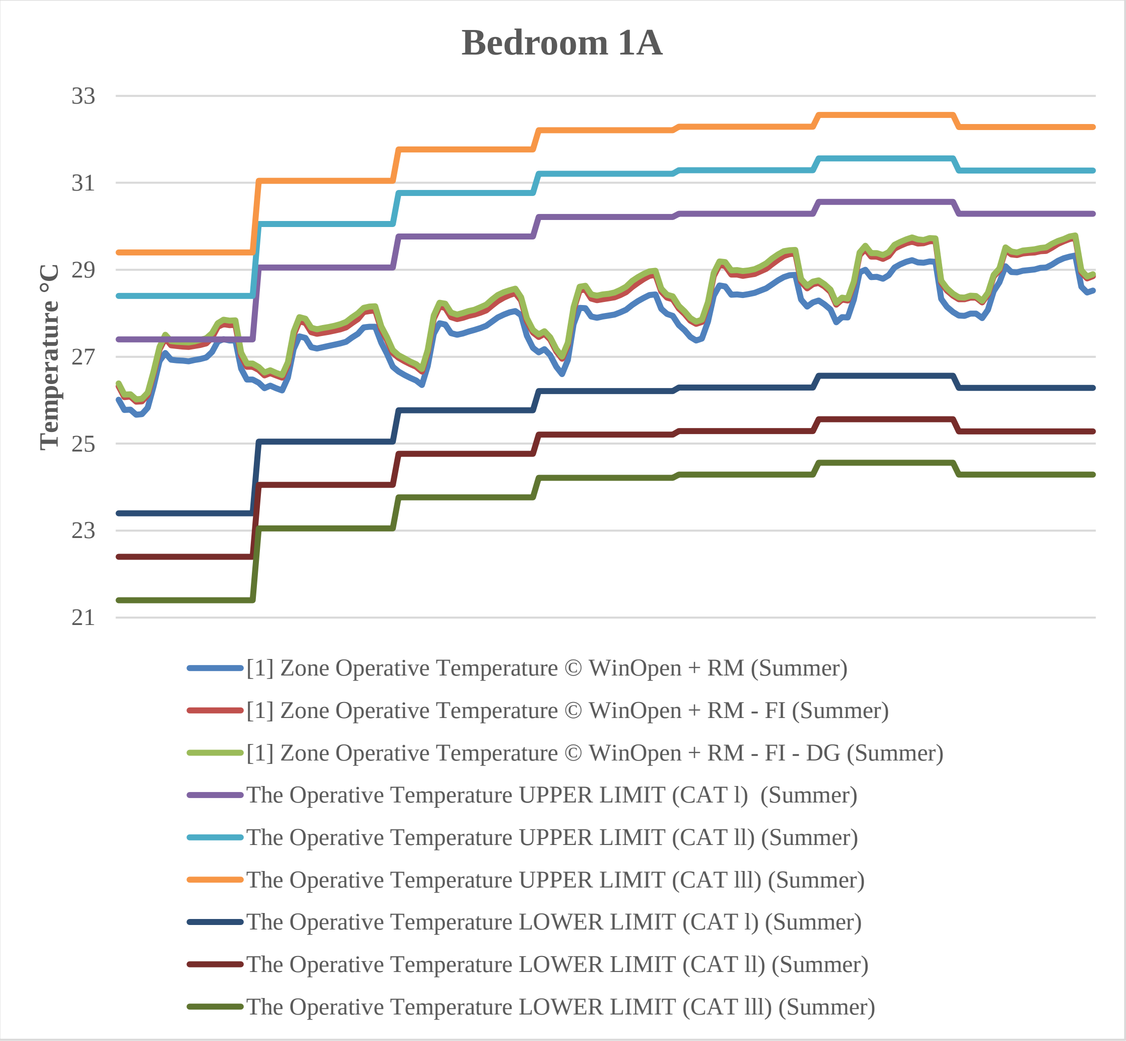


Figure 61: Summer design week EN 15251 comfort analysis for Bedroom 1A facing North orientation using windows open configuration and using different combination of measures

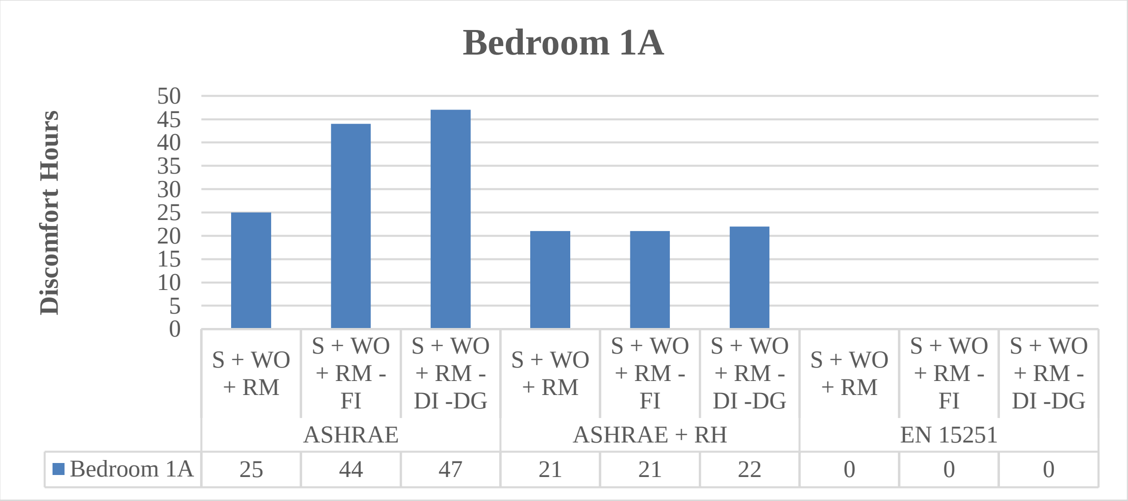
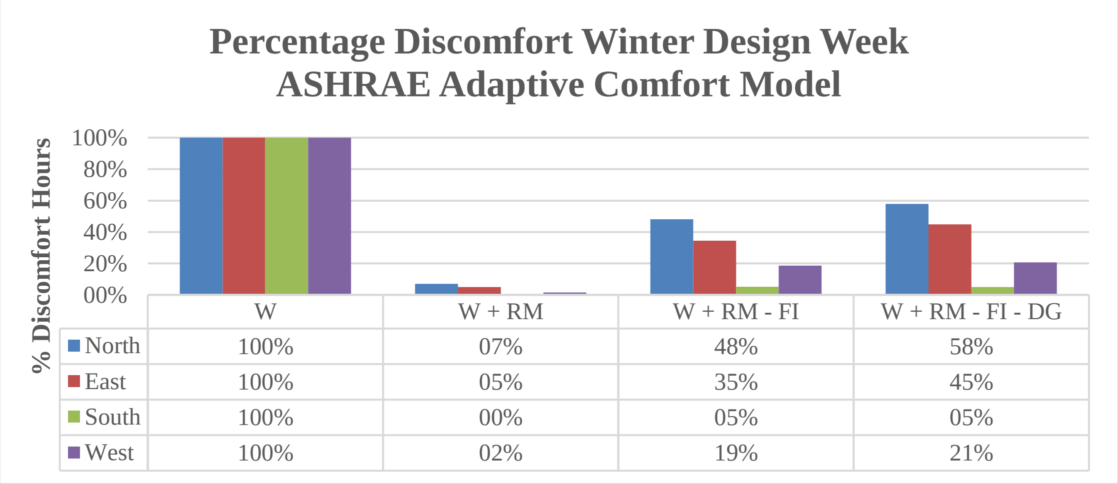


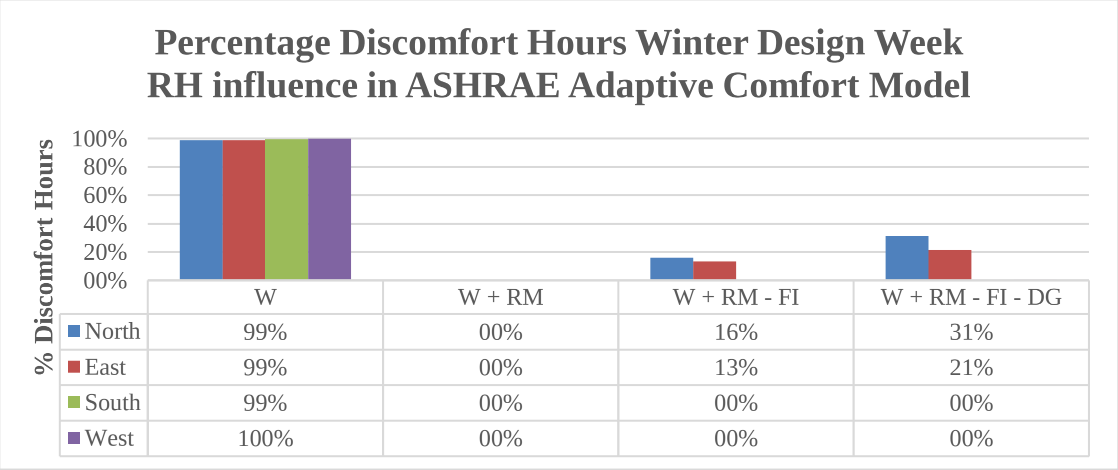
Figure 62: Summer design week number of discomfort hours for different combination of measures for the Bedroom 1A facing North orientation

The number of discomfort hours are, for winter design week, reduced once the potential retrofit measures were implemented. As the sensitivity analysis showed, all potential retrofit measures are statistically significant for the space heating demand. Therefore, discomfort hours get significantly increased as measure are eliminated. However, for South and West cardinal orientations, discomfort hours do not increase at the same rate as the bedrooms facing the North and East cardinal orientations, due to higher solar radiation gain from these orientations during winter period as seen in Figures 63, 64, 65. Once again, the comfort Category II limits were used for discomfort hours analysis. The building however complies with Category III comfort limits.



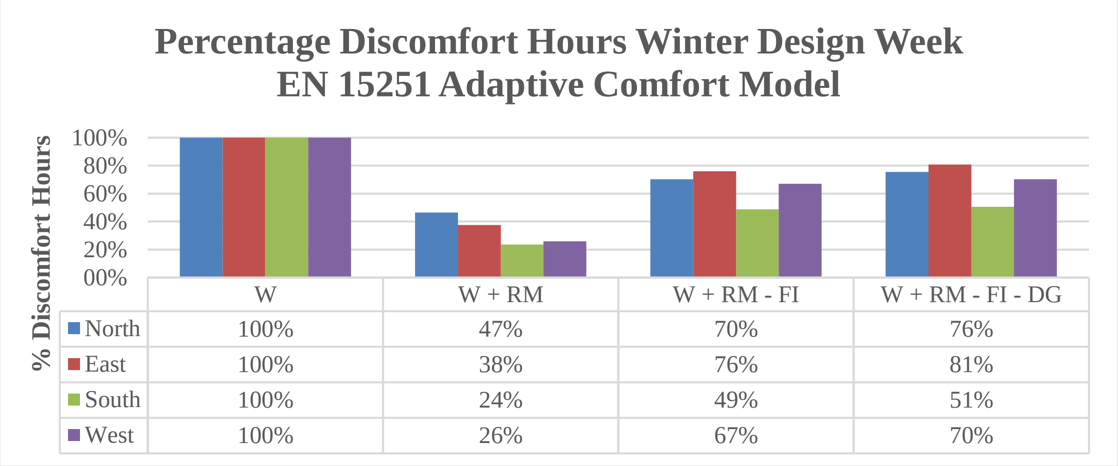
	W	W + RM	W + RM - FI	W + RM - FI - DG
🟦 North	100%	07%	48%	58%
🟥 East	100%	05%	35%	45%
🟩 South	100%	00%	05%	05%
🟪 West	100%	02%	19%	21%

Figure 63: Discomfort hours percentages for ASHRAE adaptive comfort model in Winter with measures without façade insulation and double glazing per orientation



	W	W + RM	W + RM - FI	W + RM - FI - DG
🟦 North	99%	00%	16%	31%
🟥 East	99%	00%	13%	21%
🟩 South	99%	00%	00%	00%
🟪 West	100%	00%	00%	00%

Figure 64: Discomfort hours percentage for M. Vellei et al. [36] *adaptive comfort model in Winter with measures without façade insulation and double glazing per orientation*



	W	W + RM	W + RM - FI	W + RM - FI - DG
🟦 North	100%	47%	70%	76%
🟥 East	100%	38%	76%	81%
🟩 South	100%	24%	49%	51%
🟪 West	100%	26%	67%	70%

Figure 65: Discomfort hours percentage for EN 15251 adaptive comfort model in Winter with measures without façade insulation and double glazing per orientation

In Figure 66, for Bedroom 1A facing North orientation, the plotted ASHRAE adaptive comfort model comfort results are compared with the M. Vellei et al. [36] adaptive comfort model results for the winter design week when all retrofit measures are implemented, when all retrofit measures are implemented except for the external wall façade insulation and when all retrofit measures are implemented except for the external wall façade insulation and double glazing.

In addition, in Figure 67, the results for the EN 15251 adaptive comfort model are also plotted for the same bedroom for the winter design week.

For the same room, Figure 68 summarises the number of discomfort hours resulting from the different comfort models under analysis for the winter design week.

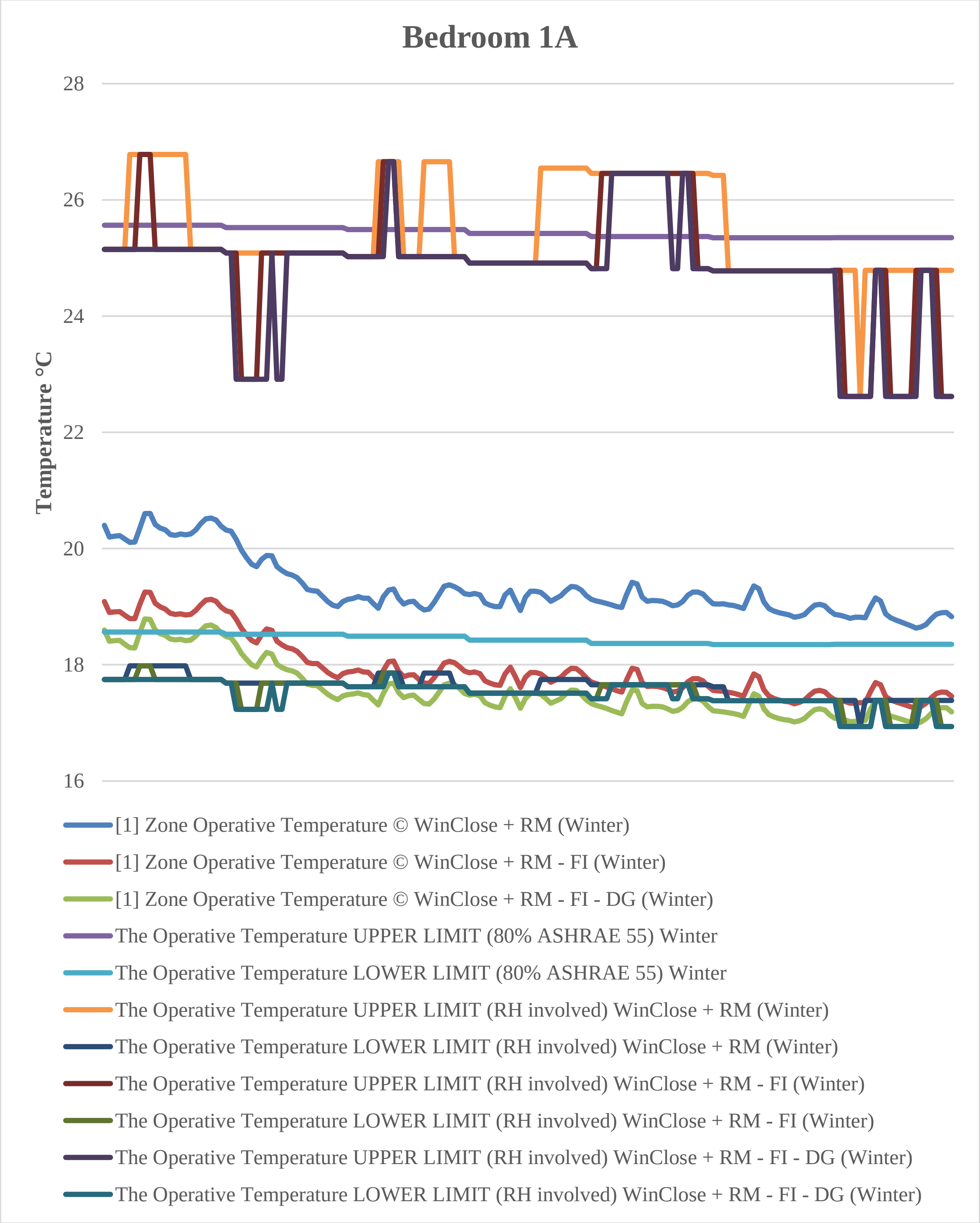


Figure 66: Winter design week ASHRAE and M. Vellei et al. [35] *comfort analysis for Bedroom 1A facing North orientation using windows open configuration and using different combination of measures*

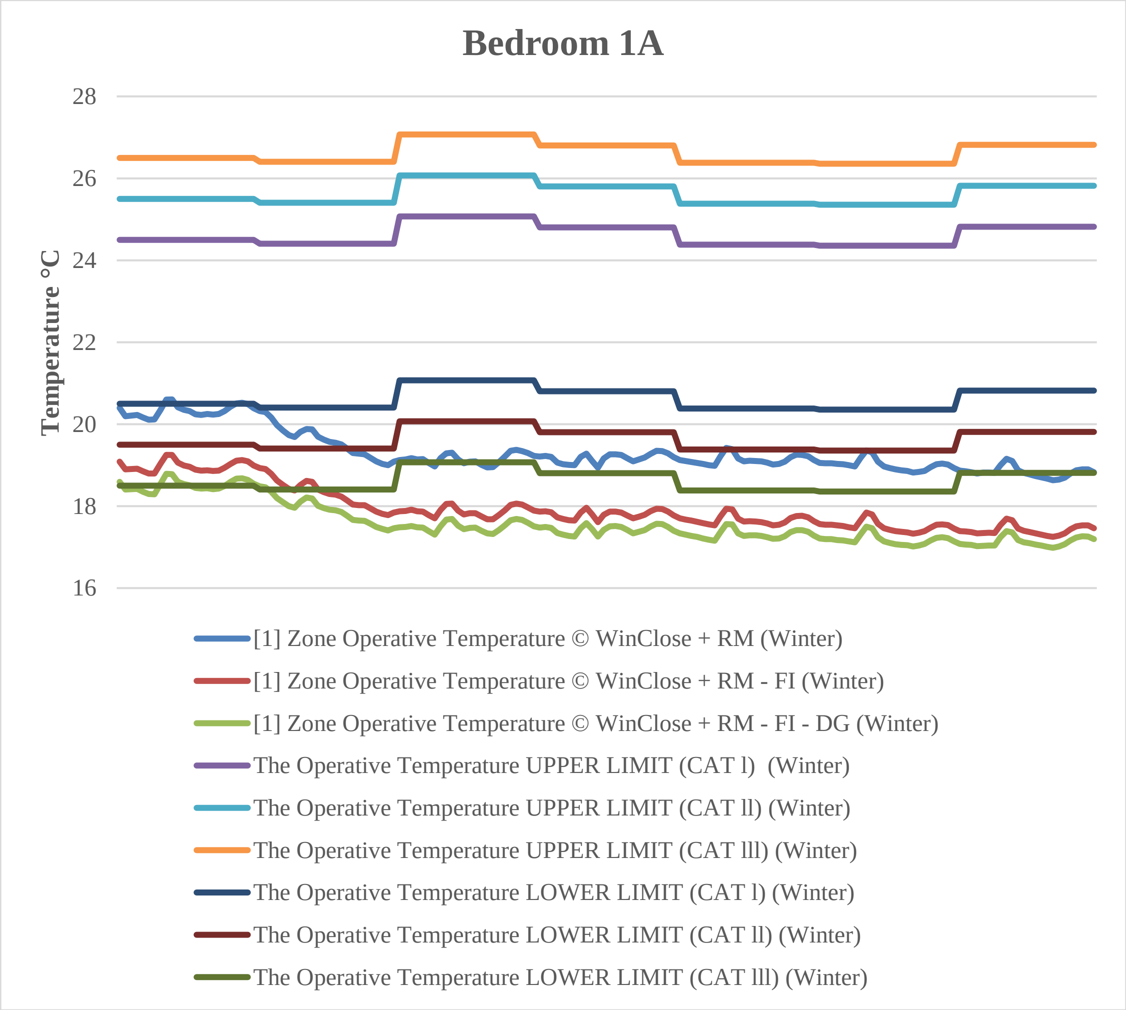


Figure 67: Winter design week EN 15251 comfort analysis for Bedroom 1A facing North orientation using windows open configuration and using different combination of measures

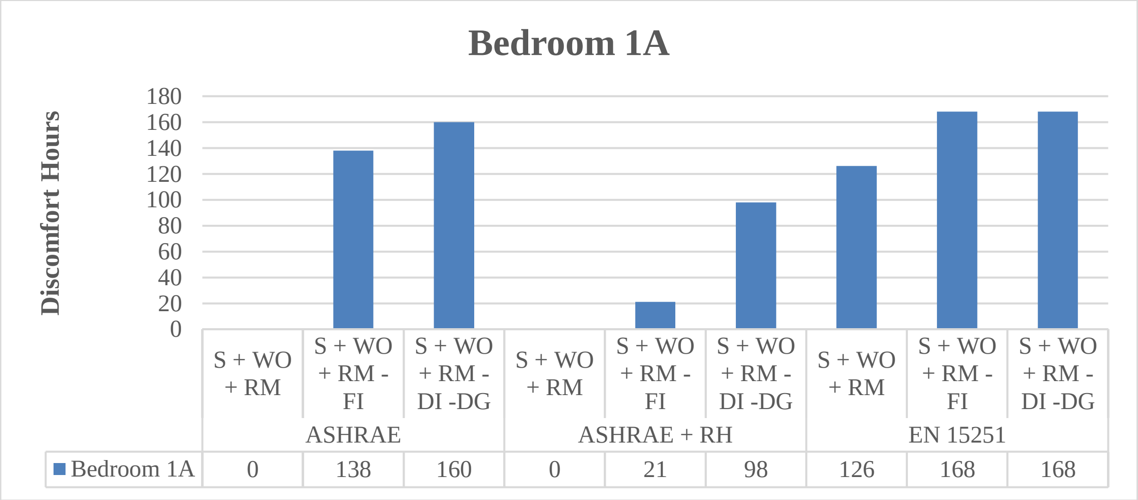


Figure 68: Winter design week number of discomfort hours for different combination of measures for the Bedroom 1A facing North orientation

4.8 Financial and Macroeconomic analysis results

The financial analysis has been carried out by:

1) Comparing the base envelope scenario using air to air heat pumps to achieve comfort versus the scenario with all measures implemented. In this scenario, adaptive thermal comfort has been taken to be achieved when all potential measures are considered and therefore the use of air to air heat pumps is not required. The analysis was carried out for each building orientation. The results are summarised in Table 22.
2) Comparing the base envelope scenario using air to air heat pumps to achieve comfort versus the scenario with all measures implemented also with heat pumps. This analysis was carried out to directly make a comparison between two scenarios attaining the same level of comfort. The analysis was carried out for each building orientation. The results are summarised in Table 23.

Table 22: Actual Building with A/C vs Building with All measures per orientation

	Financial Feasibility			Macroeconomic financial analysis
Orientation	**NPV - €**	**IRR**	**SPP (Years)**	**NPV - €**
North	-5.251,83 €	-1%	36	-4.609,10 €
East	-4.857,86 €	-1%	34	-4.284,97 €
West	-5.463,52 €	-1%	37	-4.783,25 €
South	-4.866,68 €	-1%	34	-4.292,23 €

	Actual Building with A/C		Building with all measures	
Orientation	**Global Cost - €**	**Global Cost Macroeconomic - €**	**Global Cost - €**	**Global Cost Macroeconomic - €**
North	6.400,52 €	6.925,69 €	11.652,36 €	11.312,97 €
East	6.794,49 €	7.351,99 €	11.652,36 €	11.312,97 €
West	6.188,84 €	6.696,64 €	11.652,36 €	11.312,97 €
South	6.785,67 €	7.342,44 €	11.652,36 €	11.312,97 €

Table 23: Actual Building with A/C vs Building with All measures + A/C per orientation

	Financial Feasibility			Macroeconomic financial analysis
Orientation	**NPV - €**	**IRR**	**SPP (Years)**	**NPV - €**
North	-11.483,19 €	-5%	79	-9.824,79 €
East	-11.371,47 €	-5%	77	-9.732,88 €
West	-11.394,99 €	-5%	78	-9.752,23 €
South	-11.286,21 €	-5%	75	-9.662,73 €

	Actual Building with A/C		Building with all measures + A/C	
Orientation	**Global Cost - €**	**Global Cost Macroeconomic - €**	**Global Cost - €**	**Global Cost Macroeconomic - €**
North	6.400,52 €	6.925,69 €	17.883,71 €	17.655,38 €
East	6.794,49 €	7.351,99 €	18.165,96 €	17.960,78 €
West	6.188,84 €	6.696,64 €	17.583,83 €	17.330,88 €
South	6.785,67 €	7.342,44 €	18.071,88 €	17.858,98 €

For the scenario where all measures are implemented except for the external wall façade insulation (given that it has the lowest impact on thermal comfort) the financial analysis described previously was also carried out (Tables 25, 26).

