Evaluation of resilient cooling strategies in different European climates events

María Robles Dopazo

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Master thesis

STUDENT REPORT

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María Robles Dopazo

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Chen Zhang
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Abstract—

This study evaluates resilient cooling strategies for office buildings across three distinct European climates—Copenhagen, Rome, and London—under various weather scenarios, including current, future, and extreme conditions, as well as two occupancy loads. Using dynamic simulations, the research examines the effectiveness of individual strategies in mitigating overheating, maintaining thermal comfort and optimizing energy efficiency. Strategies such as north-facing facades, smaller window areas, halved g-values, and natural ventilation consistently demonstrated strong performance across diverse contexts, whereas larger window areas and reduced U-values often undermined resilience. Double occupancy scenarios presented greater challenges than the moderate temperature increases expected in the long-term future, with heatwaves emerging as the most severe test of resilience. This work provides a robust framework for designing climate-resilient buildings and delivers actionable insights to decision-makers for assessing and implementing adaptive cooling strategies. By emphasizing context-specific solutions and sustainability, these findings contribute to future-proofing the built environment against escalating climate risks.

Preface

This thesis represents the culmination of a journey to examine the resilience of building design in the context of a rapidly changing climate. Driven by a strong passion for combining technical expertise with creativity, this work embodies the goal of making a meaningful contribution to the built environment through energy optimization and sustainable design.

This study would not have been possible without the invaluable guidance and support of my supervisors, Chen and Per, whose expertise have been invaluable throughout this process. I would also like to extend my gratitude to my peers, who have provided constructive feedback and inspiration along the way.

Aalborg University, January 8, 2025

María Robles Dopazo

María Robles Dopazo
mroble22@student.aau.dk

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Abbreviations

ACH Air Changes per Hour
AHD Annual HVAC System Total Primary Energy Use per Conditioned Floor Area
AWD Ambient Warmness Degree
BR18 Building Regulations 2018
DoS Degree of shock
EPD Environmental Product Declaration
EX Extreme weather event
FU Functional Unit
GWP Global Warming Potential
HE Hours of Exceedance
HT Historical weather event
HW Heat wave event
IEQ Indoor Environmental Quality
IOD Indoor Overheating Degree
IPCC Intergovernmental Panel on Climate Change
KPI Key Performance Indicators
LCA Life Cycle Assessment
LT Long-term weather event
N/A Not applicable
OEF Overheating Escalation Factor
SC Shading Coefficient
Δrec Shock recovery rate
Cp Specific Heat Capacity
TMY Typical Meteorological Year
UK United Kingdom
WWR Window-to-wall ratio

Chapter 1

Introduction

1.1 Background

1.1.1 Climate Change: Impact on Buildings and Occupants

Climate change is driving a global shift in environmental conditions, characterized by rising temperatures and an increase in extreme weather events such as heatwaves, floods, and droughts. These changes have profound implications for buildings and their occupants, impacting not only the structural integrity of buildings but also their energy performance and occupant comfort.

Historically, buildings have been designed based on historical climate conditions, and as climate events become more severe, these conventional designs will struggle to meet new demands. This shift results in increased energy consumption for heating and cooling, altered operational conditions, reduced system efficiency, and potential damage to structural integrity. For occupants, these effects manifest as increased discomfort, health risks, decreased productivity, and escalating economic costs. Furthermore, the energy-intensive measures required to mitigate these effects can increase greenhouse gas emissions, further exacerbating environmental challenges [1].

Among the various climate risks, heat poses one of the most significant threats to human well-being. According to the Intergovernmental Panel on Climate Change (IPCC), the average global temperature has already risen by 1.2°C above pre-industrial levels. If current trends continue, temperatures are expected to increase by 1.5°C between 2030 and 2052, with considerable regional variation [2]. This rise will have severe consequences for human health, leading to increased mortality and morbidity, particularly in urban areas, where the population is projected to increase 68% by 2050 [3].

Cities are particularly vulnerable to heatwaves due to the urban heat island effect, which can raise temperatures by 1-3°C compared to surrounding rural areas[4][5]. Between 1995 and 2015, heatwaves were responsible for 27% of weather-related deaths, and with continued warming, both the intensity and duration of heatwaves will increase, along with atmospheric humidity, often surpassing human tolerance [1].

1.1.2 Resiliency in the Built Environment

Resilience refers to the capacity of a building and its systems to function as intended despite the natural hazards imposed by climate change [6]. As the frequency and intensity of climate events continue to increase, resilience in building design has become a critical consideration.

Numerous studies emphasize the urgent need for buildings to be future-proofed against climate-related stresses [7], enabling them to withstand not only current conditions but also the more extreme weather events projected for the future.

Resilient strategies, particularly those focused on maintaining thermal comfort, are crucial. While heating demands are expected to decline across Europe due to rising temperatures, cooling demands are anticipated to increase significantly, particularly in Southern and Central European regions [8]. This underscores the necessity of developing cooling strategies that effectively mitigate overheating while ensuring energy efficiency.

This paper focuses in the concept of "climate change overheating resistivity", defined as the ability of building cooling strategies to mitigate the indoor overheating risks associated with increasing outdoor thermal severity in a changing climate [9]. It evaluates how well a building can adapt to changing external conditions while continuing to meet occupant's needs and maintaining comfort. Furthermore, the paper takes a comprehensive approach to resilience by integrating energy performance and thermal performance considerations, while also addressing environmental impact.

1.1.3 Sustainability

Designing buildings for resilience is essential, but it must be carefully balanced with sustainability goals to prevent an increased environmental footprint. Over-designing for resilience—such as installing high-capacity cooling systems—can lead to higher energy consumption and increased embodied carbon. To address this, it is vital to adopt low-energy, adaptive solutions that ensure occupant comfort without exacerbating climate change.

In 2019, the global building and construction sectors were responsible for 35% of total energy consumption and 38% of energy-related CO2 emissions [7]. By 2021, energy demand increased 4% compared to 2020, while CO2 emissions increased by 5% from 2020 and 2% from 2019, accounting for approximately 37% of total CO2 emissions [10]. In the European Union, buildings accounted for 40% of final energy consumption and 36% of CO2 emissions [11]. These figures underscore the significant challenge of meeting the EU's climate targets, which include reducing greenhouse gas emissions by 55% by 2030. Achieving these goals requires buildings to drastically lower their energy use and environmental impact while enhancing their resilience to future climate risks [11].

Buildings are both contributors to and vulnerable to climate change, highlighting the necessity of addressing a dual challenge: reducing emissions while improving resilience. This requires the integration of both adaptation and mitigation strategies to limit the environmental impact of buildings while simultaneously enhancing their ability to withstand future climate stresses [12].

1.2 Literature Review

A literature review was conducted to examine the state of the art regarding the impact of various cooling strategies on overheating under different conditions, with an additional focus on exploring the evaluation systems employed.

1.2.1 Strategies Review

This subsection aims to review the cooling strategies examined in various studies across different building types, conditions, locations, and climate events. The studies included both qualitative and quantitative assessments.

Research has primarily focused on passive, active, and hybrid cooling solutions. Passive strategies include measures such as reflective materials, green facades, and natural ventilation [1]. Active strategies encompass various approaches, including adiabatic cooling, ground source cooling, and radiant cooling [13].

A more detailed review was conducted to assess various passive strategies for addressing heat, with a focus on minimizing heat gain or removing excess heat from indoor spaces. The review prioritized strategies relevant to the Northern Hemisphere, particularly Europe, and those applicable in the early stages of design. It focused on building elements most susceptible to heat-related climate risks, such as the outer envelope, roof, and HVAC systems [14]. Strategies unrelated to building design—such as surrounding buildings, vegetation, or occupant behavior—were excluded, along with those incompatible with BSim simulations.

Several passive cooling strategies were selected to evaluate their impact in overheating and energy consumption in buildings. A comprehensive list of the reviewed strategies can be found in Appendix A.

The strategies reviewed in the literature were analyzed under various conditions, as outlined below:

- Building types: the studies addressed both new and existing structures, including residential buildings [15] [16] [17], non-residential buildings [17] [9], building stocks [18], and low energy buildings [19] [20]. These analyses also considered the associated system controls.
- Climate zones: the strategies were examined across different climatic contexts, including continental regions, such as Belgium [15], China [16], and England [19]. Specific cities were also analyzed, such us the ones referenced by ASHRAE climate zones [17], Milan [21], Brussels [18], and Dublin and Budapest [20].
- Climate events: The studies explored the impact of heatwaves [15] [16] [21] [17] [18] [13], projected historical, short-term and future weather scenarios [17] [18] [20], as well as power outages [13].

1.2.2 Evaluation Method Review

The strategies outlined in the studies mentioned above were assessed using various categories and Key Performance Indicators (KPI)s to measure their resilience:

- Energy performance: metrics such as cooling or heating loads were considered [17] [21] [18].
- Thermal comfort: a range of indicators was used, including Hours of Exceedance (HE), Indoor Overheating Degree (IOD), Ambient Warmness Degree (AWD), Overheating Escalation Factor (OEF) [16] [17] [18] [9]; absorptivity and recovery time [15]; the Mediterranean Outdoor Comfort Index (MOCI) [21]; and metrics for overheating and overcooling metrics [20].
- Sustainability impact: indicators such as total Global Warming Potential (GWP), represented by annual CO2-equivalent emissions per conditioned floor area [17], and emissions related to cooling and ventilation systems [18].

Additionally, several frameworks provide tools and guidance for implementing resilience strategies, taking the analysis further. These include REDi (Resilience-based Earthquake Design Initiative), developed by Arup [22]; R4RE (Resilience for Real Estate), created by the Observatoire de l'Immobilier Durable (OID) [23]; and RELi (Resilience Action List), a rating system integrated with LEED, adopted by the U.S. Green Building Council [24].

1.2.3 Research Gap

The strategies discussed in previous studies had been analyzed under diverse building types, conditions, weather events, and locations, limiting the ability to directly compare their performance. This project aims to address this gap by consolidating relevant strategies and evaluating them under consistent conditions, enabling a valid comparison and facilitating their future application as recommendations for building design.

Furthermore, this work allows for the analysis of strategies across various weather events and diverse European locations. It incorporates the impact of double occupancy and examines multiple variations for each strategy. Additionally, it integrates the environmental impact of the proposals, a consideration often overlooked in other studies.

1.3 Research Approach and Hypothesis

This study adopts a hypothesis-based approach, focusing on identifying and investigating certain passive and early design strategies for evaluating building resilience to overheating under certain conditions.

Parting from the research questions, the goal is to evaluate and assess the impact of various resilient cooling strategies in a room across different climate zones. The evaluation system will examine how these strategies perform under distinct climate events and different occupancy levels. The primary goal is to understand how cooling strategies contribute to building resilience across diverse contexts, helping decision-makers optimize solutions for thermal comfort, energy efficiency and sustainability.

The key research questions guiding this methodology are:

- How do resilient cooling strategies perform across different European climate zones?
- What is the impact of these strategies under different weather conditions?
- How do varying occupancy levels influence the effectiveness of the cooling strategies?
- How does an improvement in a specific cooling strategy affect or improve the overall building resilience under these conditions?

Chapter 2

Methodology

2.1 Framework

The specific research questions guiding this methodology are as follows:

- How do resilient cooling strategies perform across different European climate zones (Copenhagen, Rome, and London)?
- What is the impact of these strategies under current, future, and extreme hot weather years?
- What is the impact of these strategies under a heat wave event?
- How do varying occupancy levels (normal and double) influence the effectiveness of the cooling strategies?
- How does an improvement in a specific cooling strategy affect or improve the overall building resilience under these conditions?

The simulation framework is structured to explore the effects of various strategies under different location, climate events and occupation conditions.

2.1.1 Simulation Program

The simulations will be conducted using Bsim, a building simulation software that enables detailed modeling of thermal performance and energy use in buildings. Bsim facilitates the input of various parameters, including climate data, occupancy profiles, systems, and specific building characteristics, allowing for a comprehensive evaluation of resilient cooling strategies.

2.1.2 Building Type

The model or case room in this project will be a simplified version of an office space — a single-zone. By keeping the model simple, the need for assumptions is minimized, making the results more flexible and applicable to various scenarios. The aim is to enable the extrapolation of the findings to various room configurations and sizes, as well as to scale the results from the room level to the entire building level.

The defined room is a rectangular space with dimensions of 12 meters in length, 6 meters in depth, and 3 meters in height, resulting in a total area of 72 m^2. This layout can serve various purposes, such as an office, classroom, or meeting room, by defining different heat loads and usage profiles. The room features two windows, with the larger window (denominated window no.1. with an area of 7.2 m^2) oriented south and the smaller one (denominated window no.2, with an area of 2.4 m^2) facing east.

The building envelope constructions are designed based on ASHRAE requirements for various climate zones and common practices across Europe [25]. The systems and their operational schedules are established in accordance with Danish and European regulations, following standards such as Building Regulations 2018 (BR18) [26], ISO 17772 [27], and ISO 18523 [28], as well as typical practices in Europe [29]. See Appendix B.1 for more detail on the building envelope and the systems.

The model was validated to ensure it accurately represents a typical office room across various European climates; details of this validation are provided in Appendix C.

2.1.3 Climate Zones

The project focuses on European climates, as this allows for consistent assumptions regarding building characteristics such as geometry, layout, construction, usage, and systems. Three cities with distinct climates were selected based on ASHRAE climate classifications: Copenhagen (Denmark), Rome (Italy), and London (United Kingdom (UK)), representing climate zones 5A (cool humid), 3A (warm humid), and 4A (mixed humid), respectively [25]. These locations were chosen due to their high current and expected population growth [30], and their projected increases in cooling demand, as highlighted in [8]. The study indicates that under the projected Representative Concentration Pathway 4.5 (RCP4.5), a medium greenhouse gas (GHG) emission scenario defined by the IPCC, the mean cooling demand change ratio is expected to increase significantly, reaching 2.47 for Copenhagen, 1.36 for Rome, and 2.39 for London.

2.1.4 Climate Events

The project aims to assess various climatic events to evaluate the performance of strategies under both current and future weather conditions. This analysis will rely on two types of data: measured and projected. Measured data refers to observations from actual climate records, while projected data is generated using climate models rather than direct observations. Projected data simulates future climate conditions based on global and regional climate models, adjusted through "bias correction" methods to align with historical local climate records. These projections are based on future climate scenarios, such as the representative concentration pathways (RCPs) defined by the IPCC.

The project will employ different weather files [31]:

- Typical weather conditions: the Typical Meteorological Year (TMY) weather files provided by the IEA EBC Annex 80 [17][30]:
  - Historical TMY files are created from measured climate data, representing average weather conditions for the historical period (2001–2020). This weather event is going to be denoted as **Historical weather event (HT)** throughout the paper.
  - Future TMY files are based on projected data from the IPCC RCP8.5 scenario, covering the long-term future (2081–2100) timeframe. This weather event is going to be denoted as **Long-term weather event (LT)** throughout the paper.
- Extreme weather conditions: weather files for analyzing a building's thermal performance during extreme heat events, which are expected to become increasingly significant in the coming decades:
  - Historical extreme weather data includes the near extreme DRY dataset provided by the Build department [32], representing the hottest year recorded in Denmark. This weather event is going to be denoted as **Extreme weather event (EX)** throughout the paper.
  - Future extreme weather data includes the heat wave files provided by the IEA EBC Annex 80 [17][30], based on the IPCC RCP8.5 scenario. These heat wave files focus on extreme events, capturing the most severe and prolonged heatwaves within each reference period. In particular, this paper will focus on the heatwaves files representing the year with the most severe heatwave in the long-term future for the selected climate zones. This weather event is going to be denoted as **Heat wave event (HW)** throughout the paper.

Together, the datasets summarized above, enable a comprehensive assessment of the efficiency and resilience of building solutions in response to climate change across various climate events:

2.1.5 Occupancy Loads

Two occupancy scenarios will be tested to evaluate the impact of internal heat gains on building performance: normal occupancy, representing standard office room usage, and double occupancy, where internal heat gains are doubled due to increased occupancy. The normal occupancy scenario will be based on ISO 17772 standards [27], which specify a heat load of 11.8 W/m^2 for people in a single-office room.

2.2 Resilient Cooling Strategies

In the literature review 1.2.1, several passive strategies were identified for their potential to reduce overheating and energy consumption in buildings, their applicability across Europe, and their suitability for early-stage design. Based on this review, a set of passive strategies was selected to further analysis their impact on resilience to climate change across different regions and climate events, under the specific scope and conditions of this project. This paper focuses exclusively on passive strategies, aiming to evaluate their potential to enhance thermal comfort without relying on energy-intensive mechanical systems, thereby aligning with sustainable and low-carbon building design principles. The strategies selected to be evaluated in this paper are the following:

1 **Facade orientation and window placement:** Evaluating the impact of positioning the main facade and largest window to face north, south, west, and east in order to balance minimizing heat gain and controlling direct sunlight in summer, while allowing light and warmth in winter.

2 **Thermal capacity of facade concrete:** Analyzing the impact of using concrete with increased Specific Heat Capacity (Cp).

3 **Window-to-wall ratio (WWR):** Analyzing the impact of varying the WWR of the largest window, while proportionally adjusting the size of the smallest window.

4 **External solar shading:** Evaluating shading mechanisms with varying Shading Coefficient (SC) and user control options, such as user-operated controls during operational hours or automatic controls, compared to scenarios without solar shading.

5 **Window g-value:** Analyzing the impact of having a solar heat gain coefficient for windows that is half of what is required by regulation.

6 Window U-value: Analyzing the impact of having a thermal transmittance for windows that is half of what is required by regulation.

7 Natural ventilation: Analyzing the impact of various Air Changes per Hour (ACH) for natural ventilation, compared to the absence of natural ventilation.

8 Night cooling: Testing passive cooling strategies applied either throughout the entire night (7 hours) or during specific hours (4 hours) before operational hours, compared to scenarios without night cooling.

The focus was placed on understanding the individual impact of each strategy, rather than on simulating different strategy combinations. This approach enables a larger number of strategies to be studied under various conditions. With a clear understanding of individual impacts, reasonable assumptions can be made about their combined effects.

Table 2.1 displays the strategies and variables selected for evaluation, among with the current baseline value. The values for the actual implementation in Bsim can be seen in Appendix B.2

Table 2.1: Summary of strategies and its variables analyzed in this paper, among the defined baseline. Not applicable (N/A) indicates that the strategy is inactive or not present in the model.

	Strategy	Baseline		Variable
1	Facade and window orientation	South	*1a*	West
			1b	North
			1c	East
2	Concrete Cp	Cp=800	*2a*	Cp=1200
3	WWR	20%	*3a*	40%
			3b	10%
4	Solar shading	N/A	*4a*	SC=0.5; manual control
			4b	SC=0.15; manual control
			4c	SC=0.5; automatic control
5	g-value	Min. requirement	*5a*	Half min. requirement
6	U-value	Min. requirement	*6a*	Half min. requirement
7	Natural ventilation ACH	N/A	*7a*	ACHmax=2
			7b	ACHmax=5
			7c	ACHmax=10
8	Night cooling	N/A	*8a*	7h (22-5h)
			8b	4h (1-5h)

2.3 Simulation Scenarios

Simulations are designed to address the research questions through targeted scenarios. They will evaluate the performance of each cooling strategy across a combination of three climate zones, four climate events, and two occupancy levels. This approach results in multiple scenarios that capture a diverse range of conditions:

- Climate zones: Copenhagen, Rome, and London.
- Climate events: HT, LT, EX and HW event.
- Occupancy: Normal and double occupancy.

Table 2.2 presents the total number of potential scenarios for analysis, emphasizing those that will be examined in this paper. Below is a summary of the key scenarios to be analyzed for all locations:

1 and 2 Current climate (HT), normal and doubled occupancy: the baseline model, along with all selected strategies, will be tested under normal and doubled occupancy across all locations. This scenario aims to explore the influence of geographic location on performance today.

3 and 4 Future climate (LT), normal and doubled occupancy: the baseline model, along with all selected strategies, will be tested under normal and doubled occupancy across all locations. This scenario aims to explore the influence of geographic location on performance in hotter future climate conditions.

5 Extreme hot (EX), normal occupancy for Copenhagen: Strategies will be evaluated under extreme, one-off events at a single location. This analysis will employ the same set of strategies to assess how a climate event like this can influence performance.

6 Heatwave (HW), normal occupancy: a detailed examination of how selected strategies perform during extreme heatwave conditions will be conducted. This scenario will also examine the effect of geographic location on performance.

In total, 14 scenarios (across 3 climate locations, 4 climate events and 2 occupancy loads) will be tested across 16 strategies, resulting in 224 simulations.

2.4 Performance Indicators

The objective of this project is to evaluate the performance of various cooling strategies by assessing their resilience, measured through a building's and its systems ability to maintain thermal comfort and energy efficiency; their carbon footprint,

Table 2.2: Overview of scenarios selected for evaluation, in a certain climate zone (Copenhague, Rome, London), climate events (HT, LT, EX and HW) and occupancy loads (N-normal, D-double). Scenarios in green are going to be evaluated for all the strategies, and scenarios uncolored are not going to be evaluated.

Climate event	Occupancy	Scenarios		
		Copenhagen	Rome	London
HT	N	C-HT-n	R-HT-n	L-HT-n
HT	D	C-HT-d	R-HT-d	L-HT-d
LT	N	C-LT-n	R-LT-n	L-LT-n
LT	D	C-LT-d	R-LT-d	L-LT-d
EX	N	C-EX-n		
EX	D	C-EX-d		
HW	N	C-HW-n	R-HW-n	L-HW-n
HW	D	C-HW-d	R-HW-d	L-HW-d

and their recovery rate after a HW. The effectiveness of these strategies will be assessed using a set of KPIs defined by IEA EBC Annex 80 [33][34], as well as references from [35] and [36] for annual calculations. For the HW event, periodic KPIs will be established based on guidelines from [15] and [37].

The KPIs will be categorized into three groups to assess the performance of strategies in terms of thermal comfort, energy performance, sustainability, and outdoor conditions.

Regarding thermal comfort:

- **HE:** refers to the number of hours within a given period when the room's operative temperature exceeds the comfort limit temperature. It will be calculated for overheating (representing hours above 26 °C) in summer, during occupied hours.
- **OEF:** measures the resistance of the building toward the increasing outdoor air temperature, and its calculated as the IOD divided by the AWD as seen in Equation 2.1 [38].
  - **IOD:** quantifies indoor overheating in an indoor space as the cumulative difference between the operative temperature and the comfort limit whenever the operative temperature exceeds this limit, calculated over the occupied hours, as seen in Equation 2.2 [38].
  - **AWD:** measures outdoor heat stress, defined later under "outdoor conditions".

$$\text{OEF} = \frac{IOD}{AWD} \tag{2.1}$$

$$\text{IOD} = \frac{\sum_{i=1}^{N} \left[\left(T_{op,i} - T_{comf} \right) * t_i \right]}{\sum_{i=1}^{N} t_i} \tag{2.2}$$

Where:

$T_{op,i}$	Operative temperature at time step i	[°C]
$T_{comf,i}$	Comfort temperature set at 26°C	[°C]
N	Total occupied hours	[hours]
t	Time step	[hours]

- **Shock recovery rate (Δrec):** evaluates HW events by determining the time required for a space to stabilize after overheating. It measures the rate of temperature change as it decreases from its peak (T_{max}) to a comfortable threshold (T_{alert}) and remains there for at least 24 hours. It is calculated for the HW event according to Equations 2.3, 2.4 and 2.5, and its graphical representation can be seen in Figure 2.1 from [37].

$$\Delta_{rec} = \frac{\Delta T}{\Delta_{t,rec}} \tag{2.3}$$

$$\Delta_T = T_{max} - T_{alert} \tag{2.4}$$

$$\Delta_{t,rec} = t_{below} - t_{max} \tag{2.5}$$

Where:

T_{max}	Highest recorded temperature	[°C]
T_{alert}	Target temperature to achieve comfort. Defined as 28°C	[°C]
t_{below}	Time when temperature reaches T_{alert}	[h]
t_{max}	Time when T_{max} is recorded	[h]

The thermal comfort thresholds referenced above follow the specifications in [27], which defines four categories of Indoor Environmental Quality (IEQ) based on levels of expectation. A normal expectation level corresponds to IEQ Category II (IEQ_{II}). For an office, the maximum allowable operative temperature in summer is 26ºC.

Regarding energy performance:

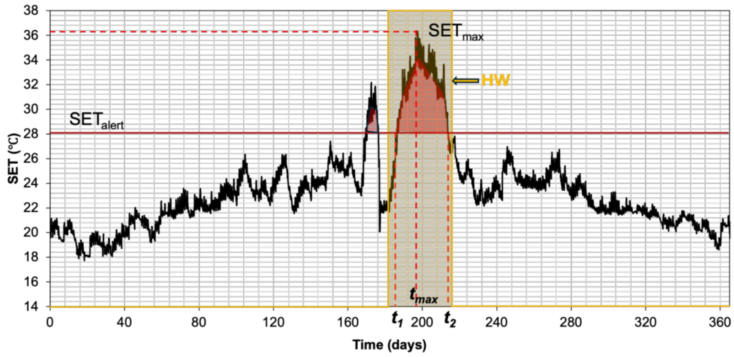


Figure 2.1: Illustration of the recovery rate parameters during a HW event [37].

