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The Impact of Climate Change on Building Energy Performance and Thermal Comfort

The Case Study of a Mixed Use Building in London

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ABSTRACT

In the context of climate change, sustainability and climate resilience efforts, this research has the aim to evaluate the feasibility of achieving thermal resilience within the building sector by 2050s and 2080s.

The impacts of climate change on the building sector are expected to manifest in several ways, such as the increased risk of overheating and a rise in energy demand for cooling. For this reason, the research approach goes beyond conventional retrofitting strategies, focusing instead on assessing a building's potential to respond to effects of climate change, even in regions historically unaffected by high cooling demands, as United Kingdom.

As a case of study, a model of a mixed-use building (residential and offices) in London was developed. The model was calibrated analysing the energy behaviour, the overheating risk, and carbon emissions within weather future scenarios. It explores the possibility of achieving a climate resilience behaviour under different future weather data and various adaptation & mitigation strategies. To conduct the analysis, the research employs a Dynamic Simulation approach using Design Builder software and uses a real consumption data from 2022 to calibrate the building's baseline performance. Key areas of examination include energy demand, carbon emissions, overheating risk assessment, evaluation of the simulation model's accuracy, choice of future climate scenarios, and identification of effective adaptation & mitigation strategies.

Keywords: Climate Change, Climate Resilience, Thermal Comfort, Adaptation and Mitigation strategies, Energy modelling, Building calibration, Future scenarios

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1. INTRODUCTION

1.1. Context

Nowadays, climate change is one of the most pressing issues affecting our planet. Human activities, by emitting greenhouse gases, are gradually altering the planet's climate balance, causing these gases to accumulate in the atmosphere and oceans.
Indeed, it is estimated that human activities are responsible for raising the global temperature by approximately 1°C compared to pre-industrial levels. This increase in temperature has had significant impacts on various aspects of the Earth's climate system (1).
If the current rate of global warming continues, it is projected that the global temperature will likely reach 1.5°C between 2030 and 2050 (1). This threshold represents a critical limit beyond which there will be significant consequences that affect human health. Additionally, it will lead to more frequent and intense weather events, have negative impacts on the entire ecosystem, and contribute to rising sea levels. These consequences highlight the urgency of taking effective measures to mitigate climate change and limit global warming.
For this reason, it is crucial to act before it is too late by raising awareness and strengthening the energy transition policy actions of international authorities. It is important to emphasize the urgency of addressing climate change and promoting sustainable measures in order to mitigate its impacts (2).

According to the IPCC (Intergovernmental Panel on Climate Change) report (2), the focus of climate discussions primarily revolves around climate change adaptation and mitigation, with the goal of achieving climate resilience. These three key concepts are defined as follows:

- **Climate change adaptation** refers to the process of adjusting to the current or expected effects to minimize potential damages or take advantage of opportunities arising from climate change (3).
- **Climate change mitigation** involves measures aimed at limiting or preventing greenhouse gas emissions by enhancing activities that remove these gases from the atmosphere (2).
- **Climate resilience** refers to the ability of a system and its components to anticipate, absorb, or recover from the effects of climate change (4).

Additionally, the Adaptation and Mitigation efforts are combined by climate resilience pathways with the final aim of achieving sustainable development. These pathways are often based on scientific models and climate change scenarios, which allow to predict future impacts and the identification of necessary actions and measures to reduce risks and improve resilience (4).

In this context, the building and energy sectors play a critical role as major contributors to global CO_2 emissions and energy consumption. It is widely recognized that energy consumption in the building sector constitutes a significant portion of the overall global consumption, accounting for 34%. Additionally, buildings are responsible for approximately 37% of the total GHG emissions in 2021 (5), 57% are indirect CO_2 emissions from generation of electricity and heat off-site whereas 18 % are from the production of concrete and steel used for construction and refurbishment (2). Mitigation and adaptation measures are also carried out in this sector. In addition to reducing CO_2 emissions and energy consumption, other necessary analyses must be performed to make buildings more efficient and climate resilient. The risk of overheating will become much more pronounced in the coming years. That is why it's essential to evaluate long-term adaptation and mitigation strategies to reduce the effects of Climate Change on building sector. Hence, considering the future impacts of climate change, the big aim of this research is to assess future building performance, in particular on a mixed-use category use.

1.2. Research Questions and Aim

The research questions that have guided the entire thesis process focuses on the following questions:

1) **Building Performance Simulation (BPS) Model**: What are the gaps between the modelling and the reality behaviour of the building? What are the less reliable parameters to consider during the calibration process? How to validate the model for the future?
2) **Future scenarios**: What are the future weather data scenarios taken in considerations? How to evaluate the risk of overheating under the impact of Climate Change? How to evaluate the energy consumption under Climate Change?
3) **Adaptation and Mitigation Strategies**: Which are the most suitable strategies to minimize the effects of Climate Change?

Considering these questions, the research is motivated by the objectives of assessing the energy behaviour and risk of overheating of buildings under impacts of Climate Change. To make these types of assessments, it is necessary to model the case study building, calibrating it to its real energy performance. However, the gap between the operational-use and design stages leads to discrepancies in results. Therefore, the disparity in energy behaviour between the operational and design stages becomes notable, especially if the analysis is conducted using future climate data that are probabilistic.

Challenged by these issues, the analysis in this study takes on a future exploration of the energy dynamics and resilience of buildings against evolving climatic conditions. It surpasses a standard retrofitting approach and concentrates on evaluating the building's adaptation and mitigation to climate change. For this reason, the building was subjected to probabilistic future climate scenarios to gain insights into its energy requirements, preparing it for a future where environmental conditions diverge from the present.

The research is related to the case study of a mixed-use building (offices and residential) located in the UK, in London. A building in United Kingdom was selected for evaluation, primarily to assess the effects of overheating in buildings that traditionally did not have a high cooling demand. However, it is evident that in the coming years, the need for cooling will likely arise even in regions where it was previously unnecessary. The choice of a mixed used building enables the examination of varying energy behaviours influenced by different set point temperatures, occupancy densities, and schedules for the use of HVAC and lighting systems.

The Dynamic Building Modelling analysis was conducted using the DesignBuilder software. It takes into account variations in the time of conditions and variables, making it more suitable for capturing the actual energy behaviour of the building under different climatic and usage conditions. Therefore, the building was modelled and calibrated through a dynamic energy analysis, starting from information based on real consumption data and occupants' data from 2022.

The big aim was the evaluation of energy behaviour, the risk of overheating and the carbon emission in future probabilistic scenarios of 2050s and 2080s in order to assess the climate resilience of the building. To reach this aim, a set of KPIs (tab.6) are chosen to compare the current, and future performance of building and its thermal comfort. Additionally, adaptation and mitigation strategies based on these KPIs are analysed.

1.3. Limitations and Scope

The research has the following limitations:

- Since the research is conducted in a case study located in the UK, it follows its current regulations and limitations.
- Input operational data come from 2022, when the effects of COVID-19 were still impacting occupancy patterns, especially in office usage.
- The lack of some data about the data building case study didn't allow to reach a certain level of reliability and accuracy, also considering the data construction of the case study.

Despite some limitations, the purpose of this thesis is to analyse the real behaviour of a building through calibration using data from 2022, a year still impacted by the consequences of COVID-19, which altered the building's energy performance. The study is focused on long-term resilience, considering that approximately 30 years from now, it is hoped that the retrofits made in the last decade will not need to be renewed. External climatic conditions are a significant factor in retrofit studies, and a building resilient to the current climate may not necessarily be resilient in the future.

2. LITERATURE REVIEW

2.1. Calibration and Building Energy Performance gap

In the UK and most countries, design targets come from compliance modelling (e.g., SBEM, DSM). These tools use building details to calculate regulated energy use under standard conditions from national methodologies (NCM). UK NCM cautions that SBEM is for compliance, not design; use specialized modelling for critical design features (6).

However, the building level analysis is affected by the phenomena of the performance gap that is between the design and operational stage. The performance gap is the difference that is between actual energy use of a building and its design performance. To predict the building's energy performance, building simulation tools are used. The significant interest in energy performance has led to the development of numerous software tools, such as EnergyPlus, for its assessment and analysis. Thanks to the analysis conducted with these tools and consequently predicting energy consumption and the risk of overheating, it is possible to comply with regulatory targets through standardized procedures (7).

The building model at the design stage includes information regarding construction, occupancy, HVAC, and boundary conditions like climate data. However, due to the complexity of representing energy flow paths and interactions, the model relies on several assumptions. As a result, numerous studies (8) have indicated that there is a performance gap between the expected and actual building performance. These differences are attributed to various factors, such as rebound and pre-bound effects, interactions between occupants and building technologies, and the accuracy of input values used in simulation models.
To comprehend better this phenomenon and overcome this level of uncertainty, several studies propose methods to address the energy performance gap. De Wilde categorized variability and subdivided the performance gap into three main aspects: first-principle predictions and measurements, machine learning and measurements, and predictions and display certificates in legislation (9).

During the design stage, the building is modelled using standardized operating conditions, such as operating schedules, air conditioning set-points, and occupant density, which are determined by national calculation methodologies like Part L in the UK. The behaviour during the operational stage within a building defines the actual real consumption of the building.
In fact, as it defined van Dronkelaar C. et al. (10) we need to distinguish the compliance modelling and the performance modelling. The compliance modelling consists in the analysis of energy performance considering the regulations and minimum requirements, excluding the operating conditions. Whereas the performance modelling considers the whole building context related to building energy end-use. Therefore, a well consistent energy performance modelling can significantly reduce the performance gap.

Under this framework the CISBE TM54 methodology helps to reduce this discrepancy, evaluating the operational energy use at the design stage (7). The TM54 can provide a good estimate of energy use in operation, even if it is important to consider a range of uncertainty level due to the actual use/operation. However, this range can be decrease considering the modelling performance under a range of future scenarios, as well as to adjust the actual operation through a calibration process.

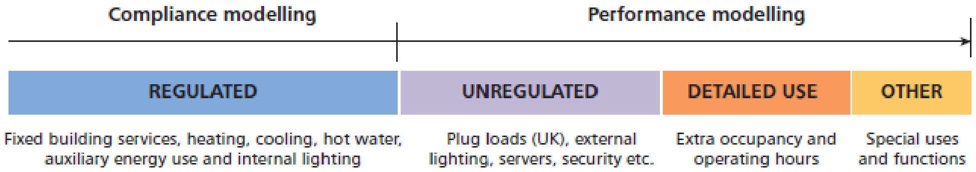

Fig. 1 Compliance vs. Performance Modelling (6)

2.1.1. Operational Performance in-Use

Once a building becomes operational, the task of understanding the reasons behind any performance gap are measurement and verification (M&V) (6). This involves not only detecting possible discrepancies between the building's actual operational stage and its initial design assumptions, but also frequently revealing technical problems that contribute to the performance gap. An energy performance M&V framework for operational buildings should have the capacity to recognize all significant issues and distinguish the following (6):

- Variations in operating conditions from design assumptions, influenced by the building's purpose and actual occupancy behaviour (e.g., difference in occupancy profiles and adjustments in heating and cooling temperature settings)
- Technical issues that cause a performance gap between design intent and actual operation. (e.g., inefficient operation of systems, lack of detailed lighting control, etc.)

2.1.2. Calibrated-based modelling to assess the impact of Climate Change

In United Kingdom to calibrated energy model TM 63 regulation is used. This methodology is followed to conduct an accurate calibration under the Measurement and Verification protocols. The following steps are then listed (11):

1) Data collection regarding architectural design (geometry, dimensions, and building envelope properties), design, commissioning, and operational information of air conditioning systems and other building systems, building operating schedules, monthly and hourly utility energy use data for the whole building, and actual weather data.
2) Identify performance issues related to changes that may have been made during the construction and actual use phases, such as changes in operating conditions or issues with system malfunctions.
3) Design performance model: Create a model at the design stage using a dynamic thermal simulation tool based on an hourly calculation method.
4) Calibration process: The goal is to develop the actual building usage. This is an iterative process where input data is manually adjusted until it is close to measured data.

2.2. Future scenarios under impact of Climate Change

2.2.1 IPCC Scenarios

Climate change scenarios have to be generated considering the future trends of the GHG emissions. The choice of scenarios plays a significant role in the climate change literature informing the IPCC Assessment Reports (ARs) and support policymakers (12).

Having a reliable understanding of future GHG emissions is still a subject of study, primarily due to the data gaps that exist. In fact, the level of uncertainty in all climate change is significant because of the difficulty to predict future trajectories of GHG emissions and scientific uncertainties due to the formulation and implementation of the climate models.

However, understanding how emissions change over time is crucial in order to comprehend how to effectively reduce them in adaptation planning. (13)

Since 1990, possible future trends of GHG emissions have been studied. The outcomes of these scenarios are used as input data for (14):

- Climate change research
- Impact assessment
- Mitigation and adaptation analysis

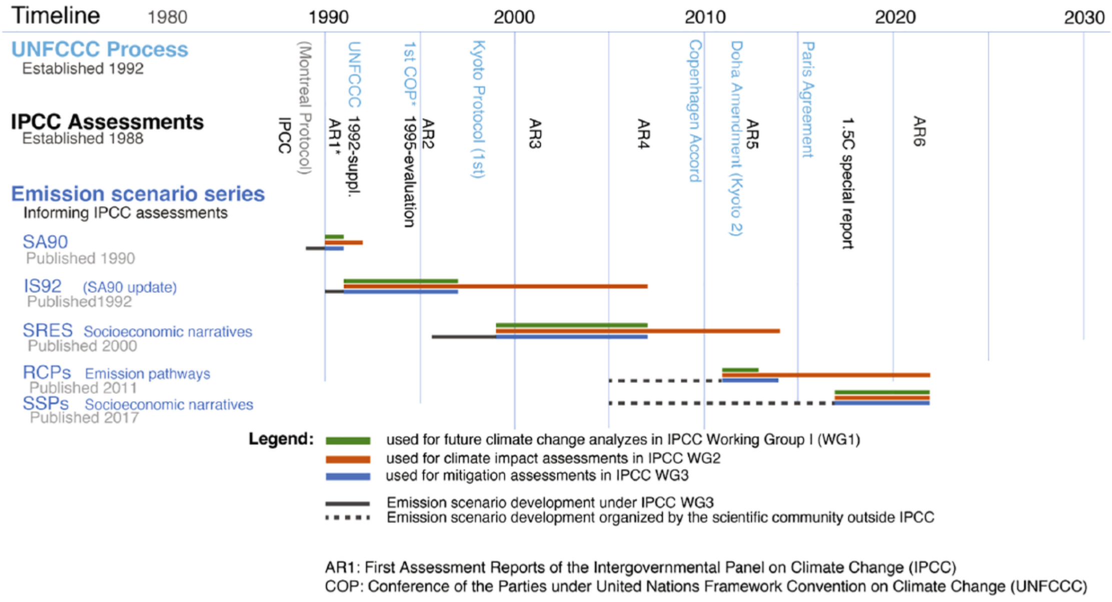

Fig. 2 Historical overview of emissions scenario (14)

Modelled scenarios and pathways are used to explore future emissions, climate change, related impacts and risks, and possible mitigation and adaptation strategies (12).

In the year 2000 (15), the IPCC described in the AR3 and AR4 Special Report on Emissions Scenarios (SRES) that they utilized six storylines based on a range of assumptions, including socio-economic variables and mitigation options.

In the SRES, scenario assumptions were changed to narrative families. Four storylines (A1, A2, B1, and B2) represent two dimensions: economic (A) or environmental (B) concerns and global (1) or regional development (2) patterns.

Scenario	**Key drivers**
A1F1	Economic growth Convergent world Fossil fuel energy
A2	Economic growth Heterogeneous world
A1B	Economic growth Convergent world Mixed energy sources
B2	Sustainability Heterogeneous world
A1T	Economic growth Convergent world No Fossil fuel energy
B1	Sustainability Convergent world

Tab. 1 Storylines emissions scenarios based on *IPCC report emissions scenarios* (15)

In the 5th and 6th assessment reports of the IPCC (2011), possible scenarios are re-evaluated. In fact, the AR5 discusses Representative Concentration Pathways (RCPs) and the AR6 discusses Shared Socioeconomic Pathways (SSPs) in combination. These scenarios are inspired by the SRES but are organized to address socio-economic mitigation and adaptation challenges.

In particular, the Shared Socioeconomic Pathways (SSPs) (2017) consider a range of different economic contexts associated with the implementation of various greenhouse gas emission management strategies. Emissions in each scenario vary based on different socio-economic assumptions, levels of climate change mitigation, and control measures for certain pollutants. Incorporating socio-economic indicators into future climate scenarios is essential as they represent the fundamental drivers of both climate change and advancements in mitigation and adaptation efforts. For this reason, the IPCC's Sixth Assessment Report (AR6) (12) combines SSPs and RCPs.

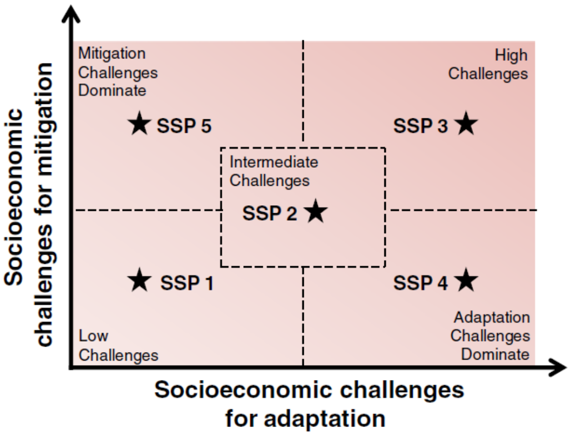

Fig. 3 The “challenges space” to be spanned by SSPs (based on Kriegler et al. 2012, Fig. 3) (16)

2.2.2 The building sector under different future scenarios

2.2.2.1. Greenhouse Gas emissions (GHG)

From a building point of view, these scenarios are also influenced by mitigation and adaptation strategies in the construction field. The most recent AR6 WGIII report (2) considers four types of future global scenarios of building emissions based on SER (Sufficiency, Efficiency, Renewable) framework as a mitigation strategy.

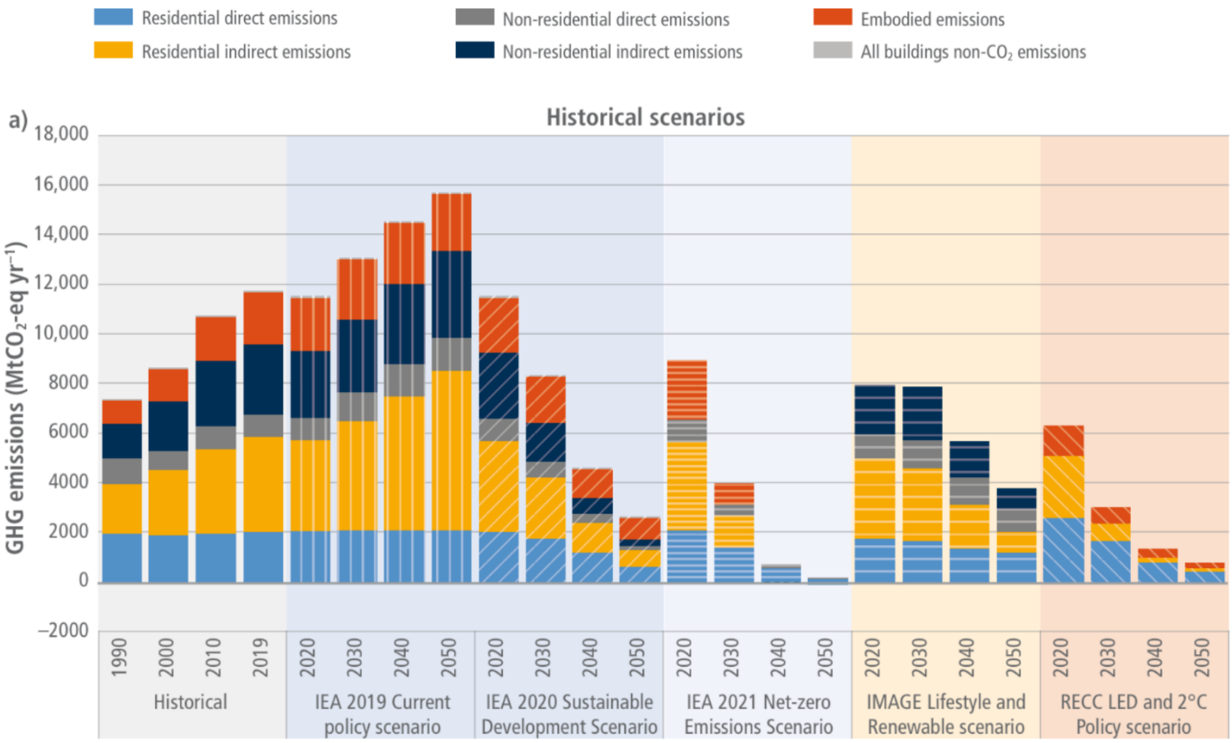

Fig. 4 Building GHG emissions reduction in four different scenarios (2)

These scenarios considered are divided into:

- International Energy Agency scenarios:
  - **2021 Net Zero emissions** by 2050 Scenario (NZE) that is the scenario in which the global energy sector reaches the zero CO2 emissions by 2050. (17)
  - **2020 Sustainable Development Scenario** (SDS) that considers the impact of Covid 2019 on health outcomes and economies.
- **IMAGE1-Lifestyle-renewable** (LiRE): It is based on a mix of the SSP2 scenario that represents intermediate socioeconomic challenge related to Climate-change adaptation and mitigation (18) and the RCP2.6 the representative concentration pathway of 2.6 W/m^2 additional forcing.

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[1] *Integrated Model to Assess the Global environment* is an integrated assessment model that simulates globally the environmental consequences of human activities. The goal is to assess the long-term dynamic and impacts of global changes that result from interacting socio-economic and environmental factors. (18)

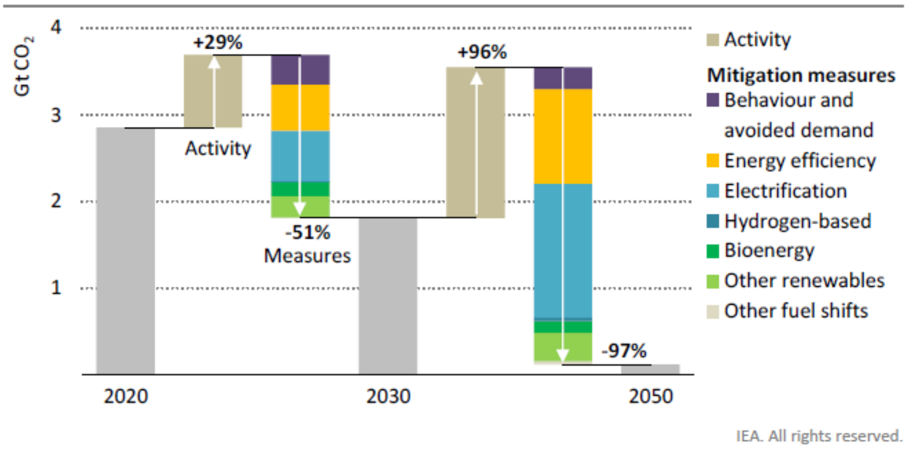
[2] There are defined five SSP (shared socioeconomic pathways) scenarios that differ in the challenges for mitigation and adaptation, and each of them is elaborated starting from a baseline scenario without a climate policy.