Table 24: Actual Building with A/C vs Building with All measures - façade insulation per orientation

	Financial Feasibility			**Macroeconomic financial analysis**
Orientation	**NPV - €**	**IRR**	**SPP (Years)**	**NPV - €**
North	-3.458,40 €	0%	30	-3.089,24 €
East	-3.064,43 €	0%	28	-2.765,12 €
West	-3.670,09 €	0%	31	-3.263,40 €
South	-3.073,25 €	0%	28	-2.772,37 €

	Actual Building with A/C		**Building with all measures - façade insulation**	
Orientation	**Global Cost - €**	**Global Cost Macroeconomic - €**	**Global Cost - €**	**Global Cost Macroeconomic - €**
North	6.400,52 €	6.925,69 €	9.858,93 €	9.571,77 €
East	6.794,49 €	7.351,99 €	9.858,93 €	9.571,77 €
West	6.188,84 €	6.696,64 €	9.858,93 €	9.571,77 €
South	6.785,67 €	7.342,44 €	9.858,93 €	9.571,77 €

Table 25: Actual Building with A/C vs Building with All measures + A/C - façade insulation per orientation

	Financial Feasibility			Macroeconomic financial analysis
Orientation	**NPV - €**	**IRR**	**SPP (Years)**	**NPV - €**
North	-10.307,17 €	-6%	84	-8.812,89 €
East	-10.280,71 €	-6%	83	-8.791,12 €
West	-10.116,07 €	-5%	79	-8.655,67 €
South	-10.124,89 €	-5%	79	-8.662,92 €

	Actual Building with A/C		Building with all measures + A/C - façade insulation	
Orientation	**Global Cost - €**	**Global Cost Macroeconomic - €**	**Global Cost - €**	**Global Cost Macroeconomic - €**
North	6.400,52 €	6.925,69 €	16.707,70 €	16.582,26 €
East	6.794,49 €	7.351,99 €	17.075,21 €	16.979,92 €
West	6.188,84 €	6.696,64 €	16.304,91 €	16.146,42 €
South	6.785,67 €	7.342,44 €	16.910,56 €	16.801,77 €

For the scenario where all measures are implemented except for the external wall façade insulation and the double glazing, a financial analysis has also been carried out. Double glazing was the measure that had the lowest impact on comfort after the façade external wall insulation (Tables 27, 28).

Table 26: Actual Building with A/C vs Building with All measures - façade insulation - double glazing per orientation

	Financial Feasibility			Macroeconomic financial analysis
Orientation	**NPV - €**	**IRR**	**SPP (Years)**	**NPV - €**
North	-1.994,56 €	1%	26	-1.848,70 €
East	-1.600,60 €	1%	24	-1.524,58 €
West	-2.206,25 €	1%	27	-2.022,86 €
South	-1.609,42 €	1%	24	-1.531,84 €

	Actual Building with A/C		Building with all measures - façade insulation - double glazing	
Orientation	**Global Cost - €**	**Global Cost Macroeconomic - €**	**Global Cost - €**	**Global Cost Macroeconomic - €**
North	6.400,52 €	6.925,69 €	8.395,09 €	8.150,57 €
East	6.794,49 €	7.351,99 €	8.395,09 €	8.150,57 €
West	6.188,84 €	6.696,64 €	8.395,09 €	8.150,57 €
South	6.785,67 €	7.342,44 €	8.395,09 €	8.150,57 €

Table 27: Actual Building with A/C vs Building with All measures +A/C - façade insulation - double glazing per orientation

	Financial Feasibility			Macroeconomic financial analysis
Orientation	**NPV - €**	**IRR**	**SPP (Years)**	**NPV - €**
North	-8.752,20 €	-5%	72	-7.497,37 €
East	-8.722,80 €	-5%	72	-7.473,18 €
West	-8.546,39 €	-5%	68	-7.328,05 €
South	-8.581,67 €	-5%	69	-7.357,07 €

	Actual Building with A/C		Building with all measures + A/C - façade insulation - double glazing	
Orientation	**Global Cost - €**	**Global Cost Macroeconomic - €**	**Global Cost - €**	**Global Cost Macroeconomic - €**
North	6.400,52 €	6.925,69 €	15.152,72 €	15.062,44 €
East	6.794,49 €	7.351,99 €	15.517,29 €	15.456,92 €
West	6.188,84 €	6.696,64 €	14.735,23 €	14.610,69 €
South	6.785,67 €	7.342,44 €	15.367,34 €	15.294,67 €

4.8.1 Discussion for the Financial and Macroeconomic analysis

An economic feasibility study for the measures was also carried out. From the results obtained for the financial analysis, from a private investor point of view, the most viable option would be to leave the building envelope as is and invest in the use of heat pumps to achieve thermal comfort. However, one should note that such social housing residents do not have the financial compatibility both to invest in heat pumps or to pay the increased energy bills resulting from mechanical space heating and cooling.

In addition, from a macroeconomic point of view that considers also the cost of carbon as per EPBD [4] recast requirements, it is still not economically feasible from a life-cycle analysis to invest in these passive measures, this despite the potential of such measures in improving the comfort and well-being of occupants, tackle energy poverty and reduce the peak power demands from the power station. This shows that in the future, the EPBD [4] should also consider these non-energy benefits for the macroeconomic calculation in addition to the cost of carbon.

Chapter 5. Conclusion

The aim of this dissertation was to identify the best retrofit measures to improve the thermal comfort and energy performance of social housing building stocks in Malta. For the scope of this study, a typical social housing building block built in the 1990s was modelled using DesignBuilder-EnergyPlus software.

The following conclusions can be made from this study:

- Given that the social building stock under study was built prior to the establishment of minimum energy performance requirements, building energy modelling using Designbuilder showed that top floor dwellings do not comply with EN 15251 comfort requirements for the summer and winter design weeks.
- The inclusion of roof insulation, external wall insulation, courtyard insulation, installation of exterior blinds and the replacement of single glazing with double glazing allow adaptive thermal comfort to comply with EN 15251 Category II comfort requirements for the summer and winter design weeks. Thus, passive measures alone can facilitate thermal comfort without the requirement for mechanical space heating and cooling.
- While all considered retrofit measures are important to achieve adaptive thermal comfort, priority should be given to roof insulation and external shading (blinds) for such buildings.
- From a private investor point of view, the most viable option would be to leave the building envelope as is and invest in the use of heat pumps to achieve thermal comfort. However, one should note that such social housing residents do not have enough financing power neither to invest in heat pumps or to pay the resulting energy bills due to the use of air conditioning.
- In addition, from a macroeconomic point of view that considers also the cost of carbon as per EPBD [4] recast requirements, it is still not economically feasible from a life-cycle analysis to invest in these passive measures, despite the potential of such measures in improving the comfort and well-being of occupants, tackling energy poverty and reducing the peak power demands from power stations. This shows that in the future, the EPBD [4] should also consider

these non-energy or social benefits for the macroeconomic calculation in addition to the cost of carbon.

5.1 Further research

The following are ideas for further research:

- Technical and economic feasibility study to improve the energy performance of social housing dwellings using active retrofit measures for domestic hot water.

- Technical and economic feasibility study to improve the energy performance of social housing dwellings using renewable energy sources.

- Thermal Comfort analysis for the middle floor and ground floor dwellings for a typical social housing block in Malta.

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Appendix 1

A.1.1 Housing Authority questionnaire

1. General

a) Entrance no.:

b) Flat no.:

c) No. of occupants:

2. Operation

a) Basic notes on typical building occupation schedule:

3. Fabric

3a. Fabric- walls

Have (insulation) upgrades been carried out to the external and/or courtyard wall construction? (Yes: 0 || No: 1)

3b. Fabric- glazing/shading

Have door/ window glazing been upgraded? (For example, to double glazing, UPVC frames, films installed etc.) (Yes: 0 || No: 1)

Is use made of internal blinds?

____

____

3c. Balconies

Have any modifications to the balconies been carried out? (Yes: 0 || No: 1)

____

____

____

4. **Equipment**

a. Lighting type

Dining room: % LEDs ____ % fluorescent ____ % incandescent____

Bathrooms: % LEDs ____ % fluorescent ____ % incandescent____

Bedrooms: % LEDs ____ % fluorescent ____ % incandescent____

Kitchen: % LEDs ____ % fluorescent ____ % incandescent____

Others: % LEDs ____ % fluorescent ____ % incandescent____

b. Space cooling and heating:

- List of zones with split-unit heat pump/s

____

____

____

- Age of heat pump equipment (are heat pumps inverter driven?):

____

____

____

- List of zones using heaters, state heating duration and type including fuel used for heaters

____

____

____

c. Domestic Hot Water (DHW)

No. and capacity of storage heaters:

- Storage heater 1: Capacity: ______ Distribution: _______________
- Storage heater 2: Capacity: ______ Distribution: _______________
- Are storage heater always switched on (0) or only prior to usage (1)? : _________
- Use of DHW heat pumps (Yes: 0 || No: 1): ___________

d. Refrigeration

- Refrigerator 1:

Class ___ Model ___

- Refrigerator 2:
  Class ___ Model ___

e. Cooking

- Is use made of electrical hobs or electric kettles? (Yes: 0 || No: 1)

  ____

- Is use made of microwave/ electric equipment for cooking? (Yes: 0 || No: 1)

  ____

  ____

f. Water

- Are aerators connected to faucets? (Yes: 0 || No: 1)

  ____

- Is water pressurised? (Yes: 0 || No: 1)

____

g. Plug loads:

- Use of dishwasher (Yes: 0 || No: 1):

- Other loads (for example PCs/ TV etc.):

5. Comfort issues

(Measurement for the next 2 questions:

1 -Hot; 2 -Warm; 3 -Slightly Warm; 4 -Neutral; 5 -Slightly Cool; 6 -Cool; 7 -Cold)

- Zones that feel uncomfortable in winter? What is done to control comfort?

  ____

  ____

  ____

  ____

- Zones that feel uncomfortably hot in summer? What is done to improve the comfort? (example opening of windows)

  ____

  ____

  ____

  ____

- Is high humidity/ lack of ventilation an issue? (Yes: 0 || No: 1):

  ____

____
___

____
___

6. General issues (example: plumbing issue, structural issues, water leakage, required plastering works, etc.)

____

____

____

____

____

____

____

____

Other notes:

- Electricity/water bills provided:

- Temperature loggers installed:

A.1.2 Data gathered from the questionnaires and energy bills

From the Questionnaire, a total of 12 variables (floor level, orientation, number of occupants, number of heat pumps, type of heater, water heater continuously being used, age of the fridge-freeze, age of the freezer, type of oven, number of electric equipment in the kitchen, age of the washing machine and other plug loads) were determined, to analyse energy performance in terms of equipment and building operation.

The results obtained are tabulated in the following tables by block house. The data configuration corresponds to the following:

- **Entrance Nº:** House block.
- **Flat Nº:** Flat number.
- **Nº of occupants:** Number of occupants by dwelling.
- **Quantity Heat Pumps:** Number of heat pumps been used in the dwelling.
- **Heaters Gas_hea / Electric_hea / None_hea:** Identifies whether the residents own a gas heater (Gas_hea), electric heater (Electric_hea) or none (None_hea).
- **Water heater Continuously On Yes / No:** Identifies whether the residents keep their water heater continuously on (Yes) or they use it prior to their needs (No).
- **Fridge-freezer Age New_dge / MidAge_dge / Old_dge / More_dge:** Identifies whether the residents had a fridge-freezer no older than 5 years (New_dge), between 5 and 10 years (MidAge_dge), more than 10 years (Old_dge) or more than one fridge-freezer (More_dge).
- **Freezer Age New_zer / MidAge_Zer / Old_zer / None_zer:** Identifies whether the residents had a freezer no older than 5 years (New_zer), between 5 and 10 years (MidAge_zer), more than 10 years (Old_zer) or more none (None_zer).
- **Oven Gas_ov / Electric_ov:** Identifies whether the residents own a gas oven (Gas_ov) or an electric oven (Electric_ov).
- **Quantity Electric Equipment for Cooking:** Number of plug loads being used in the kitchen for cooking, i.e. griglioso, microwave etc.
- **Washing Machine Age New_wm / MidAge_wm / Old_wm / More_wm:** Identifies whether the residents had a washing machine of less than than 5 years old (New_wm), between 5 and 10 years (MidAge_wm), more than 10 years (Old_wm) or more than one washing machine (More_wm).

- **Other Plug Loads:** Number of plugs loads used in the rest of the zones, i.e. TV's, computers, aquariums…
- **Total Consumption 17 kWh:** The number of kWh consumed in 2017 on each dwelling. For the dwellings were no data was collected, there is a blank space.
- **Uncomfortable_W / Comfortable_W Winter:** Identifies occupants' thermal sensation during winter period.
- **Uncomfortable_S / Comfortable_S Summer:** Identifies occupants' thermal sensation during summer period.

Table 28: Questionnaire results for block house A

Entrance N°	Flat N°	N° of occupants	Quantity Heat Pumps	Heaters Gas_hea / Electric_hea / None_hea	Water heater Continuously On Yes / No	Fridge-freezer Age New_dge / MidAge_dge / Old_dge / More_dge	Freezer Age New_zer / MidAge_zer / Old_zer / None_zer	Oven Gas_ov / Electric_ov	Quantity Electric Equipment for Cooking	Washing Machine Age New_wm / MidAge_wm / Old_wm / More_wm	Other Plug Loads	Total Consumption 17 kWh	Uncomfortable_W/ Comfortable_W Winter	Uncomfortable_S / Comfortable_S Summer
A	1	2	1	None_hea	Yes	New_dge	None_zer	Gas_ov	2	New_wm	4	1460	Comfortable_W	Uncomfortable_S
A	2	5	2	Gas_hea	No	New_dge	New_zer	Electric_ov	0	New_wm	3	1095	Uncomfortable_W	Comfortable_S
A	3	1	0	Electric_hea	No	Old_dge	None_zer	Gas_ov	2	New_wm	1	365	Uncomfortable_W	Comfortable_S
A	4	4	0	None_hea	No	MidAge_dge	None_zer	Gas_ov	2	Old_wm	3		Comfortable_W	Comfortable_S
A	5	2	1	Gas_hea	No	MidAge_dge	Old_zer	Gas_ov	2	New_wm	3	1095	Uncomfortable_W	Uncomfortable_S
A	6	3	0	Gas_hea	No	Old_dge	Old_zer	Gas_ov	2	Old_wm	1	365	Comfortable_W	Comfortable_S
A	7	5	0	Gas_hea	No	New_dge	New_zer	Electric_ov	0	New_wm	4	1460	Uncomfortable_W	Comfortable_S
A	8	5	0	Gas_hea	Yes	Old_dge	None_zer	Electric_ov	1	Old_wm	2	730	Uncomfortable_W	Comfortable_S
A	10	2	1	Gas_hea	Yes	Old_dge	None_zer	Electric_ov	0	New_wm	1	365	Uncomfortable_W	Uncomfortable_S

Table 29: Questionnaire results for block house B

Entrance N°	**Flat N°**	**N° of occupants**	**Quantity Heat Pumps**	**Heaters Gas_hea / Electric_hea / None_hea**	**Water heater Continuously On Yes / No**	**Fridge-freezer Age New_dge / MidAge_dge / Old_dge / More_dge**	**Freezer Age New_zer / MidAge_zer / Old_zer / None_zer**	**Oven Gas_ov / Electric_ov**	**Quantity Electric Equipment for Cooking**	**Washing Machine Age New_wm / MidAge_wm / Old_wm / More_wm**	**Other Plug Loads**	**Total Consumption 17 kWh**	**Uncomfortable_W/ Comfortable_W Winter**	**Uncomfortable_S / Comfortable_S Summer**
B	1	3	0	Electric_hea	No	Old_dge	Old_zer	Gas_ov	2	New_wm	0		Uncomfortable_W	Comfortable_S
B	4	1	1	None_hea	No	New_dge	None_zer	Gas_ov	2	New_wm	2	730	Comfortable_W	Uncomfortable_S
B	5	7	3	Gas_hea	Yes	MidAge_dge	None_zer	Gas_ov	1	New_wm	3	1095	Comfortable_W	Comfortable_S
B	9	5	0	Gas_hea	Yes	More_dge	None_zer	Electric_ov	2	New_wm	7	2555	Uncomfortable_W	Uncomfortable_S
B	10	2	1	Gas_hea	No	New_dge	New_zer	Gas_ov	0	MidAge_wm	2	730	Uncomfortable_W	Uncomfortable_S

Table 30: Questionnaire results for block house C

Entrance N°	Flat N°	N° of occupants	Quantity Heat Pumps	Heaters Gas_hea / Electric_hea / None_hea	Water heater Continuously On Yes / No	Fridge-freezer Age New_dge / MidAge_dge / Old_dge / More_dge	Freezer Age New_zer / MidAge_zer / Old_zer / None_zer	Oven Gas_ov / Electric_ov	Quantity Electric Equipment for Cooking	Washing Machine Age New_wm / MidAge_wm / Old_wm / More_wm	Other Plug Loads	Total Consumption 17 kWh	Uncomfortable_W/ Comfortable_W Winter	Uncomfortable_S / Comfortable_S Summer
C	1	5	0	Gas_hea	Yes	Old_dge	None_zer	Electric_ov	0	More_wm	0		Uncomfortable_W	Comfortable_S
C	2	3	0	None_hea	Yes	MidAge_dge	MidAge_zer	Gas_ov	2	New_wm	1	365	Comfortable_W	Uncomfortable_S
C	4	3	1	Gas_hea	Yes	Old_dge	MidAge_zer	Gas_ov	2	New_wm	3	1095	Comfortable_W	Uncomfortable_S
C	5	2	0	Gas_hea	No	Old_dge	None_zer	Gas_ov	2	New_wm	2	730	Comfortable_W	Comfortable_S
C	6	3	0	None_hea	Yes	MidAge_dge	None_zer	Gas_ov	1	New_wm	3		Comfortable_W	Comfortable_S
C	7	3	0	Electric_hea	Yes	MidAge_dge	None_zer	Gas_ov	1	New_wm	5	1825	Comfortable_W	Comfortable_S
C	8	4-5	2	None_hea	Yes	Old_dge	None_zer	Gas_ov	1	New_wm	0	0	Comfortable_W	Comfortable_S
C	9	4	2	None_hea	No	MidAge_dge	New_zer	Electric_ov	1	New_wm	6	2190	Uncomfortable_W	Uncomfortable_S
C	10	5	2	Gas_hea	No	MidAge_dge	New_zer	Electric_ov	0	New_wm	6	2190	Uncomfortable_W	Uncomfortable_S

Table 31: Questionnaire results for block house D

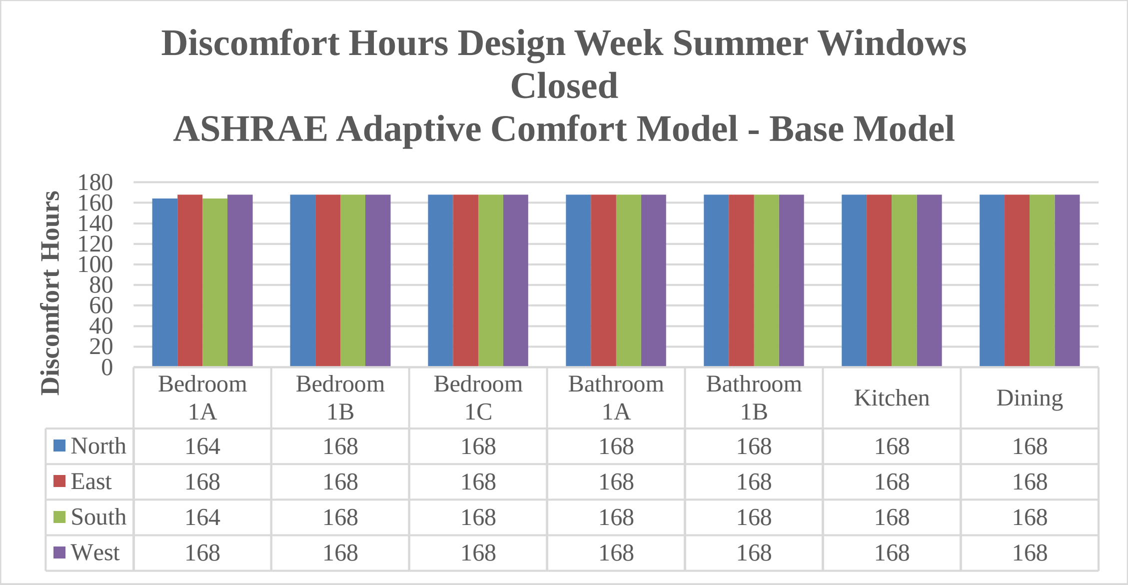
Entrance N°	Flat N°	N° of occupants	Quantity Heat Pumps	Heaters Gas_hea / Electric_hea / None_hea	Water heater Continuously On Yes / No	Fridge-freezer Age New_dge / MidAge_dge / Old_dge / More_dge	Freezer Age New_zer / MidAge_zer / Old_zer / None_zer	Oven Gas_ov / Electric_ov	Quantity Electric Equipment for Cooking	Washing Machine Age New_wm / MidAge_wm / Old_wm / More_wm	Other Plug Loads	Total Consumption 17 kWh	Uncomfortable_W/ Comfortable_W Winter	Uncomfortable_S / Comfortable_S Summer
D	3	2	2	None_hea	No	MidAge_dge	None_zer	Electric_ov	1	MidAge_wm	2	730	Comfortable_W	Uncomfortable_S
D	4	2	0	Electric_hea	Yes	New_dge	None_zer	Electric_ov	0	New_wm	1	365	Comfortable_W	Comfortable_S
D	5	2	1	None_hea	Yes	Old_dge	Old_zer	Gas_ov	2	New_wm	2	730	Comfortable_W	Uncomfortable_S
D	6	6	0	Gas_hea	No	New_dge	None_zer	Gas_ov	1	New_wm	0	0	Uncomfortable_W	Uncomfortable_S
D	7	3	1	None_hea	Yes	Old_dge	None_zer	Gas_ov	1	MidAge_wm	3	1095	Comfortable_W	Uncomfortable_S
D	8	4	0	Electric_hea	Yes	Old_dge	Old_zer	Gas_ov	2	MidAge_wm	3	1095	Comfortable_W	Comfortable_S
D	9	2	0	Electric_hea	Yes	Old_dge	None_zer	Gas_ov	0	Old_wm	1		Uncomfortable_W	Uncomfortable_S
D	10	3	2	None_hea	Yes	MidAge_dge	None_zer	Gas_ov	1	New_wm	3	1095	Uncomfortable_W	Uncomfortable_S

Appendix 2

A2.1 Discomfort hours analysis

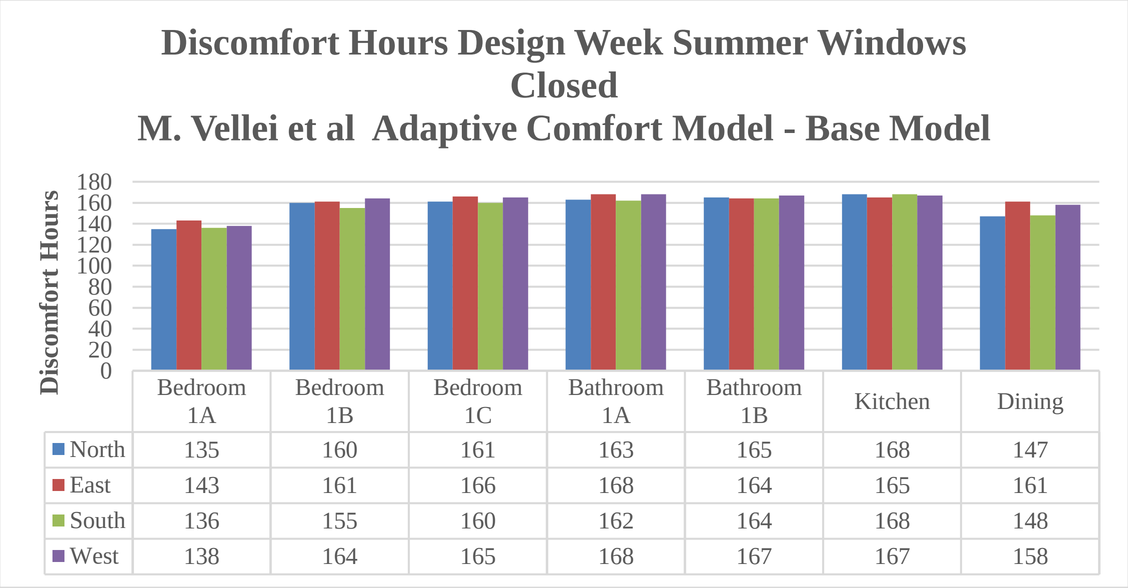
A2.1.1 Summer design week - Base building scenario

Windows close



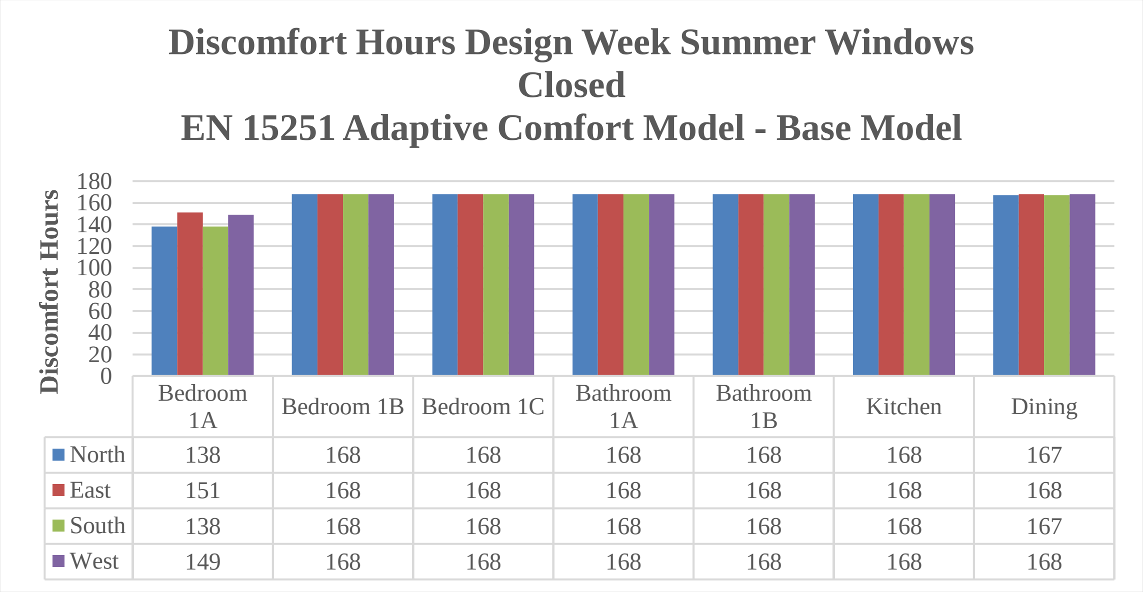
	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
■ North	164	168	168	168	168	168	168
■ East	168	168	168	168	168	168	168
■ South	164	168	168	168	168	168	168
■ West	168	168	168	168	168	168	168