- **Annual HVAC System Total Primary Energy Use per Conditioned Floor Area (AHD):** represents the total annual energy consumption of the cooling, heating and ventilation systems, normalized by the conditioned floor area.

Regarding sustainability:

- **GWP:** measure for climate change in terms of radiative forcing or a mass-unit of greenhouse gas. The assessment includes the impact of energy consumption for cooling, heating and ventilation and the influence of building elements that are added or modified compared to the baseline. It is measured in kg CO_2eq/m^2.

Regarding the outdoor conditions:

- **AWD:** quantifies outdoor heat stress by determining the total hours during which the outdoor air temperature exceeds a fixed threshold. It is calculated by summing hourly differences between the outdoor air temperature and a fixed threshold of 18 °C during the summer, as seen in Equation 2.6 [38]. The base temperature of 18°C is selected because it is lower than any minimum summer comfort temperature limit, ensuring that an AWD greater than zero indicates heat stress.

$$\text{AWD} = \frac{\sum_{i=1}^{N} \left[(T_{a,i} - T_b) * t_i \right]}{\sum_{i=1}^{N} t_i} \tag{2.6}$$

Where:

T_a	Outdoor dry-bulb air temperature	[°C]
T_b	Base temperature set at 18°C	[°C]
N	Number of occupied houts in which T_a>T_b	[hours]
t	Time step	[hours]

- **Degree of shock (DoS)** to evaluate the HW events: product of a HW's severity and duration, along with the maximum temperature reached during the event, as described in Equation 2.7. The DoS provides a standardized method for comparing HWs [37].

$$\text{doS} = \frac{T_{\text{db,HW}} - T_{\text{db,TMY}}}{T_{\text{db,TMY}}} \cdot \frac{t_{\text{HW}}}{t_{\text{HW,longest}}} \tag{2.7}$$

Where:

$T_{db,HW}$	Average dry bulb temperature during the HW	[°C]
$T_{db,TMY}$	Average TMY dry bulb temperature during the HW period	[°C]
t_{HW}	Duration of the HW	[hours]
$t_{HW,longest}$	Duration of the longest HW at any time period	[hours]

2.4.1 Resilience Evaluation System

Several of the previously outlined KPIs will be used to evaluate the resilience of strategies concerning thermal comfort and energy efficiency. This section integrates these metrics into a single resilience indicator, with weights assigned according to their relative significance to overall resilience.

The weighting system for the resilience indicator is defined as follows:

- Thermal comfort (HE and OEF), is a critical component of resilience and has a significant weight.
  - HE: direct measure of comfort, accounting for **37.5%** of the overall weight.
  - OEF: reflects the building's adaptability by linking indoor and outdoor conditions, it is weighted at **31.25%**.
- Energy performance of the HVAC system (AHD), has a moderate impact and contributes **31.25%** to the indicator.

This resilience indicator will be complemented with GWP and Δrec parameters when applicable.

2.5 KPIs Scoring System

To evaluate the previously defined KPIs, a standardized scoring system was established across all indicators. The scoring system ranges from 0 to 10 points, with 10 representing the highest performance and 0 indicating the lowest performance.

The purpose of the defined scoring system is to facilitate the interpretation and understanding of the results. However, it will not be a universal or standardized system, but rather one created specifically for this project. More information about the scoring system definition can be found in Appendix D.

For each KPI, minimum and acceptable values were determined based on agreed or defined general parameters or benchmarks. The scores for intermediate values are calculated using a linear relationship between the defined extremes.

- **HE**: the highest performance, represented by a score of 10 points, is achieved when HE is 0%, indicating that no hours exceed 26°C. Conversely, the lowest acceptable performance, with a score of 0 points, occurs when HE surpasses 5%, meaning that 5% of the total operational hours in summer have an operative temperature above 26°C. The 5% threshold was established in accordance with [35], which specifies a permissible range of deviation within thermal comfort limits. The formula and corresponding graph for this linear relationship are provided in Table 2.3 and Figure 2.2.

Table 2.3: Scoring equation for HE.

HE	Score (points)
$\leq$ 0%	10
0% < HE < 5%	$-200 * HE + 10$
$\geq$ 5%	0

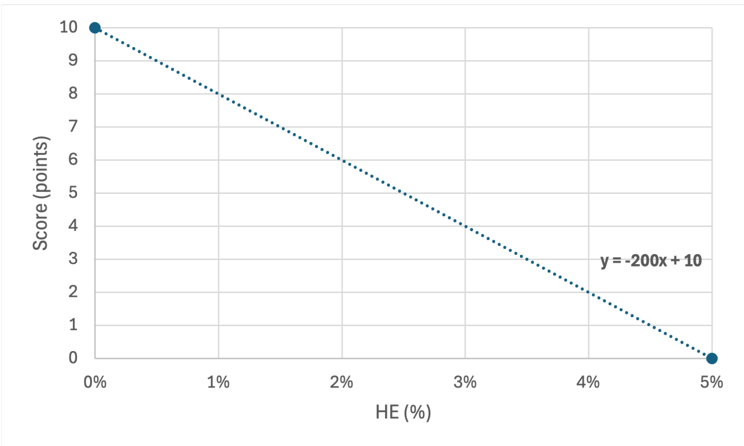


Figure 2.2: HE scoring diagram.

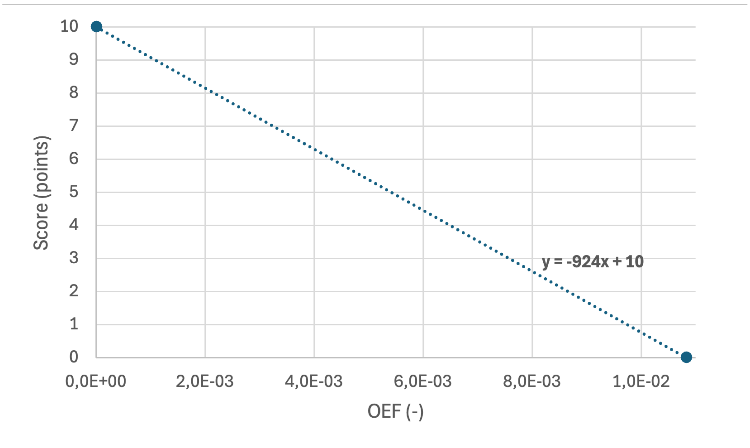
- **OEF**: the best performance (10 points) is achieved when the IOD equals 0, indicating no indoor temperatures exceeding 26°C, which results in an OEF of 0. In contrast, the lowest performance score (0 points) is assigned to the scenario with the highest OEF. This occurs when the comfort temperature of 26°C is exceeded by 0.5°C for 5% of the summer operational hours (which aligns with the allowable deviations from thermal comfort limits defined by [35]), resulting in an IOD of 0.3; and for the minimum AWD in each location across all weather events (defined in Table D.1). The formula and corresponding graph for this linear relationship are provided in Table 2.4 and Figure 2.3.

Table 2.4: Scoring equation for OEF.

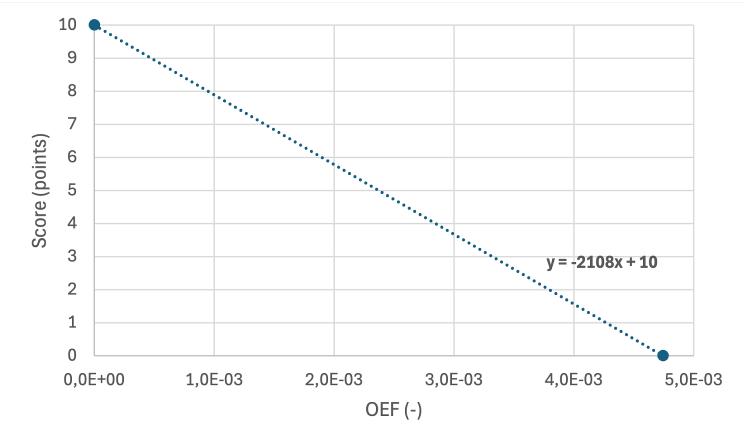
OEF	Score (points)
Copenhagen	
≤ 0	10
$0 < \text{OEF} < 0.011$	$-924 * OEF + 10$
≥ 0.011	0
Rome	
≤ 0	10
$0 < \text{OEF} < 0.005$	$-2108 * OEF + 10$
≥ 0.005	0
London	
≤ 0	10
$0 < \text{OEF} < 0.009$	$-1144 * OEF + 10$
≥ 0.009	0

- **AHD**: Actual residential energy consumption data from the European Union [39] and floor area data from the EU Building Stock Observatory [40] for each location are used to, following the approach in [41], consider these values as the average energy consumption, assigning them a score of 2.5 points, which establishes a baseline for potential improvement up to 10 points. The minimum energy consumption, and consequently the highest score for AHD, is achieved when the room has zero energy consumption. The maximum score is then extrapolated from the minimum and average values. The formula and corresponding graph for this linear relationship are provided in Table 2.5 and Figure 2.4.
- **GWP**: The maximum and minimum acceptable values for the GWP are determined by defining the maximum and minimum quantities of the elements included in the carbon footprint assessment and multiplying them by their respective emission factors. For energy consumption, the maximum and minimum acceptable values align with those defined for AHD, ranging from zero to the maximum calculated value. According to Artelia [29], the WWR in rooms ranges from 10% to 65%, which will be considered as the assumed maximum and minimum quantities. The minimum solar shading occurs when there is none, while the maximum is when the entire window area

(a) OEF scoring diagram for Copenhagen



(b) OEF scoring diagram for Rome



(c) OEF scoring diagram for London

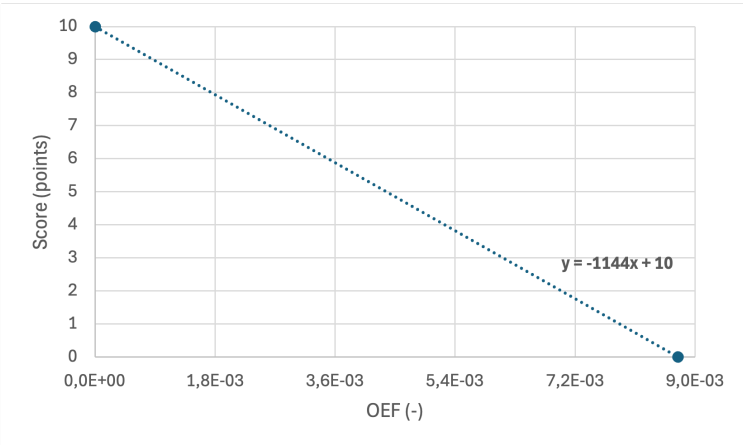
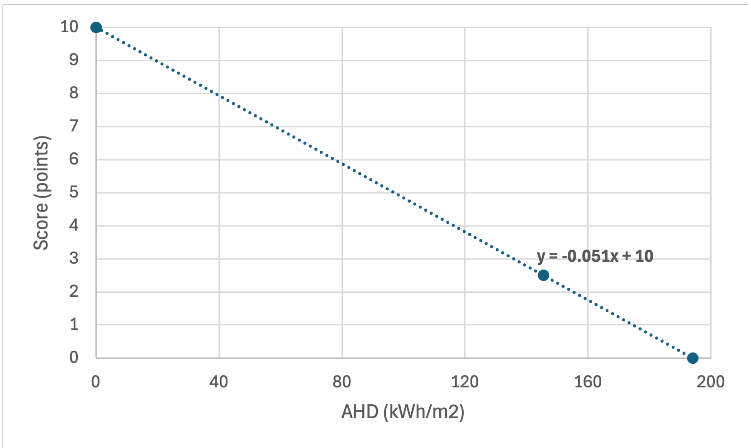
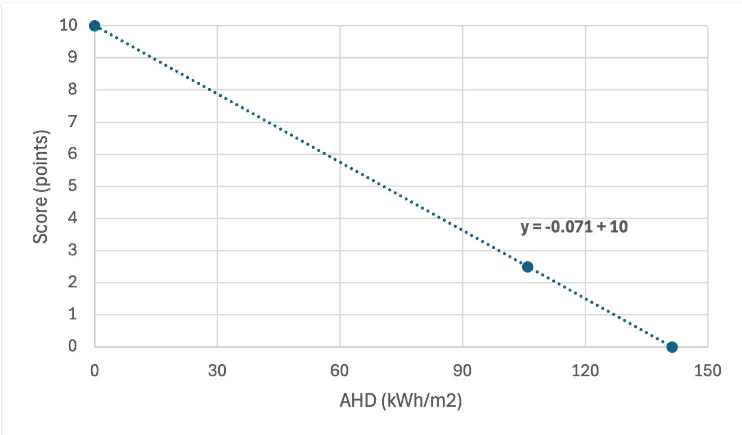


Figure 2.3: OEF scoring diagram.

(a) AHD scoring diagram for Copenhagen



(b) AHD scoring diagram for Rome



(c) AHD scoring diagram for London

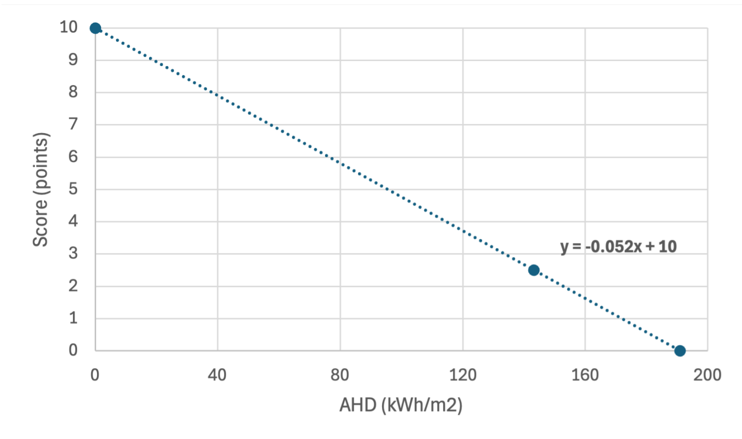


Figure 2.4: AHD scoring diagram.

Table 2.5: Scoring equation for AHD.

AHD	Score (points)
Copenhagen	
≤ 0	10
0 < AHD < 194.06	$-0.051 * AHD + 10$
≥ 194.06	0
Rome	
≤ 0	10
0 < AHD < 141.30	$-0.071 * AHD + 10$
≥ 141.30	0
London	
≤ 0	10
0 < AHD < 190.95	$-0.052 * AHD + 10$
≥ 190.95	0

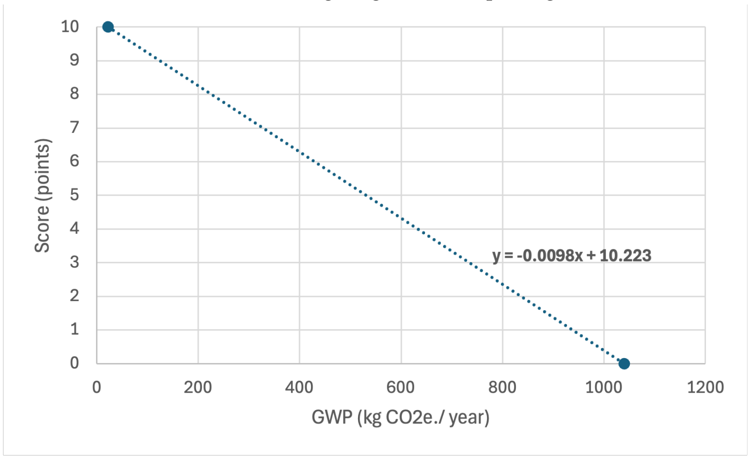
is covered. The formula and corresponding graph for this linear relationship are provided in Table 2.6 and Figure 2.5.

Table 2.6: Scoring equation for GWP.

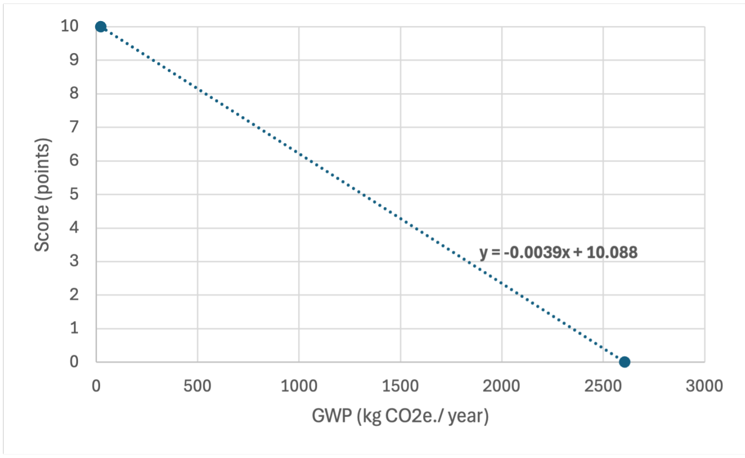
GWP	Score (points)
Copenhagen	
≤ 22.6	10
22.6 < GWP < 1040.3	$-0.0098 * GWP + 10.223$
≥ 1040.3	0
Rome	
≤ 22.6	10
22.6 < GWP < 2604.8	$-0.0039 * GWP + 10.088$
≥ 2604.8	0
London	
≤ 22.6	10
22.6 < GWP < 2741.9	$-0.0037 * GWP + 10.083$
≥ 2741.9	0

- **Δrec**: measures the recovery rate performance of the room. The minimum occurs when the peak temperature during the HW matches the threshold, while the maximum occurs at a maximum temperature with the shortest recovery time. A recovery time below one day is going to be considered acceptable in this paper. The formula and corresponding graph for this linear relationship are shown in Table 2.7 and Figure 2.6.

(a) GWP scoring diagram for Copenhagen



(b) GWP scoring diagram for Rome



(c) GWP scoring diagram for London

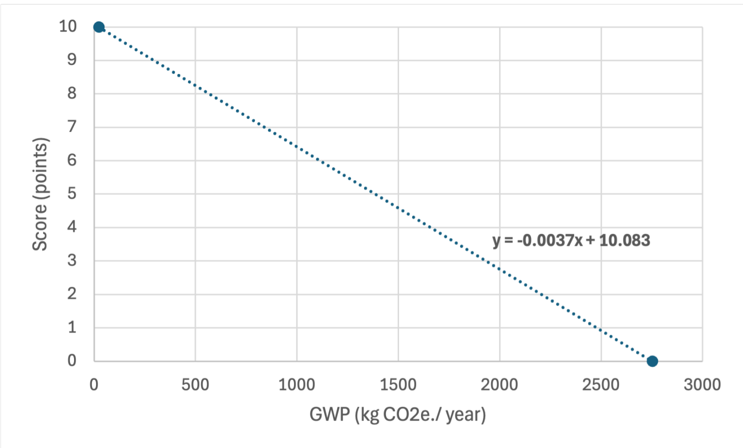
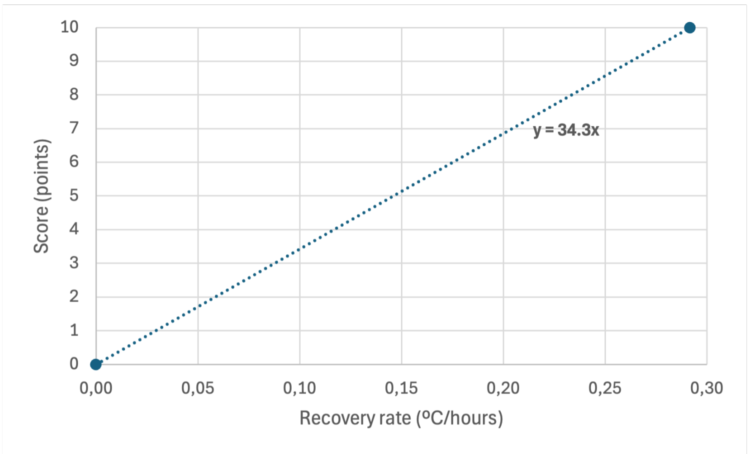
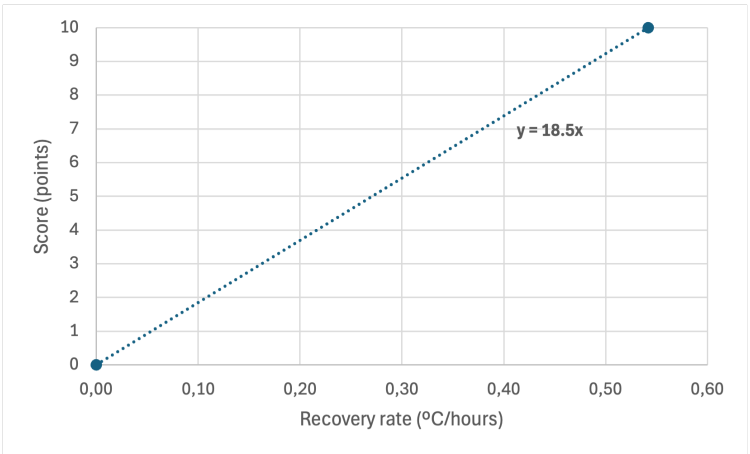


Figure 2.5: GWP scoring diagram.

(a) Recovery rate scoring diagram for Copenhagen



(b) Recovery rate scoring diagram for Rome



(c) Recovery rate scoring diagram for London

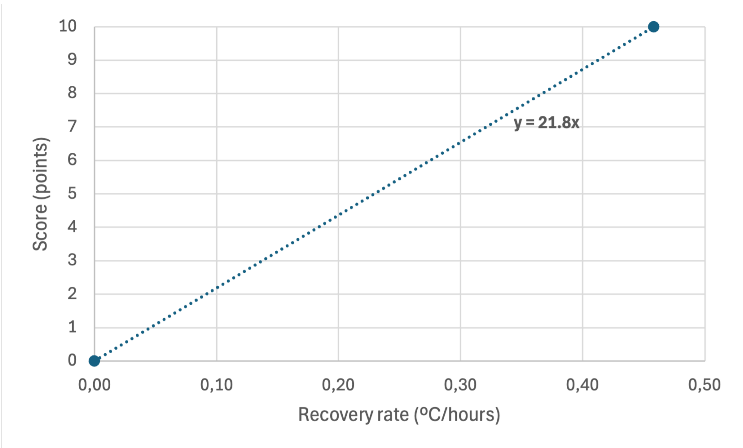


Figure 2.6: Recovery rate scoring diagram.

Table 2.7: Scoring equation for Δrec.

Δrec	Score (points)
Copenhagen	
≤ 0	0
0 < Δrec < 0.29	$34.3 * Delta, rec$
≥ 0.29	10
Rome	
≤ 0	0
0 < Δrec < 0.54	$18.5 * Delta, rec$
≥ 0.54	10
London	
≤ 0	0
0< Δrec < 0.46	$21.8 * Delta, rec$
≥ 0.46	10

2.6 Data Analysis

Each scenario will be analyzed for its impact on resilience by comparing the performance of each strategy against its baseline, defined as the office building without any added resilience strategies (in the same location, climate event, and occupancy load). The performance of each strategy will be evaluated using the selected KPI, with particular focus on:

- Effectiveness across climate zones: Identifying whether certain strategies consistently perform well across all locations, or if their impact varies depending on the climate.
- Performance under extreme events: Evaluating whether strategies that perform well under current conditions also handle future and extreme conditions effectively.
- Impact of occupancy: Investigating how the increased internal heat loads (double occupancy) affect the performance of cooling strategies, especially under future climate scenarios.

The evaluation system will provide a comparative analysis of the strategies impacts, offering a clear understanding of which solutions demonstrate the greatest resilience under the tested conditions and the lowest environmental impact. Additionally, it will include a complementary assessment of the strategies recovery rates during a HW.

Chapter 3

Results

3.1 Outdoor Conditions

This section analyzes the outdoor conditions across the three studied locations under various climate events. The events examined include: HT, representing current weather; LT, representing future weather; EX, denoting the hottest year; and HW, representing a HW event. Understanding how outdoor conditions vary under these events is essential for interpreting the effectiveness of strategies under changing climate scenarios.

Annual and Summer Climate Conditions

Figures 3.1, 3.2, 3.3, and 3.4 illustrate the yearly evolution of outdoor temperature, global solar radiation, relative humidity, and wind speed for the studied events across all locations.

Additionally, Table 3.1 provide the mean values of outdoor conditions throughout the year, emphasizing the observed increases or decreases. Across all locations and climate events, outdoor temperatures are projected to rise. Notably, Copenhagen experiences the most significant increase, with a 30% difference between HT and EX, while London and Rome show increases of 25% and 21% between HT and HW, respectively. Relative humidity and solar irradiance exhibit minor variations, with both increases and decreases observed across the three locations. Wind speed is anticipated to increase in Copenhagen and decrease in Rome and London.