- **RECC-LED3 and 2° Policy scenario**: it provides estimates of the energy and material flows related to the expansion of housing stock, which is influenced by population growth and changes in per capita floor area.

As it is possible to see the **IEA -NZE scenario** is the only one that has a significant reduction of GHG emissions. This depends on the fact that in the IEA scenario, mitigation measures are taken regarding the nearly Zero-Energy Building (n-ZEB). To reach decarbonization of energy use is necessary to adopt mitigation measures (19):

- Avoid demand for energy services
- Efficient lighting, appliances and equipment
- New buildings with high energy performance
- Onsite renewable production and use
- Improvement of existing building stock
- Enhanced use of wood products

Many of these mitigation options for buildings are largely cost-effective in their emissions abatement, with costs ranging from overall cost savings (through avoided demand and efficient equipment).



IEA. All rights reserved.

Fig. 5 Global direct CO2 emissions reductions by mitigation measure in buildings in the NZE (17)

In the NZE scenario, building envelope improvements contribute the most to reducing heating and cooling energy intensity in both retrofitting and new construction. However, heating and cooling technology also play a significant role. For this reason, The NZE brings about a transformation in space heating. The use of natural gas for heating in homes will decrease dramatically, from nearly 30% currently to less than 0.5% by 2050. In contrast, the use of electricity for heating will rise, accounting for nearly 20% of total heating currently and increasing to 35% by 2030 and approximately 55% by 2050. High-efficiency electric heat pumps will become the primary technology for space heating in the NZE.

The installation of heat pumps worldwide is expected to see substantial growth, with monthly installations rising from 1.5 million currently to around 5 million by 2030 and 10 million by 2050. In the coldest climates, hybrid heat pumps will be used to some extent, but they will meet no

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[3] *Resource Efficiency and Climate Change-Low Energy Demand (RECC-LED) scenario*

more than 5% of the heating demand by 2050 (17). Models are often also used to explore 'what-if' questions, to confirm the feasibility of certain assumptions/outcomes, and to quantify the impacts of a change such as a policy under different conditions.

2.2.3 The climate change projections for Building Performance Simulation in UK

In UK, CISBE (Chartered Institution of Building Services Engineers) has produced a set of future weather years in order to run building simulation under future climate conditions. These data come from the current CISBE TRY and DSY weather files that want to assess the current impact of climate change (13). In particular:

- Test Reference Years (TRY) refers to a "typical year" in order to calculate the average annual energy demand and compliance with the UK Building Regulations part L.
- Design Summer Year (DSY) refers to a near extreme warm summer (20). These data are used for summertime risk assessment.

The initial climate projections, known as UKCIP98 scenarios, utilized a coupled atmosphere-ocean global circulation model (AOGCM) with a spatial resolution of around 350 km. In 2002, more advanced climate models were introduced with the UKCIP02 scenarios, featuring an improved spatial resolution of 50 km. In 2009, the UKCP09 scenarios, will further enhance resolution to 25 km.

The scenarios are constructed by combining two sets of modelling data to create a comprehensive picture:

1. Projections from an Atmosphere-Ocean General Circulation Model (AOGCM) are used to predict global temperature changes for each of the four emissions scenarios and three specific time periods within the studied period.
2. Downscaled projections from a Regional Climate Model (RCM) are utilized for one emissions scenario and one time period.

Both UKCIP02 and UKCP09 scenarios are based on SRES scenarios (13). In particular UKCIP02 provide projections for four gas emissions scenarios as it shown in the table below from TM48:

Scenario	UKCIP02	UKCP09	IPCC AR4
Low	B1	B1	B1
Medium	B2(Medium-Low) A2(Medium-High)	A1B	A1B
High	A1F1	A1F1	A2

Tab. 2 SRES marker scenarios used in UKCIP02, UKCIP09 and IPCC (13)

Also, the UKCIP02 scenarios offer predictions for alterations in the monthly mean values of a designated set of 15 climate parameters (e.g., max and min temperature, relative humidity, total precipitation rate exc...). The alterations are provided for three different time periods: the 2020s, 2050s, and 2080s, and four emissions scenarios as Low, Medium-Low, Medium-High, and High emissions.

Timeslice	Emissions scenario			
	Low (B1)	Medium-Low (B2)	Medium-High (A2)	High (A1F1)
2020s	0.79	0.89	0.89	0.95
2050s	1.4	1.7	1.9	2.2
2080s	2.0	2.3	3.3	3.9
IPCC AR4 2090s	1.8	2.4	3.4	4.0

Tab. 3 Projections Emissions Scenario (UKCIP2002 Scientific Report)

The UKCIP02 scenarios are subject to uncertainties arising from various sources. These uncertainties come from factors such as projections in emissions scenarios and scientific uncertainties in the AOGCM and RCM models used.

The acknowledged uncertainties in the UKCIP02 scenarios raise concerns about their application in building simulation modelling. Whereas predictions for annual average temperature change and geographical variation in the UK are considered to have high confidence, larger projected changes in summer temperatures compared to winter temperatures are viewed with low confidence.

UKCP09, on the other hand, will differ from UKCIP02 by providing probabilistic projections. For each emissions scenario and specific time period, UKCP09 will offer a range of possible changes in climate along with associated probabilities. While the UKCIP02 projected changes can be considered the most likely projections for each scenario and time period, the numerical values of these projections are expected to change in UKCP09 (13).

The UK's latest climate projections (UKCP18) predict a substantial increase in the frequency and severity of extreme daily high temperatures across all regions (21). For example, a "hot" summer like that in 2018, historically occurring with a 10% annual probability, is projected to surge to 50% by mid-century, regardless of emissions scenarios. Moreover, there's a heightened likelihood of temperatures exceeding 40°C in the UK by 2080, particularly under high-emission scenarios.

2.3. Policy actions and Frameworks in UK under the impact of Climate Change

According to data from the Climate Change Performance Index, United Kingdom is one of the leading countries in terms of addressing climate change, ranking among the top ten performers (22). Especially in terms of reducing GHG (greenhouse gas) emissions, England has made significant progress, which can be attributed to the implementation of policies such as the Climate Change Act (CCA) introduced in 2008 and redefined in 2019.
It is a world-first national legislation that provides an overall framework for climate mitigation and adaptation action preparing for the impacts of climate change (23). An important role is assigned to the Climate Change Committee (CCC) that monitor and report the progress towards the targets defined by the UK Government.

The Climate Change Act (2008) made the UK the first country to establish a long-term legally binding framework to cut carbon emissions. The target is to reduce the levels of GHG emissions at least 100% of 1990 by 2050 (23).
The UK's policy climate targets are managed by "carbon budgets". These limits cumulative GHG emissions over a five-year period and are legally binding. Following the adoption of the UK's Climate Change Act in 2008, five initial budgets were provided which cover the period from 2008–2032. These budgets were set with the aim of reducing emissions to 80% below 1990 levels in 2050, that was the initial target of CCA in 2008 (24).
To reach the ultimate target by 2050, the UK's climate policy follows a pathway based on carbon budgets each 4 year until to arrive at 2050 where it should reach the Net Zero Target (25).

The CCC provides guidance on the appropriate level of each carbon budget, which is intended to achieve the UK's long-term climate change objectives in a cost-effective manner. Once a carbon budget is established, the Climate Change Act mandates the Government to develop policies to ensure that the budget is met, in that way it ensures progress towards the country's climate goals (23).

The Climate Change Act mandates the UK Government to publish a UK Climate Change Risk Assessment (CCRA) every five years since 2012. The latest assessment, CCRA3 (2022), presents the current and future climate change understanding in the UK and evaluates 61 risks and opportunities across various key areas, including the natural environment, infrastructure, human health, built environment, businesses, and international dimensions.
In response to the CCRA, the Climate Change Act also requires the UK government to create a National Adaptation Programme (NAP) specifically for England. Meanwhile, the devolved administrations produce their own adaptation programs and policies. The NAP plays an important role in driving adaptation actions in UK (26).

2.3.1. The impact of climate change in Building sector in UK

In UK, a significant proportion of the domestic building stock, specifically 83.2%, was constructed before 1990 (27), whereas the 25% non-domestic one was built before 1900 and 67% before 1970 (28).

Taking into account the construction period of the majority of buildings, approximately 17% of CO2 emissions come from the built environment (25) and consume about 59% of the electrical energy in UK, in fact, only about 40% of buildings have an EPC rating of band C and above (29).

Unfortunately, the policies for buildings are less developed than for other sectors. In fact, in the annual Progress Adaptation Climate report published by the CCC (30), it is evident that emissions in 2022 compared to 2021 increased by 5% in non-residential buildings and only decreased by 6% for residential buildings. In the built environment section of the CCRA UK technical report (31) the following current and future risks are defined:

- Current and future risks of moisture damage
- Current and future risks of wind damage
- Current and future risks of subsidence
- Current and future risks of landslides
- Future risks of overheating

In order to reduce emissions from buildings by 2050, it is necessary to implement certain measures in the following areas (32):

- changing the operational behaviour in homes
- increasing the energy efficiency reaching the C band of EPC by 2035 (29)
- improving the energy efficiency of lighting and electrical appliances
- using renewable sources instead fossil fuel for heating

2.3.1.1. Thermal comfort: the risk of overheating in UK

Another consequence of climate change is the risk of overheating, which concerns to the rise in temperature during summer periods, thereby impacting the building sector and consequently human health as well as the economy and productivity. In addition to this, a crucial role in mitigating the risk of overheating is played by the cooling system, whose consumption will necessarily increase in order to reduce this risk. In fact, the cooling demand is increased of 2 % from 2012 to 2019 (21) and it will increase more.

Furthermore, future climate changes, an aging population, and the characteristics of UK buildings will collectively contribute to an elevated risk of overheating (33) in the UK unless additional adaptations are implemented (21).

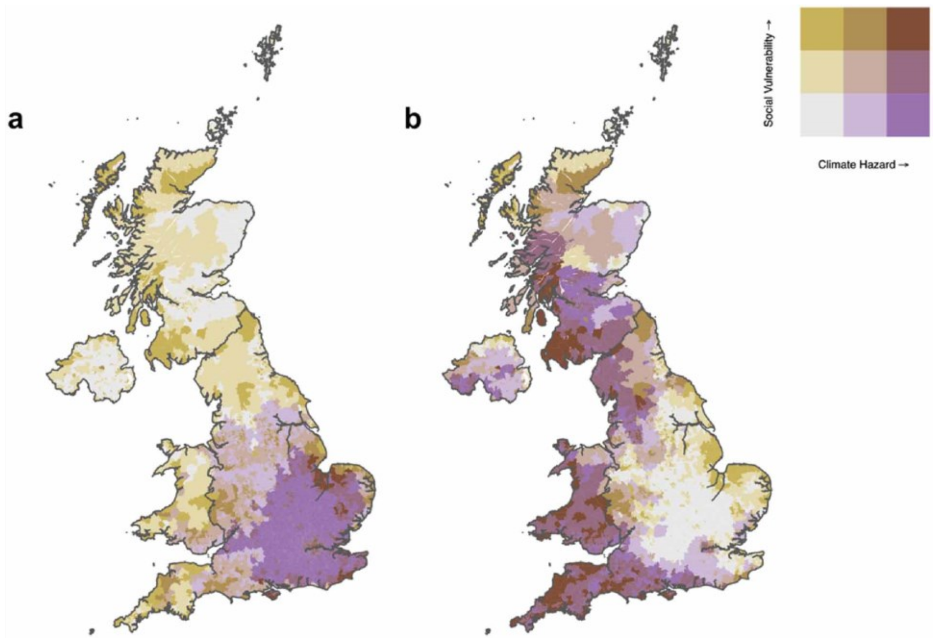

Fig. 6 *Relative risk (in terms of climate hazards and socio-economic vulnerability) across the UK for (a) the recent past (1990–2019) and (b) for the projected change between recent past and +3.0 ◦C warming* (33).

In this context, a significant portion of buildings is being retrofitted. However, the question that arises is: Will these retrofitted buildings achieve zero emissions by 2050 and be resilient to a warmer climate?

2.4. Achieving thermal resilience through Adaptation and Mitigation strategies in the building sector

As these objectives are outlined, there is an increasing focus on the development of adaptation and mitigation strategies for climate change. Research is progressively leaning towards advanced technologies that can enhance the resilience of buildings to the effects of climate change. The following table shows what is the meaning of some topic treats on this dissertation.

Topic	Definition	Reference
Mitigation	**Mitigation** (of climate change) A human intervention to reduce the emissions or enhance the sinks of greenhouse gases.	IPCC, 2022. *Climate Change 2022: mitigation of climate change. Contribution of working group III to the sixth Assessment Report of the intergovermental Panel on climate Change*
	Mitigation measures, In climate policy, mitigation Measures are technologies, process or practices that contribute to mitigation, for example, renewable energy technologies, wate minimisation processes and public transport commuting practices.	IPCC, 2022. *Climate Change 2022: mitigation of climate change. Contribution of working group III to the sixth Assessment Report of the intergovermental Panel on climate Change*
Adaptation	**Adaptation,** in human systems the	IPCC 2014 Climate Change 2014:

	process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In Natural systems, the process of adjustment to actual climate and its effect.	*Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* IPCC, 2022
	Adaptation options, the array of strategies and measures that are available and appropriate for addressing adaptation. They include a wide range of actions that can be categorised as structural, institutional ecological or behavioural	- IPCC 2014 Climate Change 2014: *Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* - IPCC, 2022
Resilience	**Resilience** the capacity of interconnected social, economic and ecological systems to cope with the a hazardous event, trend or disturbance responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation.	IPCC, 2022. *Climate Change 2022: mitigation of climate change. Contribution of working group III to the sixth Assessment Report of the intergovermental Panel on climate Change*

Tab. 4 Definitions of the terms Adaptation, Mitigation and Resilience concepts

Understanding the factors influencing thermal resilience is important for effective retrofitting. Four categories of factors that impact the thermal resilience of buildings include (34):

- Outdoor Environment
- Building Characteristics
- Occupant Characteristics
- Power Grid Characteristics

To achieve resilient buildings, it is essential to identify technologies and design strategies that can enhance resilience. In Annex 80, a set of research activities within the Buildings and Communities Programme (EBC) explores publications related to climate resilience and resilient cooling strategies in the building sector. Two groups of technologies, encompassing both active and passive cooling strategies, are addressed with distinct objectives:

Aims	Strategy	Technologies	References
Reduce heat loads to people and indoor environments	Advanced window/glazing and shading technologies	Glazing Technologies: Low-emissivity coatings	Sadrzadehrafiei et al. (35) Jaber et al. (36)
		Shading devices and systems: Interior operable shading systems	O'Brien et al. (37)

Remove Sensible heat from environments	Ventilative cooling	Natural ventilation	Lomas et al. (38)
	Compression refrigeration	Variable Refrigerant Flow (VRF) systems	Annex 80 (39)

Tab. 5 Technologies proposal to reach cooling resilient from Annex 80

The technologies considered by Annex 80 (39) are related to the technologies utilized or examined in the case study.

2.4.1. Advanced window/glazing and shading technologies

Fenestration systems, encompassing windows and shading elements, assume an important role in influencing the cooling energy consumption, load characteristics, and resilience of buildings. They also exert a significant impact on indoor thermal comfort. The technical emphasis on windows primarily centres on the glazing, typically constituting the majority of the fenestration area. In non-residential curtain walls, insulated opaque panels may form part of the system. While the cooling analysis highlights the importance of glazing, it is noteworthy that in heating-dominated climates, the oversimplification of neglecting frame and sash properties may prove unsuitable. Solar influences on cooling loads and comfort extend beyond windows to encompass the effects of shading systems positioned in various configurations on the building envelope.

Numerous studies have investigated the performance of various types of glazing technology. The market offers diverse configurations of glazing, ranging from double glazing to triple glazing, filled with argon or other gases depending on the desired performance. The solar heat gain of each window is determined not only by the type of glass and layers composing the window but also by factors such as climate, building type, and building orientation. In a study conducted in 2011 (36) various simulations were carried out, considering different glazing technologies in diverse locations. As a result, an assessment of glazing technology choice must be made, taking into account building orientation, location, and window properties.

Research conducted by Sarzadehrafiei et al. (35) demonstrates how advanced glazing technologies, such as Low-E (Low emissivity coatings) pane glazing, can significantly reduce annual electricity consumption by up to 6.4% compared to single clear glazing. These Low-E coatings exhibit high reflectance in the 4-50 µm range, causing the Insulating Glass Unit to decrease and thereby reducing long-wave radiative heat transfer.

Shading technologies are essential for controlling the entry of sunlight through windows. In the market, there are various ways to position shading elements:

- Interior
- Within the gap between glazing layers (the window must be double or triple glazed),
- Outside the window

All these methods affect both daylight transmittance and the view, as well as the regulation of solar gain. When considering shadings placed inside the window, their effectiveness in reducing cooling load depends on manual control by occupants. Consequently, numerous studies highlight how occupants' actions can either underestimate or overestimate the cooling load (37).

2.4.2. Ventilative Cooling

Various strategies and solutions can be employed for ventilative cooling, such as mechanical ventilation, natural ventilation, or a combination of both. Ventilative cooling has the potential to reduce the energy demand of buildings while simultaneously ensuring the thermal comfort of occupants. Naturally, the performance of ventilative cooling depends on several parameters, including climatic conditions, building characteristics, and occupants' behaviour. The vulnerability of the occupants is one of the major factors influencing the effectiveness of ventilative cooling. In their assessment of different natural ventilation strategies for achieving climate resilience in future scenarios, Lomas et al. (38) found that buildings utilizing advanced natural ventilation strategies demonstrate greater resilience compared to those employing a single side ventilation. They also highlight that, although natural ventilation is preferable to mechanical ventilation due to no-production of CO2 emissions, a precise evaluation is necessary to mitigate the risk of overheating. Therefore, one of the limitations is that natural ventilation may not consistently meet thermal comfort requirements during summer periods.

2.4.3. Compression refrigeration

The most widely utilized active technology for generating cooling effects is Vapor Compression Refrigeration. These systems can be categorized based on factors such as the heat source and sink, the type of thermal power produced, overall technology, compressor technology, refrigerant type, cooling capacity, and reversibility. Vapor compression refrigeration systems are also classifies based on technology ranging from conventional chillers to Variable Refrigerant Flow.

In general, while vapor compression systems provide operational flexibility, their limitations include energy consumption. The electricity required to drive heat against the temperature gradient poses a significant constraint, resulting in a lower system Energy Efficiency Ratio (EER). In contrast, passive systems, leveraging lower-temperature heat sinks, demonstrate higher EERs. They rely mainly on pumps and fans, minimizing electricity consumption compared to vapor compression systems.

In particular, Variable Refrigerant Flow (VRF) systems, allow indoor units to function as evaporators, condensers, or a combination of both, depending on the mode of operation. The outdoor unit, correspondingly, serves as an evaporator or condenser. The advantage of the cooling/heating mix mode lies in achieving heat transfer between zones, reducing overall energy consumption for building heating and cooling. VRF systems stand out as particularly suitable for retrofitting due to their adaptability to existing buildings with relative ease. Additionally, another notable advantage is their operational efficiency, with VRF systems capable of saving up to 40% in energy costs compared to traditional HVAC systems.

At the same time there are some disadvantages such as the installation and maintenance high cost and the presence of hazardous refrigerant used as heat exchange medium that can pose potential risks if leaks occur.

3. METHODOLOGY

This chapter follows the overview of the methodology and the evaluation of research strategies used in this dissertation. Firstly, the research was conducted through a literature review on the following topics: the energy performance gap during the calibration process for energy performance in-use, climate change future scenarios, and Climate Resilience in building sector listing some adaptation and mitigation strategies. By studying these subjects, it was possible to identify the current context of building energy analysis and its levels of strengths and weaknesses. The aim was to understand how to best conduct energy modelling in view to reach thermal comfort and low energy consumption by 2050 in UK.

Subsequently, the various topics discussed earlier were applied to a case study building to carry out the research objectives and perform a comparison and analysis.
In the final phase of the research, the model of the case study building was calibrated to project it into the future scenarios of 2050 and 2080, and then assessing several adaptation and mitigation strategies to reach Climate Resilience.

Therefore, the methodology is essentially divided into three parts: building data collection, building modelling and calibration process, and different analyses of adaptation and mitigation.

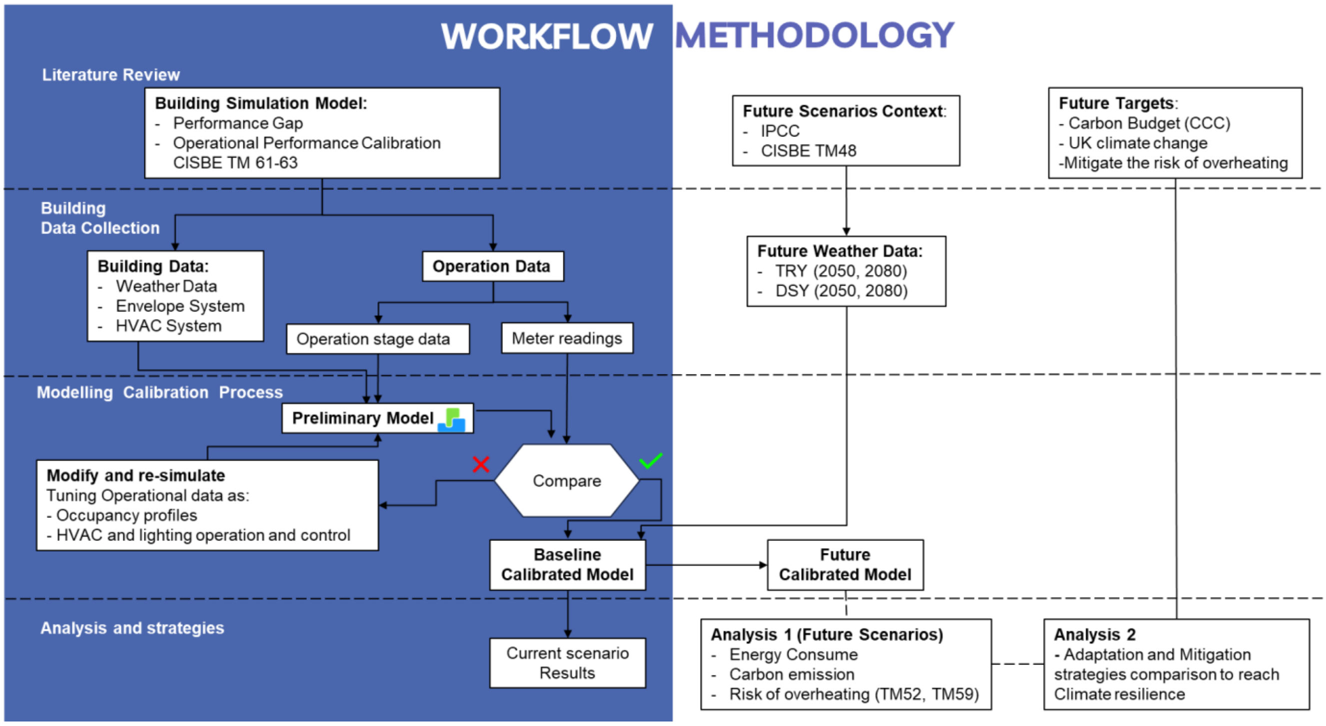

Fig. 7 Methodology Workflow

3.1 Collecting and analysing building data

After identifying the case study, the data collection phase is primarily divided into two phases the data related to the building construction and the data related to the building in use (operational data):

I) The modelling phase was carried out using the DesignBuilder tool, utilizing drawings plans and information related to construction materials and systems datasheets.