Figure 69: Base scenario number of Discomfort Hours during the Summer design week for windows close configuration on the ASHRAE adaptive comfort model



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
■ North	135	160	161	163	165	168	147
■ East	143	161	166	168	164	165	161
■ South	136	155	160	162	164	168	148
■ West	138	164	165	168	167	167	158

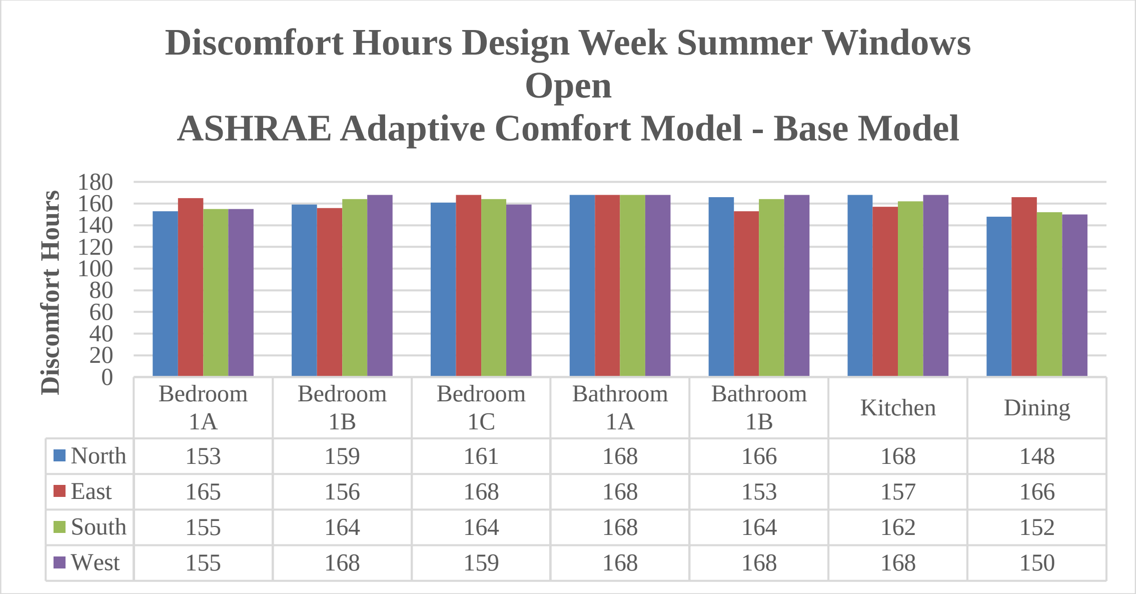
Figure 70: Base scenario number of Discomfort Hours during the Summer design week for windows close configuration on the M. Vellei et al. [35] ***model***



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
■ North	138	168	168	168	168	168	167
■ East	151	168	168	168	168	168	168
■ South	138	168	168	168	168	168	167
■ West	149	168	168	168	168	168	168

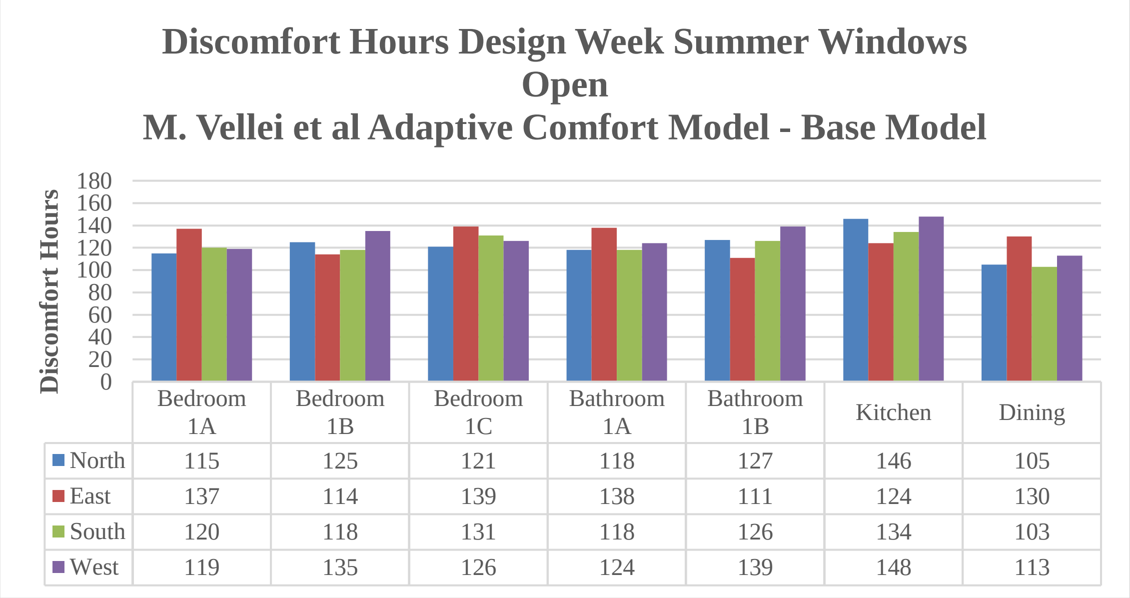
Figure 71: Base scenario number of Discomfort Hours during the Summer design week for windows close configuration on the EN 15251 adaptive comfort model

Windows open



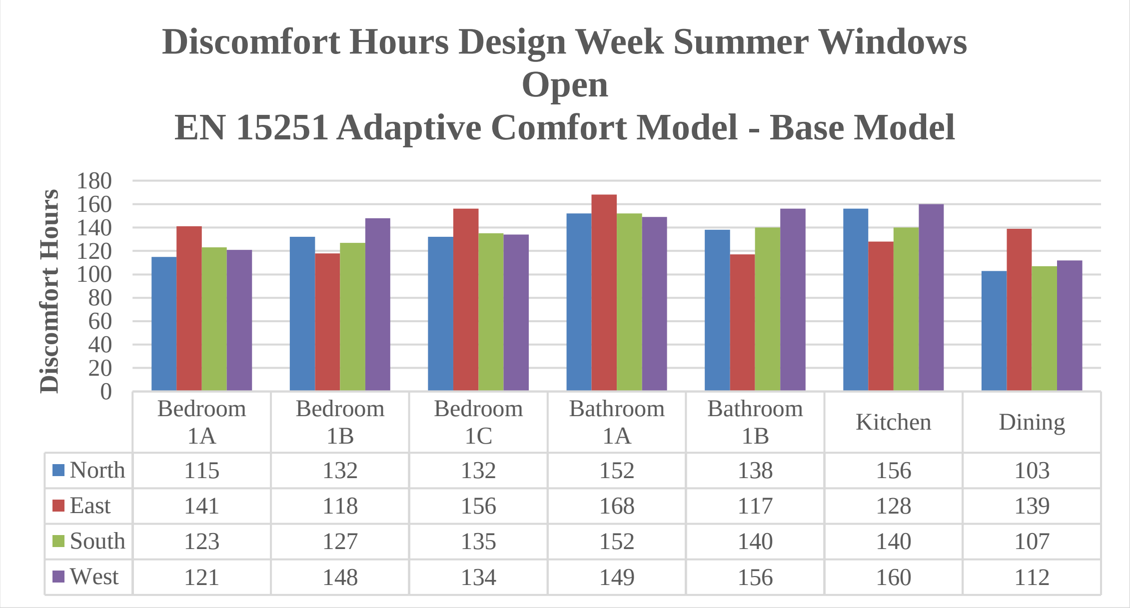
	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	153	159	161	168	166	168	148
🟥 East	165	156	168	168	153	157	166
🟩 South	155	164	164	168	164	162	152
🟪 West	155	168	159	168	168	168	150

Figure 72: Base scenario number of Discomfort Hours during the Summer design week for windows open configuration on the ASHRAE adaptive comfort model



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	115	125	121	118	127	146	105
🟥 East	137	114	139	138	111	124	130
🟩 South	120	118	131	118	126	134	103
🟪 West	119	135	126	124	139	148	113

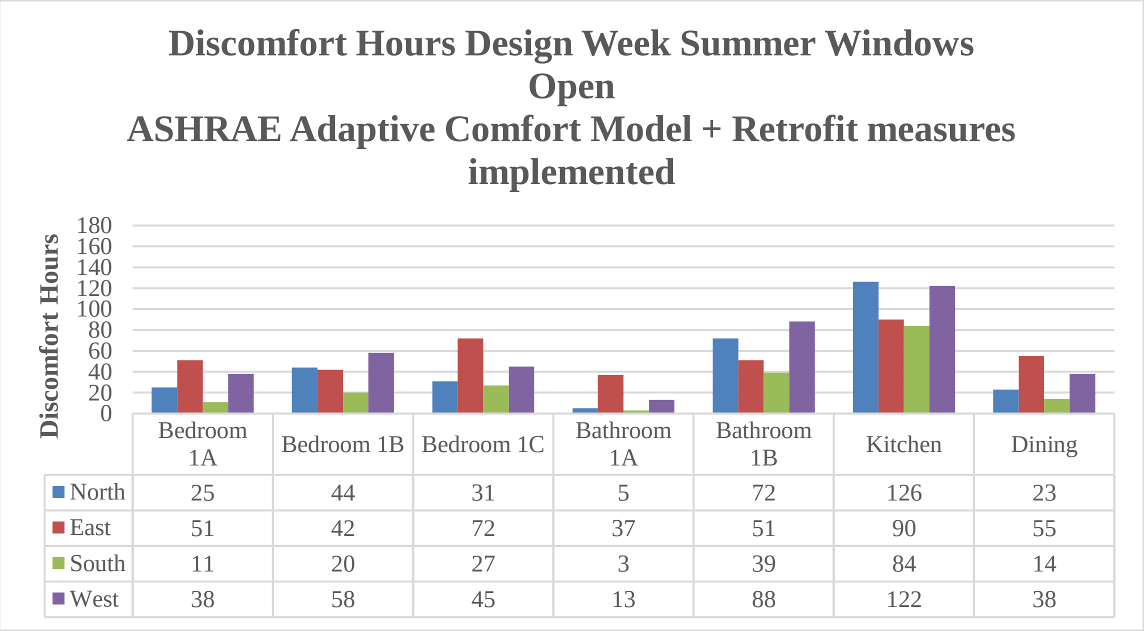
Figure 73: Base scenario number of Discomfort Hours during the Summer design week for windows open configuration on the M. Vellei et al. [35] ***model***



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	115	132	132	152	138	156	103
🟥 East	141	118	156	168	117	128	139
🟩 South	123	127	135	152	140	140	107
🟪 West	121	148	134	149	156	160	112

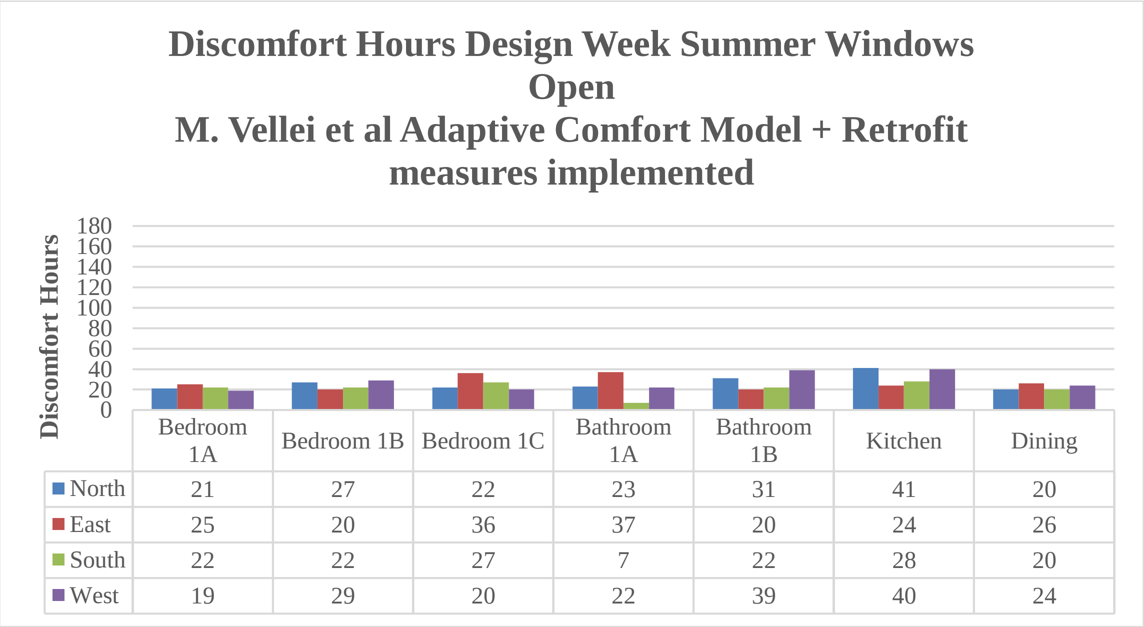
Figure 74: Base scenario number of Discomfort Hours during the Summer design week for windows open configuration on the EN 15251 adaptive comfort model

A2.1.2 Summer design week - Building with all retrofit measures



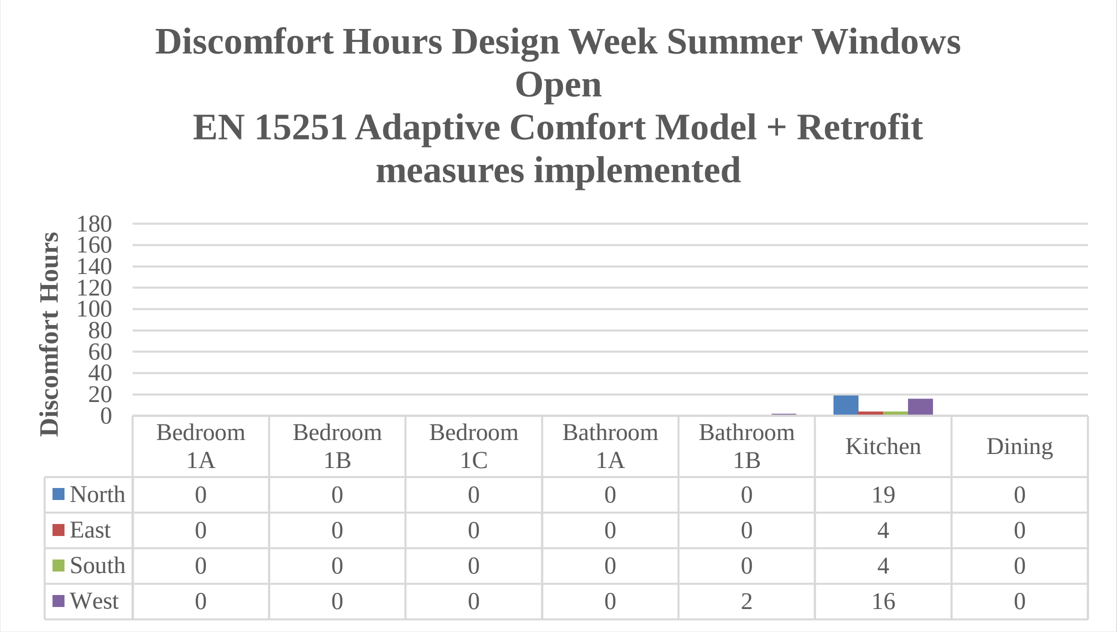
	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	25	44	31	5	72	126	23
🟥 East	51	42	72	37	51	90	55
🟩 South	11	20	27	3	39	84	14
🟪 West	38	58	45	13	88	122	38

Figure 75: Base scenario number of Discomfort Hours during the Summer design week for windows open configuration and all retrofit measures implemented on the ASHRAE adaptive comfort model



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	21	27	22	23	31	41	20
🟥 East	25	20	36	37	20	24	26
🟩 South	22	22	27	7	22	28	20
🟪 West	19	29	20	22	39	40	24

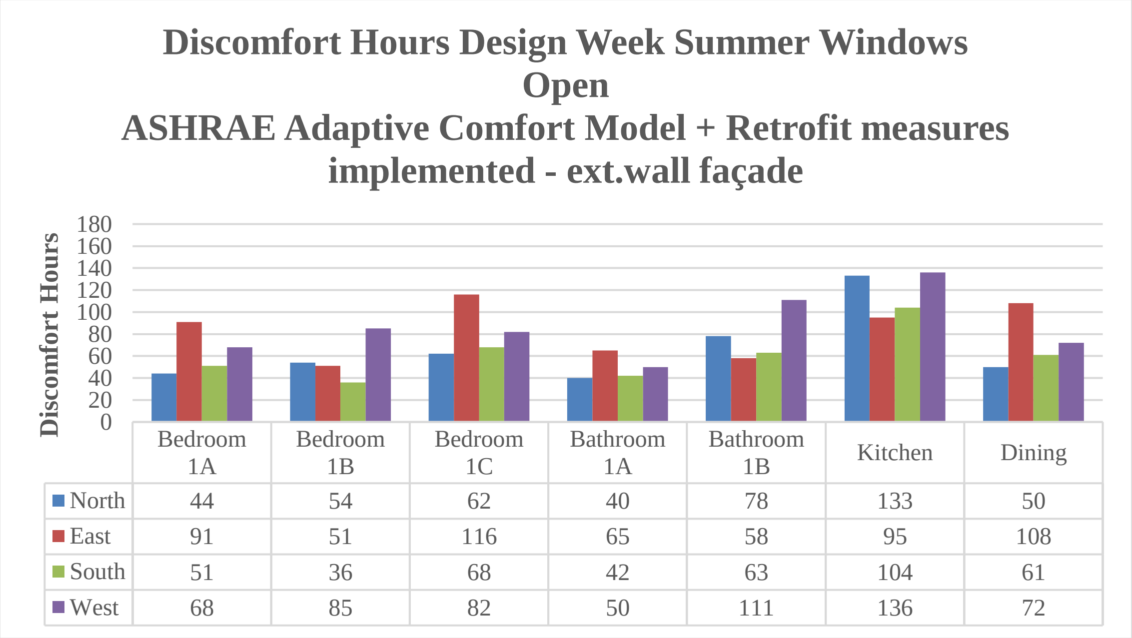
Figure 76: Base scenario number of Discomfort Hours during the Summer design week for windows open configuration and all retrofit measures implemented on the M. Vellei et al. [35] ***model***



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	0	0	0	0	0	19	0
🟥 East	0	0	0	0	0	4	0
🟩 South	0	0	0	0	0	4	0
🟪 West	0	0	0	0	2	16	0

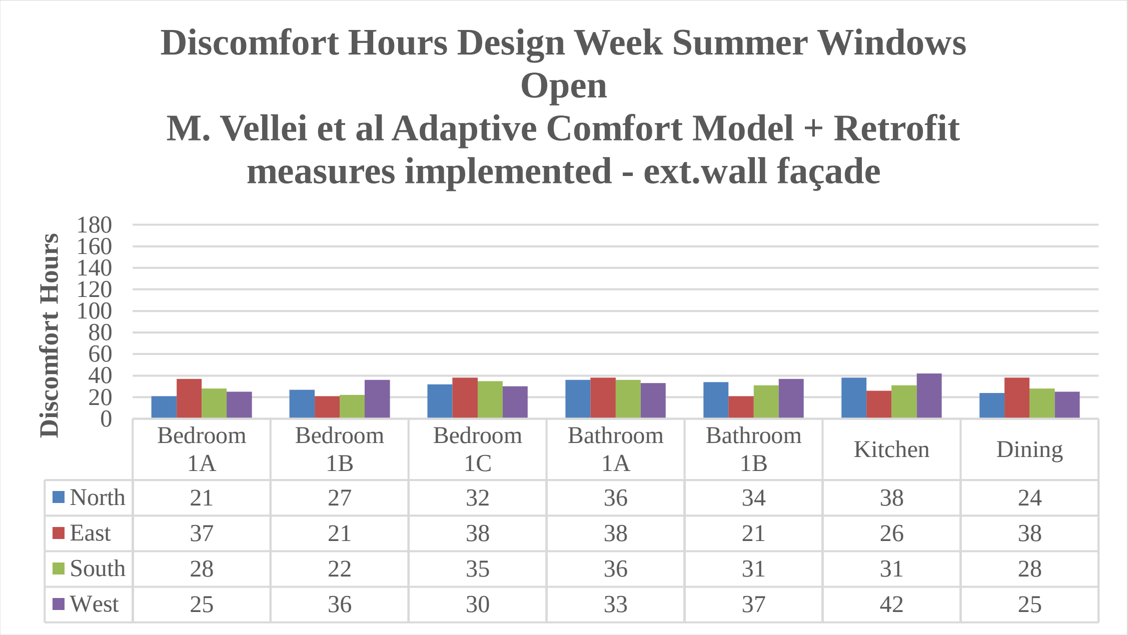
Figure 77: Base scenario number of Discomfort Hours during the Summer design week for windows open configuration and all retrofit measures implemented on the EN 15251 adaptive comfort model

A2.1.3 Summer design week- Building with all retrofit measures except for the external wall façade



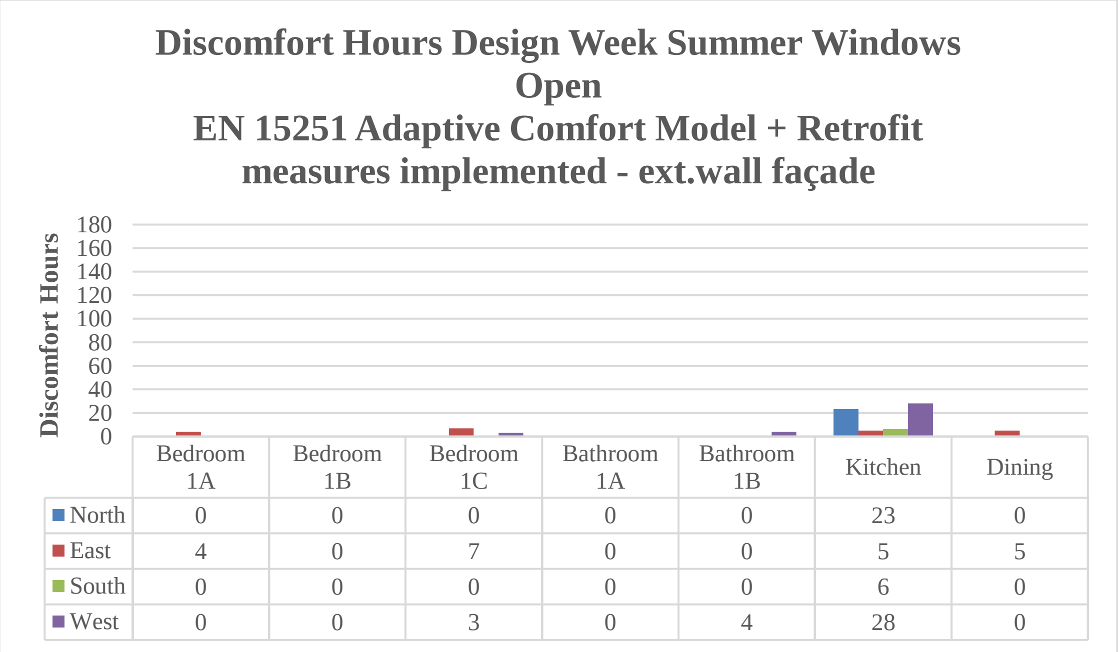
	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	44	54	62	40	78	133	50
🟥 East	91	51	116	65	58	95	108
🟩 South	51	36	68	42	63	104	61
🟪 West	68	85	82	50	111	136	72

Figure 78: Base scenario number of Discomfort Hours during the Summer design week for windows open configuration and all retrofit measures implemented except for the external wall façade insulation on the ASHRAE adaptive comfort model



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
North	21	27	32	36	34	38	24
East	37	21	38	38	21	26	38
South	28	22	35	36	31	31	28
West	25	36	30	33	37	42	25

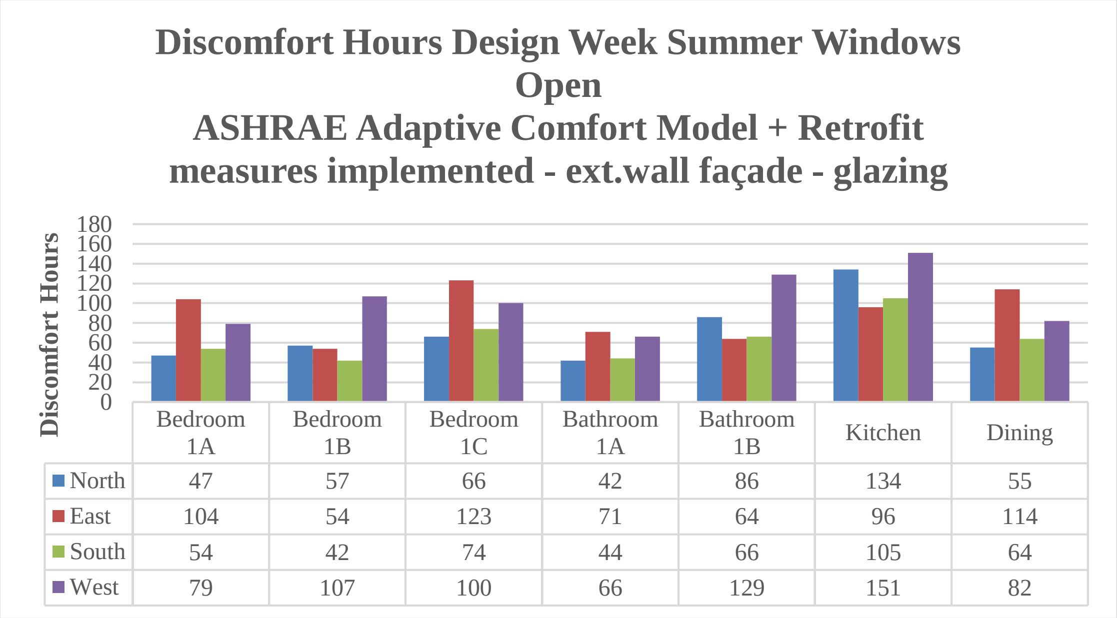
Figure 79: Base scenario number of Discomfort Hours during the Summer design week for windows open configuration and all retrofit measures implemented except for the external wall façade insulation on the M. Vellei et al. [35] ***model***



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
North	0	0	0	0	0	23	0
East	4	0	7	0	0	5	5
South	0	0	0	0	0	6	0
West	0	0	3	0	4	28	0