Table 3.2 focuses on the mean values for the summer season. During the summer, the mean outdoor temperatures for the HT scenario are 14.45°C, 16.46°C, and 21.75°C in Copenhagen, London, and Rome, respectively. The data indicate a general increase in outdoor temperatures across the three locations and weather events in the summer. The rise in temperatures from HT to HW in London and Rome is 23% and 22%, respectively, while the increase in Copenhagen is 25%. Currently, solar radiation is highest in Rome, followed by Copenhagen and London. However, future weather events indicate a decreasing trend in Rome, while it increases in Copenhagen and London. Across the scenarios, solar radiation generally decreases for all three locations in the LT scenario and during the HW scenario specifically in Rome. Conversely, solar radiation increases in the EX scenario in Copenhagen and in the HW scenario in both Copenhagen and London. Currently, wind speed is highest in London, followed by Rome and Copenhagen. In the future, the overall trend across all scenarios shows a decrease in wind speed, except for the EX scenario in Copenhagen.

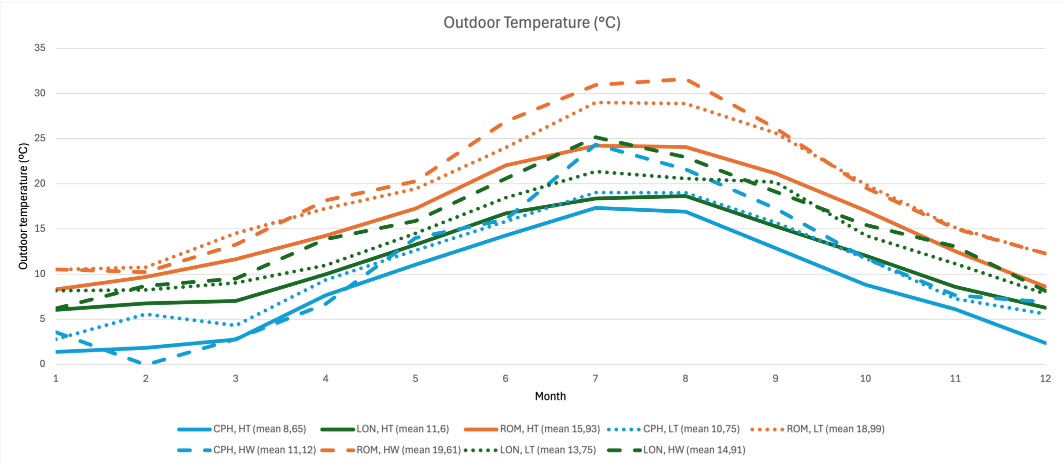


Figure 3.1: Mean and yearly evolution of outdoor temperature for different climate events in each location.

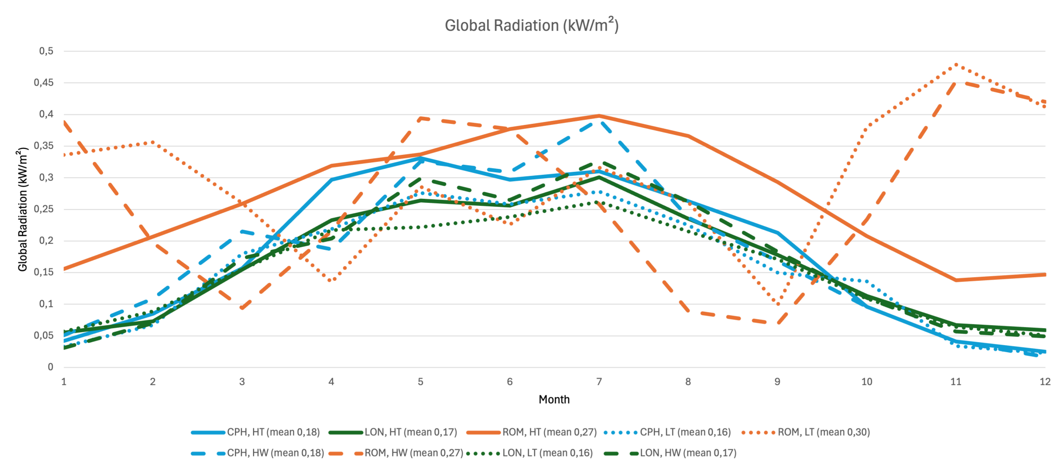


Figure 3.2: Mean and yearly evolution of solar radiation for different climate events in each location.

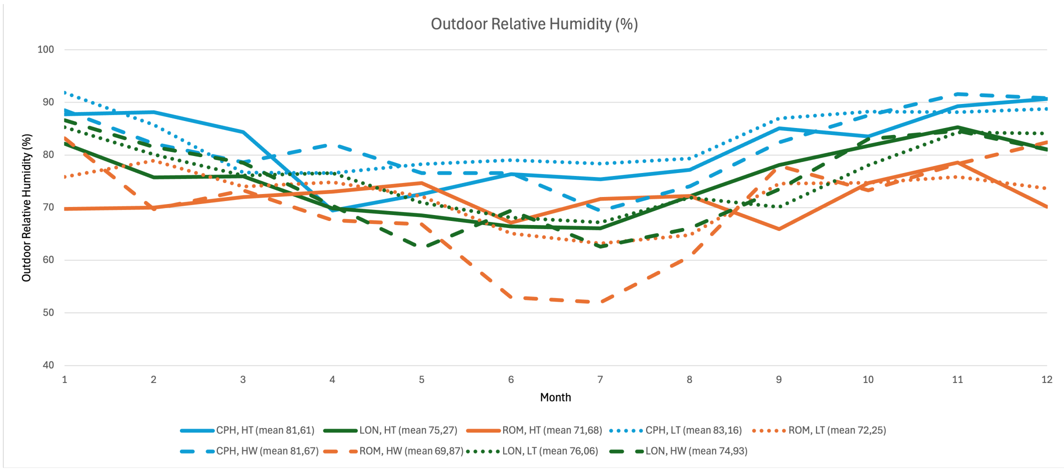


Figure 3.3: Mean and yearly evolution of outdoor relative humidity for different climate events in each location.

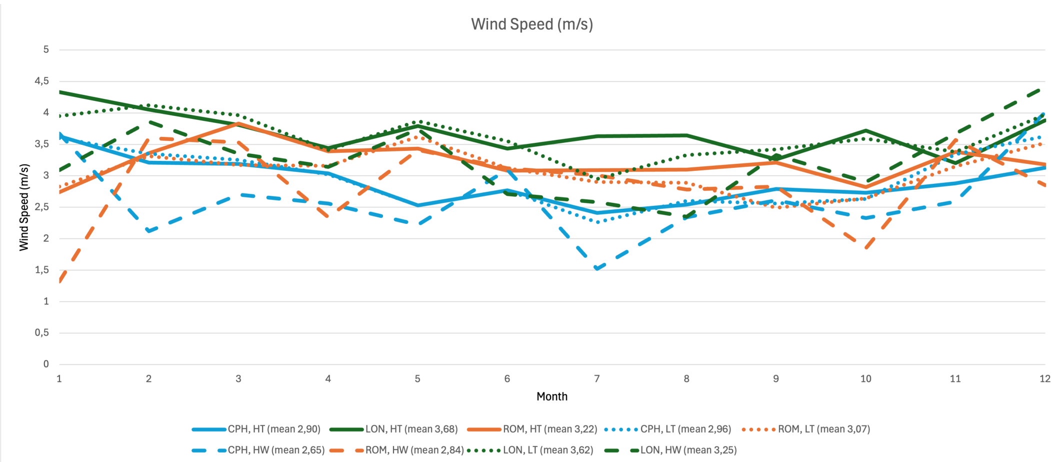


Figure 3.4: Mean and yearly evolution of wind speed for different climate events in each location.

Table 3.1: Mean values in outdoor conditions during the year for the different weather events in each location. Cells in red represent an increase, while cells green represent a decrease, in comparison with the historical data (HT).

City		Copenhagen	Rome	London
Temperature (°C)	HT	8.65	15.93	11.6
	LT	10.75	18.99	13.75
	EX	11.71	-	-
	HW	11.12	19.62	14.91
Solar irradiance (kW/m²)	HT	0.18	0.27	0.17
	LT	0.16	0.30	0.16
	EX	0.18	-	-
	HW	0.19	0.27	0.17
Wind speed (m/s)	HT	2.90	3.22	3.68
	LT	2.96	3.08	3.62
	EX	3.51	-	-
	HW	3.51	2.85	3.25
Relative humidity (%)	HT	81.61	71.68	75.27
	LT	83.16	72.25	76.06
	EX	80.96	-	-
	HW	81.67	69.87	74.93

AWD Evaluation

AWD quantifies outdoor heat stress by summing hourly differences above a fixed 18°C threshold in summer (Equation 2.6). The 18°C base ensures any AWD above 0 indicates heat stress, as it is below minimum summer comfort limits. The AWD for the three locations across the studied weather events can be seen in Table 3.3.

The AWD across the three locations is 2.31 in Copenhagen, 2.86 in London, and 5.27 in Rome. Compared to Copenhagen, the AWD is 21% higher in London and 78% higher in Rome. In Copenhagen, the LT scenario shows a 7% increase compared to the HT, followed by a 43% rise for the EX and a 63% increase for the HW, relative to the HT. In Rome, the LT scenario shows a 45% increase compared to the HT, while the HW represents a 60% increase relative to the HT. In London, the LT scenario increases by 30% compared to the HT, with a 52% rise for the HW relative to the HT.

HW Evaluation

The HW event is further quantified by the DoS, combining its severity, duration, and peak temperature reached during the event (as seen in Equation 2.7).

Table 3.2: Mean values in outdoor conditions during the summer months from May to September, for the different weather events in each location. Cells in red represent an increase, while cells green represent a decrease, in comparison with the historical data (HT).

City		Copenhagen	Rome	London
Temperature (°C)	HT	14.45	21.75	16.46
	LT	16.44	25.39	19.01
	EX	17.78	-	-
	HW	18.65	27.17	20.73
Solar irradiance (kW/m²)	HT	0.28	0.35	0.25
	LT	0.24	0.24	0.22
	EX	0.30	-	-
	HW	0.29	0.24	0.27
Wind speed (m/s)	HT	2.61	3.18	3.55
	LT	2.54	3.00	3.42
	EX	2.65	-	-
	HW	2.36	3.03	2.94
Relative humidity (%)	HT	77.32	70.33	70.26
	LT	80.39	67.96	69.67
	EX	75.04	-	-
	HW	75.81	62.09	66.79

The HW detection method follows the approach defined by [42] (and shown in Figure 3.5), regarded as the most suitable for building applications according to [43] and [30]. This method identifies a HW when the Spic threshold (99.5th percentile) is reached. The HW begins once the Sdeb threshold (97.5th percentile) is exceeded and ends when temperatures fall below the Sint threshold (95th percentile) or remain below Sdeb for three consecutive days. For more detail on the HW calculation see Appendix E.

Information about the HW tested for the three locations is summarized in Table 3.4. The DoS varies across Copenhagen, Rome, and London, with Copenhagen showing the highest value (0.21), followed by London (0.14), and the lowest in Rome (0.09).

Copenhagen's DoS is elevated due to its very high severity (0.21), driven by a low $T_{db,TMY}$, and a duration factor of 1, which reflects the longest heatwave at any period (54 days) and a maximum $T_{db,HW}$ of 35°C. Rome's low DoS results from minimal severity (0.09), attributed to its very high $T_{db,TMY}$, and a duration factor of 1, which reflects the longest heatwave at any period (96 days) and a maximum $T_{db,HW}$ of 41°C. London's intermediate DoS is caused from high severity (0.12), influenced by its relatively high $T_{db,HW}$ and $T_{db,TMY}$, and a duration factor of 1, indicating the longest heatwave duration at any period (41 days), with a maximum

Table 3.3: AWD for the three locations across the studied weather events.

Climate location	Period	AWD [°C]
Copenhagen	HT	2.31
	LT	2.48
	EX	3.59
	HW	4.44
Rome	HT	5.27
	LT	8.31
	HW	9.78
London	HT	2.86
	LT	3.86
	HW	4.88

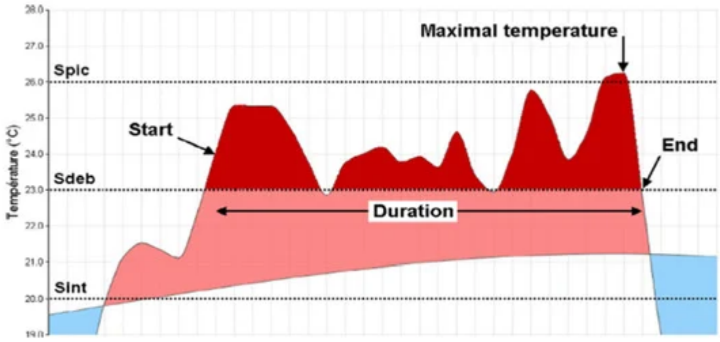


Figure 3.5: Heatwave detection from [42].

$T_{db,HW}$ of 39°C.

3.2 Evaluation of Thermal Comfort, Energy Performance, and Sustainability Impact of Strategies

3.2.1 Thermal Comfort and Energy Consumption

Assessment and Results of HE

HE represents the total hours within a specified period during which the room's operative temperature surpasses the comfort limit. Using Bsim software, it will be calculated for overheating by determining the hours when the room temperature exceeds 26°C in summer, then dividing this value by the total occupied hours during the same period.

Table 3.4: Determination of the HW duration, the DoS, and the peak temperature reached during the HW (Max Tdb,HW).

Climate location	Period	Duration (days)	doS	Max Tdb,HW (C)
Copenhagen	Long-term	54	0.21	35
Rome	Long-term	96	0.09	41
London	Long-term	41	0.12	39

The detailed evaluation of HE performance for each strategy across the three locations and climate events is presented in Appendix F. The HE score across the strategies in the three locations can be seen in Figure 3.6.

In summary, strategies perform best in Rome, followed by London, and worst in Copenhagen. Across all locations, the HW exhibits the lowest overall performance, followed by scenarios with double occupancy, the EX event, LT, and HT. This trend reflects the results observed in the outdoor conditions associated with these scenarios in Section 3.1, which indicated that outdoor temperatures are projected to increase across all locations and events compared to HT.

Across Copenhagen, Rome, and London, strategy performance for HE revealed common trends alongside location-specific variations. Strategies such as north-facing facade (1b), smaller window area (3b), and halved g-value (5a) consistently emerged as top performers across all locations and weather events, showcasing strong resilience to overheating. The inclusion of night cooling (8-series) also demonstrated robust performance. Conversely, having a larger window area (3a) universally underperformed, consistently scoring 0 points across all scenarios and locations, emphasizing the sensitivity of window area on thermal comfort. Similarly, strategies such as halved U-value (6a) and west-facing facade (1a) also performed poorly in the most intense scenarios (the ones with double occupancy or the HW event).

In **Copenhagen**, performance declined sharply during extreme events, with the HW scenario yielding the lowest average scores (1.5 points), highlighting the city's susceptibility to overheating due to its high DoS (ass seen in Section 3.1). Strategies such as north-facing facade (1b), smaller window area (3b), halved g-value (5a), and solar shading measures (4b and 4c) proved effective, maintaining scores above the medium threshold even under challenging conditions.

Rome experienced less pronounced performance variability due to its higher cooling capacity and reduced solar radiation in future scenarios. This led to generally strong results across all strategies, with top performers including west and north facing facade (1a and 1b), increased Cp (2a), smaller window area (3b), halved g-value (5a), and the inclusion of night cooling (8-series). Even during HW, most strategies performed above the baseline, except for the persistently poor performance of having a larger window area (3a).

London followed trends similar to Copenhagen, with high scores under normal conditions and notable declines during HW, where the average dropped to 5.7 points. Strategies such as north-facing facade (1b), smaller window area (3b), and halved g-value (5a) continued to excel, while larger window areas (3a), east-facing facade (1c), and halved U-value (6a) performed poorly, often below the baseline.

A key observation is that double occupancy often has a more significant negative impact on performance than a "hotter" climate. For example, comparing HT with double occupancy (HT-d) to LT with normal occupancy (LT-n) reveals a greater performance decline in the former. Additionally, performance under EX with normal occupancy (EX-n) in Copenhagen appears comparable to that of HT-d.

As outlined in Section 3.1, global solar radiation is expected to decrease in certain events and locations, which could improve the performance of window-related strategies (e.g., size, glazing properties, orientation) in LT compared to HT. This can be seen happening in Copenhagen.

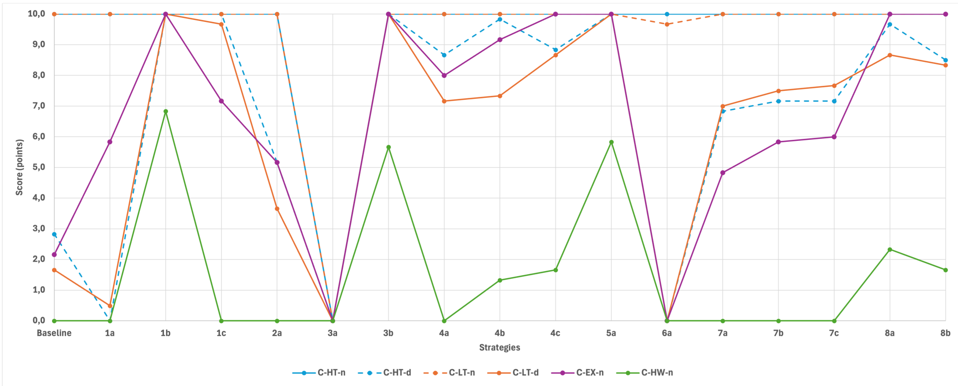
Assessment and Results of OEF

The OEF evaluates a building's resistance to rising outdoor air temperatures and is calculated as the ratio of IOD to AWD as seen in Equation 2.1. The IOD quantifies indoor overheating during the summer period over the occupied hours, as seen in Equation 2.2. It is computed using Bsim software as the sum of the differences between the operative temperature and the comfort limit whenever the operative temperature exceeds this limit, divided by the total occupied hours in summer. The comfort limit is set at 26°C, based on IEQ Category II (IEQ_{II}). The AWD as described in Equation 2.6 in Section 3.1, quantifies outdoor heat stress, and the calculated AWD values can be found in Table 3.3.

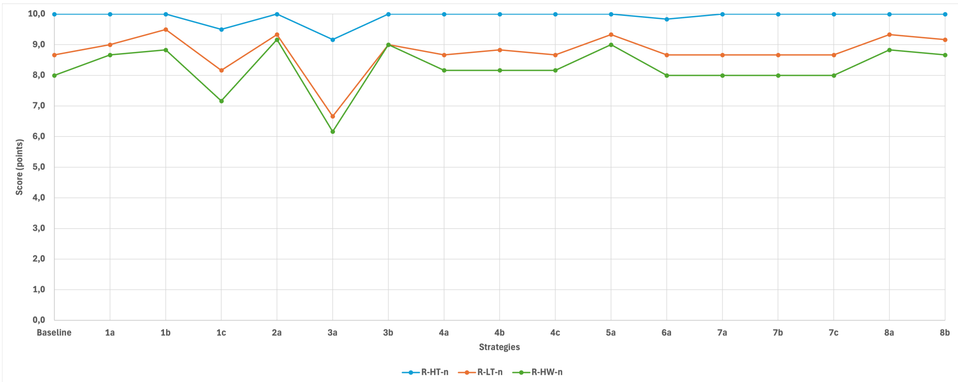
The detailed evaluation of OEF performance for each strategy across the three locations and climate events is presented in Appendix F. The OEF score across the strategies in the three locations can be seen in Figure 3.7.

Copenhagen and London show similar trends and averages in OEF and HE. Scenarios with normal occupancy (HT, LT and EX) maintain relatively high average performance across strategies (around 7–7.7 points), while double occupancy scenarios (HT, LT) and HW lead to slightly lower scores (6–6.7). These trends suggest that future and extreme weather events (LT and EX) are not drastically different from HT, but double occupancy and heatwaves (HW) significantly increase overheating risks. Rome diverges from Copenhagen and London. OEF values are con-

(a) HE score across strategies in Copenhagen



(b) HE score across strategies in Rome



(c) HE score across strategies in London

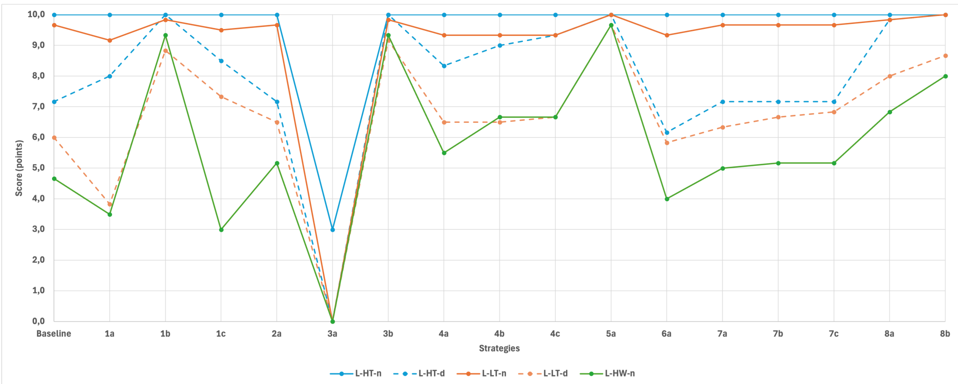


Figure 3.6: HE score across strategies in the three locations.

sistently lower if compared with HE, reflecting a greater number of hours above 26°C rather than degrees above it.

The most effective strategies across scenarios and weather events are the north-facing facade (1b), smaller window area (3b), halved g-value (5a), and including natural ventilation (particularly 7b and 7c). These strategies consistently deliver strong performance in mitigating overheating. A larger window area (3a) is the least effective strategy across all scenarios and consistently performs worse than the baseline model in all locations.

Assessment and Results of AHD

The AHD measures the annual energy demand for cooling, ventilation and heating in the room, and it is calculated with Bsim software.

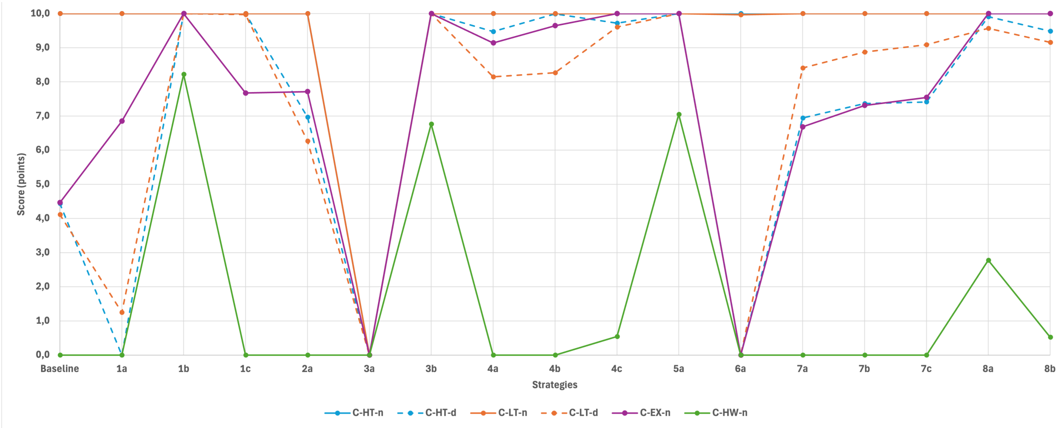
The detailed evaluation of AHD performance for each strategy across the three locations and climate events is presented in Appendix F. The AHD score across the strategies in the three locations can be seen in Figure 3.8.

In summary, AHD across Copenhagen, Rome, and London highlights the interconnectedness of thermal comfort and energy use for cooling and ventilation. Strategies such as north-facing facade (1b), halved g-value (5a), and the inclusion of natural ventilation (7-series) consistently emerged as top performers across all locations and scenarios, with 7c (including a high ACH for natural ventilation) demonstrating the most significant improvements over the baseline, particularly under challenging conditions. Conversely, a larger window area (3a) was the weakest strategy performer across all scenarios and locations, with consistent underperformance relative to the baseline.

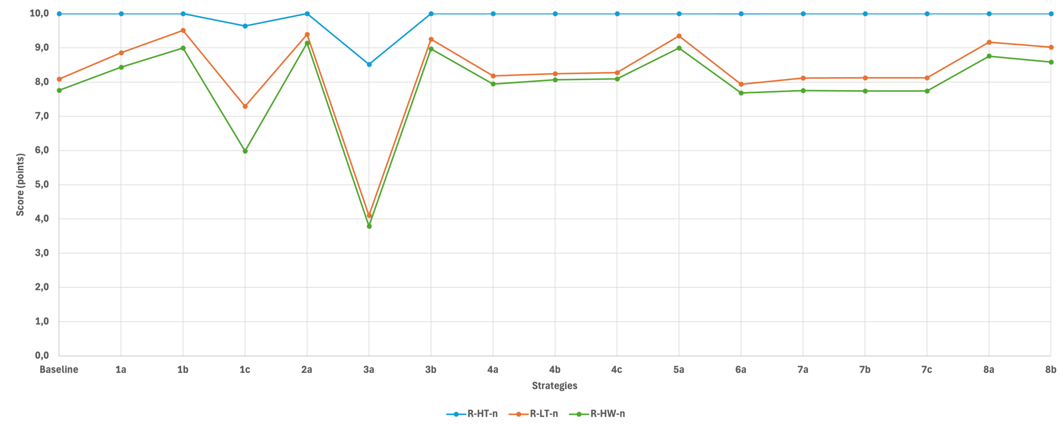
In **Copenhagen**, AHD scores were generally above average, with mean scores of 7–7.5 under normal occupancy for HT, LT, and EX. Double occupancy and HW conditions led to slight declines, with mean scores of 6.5–6.7. Strategies such as north and east facing facade (1b and 1c), smaller window area (3b), and including natural ventilation (7-series) performed well, while larger window areas (3a) and including 7h of night cooling (8a) underperformed.