II) Building in-use Data: Data was collected regarding operation stage (activities data) data and meter readings of electrical energy for the year 2022.

3.2 Calibration Process and Model Validation

The most important aspect of this research was constructing the building model in a way that allowed for the assessment of energy demand projected into future scenarios. The process was essentially divided into three phases:

I) Building a baseline model using DesignBuilder Software. The baseline model is developed based on the most recent architectural plans of the case study and operation data.

II) Calibrating the model by fine-tuning the baseline Model. Manual calibration is performed by considering the simulation outcomes of the baseline model and the case study's meter readings of electrical consumption in 2022. During calibration, the parameters managed include HVAC systems with their auxiliaries and lighting in the design stage. In the operational stage, occupancy and equipment profiles are adjusted following the TM 63 methodology. The last step of calibration involves validating the model based on its accuracy. To validate a model, statistical indices are utilized (40): Mean Bias Error (MBE), the Root Mean Square Error (RMSE) and the Coefficient of Variation of the RMSE (Cv(RMSE)) are calculated considering the ASHRAE guideline 14 limits in the table below

ASHRAE Limits guideline 14 (2014)		
Values Type	NMBE	Cv(RMSE)
Monthly	±5%	15%
Hourly	±10%	30%

Tab. 6 ASHRAE Guideline 14 limits for uncertainty indices and evaluation of degree of confidence

Considering both indices helps avoid calibration errors caused by compensating for mistakes.

- **Normalized Mean Bias Error** (NMBE) indicates the average error between the simulated and measured values, and it shows how closely the simulated data matches to the monitored ones:

$$NMBE = \frac{1}{\bar{m}} \cdot \frac{\sum_{i=1}^{n} m_i - s_i}{n}$$

- **Coefficient of Variation of the Root Mean Square Error** (CV(RMSE)) measures the variability of the errors between measured and simulated values. It indicates the ability of the model to predict the overall load shape that is reflected in the data.

$$CV(RMSE) = \frac{1}{\bar{m}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}}$$

Where:

- $\bar{m}$ is the mean of measured values
- m_i is the measured value
- s_i is the simulated value
- n is the number of data points

III) if the uncertainty indexes did not respect the limits imposed by ASHRAE, some parameters and schedules[4] (tab.) were adjusted:

Parameters adjusted during calibration process
Occupancy Density [people/m^2]
Density occupancy schedule
Heating Set Point Temperature[°C]
Cooling Set Point Temperature [°C]
Heating schedule
Cooling schedule
Power density of equipment [W/m^2]
Equipment schedule

Fig. 8 Parameters that are adjusted during calibration process

3.3 Evaluation of the Effects of Climate change

After obtaining a calibrated model of the case study, two analyses are conducted:

- **Analysis 1:** Evaluation of the Risk of Overheating under medium emissions future weather data. The analysis was conducted using UK regulations to assess the risk of overheating. Given that the building is a mixed-use building, it was necessary to perform two separate analyses based on different intended uses:
  - **CISBE TM52**: For non-domestic zones, including offices and landlords. This method is based on adaptive methodology to assess the predicted level of thermal comfort within a building. A building failing two or more of the criteria is considered at an unacceptable risk of overheating:
    1) Criterion 1: Hours of Exceedance
    2) Criterion 2: Daily Weighted Exceedance
    3) Criterion 3: Upper Limit Temperature
  - **CISBE TM59:** Applied to domestic areas. TM59 constitutes an industry standardized method for forecasting the risk of overheating in

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[4] A Schedule consists of one daily profile for each day of the week, for each month of the year.

residential buildings, whether they are new constructions or involve significant refurbishments. It employs dynamic thermal analysis, with a particular emphasis on flats, given their tendency to exhibit a higher risk of overheating compared to houses. It follows the verification of two criteria based on the hours of exceedance in kitchen living room and bedrooms.

- **Analysis 2**: Calculating Energy Demand and CO2 Emissions under climate projections (medium-level emissions) weather data at different percentiles. In the DesignBuilder Tool, it is possible to generate parametric outputs (KPIs) for different future weather files. The outputs, which served as evaluation indicators, were the energy consumption for heating and cooling, and the quantity of CO2 emissions. Through parametric analysis, it became more straightforward to relate the current and future energy behaviour of the building, in order to identify the most suitable strategies to reach the climate resilience of building in long term period.

3.3.1. KPIs

The following key performance indicators (KPIs) were used for the performance assessment of the choice of adaptation and mitigation strategies:

Category	KPI	Measure Unit	Definition
Contaminants	**CO_2 emissions** Annual CO_2 emissions	$kgCo_2/m^2$ per year	Quantity of embodied and operational carbon
Building energy performance	**$EPC_{,nd}$**, Annual thermal energy need for space cooling	kWh/m^2 per year	Annual thermal energy need for space cooling
	EP_{el}, Annual Electrical Energy Consumption for the total building	kWh/m^2 per year	Annual electrical energy consumption (from the grid)
Thermal comfort	**HE** Hours of Exceedance	%	The number of hours where the operative temperature of the zone is greater than the upper limit temperature during the occupied hours of a typical non-heating season
	DWE Daily Weighted Exceedance	K.hr	Criterion that deals with the severity of overheating within any one day, which can be as important as its frequency, the level of which is a function of both temperatures rise and its duration. This criterion sets a daily limit for acceptability
	ULT Upper Limit Temperature	hr	Criterion that sets an absolute maximum daily temperature for a room, beyond which the level of overheating is unacceptable.

Tab. 7 KPIs Key Performance Indicators

4. CASE STUDY: The Dunn's Hat Factory

4.1. Introduction

The building is located between Kentish Town and Camden Town, London (NW1 9PX). It is a 6-stories structure with a lower ground floor. The first four floors below ground level are office spaces, whereas the last 2 floors are allocated for apartments (15 flats). The lower ground floor houses bike storage areas and technical rooms.

Originally constructed in 1930 as a hat factory, the building underwent a deep renovation in 2006, and in 2016, the façades were renovated. The building stands at approximately 25 m in height, with a floor-to-ceiling height of approximately 2.7 m on each floor. Double-glazed windows are installed on each office floor and the 5th floor, while the 6th floor features continuous facades.

The building is comprised of two rectangular blocks that are interlocked and rotated at approximately 30-degree angle. The roof is accessible only for maintenance purposes and houses various utility systems.

Fig. 9 Aerial Photo from Google Maps

Latitude, Longitude	51.52; -0.14
Altitude (m)	31
ASHRAE Climatic Zone	4A
GIA (m^2)	6583,6
Elevation (m)	25
Category of Use	B1 (1-4th floor) Residential (5-6th floor)

Tab. 8 Building information

Fig. 10 East Façade

Fig. 11 West Façade

4.2. Data Collection

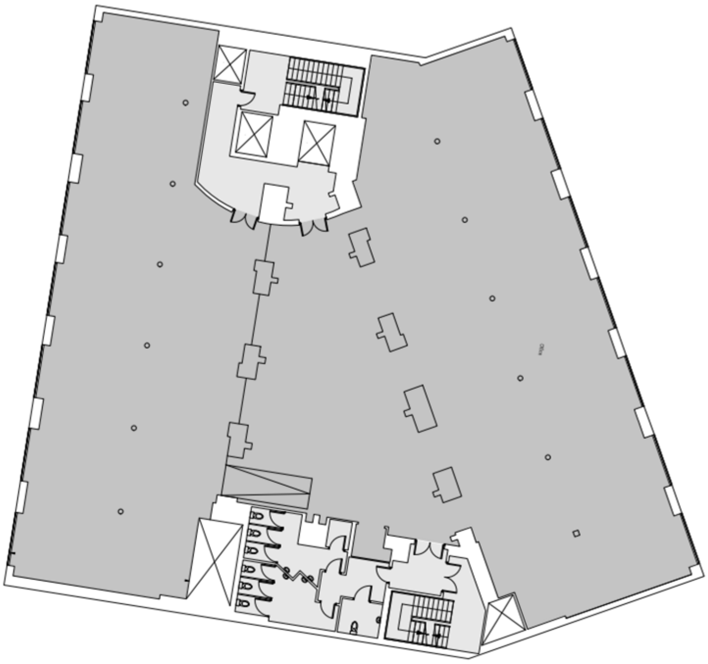

Fig. 12 Office Plan[5]

4.2.1. Envelope

Firstly, the information about the building is taken from plans drawings and thanks to a survey on the roof to have information about technical systems. The data that could not be obtained, given the building's age, has been extrapolated based on its construction date and the fact that it underwent redevelopment in 2006, followed by a partial renovation of both facades in 2016. Additionally, some data has been extracted from the UK government website "Find an Energy Certificate."

The entire building features an exterior wall made of bricks and covered with plaster for the first 6 above-ground floors, while the top floor is distinguished by a continuous façade. All the external windows and doors consist of double glazing. A portion of the accessible roof is allocated for installations, whereas around 600 m^2 of the roof is no-accessible, with a gradient of approximately 2%.

Envelope component	U Value [W/m^2K]	Description	Minimum Requirements Standards regulation UK PART L (2016) [W/m^2K]
External Wall	0,872	Brick wall covered with plaster without insulation	0,35
Flat Roof	0,42	100 mm insulation	0,25
Internal floor	1,16	Reinforced concrete	-
Ground Floor	1,45	Reinforced concrete	-
Internal wall	1,78	Plasterboard	-

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[5] Not in scale

External doors	2,76	Glazing doors	2,2
Windows	2,76	Double glazing filled with air	2,2
Curtain wall	2,76		2,2

Tab. 9 Envelope Components

4.2.2. Systems

Fig. 13 Roof

The outdoor unit systems are located on the roof of the building. Data about systems are taken during a survey done on 27th April 2023. Additionally, data has been extracted from the UK government website "Find an Energy Certificate"[6], where an "Air conditioning inspection report" was written in 2020 after the inspection done in 2020.

HVAC system

There are 14no VRF systems installed in the office areas, 6no VRF systems installed in the flats, and 2no split systems installed in the reception and atrium. Fresh air is supplied to the offices by 2no AHU located on the roof. There are control panels in each office area to control the VRF systems.

- Heating and cooling equipment

16no VRF systems are more than 20 years old and are charged with R407C. The remaining 4no systems are more recent and are charged with R410A.

- AHU units

There are 2no air handling units located on the roof that were installed in 2001.

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[6] https://www.gov.uk/find-energy-certificate

- Terminal units

The VRF systems have either ducted units at ceiling level or floor mounted units.

- Control system

There are control panels in each office area to control the VRF systems. There are wall mounted controls in the reception and the atrium (April 2023 Setpoint temperature: 19°C).

Systems	Model	Details	Zones Description	
2no AHU	Mechanical ventilation	-	Offices zone, atrium and reception Extraction fan in toilet areas	
4noVRF-Heating and cooling	Mitsubishi electric PURY-300YLMF-A1	Heating set-point: 20-22 °C SCoP: 4,70 Total Capacity: 150kW	Offices	
		Cooling set-point: 23-24 °C SEER: 6,90 Total Capacity: 119,2 kW		
2noHeat pump	Mr Slim Power Inverter Outdoor Units (PUHZ ZRP125VKA2)	Heating set-point: 20-22 °C SCoP: 4,70 Total capacity: 23,8 kW	Atrium, Reception	
		Cooling set-point: 23-24 °C SEER: 6,40 Total Capacity: 23kW		
16noVRF-Heating and cooling Total	Mitsubishi electric PURY-P250YMF-C	Heating set-point: 20-22 °C SCoP:2.3[7] Total Capacity: 504kW	Flat 1 Flat 2 Flat 2A Flat 3 Flat 4 Flat 6 Flat 7 Flat 8 Flat 9 Flat 10 Flat 12 Flat 13 Flat 14	Offices Relax Areas
		Cooling set-point: 22-24 °C SEER: 2.8 Total Capacity: 448 kW		
Electric Heating	-	Heated floor	Flat 5	
Auxiliary energy	-	Pump power density: 1,40 W/m^2	In all zones	
DHW	Megaflo Eco	Unvented Cylinder	For all areas	

Tab. 10 Case Study systems Description with details referred to flats.

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[7] In simulation it was considered a SCoP and SEER decreased approximately of 30% due to the age of the machines (2001)

Code	System HVAC
AAA	VRF+AHU
BBB	VRF + exhaust fan
CCC	Natural ventilation and heated floor
CCD	Natural Ventilation with Extract fan + heated floor
DDD	Natural Ventilation with Extract fan + electric radiator
FFF	Only AHU
GGG	Only natural ventilation

Tab. 11 HVAC code insert in the model

Lighting

In all floors of Offices LED lighting are installed, whereas it is assumed that in apartment floors there are installed LED lighting. The normalised power density is 1,4 W/m^2 -100lux.

Zone	lux
Offices, reception	300
Reception	200
Atrium	150
Circulation areas	100
Storage areas	100
Flats	120

Tab. 12 Lux values for each zone based on the recommended lux levels by NCM activity Database.

4.3. Building use

Since it was not possible to obtain much of the building operation data, the data in the table below was based on surveys of the building in use.

4.3.1. No-domestic Areas

The offices, including the first four floors and the ground floor, are occupied from Monday to Friday during working hours, which are approximately from 8 AM to 6 PM. Currently Some offices are vacant and also occupancy schedules are not in normally operation of the building due to smart working.

Category	Density
Occupancy	For main aeras 0.13 people/m2
Lighting	1.3 W/m^2-100lux
Power Gains	5 W/m^2 for main areas
Heating and Cooling	Setpoint and Setback
HVAC Auxiliary (Pump Power)	1.4 W/m^2
DHW	0,8 l/m^2 per day (only in Toilet zones)

Tab. 13 Building Operation Offices

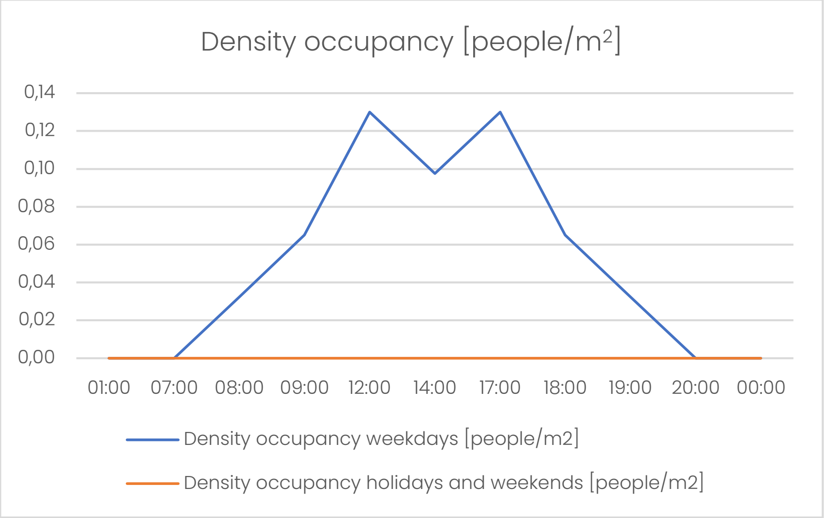

Fig. 14 Density occupancy Offices

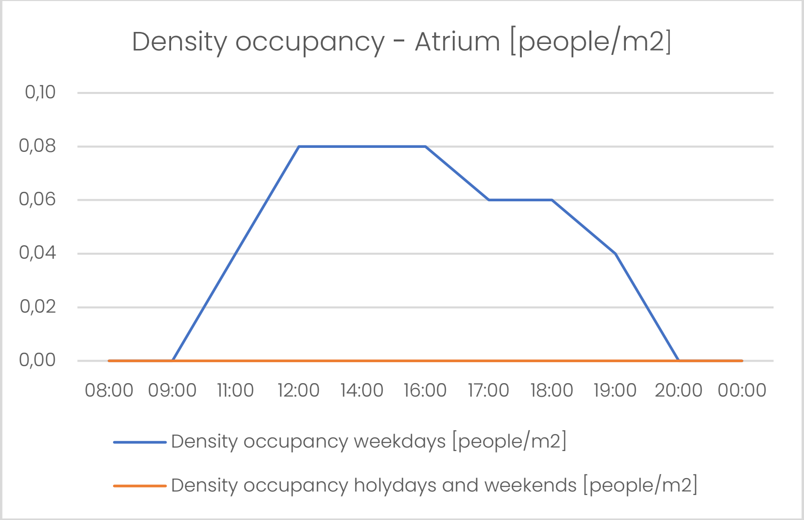

Fig. 15 Density occupancy Atrium

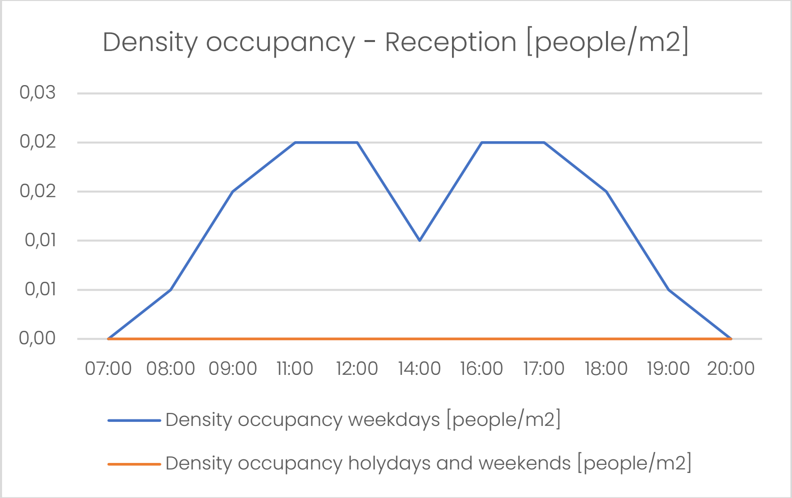

Fig. 16 Density occupancy Reception

Name	Start date	Number of days
New Years Day	02-Jan	1
Good Friday	14-Apr	1
Easter Monday	17-Apr	1
May Day	01-May	1
Spring Bank Holiday	29-May	1
Summer Bank Holiday	28-Aug	1
Christmas	25-Dec	2

Tab. 14 UK holidays (NCM)

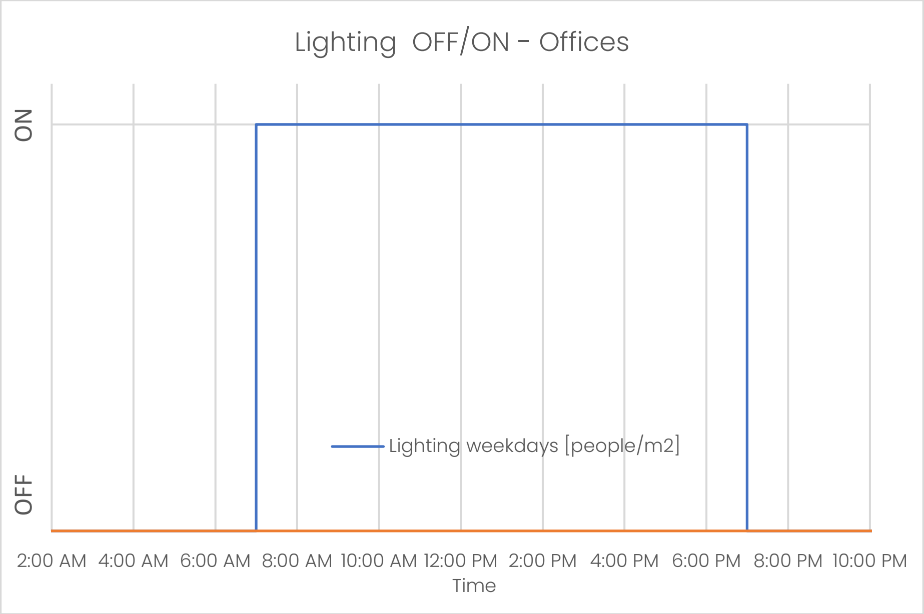

Fig. 17 Lighting OFF/ON schedule

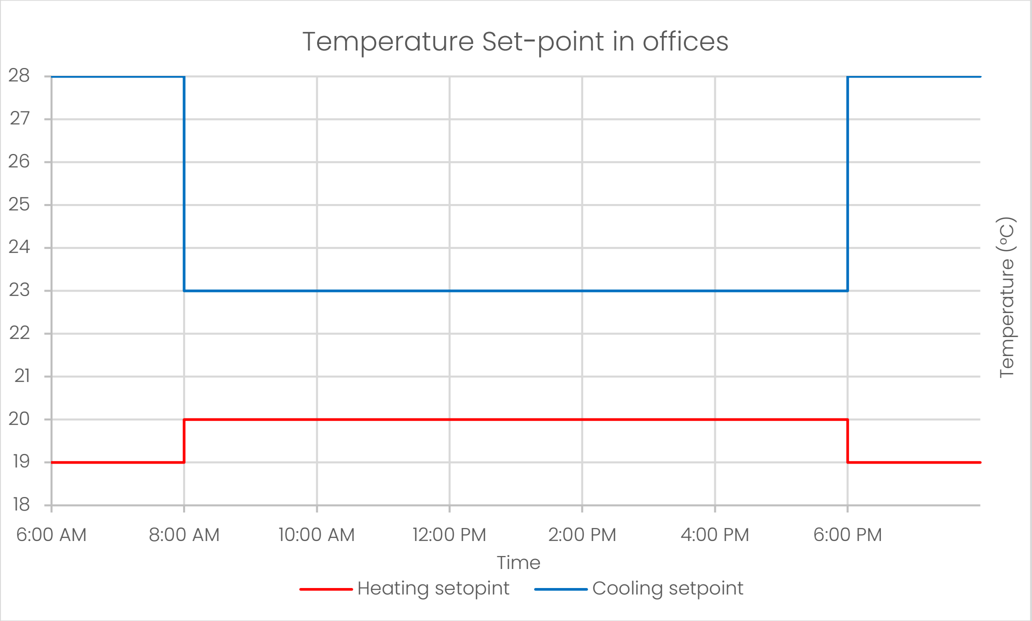

Fig. 18 Temperature Set-point during occupied hours

4.3.2. Domestic Areas

There are 15 apartments in the last 2 floors.