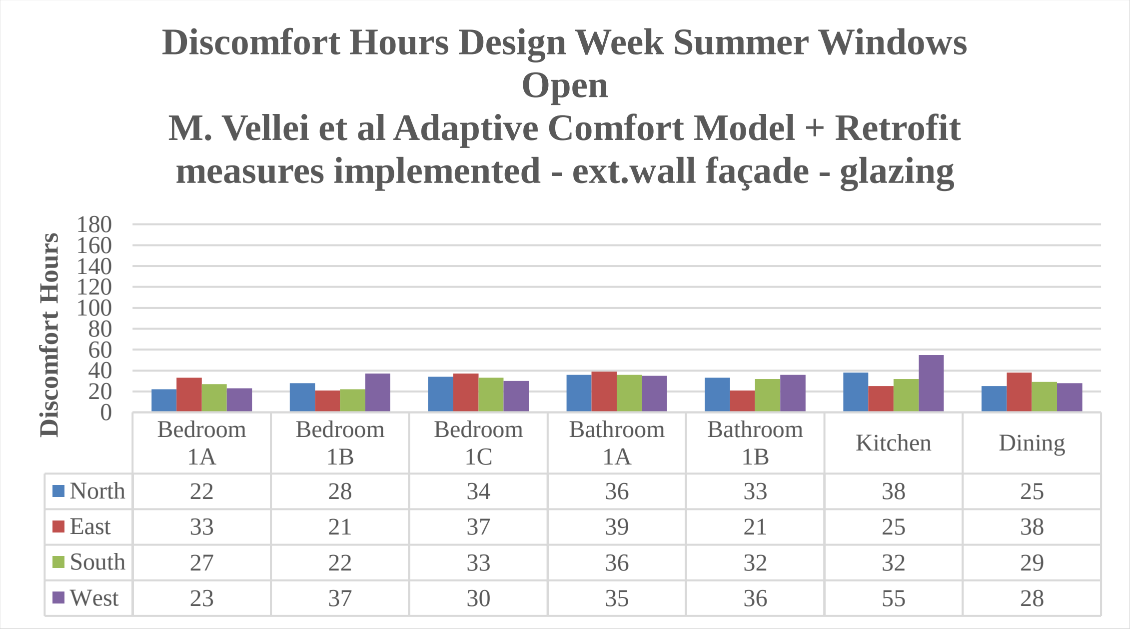
Figure 80: Base scenario number of Discomfort Hours during the Summer design week for windows open configuration and all retrofit measures implemented except for the external wall façade insulation on the EN 15251 adaptive comfort model

A2.1.4 Summer design week - Building with all retrofit measures except for the external wall façade and double glazing



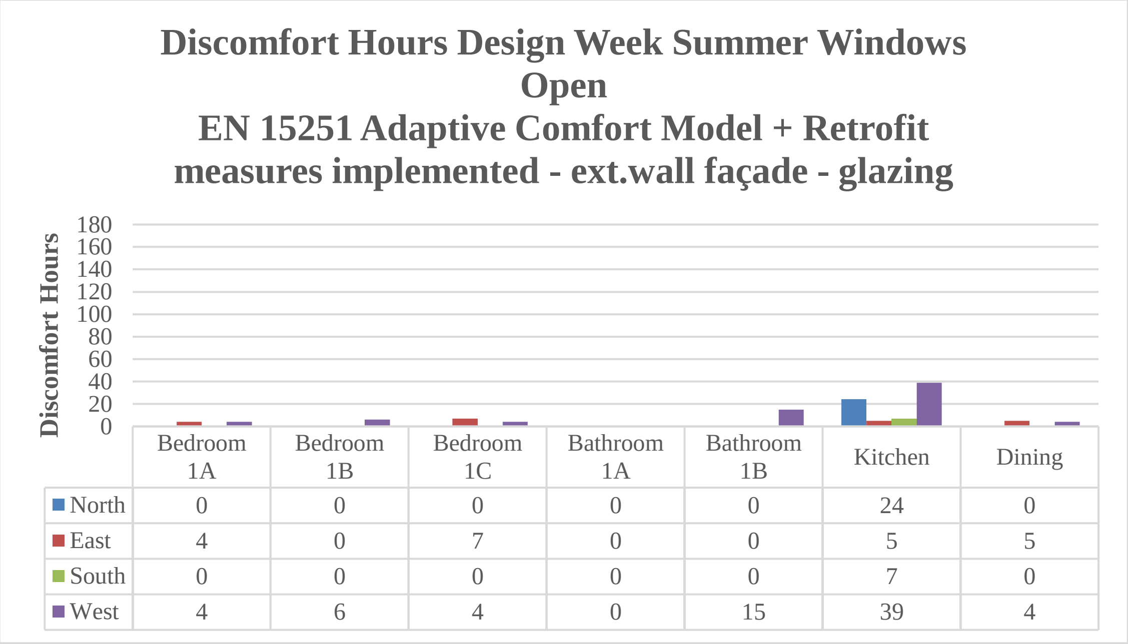
	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	47	57	66	42	86	134	55
🟥 East	104	54	123	71	64	96	114
🟩 South	54	42	74	44	66	105	64
🟪 West	79	107	100	66	129	151	82

Figure 81: Base scenario number of Discomfort Hours during the Summer design week for windows open configuration and all retrofit measures implemented except for the external wall façade insulation and double glazing on the ASHRAE adaptive comfort model



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	22	28	34	36	33	38	25
🟥 East	33	21	37	39	21	25	38
🟩 South	27	22	33	36	32	32	29
🟪 West	23	37	30	35	36	55	28

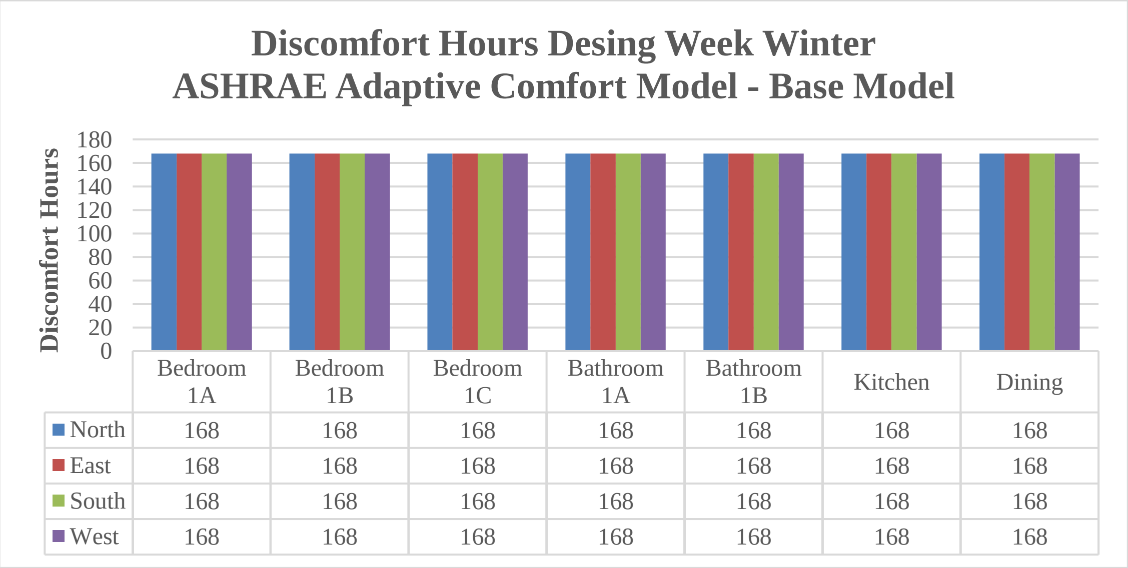
Figure 82: Base scenario number of Discomfort Hours during the Summer design week for windows open configuration and all retrofit measures implemented except for the external wall façade insulation and double glazing on the M. Vellei ***et al.*** [35] *model*



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	0	0	0	0	0	24	0
🟥 East	4	0	7	0	0	5	5
🟩 South	0	0	0	0	0	7	0
🟪 West	4	6	4	0	15	39	4

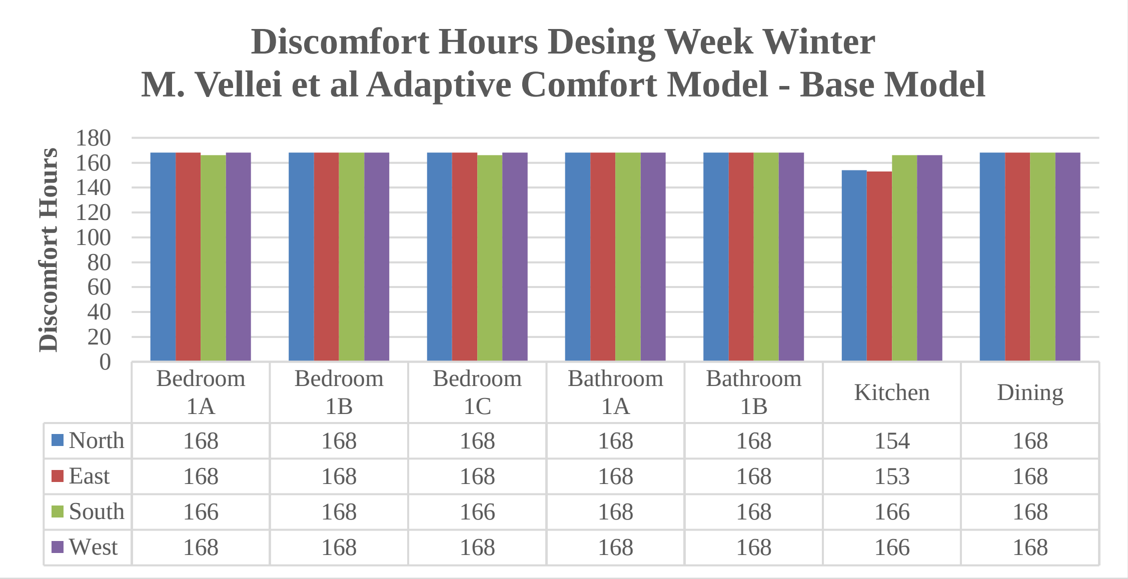
Figure 83: Base scenario number of Discomfort Hours during the Summer design week for windows open configuration and all retrofit measures implemented except for the external wall façade insulation and double glazing on the EN 15251 adaptive comfort model

A2.1.5 Winter design week - Base building scenario



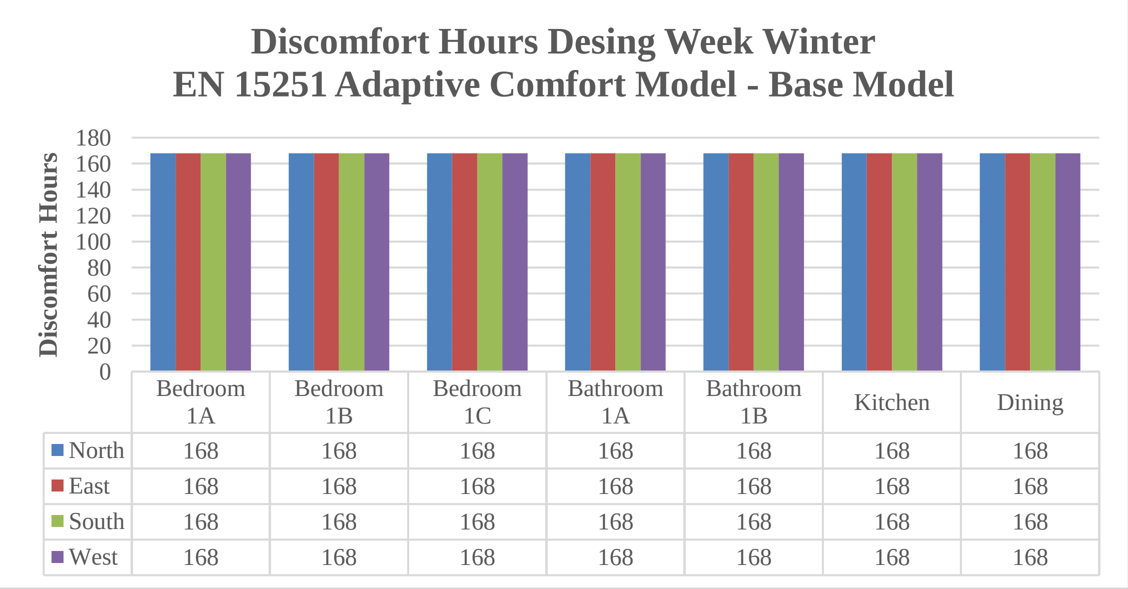
	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	168	168	168	168	168	168	168
🟥 East	168	168	168	168	168	168	168
🟩 South	168	168	168	168	168	168	168
🟪 West	168	168	168	168	168	168	168

Figure 84: Base scenario number of Discomfort Hours during the Winter design week for windows close configuration on the ASHRAE adaptive comfort model



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	168	168	168	168	168	154	168
🟥 East	168	168	168	168	168	153	168
🟩 South	166	168	166	168	168	166	168
🟪 West	168	168	168	168	168	166	168

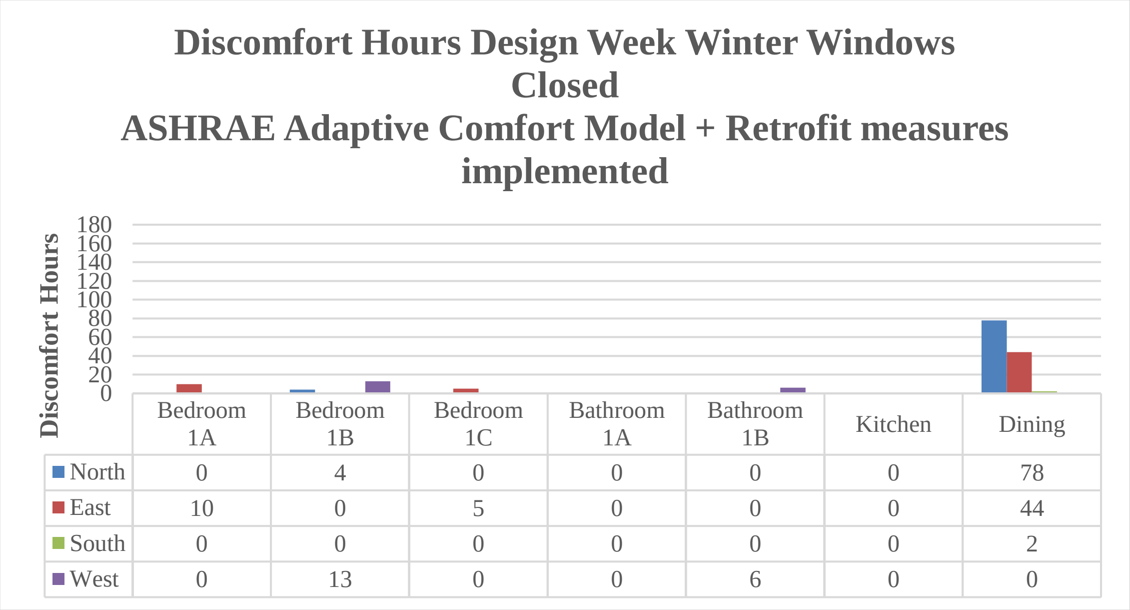
Figure 85: Base scenario number of Discomfort Hours during the Winter design week for windows close configuration on the M. Vellei et al. [35] ***model***



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	168	168	168	168	168	168	168
🟥 East	168	168	168	168	168	168	168
🟩 South	168	168	168	168	168	168	168
🟪 West	168	168	168	168	168	168	168

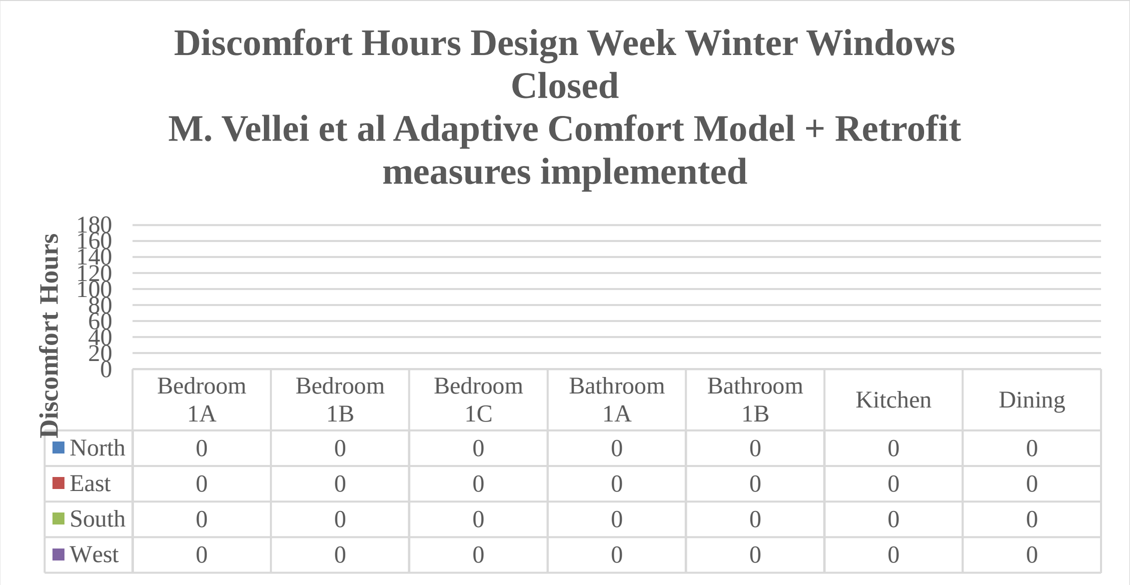
Figure 86: Base scenario number of Discomfort Hours during the Winter design week for windows close configuration on the EN 15251 adaptive comfort model

A2.1.6 Winter design week - Building with all retrofit measures



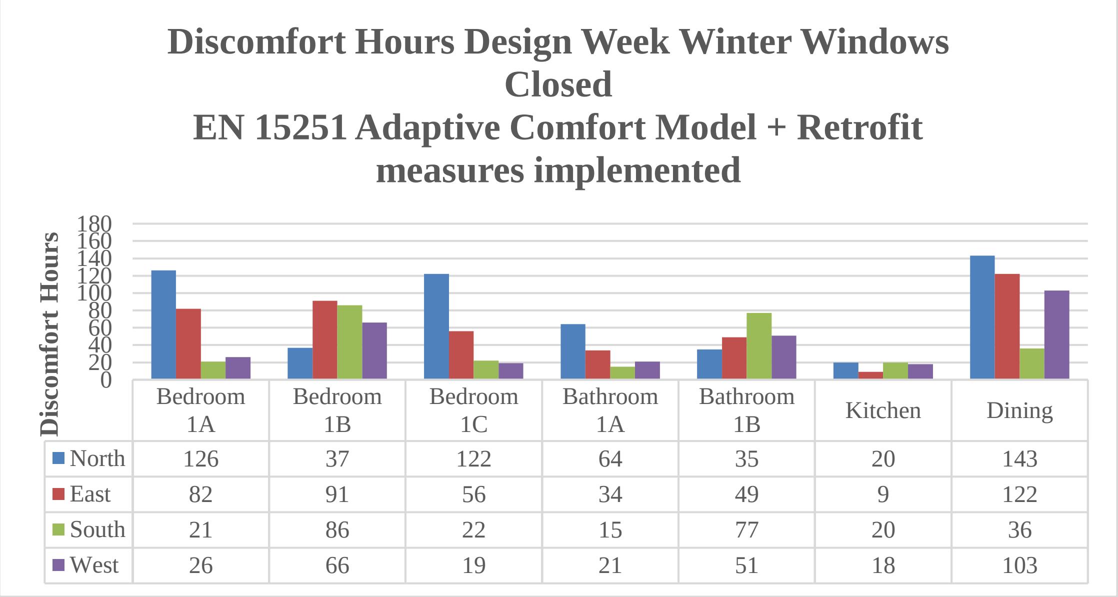
	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	0	4	0	0	0	0	78
🟥 East	10	0	5	0	0	0	44
🟩 South	0	0	0	0	0	0	2
🟪 West	0	13	0	0	6	0	0

Figure 87: Base scenario number of Discomfort Hours during the Winter design week for windows close configuration and all retrofit measures implemented on the ASHRAE adaptive comfort model



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	0	0	0	0	0	0	0
🟥 East	0	0	0	0	0	0	0
🟩 South	0	0	0	0	0	0	0
🟪 West	0	0	0	0	0	0	0

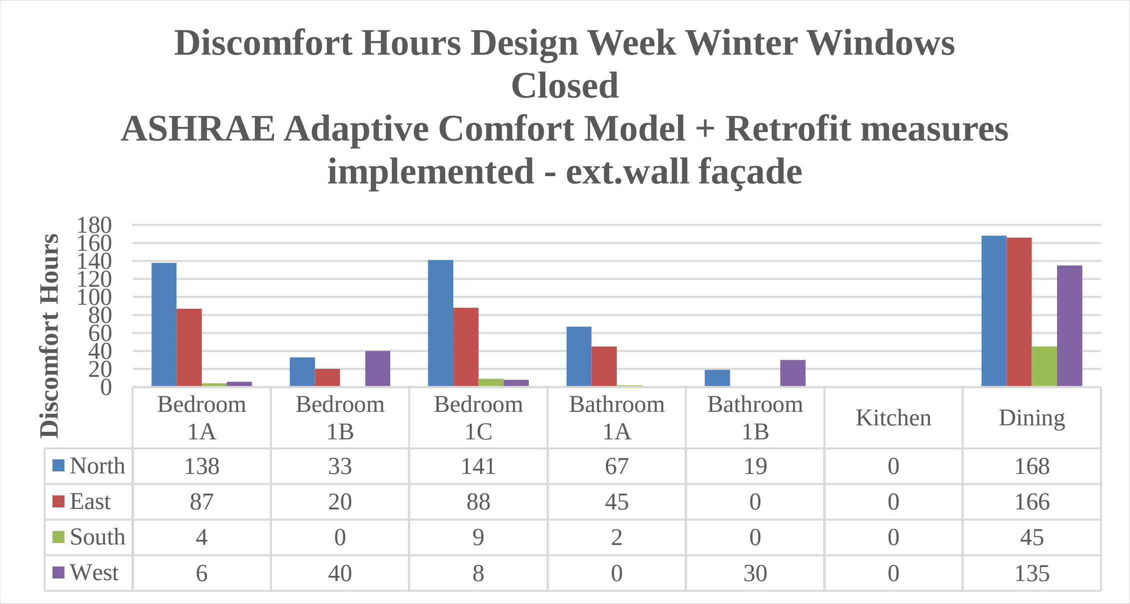
Figure 88: Base scenario number of Discomfort Hours during the Winter design week for windows close configuration and all retrofit measures implemented on the M. Vellei et al. [35] *model*



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	126	37	122	64	35	20	143
🟥 East	82	91	56	34	49	9	122
🟩 South	21	86	22	15	77	20	36
🟪 West	26	66	19	21	51	18	103

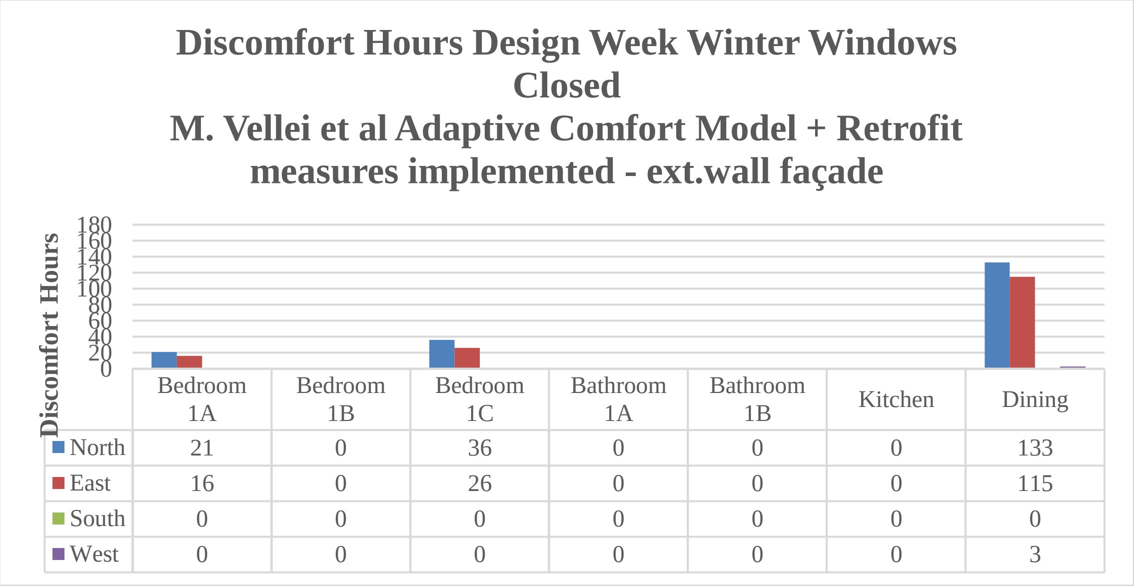
Figure 89: Base scenario number of Discomfort Hours during the Winter design week for windows close configuration and all retrofit measures implemented on the EN 15251 adaptive comfort model

A2.1.7 Winter design week - Building with all retrofit measures except for the external wall façade insulation



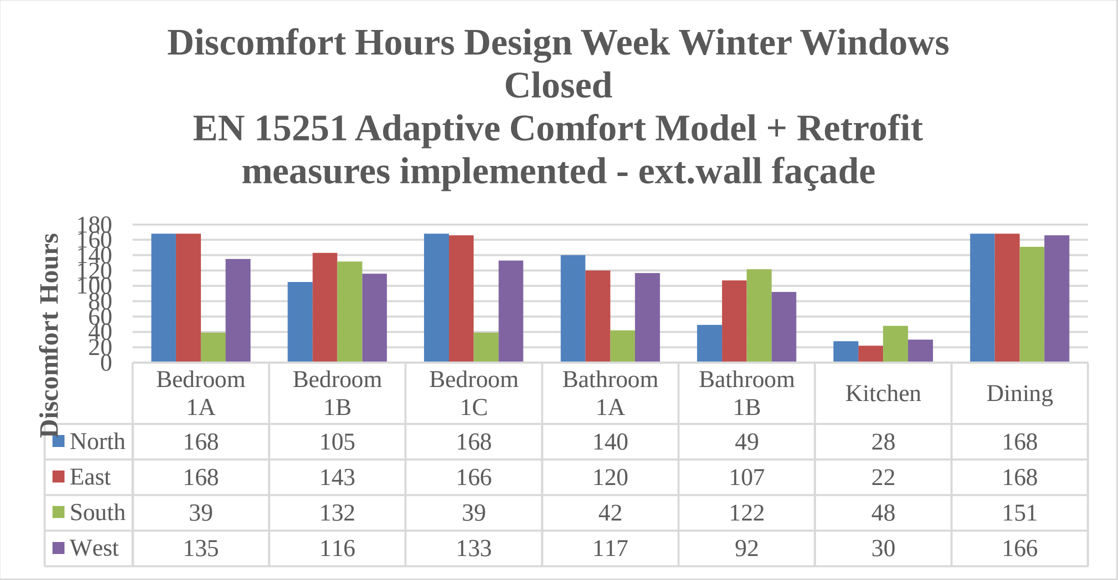
	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	138	33	141	67	19	0	168
🟥 East	87	20	88	45	0	0	166
🟩 South	4	0	9	2	0	0	45
🟪 West	6	40	8	0	30	0	135