Rome demonstrated excellent thermal comfort but significantly lower AHD scores, indicating a substantial dependence on cooling energy. This aligns with the projected increase in cooling demand described in [8] and discussed in Subsection 2.1.3. Mean AHD scores of 4.5, 2.6, and 2.4 for HT, LT, and HW, respectively, highlighted this trade-off. Strategies such as north-facing facade (1b), halved g-value (5a), and including a high ACH for natural ventilation (7c) delivered the best performance, while larger window area (3a) and halved U-value (6a) consistently underperformed.

(a) OEF score across strategies in Copenhagen



(b) OEF score across strategies in Rome



(c) OEF score across strategies in London

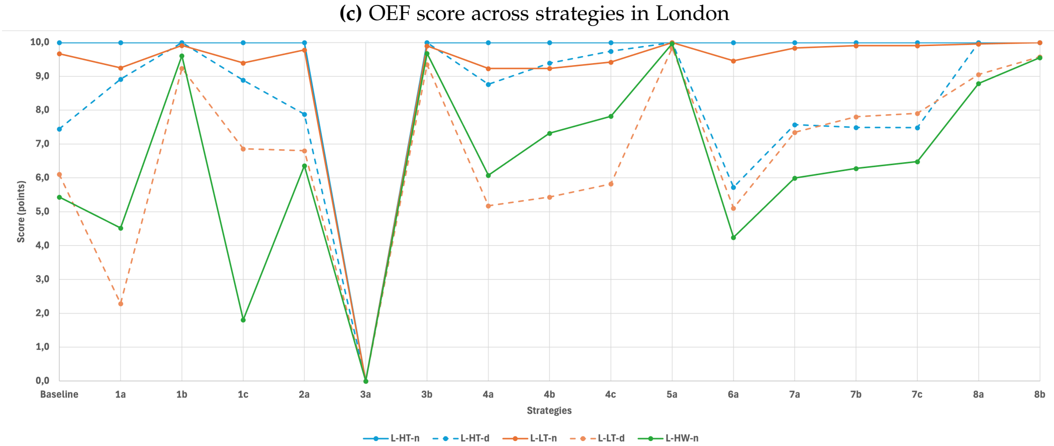


Figure 3.7: OEF score across strategies in the three locations.

London's AHD results mirrored Copenhagen's trends, with normal occupancy achieving mean scores of 7.3–7.6 for HT and LT. Double occupancy led to slightly lower scores (6–6.5), comparable to HW under normal occupancy (6.7). Strategies such as smaller window area (3b), halved g-value (5a), and including natural ventilation (7-series, and particularly 7c with a higher ACH), which offered the largest improvement over the baseline. Strategies such as halved U-value (6a) and including 7h of night cooling (8a) performed on par with the baseline under most scenarios but lagged under double occupancy.

Assessment and Results of Δrec

Δrec assesses how long a space requires to stabilize after overheating for a HW event, according to Equations 2.3, 2.4 and 2.5.

The recovery rate underscores the ability of strategies to restore comfortable indoor conditions efficiently. The detailed evaluation of Δrec performance for each strategy across the three locations and climate events is presented in Appendix F. The Δrec score across the strategies in the three locations can be seen in Figure 3.9.

In summary, across all locations, recovery rates remain low, indicating that rooms generally do not recover within a day. Copenhagen achieves the highest average recovery rate (2.8), followed by Rome (2.6) and London (2.2).

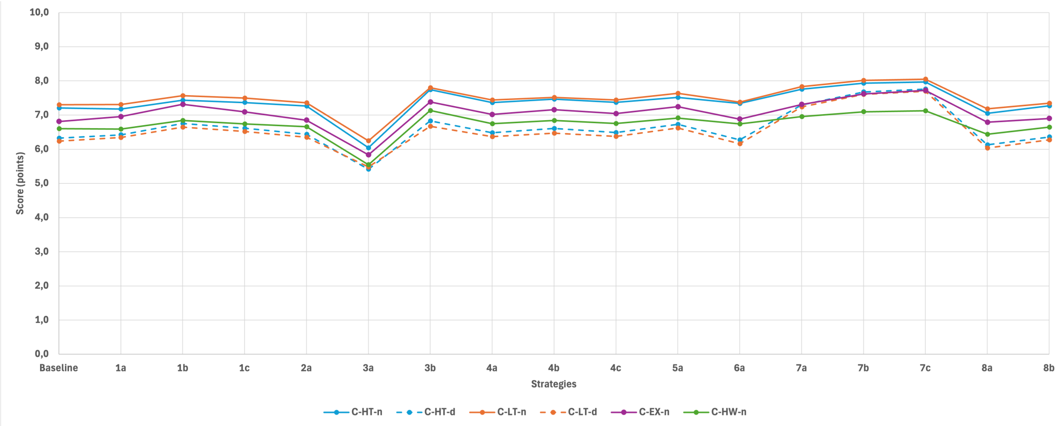
In **Copenhagen**, larger window areas (3a) emerges as the top performer strategy, offering the fastest temperature reduction, followed by north-facing facades (1b), manual solar shadings (4a and 4b), and the inclusion of night cooling (8-series) which also deliver substantial improvements over the baseline. Conversely, increased Cp (2a) underperforms, reducing the recovery rate relative to the baseline.

In **Rome**, west-facing facade (1a) and larger window area (3a) achieve the best recovery rates, with strategy north-facing facade (1b) and halved g-value (5a) also performing well. However, strategies such as increased Cp (2a) again negatively impacts the recovery rate, while the majority of other strategies exhibit negligible differences from the baseline.

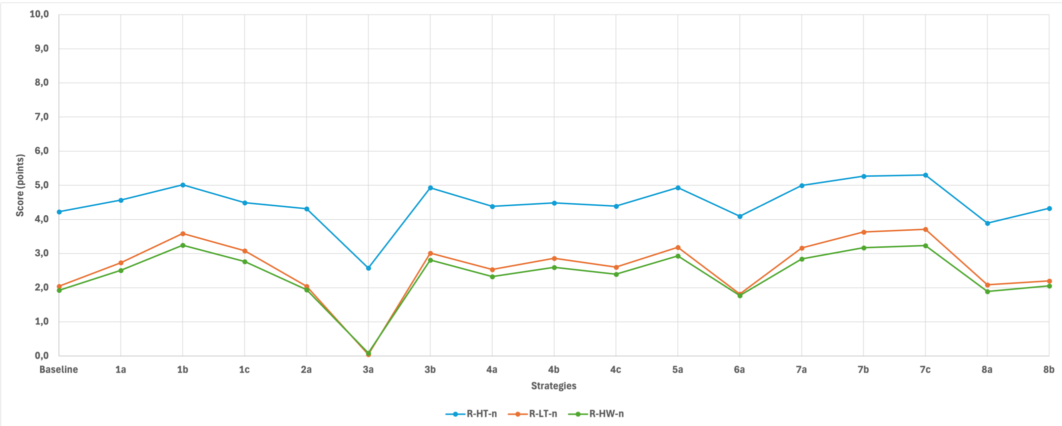
London exhibits the lowest recovery rates overall, with many strategies performing worse than the baseline. However, strategies such as manual solar shading (4a and 4b), and including 7h of night cooling (8a) stand out for their relatively higher recovery rates.

Across all locations, strategies such as larger window area (3a) and north-facing facade (1b) are the most consistent high performers, demonstrating strong recovery rates in both Copenhagen and Rome. Strategies such as manual solar shading (4a and 4b), and including 7h of night cooling (8a) also show promise, particularly

(a) AHD score across strategies in Copenhagen



(b) AHD score across strategies in Rome



(c) AHD score across strategies in London

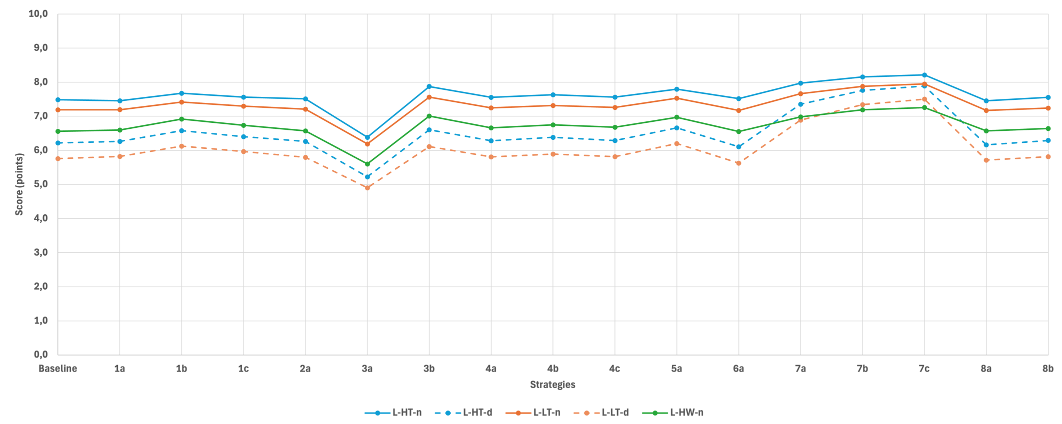


Figure 3.8: AHD score across strategies in the three locations.

in Copenhagen and London. Conversely, increased Cp (2a) consistently underperforms, reducing recovery rates in all locations. An increased Cp (strategy 2a) of concrete negatively affects the recovery rate as it allows the material to store more thermal energy while also delaying its release. This prolonged heat retention slows the return of indoor temperatures to comfortable levels, thereby reducing the recovery rate.

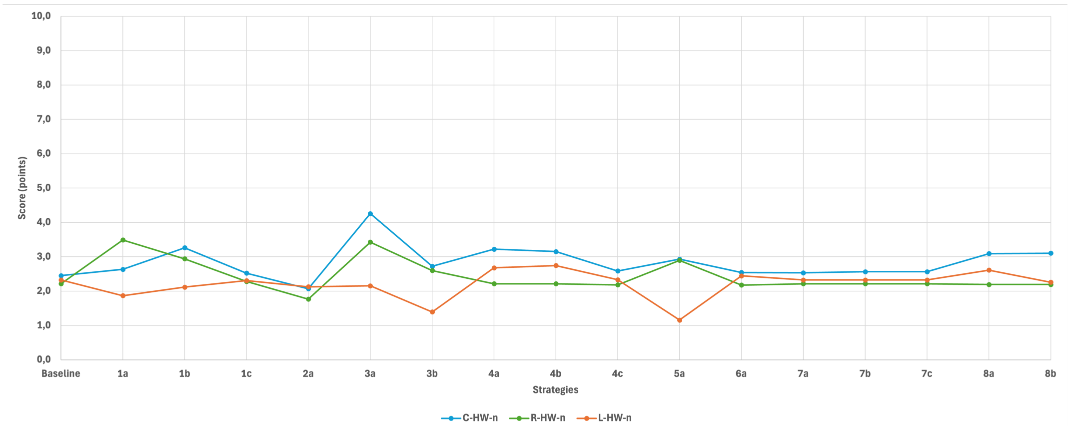


Figure 3.9: Δrec score across strategies in the three locations.

3.2.2 Sustainability Impact

The sustainability assessment evaluates the impact of energy consumption for cooling, heating and ventilation and the influence of building elements that are added or modified compared to the baseline (e.g., increased or reduced window area and the inclusion of solar shading devices).

The analysis evaluates the GWP, assessed over a reference period of 50 years, as defined by BR18. Results will be expressed in kg CO_2eq/ year, ensuring comparability with other KPIs. The calculation will be conducted through a Life Cycle Assessment (LCA), which examines the environmental impacts and potential effects associated with a product's entire life cycle, including raw material extraction, production, use, and end-of-life stages [44].

The process for conducting an LCA and the life-cycle stages to be considered are defined in DS/EN 15978 [45], and the Danish BR18 [26] which specifies the mandatory stages to include, which are the following: the product stage (modules A1 – "Raw material supply," A2 – "Transport," and A3 – "Manufacturing"); the use stage (module B4 – "Replacement," and B6 – "Operational energy use"); and the end-of-life stage (module C3 – "Waste processing," and C4 – "Disposal"). Additionally, voluntary Module D covers the benefits and loads beyond the system boundary, such as reuse, recovery, and recycling of materials.

For windows and shading mechanisms, the Environmental Product Declaration (EPD) specifies their expected lifetime. If this is shorter than the 50-year study period, replacement is assumed. This is accounted for in Module B4 – "Replacement," calculated as $(50/\text{lifetime} - 1)$ multiplied by the total impact of Modules A1-A3 and C3-C4.

The following assumptions are considered in the calculation:

- Location independence of products: the environmental impact of elements such as windows and solar shading devices is assumed to be independent of location. This is based on the assumption that products manufactured within Europe can be used across different locations.
- Heating, cooling and ventilation energy impacts: the analysis includes the impact of energy consumption for cooling, heating and ventilation, as they are influenced by the tested strategies.
- Single EPD for windows: windows with varying glazing properties are analyzed using the same EPD. Although multiple glazing properties are considered (location-specific, and for two of the strategies), the lack of universally available EPDs for all glazing types and inconsistencies in EPD assumptions across manufacturers make this approach more accurate and reliable.
- Sigle EPD for solar shading: solar shading devices with different shading coefficients are also analyzed using the same EPD, as specified above. Operational energy use for automatic solar shading is location-dependent and is calculated using the energy mix specific to each location.

Cooling and Ventilation Energy Consumption

The impact of the cooling and ventilation energy consumption relative to the baseline is assessed for Module B6, representing operational energy use throughout the building's life cycle. Since cooling and ventilation systems typically rely on electricity, the impact is calculated by multiplying the electricity consumption by the projected emission factor for each of the three locations.

Heating Energy Consumption

The impact of the heating energy consumption relative to the baseline is assessed for Module B6, representing operational energy use throughout the building's life cycle. This is determined by multiplying the energy consumption by the projected emission factor for each of the three locations. For each of the locations, the energy source for heating is different; for Denmark is commonly district heating, while for United Kingdom and Italy is natural gas.

Windows

The glazing area, whether increased or reduced, affects several life-cycle modules, including the product stage (modules A1 – "Raw material supply," A2 – "Transport," and A3 – "Manufacturing"), the use stage (module B4 – "Replacement"), the end-of-life stage (module C3 – "Waste processing" and C4 – "Disposal"), and Module D (accounting for benefits from reuse, recovery, and recycling). The chosen windows are from the Aluminium Spanish Association (AEA) [46], whom provides the relevant environmental data though the EPD.

Solar Shading Mechanisms

The implementation of solar shading mechanisms influences all life-cycle modules. This includes the product stage (modules A1 – "Raw material supply," A2 – "Transport," and A3 – "Manufacturing"), the use stage (module B4 – "Replacement," and module B6 – "Operational energy use," for automated systems), the end-of-life stage (module C3 – "Waste processing," and C4 – "Disposal"), and Module D (addressing benefits from reuse, recovery, and recycling). The selected shading mechanisms are from Griesser [47], whom provides the relevant environmental data though the EPD.

The emission factors for each element in the different locations can be seen in Table 3.5. More detail about the calculation process and the emission factors can be found in Appendix G.

The environmental impact is assessed for current conditions and is not applicable to future scenarios. However, the methodology outlined in this paper supports calculations for future scenarios by incorporating updated conversion factors for electricity and revised EPD data.

The detailed evaluation of GWP performance for each strategy across the three locations and climate events is presented in Appendix F. The GWP score across the strategies in the three locations can be seen in Figure 3.10.

In summary, **Copenhagen** exhibits the strongest performance, with average GWP scores ranging from 7.2 to 7.6 across scenarios, reflecting its favorable AHD results and greener energy use. The best-performing strategies are smaller window area (3b) and the inclusion of natural ventilation (7-series), with smaller window area (3b) excelling in HT and EX scenarios under normal occupancy, and including natural ventilation, particularly 7b and 7c delivering significant improvements in HT scenarios under double occupancy. Larger window area (3a) strategies consistently performs the worst, a trend mirrored across all locations. The success of a smaller window area (3b) stems from its reduced window area and lower energy demand, while including natural ventilation (7-series) achieves favorable GWP results due

Table 3.5: Emission factors per Functional Unit (FU) for a 50 year period in the three locations.

		GWP ($kgCO_2$eq./FU)				
Component	**FU**	**A1-A3**	**B4**	**B6**	**C3-C4**	**D**
Denmark						
Cooling Energy	kW	-	-	0.05	-	-
Heating Energy	kW	-	-	0.07	-	-
Ventilation Energy	kW	-	-	0.05	-	-
Solar shadings	m^2	40.70	41.70	4.33	1.03	-11.70
Windows	m^2	117.00	118.00	-	0.81	-12.7
United Kidgdom						
Cooling Energy	kW	-	-	0.17	-	-
Heating Energy	kW	-	-	0.20	-	-
Ventilation Energy	kW	-	-	0.17	-	-
Solar shadings	m^2	40.70	41.70	14.84	1.03	-11.70
Windows	m^2	117.00	118.00	-	0.81	-12.7
Italy						
Cooling Energy	kW	-	-	0.27	-	-
Heating Energy	kW	-	-	0.20	-	-
Ventilation Energy	kW	-	-	0.27	-	-
Solar shadings	m^2	40.70	41.70	23.59	1.03	-11.70
Windows	m^2	117.00	118.00	-	0.81	-12.7

to the absence of additional elements combined with low energy demand.

In **Rome**, including natural ventilation (particularly 7b and 7c) leads in performance, followed by strategies north-facing facade (1b), smaller window area (3b), halved g-value (5a). On the other hand, strategies such as larger window area (3a) and halved U-value (6a) exhibit the poorest results.

In **London**, the 7-series (including natural ventilation) strategies again stand out as the top performers, followed by smaller window area (3b). These strategies have a greater impact in normal occupancy scenarios compared to double occupancy, where several strategies fall below the baseline performance.

Across all locations, the 7-series (including natural ventilation) and smaller window area (3b) consistently deliver the best GWP results, emphasizing their energy efficiency and minimal embodied carbon. Conversely, the larger window area (3a) strategy emerges as the weakest performer, underscoring its high energy demand and embodied carbon.

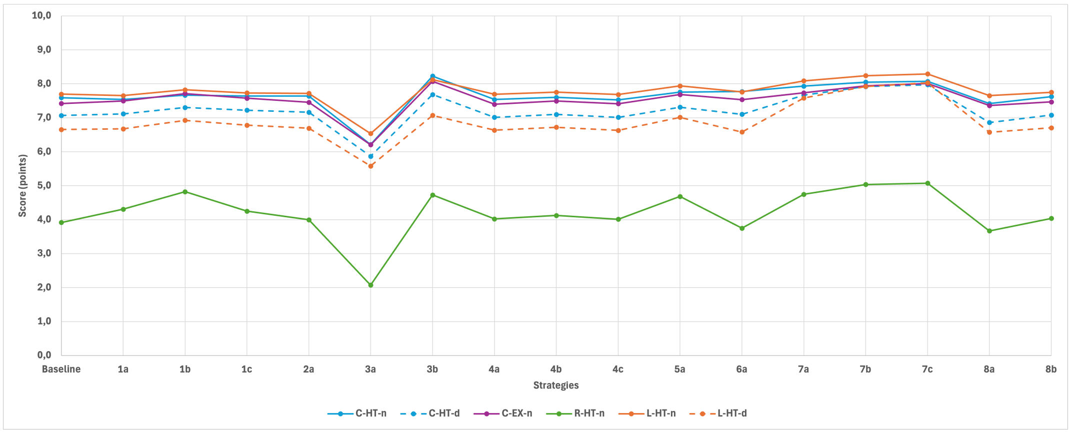


Figure 3.10: GWP score across strategies in the three locations.

3.3 Evaluation of Resilience

This section analyzes the resilience results of the strategies. To simplify the evaluation and because the study found that certain scenarios across locations perform similarly, the scenarios are grouped into three intensity levels based on their mean resilience scores. Each location's scenarios are categorized into these intensity levels, with details provided in Table 3.6:

- High intensity (above 8 points): Representing the most intense scenarios.
- Medium intensity (5 to 8 points): Representing moderately intense scenarios.
- Low intensity (below 5 points): Representing the least intense scenarios.

Table 3.6: Scenario categorization across the three locations. The mean score across strategies is detailed for each scenario in parenthesis.

Scenario category	Copenhagen	Rome	London
Low intensity	C-HT-n (8.6) C-LT-n (8.6)	R-HT-n (8.0)	L-HT-n (8.7) L-LT-n (8.4)
Medium intensity	C-HT-d (6.6) C-LT-d (6.7) C-EX-n (6.9)	R-LT-n (6.5) R-HW-n (6.2)	L-HT-d (7.4) L-LT-d (6.1) L-HW-n (6.2)
High intensity	C-HW-n (3.1)		

3.3.1 Copenhagen

Table 3.7 presents the resilience evaluation results, along with the GWP and Δrec where applicable, for all strategies across all scenarios. These results are visually represented in Figure 3.11.

In Copenhagen, the **low-intensity scenario** encompasses the HT and LT scenarios under normal occupancy (HT-n and LT-n). These scenarios show similar resilience outcomes and trends across strategies, with an overall strong performance reflected in a mean score of 8.6 across all strategies and minimal variability from the baseline. The only strategy deviating significantly from the high average is the larger window area (3a), which underperforms relative to the others.

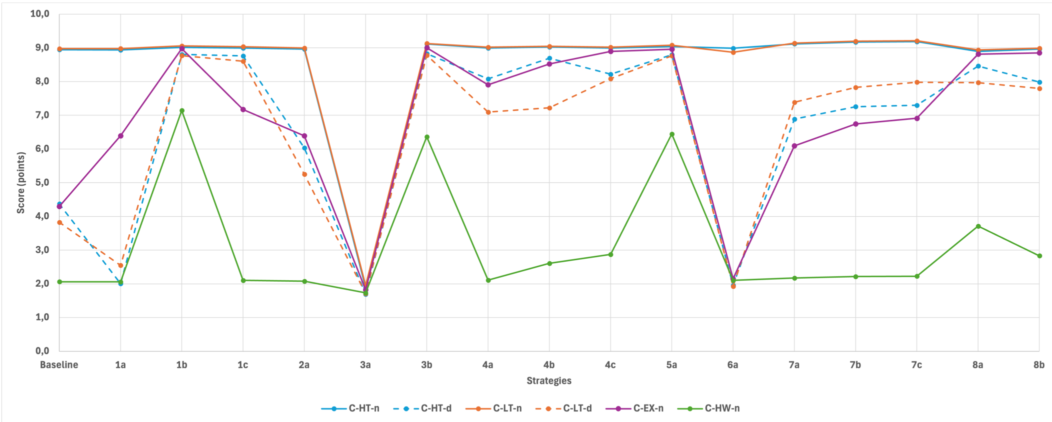
The **medium intensity scenario** comprehends the HT and LT scenarios under double occupancy (HT-n and LT-n) and the EX (EX-n), with a mean score of 6.6–6.9; significantly dropping compared to the low intensity scenario, and demonstrating greater variability relative to the baseline. The best-performing strategies are the north-facing facade (1b), east-facing facade (1c), smaller window area (3b), automatic solar shading (4c), halved g-value (5a), and including 4h of night cooling (8b). The weakest performers in terms of resilience are strategies: west-facing facade (1a) (except for the EX), larger window area (3a), and halved U-value (6a).

The **high intensity scenario** comprehends the HW scenario (HW-n), with a mean score that declines sharply to 3.1, significantly lower than in other scenarios, highlighting the city's susceptibility to overheating due to its high DoS (ass seen in Section 3.1). The most effective strategies are north-facing facade (1b), smaller window area (3b), and halved g-value (5a), with strategy north-facing facade (1b) achieving a high recovery rate. These strategies have a greater impact on the results in the HW scenario compared to the baseline than in the other tested scenarios, even though their final scores are lower. The least resilient strategy is the larger window area (3a), although it does provide a high recovery rate.

Across all scenarios, the best-performing strategies in terms of GWP are the 7-series (including natural ventilation) and smaller window area (3b). Conversely, the larger window area (3a) strategy consistently ranks as the worst-performing option.

Figures 3.12, 3.13, and 3.14 illustrate the influence of HE, OEF, and AHD on the resilience score of each strategy across all scenarios, presented in a spider diagram. They highlight the strong performance of all strategies, except larger window area (3a), in terms of HE and OEF across the low-intensity scenarios. This is followed by moderate performance in the medium-intensity scenarios, and weaker results in the high-intensity scenario. Across all strategies and scenarios, AHD demonstrates robust performance, even under high-intensity scenarios and with more challenging strategies like larger window area (3a).