Floor	Nº flat	Floor Area (m^2)	Number of people[8]
5th	1	84.71	2
	2	59.65	2
	2A	59.48	1
	3	57.80	2
	4	75.24	2
	5	47.76	1
	6	93.23	1
	7	109.25	3
	8	86.99	3
6th	9	112.21	2
	10	61.53	2
	11	92.05	1
	12	85.12	2
	13	129.55	3
	14	118.37	3
Total Area		1273 m^2	

Tab. 15 Flats Occupancy

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[8] Data referred to May 2023

Category	Density
Lighting	1.4 W/m²–100lux
Power Gains	Average of 3 W/m²
Heating and Cooling	Setpoint and Setback
HVAC Auxiliary (Pump Power)	1.4 W/m²
DHW	0,8 l/m² per day

Tab. 16 Building Operation Flats

Temperature Set point

In contrast to offices, in residential areas, the behaviour of occupants is unpredictable with respect to the setpoint temperature trends. The following temperatures have been considered based on the approximate knowledge of their behaviour:

Floor	Nº flat	Heating set point	Cooling set point
5th	1	19 °C	23 °C
	2	20.5 °C	22°C
	2A	20 °C	23°C
	3	23 °C	24°C
	4	20 °C	22°C
	5	19.5 °C	23°C
	6	20°C	22°C
	7	24°C	22°C
	8	23°C	22°C
6th	9	20 °C	23°C
	10	19°C	23°C
	11	20.5°C	23°C
	12	21.5°C	23°C
	13	20°C	23°C
	14	19 °C	23°C

Tab. 17 Flat current Temperature Set point

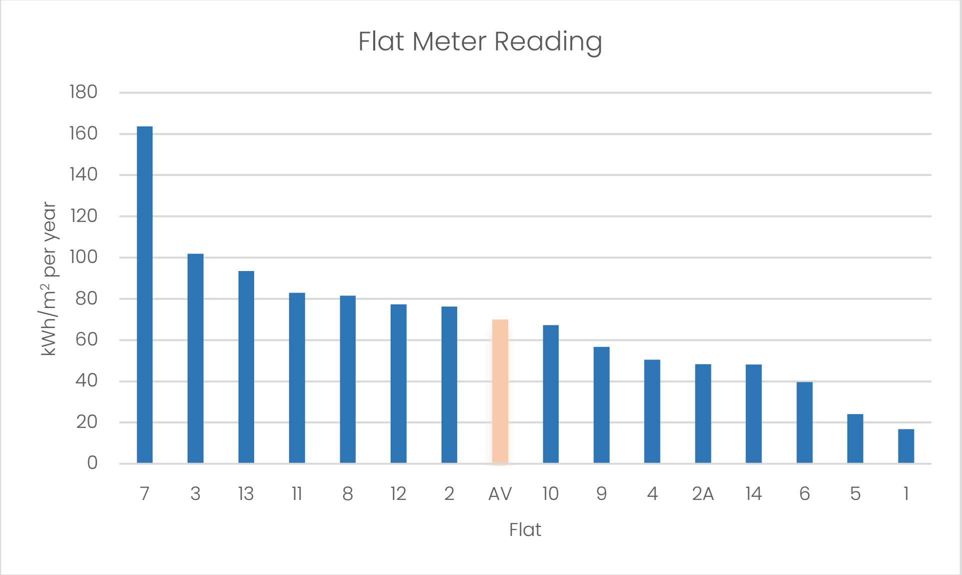

Fig. 19 Electrical meter readings flats

The flats consume an average of 70 kWh/m^2, this value is very low considering the low efficiency of the heat pump. The reason is that half of flats are vacant or not used a lot during the day.

In the tables of ANNEX B, the meters readings for each zone are calculated considering a period of ten months for no-domestic areas and 1 year for domestic areas.

Considering that the energy benchmarking the energy consume in electric heated flat (Fig.32) has an average of 123 kW/m^2, in this case study it is under the typical practice electricity. The reason is that the CISBE benchmarking considers also flats electrical heater where the efficiency is very low, as consequence the average of electrical consume will be very high.

Use category: Flat (electric heated)

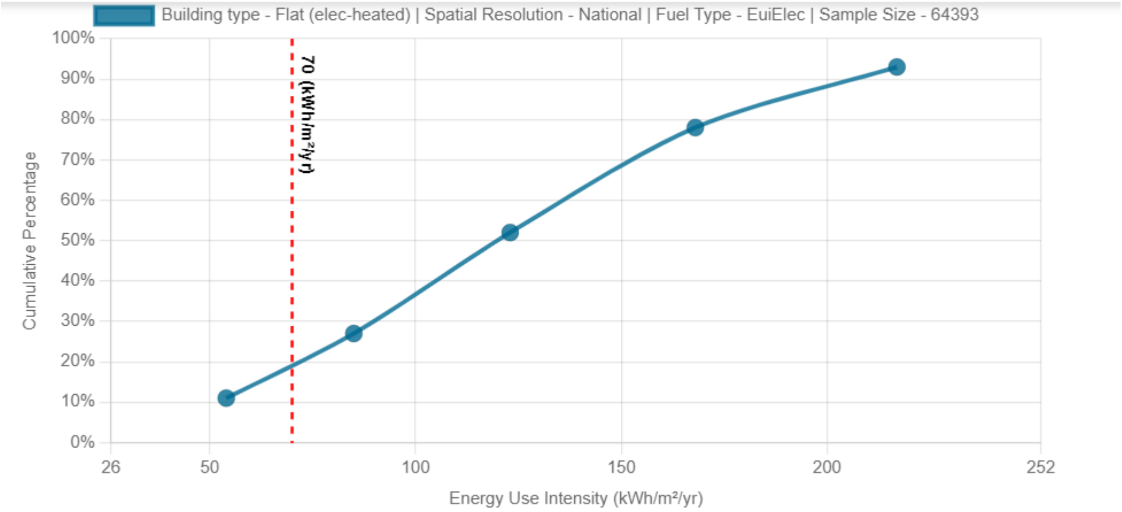

Fig. 20 CIBSE Energy Benchmarking Tool Dashboard of Flats electric heated (Source:https://www.cibse.org/knowledge-research/knowledge-resources/knowledge-toolbox/energy-benchmarking-tool)

5. BUILDING PERFORMANCE SIMULATION AND CALIBRATION

5.1. Design Builder

The software used for the energy simulation of the model is DesignBuilder®, released by the British company Design Builder Software Ltd. The first version of this software was released as a graphical interface for EnergyPlus, an important dynamic building simulation engine created by the US Department of Energy (DOE). Design Builder also utilizes the capabilities of EnergyPlus to perform simulations, but it provides a more user-friendly approach.

Thanks to Design Builder, it is possible to model the building in 3D, define detailed building characteristics, calculate energy needs and thermal gains, evaluate economic aspects, and compare various design solutions through optimization analyses. After creating the 3D model, it is possible to configure various settings related to different aspects of the building, such as technical aspects, building systems, internal loads, occupancy scenarios and other parameters.

The first step after creating the 3D model is setting the location. Through the "Location" command, the location, geographical coordinates, and some characteristics of the site are defined, including wind exposure and monthly temperatures. The database of climate data allows simulations to be carried out for every day of the year, and it is also possible to import new weather climate data.

Finally, the outputs generated by the software can be displayed in graphical or tabular form, and it is possible to read parameters related to environmental comfort, energy consumption, different temperatures such as ambient and external temperatures.

After defining all the building characteristics and determining all the necessary parameters in the various panels, it is possible to initiate the simulations and thus obtain the required results. The software returns, at time intervals, the variables that influence the energy performance of the building.

Through the "Simulations" panel, it is possible to set the simulation time period, the number of calculation steps per hour, and settings related to shadows and reflections. The outputs generated by Design Builder include internal heat gains, lighting, computer equipment, and other appliances, as well as temperatures and energy consumption.

Furthermore, it is possible to calculate construction costs and CO2 emissions due to the technologies used. The simulations carried out by DesignBuilder are in dynamic mode, which means that the software simultaneously analyses multiple variables, such as climate and environmental conditions, thermal and physical characteristics of the building, yielding much more reliable results compared to other types of programs.

5.2. Calibration Process

A calibrated model was developed using the input data in the tables above. The metering readings data (referred to the year 2022[9]) and the available data is the consumption over 10

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[9] Annex B

months. Therefore, the calibration was conducted over 10 months, from February to November. In that year, the effects of COVID-19 were still present, and that's why the consumption varies significantly from month to month. This variation can be attributed to the impact of remote work (smart working).

Furthermore, some of the office floors were vacant. However, since the research aims to understand the future emissions and consumption, consideration was given to the office floor with the most linear and realistic energy consumption pattern.

Moreover, the meter readings pertained to the total electricity consumed, without precise information on how much was allocated for each subsystem (HVAC systems, lighting, and auxiliary energy).

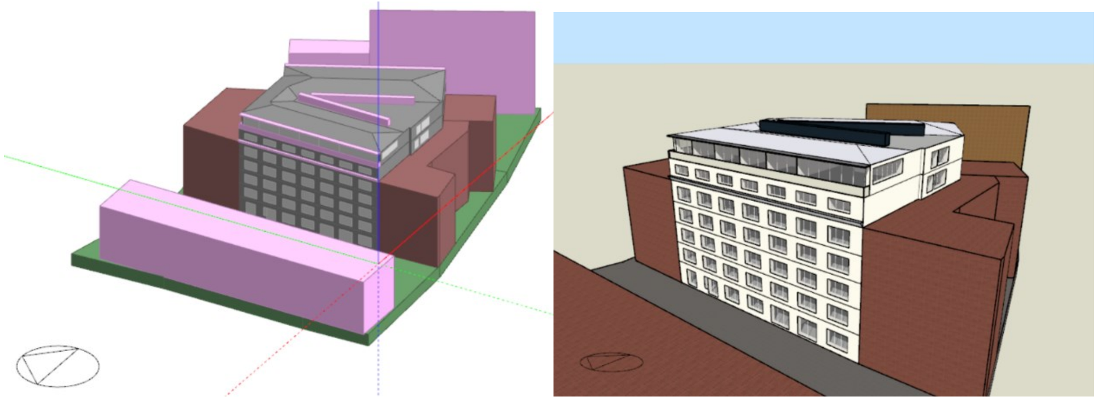

Fig. 21 DesignBuilder® Model

For Offices, the calibration was carried out on the meter readings of the first floor, which, unlike the other floors, happens to have the highest and reasonable consumption. Nevertheless, as can be observed from the graph below, in the months of February and especially March, due to the presence of COVID-19, smart working was favoured. As a result, the electrical consumption is much lower than the average during these months.

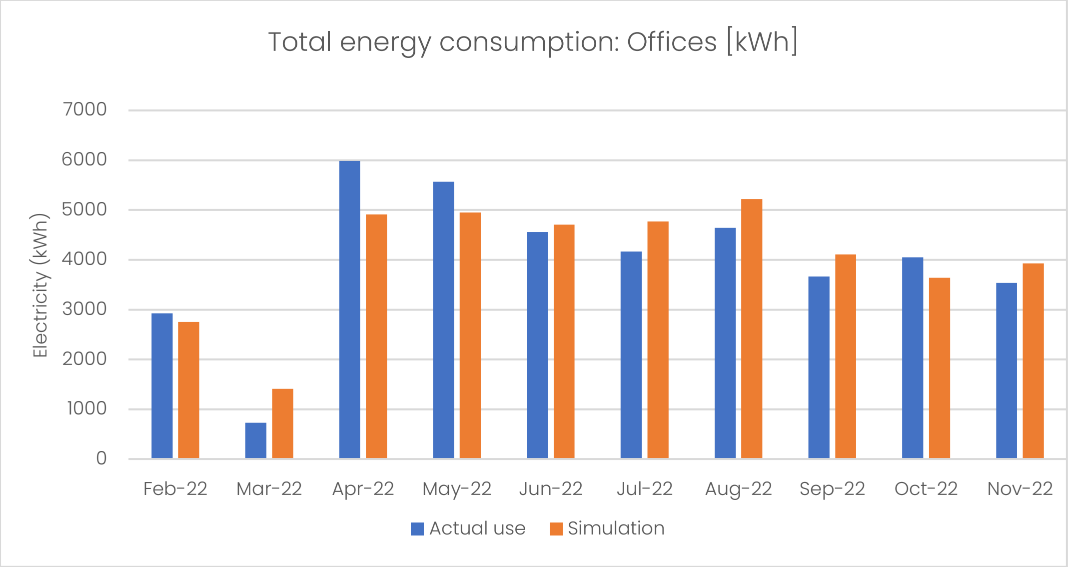

Fig. 22 Calibration Results: Offices (1^{st} floor)

Uncertainty index	values	Pass/Fail
CVRSME	14%	Pass
NMBE	-1%	Pass

Tab. 18 Uncertainty index (Offices)

A separate calibration was performed for each flat. This approach was taken because each flat has distinct occupancy, different set point temperatures, and various electrical equipment, different in each flat. Additionally, there are variations in the usage of equipment, which naturally differs from one apartment to another.

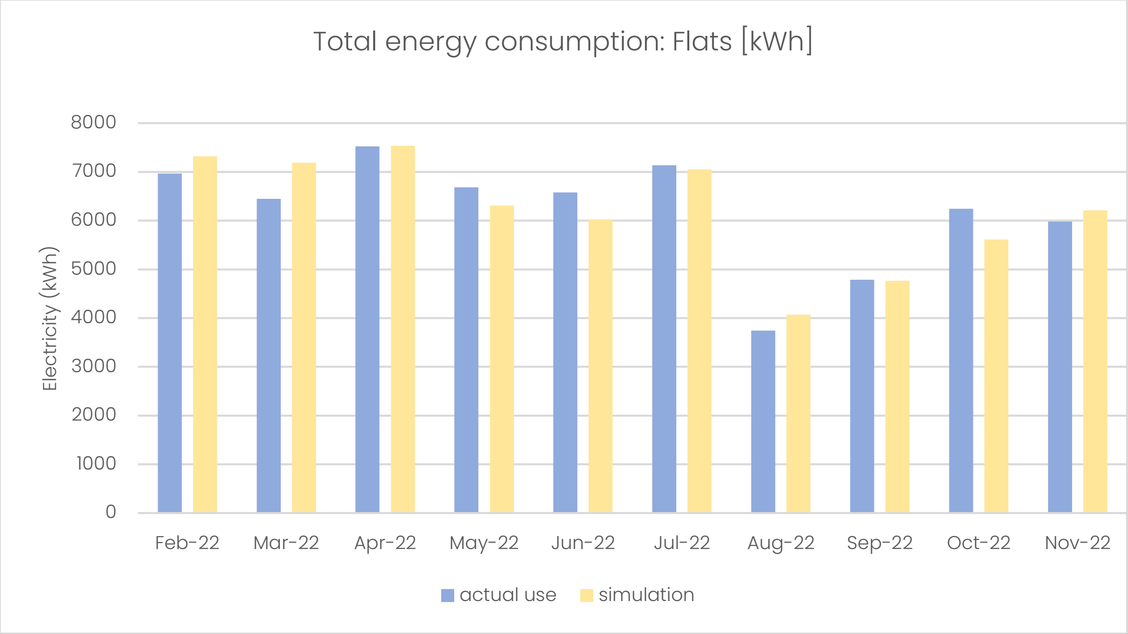

Fig. 23 Calibration Results: Apartments

Uncertainty index	values	Pass/Fail
CVRSME	7%	Pass
NMBE	0%	Pass

Tab. 19 Uncertainty index (Apartments)

Landlords include all the common areas of the building. As can be seen from the graph below, the calibration exhibits an outlier in the month of July. The cause could not be identified, and it was not clear which component of the meter readings represents, since the meter readings show the overall electricity energy consumption and not the subsystem electricity consumption.

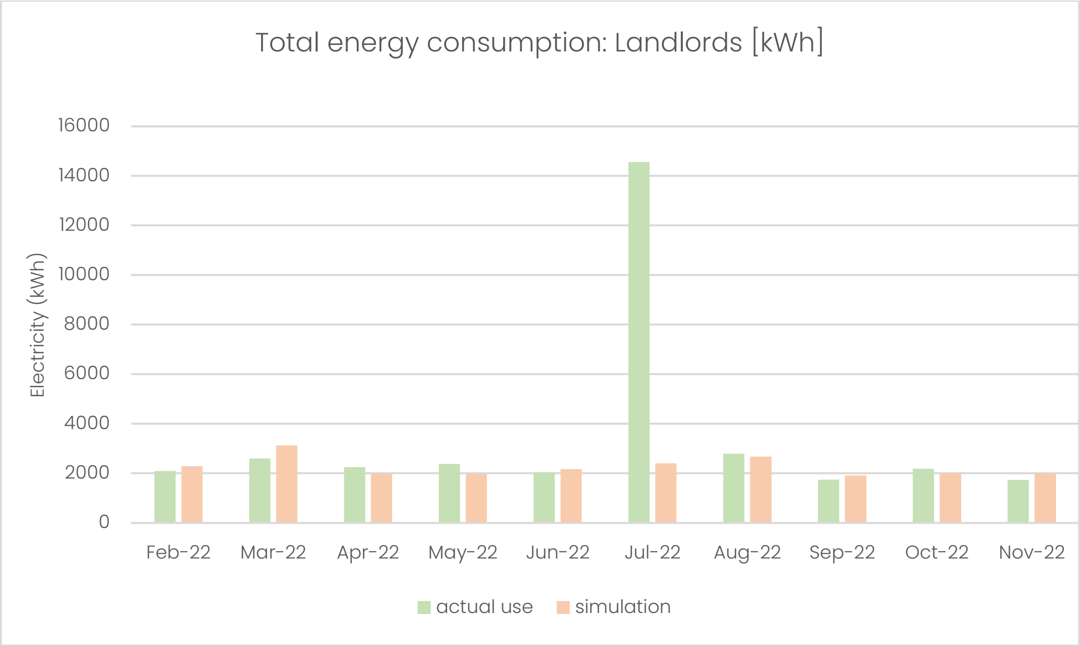

Fig. 24 Calibration Results: Landlords

If the calibration is conducted over 9 months instead of 10, the following results are obtained:

Uncertainty index	values	Pass/Fail
CVRSME	13%	Pass
NMBE	-2%	Pass

Tab. 20 Uncertainty index (Landlords)

5.3. Current Building energy consumption

The absence of precise input data regarding the breakdown of energy consumption into HVAC, lighting, and DHW did not allow to calibrate the consumption fuel breakdown for each subsystem.

Building subsystem	Simulation electricity consume [kWh/m^2] (1 year)	End uses Electricity (10 months) [kWh/m^2]
Equipment	12,35	30,41
Systems Pumps	2,37	
Heating (electricity)	17,43	
Cooling (electricity)	2,1	
Lighting	7,98	
DHW	3,61	
Total	**45,84**	
Total 10 months[10]	35	

Tab. 21 Electricity consumption for each subsystem

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[10] From February to November 2022

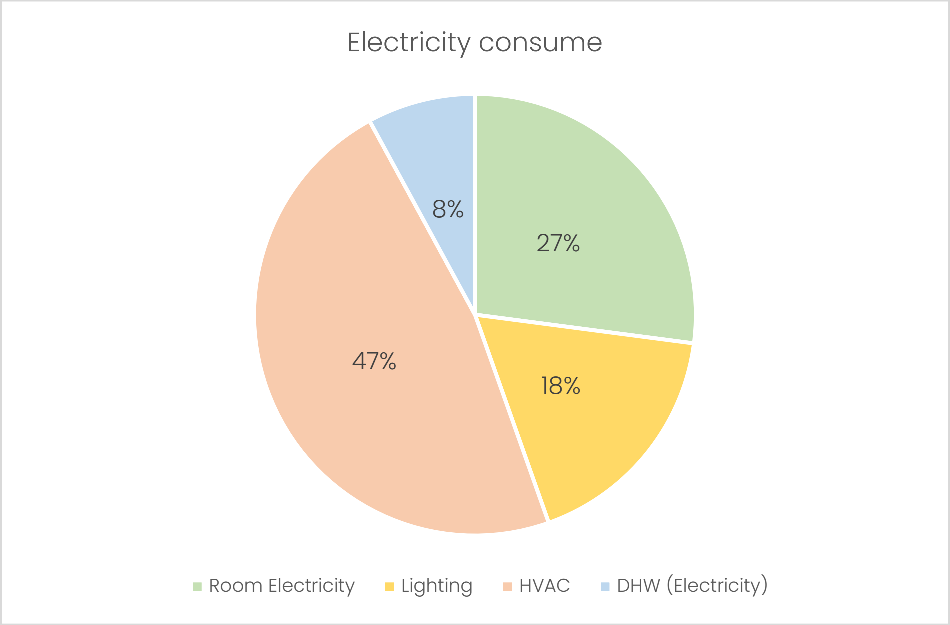

Fig. 25 Percentage electricity consume

During the calibration It was considered approximately +12% (41) of energy consumption since still were consequences of Covid-19 and also some of offices were vacant waiting to be rented.

6. FUTURE SCENARIOS

Weather is a key driver for buildings consumption since it obviously affects HVAC, DHW, energy demand and comfort.

The weather data used in this research are related to London Heathrow Airport and the following are uploaded in DesignBuilder® to do simulation for different analysis:

- TRY for three time periods current period, 2050s (2041-2070) and 2080s (2071-2100), for the following emissions scenarios:
  - 2050s – Medium – 10th, 50th, 90th[11],
  - 2080s – Medium – 10th, 50th, 90th,
- DSY: the area is outside CAZ and as it is defined in TM 49 (20) the weather data used are from LHA and not from LWC (London Weather Centre). DSY data includes 3 different types of weather file:
  - DSY1 - A moderately warm summer. Summers will have a 1-in-7 chance of being equal or hotter than this DSY.
  - DSY2–A summer with a short intense warm spell. An intense summer with a heat event the same length of that of DSY1, but with a higher intensity.
  - DSY3- A summer with a long less intense warm spell. The heat event is less intense than that of DSY2 but has a higher intensity than DSY1. It has a longer duration than that of DSY1.

The future TRY weather data are used to do simulations consider different adaptation strategies, whereas the DSY weather data for the overheating assessment.

The future weather data show different degree days and climatic zone for the same site. This is the consequence of the increase of temperature that will influence the behaviour of the building in the future.

Future scenarios (TRY)	CDD	HDD	Climatic zone
LHA_2050_Medium_10	1343	2220	4A
LHA_2050_Medium_50	1570	1969	3C
LHA_2050_Medium_90	1876	1700	3C
LHA_2080_Medium_10	1473	2085	4A
LHA_2080_Medium_50	1827	1744	3C
LHA_2080_Medium_90	2316	1378	3C

Tab. 22 Weather data for each future scenarios

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[11] Medium level of emissions at different percentile. The percentile indicates the percentage of probability that temperatures will fall below this threshold for that time period.

6.1. Current Building under future projections

6.1.1. Heading load and cooling load of the building in the future

For this reason, it is expected that the heating load will decrease over the years, while the cooling load will increase (fig.26).

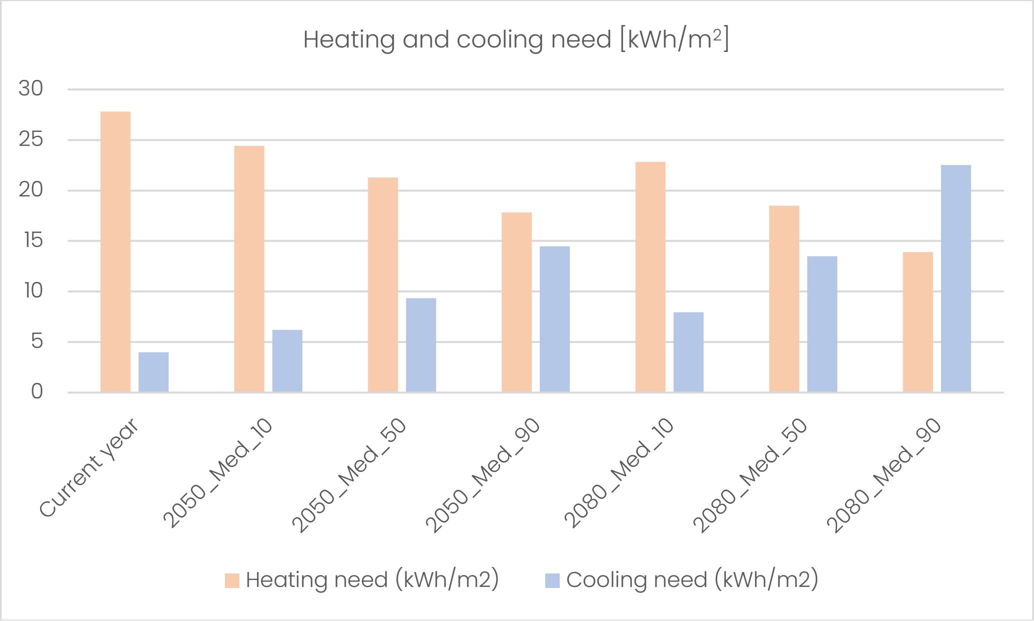

Fig. 26 Heating load and cooling load current building in future scenarios

As consequence the electrical consumption for heating will decrease, whereas for cooling will increase.