Figure 90: Base scenario number of Discomfort Hours during the Winter design week for windows close configuration and all retrofit measures implemented except for the external wall façade insulation on the ASHRAE adaptive comfort model



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	21	0	36	0	0	0	133
🟥 East	16	0	26	0	0	0	115
🟩 South	0	0	0	0	0	0	0
🟪 West	0	0	0	0	0	0	3

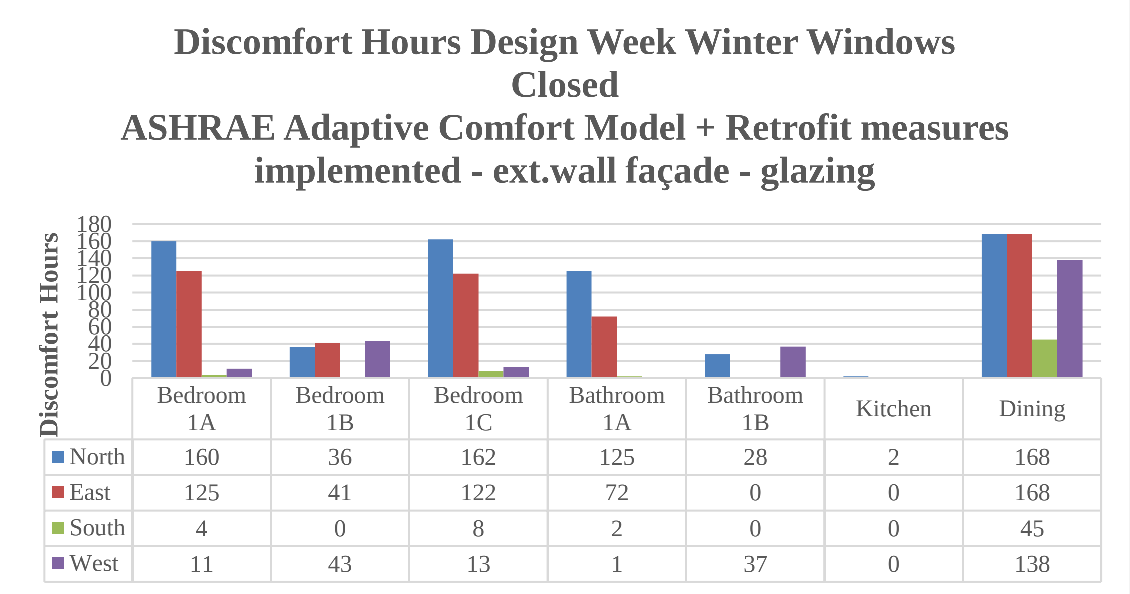
Figure 91: Base scenario number of Discomfort Hours during the Winter design week for windows close configuration and all retrofit measures implemented except for the external wall façade insulation on the M. Vellei ***et al.*** [35] *model*



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	168	105	168	140	49	28	168
🟥 East	168	143	166	120	107	22	168
🟩 South	39	132	39	42	122	48	151
🟪 West	135	116	133	117	92	30	166

Figure 92: Base scenario number of Discomfort Hours during the Winter design week for windows close configuration and all retrofit measures implemented except for the external wall façade insulation on the EN 15251 adaptive comfort model

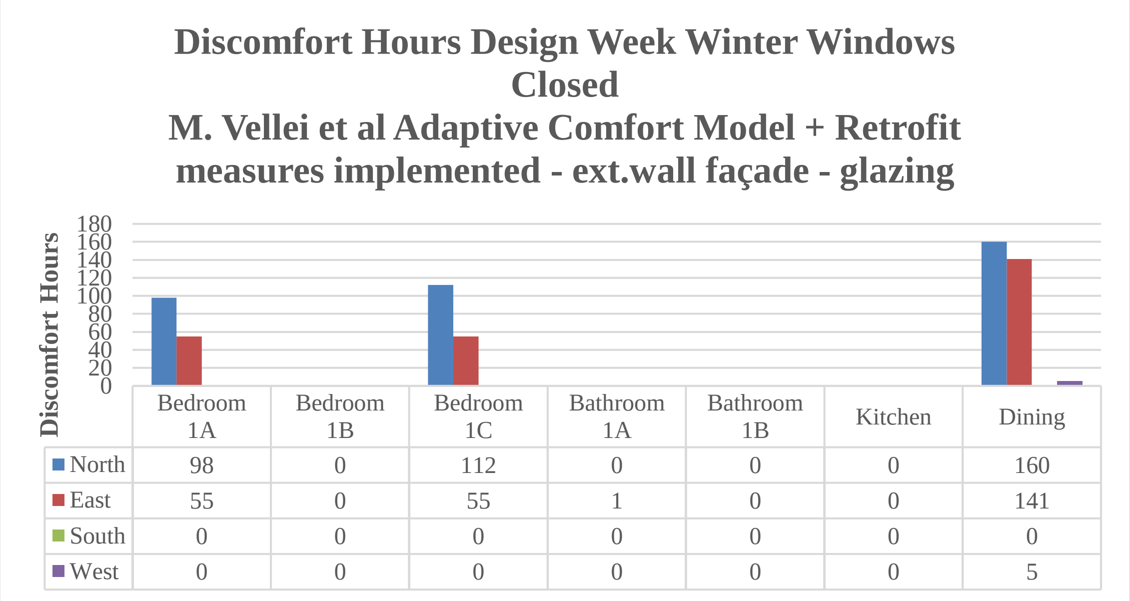
A2.1.8 Winter design week - Building with all retrofit measures except for the external wall façade and double glazing



Discomfort Hours Design Week Winter Windows Closed
ASHRAE Adaptive Comfort Model + Retrofit measures implemented - ext.wall façade - glazing

	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	160	36	162	125	28	2	168
🟥 East	125	41	122	72	0	0	168
🟩 South	4	0	8	2	0	0	45
🟪 West	11	43	13	1	37	0	138

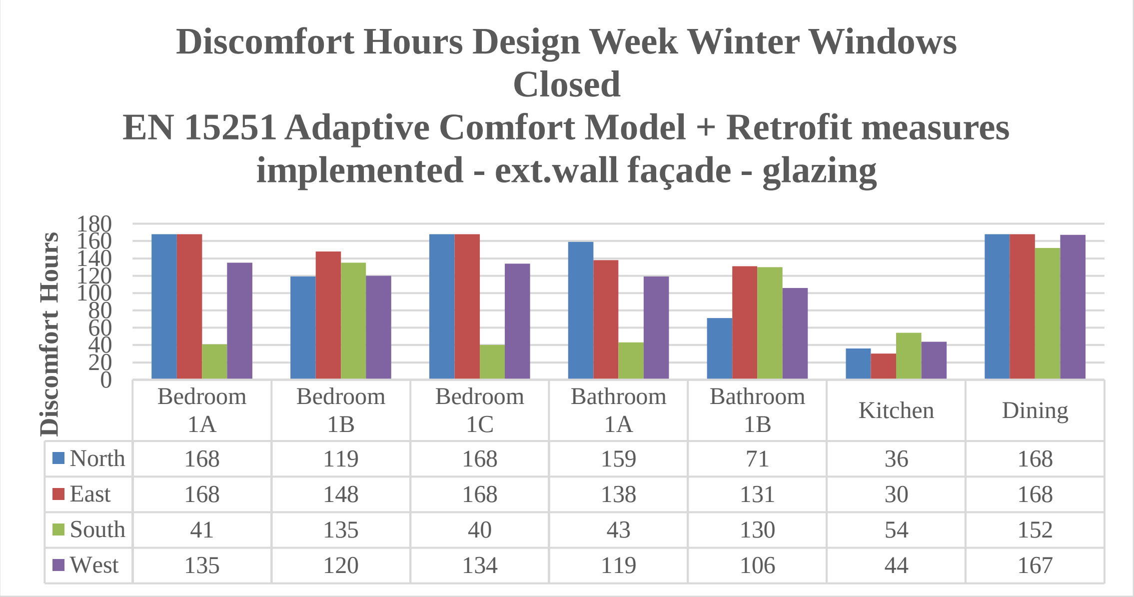
Figure 93: Base scenario number of Discomfort Hours during the Winter design week for windows close configuration and all retrofit measures implemented except for the external wall façade insulation and double glazing on the ASHRAE adaptive comfort model



Discomfort Hours Design Week Winter Windows Closed
M. Vellei et al Adaptive Comfort Model + Retrofit measures implemented - ext.wall façade - glazing

	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	98	0	112	0	0	0	160
🟥 East	55	0	55	1	0	0	141
🟩 South	0	0	0	0	0	0	0
🟪 West	0	0	0	0	0	0	5

Figure 94: Base scenario number of Discomfort Hours during the Winter design week for windows close configuration and all retrofit measures implemented except for the external wall façade insulation and double glazing on the M. Vellei et al. [35] *model*



	Bedroom 1A	Bedroom 1B	Bedroom 1C	Bathroom 1A	Bathroom 1B	Kitchen	Dining
🟦 North	168	119	168	159	71	36	168
🟥 East	168	148	168	138	131	30	168
🟩 South	41	135	40	43	130	54	152
🟪 West	135	120	134	119	106	44	167

Figure 95: Base scenario number of Discomfort Hours during the Winter design week for windows close configuration and all retrofit measures implemented except for the external wall façade insulation and double glazing on the EN 15251 adaptive comfort model

A2.2 Comfort analysis using scatter plots

A2.2.1 Summer design week - Base building comparison for windows open and windows close

Bedroom 1A North

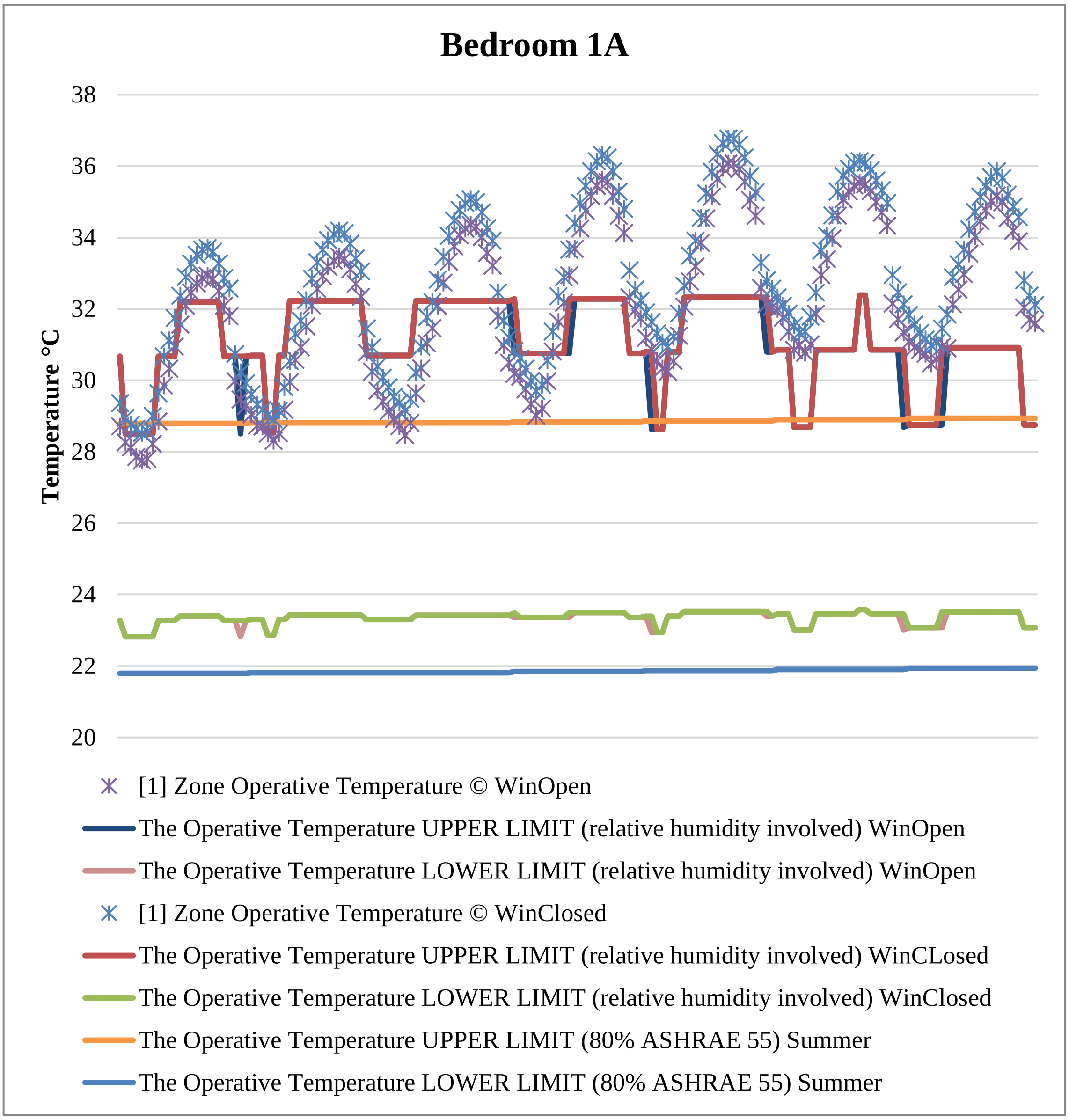


Figure 96: Summer design week ASHRAE and M. Vellei et al. [35] ***comfort analysis for Bedroom 1A facing North orientation using different windows opening configurations***

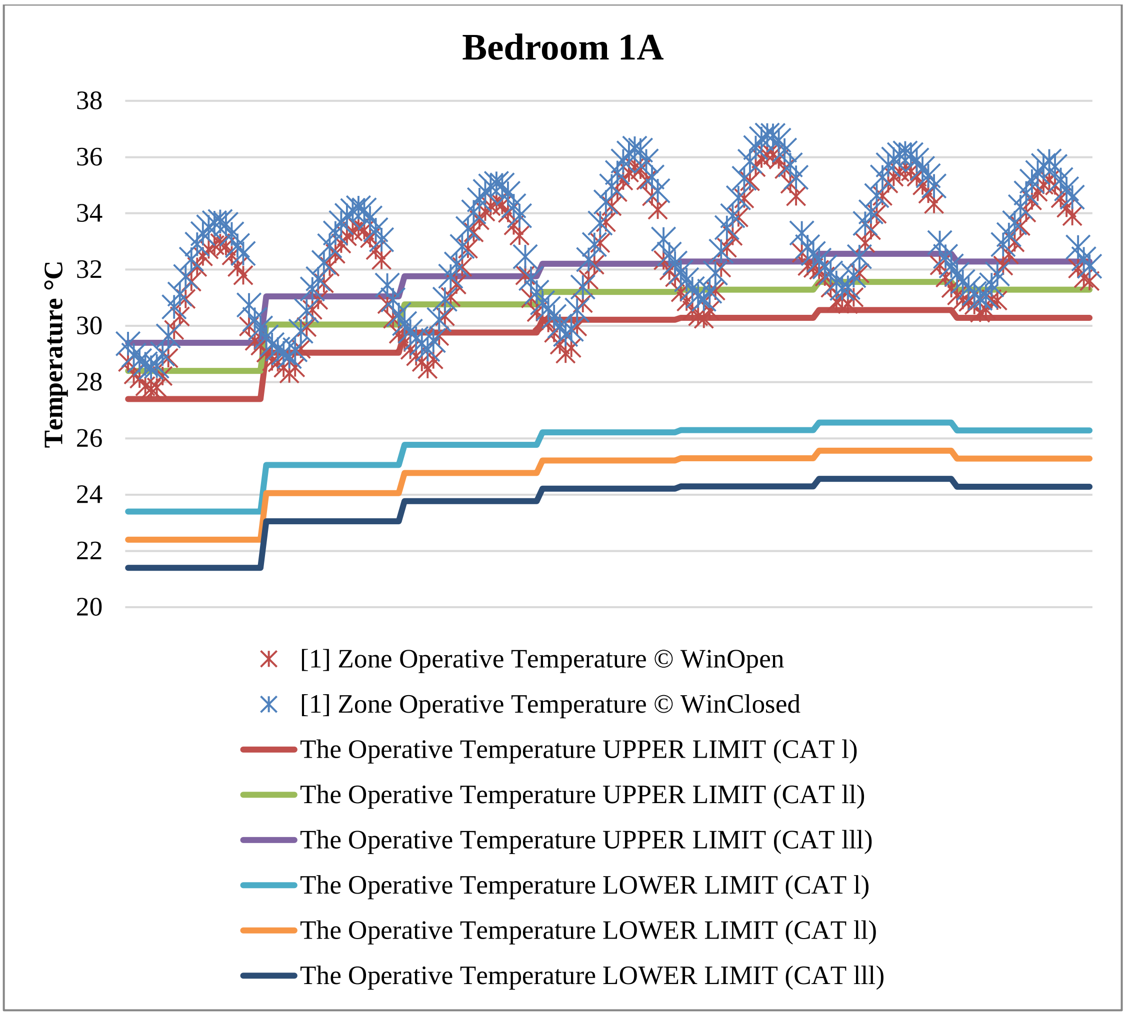


Figure 97: Summer design week EN 15251 comfort analysis for Bedroom 1A facing North orientation using different windows opening configurations

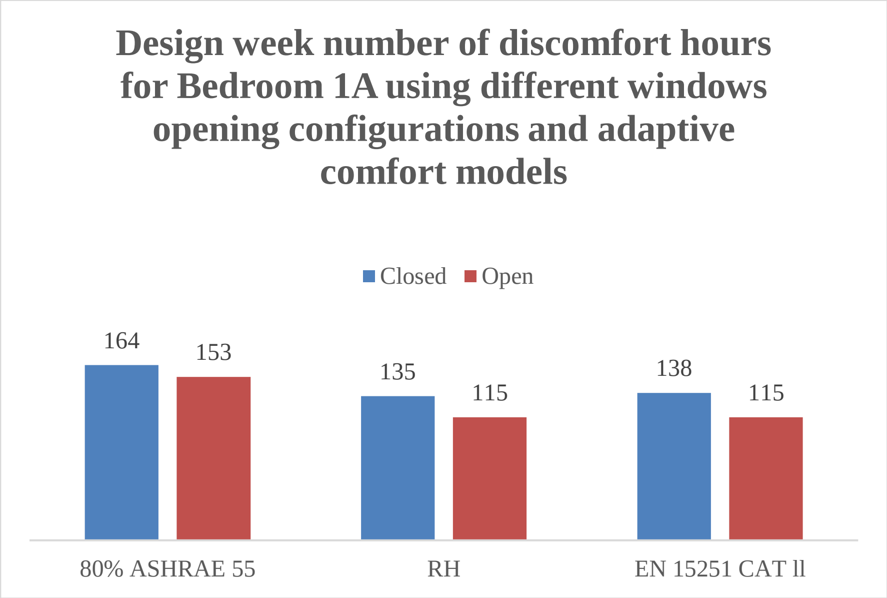


Figure 98: Summer design week number of discomfort hours for Bedroom 1A facing North orientation using different windows opening configurations and adaptive comfort models

Kitchen North

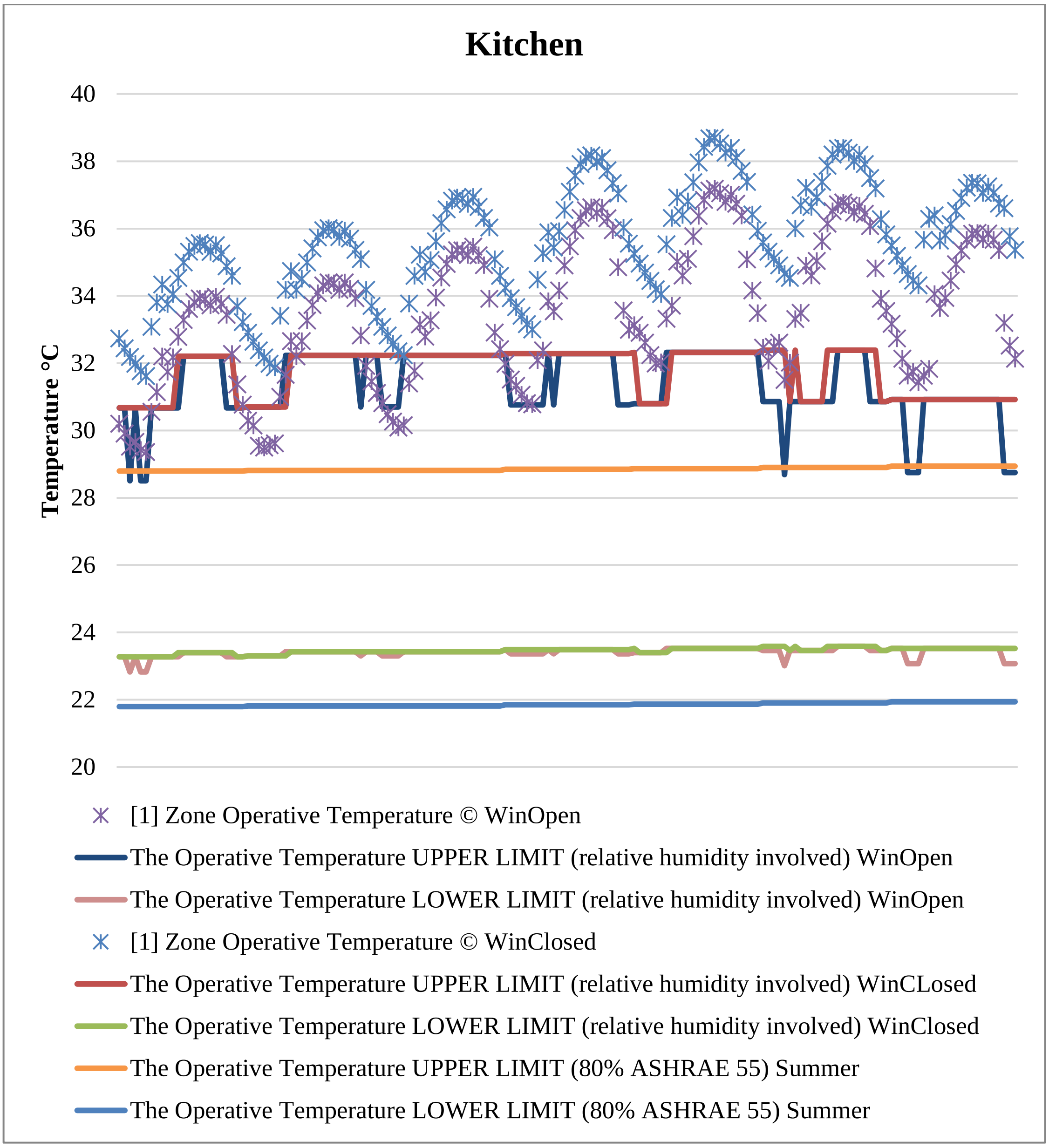


Figure 99: Summer design week ASHRAE and M. Vellei et al. [35] ***comfort analysis for Kitchen facing North orientation using different windows opening configurations***

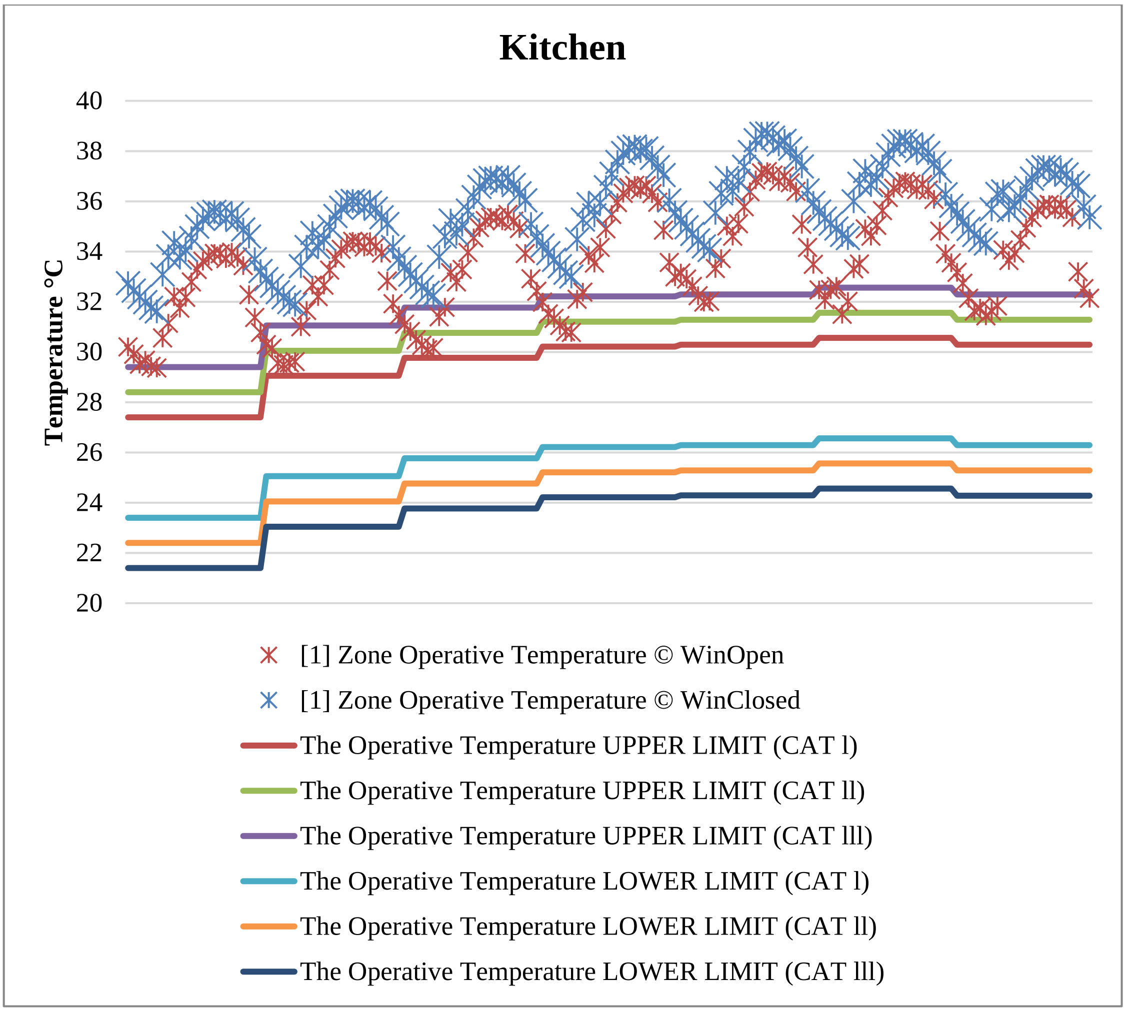


Figure 100: Summer design week EN 15251 comfort analysis for Kitchen facing North orientation using different windows opening configurations