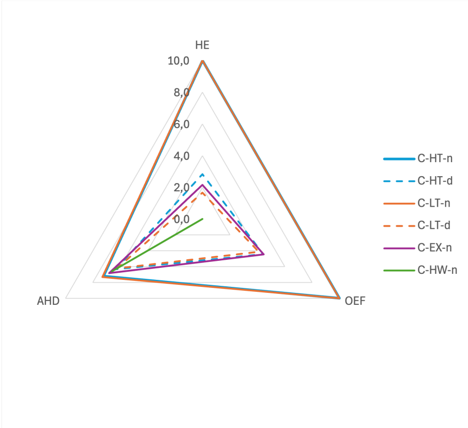
(a) Resilience score across strategies in Copenhagen



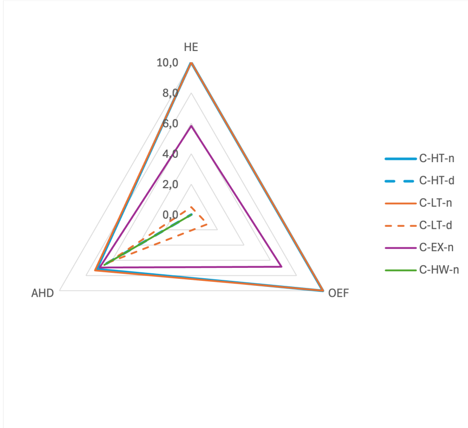
(b) Resilience difference compared to baseline across strategies in Copenhagen

Figure 3.11: Resilience score and difference compared to baseline across strategies in Copenhagen.

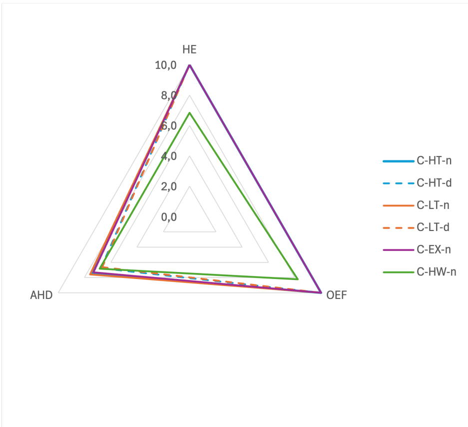
(a) Baseline in Copenhagen.



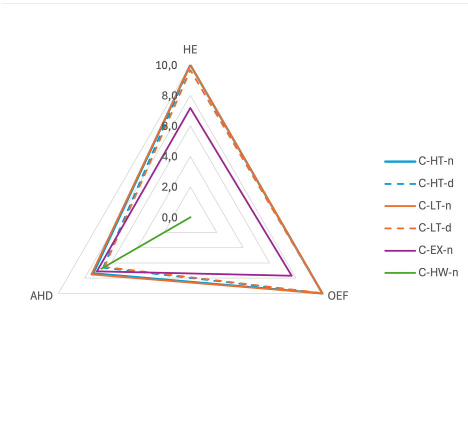
(b) Strategy 1a in Copenhagen.



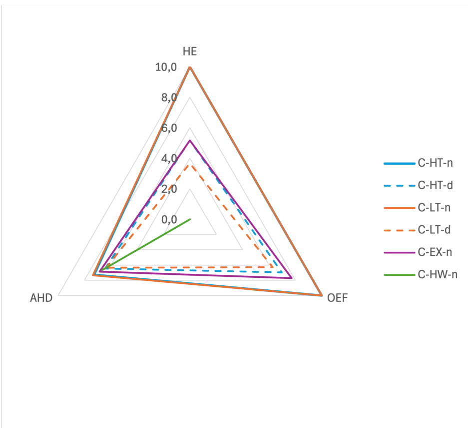
(c) Strategy 1b in Copenhagen.



(d) Strategy 1c in Copenhagen.



(e) Strategy 2a in Copenhagen.



(f) Strategy 3a in Copenhagen.

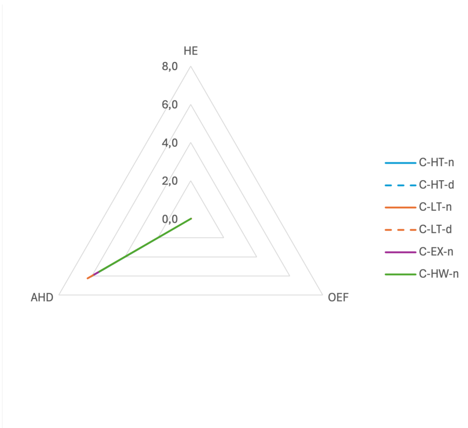
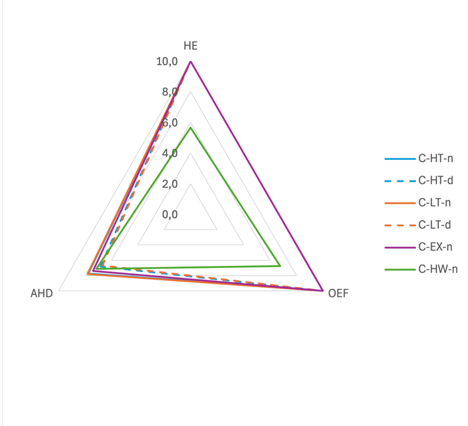
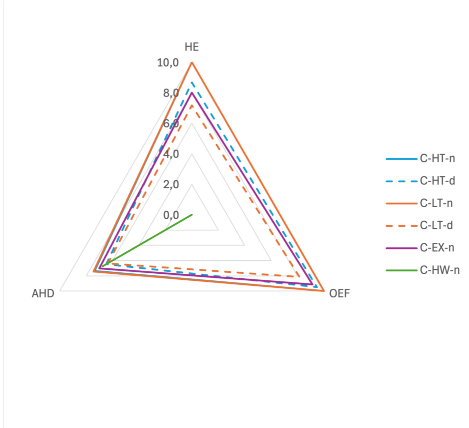


Figure 3.12: Impact of HE, OEF and AHD on the resilience of strategies (baseline and strategies 1a to 3a) in Copenhagen.

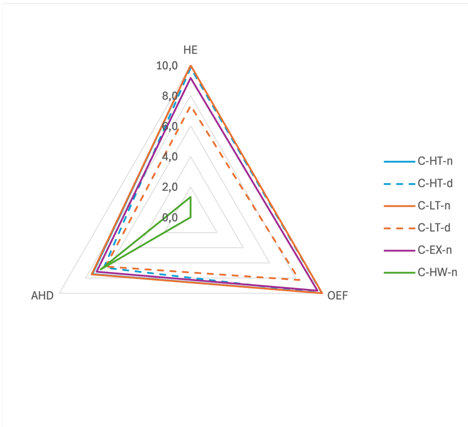
(a) Strategy 3b in Copenhagen.



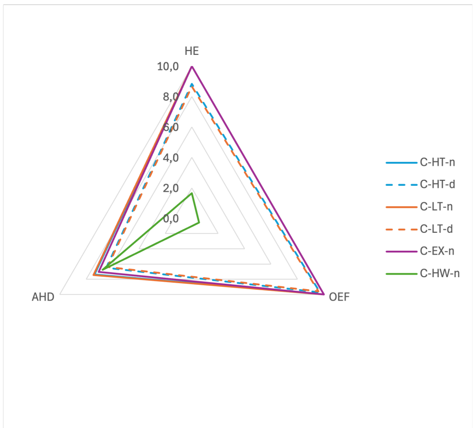
(b) Strategy 4a in Copenhagen.



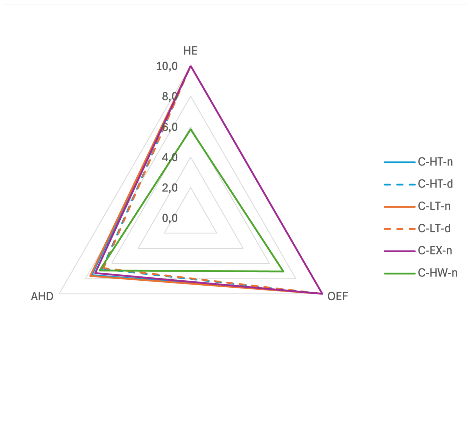
(c) Strategy 4b in Copenhagen.



(d) Strategy 4c in Copenhagen.



(e) Strategy 5a in Copenhagen.



(f) Strategy 6a in Copenhagen.

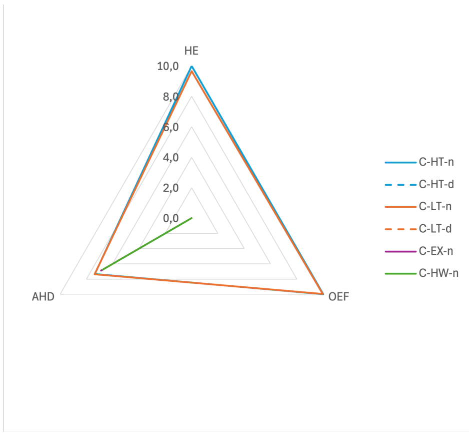
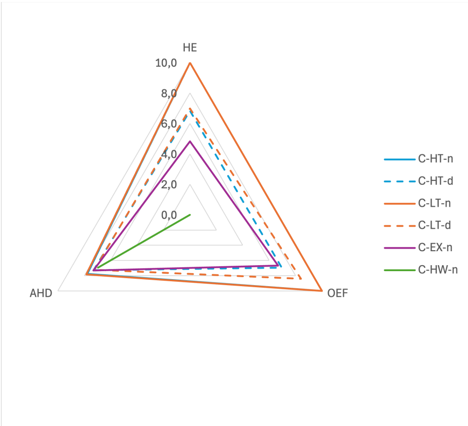
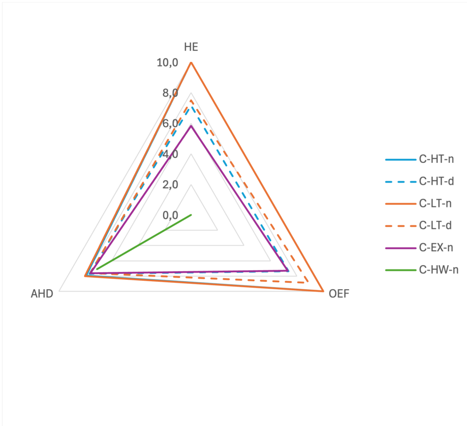


Figure 3.13: Impact of HE, OEF and AHD on the resilience of strategies (strategies 3b to 6a) in Copenhagen.

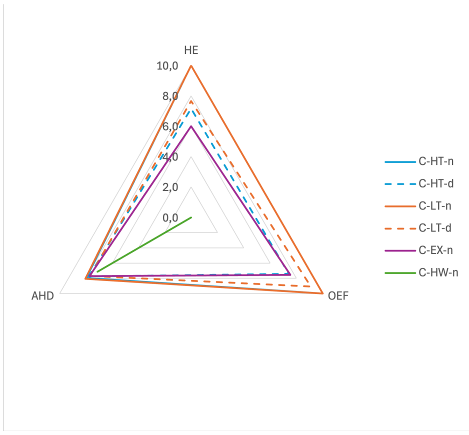
(a) Strategy 7a in Copenhagen.



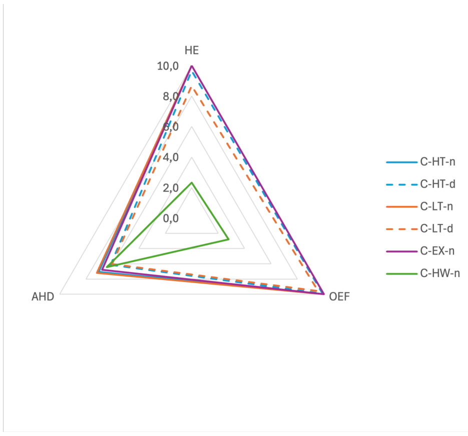
(b) Strategy 7b in Copenhagen.



(c) Strategy 7c in Copenhagen.



(d) Strategy 8a in Copenhagen.



(e) Strategy 8b in Copenhagen.

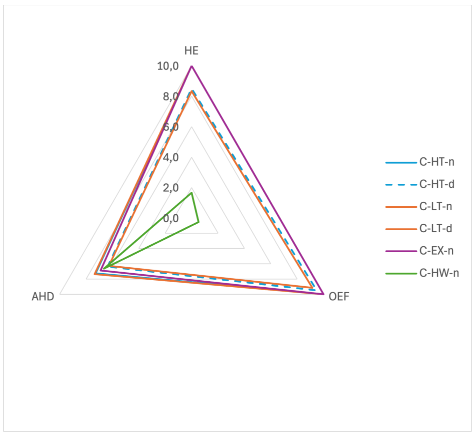


Figure 3.14: Impact of HE, OEF and AHD on the resilience of strategies (strategies 7a to 8b) in Copenhagen.

Table 3.7: Summary of the resilience evaluation (referred to as "RES"), including the total score and the percentage difference from the baseline; GWP and the recovery rate (percentage difference from the baseline in applicable scenarios) for all strategies across all scenarios in Copenhagen.

	C-HT-n		**C-HT-d**		**C-LT-n**	**C-LT-d**	**C-EX-n**		**C-HW-n**	
	RES	GWP	RES	GWP	RES	RES	RES	GWP	RES	Δrec
Base.	8.9		4.4		9.0	3.8	4.3		2.1	
1a	8.9 *-0.1%*	-0.7%	2.0 *-54.1%*	0.7%	9.0 0.0%	2.5 *-33.4%*	6.4 *48.9%*	1.0%	2.1 *-0.2%*	7.4%
1b	9.0 *0.8%*	1.0%	8.8 *101.3%*	3.3%	9.1 *0.9%*	8.8 *129.2%*	9.0 *109.1%*	3.9%	7.1 *246.3%*	33.1%
1c	9.0 *0.6%*	0.6%	8.8 *100.3%*	2.2%	9.0 *0.7%*	8.6 *124.8%*	7.2 *67.0%*	2.1%	2.1 *2.1%*	3.0%
2a	9.0 *0.2%*	0.6%	6.0 *38.0%*	1.3%	9.0 *0.2%*	5.3 *37.2%*	6.4 *48.9%*	0.5%	2.1 *0.8%*	-15.6%
3a	1.9 *-78.9%*	-18.2%	1.7 *-61.3%*	-17.0%	2.0 *-78.3%*	1.7 *-55.3%*	1.8 *-57.5%*	-16.3%	1.7 *-16.0%*	73.6%
3b	9.1 *1.9%*	8.4%	8.8 *101.9%*	8.7%	9.1 *1.7%*	8.8 *129.4%*	9.0 *109.6%*	8.8%	6.4 *208.5%*	11.1%
4a	9.0 *0.6%*	-0.7%	8.1 *84.7%*	-0.8%	9.0 *0.5%*	7.1 *85.3%*	7.9 *84.1%*	-0.3%	2.1 *2.2%*	31.3%
4b	9.0 *0.9%*	0.1%	8.7 *98.9%*	0.4%	9.0 *0.8%*	7.2 *88.7%*	8.5 *98.5%*	1.0%	2.6 *26.6%*	28.5%
4c	9.0 *0.6%*	-0.8%	8.2 *87.9%*	-0.8%	9.0 *0.5%*	8.1 *111.3%*	8.9 *107.1%*	-0.1%	2.9 *39.3%*	5.6%
5a	9.0 *1.1%*	2.2%	8.8 *101.1%*	3.4%	9.1 *0.5%*	8.8 *129.0%*	9.0 *108.6%*	3.6%	6.4 *212.4%*	19.6%
6a	9.0 *0.5%*	2.4%	2.0 *-55.2%*	0.5%	8.9 *-1.2%*	1.9 *-49.7%*	2.2 *-49.9%*	1.5%	2.1 *2.1%*	3.7%
7a	9.1 *1.9%*	4.5%	6.9 *57.5%*	8.5%	9.1 *1.9%*	7.4 *93.0%*	6.1 *42.0%*	4.3%	2.2 *5.4%*	3.4%
7b	9.2 *2.5%*	6.0%	7.3 *66.0%*	12.0%	9.2 *2.5%*	7.8 *104.5%*	6.7 *57.1%*	7.0%	2.2 *7.5%*	4.7%
7c	9.2 *2.6%*	6.3%	7.3 *66.9%*	12.8%	9.2 *2.6%*	8.0 *108.5%*	6.9 *60.9%*	7.9%	2.2 *8.0%*	4.7%
8a	8.9 *-0.6%*	-2.3%	8.5 *93.5%*	-2.9%	8.9 *-0.4%*	8.0 *108.2%*	8.8 *105.3%*	-0.8%	3.7 *79.9%*	26.1%
8b	9.0 *0.2%*	0.4%	8.0 *82.6%*	0.2%	9.0 *0.2%*	7.8 *103.7%*	8.9 *106.1%*	0.7%	2.8 *37.4%*	26.6%

3.3.2 Rome

Table 3.8 presents the resilience evaluation results, along with the GWP and Δrec where applicable, for all strategies across all scenarios. These results are visually represented in Figure 3.15.

In Rome, the **low intensity scenario** comprehends the HT scenario under normal occupancy (HT-n), which achieves a mean resilience score of 8.0 across strategies, with minimal variability compared to the baseline. Noteworthy performers include strategy north-facing facade (1b) and the including natural ventilation (7-series). In contrast, a larger window area (3a) is the poorest performer.

The **medium intensity scenario** comprehends the LT scenario under normal occupancy (LT-n) and the HW scenario (HW-n), which achieve a mean score of 6.2-6.6, slightly decreasing compared to the low intensity scenario. The best-performing strategies are north-facing facade (1b), increased Cp (2a), smaller window area (3b), and halved g-value (5a), all of which (except 2a) also have a good performance in terms of recovery rate. Conversely, a larger window area (3a) perform the worst, both negatively impacting resilience and reducing the recovery rate. Figure 3.15b shows that resilience variations (compared to the baseline) across the strategies are minimal in all the scenarios tested for Rome, except for the strategies mentioned above, this is due to its higher cooling capacity and reduced solar radiation in future scenarios.

Across all scenarios, strategies such as north-facing facade (1b), halved g-value (5a), and the inclusion of natural ventilation (7-series) also achieve good results in terms of GWP. Conversly, a larger window area (3a) is the poorest performer.

Figures 3.16, 3.17, and 3.18 illustrate the influence of HE, OEF, and AHD on the resilience score of each strategy across all scenarios, presented in a spider diagram. They illustrate the strong performance of all strategies (including a larger window area (3a)) in terms of HE and OEF across all tested scenarios. However, AHD shows relatively low performance across all strategies and scenarios, demonstrating Rome's heavy reliance on cooling energy.

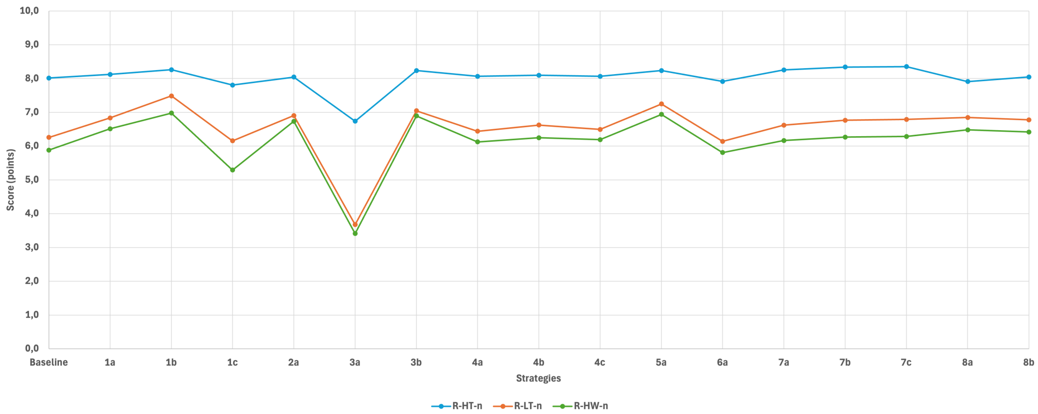
3.3.3 London

Table 3.9 presents the resilience evaluation results, along with the GWP and Δrec where applicable, for all strategies across all scenarios. These results are visually represented in Figure 3.19.

In London, the **low intensity scenario** comprehends the HT and LT scenarios under normal occupancy (HT-n and LT-n), which exhibit mean scores of 8.7 and 8.4, respectively. All strategies show a very good performance, with minimal variation compared to the baseline; except for strategy 3a (larger window area) which consistently performs the worst.

The **medium intensity scenario** comprehends the HT and LT scenarios undeer double normal occupancy (HT-d and LT-d) and the HW scenario (HW-n), which exhibit mean resilience scores of 6.1-7.4. The top-performing strategies are north-facing facade (1b), smaller window area (3b), halved g-value (5a), including natural ventilation (7-series), and the inclusion of night cooling (8-series). Conversely, the worst-performing strategies for resilience include west and east facing facade (1a and 1c) (except HT), as well as larger window areas (3a). Higher variations in resilience are observed in Figure 3.19b compared to Rome. Regarding the recovery rate under HW, including solar shadings (4-series) and including 7h of night cooling (8a) emerge as the strategies that show the best recovery rates, whereas smaller

(a) Resilience score across strategies in Rome



(b) Resilience difference compared to baseline across strategies in Rome

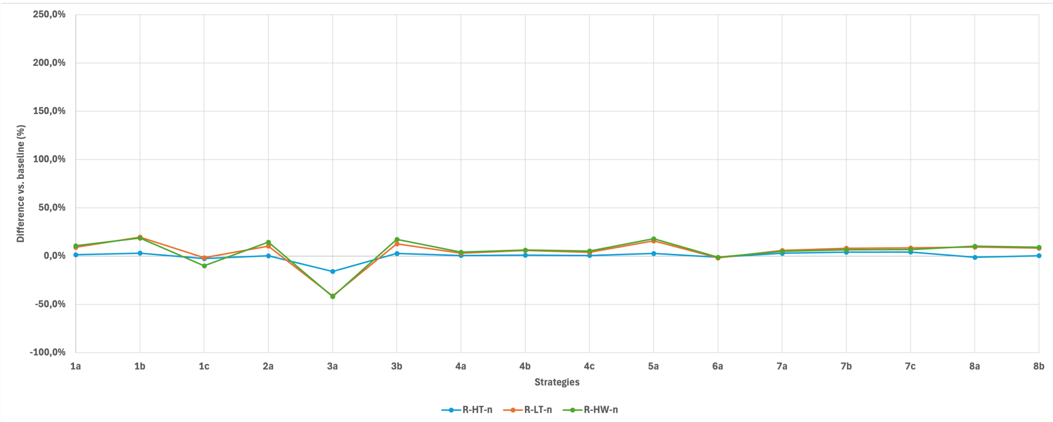
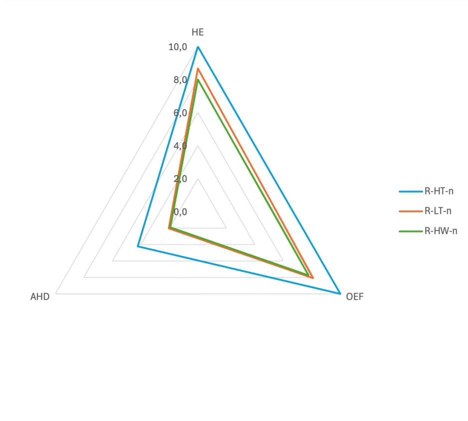
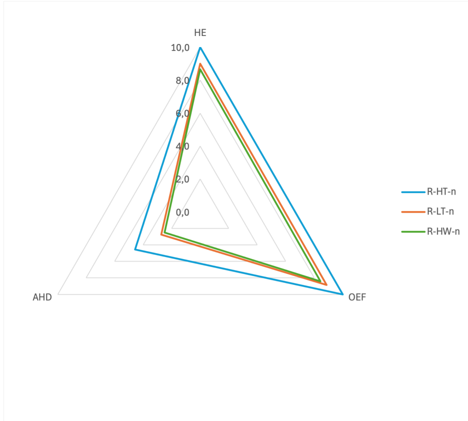


Figure 3.15: Resilience score and difference compared to baseline across strategies in Rome.

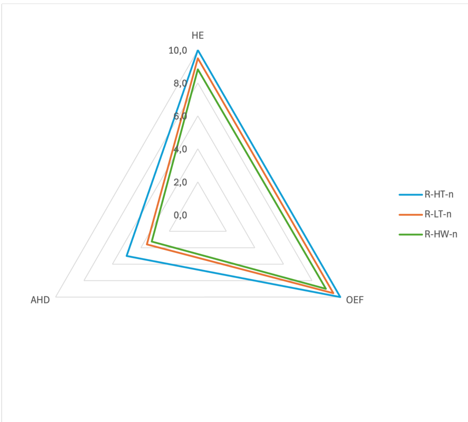
(a) Baseline in Rome.