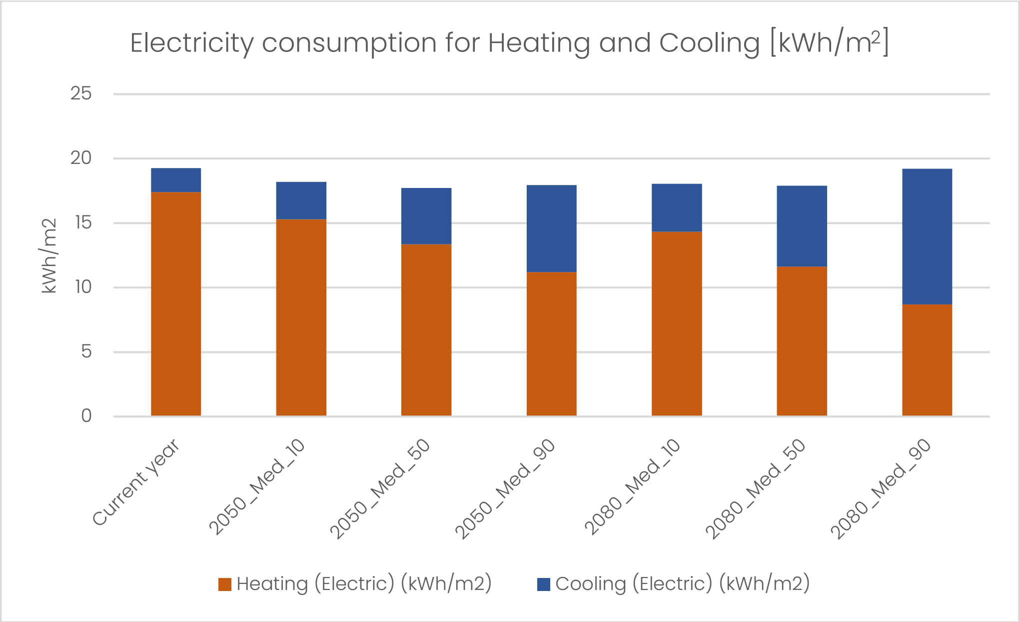

Fig. 27 Electricity consumption for Heating and cooling current building in future scenarios

6.1.2. CO2 emissions in future scenarios

When we talk about Carbon emissions, it is necessary to distinguish the embodied carbon from the operational carbon. In fact, the operational carbon refers to carbon used during the lifetime of a building, so energy used for HVAC system, DHW, electricity for equipment and lighting. Whereas the embodied carbon refers to energy used to source and manufacture all the construction materials.

DesignBuilder assesses embodied carbon from construction materials of the building and the operational carbon from fuel, in this case electricity.

It must be considered that the fuel carbon factor varies from year to year and has a different value in each state. The value of the fuel carbon emissions from grid electricity in 2022 is 0.19338 kgCO2/kWh (42). It is anticipated that by 2050, a value of approximately 0.002 kgCO2/kWh will be reached (43).

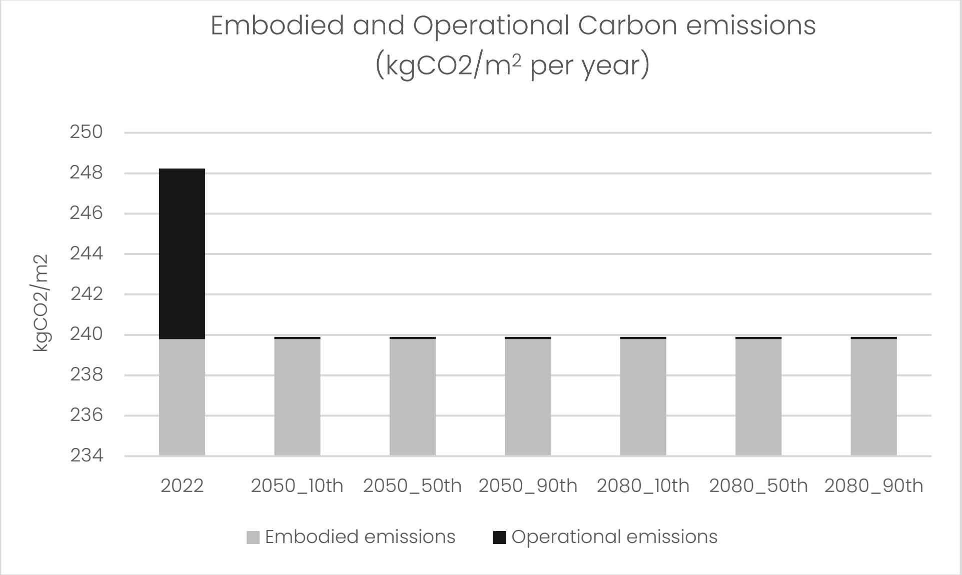

Fig. 28 Embodied and operational carbon current building (results from DesignBuilder)

The emissions that are found to be high are the embodied emissions, while the emissions from electricity generation are projected to be minimal in the coming years. This is certainly a probabilistic value depending on how much the electricity grid in the UK will be decarbonized.

7. ADAPTATION AND MITIGATION STRATEGIES

Considering that the building's facades were renovated in 2016, it was decided not to assess the possibility of retrofitting the building envelope. Instead, the approach was to adopt strategies to mitigate the risk of overheating, electrical energy consumption, and operational carbon emissions.

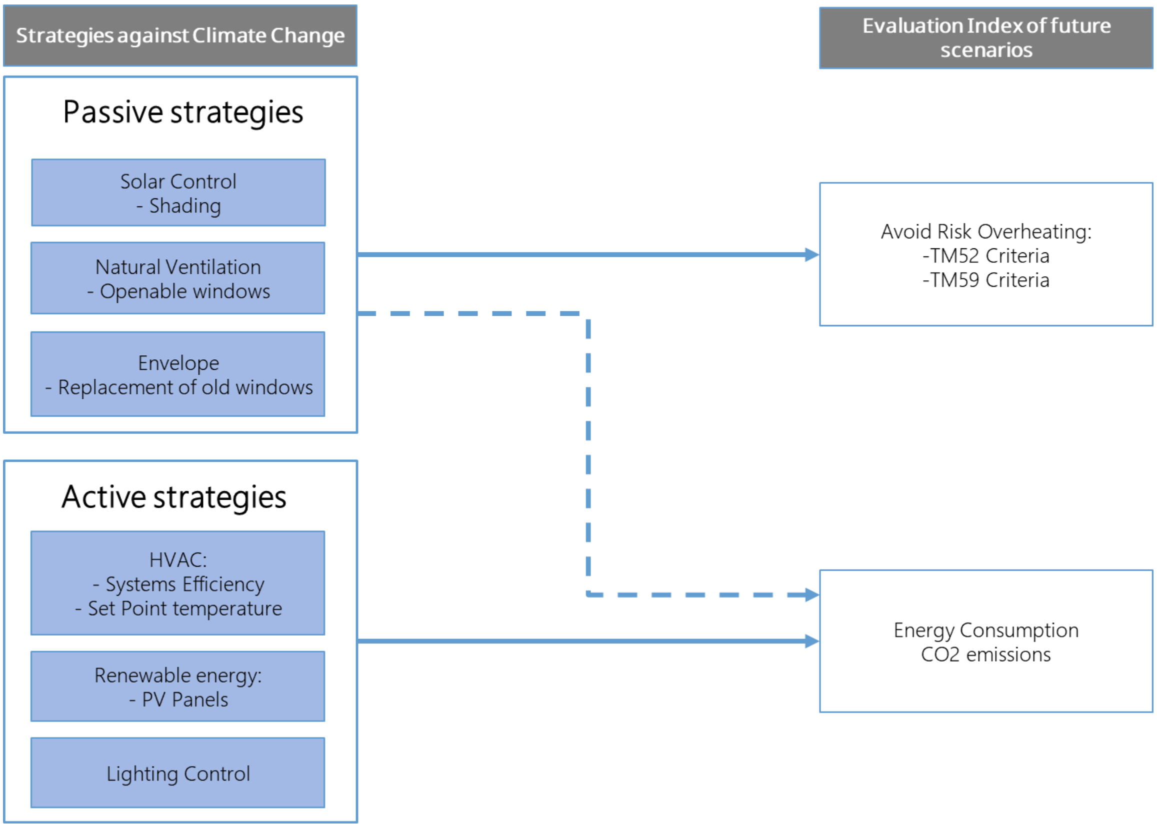

Fig. 29 Adaptation and Mitigation Strategies Workflow

In the selection of strategies to adopt, passive strategies were initially considered. The retrofitting of the building envelope was not taken into account because the façade had been recently renovated, and the decision was made not to increase embodied carbon emissions. However, alternatives such as replacing the initially non-openable office windows with operable windows to promote natural ventilation and enhance efficiency, as well as adding internal window shading, were explored to avoid overheating risk in future scenarios.

Regarding active strategies, the option of replacing some of the older VRF systems and installing photovoltaic panels was evaluated. Additionally, the installation of a lighting control system in the office corridors and office toilets was assessed.

7.1. Passive strategies: Comfort and the risk of overheating

Considering that future scenarios predict higher temperatures, it is important to ensure that in areas without air conditioning, there is no risk of overheating.

The Overheating within buildings occurs when people feel uncomfortable due to high internal temperatures. There are two main approaches that derive from CISBE standard methodology to assess the overheating based on measured temperatures: the static and adaptive approaches (21).

- The **static approach** uses a fixed temperature threshold and states the number of hours of exceedance of this threshold that is deemed to constitute overheating.
- The **adaptive approach** recognises that people adapt to warmer temperatures, both psychologically and physiologically. The adaptive temperature threshold increases as the average temperature rises.

In Design Builder it is possible to assess the overheating risk using TM52 and TM 59 developed by CISBE. Whereas TM52 can be used to assess any type of building, TM59 is addressed to specific target overheating risk in domestic building.

7.1.1. TM 52 - overheating in non-domestic common areas without air conditioning

This assessment can be carried out at the detailed design stage by way of Dynamic Simulation Model. CIBSE TM52 sets three criteria for compliance. A building that fails two or more of the criteria is deemed to be at unacceptable risk of overheating:

I. Criterion A: indicates the percentage of Hours of Exceedance (max 3%) on the comfort temperature in the occupied zones during the heating season.
II. Criterion B: indicates the Daily Weighted Exceedance
III. Criterion C: indicates the Upper Limit Temperature, it sets a T_{max} +4°C beyond the threshold of overheating is unacceptable.

In this case study TM 52 was used for all non-domestic unconditioned zones: corridors, storage areas. The analysis is made considering the three different weather data at different percentile from 1st May to 30th September.

For the study of overheating, three different scenarios are studied:

1) **Baseline Scenario**: No openable windows, and cooling is only available in office areas.
2) **Only Natural Ventilation scenario**[12]: Offices with totally openable windows and natural ventilation during the summer period without cooling, with control solar shading.
3) **Mixed-mode scenario**: Cooling with openable windows and control solar shading, in order to maximize natural ventilation and reduce cooling loads. If natural ventilation cannot provide comfort conditions, active cooling is introduced.

Considering the current scenario in which there are non-openable windows and active cooling, there is no risk of overheating. Nevertheless, the electricity consumption for cooling (from May to September) is calculated in different summer scenarios.

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[12] Results in ANNEX C

From the analysis conducted using Design Builder (tables in Annex C) following TM52, it can be observed that for moderately warm summers, natural ventilation is sufficient to meet the criteria previously described. However, in the case of longer or more intense summers, natural ventilation is not enough, and it becomes necessary to introduce cooling.
Therefore, in the third scenario, it is considered the possibility of installing windows that can be opened, enabling a combination of natural ventilation and air conditioning. The current cooling setpoint temperature for offices is set at 23°C. It's essential to ensure that the temperatures for natural ventilation and cooling are accurate and that the air conditioning is deactivated when the windows are open. This concept involves a changeover design where the building alternates between relying on natural ventilation and air conditioning, which can occur on a seasonal or daily basis. The building's automated system determines the operating mode based on factors such as outdoor temperature, occupancy sensors, window status (open or closed), or commands from operators.

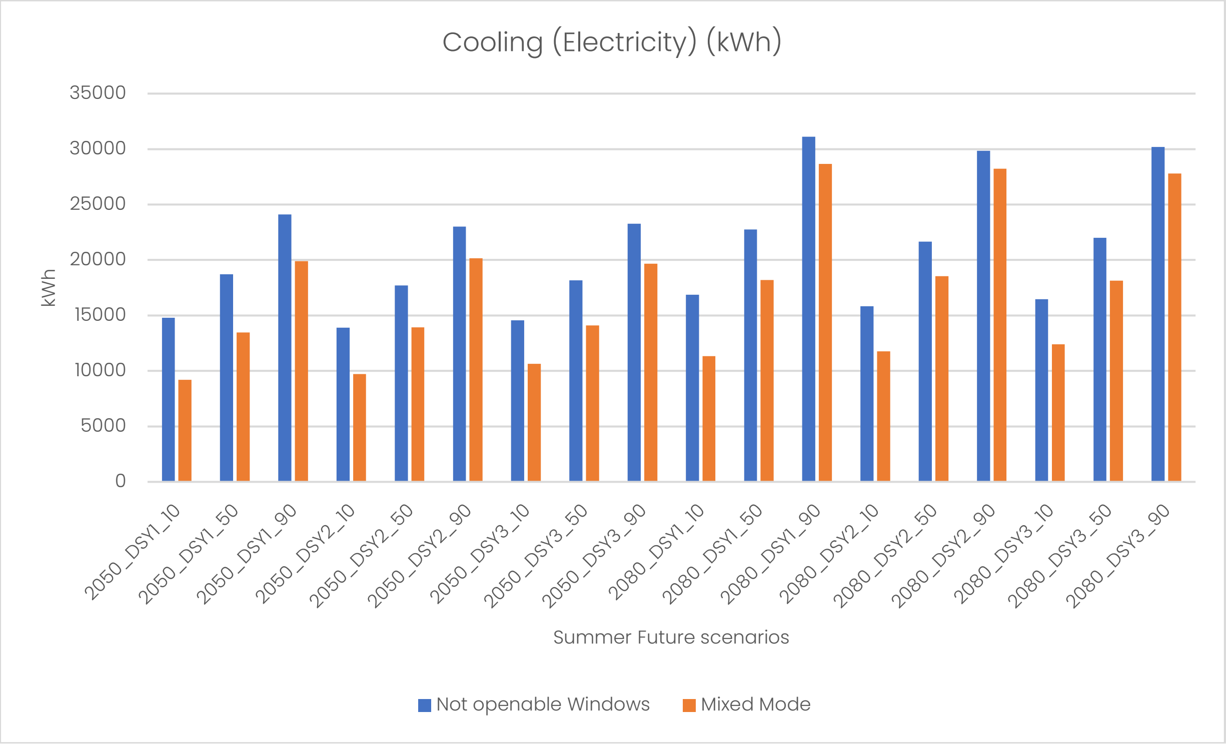

Fig. 30 Cooling Electricity consume between May and September in case not openable windows and mixed mode (Natural Ventilation and Cooling).

It can be observed that there is an average reduction of approximately 25% in electricity consumption during the periods from May 1st to September 30th in 2050, and a 17% reduction in 2080. This could potentially serve as an adaptive strategy to enhance climate resilience.

7.1.1.1. The contribute of orientation in the risk of overheating

The orientation of areas to the east and west significantly impacts the occurrence of overheating throughout the day. When there's maximum sun exposure in the morning to the east, the peak exposure shifts to the west in the afternoon, with shaded conditions during the morning. This leads to cooler temperatures in the morning and warmer conditions in the

afternoon for the west-facing areas. This effect is notably evident, especially given that office hours typically occur in the afternoon, when it's warmer, rather than in the early morning when it's cooler.
For instance, when we examine the 4th floor offices in Annex C tables, we observe that those oriented west have a higher "Hours of Exceedance on the comfort temperature" in comparison to east-oriented offices.

Considering the occupied hours from 1st May to 30th September it observed that during summer period the number of hours doesn't meet comfort criteria if we don't consider the presence of cooling:

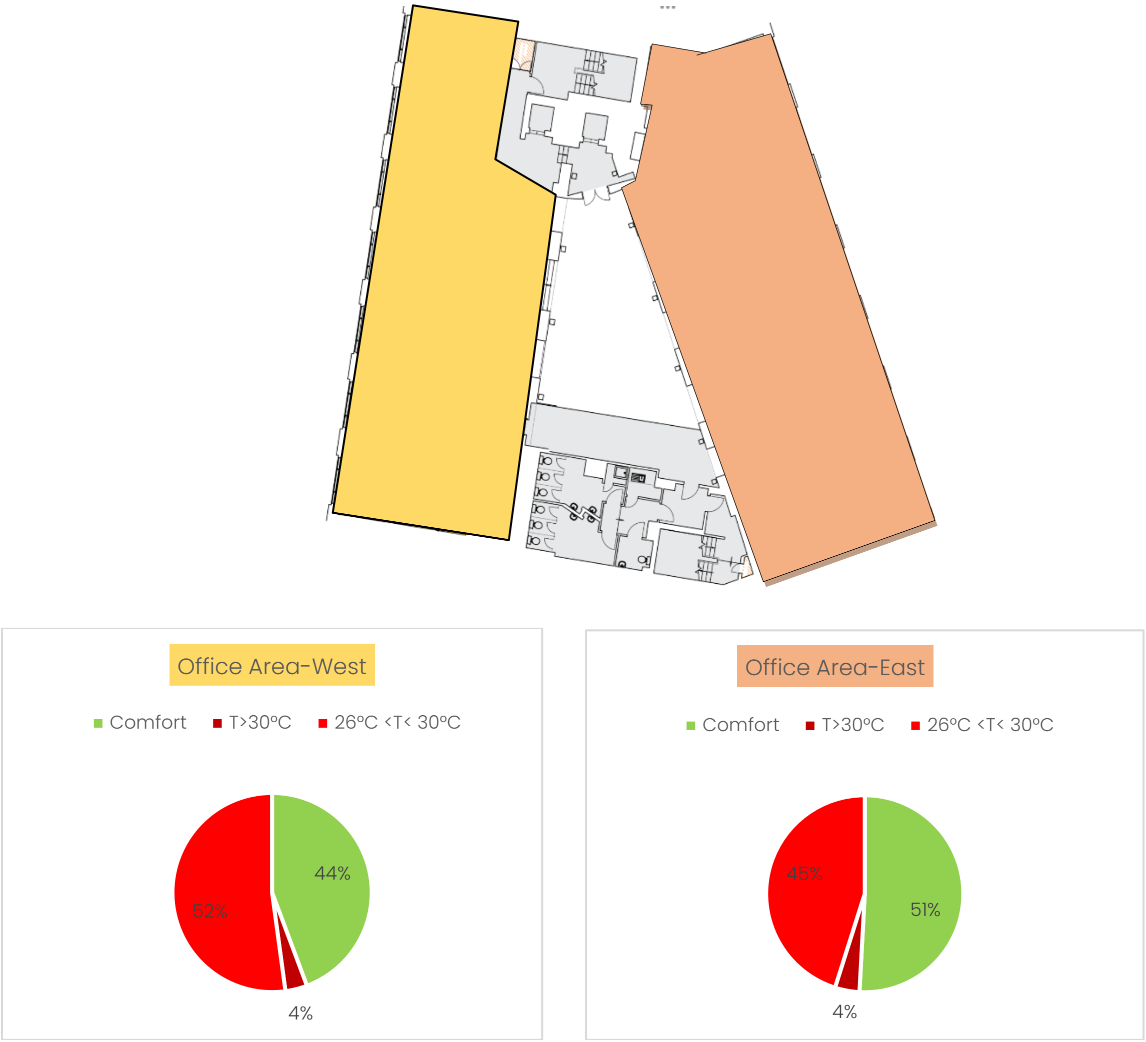

Fig. 31 Operative temperature percentage during occupied hours considering only Natural ventilation

This is also due to the fact that the occupied hours in these offices coincide with the warmer afternoon hours, rather than the cooler morning period. As a result, the opposite orientation of offices influences the use of heating and cooling systems, which, in this scenario, will be used in opposite ways.

In this context, it's interesting to note that some offices are precisely oriented to the west, while others face north-east, highlighting the diverse thermal conditions within the building, which are a result of its orientation and design.

7.1.2. TM 59 – The risk of overheating in domestic areas naturally ventilated

For domestic areas the overheating assessment is made using the TM59 during the summer design week. Although all domestic areas (except flat 5) cooling and openable windows, are equipped with both cooling and openable windows, it is essential to assess whether their presence is truly required in every area, or if natural ventilation alone is sufficient.

The TM59 in ventilated building uses two criteria:

A) For living, kitchen, and bedrooms: the temperature may only exceed 26°C for 3% of the annual occupied hours during the period May to September.

B) For Bedrooms only: During sleeping hours from 10 p.m. to 7 a.m., 26°C must not be exceeded for more than 1% of annual hours.

The analysis was conducted for a future moderately warm summer DSY1-10th, DSY2-10th, DSY3-10th because if it does not pass for this scenario, it won't pass for 50th and 90th percentile.

Block	Zone	Criterion A (%)	Criterion B (hr)	Pass/Fail
5th	008X501XBBBXbed1	0.00	342.50	Fail
	008X501XBBBXbed2	0.32	18.50	Pass
	008X502AXBBBXbed	18.86	811.50	Fail
	008X502XBBBXbed	15.25	878.50	Fail
	008X503XBBBXbed	17.42	836.25	Fail
	008X504XBBBXbed1	0.05	369.50	Fail
	008X504XBBBXbed2	0.40	24.00	Pass
	008X505XCCCXbed[13]	1.68	31.50	Pass
	008X506XBBBXbed1	0.44	20.25	Pass
	008X506XBBBXbed2	0.45	469.25	Fail
	008X507XBBBXbed1	1.10	500.25	Fail
	008X507XBBBXbed2	1.47	600.50	Fail
	008X508XBBBXbed1	0.26	17.50	Pass
	008X508XBBBXbed2	0.04	443.50	Fail
	012X505XCCDXlivXkit	1.48	N/A	Pass
6th	008X609XBBBXbed1	9.33	284.50	Fail
	008X609XBBBXbed2	25.08	809.00	Fail
	008X610XBBBXbed	12.71	707.50	Fail
	008X611XBBBXbed1	11.94	255.50	Fail
	008X611XBBBXbed2	13.28	389.75	Fail
	008X612XBBBXbed1	14.67	579.50	Fail
	008X612XBBBXbed2	9.73	477.00	Fail
	008X613XBBBXbed1	10.94	89.25	Fail
	008X613XBBBXbed2	30.13	916.25	Fail
	008X614XBBBXbed1	9.72	33.75	Fail
	008X614XBBBXbed2	9.81	84.75	Fail
	008X614XBBBXbed3	24.88	854.25	Fail
	011X609XGGGXlounge	7.64	N/A	Fail

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[13] Flat 5 does not have air conditioning in the current building.