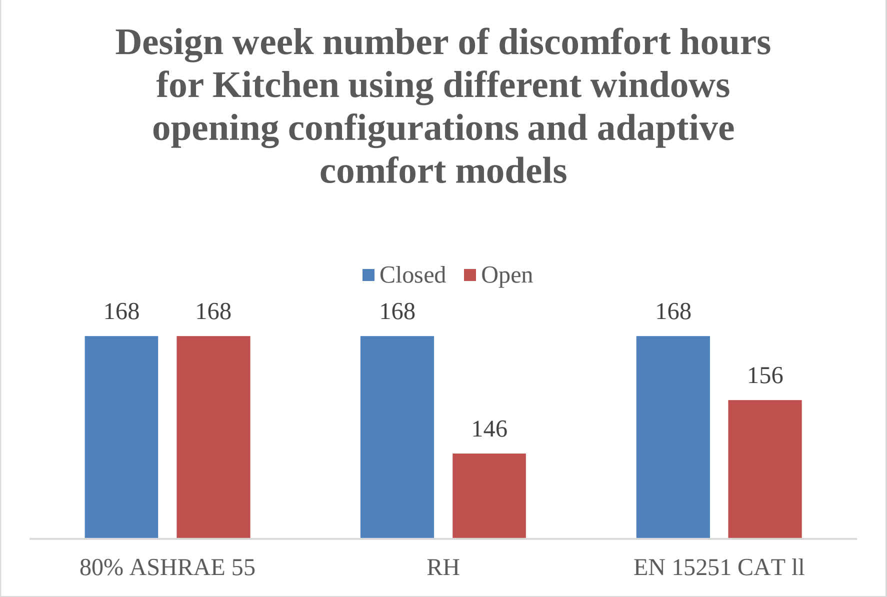


Figure 101: Summer design week number of discomfort hours for Kitchen facing North orientation using different windows opening configurations and adaptive comfort models

A2.2.2 Summer design week - Building comparison with all retrofit measures and after sensitivity analysis

Bedroom 1C East

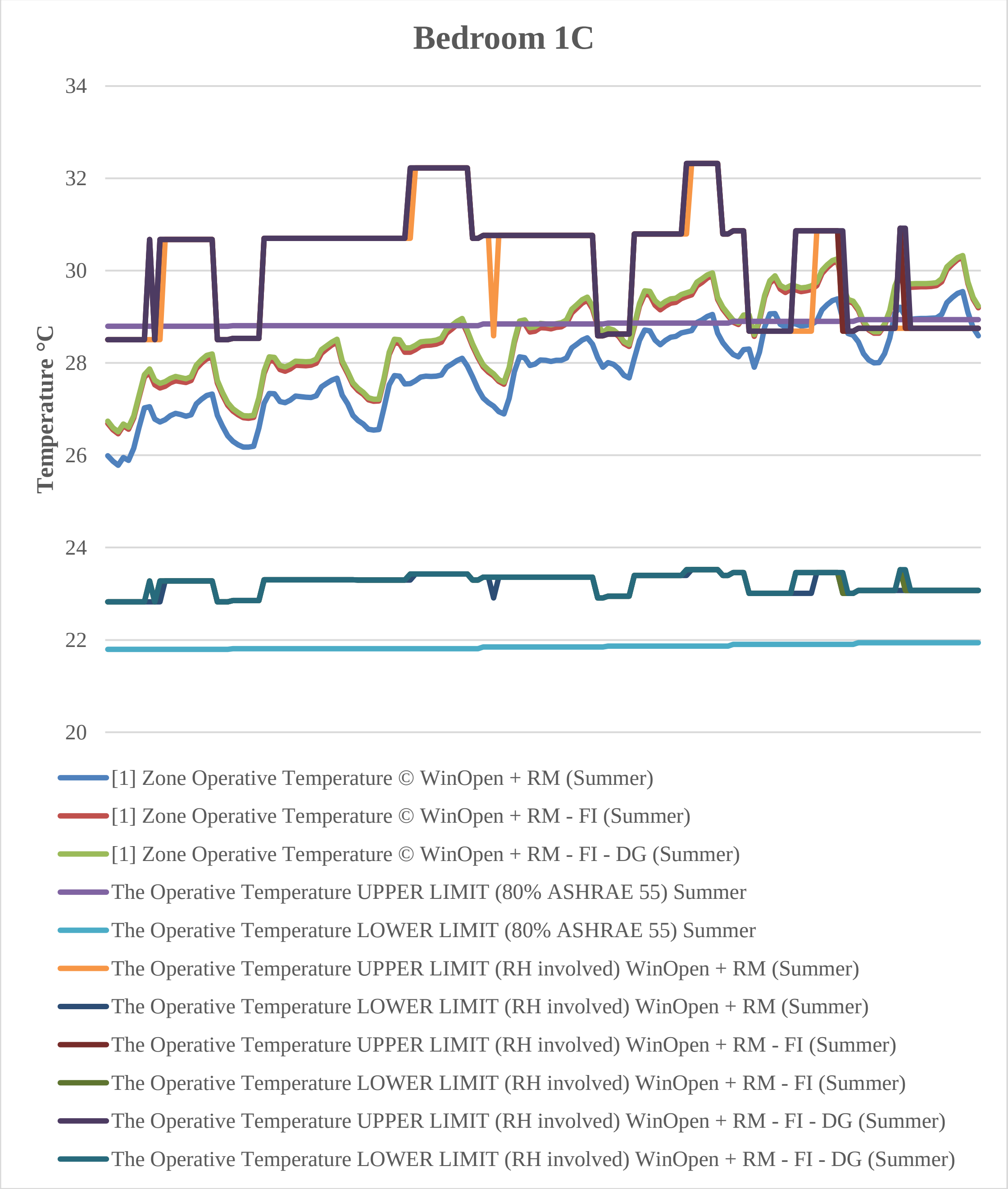


Figure 102: Summer design week ASHRAE and M. Vellei et al. [35] *comfort analysis for Bedroom 1C facing East orientation using windows open configuration*

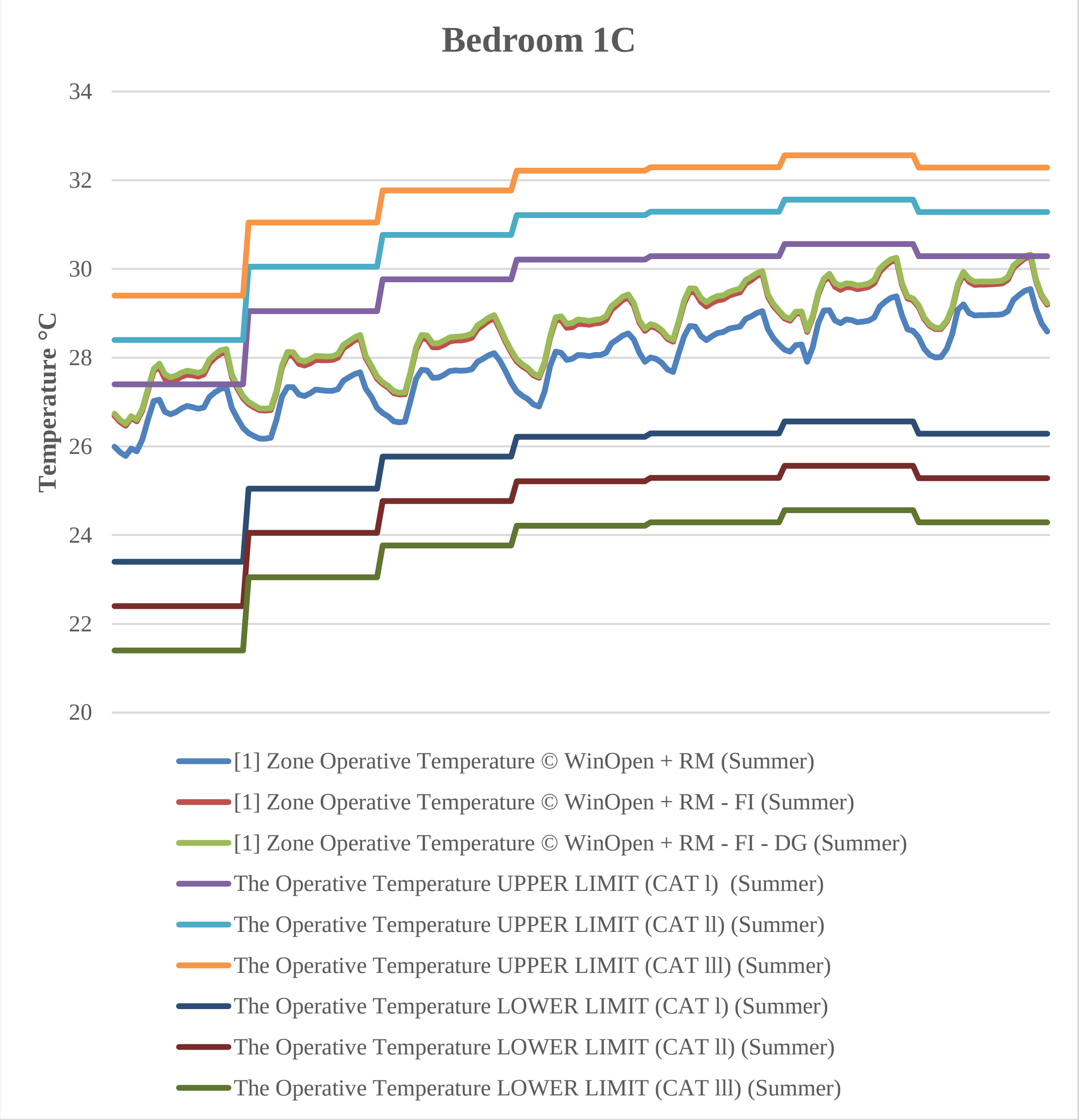
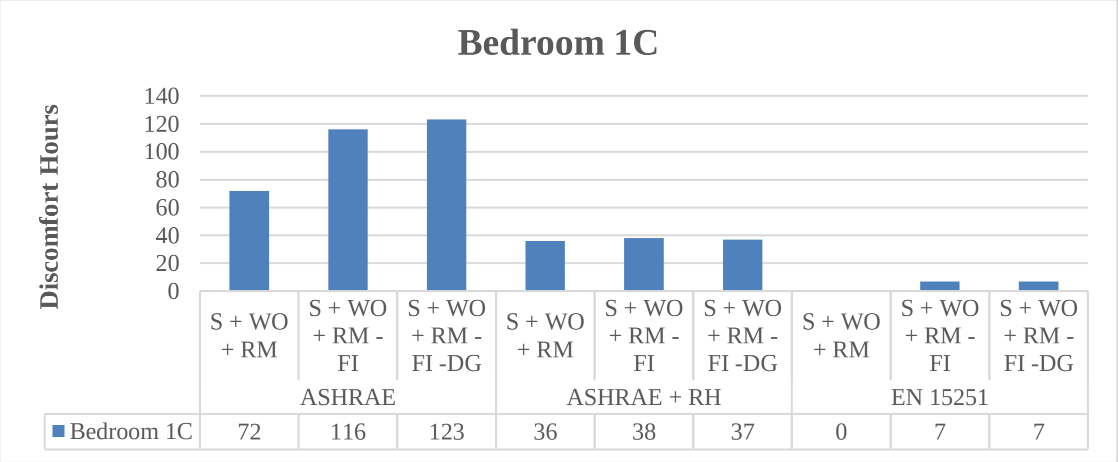


Figure 103: Summer design week EN 15251 comfort analysis for Bedroom 1C facing East orientation using windows open configuration using different combination of measures



	ASHRAE			ASHRAE + RH			EN 15251		
	S + WO + RM	S + WO + RM - FI	S + WO + RM - FI -DG	S + WO + RM	S + WO + RM - FI	S + WO + RM - FI -DG	S + WO + RM	S + WO + RM - FI	S + WO + RM - FI -DG
■ Bedroom 1C	72	116	123	36	38	37	0	7	7

Figure 104: Summer design week number of discomfort hours for different combination of measures for Bedroom 1C facing East orientation

Kitchen East

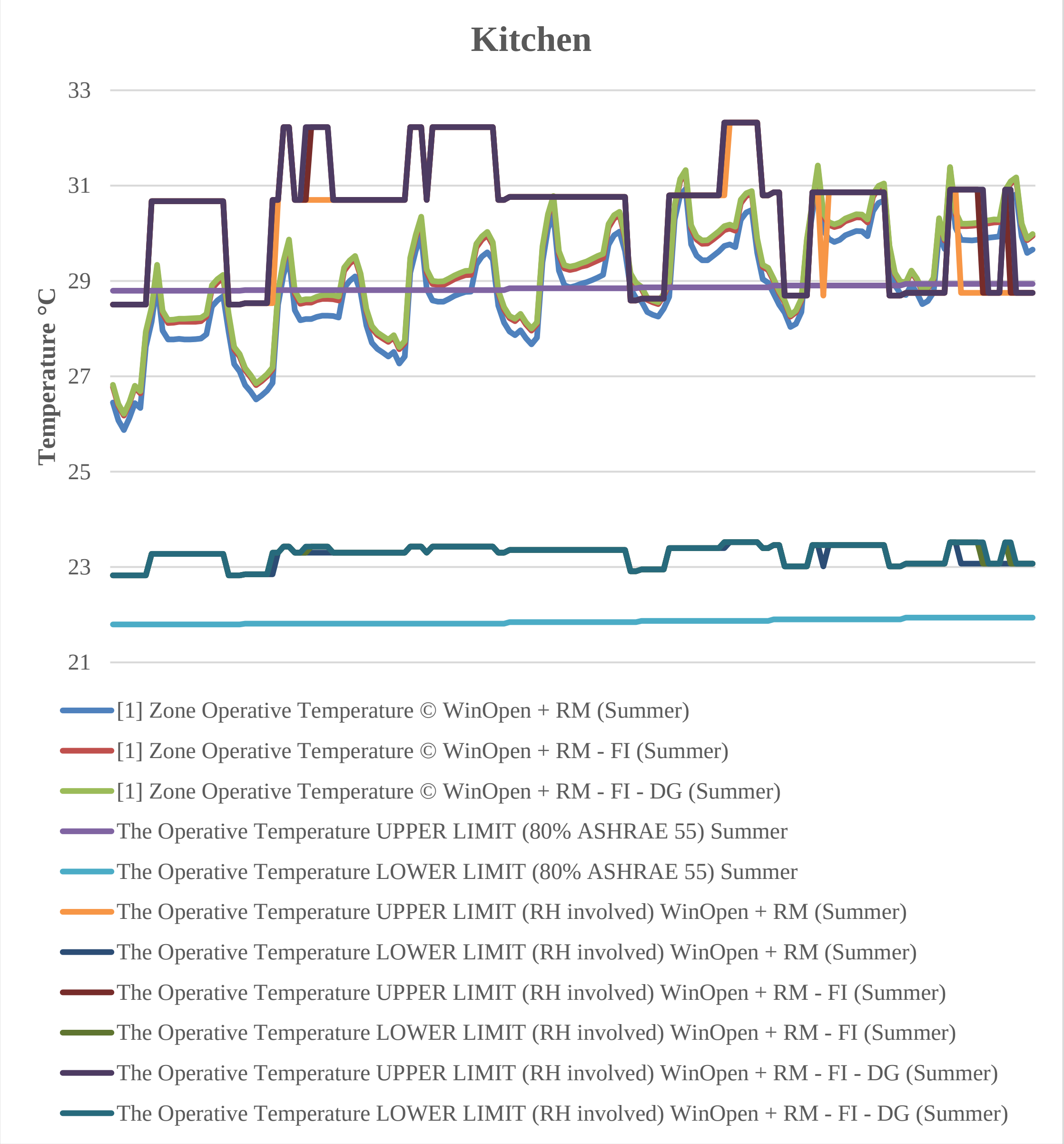


Figure 105: Summer design week ASHRAE and M. Vellei et al. [35] ***comfort analysis for Kitchen facing East orientation using windows open configuration and using different combination of measures***

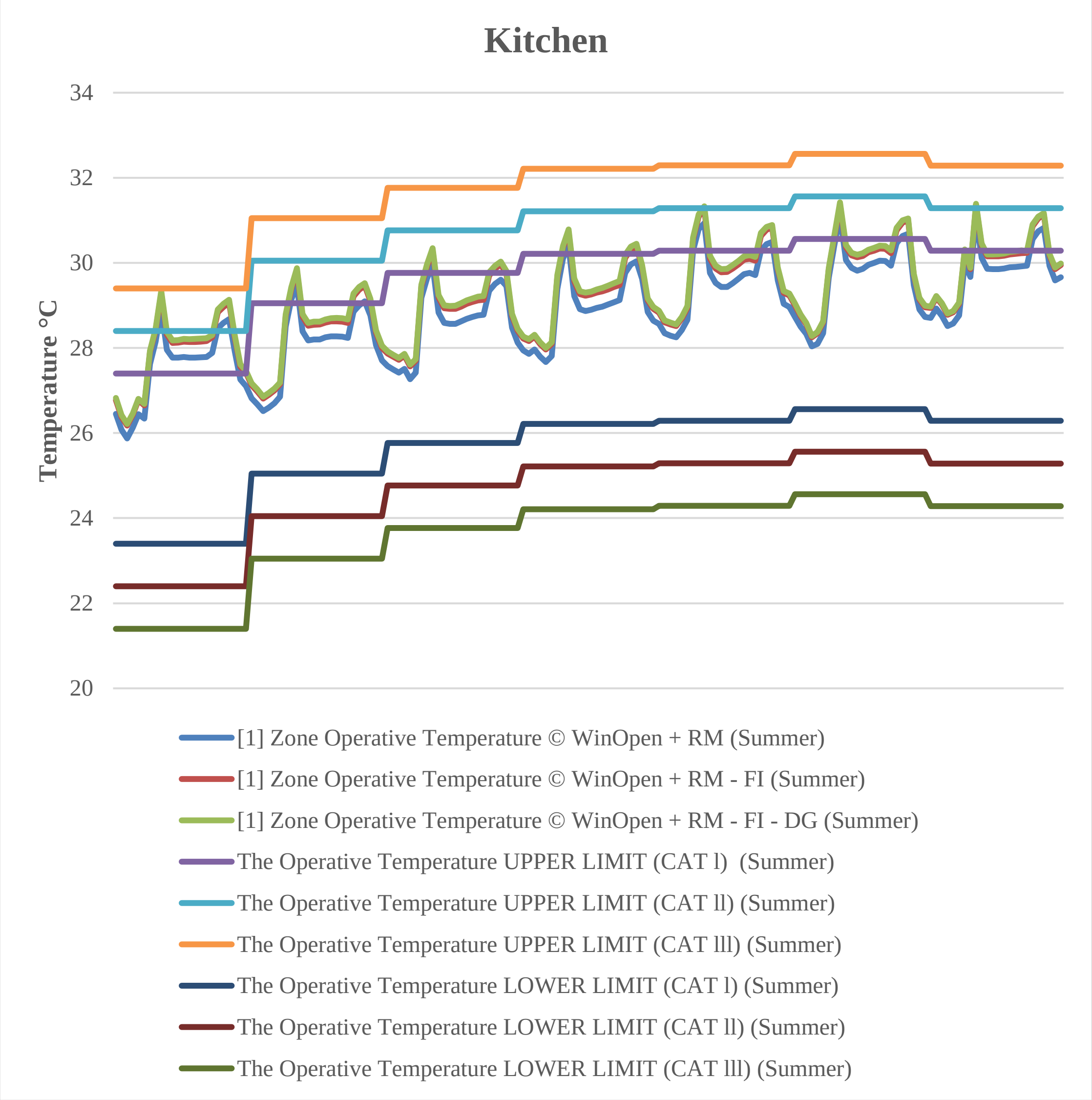
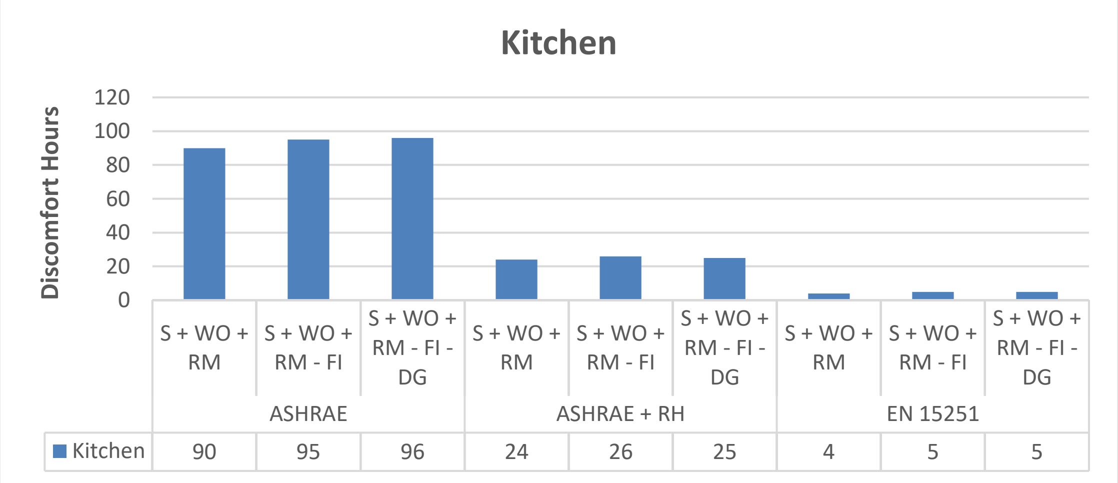


Figure 106: Summer design week EN 15251 comfort analysis for Kitchen facing East direction using windows open configuration and using different combination of measures



	ASHRAE			ASHRAE + RH			EN 15251		
	S + WO + RM	S + WO + RM - FI	S + WO + RM - FI - DG	S + WO + RM	S + WO + RM - FI	S + WO + RM - FI - DG	S + WO + RM	S + WO + RM - FI	S + WO + RM - FI - DG
■ Kitchen	90	95	96	24	26	25	4	5	5

Figure 107: Summer design week number of discomfort hours for different combination of measures for the Kitchen facing East orientation

Dining East

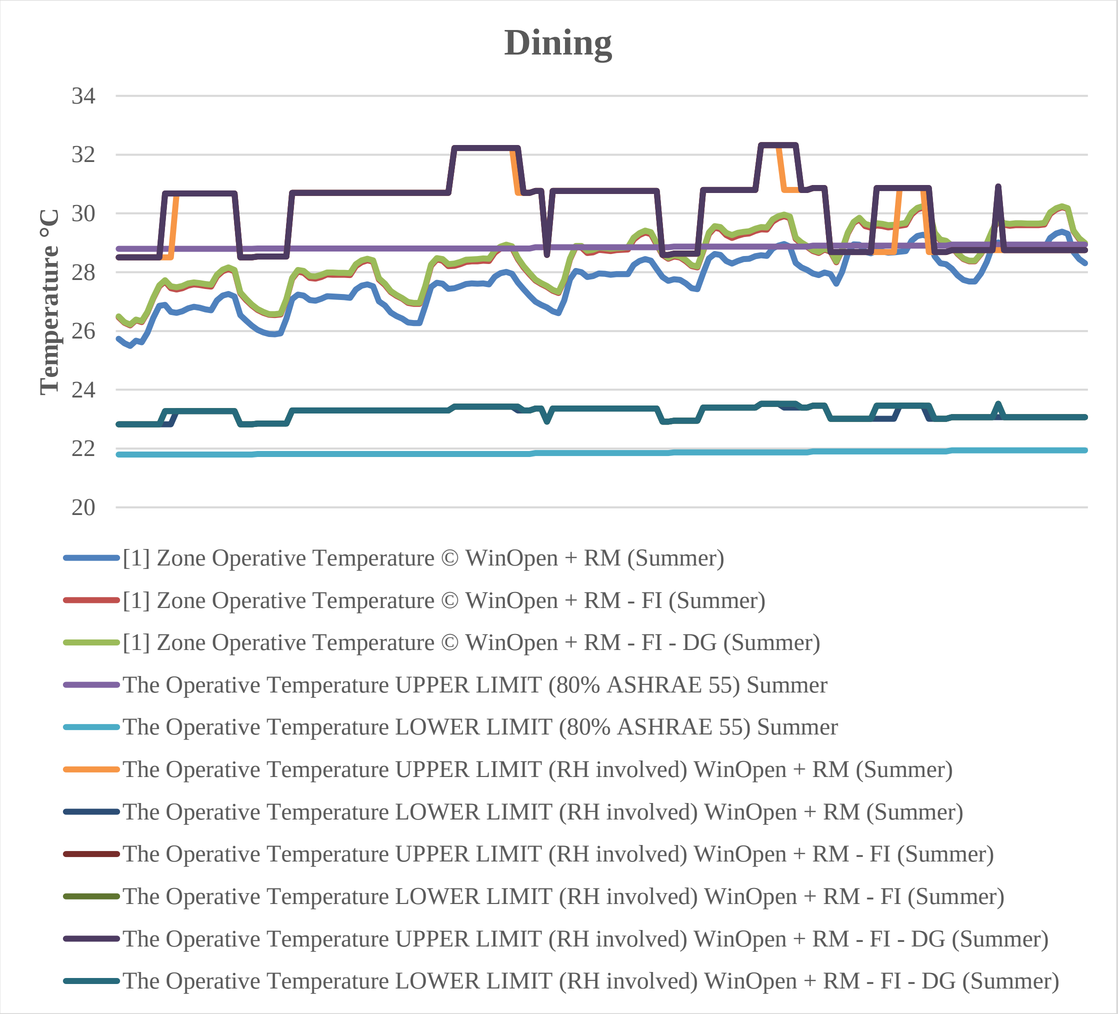


Figure 108: Summer design week ASHRAE and M. Vellei et al.** [35] **comfort analysis for Dining facing East orientation using windows open configuration and using different combination of measures