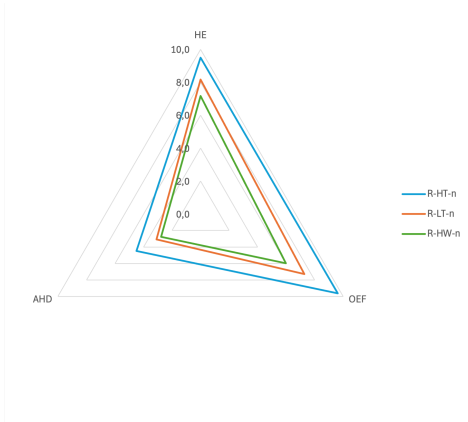
(b) Strategy 1a in Rome.



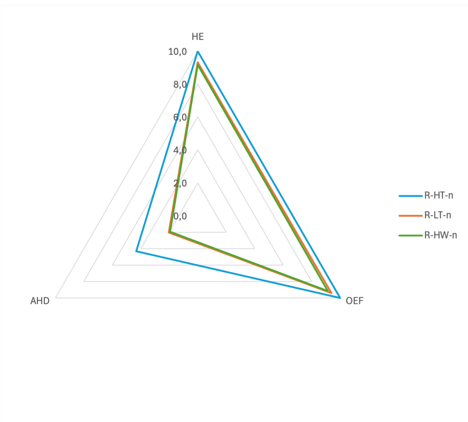
(c) Strategy 1b in Rome.



(d) Strategy 1c in Rome.



(e) Strategy 2a in Rome.



(f) Strategy 3a in Rome.

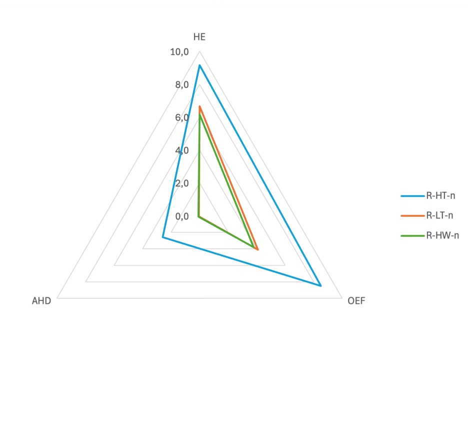
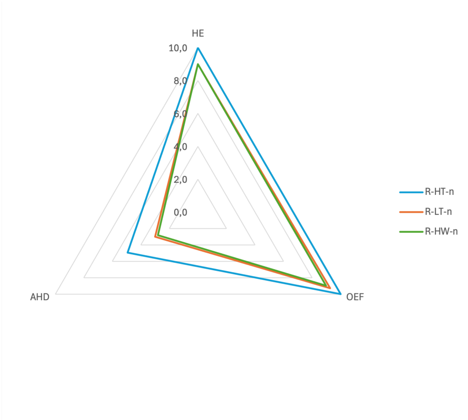
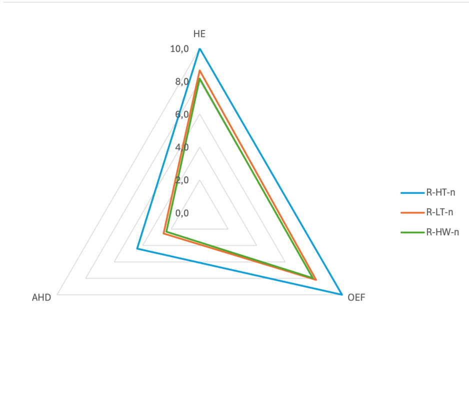


Figure 3.16: Impact of HE, OEF and AHD on the resilience of strategies (baseline and strategies 1a to 3a) in Rome.

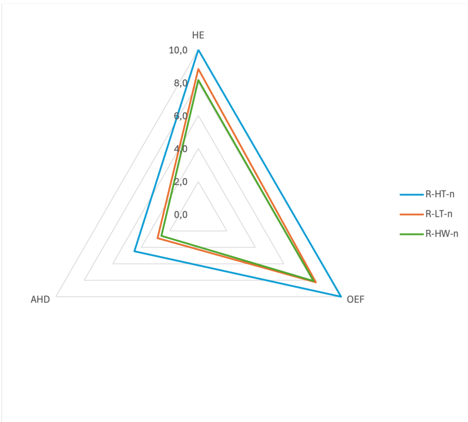
(a) Strategy 3b in Rome.



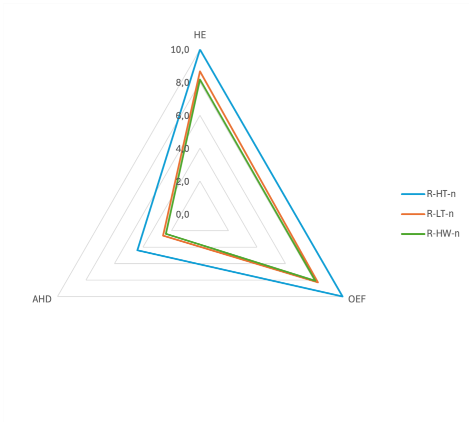
(b) Strategy 4a in Rome.



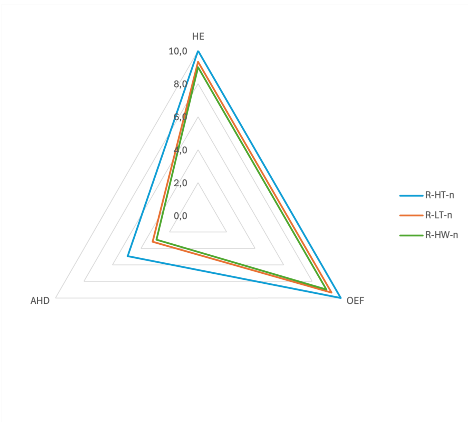
(c) Strategy 4b in Rome.



(d) Strategy 4c in Rome.



(e) Strategy 5a in Rome.



(f) Strategy 6a in Rome.

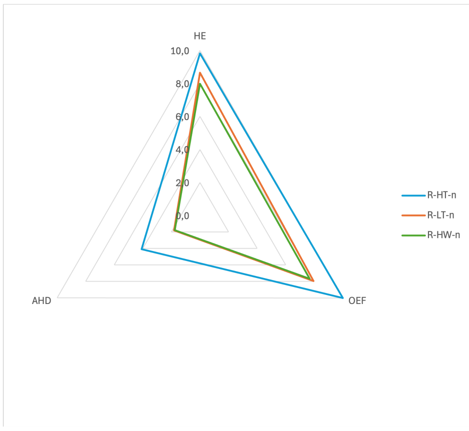
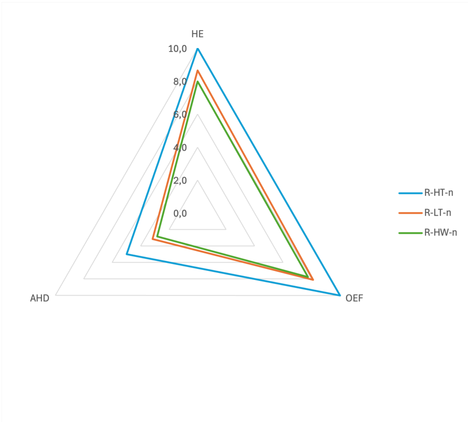
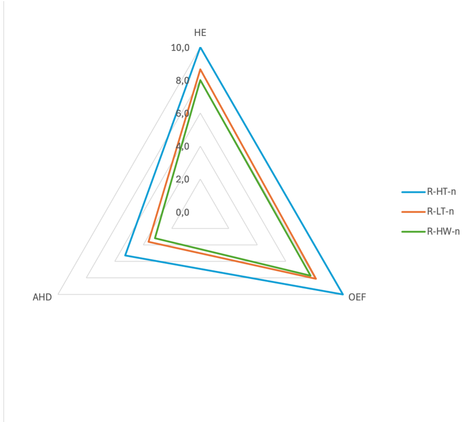


Figure 3.17: Impact of HE, OEF and AHD on the resilience of strategies (strategies 3b to 6a) in Rome.

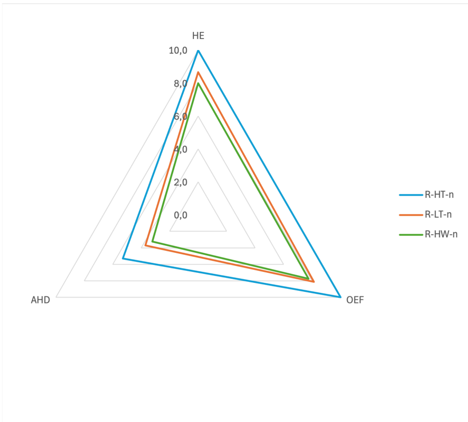
(a) Strategy 7a in Rome.



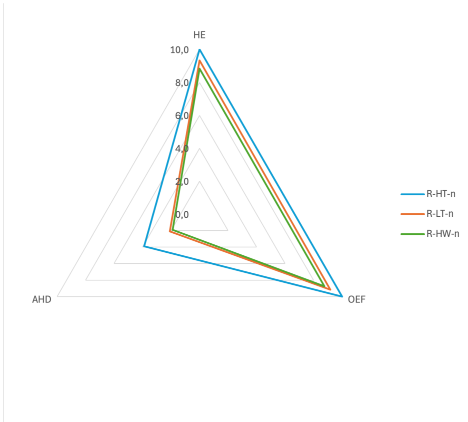
(b) Strategy 7b in Rome.



(c) Strategy 7c in Rome.



(d) Strategy 8a in Rome.



(e) Strategy 8b in Rome.

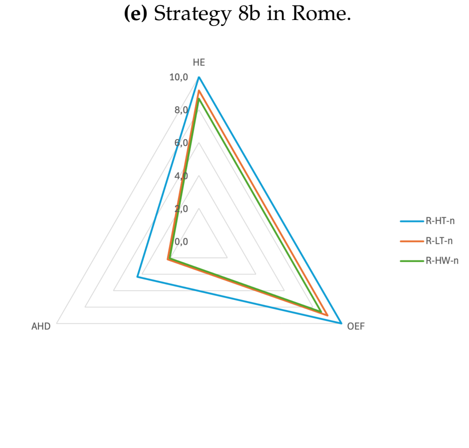


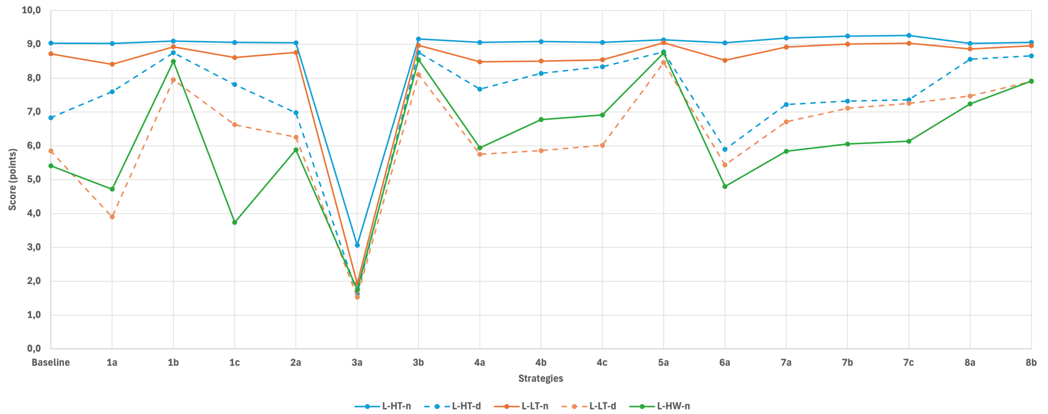
Figure 3.18: Impact of HE, OEF and AHD on the resilience of strategies (strategies 7a to 8b) in Rome.

window area (3b) and halved g-value (5a) show the least favorable performance.

The best results in terms of GWP are the inclusion of natural ventilation (7-series) and smaller window area (3b), while larger window area (3a) remains the poorest performer.

Figures 3.20, 3.21, and 3.22 illustrate the influence of HE, OEF, and AHD on the resilience score of each strategy across all scenarios, presented in a spider diagram. They reveal results similar to those in Copenhagen, with good performance in terms of HE and OEF for all strategies (except larger window area (3a)) across the low intensity scenarios. This is followed by performance in medium intensity scenarios. AHD shows good performance across all strategies and scenarios, even under high-intensity scenarios and with the more challenging strategies, such as larger window area (3a).

(a) Resilience score across strategies in London



(b) Resilience difference compared to baseline across strategies in London

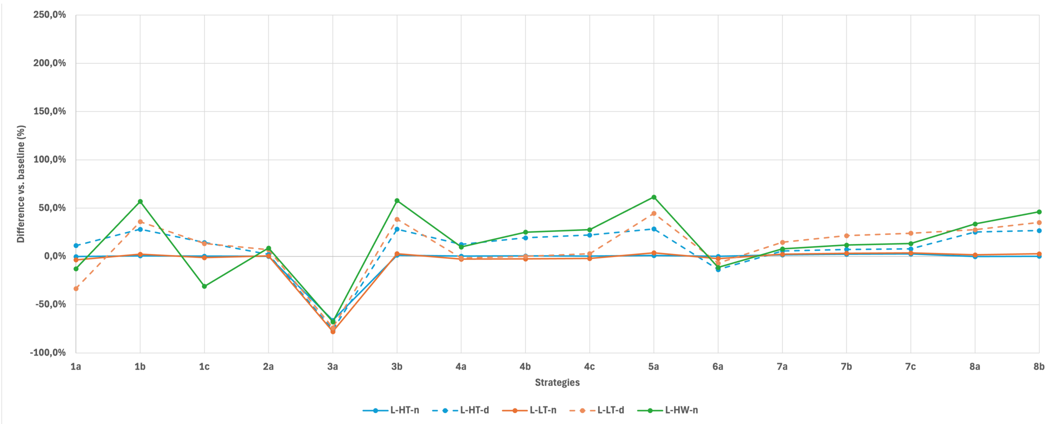
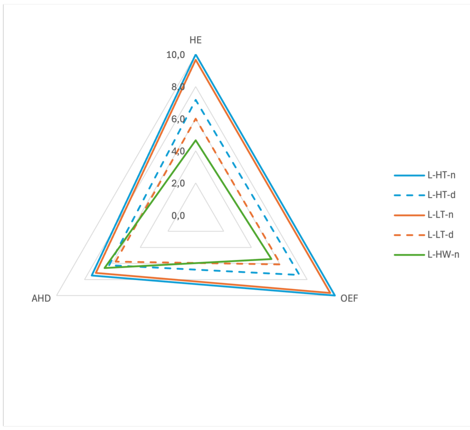
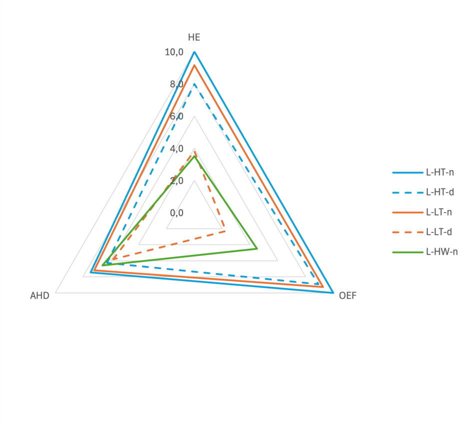


Figure 3.19: Resilience score and difference compared to baseline across strategies in London.

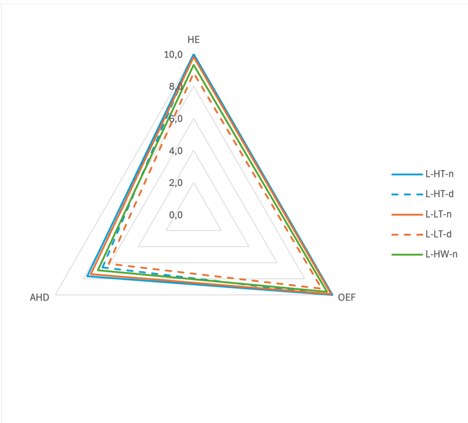
(a) Baseline in London.



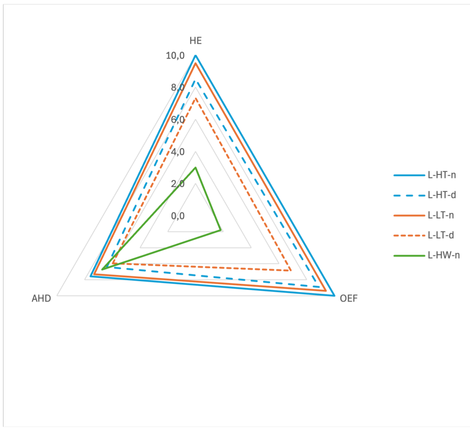
(b) Strategy 1a in London.



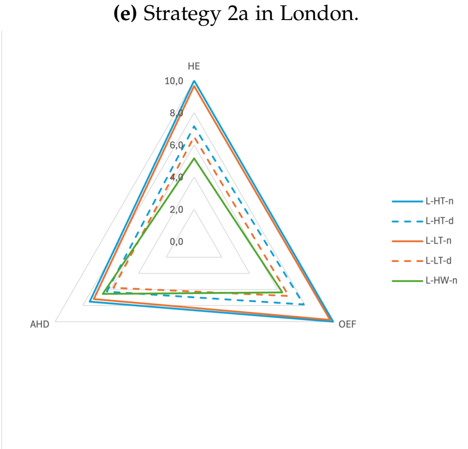
(c) Strategy 1b in London.



(d) Strategy 1c in London.



(e) Strategy 2a in London.



(f) Strategy 3a in London.

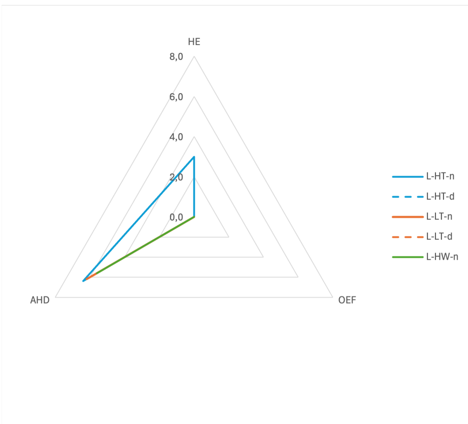
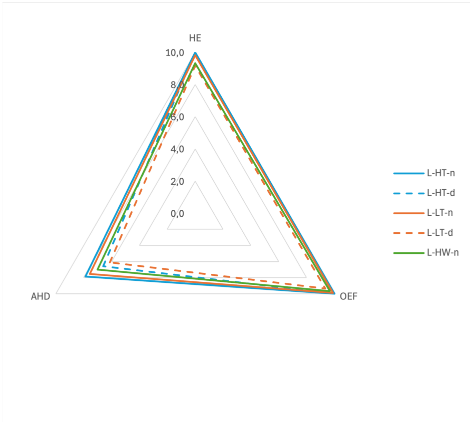
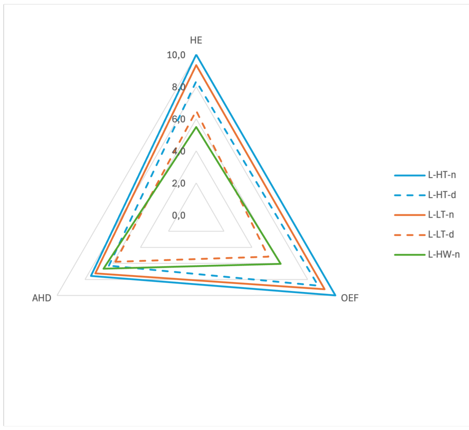


Figure 3.20: Impact of HE, OEF and AHD on the resilience of strategies (baseline and strategies 1a to 3a) in London.

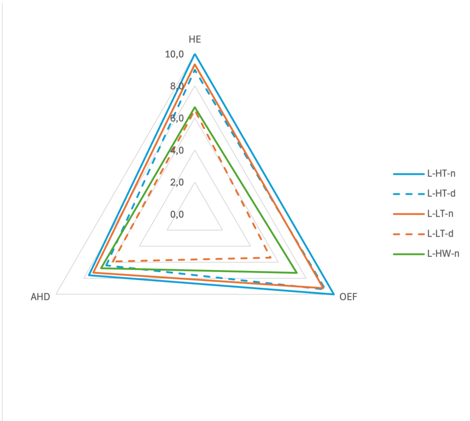
(a) Strategy 3b in London.



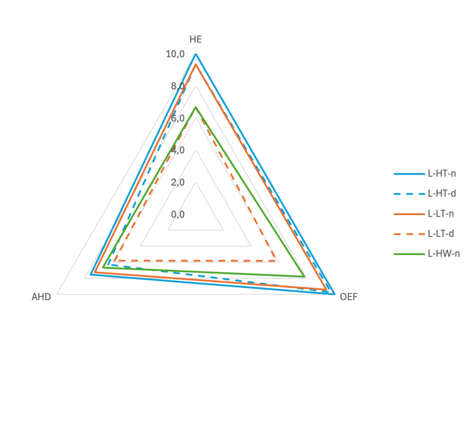
(b) Strategy 4a in London.



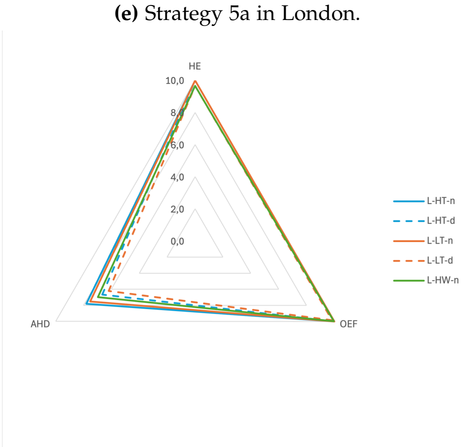
(c) Strategy 4b in London.



(d) Strategy 4c in London.



(e) Strategy 5a in London.



(f) Strategy 6a in London.

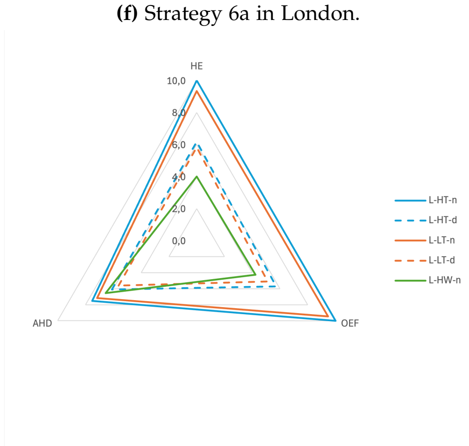
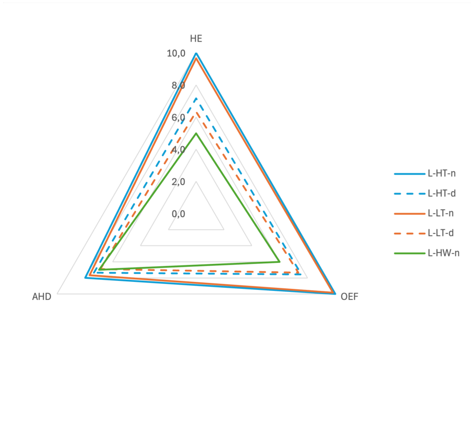
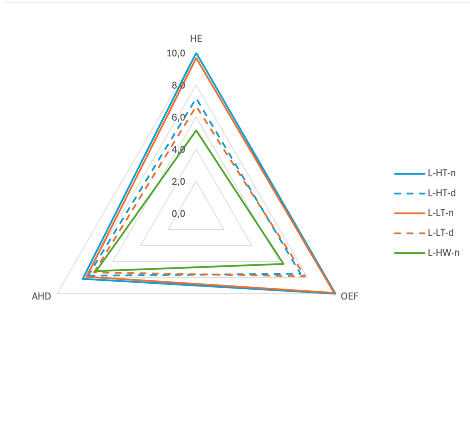


Figure 3.21: Impact of HE, OEF and AHD on the resilience of strategies (strategies 3b to 6a) in London.

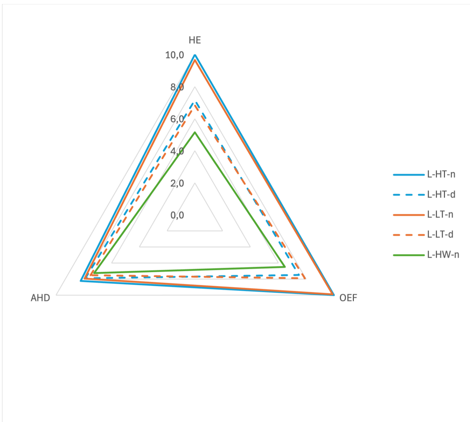
(a) Strategy 7a in London.



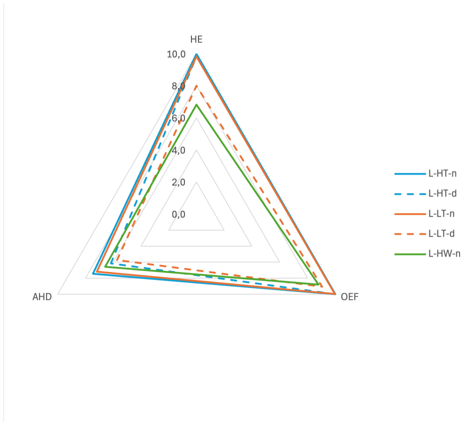
(b) Strategy 7b in London.



(c) Strategy 7c in London.