	011X610XGGGXlounge	13.88	N/A	Fail
	011X612XGGGXlounge	38.49	N/A	Fail
	013X600XGGGXcirc	4.87	N/A	Fail
	014X611XDDDXkit	30.31	N/A	Fail
	015X611XBBBXliv	21.96	N/A	Fail

Tab. 23 TM59_DSY1_2050_10th

Block	Zone	Criterion A (%)	Criterion B (hr)	Pass/Fail
5th	008X501XBBBXbed1	0.63	159.50	Fail
	008X501XBBBXbed2	0.49	34.75	Fail
	008X502AXBBBXbed	3.97	755.00	Fail
	008X502XBBBXbed	1.68	694.25	Fail
	008X503XBBBXbed	4.04	739.00	Fail
	008X504XBBBXbed1	1.16	144.50	Fail
	008X504XBBBXbed2	0.73	41.75	Fail
	008X505XCCCXbed	2.73	71.75	Fail
	008X506XBBBXbed1	0.97	60.50	Fail
	008X506XBBBXbed2	3.88	258.00	Fail
	008X507XBBBXbed1	1.11	312.50	Fail
	008X507XBBBXbed2	2.25	361.50	Fail
	008X508XBBBXbed1	0.44	51.50	Fail
	008X508XBBBXbed2	0.73	244.50	Fail
	012X505XCCDXlivXkit	2.47	N/A	Pass
6th	008X609XBBBXbed1	4.26	163.50	Fail
	008X609XBBBXbed2	5.76	583.00	Fail
	008X610XBBBXbed	3.34	408.25	Fail
	008X611XBBBXbed1	6.26	145.50	Fail
	008X611XBBBXbed2	6.27	160.25	Fail
	008X612XBBBXbed1	7.35	302.75	Fail
	008X612XBBBXbed2	7.85	246.25	Fail
	008X613XBBBXbed1	8.00	107.75	Fail
	008X613XBBBXbed2	12.56	619.25	Fail
	008X614XBBBXbed1	7.21	47.00	Fail
	008X614XBBBXbed2	7.20	103.25	Fail
	008X614XBBBXbed3	10.45	632.50	Fail
	011X609XGGGXlounge	2.39	N/A	Pass
	011X610XGGGXlounge	4.10	N/A	Fail
	011X612XGGGXlounge	21.82	N/A	Fail
	013X600XGGGXcirc	3.43	N/A	Fail
	014X611XDDDXkit	16.75	N/A	Fail
	015X611XBBBXliv	10.82	N/A	Fail

Tab. 24 TM59_DSY2_2050_10th

Block	Zone	Criterion A (%)	Criterion B (hr)	Pass/Fail
5th	008X501XBBBXbed1	0.25	269.50	Fail

	008X501XBBBXbed2	1.17	53.00	Fail
	008X502AXBBBXbed	7.19	680.25	Fail
	008X502XBBBXbed	3.01	670.25	Fail
	008X503XBBBXbed	6.68	707.25	Fail
	008X504XBBBXbed1	0.44	240.25	Fail
	008X504XBBBXbed2	1.58	63.50	Fail
	008X505XCCCXbed	4.21	91.50	Fail
	008X506XBBBXbed1	1.21	87.25	Fail
	008X506XBBBXbed2	1.50	436.75	Fail
	008X507XBBBXbed1	0.85	466.75	Fail
	008X507XBBBXbed2	1.54	515.25	Fail
	008X508XBBBXbed1	0.71	83.75	Fail
	008X508XBBBXbed2	0.24	407.75	Fail
	012X505XCCDXlivXkit	3.39	N/A	Fail
6th	008X609XBBBXbed1	6.54	257.75	Fail
	008X609XBBBXbed2	9.75	602.75	Fail
	008X610XBBBXbed	4.34	558.75	Fail
	008X611XBBBXbed1	9.15	248.25	Fail
	008X611XBBBXbed2	8.87	282.50	Fail
	008X612XBBBXbed1	8.35	505.75	Fail
	008X612XBBBXbed2	10.02	417.00	Fail
	008X613XBBBXbed1	10.66	166.75	Fail
	008X613XBBBXbed2	23.67	716.00	Fail
	008X614XBBBXbed1	8.98	79.75	Fail
	008X614XBBBXbed2	9.36	157.00	Fail
	008X614XBBBXbed3	17.35	693.25	Fail
	011X609XGGGXlounge	3.49	N/A	Fail
	011X610XGGGXlounge	5.95	N/A	Fail
	011X612XGGGXlounge	26.72	N/A	Fail
	013X600XGGGXcirc	5.23	N/A	Fail
	014X611XDDDXkit	20.61	N/A	Fail
	015X611XBBBXliv	15.64	N/A	Fail

Tab. 25 TM59_DSY3_2050_10th

It can be noticed that the criteria are not being met for two reasons. Firstly, in some flats, the sleeping areas lack windows, and secondly, natural ventilation at times fails to meet the TM59 criteria. Additionally, there is a notable risk of overheating on the sixth floor, also due to the presence of a curtain wall. To reduce it, it could be beneficial to install openings (windows or glass) with Low-E (Low-Emissivity) Coatings, as well as to install air conditioning. These coatings help maintain a cooler indoor environment during the summer and a warmer one in the winter by minimizing heat loss and reducing solar heat gain.

7.2. Active strategies: Renewable Energy and Systems efficiency

7.2.1. Renewable Energy: PV Panels

In order to reduce the operational carbon emissions and energy consumption, active strategies are proposed. It was evaluated the possibility to add PV panels on the roof since the building is not in conservation area (44). Considering that there are approximately 600m^2 of unused roof space and that the building's primary energy source is electricity, it was decided to install a total of 112 photovoltaic panels (around 40%[14] of roof area) with a total capacity of 36,9 kWp. Using a calculation tool from European commission (PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM), the amount of energy generated by the photovoltaic panel system was determined.

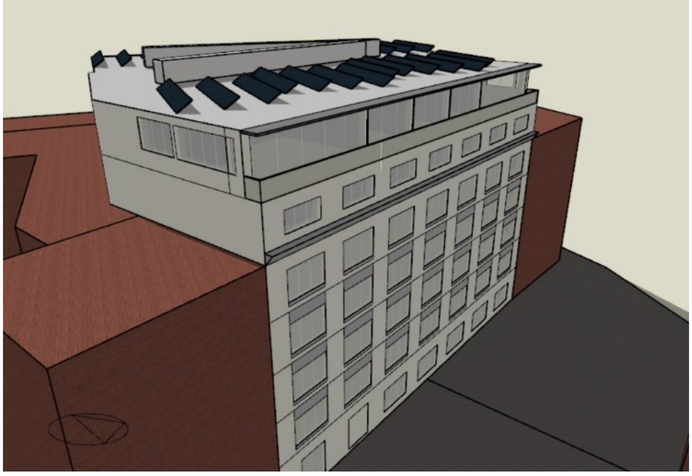

Fig. 33 PV panels installed in the model

Provided inputs:	
Location [Lat/Lon]:	51.544, -0.141
PV technology:	Crystalline silicon
PV installed [kWp]:	36.9
System loss [%]:	15.7
Simulation outputs:	
Slope angle [°]:	40
Azimuth angle [°]:	-4
Yearly PV energy production [kWh]:	36162.81
Yearly in-plane irradiation [kWh/m2]:	1228.17
Changes in output due to:	
Angle of incidence [%]:	-3.06
Spectral effects [%]:	1.91
Temperature and low irradiance [%]:	-4.18
Total loss [%]:	-20.2

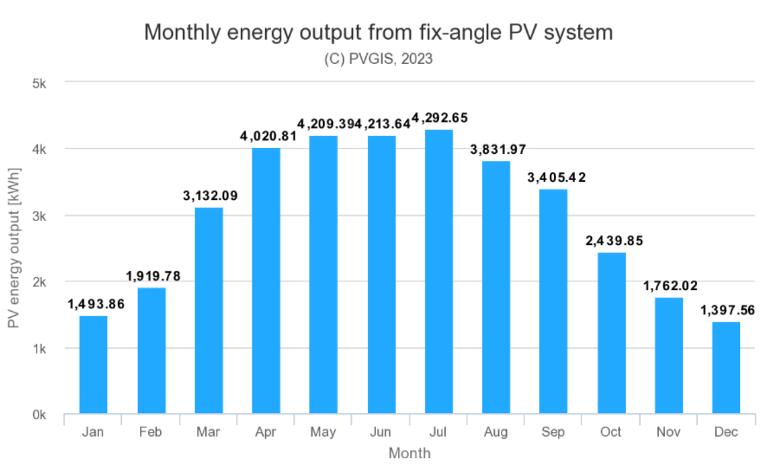

Fig. 32 Monthly energy output from fix angle-PV system (calculation from PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM European commission https://re.jrc.ec.europa.eu/pvg_tools/en/#api_5.1)

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[14] It was assumed 40% of the roof taking into accoun

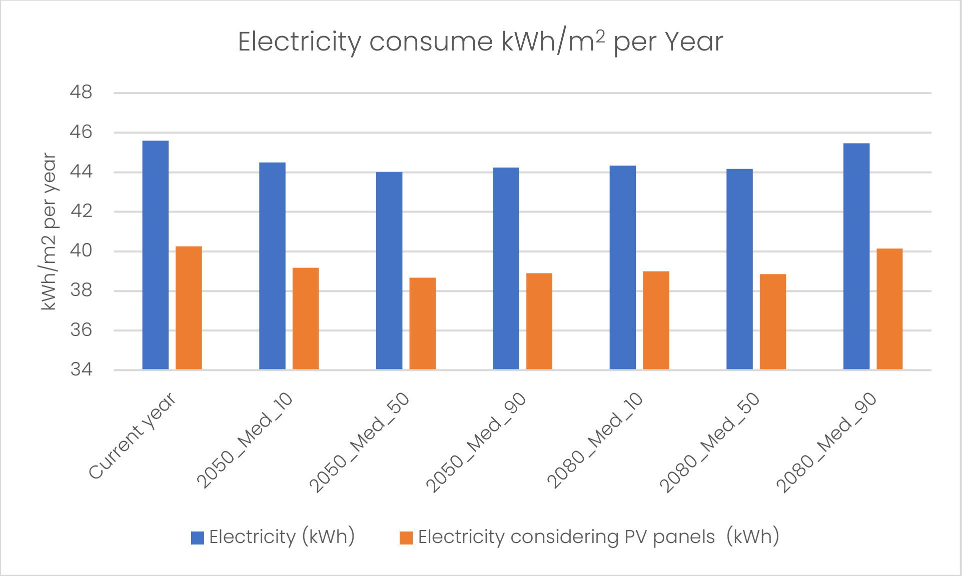

Fig. 34 Electricity consumption considering PV panels installation.

7.2.2. Systems upgrading and PV panels

Considering that 14 out of the 20 condensers located on the roof are over 20 years old and, as a result, use the refrigerant R407c which has been banned by current regulations since 2014. Furthermore, the new regulations require systems to be replaced every 17 years.

LETI (London Energy Transformation Initiative) provides recommended measures to improve system efficiency in buildings. Some recommends for Offices include Efficient HVAC Systems as:

- MVHR 90% (efficiency)
- SCoP ≥ 2.8
- SEER ≥ 5.5
- A/C set points 20-26°C

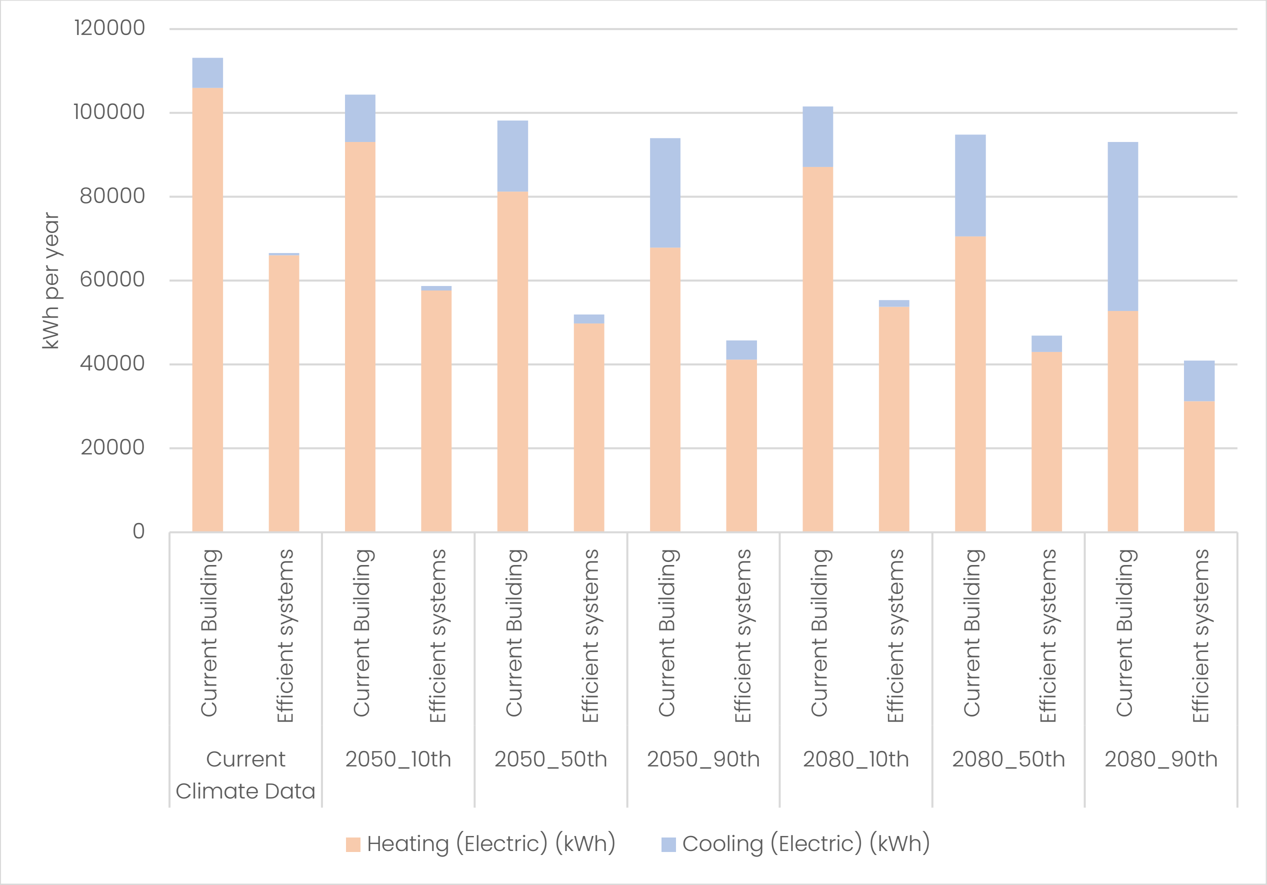

Fig. 35 Comparison Heating and Cooling consume in different scenarios and systems efficiency.

As evident from the chart, the decrease in energy consumption for heating and cooling exceeds 40%. Therefore, changing the oldest systems is an action that helps to reduce the annual energy consume of the building.

8. RESULTS

In the final analysis, considering all the hypothesized strategies, a final average consumption reduction of 40%, without taking into account strategies related to the external envelope.

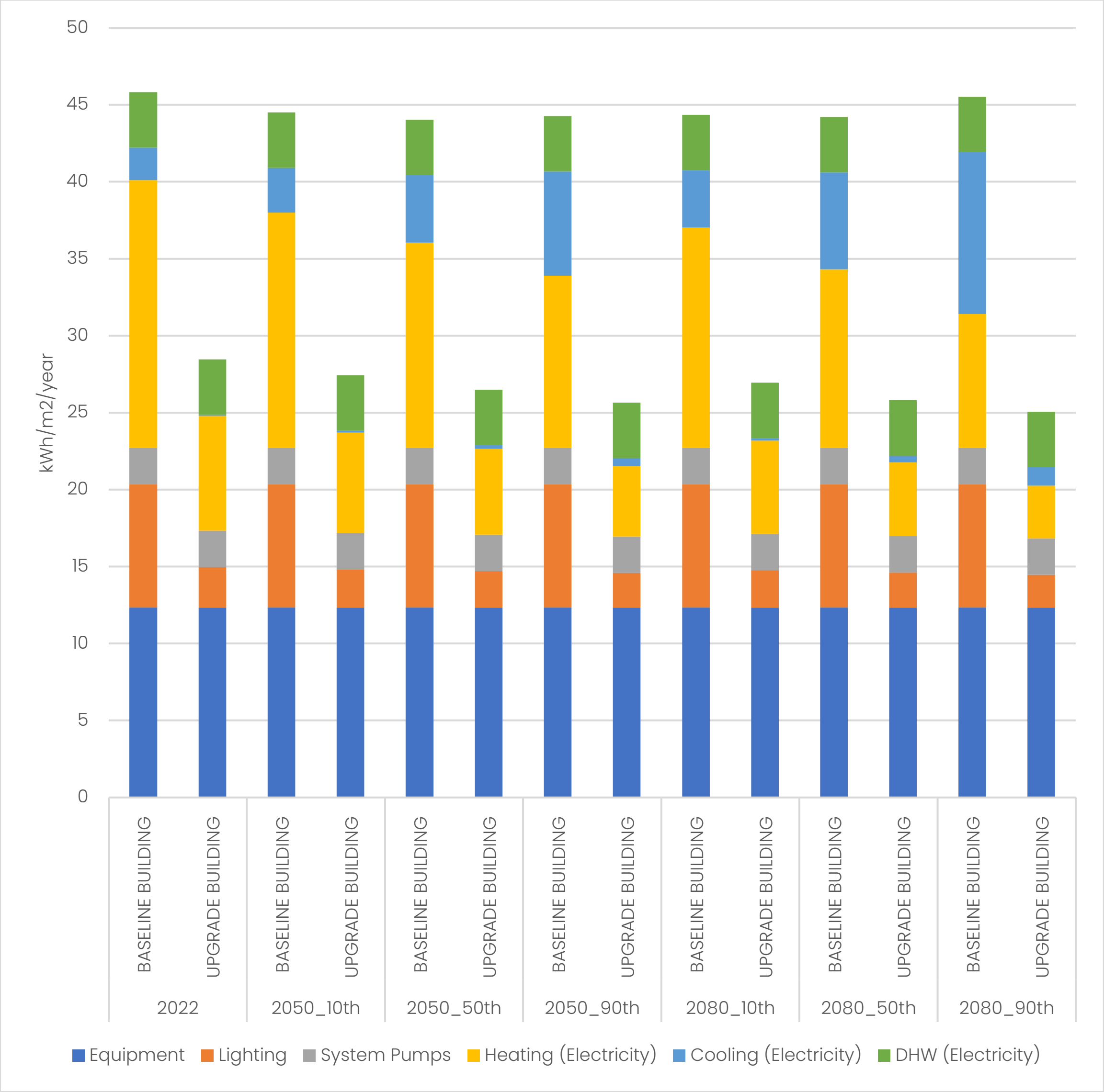

Fig. 36 Fuel breakdowns comparison Upgrade and Baseline Building based on numeric results of DesignBuilder

The results are probabilistic for several reasons. The climatic data used in each energy simulation refer to medium emissions levels, but there are also High and Low emissions levels, which were not considered in this research. Furthermore, climatic data is inherently variable and is based on the probability of a temperature value exceeding or not exceeding the set temperature value in weather data file.

Other aspects occur to occupancy profiles and facility users behaviour. It is not guaranteed that the same number of people will be present in 30 years, especially in residential areas. Also, the facility users behaviour can significantly affect the results.

Regarding the CO2 emission values, there is a decreasing around 4%. If we had conducted a complete retrofit of the building envelope, the energy consumption value would certainly have decreased, especially in winter, but the embodied carbon would have increased by about 16%. Considering that some retrofitting of the envelope had already been done in 2016, it was decided not to proceed along this path.

CONCLUSION

This research was motivated by the aim of evaluating the feasibility for achieving climate resilience within the building sector by the 2050s and 2080s.

Central questions focused on evaluating energy demand, simulating building performance, risk of overheating and CO2 emissions under future climate scenarios, all aimed at identifying the most suitable adaptation strategies.

Considering that a significant gap often exists between the phases of designing a building retrofit and its actual operational-use, this research analyses the real behaviour of the building while taking into account variable parameters like occupancy density and the facility users’ behaviour. Given the futuristic orientation of this analysis, the research projected into the future to investigate how the future climate might impact in today's retrofit adaptation strategies.

To assess how the climate might affect the building sector, a mixed-use (residential and offices) building situated in London, UK, was selected as the case study. This choice was made to assess the effects of overheating in regions that traditionally did not have high cooling demands but are likely to experience an increased need for cooling in the future.

The Dynamic Building Modelling analysis, conducted using DesignBuilder software, enabled the calibration of the building's actual energy behaviour through the real consumption data from 2022. However, certain limitations influenced the calibration phase, such as operational data from 2022, which was influenced by the pandemic, as well as the lack of data regarding the building's envelope and precise users activity schedules.

Following the calibration process, the energy model was subjected to testing under future within probabilistic scenarios for 2050s and 2080s. Adaptation strategies to mitigate the risk of overheating and its impact on the future climate were assessed, including passive strategies, whereas active strategies placed a stronger emphasis on the reduction of energy consumption and CO2 emissions.

The results indicate an average reduction of around 40% in energy consumption with the implementation of passive and active strategies, excluding those related to the external envelope. Nevertheless, the predictions are probabilistic due to variations in climate data, vulnerability of occupants, all of which are uncertain, particularly in the future.

The primary objective has never been to provide definitive answers, but rather to establish an approach to energy analysis that differs from a generic retrofitting and effectively accounts for the implications of climate change in the future. This highlights the understanding that what is retrofitted today may not always be resilient to the climate of tomorrow.