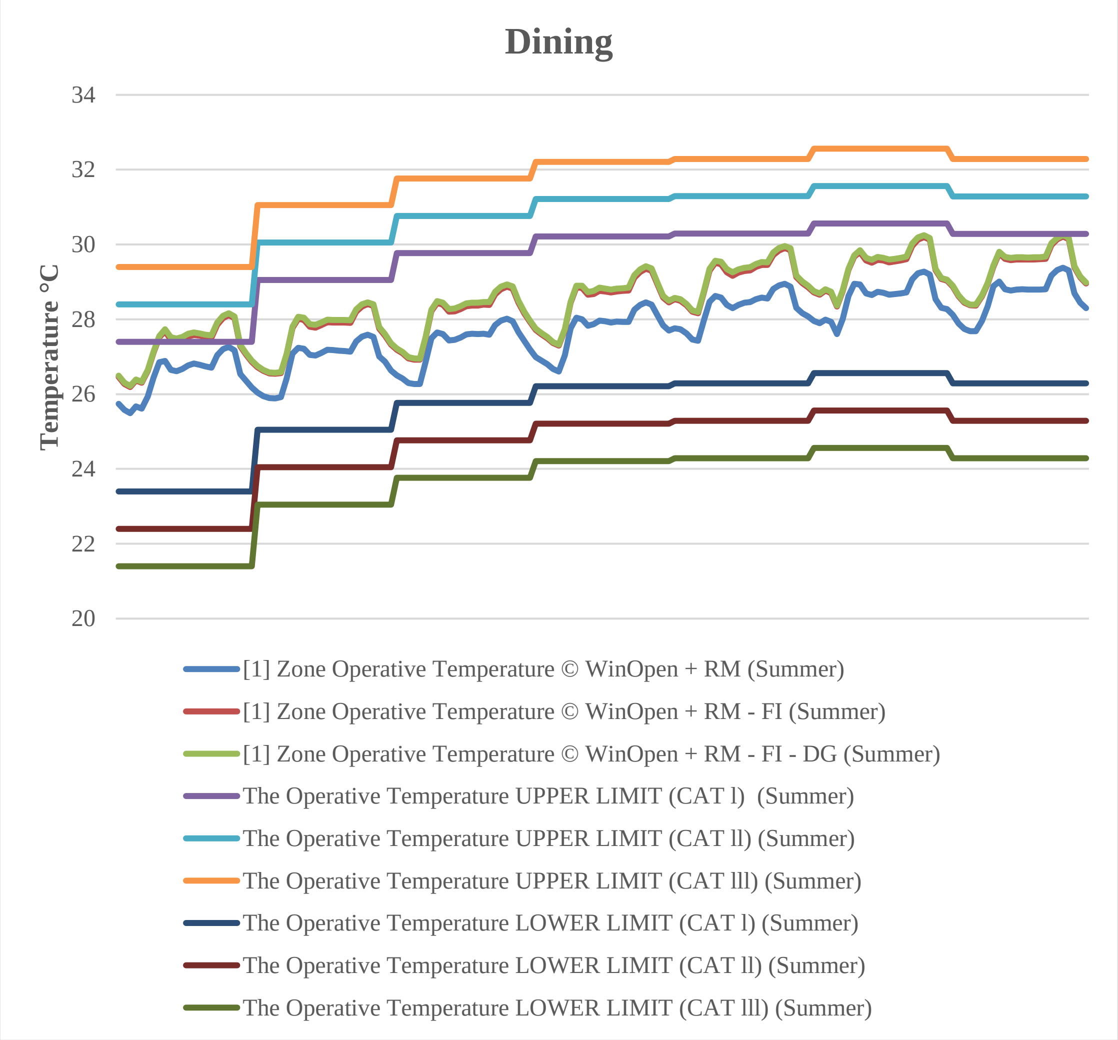


Figure 109: Summer design week EN 15251 comfort analysis for Dining facing East orientation using windows open configuration and using different combination of measures

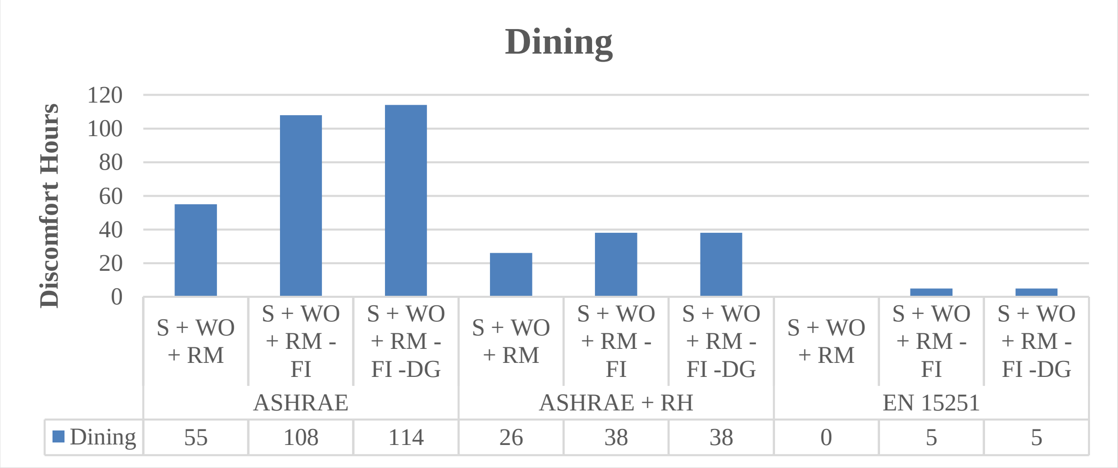


Figure 110: Summer design week number of discomfort hours for different combination of measures for the Dining facing East orientation

A2.2.3 Winter design week - Base building scenario

Bedroom 1C North

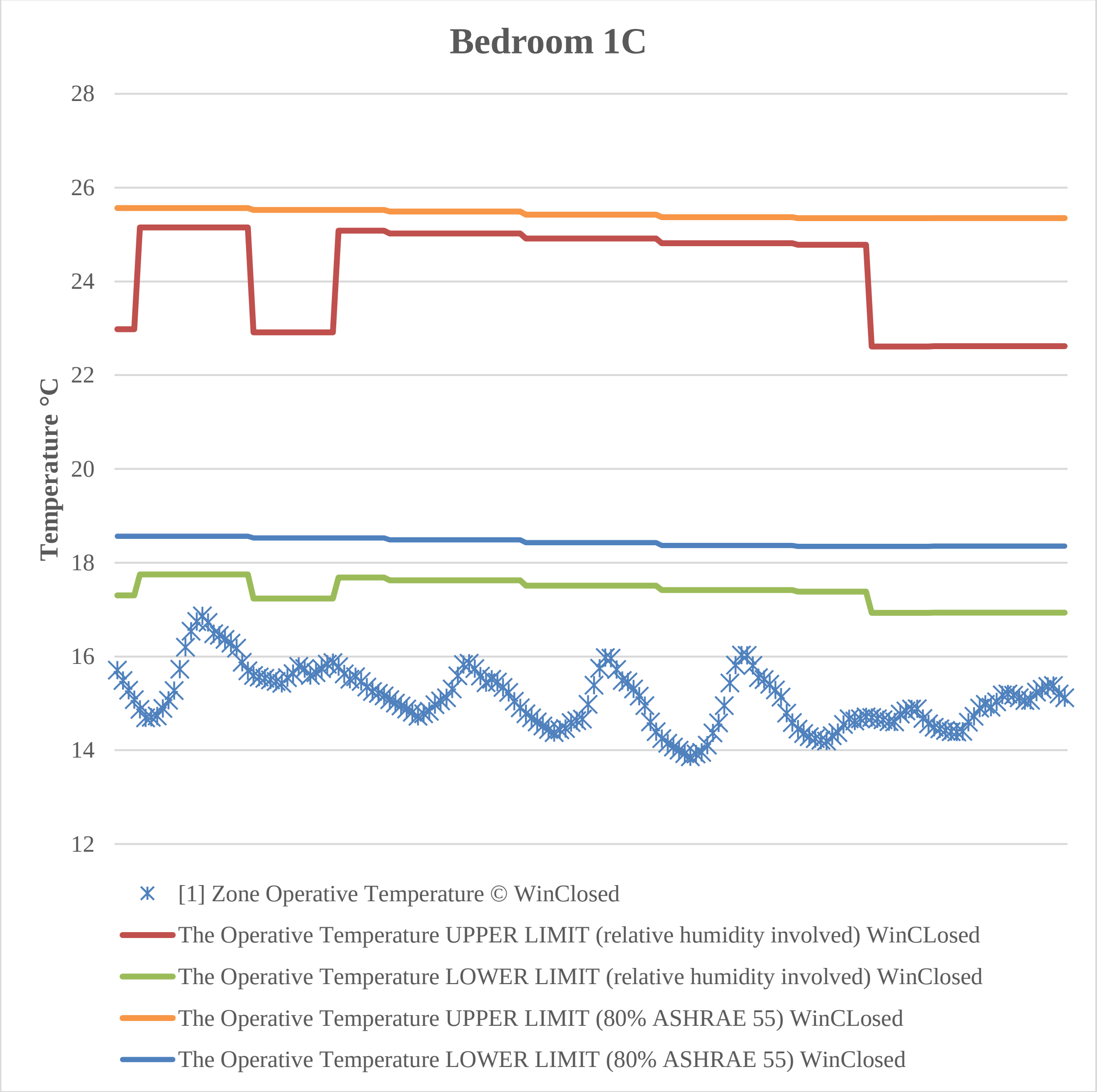


Figure 111: Winter design week ASHRAE and M. Vellei et al. [35] ***comfort analysis for Bedroom 1C facing North orientation using windows close configuration***

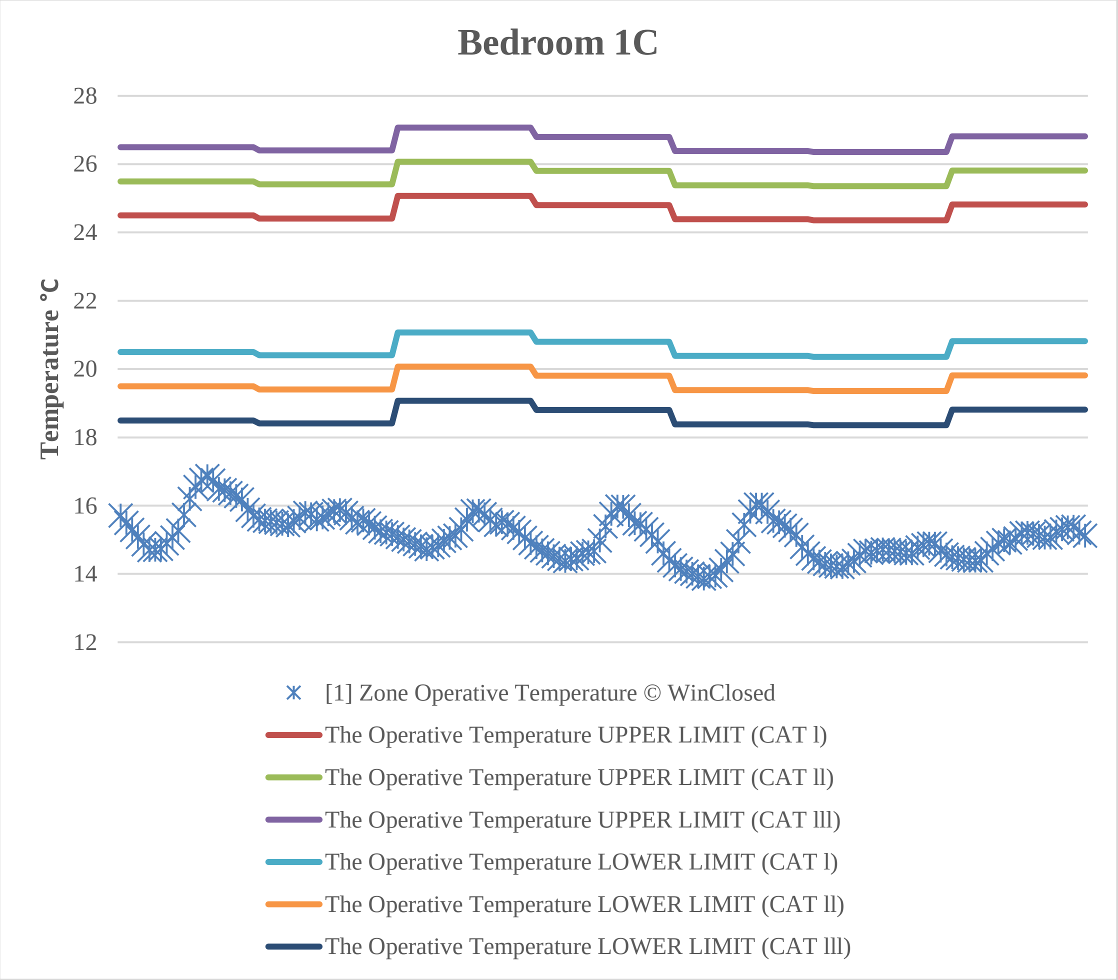


Figure 112: Winter design week EN 15251 comfort analysis for Bedroom 1C facing North orientation using windows close configuration

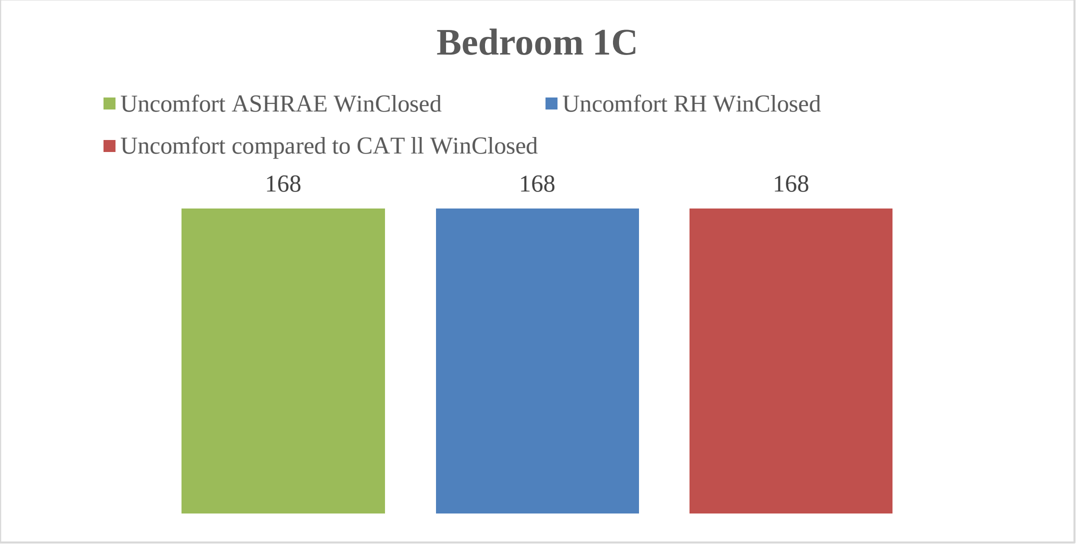


Figure 113: Winter design week number of discomfort hours for Bedroom 1C facing North orientation using windows close configuration and different comfort models

A2.2.4 Winter design week - Building comparison with all retrofit measures and after sensitivity analysis

Bedroom 1C North

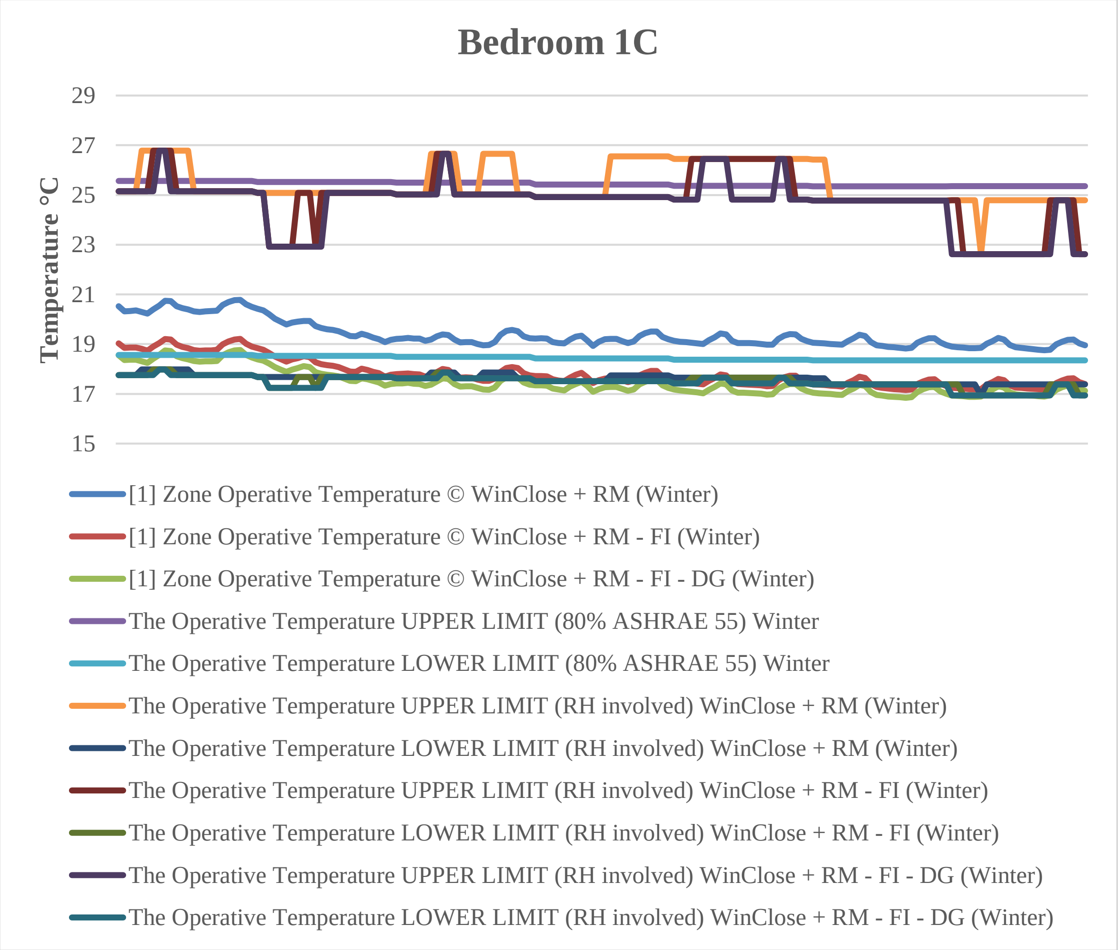


Figure 114: Winter design week ASHRAE and M. Vellei et al. [35] *comfort analysis for Bedroom 1C facing North orientation using windows open configuration and using different combination of measures*

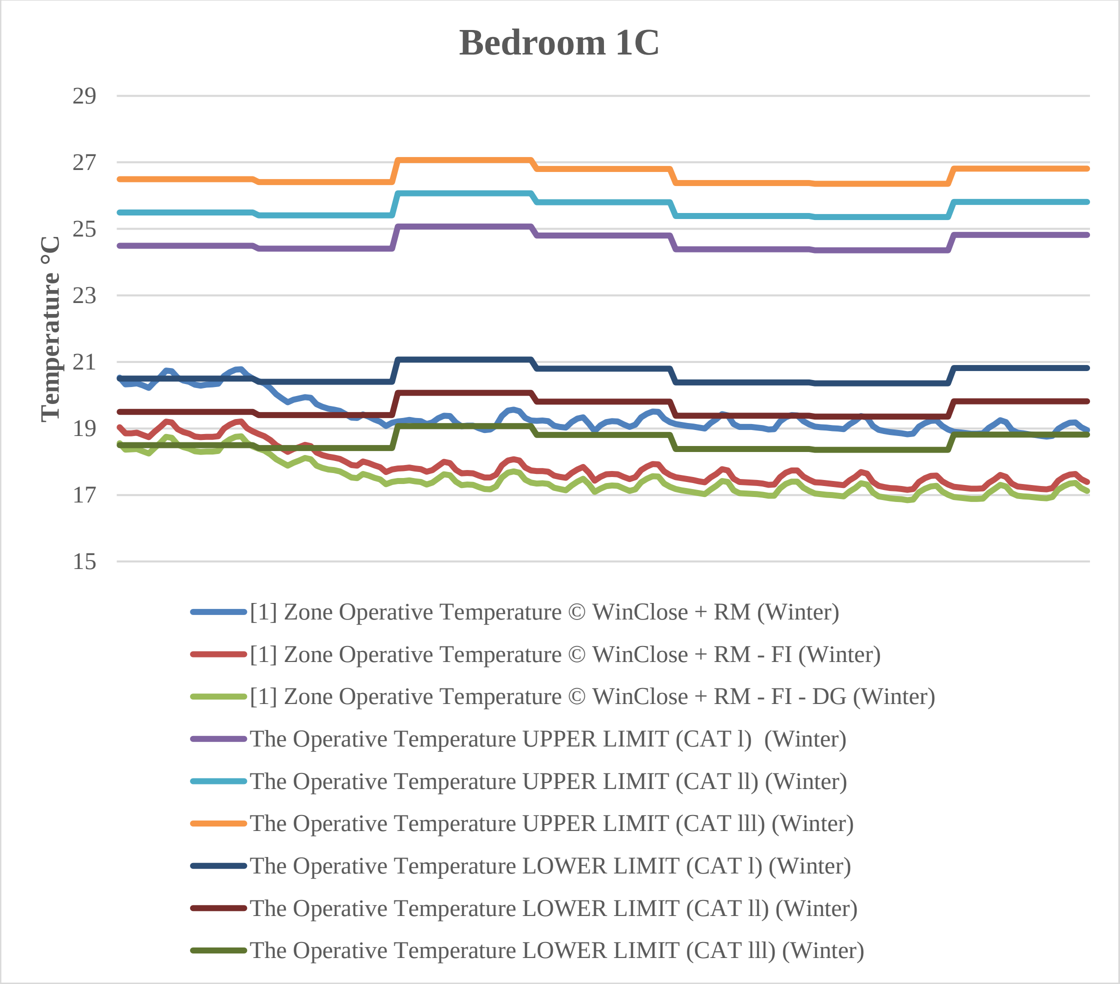
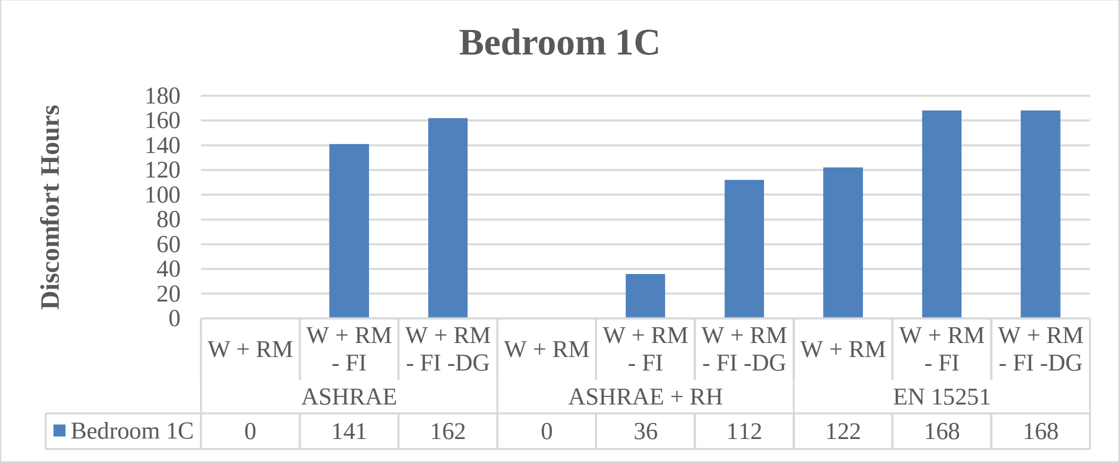


Figure 115: Winter design week EN 15251 comfort analysis for Bedroom 1C facing North orientation using windows open configuration and using different combination of measures



	ASHRAE			ASHRAE + RH			EN 15251		
	W + RM	W + RM - FI	W + RM - FI -DG	W + RM	W + RM - FI	W + RM - FI -DG	W + RM	W + RM - FI	W + RM - FI -DG
■ Bedroom 1C	0	141	162	0	36	112	122	168	168

Figure 116: Winter design week number of discomfort hours for different combination of measures for the Bedroom 1C facing North orientation