(d) Strategy 8a in London.



(e) Strategy 8b in London.

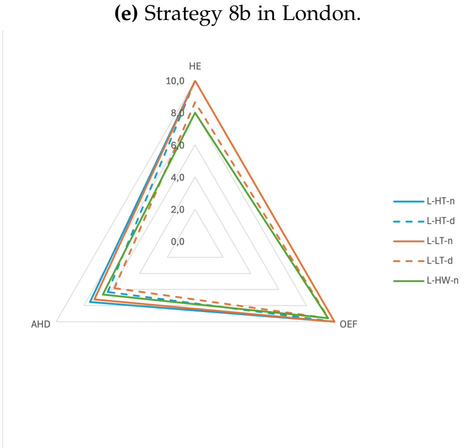


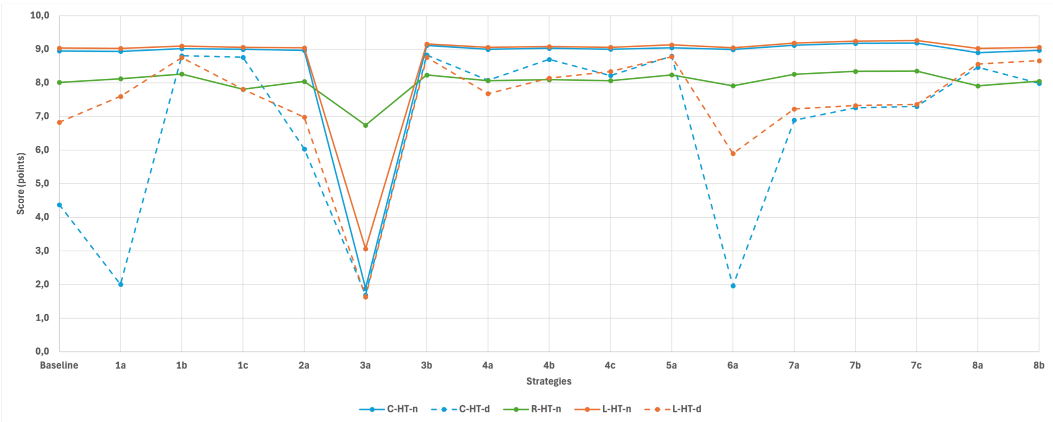
Figure 3.22: Impact of HE, OEF and AHD on the resilience of strategies (strategies 7a to 8b) in London.

3.3.4 Across scenarios

The evaluation of resilience across Copenhagen, Rome, and London demonstrates both shared trends and location-specific variations, this can be seen in Figure 3.23 which illustrates resilience scores under different weather events (HT, LT, EX, and HW) and occupancy scenarios. These findings highlight the interplay between outdoor conditions, strategy performance, and scenario intensity.

Historical Weather Event (HT)

(a) Resilience score across strategies in HT



(b) Resilience difference compared to baseline across strategies in HT

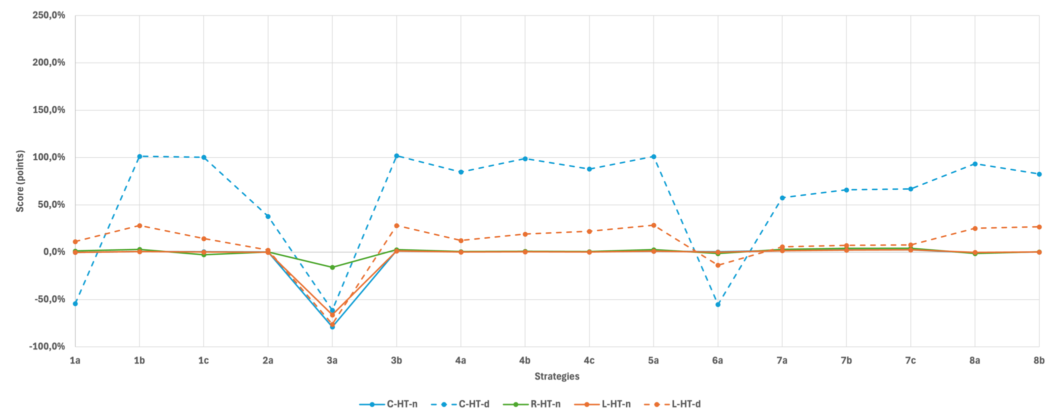


Figure 3.23: Resilience score and difference compared to baseline across strategies during the HT event.

As seen in Figure 3.23, under HT, normal occupancy achieved good mean resilience scores with low variability across all locations, except for the consistently underperforming larger window area (3a). Rome, with its higher outdoor temperatures and solar radiation (3.1), showed lower performance compared to Copenhagen and London. Normal occupancy consistently outperformed double occupancy across all locations.

In the more intense double occupancy scenario, resilience scores displayed greater variability, with strategies such as west-facing facade (1a), larger window area (3a), and halved U-value (6a) failing to maintain resilience; and north and east facing facades (1b and 1c), smaller window area (3b), halved g-value (5a), and night cooling (8-series), outperforming.

London outperformed Copenhagen in certain strategies such as west facing facades (1a), halved U-value (6a) and night cooling (8-series) strategies. Nevertheless, due to Copenhagen relatively low resilience in the baseline, strategies showed a greatest positive performance compared to it. Strategies in which Copenhagen performed best are east facing facades (1c) and the inclusion of solar shadings (4-series).

Long-Term Weather Event (LT)

As illustrated in Figure 3.24, the trends observed under HT continued under LT, maintaining the distinction between normal and double occupancy scenarios. Under normal occupancy, Copenhagen and London performed similarly, with Copenhagen slightly outperforming London. Both cities significantly exceeded Rome's resilience scores, as expected due to its calculated AWD in Section 3.1.

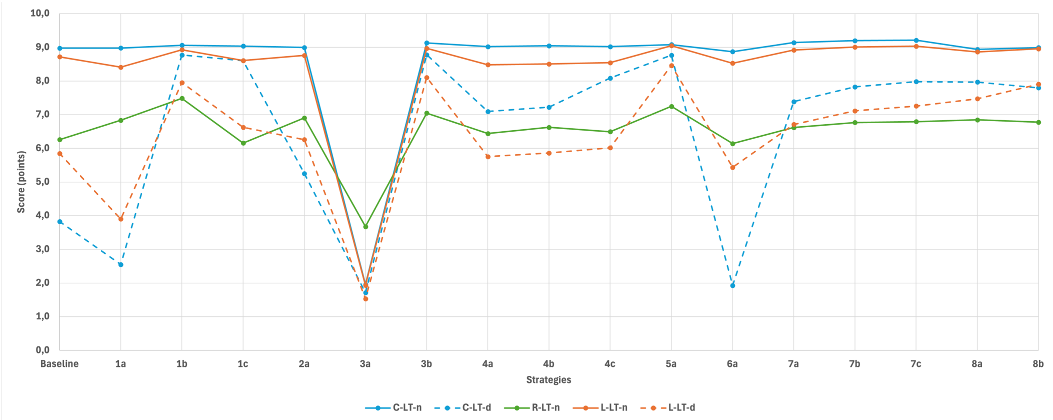
Under double occupancy, London only outperformed Copenhagen for strategies such as west-facing facades (1a) and halved U-values (6a), benefiting from lower expected global radiation. However, Copenhagen showed greater positive variation relative to the baseline and surpassed London with strategies like north- and east-facing facades (1b and 1c), solar shading (4-series), and natural ventilation (7-series), driven by its higher wind speeds.

Consistently poor performers across all scenarios included west-facing facades (1a), larger window areas (3a), and halved U-values (6a).

Extreme Weather Event (EX)

As seen in Figure 3.25, under the EX event in Copenhagen, the performance across strategies variates greatly. Top performers are north-facing facades (1b), smaller window areas (3b), halved g-value (5a), and night cooling (8-series) strategies. On the contrary, the strategies that perform the worst in terms of resilience are larger window areas (3a) and halved U-values (6a).

(a) Resilience score across strategies in LT



(b) Resilience difference compared to baseline across strategies in LT

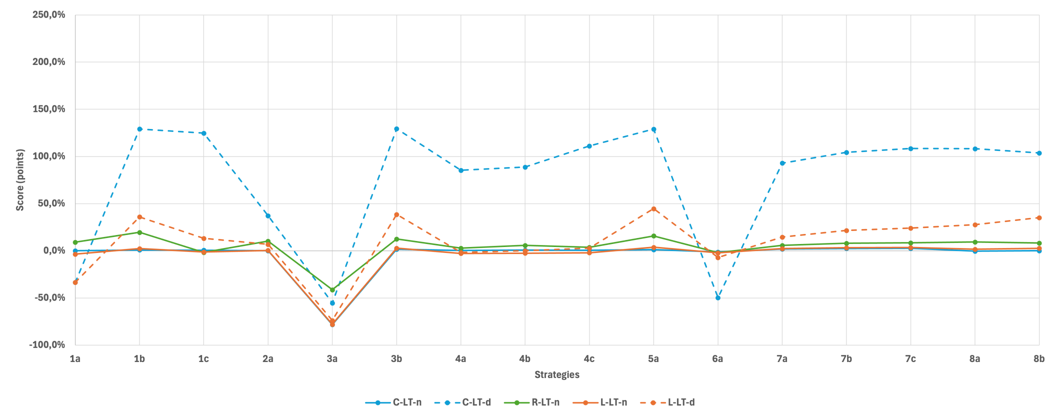
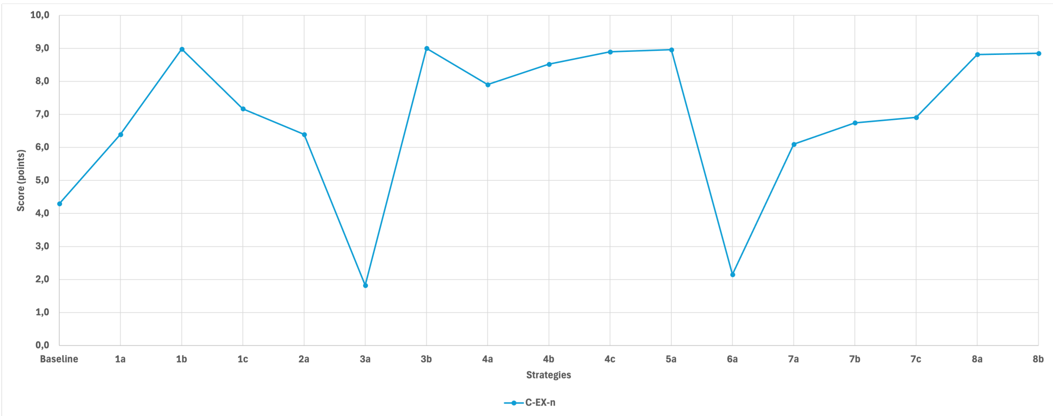


Figure 3.24: Resilience score and difference compared to baseline across strategies during the LT event.

(a) Resilience score across strategies in EX



(b) Resilience difference compared to baseline across strategies in EX

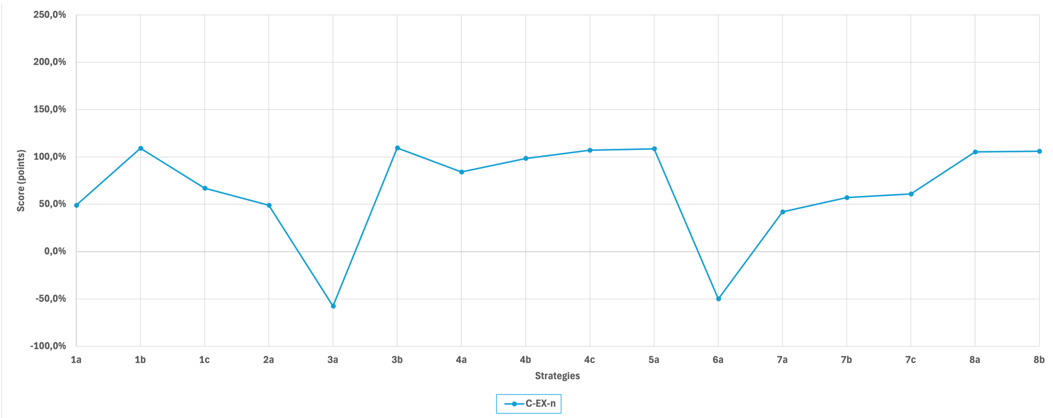
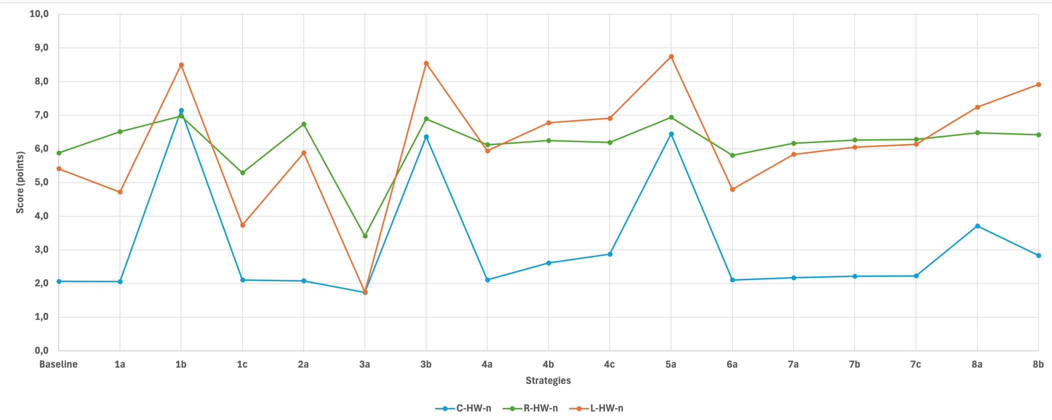


Figure 3.25: Resilience score and difference compared to baseline across strategies during the EX event.

(a) Resilience score across strategies in HW



(b) Resilience difference compared to baseline across strategies in HW

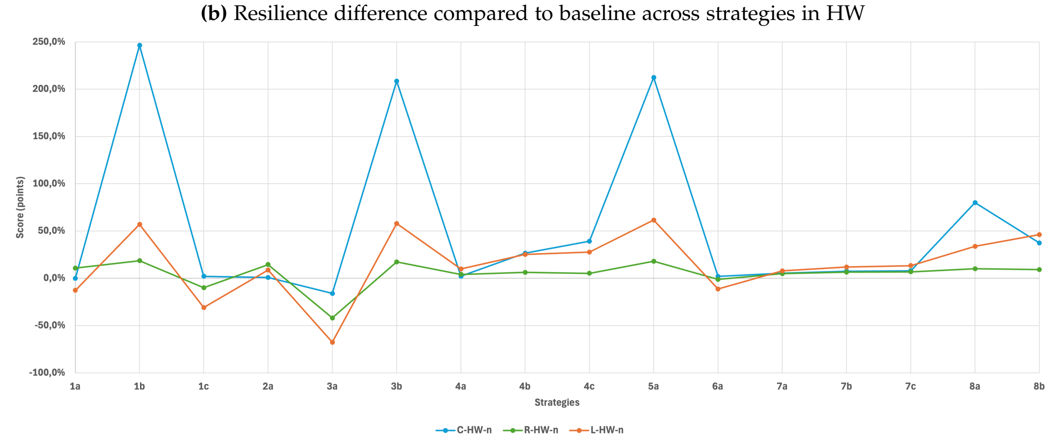


Figure 3.26: Resilience score and difference compared to baseline across strategies during the HW event.

Heatwave Event (HW)

As seen in Figure 3.26, the HW scenario posed the most significant challenges, with mean resilience scores declining across all locations compared to HT and LT. This decrease is particularly significant for Copenhagen, due to its high DoS during a HW. Rome and London performed similarly overall, but Rome's scores were more stable, while London exhibited greater variability.

High-performing strategies under HW included north-facing facades (1b), smaller window areas (3b), halved g-values (5a), and 4 hours of night cooling (8b). Conversely, west-facing facades (1a), east-facing facades (1c), larger window areas (3a), and halved U-values (6a) underperformed significantly. Copenhagen showed the lowest resilience scores under HW, but certain strategies—north-facing facades (1b), smaller window areas (3b), and halved g-values (5a) still achieved notable improvements relative to the baseline.

Strategy Performance Across Scenarios

The results of the study reveal significant variability in the effectiveness of cooling strategies across different European climates, highlighting the importance of context-specific recommendations.

- **North-facing facades (1b), smaller window area (3b) and halved g-values (5a)** consistently demonstrated strong performance across all locations and scenarios. By effectively minimizing solar heat gains, these strategies had a particularly significant impact under high-intensity scenarios such as HW, EX, and double occupancy, as well as in climates with intense solar radiation and high DoS, such as Copenhagen in the future and during a HW. Their consistent performance underscores their suitability for managing overheating and reducing cooling demands, making them versatile solutions for enhancing resilience under both current and future conditions. Additionally, these strategies excelled in terms of GWP, further contributing to their sustainability.
- **Natural ventilation (7-series)** strategies demonstrated overall strong performance, particularly during HT and LT events, with the exception of HW scenarios in Copenhagen. These strategies also excelled in terms of GWP.
- **Night cooling (8-series)** strategies maintained a overall good performance, specially under high intensity scenarios such as double occupancy, EX and HW events.
- **Larger window areas (3a) and halved U-values (6a)** consistently underperformed across all scenarios and locations, with their negative effects am-

plified in high intensity scenarios (such as double occupancy, EX and HW events), with higher solar radiation and extreme heat. However, strategy 3a (larger window area) demonstrates that during a heatwave (HW), this strategy exhibits the best recovery rates, which can be attributed to its ability to facilitate rapid heat dissipation once external temperatures drop.

These findings highlight the interplay between local climatic conditions, building orientation, and thermal dynamics. While certain strategies, such as north-facing facades (1b), smaller window areas (3b), and halved g-values (5a), demonstrated consistent effectiveness, their relative performance depended on location and scenario intensity. Poor performers, like larger window areas (3a), revealed their vulnerabilities more acutely under extreme conditions or double occupancy. These insights emphasize the need for tailored strategies to optimize resilience and energy efficiency in specific geographic and climatic contexts, particularly under future and extreme weather scenarios.

3.3.5 Resilience Compass

A "resilience compass" is defined (Figure 3.27) to provide an overview of the strategies with the most significant positive and negative impacts on resilience, as well as those showing negligible differences compared to the baseline, across the three locations and scenarios. Its objective is to provide more targeted recommendations based on climatic zones, and scenario intensity.

The three grey concentric circles represent the three impact categories, denoted by the symbols "-", "=", and "+":

- "-": Represents strategies with the greatest negative impact on resilience.
- "=": Denotes strategies that show no notable difference in resilience compared to the baseline.
- "+": Indicates strategies with the highest positive impact on resilience.

Within each impact category ("-", "=", "+"), strategies are organized in "steps" from the least to the most intense scenario (from inside to outside). For example, in Copenhagen (represented with blue shades):

- The inner grey circle (marked "-") represents strategies with the highest negative impact on resilience across all scenarios. Inside, strategies are displayed in "steps" from the least to the most intense scenarios.
- The middle grey circle (marked "=") indicates strategies with no significant impact, categorized in "steps" based on scenario intensity.

- The outermost grey circle (marked "+") shows strategies with the greatest positive impact on resilience, also grouped by scenario intensity.

In Copenhagen, the three "steps" symbolize the low, medium and high intensity scenarios; while for Rome and London two "steps" symbolize the low and medium intensity scenarios, as defined in Table 3.6.

The strategies are written in dark blue, except for those that have the greatest positive impact on GWP under current conditions, which are written in green, and those that have the best performance in terms of recovery rate under the HW scenario, which are written in red.

As shown in Table 3.6, in Copenhagen, the heatwave (HW) under normal occupancy poses the greatest resilience challenge, followed by HT and LT under double occupancy, and EX under normal occupancy, all classified as medium intensity. The least challenging scenarios are HT and LT under normal occupancy. In Rome, LT and HW under normal occupancy present medium challenges, while HT is considered low intensity. In London, medium-intensity scenarios include HT and LT under double occupancy, and HW under normal occupancy, with HT and LT under normal occupancy classified as low intensity.

As shown in Figure 3.27, among the evaluated strategies, increasing window area (3a) exhibits the most significant **negative impact** on resilience across all locations and scenarios. In medium-intensity scenarios, poor performance is also noted, particularly in London, for west- and east-facing facade strategies (1a and 1c). In Copenhagen, negative impacts are observed for the west-facing facade strategy (1a) and halved U-value (6a). However, during the HW scenario in Copenhagen, the larger window area strategy (3a) demonstrates a notable recovery rate.

Strategies that show the most **similar performance** to the baseline, with minimal positive or negative impact, include increased Cp (2a) and night cooling (8-series) across all locations, as well as east-facing facades (1c) and solar shading strategies (4-series) in London and Rome. In Rome, the halved U-value (6a) strategy also demonstrates negligible impact. Notably, manual solar shading strategies (4a and 4b) significantly improve recovery rates during HW.

Several strategies exhibit significant **positive impacts** on resilience. Across all locations, smaller window areas (3b), north-facing facades (1b), and halved g-values (5a) perform exceptionally well in high-intensity scenarios (for Copenhagen) and medium-intensity scenarios (for Rome and London). Additionally, strategy 3b shows strong performance in terms of GWP. For medium-intensity scenarios, additional strong performers include night cooling strategies (8-series) in London, west-facing facades (1a) in Rome, and east-facing facades (1c) in Copenhagen. In low-intensity scenarios, natural ventilation strategies (7-series) demonstrate the

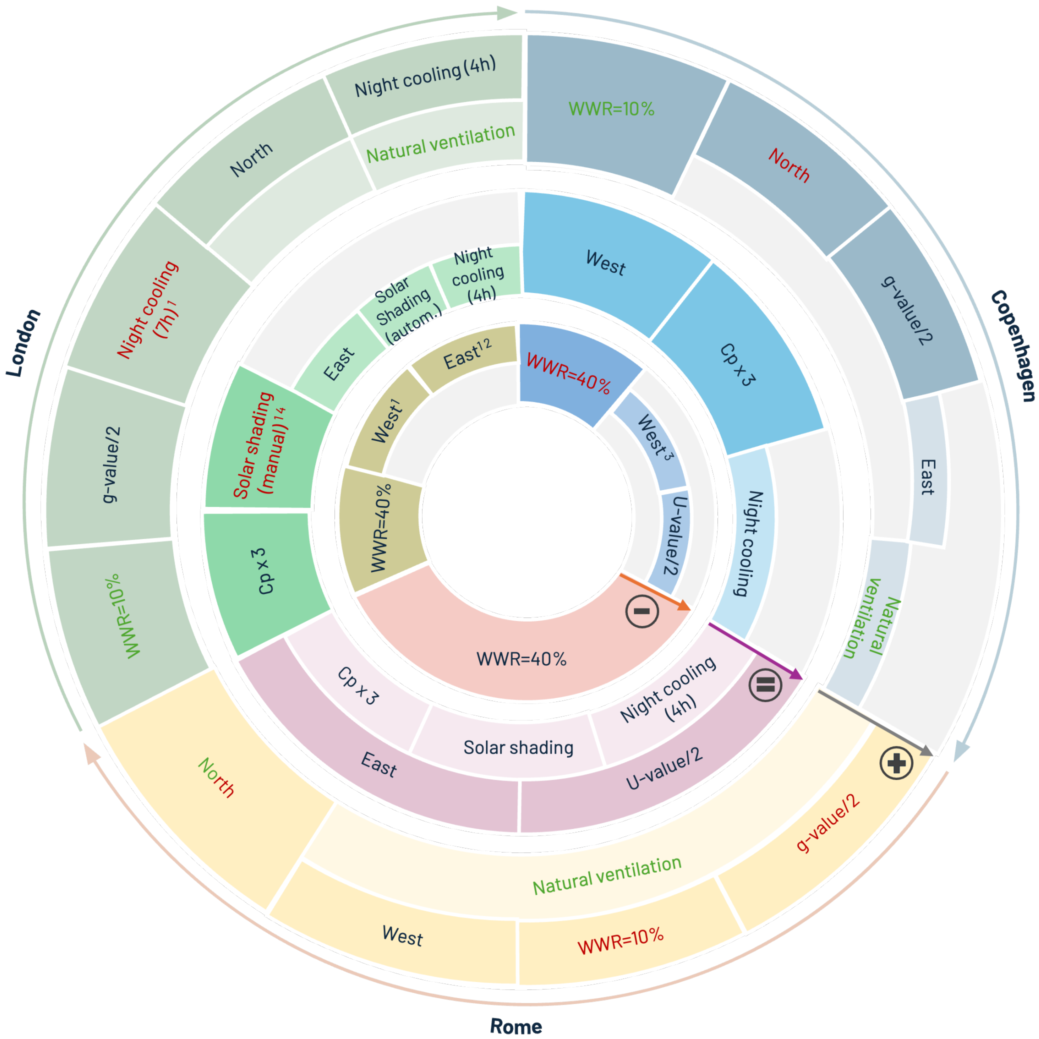


Figure 3.27: Overview of strategies with the highest positive and negative impacts on resilience and those with negligible differences compared to the baseline across Copenhagen (blue), Rome (orange), and London (green). Strategies are grouped into three impact categories: "-" (negative impact), "=" (no impact), and "+" (positive impact). Within each impact category, scenarios are further divided into high, medium, and low intensity levels, represented by "steps". Strategies that have the greatest impact on GWP are highlighted in green, while those with the better results on recovery rate are highlighted in red. The footnotes correspond to: ([1]) not applicable for HT; ([2]) not applicable for LT; ([3]) not applicable for EX; and ([4]) not applicable for HW.

greatest improvement across all locations in terms of resilience and GWP. Recovery rates vary by location, with the best performances observed in the north-facing facade strategy (1b) in Copenhagen, 4 hours of night cooling (8b) in London, and a combination of north-facing facade (1b), larger window area (3a), and halved g-value (5a) in Rome.