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APPENDIX A

The construction elements defined are described below, for each of them will be reported:

- U = Thermal transmission coefficient
- Composition of the layers (thickness; material thermal conductivity)
- Cross section (From DesignBuilder and out of scale)

External wall

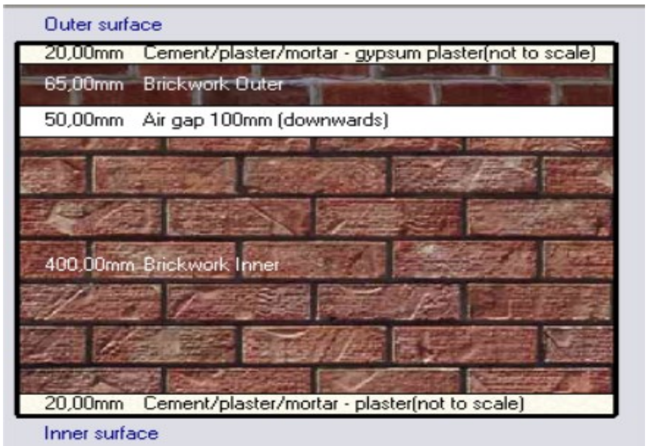


Fig. 37 Cross section external wall

1. Cement/plaster λ=0,51 W/mK
2. Brickwork outer λ= 0,84 W/mK
3. Airgap
4. Brickwork inner λ=0,61 W/mK
5. Cement/plaster λ= 0,35 W/mK

U= 0,827 W/m^{2}K

Internal partition

Fig. 38 Cross section internal partition

1. Plasteboardr λ=0,21 W/mK
2. Insulation λ= 0,035 W/mK
3. Plasteboardr λ=0,21 W/mK

U= 0,62 W/m²K

Flat roof

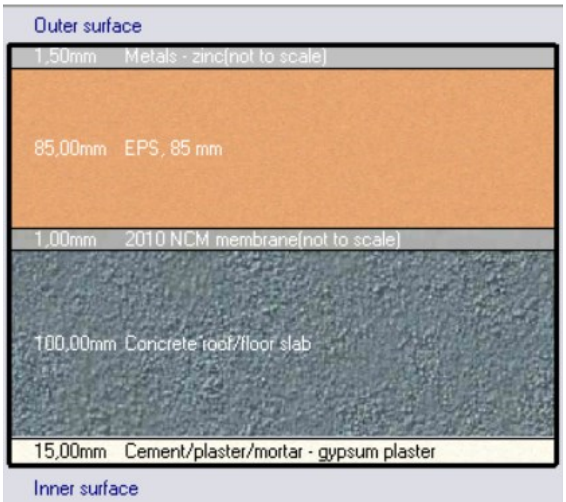
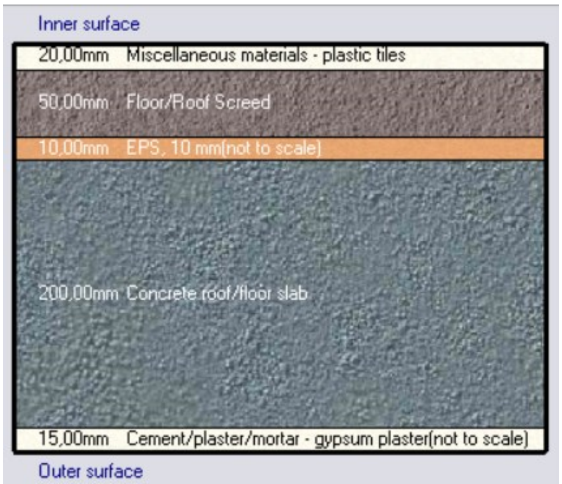


Fig. 39 Cross section Flat roof

1. Metal sheet λ=113 W/mK
2. EPS λ= 0,04 W/mK
3. Membrane λ=1 W/mK
4. Concrete λ=2 W/mK
5. Plaster gypsum λ= 0,51 W/mK

U= 0,42 W/m²K

Internal floor



Inner surface

20,00mm Miscellaneous materials - plastic tiles

50,00mm Floor/Roof Screed

10,00mm EPS, 10 mm(not to scale)

200,00mm Concrete roof/floor slab

15,00mm Cement/plaster/mortar - gypsum plaster(not to scale)

Outer surface

Fig. 40 Cross section internal floor

1. Plastic Tiles λ=0,5W/mK
2. Floor screed λ=0,4W/mK
3. EPS λ=0,04 W/mK
4. Reinforced Concrete λ=2,3 W/mK
5. Plaster gypsum λ= 0,51 W/mK

U= 1,16 W/m^{2}K

Windows glazing

Double glazed window filled with air with painted wood frame.

U_w=2,76 W/m^{2}K

APPENDIX B

Meter readings from 2022

Month	Landlord	LG	G floor	1st floor	2nd floor	3rd floor	4th floor
	[kWh]						
February	2094,00	0,00	2941,00	2925	973	582	2157
March	2597,00	28,00	952,00	727	1363	1559	8480
April	2248,00	33,00	914,00	5988	1260	1898	2296
May	2383,00	0,00	1116,00	5565	1710	2306	3046
June	2044,00	1,00	531,00	4558	1288	591	2703
July	14558,00	21,00	2331,00	4166	1330	343	2640
August	2788,00	19,00	1158,00	4642	1652	629	1487
September	1750,00	7,00	885,00	3666	1336	381	3315
October	2180,00	3,00	1055,00	4051	1812	467	1578
November	1740,00	0,00	875,00	3534	1472	261	1205

Tab. 26 Offices and Landlords Meter readings 2022 (10 months)

Month	F1	F2	F2A	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
	[kWh]														
January	81	701	237	909	399	132	387	3108	945	832	418	2146	120	1781	354
February	282	298	169	389	207	37	148	1258	440	308	192	987	1344	729	179
March	58	445	205	474	205	60	241	1612	330	488	257	758	596	443	273
April	35	517	220	481	333	131	393	1900	397	669	306	588	510	718	328
May	42	465	199	564	229	107	257	1970	301	469	289	473	490	487	342
June	58	462	196	448	221	97	203	2241	420	403	284	431	400	352	362
July	354	551	290	517	533	139	384	1239	581	436	261	408	323	418	703
August	42	203	130	191	192	44	147	550	323	354	207	331	113	333	585
September	67	172	202	305	405	87	182	751	535	352	285	360	139	392	551
October	47	102	354	462	479	110	310	926	878	409	344	377	148	648	651
November	33	312	232	395	357	140	294	713	791	412	275	117	423	890	594
December	294	114	302	471	531	140	364	976	1502	1199	714	736	1514	2980	931

Tab. 27 Flat Meter readings 2022 (one year)

APPENDIX C

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	004X005XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	006X007XAAAXrec	0.00	0.00	0.00	Pass
02Ground	007X002XAAAXoff	0.00	0.00	0.00	Pass
02Ground	007X006XAAAXoff	0.00	0.00	0.00	Pass
031st	001X101XAAAXeatXdr	0.00	0.00	0.00	Pass
031st	002X104XDDDXWC	0.00	0.00	0.00	Pass
031st	004X102XGGGXcirc	0.00	0.00	0.00	Pass
031st	004X105XGGGXcirc	0.00	0.00	0.00	Pass
031st	007X103XAAAXoff	0.04	0.50	0.00	Pass
031st	007X106XAAAXoff	0.06	0.75	0.00	Pass
042nd	001X201XAAAXeatXdr	0.00	0.00	0.00	Pass
042nd	002X204XDDDXWC	0.00	0.00	0.00	Pass
042nd	004X202XGGGXcirc	0.00	0.00	0.00	Pass
042nd	004X205XGGGXcirc	0.00	0.00	0.00	Pass
042nd	007X106XAAAXoff	1.01	4.25	0.00	Pass
042nd	007X203XAAAXoff	0.37	4.75	0.00	Pass
053rd	001X301XAAAXeatXdr	0.00	0.00	0.00	Pass
053rd	002X304XDDDXWC	0.00	0.00	0.00	Pass
053rd	004X302XGGGXcirc	0.00	0.00	0.00	Pass
053rd	004X305XGGGXcirc	0.00	0.00	0.00	Pass
053rd	007X303XAAAXoff	0.49	5.00	0.00	Pass
053rd	007X306XAAAXoff	1.36	4.75	0.00	Pass
064th	001X401XAAAXeatXdr	0.00	0.00	0.00	Pass
064th	002X404XDDDXWC	0.00	0.00	0.00	Pass
064th	004X402XGGGXcirc	0.00	0.00	0.00	Pass
064th	004X405XGGGXcirc	0.00	0.00	0.00	Pass
064th	007X403XAAAXoff	0.68	5.25	0.00	Pass
064th	007X406XAAAXoff	1.42	5.00	0.00	Pass

Tab. 28 TM52_DSY1_2050_10_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	004X005XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	006X007XAAAXrec	0.00	0.00	0.00	Pass
02Ground	007X002XAAAXoff	0.47	2.00	0.00	Pass
02Ground	007X006XAAAXoff	0.00	0.00	0.00	Pass
031st	001X101XAAAXeatXdr	0.00	0.00	0.00	Pass
031st	002X104XDDDXWC	0.00	0.00	0.00	Pass
031st	004X102XGGGXcirc	0.00	0.00	0.00	Pass
031st	004X105XGGGXcirc	0.00	0.00	0.00	Pass
031st	007X103XAAAXoff	0.82	5.50	0.00	Pass
031st	007X106XAAAXoff	1.23	4.75	0.00	Pass
042nd	001X201XAAAXeatXdr	0.00	0.00	0.00	Pass
042nd	002X204XDDDXWC	0.00	0.00	0.00	Pass
042nd	004X202XGGGXcirc	0.18	2.25	0.00	Pass
042nd	004X205XGGGXcirc	0.00	0.00	0.00	Pass
042nd	007X106XAAAXoff	2.43	9.50	0.00	Pass
042nd	007X203XAAAXoff	2.01	11.00	0.00	Pass
053rd	001X301XAAAXeatXdr	0.18	0.75	0.00	Pass
053rd	002X304XDDDXWC	0.00	0.00	0.00	Pass
053rd	004X302XGGGXcirc	1.01	7.25	0.00	Pass
053rd	004X305XGGGXcirc	0.00	0.00	0.00	Pass
053rd	007X303XAAAXoff	2.45	12.00	0.00	Pass
053rd	007X306XAAAXoff	3.56	11.50	0.00	Fail
064th	001X401XAAAXeatXdr	0.18	0.75	0.00	Pass
064th	002X404XDDDXWC	0.00	0.00	0.00	Pass
064th	004X402XGGGXcirc	1.19	8.00	0.00	Pass
064th	004X405XGGGXcirc	0.02	0.25	0.00	Pass
064th	007X403XAAAXoff	3.00	12.25	0.00	Pass
064th	007X406XAAAXoff	4.07	11.50	0.00	Fail

Tab. 29 TM52_DSY1_2050_50_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail

01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	004X005XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	006X007XAAAXrec	0.16	1.25	0.00	Pass
02Ground	007X002XAAAXoff	1.83	7.25	0.00	Pass
02Ground	007X006XAAAXoff	0.31	4.00	0.00	Pass
031st	001X101XAAAXeatXdr	0.29	1.25	0.00	Pass
031st	002X104XDDDXWC	0.00	0.00	0.00	Pass
031st	004X102XGGGXcirc	1.73	8.75	0.00	Pass
031st	004X105XGGGXcirc	0.94	6.75	0.00	Pass
031st	007X103XAAAXoff	5.28	14.25	0.00	Fail
031st	007X106XAAAXoff	4.95	12.75	0.00	Fail
042nd	001X201XAAAXeatXdr	1.93	3.50	0.00	Pass
042nd	002X204XDDDXWC	1.00	4.75	0.00	Pass
042nd	004X202XGGGXcirc	6.00	18.75	0.00	Fail
042nd	004X205XGGGXcirc	2.49	10.00	0.00	Pass
042nd	007X106XAAAXoff	8.14	18.50	0.00	Fail
042nd	007X203XAAAXoff	8.39	21.00	0.00	Fail
053rd	001X301XAAAXeatXdr	2.92	4.50	0.00	Pass
053rd	002X304XDDDXWC	2.12	6.00	0.00	Pass
053rd	004X302XGGGXcirc	8.01	21.25	0.00	Fail
053rd	004X305XGGGXcirc	4.97	14.75	0.00	Fail
053rd	007X303XAAAXoff	9.91	22.00	0.00	Fail
053rd	007X306XAAAXoff	11.45	23.00	0.00	Fail
064th	001X401XAAAXeatXdr	3.27	5.00	0.00	Pass
064th	002X404XDDDXWC	2.71	6.50	0.00	Pass
064th	004X402XGGGXcirc	9.10	21.75	0.00	Fail
064th	004X405XGGGXcirc	5.87	19.00	0.00	Fail
064th	007X403XAAAXoff	10.92	22.50	0.00	Fail
064th	007X406XAAAXoff	12.09	23.75	0.00	Fail

Tab. 30 TM52_DSY1_2050_90_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass

01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	004X005XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	006X007XAAAXrec	0.00	0.00	0.00	Pass
02Ground	007X002XAAAXoff	0.43	3.00	0.00	Pass
02Ground	007X006XAAAXoff	0.00	0.00	0.00	Pass
031st	001X101XAAAXeatXdr	0.00	0.00	0.00	Pass
031st	002X104XDDDXWC	0.00	0.00	0.00	Pass
031st	004X102XGGGXcirc	0.00	0.00	0.00	Pass
031st	004X105XGGGXcirc	0.00	0.00	0.00	Pass
031st	007X103XAAAXoff	1.25	10.25	0.00	Pass
031st	007X106XAAAXoff	1.17	5.75	0.00	Pass
042nd	001X201XAAAXeatXdr	0.18	0.75	0.00	Pass
042nd	002X204XDDDXWC	0.00	0.00	0.00	Pass
042nd	004X202XGGGXcirc	0.00	0.00	0.00	Pass
042nd	004X205XGGGXcirc	0.00	0.00	0.00	Pass
042nd	007X106XAAAXoff	1.91	10.75	0.00	Pass
042nd	007X203XAAAXoff	1.95	13.25	0.00	Pass
053rd	001X301XAAAXeatXdr	0.29	1.25	0.00	Pass
053rd	002X304XDDDXWC	0.00	0.00	0.00	Pass
053rd	004X302XGGGXcirc	0.47	5.50	0.00	Pass
053rd	004X305XGGGXcirc	0.00	0.00	0.00	Pass
053rd	007X303XAAAXoff	2.18	15.75	0.00	Pass
053rd	007X306XAAAXoff	2.73	12.25	0.00	Pass
064th	001X401XAAAXeatXdr	0.29	1.25	0.00	Pass
064th	002X404XDDDXWC	0.00	0.00	0.00	Pass
064th	004X402XGGGXcirc	0.97	7.00	0.00	Pass
064th	004X405XGGGXcirc	0.00	0.00	0.00	Pass
064th	007X403XAAAXoff	2.53	16.50	0.00	Pass
064th	007X406XAAAXoff	2.82	13.00	0.00	Pass

Tab. 31 TM52_DSY2_2050_10_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass

01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	004X005XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	006X007XAAAXrec	0.00	0.00	0.00	Pass
02Ground	007X002XAAAXoff	0.94	7.00	0.00	Pass
02Ground	007X006XAAAXoff	0.31	4.00	0.00	Pass
031st	001X101XAAAXeatXdr	0.18	0.75	0.00	Pass
031st	002X104XDDDXWC	0.00	0.00	0.00	Pass
031st	004X102XGGGXcirc	0.14	1.75	0.00	Pass
031st	004X105XGGGXcirc	0.00	0.00	0.00	Pass
031st	007X103XAAAXoff	2.32	15.50	0.00	Pass
031st	007X106XAAAXoff	2.12	11.25	0.00	Pass
042nd	001X201XAAAXeatXdr	0.65	2.50	0.00	Pass
042nd	002X204XDDDXWC	0.22	1.25	0.00	Pass
042nd	004X202XGGGXcirc	2.17	8.75	0.00	Pass
042nd	004X205XGGGXcirc	0.61	6.75	0.00	Pass
042nd	007X106XAAAXoff	3.81	17.50	0.00	Fail
042nd	007X203XAAAXoff	3.79	20.75	0.00	Fail
053rd	001X301XAAAXeatXdr	0.88	3.50	0.00	Pass
053rd	002X304XDDDXWC	0.55	3.75	0.00	Pass
053rd	004X302XGGGXcirc	3.56	10.00	0.00	Fail
053rd	004X305XGGGXcirc	1.63	8.50	0.00	Pass
053rd	007X303XAAAXoff	4.44	21.75	0.00	Fail
053rd	007X306XAAAXoff	5.11	19.25	0.00	Fail
064th	001X401XAAAXeatXdr	1.06	3.50	0.00	Pass
064th	002X404XDDDXWC	0.63	4.25	0.00	Pass
064th	004X402XGGGXcirc	4.19	14.75	0.00	Fail
064th	004X405XGGGXcirc	1.99	9.00	0.00	Pass
064th	007X403XAAAXoff	5.15	22.50	0.00	Fail
064th	007X406XAAAXoff	5.29	19.25	0.00	Fail

Tab. 32 TM52_DSY2_2050_50_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass

02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	004X005XGGGXcirc	0.10	0.75	0.00	Pass
02Ground	006X007XAAAXrec	0.41	3.50	0.00	Pass
02Ground	007X002XAAAXoff	2.32	13.00	0.00	Pass
02Ground	007X006XAAAXoff	0.84	10.00	0.00	Pass
031st	001X101XAAAXeatXdr	0.78	3.75	0.00	Pass
031st	002X104XDDDXWC	0.40	4.00	0.00	Pass
031st	004X102XGGGXcirc	3.34	10.75	0.00	Fail
031st	004X105XGGGXcirc	2.07	9.25	0.00	Pass
031st	007X103XAAAXoff	5.79	24.75	0.00	Fail
031st	007X106XAAAXoff	5.05	19.50	0.00	Fail
042nd	001X201XAAAXeatXdr	2.46	6.50	0.00	Pass
042nd	002X204XDDDXWC	2.29	8.75	0.00	Pass
042nd	004X202XGGGXcirc	6.31	22.00	0.00	Fail
042nd	004X205XGGGXcirc	4.08	18.50	0.00	Fail
042nd	007X106XAAAXoff	8.13	26.75	0.00	Fail
042nd	007X203XAAAXoff	8.55	31.25	0.00	Fail
053rd	001X301XAAAXeatXdr	3.97	7.75	0.00	Fail
053rd	002X304XDDDXWC	3.27	11.25	0.00	Fail
053rd	004X302XGGGXcirc	9.30	24.25	0.00	Fail
053rd	004X305XGGGXcirc	5.29	21.75	0.00	Fail
053rd	007X303XAAAXoff	10.04	34.00	0.00	Fail
053rd	007X306XAAAXoff	10.34	28.75	0.00	Fail
064th	001X401XAAAXeatXdr	4.45	8.00	0.00	Fail
064th	002X404XDDDXWC	3.76	12.50	0.00	Fail
064th	004X402XGGGXcirc	10.41	29.50	0.00	Fail
064th	004X405XGGGXcirc	6.57	22.25	0.00	Fail
064th	007X403XAAAXoff	10.90	36.50	0.00	Fail
064th	007X406XAAAXoff	10.88	29.50	0.00	Fail

Tab. 33 TM52_DSY2_2050_90_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass

02Ground	004X005XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	006X007XAAAXrec	0.00	0.00	0.00	Pass
02Ground	007X002XAAAXoff	1.19	4.25	0.00	Pass
02Ground	007X006XAAAXoff	0.00	0.00	0.00	Pass
031st	001X101XAAAXeatXdr	0.12	0.50	0.00	Pass
031st	002X104XDDDXWC	0.00	0.00	0.00	Pass
031st	004X102XGGGXcirc	0.29	3.25	0.00	Pass
031st	004X105XGGGXcirc	0.00	0.00	0.00	Pass
031st	007X103XAAAXoff	3.50	12.00	0.00	Fail
031st	007X106XAAAXoff	3.13	10.25	0.00	Fail
042nd	001X201XAAAXeatXdr	1.11	2.00	0.00	Pass
042nd	002X204XDDDXWC	0.30	2.00	0.00	Pass
042nd	004X202XGGGXcirc	3.94	8.50	0.00	Fail
042nd	004X205XGGGXcirc	1.09	5.00	0.00	Pass
042nd	007X106XAAAXoff	4.91	16.00	0.00	Fail
042nd	007X203XAAAXoff	4.77	17.50	0.00	Fail
053rd	001X301XAAAXeatXdr	1.75	3.00	0.00	Pass
053rd	002X304XDDDXWC	1.36	3.75	0.00	Pass
053rd	004X302XGGGXcirc	5.07	9.75	0.00	Fail
053rd	004X305XGGGXcirc	2.71	7.75	0.00	Pass
053rd	007X303XAAAXoff	5.39	19.00	0.00	Fail
053rd	007X306XAAAXoff	5.74	18.25	0.00	Fail
064th	001X401XAAAXeatXdr	1.99	3.50	0.00	Pass
064th	002X404XDDDXWC	1.86	4.25	0.00	Pass
064th	004X402XGGGXcirc	5.59	13.00	0.00	Fail
064th	004X405XGGGXcirc	3.55	8.75	0.00	Fail
064th	007X403XAAAXoff	5.74	19.50	0.00	Fail
064th	007X406XAAAXoff	5.96	18.75	0.00	Fail

Tab. 34 TM52_DSY3_2050_10_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	004X005XGGGXcirc	0.29	1.50	0.00	Pass
02Ground	006X007XAAAXrec	0.65	2.25	0.00	Pass
02Ground	007X002XAAAXoff	2.92	8.00	0.00	Pass

02Ground	007X006XAAAXoff	1.34	5.00	0.00	Pass
031st	001X101XAAAXeatXdr	1.58	2.00	0.00	Pass
031st	002X104XDDDXWC	0.69	3.25	0.00	Pass
031st	004X102XGGGXcirc	4.21	9.00	0.00	Fail
031st	004X105XGGGXcirc	1.44	6.50	0.00	Pass
031st	007X103XAAAXoff	5.28	17.25	0.00	Fail
031st	007X106XAAAXoff	5.20	15.25	0.00	Fail
042nd	001X201XAAAXeatXdr	3.15	4.25	0.00	Pass
042nd	002X204XDDDXWC	2.56	5.50	0.00	Pass
042nd	004X202XGGGXcirc	6.51	17.50	0.00	Fail
042nd	004X205XGGGXcirc	4.89	10.00	0.00	Fail
042nd	007X106XAAAXoff	6.97	19.25	0.00	Fail
042nd	007X203XAAAXoff	7.15	21.00	0.00	Fail
053rd	001X301XAAAXeatXdr	4.09	5.25	0.00	Pass
053rd	002X304XDDDXWC	3.47	9.75	0.00	Fail
053rd	004X302XGGGXcirc	8.18	21.25	0.00	Fail
053rd	004X305XGGGXcirc	5.87	17.00	0.00	Fail
053rd	007X303XAAAXoff	8.14	27.25	0.00	Fail
053rd	007X306XAAAXoff	8.41	26.50	0.00	Fail
064th	001X401XAAAXeatXdr	4.21	5.75	0.00	Pass
064th	002X404XDDDXWC	3.81	11.00	0.00	Fail
064th	004X402XGGGXcirc	8.59	22.50	0.00	Fail
064th	004X405XGGGXcirc	6.92	19.50	0.00	Fail
064th	007X403XAAAXoff	8.84	29.00	0.00	Fail
064th	007X406XAAAXoff	8.92	26.75	0.00	Fail

Tab. 35 TM52_DSY3_2050_50_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	1.61	7.25	0.00	Pass
02Ground	004X005XGGGXcirc	2.40	8.25	0.00	Pass
02Ground	006X007XAAAXrec	1.81	5.75	0.00	Pass
02Ground	007X002XAAAXoff	3.63	14.50	0.00	Fail
02Ground	007X006XAAAXoff	2.48	12.00	0.00	Pass
031st	001X101XAAAXeatXdr	2.85	5.50	0.00	Pass
031st	002X104XDDDXWC	2.37	10.50	0.00	Pass