Bedroom 1C West

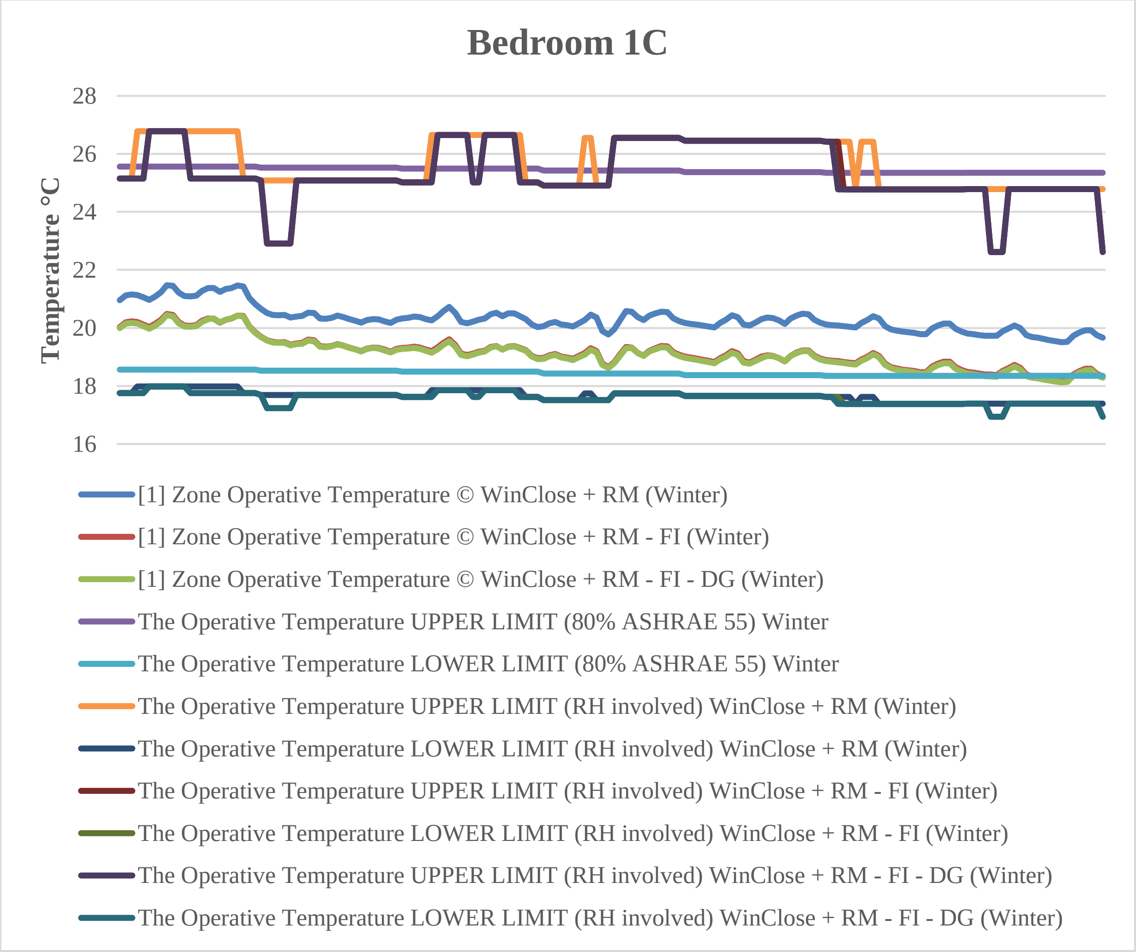


Figure 117: Winter design week ASHRAE and M. Vellei et al. [35] ***comfort analysis for Bedroom 1C facing West orientation using windows open configuration and using different combination of measures***

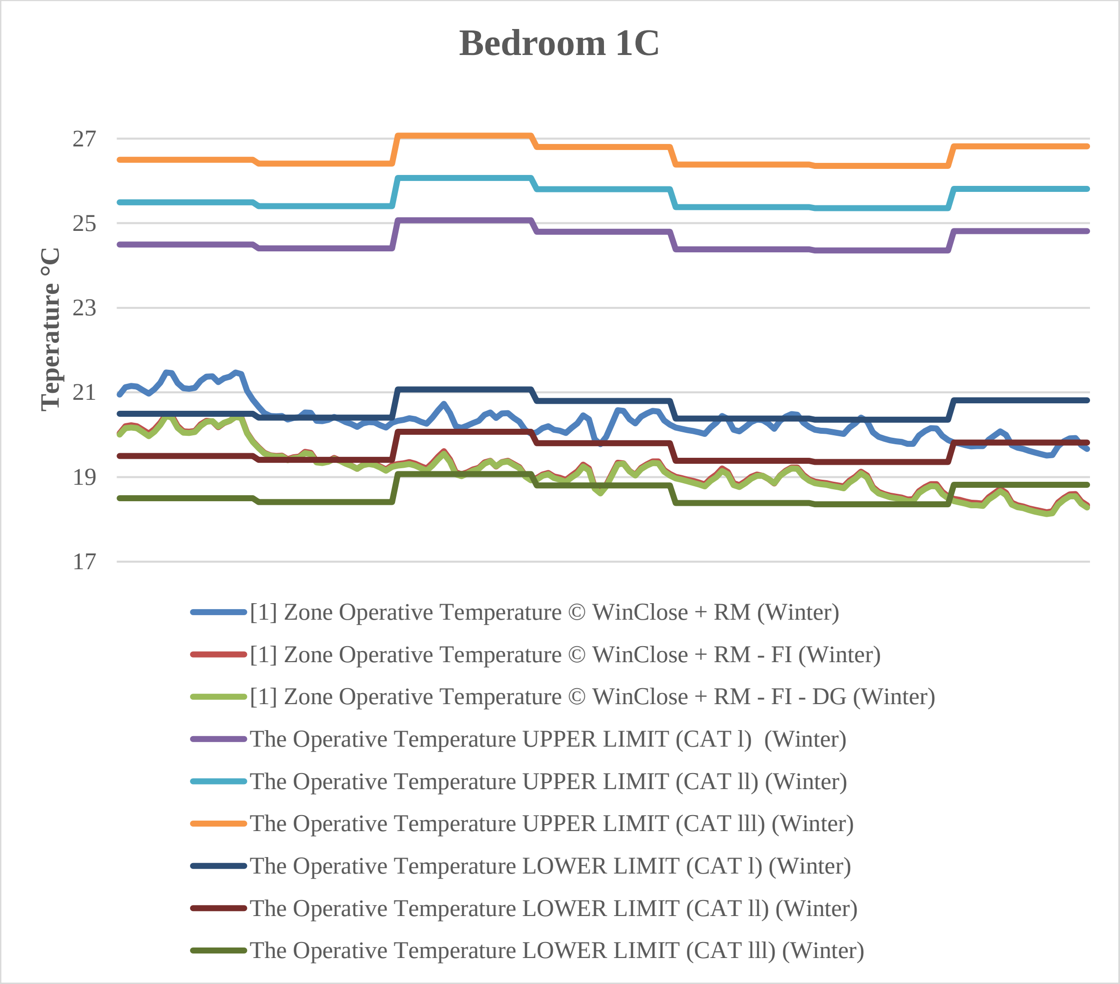
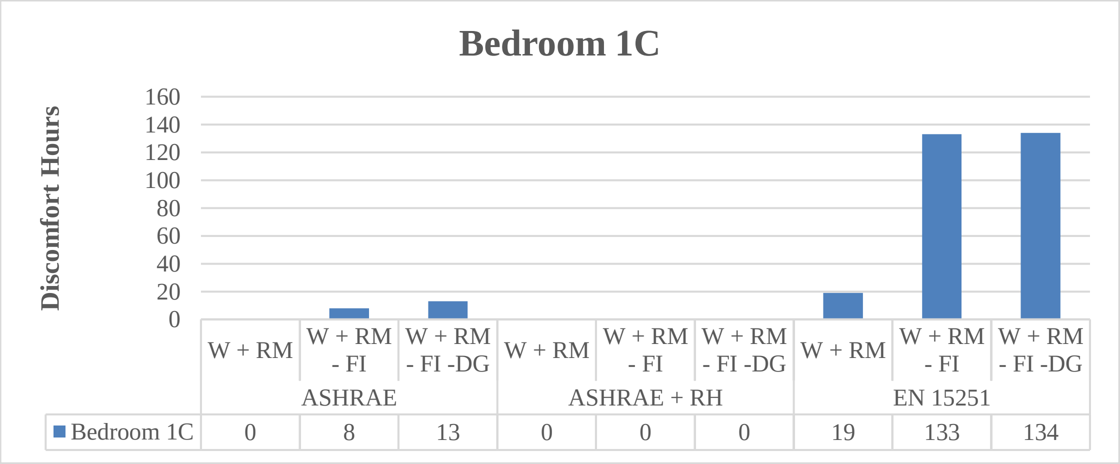


Figure 118: Winter design week EN 15251 comfort analysis for Bedroom 1C facing West orientation using windows open configuration and using different combination of measures



	ASHRAE			ASHRAE + RH			EN 15251		
	W + RM	W + RM - FI	W + RM - FI -DG	W + RM	W + RM - FI	W + RM - FI -DG	W + RM	W + RM - FI	W + RM - FI -DG
■ Bedroom 1C	0	8	13	0	0	0	19	133	134

Figure 119: Winter design week number of discomfort hours for different combination of measures for the Bedroom 1C facing West orientation

Dining North

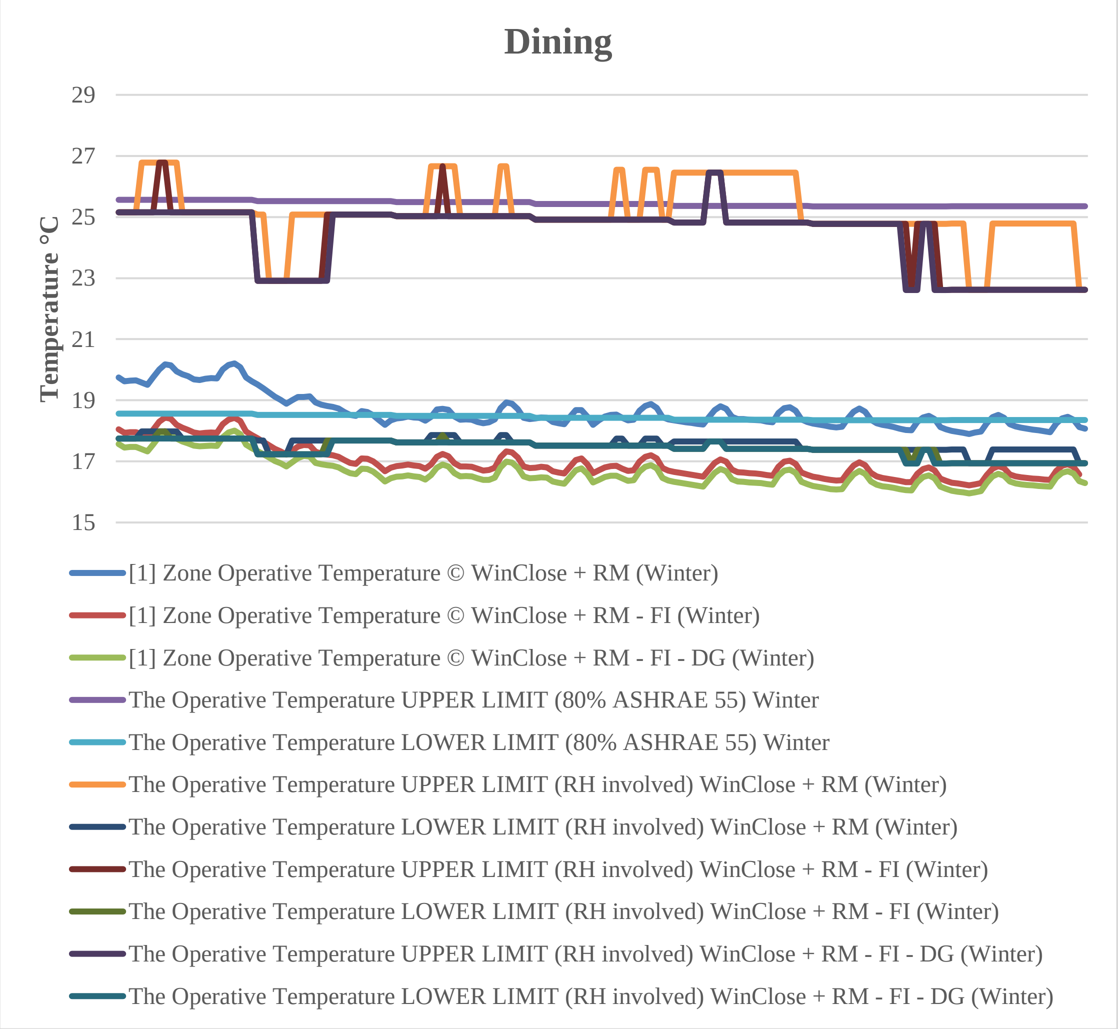


Figure 120: Winter design week ASHRAE and M. Vellei et al.* [35] *comfort analysis for Dining facing North orientation using windows open configuration and using different combination of measures

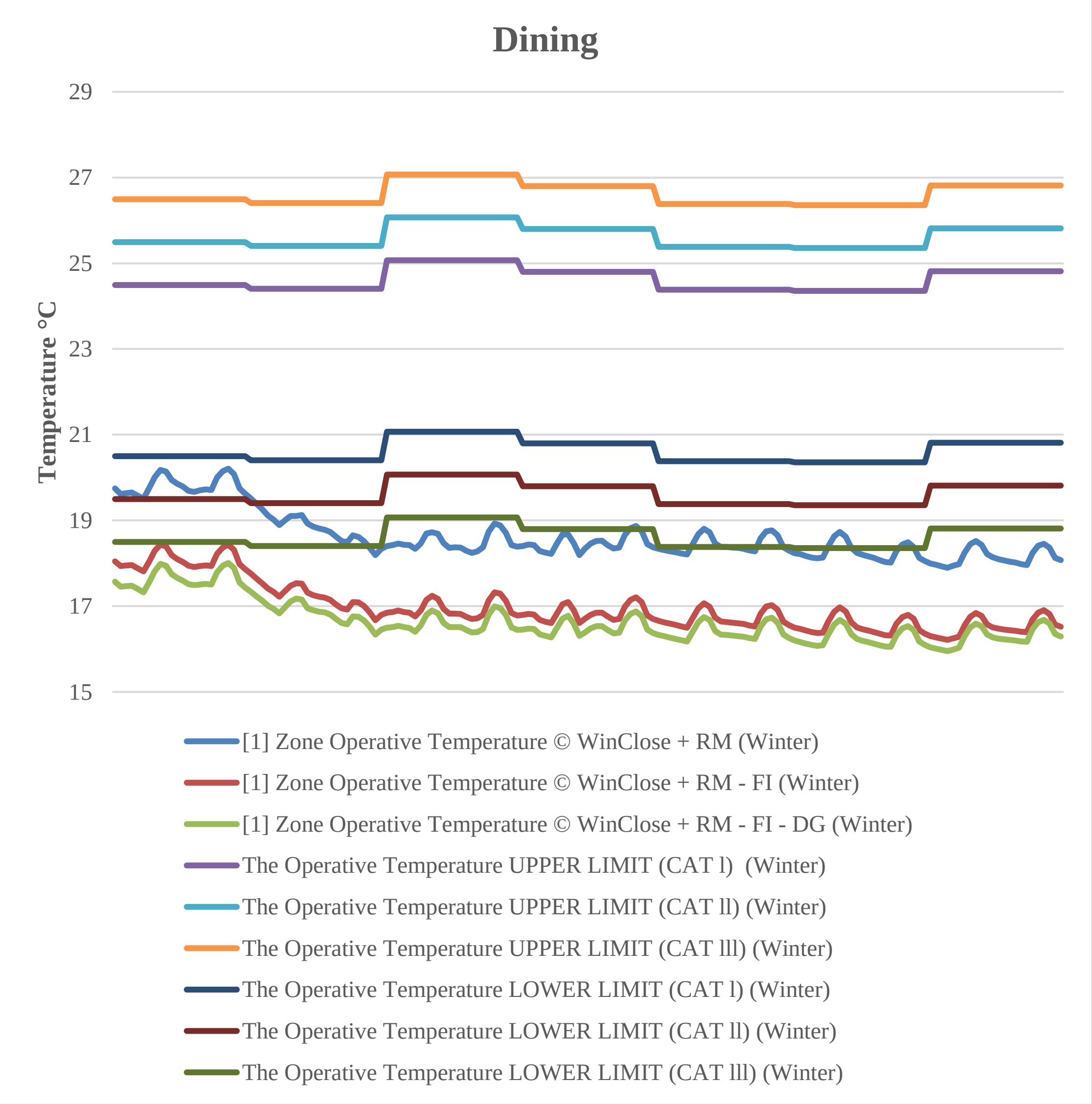


Figure 121: Winter design week EN 15251 comfort analysis for Dining facing North orientation using windows open configuration and using different combination of measures

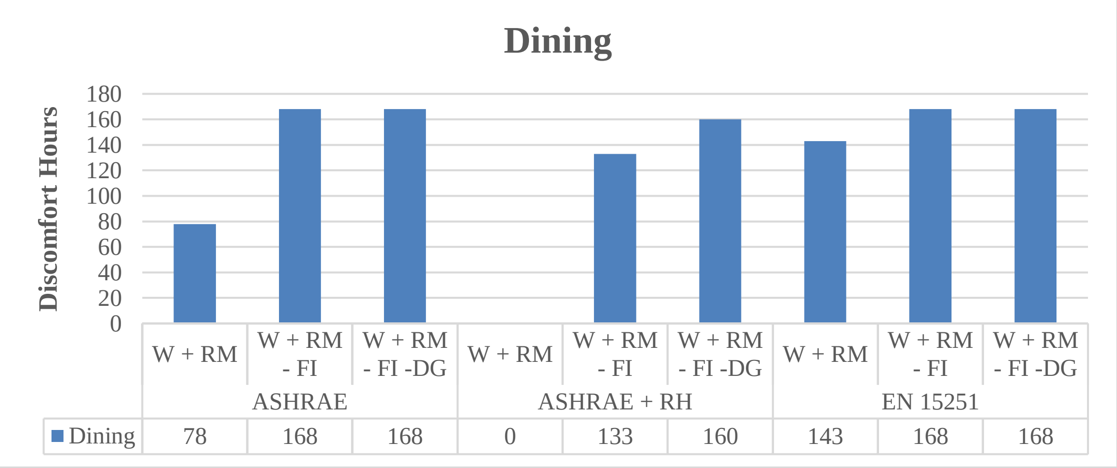


Figure 122: Winter design week number of discomfort hours for different combination of measures for the Dining facing North orientation

Dining West

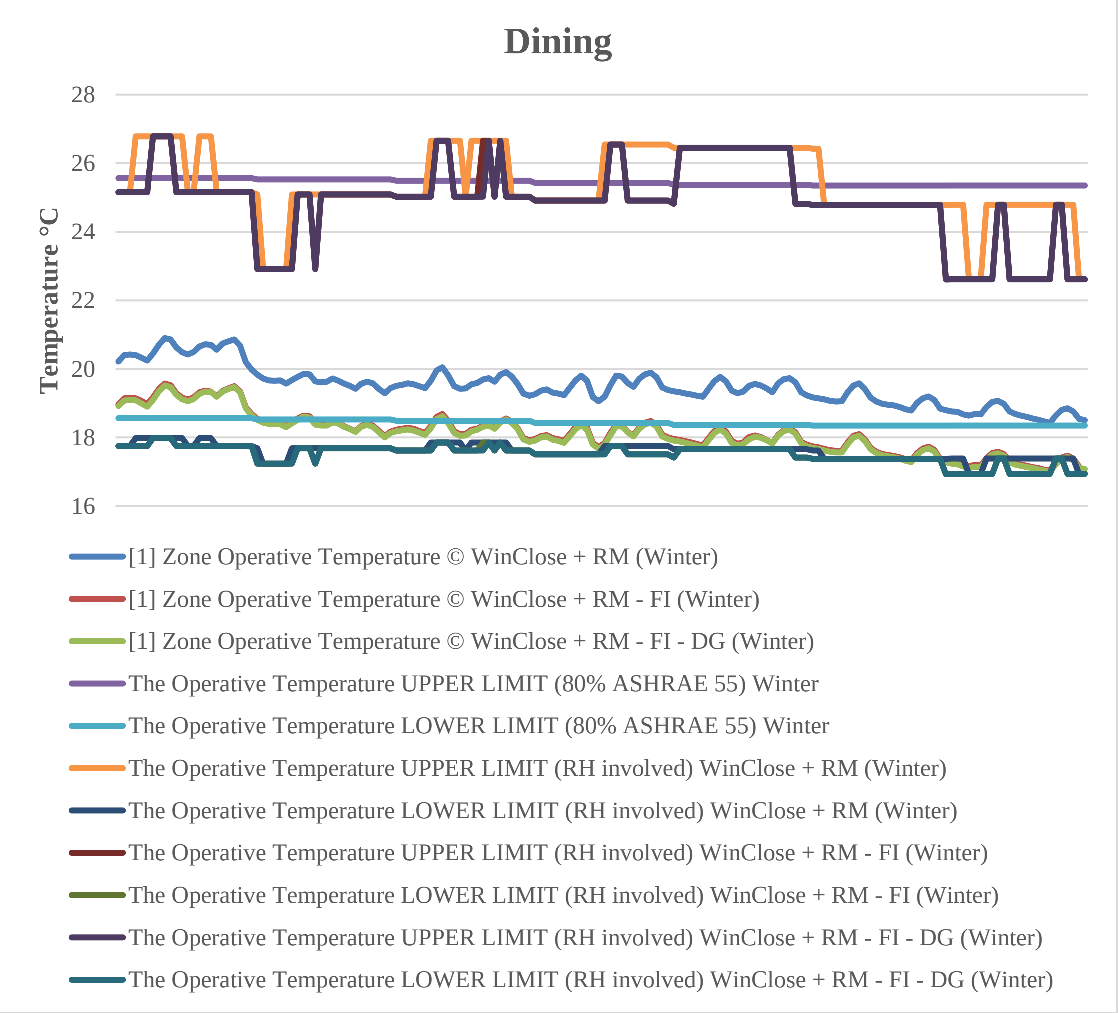


Figure 123: Winter design week ASHRAE and M. Vellei et al.* [35] *comfort analysis for Dining facing West orientation using windows open configuration and using different combination of measures

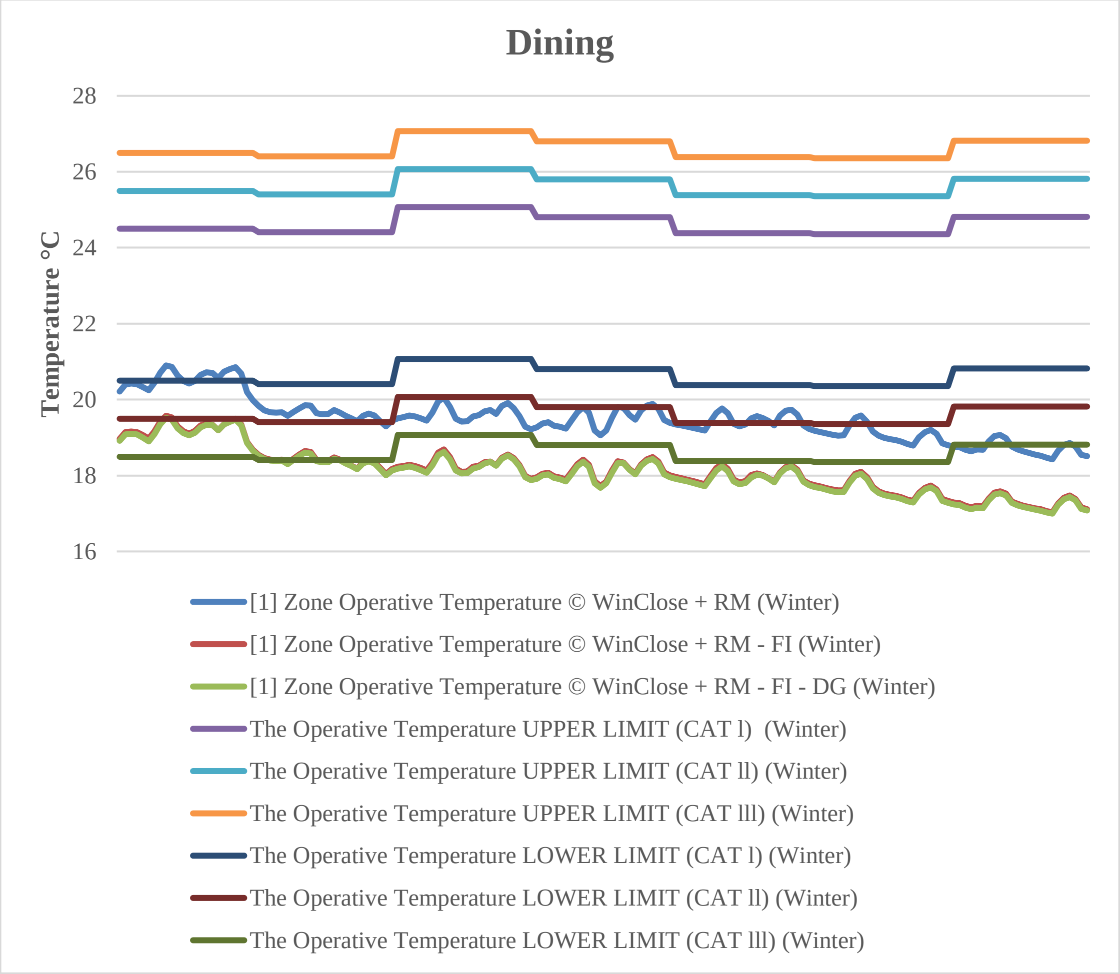


Figure 124: Winter design week EN15251 comfort analysis for Dining facing West orientation using windows open configuration and using different combination of measures

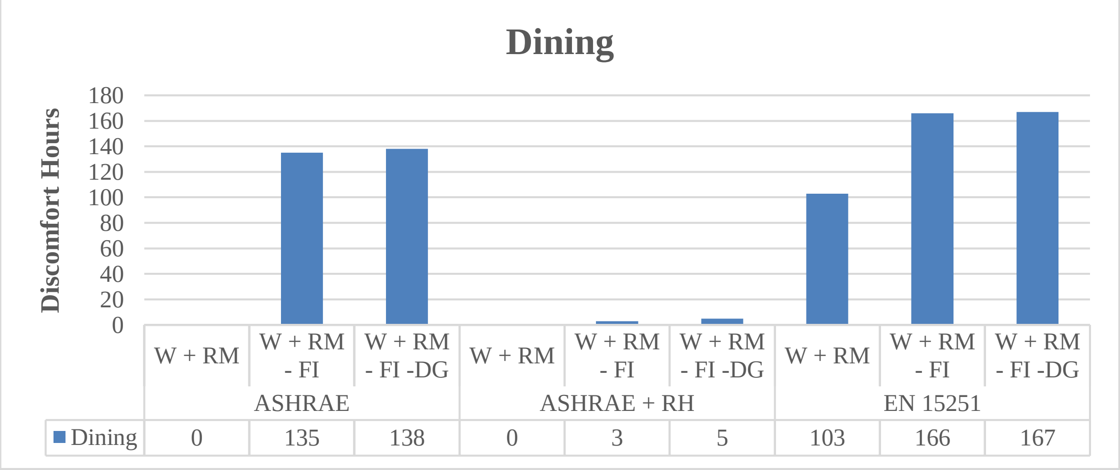


Figure 125: Winter design week number of discomfort hours for different combination of measures for the Dining facing West orientation