031st	004X102XGGGXcirc	6.35	21.25	0.00	Fail
031st	004X105XGGGXcirc	4.78	17.75	0.00	Fail
031st	007X103XAAAXoff	6.08	23.25	0.00	Fail
031st	007X106XAAAXoff	5.90	22.50	0.00	Fail
042nd	001X201XAAAXeatXdr	4.33	8.25	0.00	Fail
042nd	002X204XDDDXWC	4.25	14.75	0.00	Fail
042nd	004X202XGGGXcirc	9.93	31.25	0.00	Fail
042nd	004X205XGGGXcirc	7.93	23.25	0.00	Fail
042nd	007X106XAAAXoff	10.19	31.25	0.00	Fail
042nd	007X203XAAAXoff	10.50	33.25	0.00	Fail
053rd	001X301XAAAXeatXdr	5.20	9.25	0.00	Fail
053rd	002X304XDDDXWC	6.62	20.75	0.00	Fail
053rd	004X302XGGGXcirc	11.92	35.00	0.00	Fail
053rd	004X305XGGGXcirc	9.77	31.00	0.00	Fail
053rd	007X303XAAAXoff	12.33	37.00	2.75	Fail
053rd	007X306XAAAXoff	13.22	36.75	7.50	Fail
064th	001X401XAAAXeatXdr	5.57	9.75	0.00	Fail
064th	002X404XDDDXWC	7.05	21.75	0.00	Fail
064th	004X402XGGGXcirc	12.62	36.00	0.00	Fail
064th	004X405XGGGXcirc	10.08	33.50	0.00	Fail
064th	007X403XAAAXoff	13.57	39.25	4.00	Fail
064th	007X406XAAAXoff	14.07	37.75	10.00	Fail

Tab. 36 TM52_DSY3_2050_90_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	004X005XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	006X007XAAAXrec	0.00	0.00	0.00	Pass
02Ground	007X002XAAAXoff	0.06	0.50	0.00	Pass
02Ground	007X006XAAAXoff	0.00	0.00	0.00	Pass
031st	001X101XAAAXeatXdr	0.00	0.00	0.00	Pass
031st	002X104XDDDXWC	0.00	0.00	0.00	Pass
031st	004X102XGGGXcirc	0.00	0.00	0.00	Pass
031st	004X105XGGGXcirc	0.00	0.00	0.00	Pass
031st	007X103XAAAXoff	0.31	4.00	0.00	Pass

031st	007X106XAAAXoff	0.60	3.25	0.00	Pass
042nd	001X201XAAAXeatXdr	0.00	0.00	0.00	Pass
042nd	002X204XDDDXWC	0.00	0.00	0.00	Pass
042nd	004X202XGGGXcirc	0.00	0.00	0.00	Pass
042nd	004X205XGGGXcirc	0.00	0.00	0.00	Pass
042nd	007X106XAAAXoff	1.42	5.00	0.00	Pass
042nd	007X203XAAAXoff	0.84	5.50	0.00	Pass
053rd	001X301XAAAXeatXdr	0.00	0.00	0.00	Pass
053rd	002X304XDDDXWC	0.00	0.00	0.00	Pass
053rd	004X302XGGGXcirc	0.00	0.00	0.00	Pass
053rd	004X305XGGGXcirc	0.00	0.00	0.00	Pass
053rd	007X303XAAAXoff	1.52	6.00	0.00	Pass
053rd	007X306XAAAXoff	1.99	8.75	0.00	Pass
064th	001X401XAAAXeatXdr	0.00	0.00	0.00	Pass
064th	002X404XDDDXWC	0.00	0.00	0.00	Pass
064th	004X402XGGGXcirc	0.00	0.00	0.00	Pass
064th	004X405XGGGXcirc	0.00	0.00	0.00	Pass
064th	007X403XAAAXoff	1.65	7.25	0.00	Pass
064th	007X406XAAAXoff	2.08	8.75	0.00	Pass

Tab. 37 TM52_DSY1_2080_10_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	004X005XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	006X007XAAAXrec	0.00	0.00	0.00	Pass
02Ground	007X002XAAAXoff	0.99	4.50	0.00	Pass
02Ground	007X006XAAAXoff	0.00	0.00	0.00	Pass
031st	001X101XAAAXeatXdr	0.00	0.00	0.00	Pass
031st	002X104XDDDXWC	0.00	0.00	0.00	Pass
031st	004X102XGGGXcirc	0.39	5.00	0.00	Pass
031st	004X105XGGGXcirc	0.00	0.00	0.00	Pass
031st	007X103XAAAXoff	2.88	12.00	0.00	Pass
031st	007X106XAAAXoff	2.86	9.75	0.00	Pass
042nd	001X201XAAAXeatXdr	0.41	1.50	0.00	Pass
042nd	002X204XDDDXWC	0.00	0.00	0.00	Pass

042nd	004X202XGGGXcirc	2.10	9.00	0.00	Pass
042nd	004X205XGGGXcirc	1.03	7.25	0.00	Pass
042nd	007X106XAAAXoff	5.65	15.25	0.00	Fail
042nd	007X203XAAAXoff	5.30	14.00	0.00	Fail
053rd	001X301XAAAXeatXdr	0.76	2.25	0.00	Pass
053rd	002X304XDDDXWC	0.58	3.25	0.00	Pass
053rd	004X302XGGGXcirc	4.33	11.75	0.00	Fail
053rd	004X305XGGGXcirc	1.38	8.50	0.00	Pass
053rd	007X303XAAAXoff	6.81	17.50	0.00	Fail
053rd	007X306XAAAXoff	7.77	17.75	0.00	Fail
064th	001X401XAAAXeatXdr	0.99	2.50	0.00	Pass
064th	002X404XDDDXWC	0.76	3.75	0.00	Pass
064th	004X402XGGGXcirc	5.53	17.00	0.00	Fail
064th	004X405XGGGXcirc	2.20	9.25	0.00	Pass
064th	007X403XAAAXoff	7.96	19.25	0.00	Fail
064th	007X406XAAAXoff	8.47	17.75	0.00	Fail

Tab. 38 TM52_DSY1_2080_50_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	1.45	10.25	0.00	Pass
02Ground	004X005XGGGXcirc	2.05	7.75	0.00	Pass
02Ground	006X007XAAAXrec	1.92	4.75	0.00	Pass
02Ground	007X002XAAAXoff	6.37	14.75	0.00	Fail
02Ground	007X006XAAAXoff	2.96	12.00	0.00	Pass
031st	001X101XAAAXeatXdr	3.13	5.50	0.00	Pass
031st	002X104XDDDXWC	2.67	7.50	0.00	Pass
031st	004X102XGGGXcirc	9.20	22.50	0.00	Fail
031st	004X105XGGGXcirc	5.35	20.50	0.00	Fail
031st	007X103XAAAXoff	14.08	25.75	0.00	Fail
031st	007X106XAAAXoff	12.36	23.75	0.00	Fail
042nd	001X201XAAAXeatXdr	6.79	8.25	0.00	Fail
042nd	002X204XDDDXWC	6.52	15.75	0.00	Fail
042nd	004X202XGGGXcirc	15.72	34.00	0.00	Fail
042nd	004X205XGGGXcirc	11.19	24.25	0.00	Fail
042nd	007X106XAAAXoff	16.59	32.50	1.00	Fail

042nd	007X203XAAAXoff	17.97	34.50	0.00	Fail
053rd	001X301XAAAXeatXdr	9.13	9.75	0.00	Fail
053rd	002X304XDDDXWC	9.14	17.25	0.00	Fail
053rd	004X302XGGGXcirc	21.44	35.50	0.00	Fail
053rd	004X305XGGGXcirc	14.41	33.50	0.00	Fail
053rd	007X303XAAAXoff	20.59	36.00	0.00	Fail
053rd	007X306XAAAXoff	20.05	37.25	4.75	Fail
064th	001X401XAAAXeatXdr	9.92	10.00	0.00	Fail
064th	002X404XDDDXWC	10.30	20.75	0.00	Fail
064th	004X402XGGGXcirc	23.61	36.50	0.00	Fail
064th	004X405XGGGXcirc	15.98	34.25	0.00	Fail
064th	007X403XAAAXoff	22.52	40.00	0.00	Fail
064th	007X406XAAAXoff	21.09	38.00	5.25	Fail

Tab. 39 TM52_DSY1_2080_90_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	004X005XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	006X007XAAAXrec	0.00	0.00	0.00	Pass
02Ground	007X002XAAAXoff	0.72	4.25	0.00	Pass
02Ground	007X006XAAAXoff	0.16	2.00	0.00	Pass
031st	001X101XAAAXeatXdr	0.06	0.25	0.00	Pass
031st	002X104XDDDXWC	0.00	0.00	0.00	Pass
031st	004X102XGGGXcirc	0.00	0.00	0.00	Pass
031st	004X105XGGGXcirc	0.00	0.00	0.00	Pass
031st	007X103XAAAXoff	1.65	12.75	0.00	Pass
031st	007X106XAAAXoff	1.64	9.50	0.00	Pass
042nd	001X201XAAAXeatXdr	0.35	1.50	0.00	Pass
042nd	002X204XDDDXWC	0.00	0.00	0.00	Pass
042nd	004X202XGGGXcirc	0.74	6.25	0.00	Pass
042nd	004X205XGGGXcirc	0.00	0.00	0.00	Pass
042nd	007X106XAAAXoff	2.84	13.00	0.00	Pass
042nd	007X203XAAAXoff	2.67	17.50	0.00	Pass
053rd	001X301XAAAXeatXdr	0.53	2.00	0.00	Pass
053rd	002X304XDDDXWC	0.00	0.00	0.00	Pass

053rd	004X302XGGGXcirc	1.81	8.50	0.00	Pass
053rd	004X305XGGGXcirc	0.41	5.25	0.00	Pass
053rd	007X303XAAAXoff	3.29	20.00	0.00	Fail
053rd	007X306XAAAXoff	3.49	17.25	0.00	Fail
064th	001X401XAAAXeatXdr	0.70	2.25	0.00	Pass
064th	002X404XDDDXWC	0.19	2.25	0.00	Pass
064th	004X402XGGGXcirc	2.20	9.00	0.00	Pass
064th	004X405XGGGXcirc	0.68	7.25	0.00	Pass
064th	007X403XAAAXoff	3.60	20.25	0.00	Fail
064th	007X406XAAAXoff	3.74	17.25	0.00	Fail

Tab. 40 TM52_DSY2_2080_10_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	004X005XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	006X007XAAAXrec	0.31	1.75	0.00	Pass
02Ground	007X002XAAAXoff	1.92	10.25	0.00	Pass
02Ground	007X006XAAAXoff	0.79	7.75	0.00	Pass
031st	001X101XAAAXeatXdr	0.71	2.50	0.00	Pass
031st	002X104XDDDXWC	0.44	3.00	0.00	Pass
031st	004X102XGGGXcirc	2.51	9.00	0.00	Pass
031st	004X105XGGGXcirc	1.29	7.75	0.00	Pass
031st	007X103XAAAXoff	4.60	21.75	0.00	Fail
031st	007X106XAAAXoff	4.15	17.75	0.00	Fail
042nd	001X201XAAAXeatXdr	1.90	5.00	0.00	Pass
042nd	002X204XDDDXWC	1.57	5.25	0.00	Pass
042nd	004X202XGGGXcirc	4.75	19.50	0.00	Fail
042nd	004X205XGGGXcirc	3.26	10.75	0.00	Fail
042nd	007X106XAAAXoff	6.51	24.50	0.00	Fail
042nd	007X203XAAAXoff	6.75	28.75	0.00	Fail
053rd	001X301XAAAXeatXdr	2.92	6.50	0.00	Pass
053rd	002X304XDDDXWC	2.54	9.00	0.00	Pass
053rd	004X302XGGGXcirc	6.17	21.75	0.00	Fail
053rd	004X305XGGGXcirc	4.44	19.00	0.00	Fail
053rd	007X303XAAAXoff	7.72	30.00	0.00	Fail

053rd	007X306XAAAXoff	8.08	26.75	0.00	Fail
064th	001X401XAAAXeatXdr	3.33	6.50	0.00	Fail
064th	002X404XDDDXWC	2.91	10.50	0.00	Pass
064th	004X402XGGGXcirc	7.36	22.50	0.00	Fail
064th	004X405XGGGXcirc	4.77	20.75	0.00	Fail
064th	007X403XAAAXoff	8.29	31.00	0.00	Fail
064th	007X406XAAAXoff	8.63	27.00	0.00	Fail

Tab. 41 TM52_DSY2_2080_50_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.25	2.75	0.00	Pass
02Ground	004X001XGGGXcirc	2.67	11.50	0.00	Pass
02Ground	004X005XGGGXcirc	2.89	10.25	0.00	Pass
02Ground	006X007XAAAXrec	2.11	9.00	0.00	Pass
02Ground	007X002XAAAXoff	6.43	23.00	0.00	Fail
02Ground	007X006XAAAXoff	4.29	20.25	0.00	Fail
031st	001X101XAAAXeatXdr	6.07	9.00	0.00	Fail
031st	002X104XDDDXWC	3.83	13.00	0.00	Fail
031st	004X102XGGGXcirc	11.54	29.25	0.00	Fail
031st	004X105XGGGXcirc	8.13	22.75	0.00	Fail
031st	007X103XAAAXoff	13.85	41.25	0.00	Fail
031st	007X106XAAAXoff	12.13	32.75	0.00	Fail
042nd	001X201XAAAXeatXdr	10.85	12.00	0.00	Fail
042nd	002X204XDDDXWC	8.90	21.50	0.00	Fail
042nd	004X202XGGGXcirc	18.49	36.25	0.00	Fail
042nd	004X205XGGGXcirc	14.10	34.75	0.00	Fail
042nd	007X106XAAAXoff	17.16	41.00	1.75	Fail
042nd	007X203XAAAXoff	18.55	48.00	0.00	Fail
053rd	001X301XAAAXeatXdr	13.11	13.25	0.00	Fail
053rd	002X304XDDDXWC	11.68	25.50	0.00	Fail
053rd	004X302XGGGXcirc	22.78	44.50	0.00	Fail
053rd	004X305XGGGXcirc	17.43	36.25	0.00	Fail
053rd	007X303XAAAXoff	20.28	53.00	0.00	Fail
053rd	007X306XAAAXoff	20.83	48.50	3.00	Fail
064th	001X401XAAAXeatXdr	13.97	13.75	0.00	Fail
064th	002X404XDDDXWC	12.73	26.50	0.00	Fail

064th	004X402XGGGXcirc	25.27	47.00	0.00	Fail
064th	004X405XGGGXcirc	19.64	40.75	0.00	Fail
064th	007X403XAAAXoff	21.73	53.50	1.00	Fail
064th	007X406XAAAXoff	21.96	48.50	6.25	Fail

Tab. 42 TM52_DSY2_2080_90_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	004X005XGGGXcirc	0.00	0.00	0.00	Pass
02Ground	006X007XAAAXrec	0.12	1.25	0.00	Pass
02Ground	007X002XAAAXoff	1.77	5.75	0.00	Pass
02Ground	007X006XAAAXoff	0.27	3.00	0.00	Pass
031st	001X101XAAAXeatXdr	0.58	1.50	0.00	Pass
031st	002X104XDDDXWC	0.00	0.00	0.00	Pass
031st	004X102XGGGXcirc	2.10	7.00	0.00	Pass
031st	004X105XGGGXcirc	0.00	0.00	0.00	Pass
031st	007X103XAAAXoff	4.07	13.00	0.00	Fail
031st	007X106XAAAXoff	3.95	11.50	0.00	Fail
042nd	001X201XAAAXeatXdr	1.99	3.25	0.00	Pass
042nd	002X204XDDDXWC	1.54	4.00	0.00	Pass
042nd	004X202XGGGXcirc	5.26	11.25	0.00	Fail
042nd	004X205XGGGXcirc	3.10	8.00	0.00	Fail
042nd	007X106XAAAXoff	5.84	18.00	0.00	Fail
042nd	007X203XAAAXoff	5.72	19.50	0.00	Fail
053rd	001X301XAAAXeatXdr	2.63	4.25	0.00	Pass
053rd	002X304XDDDXWC	2.38	5.00	0.00	Pass
053rd	004X302XGGGXcirc	6.47	16.75	0.00	Fail
053rd	004X305XGGGXcirc	4.77	9.75	0.00	Fail
053rd	007X303XAAAXoff	6.37	20.75	0.00	Fail
053rd	007X306XAAAXoff	6.70	22.50	0.00	Fail
064th	001X401XAAAXeatXdr	2.80	4.50	0.00	Pass
064th	002X404XDDDXWC	2.71	5.75	0.00	Pass
064th	004X402XGGGXcirc	7.00	19.00	0.00	Fail
064th	004X405XGGGXcirc	5.20	11.75	0.00	Fail
064th	007X403XAAAXoff	7.30	22.75	0.00	Fail

064th	007X406XAAAXoff	7.05	23.75	0.00	Fail

Tab. 43 TM52_DSY3_2080_10_openable_windows

Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.00	0.00	0.00	Pass
02Ground	004X001XGGGXcirc	0.42	2.75	0.00	Pass
02Ground	004X005XGGGXcirc	1.70	4.75	0.00	Pass
02Ground	006X007XAAAXrec	1.88	4.50	0.00	Pass
02Ground	007X002XAAAXoff	4.07	11.25	0.00	Fail
02Ground	007X006XAAAXoff	3.08	6.50	0.00	Fail
031st	001X101XAAAXeatXdr	3.49	3.75	0.00	Pass
031st	002X104XDDDXWC	2.48	5.50	0.00	Pass
031st	004X102XGGGXcirc	6.62	17.00	0.00	Fail
031st	004X105XGGGXcirc	4.95	10.25	0.00	Fail
031st	007X103XAAAXoff	6.25	21.25	0.00	Fail
031st	007X106XAAAXoff	6.23	19.00	0.00	Fail
042nd	001X201XAAAXeatXdr	4.99	6.50	0.00	Fail
042nd	002X204XDDDXWC	4.54	11.75	0.00	Fail
042nd	004X202XGGGXcirc	10.02	23.00	0.00	Fail
042nd	004X205XGGGXcirc	8.16	21.00	0.00	Fail
042nd	007X106XAAAXoff	9.46	27.75	0.00	Fail
042nd	007X203XAAAXoff	9.05	30.75	0.00	Fail
053rd	001X301XAAAXeatXdr	6.07	8.00	0.00	Fail
053rd	002X304XDDDXWC	5.37	14.50	0.00	Fail
053rd	004X302XGGGXcirc	12.61	30.75	0.00	Fail
053rd	004X305XGGGXcirc	9.52	23.00	0.00	Fail
053rd	007X303XAAAXoff	11.18	32.75	0.00	Fail
053rd	007X306XAAAXoff	12.00	34.25	2.25	Fail
064th	001X401XAAAXeatXdr	6.43	8.50	0.00	Fail
064th	002X404XDDDXWC	6.37	16.75	0.00	Fail
064th	004X402XGGGXcirc	13.39	33.25	0.00	Fail
064th	004X405XGGGXcirc	10.71	26.50	0.00	Fail
064th	007X403XAAAXoff	12.58	34.75	0.25	Fail
064th	007X406XAAAXoff	12.74	35.00	3.00	Fail

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Block	Zone	Criterion 1 (%)	Criterion 2 (K.hr)	Criterion 3 (hr)	Pass/Fail
01LowerGround	001XLG01XAAA1Xatr	0.00	0.00	0.00	Pass
01LowerGround	002XLG02XDDDXWC	0.00	0.00	0.00	Pass
01LowerGround	003XLG03XFFFXst	0.00	0.00	0.00	Pass
01LowerGround	004XLG04XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	004XLG05XFFFXcirc	0.00	0.00	0.00	Pass
01LowerGround	005XLG06XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG07XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG08XGGGXlig	0.00	0.00	0.00	Pass
01LowerGround	005XLG09XGGGXlig	0.00	0.00	0.00	Pass
02Ground	001X003XAAA1Xatr	0.00	0.00	0.00	Pass
02Ground	002X004XDDDXWC	0.80	5.00	0.00	Pass
02Ground	004X001XGGGXcirc	4.17	19.50	0.00	Fail
02Ground	004X005XGGGXcirc	3.91	19.00	0.00	Fail
02Ground	006X007XAAAXrec	2.98	13.25	0.00	Pass
02Ground	007X002XAAAXoff	6.40	23.75	0.00	Fail
02Ground	007X006XAAAXoff	3.76	21.25	0.00	Fail
031st	001X101XAAAXeatXdr	5.48	10.50	0.00	Fail
031st	002X104XDDDXWC	5.92	21.00	0.00	Fail
031st	004X102XGGGXcirc	11.94	35.25	0.00	Fail
031st	004X105XGGGXcirc	9.10	32.25	0.00	Fail
031st	007X103XAAAXoff	15.26	38.75	1.50	Fail
031st	007X106XAAAXoff	13.24	36.25	2.50	Fail
042nd	001X201XAAAXeatXdr	10.59	13.25	0.00	Fail
042nd	002X204XDDDXWC	9.49	28.50	0.00	Fail
042nd	004X202XGGGXcirc	21.75	46.25	0.00	Fail
042nd	004X205XGGGXcirc	15.09	39.50	0.00	Fail
042nd	007X106XAAAXoff	20.43	45.75	10.50	Fail
042nd	007X203XAAAXoff	20.83	46.75	7.50	Fail
053rd	001X301XAAAXeatXdr	12.76	14.75	0.25	Fail
053rd	002X304XDDDXWC	12.83	32.00	0.00	Fail
053rd	004X302XGGGXcirc	25.60	49.00	0.00	Fail
053rd	004X305XGGGXcirc	20.62	46.25	0.00	Fail
053rd	007X303XAAAXoff	23.21	50.75	11.75	Fail
053rd	007X306XAAAXoff	23.45	51.25	13.75	Fail
064th	001X401XAAAXeatXdr	13.58	15.75	0.75	Fail
064th	002X404XDDDXWC	13.97	33.25	0.00	Fail
064th	004X402XGGGXcirc	27.59	54.00	8.50	Fail
064th	004X405XGGGXcirc	22.59	48.25	0.00	Fail
064th	007X403XAAAXoff	24.62	55.25	14.25	Fail
064th	007X406XAAAXoff	24.49	53.25	15.25	Fail

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Appendix D

Embodied Carbon results[15]

Materials Embodied Carbon and Inventory	Area (m2)	Embodied Carbon (kgCO2)
DF_Glass - cellular sheet	54.3	387.9
Plasterboard (wallboard)	9360.9	31125.2
Membrane	903.6	0.0
Cement/plaster/mortar - plaster	1382.2	3151.3
Cement/plaster/mortar - gypsum plaster	8377.8	17781.9
Miscellaneous materials - plastic tiles	6146.3	326553.8
Metals - zinc	903.6	31405.1
Glass - cellular sheet	9.6	9.1
EPS 10 mm	6146.3	2304.9
Clay underfloor 750 mm	903.6	223642.0
EPS 85 mm	903.6	3755.9
EPS 50 mm	903.6	1694.3
Concrete roof/floor slab	7953.5	611169.5
Flooring screed	903.6	5204.8
Floor/Roof Screed	6146.3	59004.6
Cast Concrete	3.4	81.6
Brickwork Inner	1382.2	206772.0
Brickwork Outer	1382.2	33600.5
Sub Total		1557644.0

Constructions Embodied Carbon and Inventory	Area (m2)	Embodied Carbon (kgCO2)
DF_Flat_Roof	903.6	74934.5
DF_External Wall_EAST	54.3	9959.2
DF_External door	4.8	9.2
DF_External Wall_West	1327.8	237521.7
DF_ Internal Wall	4680.5	31125.2
DF_Intermediate floor	6146.3	916544.9
DF_Ground floor insulated	903.6	287468.1
Sub Total	14024.4	1557644.39

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[15] Results from DesignBuilder

Glazing Embodied Carbon and Inventory	Area (m2)	Embodied Carbon (kgCO2)
DF_ Double glazing_6mm/10mm	588.1	21172.1
Sub Total	588.1	21172.1

Building Total	**14612.5**	**1.578.735,7**