Table 3.8: Summary of the resilience evaluation (referred to as "RES"), including the total score and the percentage difference from the baseline; GWP and the recovery rate (percentage difference from the baseline in applicable scenarios) for all strategies across all scenarios in Rome.

	R-HT-n		**R-LT-n**	**R-HW-n**	
	RES	GWP	RES	RES	Rec.rate
Base.	8.0		6.3	5.9	
1a	8.1 *1.3%*	10.0%	6.8 *9.2%*	6.5 *10.7%*	10.7%
1b	8.3 *3.1%*	23.1%	7.5 *19.6%*	7.0 *18.6%*	18.6%
1c	7.8 *-2.6%*	8.5%	6.2 *-1.6%*	5.3 *-10.0%*	-10.0%
2a	8.0 *0.3%*	2.0%	6.9 *10.3%*	6.7 *14.5%*	14.5%
3a	6.7 *-15.9%*	-47.1%	3.7 *-41.3%*	3.4 *-42.0%*	-42.0%
3b	8.2 *2.7%*	20.7%	7.0 *12.6%*	6.9 *17.2%*	17.2%
4a	8.1 *0.6%*	2.7%	6.4 *2.9%*	6.1 *4.1%*	4.1%
4b	8.1 *1.0%*	5.3%	6.6 *5.9%*	6.2 *6.3%*	6.3%
4c	8.1 *0.6%*	2.4%	6.5 *3.8%*	6.2 *5.3%*	5.3%
5a	8.2 *2.7%*	19.6%	7.2 *15.8%*	6.9 *18.0%*	18.0%
6a	7.9 *-1.3%*	-4.3%	6.1 *-1.9%*	5.8 *-1.2%*	-1.2%
7a	8.3 *3.0%*	21.2%	6.6 *5.8%*	6.2 *4.9%*	4.9%
7b	8.3 *4.0%*	28.5%	6.8 *8.1%*	6.3 *6.5%*	6.5%
7c	8.4 *4.2%*	29.6%	6.8 *8.5%*	6.3 *6.8%*	6.8%
8a	7.9 *-1.3%*	-6.3%	6.8 *9.4%*	6.5 *10.2%*	10.2%
8b	8.0 *0.4%*	3.1%	6.8 *8.3%*	6.4 *9.1%*	9.1%

Table 3.9: Summary of the resilience evaluation (referred to as "RES"), including the total score and the percentage difference from the baseline; GWP and the recovery rate (percentage difference from the baseline in applicable scenarios) for all strategies across all scenarios in London.

	L-HT-n		**L-HT-d**		**L-LT-n**	**L-LT-d**	**L-HW-n**	
	RES	GWP	RES	GWP	RES	RES	RES	RecRate
Base.	9.0		6.8		8.7	5.8	5.4	
1a	9.0 *-0.1%*	-0.6%	7.6 *11.3%*	0.3%	8.4 *-3.5%*	3.9 *-33.3%*	4.7 *-12.8%*	-19.7%
1b	9.1 *0.7%*	1.6%	8.8 *28.2%*	4.1%	8.9 *2.4%*	8.0 *36.0%*	8.5 *57.0%*	-8.9%
1c	9.1 *0.3%*	0.4%	7.8 *14.4%*	1.9%	8.6 *-1.3%*	6.6 *13.3%*	3.7 *-30.9%*	-0.7%
2a	9.0 *0.1%*	0.3%	7.0 *2.2%*	0.6%	8.8 *0.5%*	6.3 *7.0%*	5.9 *8.7%*	-8.5%
3a	3.1 *-66.1%*	-15.1%	1.6 *-76.1%*	-16.1%	1.9 *-77.8%*	1.5 *-73.8%*	1.8 *-67.7%*	-7.3%
3b	9.2 *1.3%*	5.5%	8.8 *28.3%*	6.3%	9.0 *2.8%*	8.1 *38.6%*	8.5 *57.9%*	-40.0%
4a	9.1 *0.2%*	-0.1%	7.7 *12.4%*	-0.2%	8.5 *-2.7%*	5.8 *-1.6%*	5.9 *9.8%*	15.2%
4b	9.1 *0.5%*	0.7%	8.1 *19.2%*	1.0%	8.5 *-2.5%*	5.9 *0.2%*	6.8 *25.2%*	18.1%
4c	9.1 *0.3%*	-0.2%	8.3 *22.1%*	-0.4%	8.5 *-2.0%*	6.0 *2.9%*	6.9 *27.7%*	0.4%
5a	9.1 *1.1%*	3.1%	8.8 *28.5%*	5.4%	9.0 *3.8%*	8.5 *44.7%*	8.7 *61.6%*	-50.1%
6a	9.0 *0.1%*	0.8%	5.9 *-13.6%*	-1.1%	8.5 *3.8%*	5.4 *-7.0%*	4.8 *-11.3%*	5.2%
7a	9.2 *1.7%*	5.1%	7.2 *5.8%*	14.0%	8.9 *3.8%*	6.7 *14.7%*	5.8 *7.9%*	0.0%
7b	9.2 *2.3%*	7.1%	7.3 *7.3%*	19.1%	9.0 *3.8%*	7.1 *21.6%*	6.1 *11.8%*	0.0%
7c	9.3 *2.5%*	7.7%	7.4 *7.8%*	20.7%	9.0 *3.8%*	7.3 *24.1%*	6.1 *13.4%*	0.0%
8a	9.0 *-0.1%*	-0.6%	8.6 *25.3%*	-1.2%	8.9 *3.8%*	7.5 *27.7%*	7.2 *33.7%*	12.4%
8b	9.1 *0.2%*	0.7%	8.7 *26.8%*	0.8%	9.0 *2.7%*	7.9 *35.1%*	7.9 *46.2%*	-2.8%

Chapter 4

Discussion

This study offers a comprehensive evaluation of resilient cooling strategies tailored for office buildings in distinct European climates. The findings emphasize the critical role of adaptive measures in mitigating climate change-induced overheating while balancing energy efficiency and sustainability goals. Using simulations across Copenhagen, Rome, and London, the study provides valuable insights into how local climate conditions, occupancy levels, and extreme weather events influence the effectiveness of cooling strategies. The introduction of the Resilience Compass further provides clear and accessible recommendations for decision-makers by identifying strategies with the most significant positive, negative, or neutral impacts on resilience, tailored to specific climatic zones and scenario intensities.

Outdoor Conditions and Scenario Intensity

Outdoor conditions, such as temperature, solar radiation, and humidity, significantly shaped strategy performance. Rome exhibited the highest AWD, making it the most challenging scenario, though its higher cooling capacities offer some adaptive potential. In contrast, Copenhagen faces the largest temperature increases from current (HT) to future heatwave (HW) conditions in the summer, reflecting its vulnerability to future warming. Solar radiation is projected to increase in Copenhagen, surpassing levels in London and Rome, which are expected to decrease, potentially enhancing the performance of window-related strategies in these locations. Notably, Copenhagen's high DoS during HW events leads to sharp resilience declines, followed by London and Rome, reflecting differences in heatwave severity and duration.

Scenario intensity varied slightly across locations. In Copenhagen, normal occupancy scenarios (HT and LT) are low-intensity, while double occupancy, extreme hot years (EX), and HW are significantly more intense, with HW posing the greatest challenges. Rome's normal occupancy scenarios like HT scenarios are low-intensity, but LT and HW shift to medium intensity due to increased heat stress. London follows a similar trend, with HT and LT under normal occupancy classified as low-intensity, while double occupancy and HW escalate to medium intensity. Notably, double occupancy consistently amplified internal heat loads, often posing a greater challenge than temperature increases expected in future climate scenarios.

Strategy Performance

Most strategies performed well under low-intensity scenarios but showed reduced effectiveness in high-intensity conditions. Strategies such as north-facing facades (1b), smaller window areas (3b), halved g-values (5a), natural ventilation systems (7-series), and night cooling strategies (8-series) exhibited strong resilience, particularly under high-intensity scenarios. Conversely, west-facing facades (1a), larger window areas (3a), and halved U-values (6a) often underperformed, as they either trapped heat or amplified solar gains, exacerbating internal heat stress.

Some strategy series, such as the 4-series (solar shading mechanisms) and 8-series (night cooling strategies), showed minimal performance differences across their variations. Solar shading strategies performed consistently regardless of shading type or control method, while night cooling strategies provided similar relief whether implemented as full-night (8a) or partial-night cooling (8b).

Holistic Cooling Solutions and Limitations

The findings underscore the need for holistic cooling solutions that integrate thermal comfort, energy efficiency, recovery capabilities, and lifecycle sustainability to create robust and adaptive designs. Strategies like north-facing facades (1b), smaller window areas (3b), and natural ventilation systems (7-series) not only performed well in thermal comfort and energy efficiency but also minimized embodied carbon and operational emissions, making them sustainable and resilient solutions. Conversely, night cooling strategies (8-series), while effective in recovery from overheating, demonstrated trade-offs in energy demand and GWP, necessitating careful evaluation.

The recovery rate emerged as a critical metric for evaluating resilience under extreme events like HW. Strategies such as night cooling (8-series) and larger window areas (3a) excelled in quickly restoring thermal comfort, minimizing occupant discomfort and easing strain on cooling systems. However, strategies like 3a, while strong in recovery, underperformed in overall resilience, highlighting the challenge of balancing rapid recovery with sustained performance in thermal comfort and energy efficiency.

These findings enhance the existing body of knowledge by offering a detailed analysis of individual strategy performance under varying conditions. However, certain limitations remain, which can be addressed through future work, outlined in Chapter 5.

Chapter 5

Conclusion

This study establishes a comprehensive framework for evaluating resilient cooling strategies tailored to office buildings across diverse European climates. By integrating considerations of thermal comfort, energy efficiency, and sustainability, it delivers insights into how localized climatic conditions, varying weather scenarios, and occupancy loads influence strategy performance. The findings emphasize the importance of adaptive, context-specific approaches in designing climate-resilient buildings capable of mitigating the impacts of global warming.

5.1 Summary of Project Scope

The project scope encompassed the following:

- Building type: Office buildings.
- Room-level analysis: Analysis at the room level, enabling scalability to multiple rooms and building levels while maintaining functional independence.
- Climate zones: Diverse European locations, including Copenhagen (cool-humid), Rome (warm-humid), and London (mixed-humid).
- Climate events: Historical weather (HT), long-term weather (LT), extreme hot weather (EX), and heatwave event (HW).
- Occupancy loads: Normal and double occupancy, examining the impact of increased internal heat loads.
- Evaluation and comparison of strategies: Individual analysis of passive cooling strategies, including facade orientations, window properties, natural ven-

tilation, and solar shading, to identify their resilience and sustainability impacts.

5.2 Key Findings and Conclusions

1 **Impact of Outdoor Conditions:** The performance of cooling strategies is significantly influenced by outdoor conditions, including temperature, solar radiation, and humidity. Rome exhibited the highest AWD, making it the most challenging location, although its higher cooling capacities may enhance adaptation. In contrast, Copenhagen exhibited sharp declines under HW due to its high DoS, highlighting its susceptibility to overheating. Projected increases in solar radiation in Copenhagen and decreases in London and Rome will impact window-related strategies. These findings emphasize the need for location-specific cooling solutions.

2 **Scenario Intensity Impacts:** Scenarios under normal occupancy, such as HT and LT, were classified as low-intensity across all locations, while double occupancy, extreme hot years (EX), and heatwaves (HW) represented medium to high-intensity challenges. Double occupancy consistently amplified internal heat loads, presenting greater challenges than moderate temperature increases from future climate scenarios.

3 **Strong-Performing Strategies:** Strategies such as north-facing facades (1b), smaller window areas (3b), halved g-values (5a), natural ventilation systems (7-series), and night cooling (8-series) consistently performed well in terms of resilience across varying scenarios, particularly in high-intensity conditions. These strategies achieved a strong balance of thermal comfort and energy efficiency.

4 **Underperforming Strategies:** Strategies like west-facing facades (1a), larger window areas (3a), and halved U-values (6a) often underperformed, either trapping heat or amplifying solar gains, which intensified internal heat stress, particularly in high-intensity scenarios.

5 **Minimal Variation in Certain Strategies:** Strategy series like solar shading (4-series) and night cooling (8-series) exhibited minimal differences in performance across variations, with solar shading performing consistently regardless of control type and night cooling showing similar results regardless of duration.

6 **Balancing Resilience and Sustainability:** Strategies like smaller window areas (3b) and natural ventilation systems (7-series) enhanced resilience while minimizing embodied carbon and operational emissions.

7 **Balancing Resilience and Recovery during Heatwaves:** Quick recovery after heatwaves (HW) is crucial for minimizing occupant discomfort and cooling demands. Strategies like 8-series (night cooling) and 3a (larger window area) excelled in recovery, but 3a's poor overall resilience highlights the need to balance recovery speed with thermal comfort and energy efficiency.

9 **Development of the Resilience Compass:** To offer more precise recommendations, focusing on strategies with the most substantial positive and negative impacts on resilience, as well as those with minimal variation from the baseline, tailored to specific climatic zones and scenario intensities.

5.3 Limitations and Future Work

While the study provides valuable insights, several limitations must be highlighted:

- Simplified building model: The single-zone approach facilitated the analysis but did not capture complexities of multi-zone or mixed-use buildings.
- Baseline definition limitations: While the baseline was primarily based on established requirements, certain assumptions were made regarding the room's size, orientation, and layout. These simplified choices aimed to maximize generalizability but may not fully capture the diversity of real-world configurations, potentially limiting the applicability of the findings.
- Location-specific in baseline: Baseline specifications and cooling capacities tailored to each location enhance relevance but limit cross-comparison standardization.
- Parameters in resilience indicator: The resilience indicator prioritized thermal comfort (68.75% weight) over energy performance (31.25%), potentially overlooking other critical aspects, such as GWP impacts. Incorporating GWP effectively will require reliable future emission factor projections, which were unavailable in this study and thus represent a key limitation.
- Subjectivity in scoring system: The system was specifically developed for this project and incorporates available standards where possible. However, in the absence of guidelines, it relied on informed assumptions, introducing some subjectivity that may impact the reproducibility and comparability of the findings.

Future work directions include:

- Expand to diverse building types and multi-zone configurations.

- Explore additional climates, weather events, and occupancy types (e.g., varying loads and activities).
- Conduct sensitivity analysis of the baseline parameters to understand their influence on the outcomes.
- Investigate synergistic effects of combined strategies.
- Include operational data (such as energy use, occupant behavior, and system performance) for validation and refinement of findings.
- Expand the resilience indicator by integrating parameters like GWP, costs, or vulnerability of the location for a more holistic assessment.
- Use widely recognized standards or guidelines to establish the scoring systems for evaluating the results.

5.4 Final remarks

By providing decision-makers with a practical and adaptable framework, this study supports the implementation of resilient cooling strategies to specific contexts. Emphasizing sustainability and resilience, the findings contribute to future-proofing the built environment against intensifying climate risks related to heat. Addressing the identified limitations outlined and advancing the proposed future work will further enhance the framework's relevance and effectiveness in addressing the challenges of a changing climate.

Bibliography

[1] (UNEP) United Nations Environment Programme. "A Practical Guide to Climate-resilient Buildings and Communities". In: (2021). URL: https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/36405/Adapbuild.pdf.

[2] IPCC. *Global Warming of 1.5C*.

[3] Nick Watts et al. "The 2018 report of the Lancet Countdown on health and climate change: shaping the health of nations for centuries to come". In: *Lancet (London, England)* 392.10163 (2018), 2479–2514.

[4] Alistair Hunt and Paul Watkiss. "Climate change impacts and adaptation in cities: a review of the literature". In: *Climatic Change* 104.1 (2011), 13–49.

[5] Lei Zhao et al. "Strong contributions of local background climate to urban heat islands". In: *Nature (London)* 511.7508 (2014), 216–219.

[6] Shady Attia et al. "Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition". In: *Energy and Buildings* 239 (2021), p. 110869.

[7] United Nations Environment Programme. *2020 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION*. 2020.

[8] M. A. D. Larsen et al. "Climate change impacts on trends and extremes in future heating and cooling demands over Europe". In: *Energy and Buildings* 226 (2020), p. 110397.

[9] R. Rahif et al. "Simulation-based framework to evaluate resistivity of cooling strategies in buildings against overheating impact of climate change". In: *Building and Environment* 208 (2022). Impacts of climate change on buildings in Belgium during summer, p. 108599.

[10] United Nations Environment Programme. *2020 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION*. 2022.

[11] *DIRECTIVE (EU) 2024/1275 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL*. 2024.

[12] Stelios Grafakos et al. "Analytical framework to evaluate the level of integration of climate adaptation and mitigation in cities". In: *Climatic Change* 154.1-2 (2019), 87–106.

[13] Chen Zhang et al. "Resilient cooling strategies – A critical review and qualitative assessment". In: *Energy and Buildings* 251 (2021), p. 111312.

[14] European Commission. *EU-level technical guidance*. Best practice Guidance. 2023.

[15] Abantika Sengupta et al. "Building and system design's impact on thermal resilience to overheating during heatwaves: An uncertainty and sensitivity analysis". In: *Building and Environment* 265 (2024), p. 112031.

[16] Bin Qian et al. "Suitability of heat wave event definitions for assessing indoor overheating in current and future climate: A case study in China". In: *Building and Environment* 241 (2023), p. 110487.

[17] *IEA EBC Annex 80 - Resilient Cooling of Buildings*. URL: `https://annex80.iea-ebc.org`.

[18] Essam Elnagar et al. "Integration of resilient cooling technologies in building stock: Impact on thermal comfort, final energy consumption, and GHG emissions". In: *Building and Environment* 261 (2024), p. 111666.

[19] Azlizawati Ibrahim and Sofie L. J. Pelsmakers. "Low-energy housing retrofit in North England: Overheating risks and possible mitigation strategies". In: *Building Services Engineering Research and Technology* 39.2 (2018), 161–172.

[20] Adam O' Donovan, Michael D. Murphy, and Paul D. O'Sullivan. "Passive control strategies for cooling a non-residential nearly zero energy office: Simulated comfort resilience now and in the future". In: *Energy and Buildings* 231 (2021), p. 110607.

[21] Serena Falasca et al. "High albedo materials to counteract heat waves in cities: An assessment of meteorology, buildings energy needs and pedestrian thermal comfort". In: *Building and Environment* 163 (2019), p. 106242.

[22] ARUP. *REDi Rating System*. URL: `https://www.redi.arup.com`.

[23] Observatoire de l'Immobilier Durable (OID). *R4RE (Resilience for Real Estate)*. URL: `https://r4re.resilience-for-real-estate.com/resilience/analysis`.

[24] Perkins and Will. *RELi Reslience Action List*. URL: `https://research.perkinswill.com/projects/reli-reslience-action-list-credit-catalog/`.

[25] ANSI/ASHRAE/IES Standard 90.1. *Energy Standard for Buildings Except Low-Rise Residential Buildings*. 2016.

[26] Bolig og Planstyrelsen. *BR18*. 2023. URL: `https://bit.ly/4312WAl` (visited on 11/21/2023).

[27] *Bygningers energieffektivitet -Indeklimakvalitet -Del 1: Inputparametre for indeklima til projektering og vurdering af bygningers energimaessige ydeevne = Energy performance of buildings - Indoor environmental quality - Part 1: Indoor environmental input parameters for the design and assessment of energy performance of buildings*. eng. DS/ISO17772-1. Dansk Standard, 2017.

[28] *Bygningers energieffektivitet -Brugsmønster og konditionering af bygninger, bygningszoner og -rum for energiberegninger -Del 1: Erhvervsbygninger = Energy performance of buildings - Schedule and condition of building, zone and space usage for energy calculation - Part 1: Non-residential buildings*. eng. DS/ISO18523-1. Dansk Standard, 2016.

[29] MOE A/S. *Vejledning til BSim Template Konsistent modellering af kontor-rum i BSim Dokumentation og vejledning*. 2021.

[30] Anaïs Machard et al. "Typical and extreme weather datasets for studying the resilience of buildings to climate change and heatwaves". In: (2024).

[31] Manuel Herrera et al. "A review of current and future weather data for building simulation". In: *Building Services Engineering Research and Technology* 38.5 (2017).

[32] BY O. M. BUILD INSTITUT FOR BYGGERI. *KLIMADATA*. URL: `https://www.build.aau.dk/til-byggebranchen/software/bsim/klimadata`.

[33] International Energy Agency. *Resilient Cooling of Buildings Key Performance Indicators Report (Annex 80)*. Energy in Buildings and Communities Technology Collaboration Programme. 2024.

[34] Chen Zhang et al. *IEA EBC Annex 80 - Dynamic simulation guideline for the performance testing of resilient cooling strategies: Version 2*. 2023.

[35] *Bygningers energieffektivitet - Ventilation i bygninger - Del 1: Indeklimamæssige inputparametre til beregning og evaluering af bygningers energieffektivitet i forbindelse med indendørs luftkvalitet, termisk miljø, belysning og akustik - Modul M1-6 = Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6*. eng. Elektronisk udgave. DS/EN ; 16798-1. Charlottenlund: Dansk Standard, 2019.

[36] Shady Attia et al. *Framework to evaluate the resilience of different cooling technologies*. Feb. 2021.

[37] Douaa Al Assaad et al. "Resilient passive cooling strategies during heat waves: A quantitative assessment in different climates". In: (2024).

[38] Mohamed Hamdy et al. "The impact of climate change on the overheating risk in dwellings—A Dutch case study". In: *Building and Environment* 122 (2017), 307–323. URL: https://www-sciencedirect-com.zorac.aub.aau.dk/science/article/pii/S0360132317302664.

[39] Eurostat. *Disaggregated final energy consumption in households*. URL: https://ec.europa.eu/eurostat/databrowser/view/nrg_d_hhq__custom_13867054/default/table?lang=en.

[40] European Comission. *BSO - EU Building Stock Observatory*. URL: https://building-stock-observatory.energy.ec.europa.eu/database/.

[41] Å Wahlström and H. Brohus. "An Eco-factor method for assessment of building performance". In.

[42] G. Ouzeau et al. "Heat waves analysis over France in present and future climate: Application of a new method on the EURO-CORDEX ensemble". In: *Climate Services* 4 (2016), 1–12.

[43] S. Flores-Larsen, F. Bre, and M. Hongn. "A performance-based method to detect and characterize heatwaves for building resilience analysis". In: *Renewable and sustainable energy reviews* 167 (2022), p. 112795.

[44] *Miljøledelse – Livscyklusvurdering – Principper og struktur – Tillæg 1 = Environmental management – Life cycle assessment – Principles and framework – Amendment 1 (ISO 14040:2006/Amd 1:2020).* eng. Elektronisk udgave. DS/EN ISO 14040:2006/A1:2020. Accessed: May 20, 2024. Charlottenlund: Dansk Standard, 2020.

[45] *Bæredygtighed inden for byggeri og anlæg - Vurdering af bygningers miljømæssige kvalitet - Beregningsmetode = Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.* eng. Elektronisk udgave. DS/EN ; 15978. Accessed: May 5, 2024. Charlottenlund: Dansk Standard, 2012.

[46] Aluminium Spanish Association (AEA). *Environmental Product Declaration - Aluminium windows*.

[47] GRIESSER AG. *Environmental Product Declaration - Lamisol, Aluflex, Grinotex and Solomatic external venetian blinds with aluminium slats*.

[48] Observatoire de l'immobilier durable (OID). "Guide des actions adaptatives au changement climatique". In: (2024). URL: https://resources.taloen.fr/resources/documents/1621_240117_Guide_des_actions_adaptatives_au_changement_climatique.pdf.

[49] LEED. *Design for Enhanced Resilience*. URL: https://www.usgbc.org/credits/new-construction-core-and-shell-schools-new-construction-retail-new-construction-27.

[50] UK goverment. *Greenhouse gas reporting: conversion factors 2023*. URL: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023.

[51] Ecoinvent. *Ecoinvent database*. URL: https://ecoinvent.org.

[52] UK goverment. *Energy and emissions projections 2022 to 2040*. 2023.

[53] European Commission. *Climate Action: Italy*. Tech. rep. URL: https://climate.ec.europa.eu/document/download/56deb7d7-65f0-47b0-8f57-1164c7d740a1_en?filename=it_2023_factsheet_en.pdf.

Appendix A

Strategies Literature Review

The literature review focused on evaluating strategies for mitigating heat, with an emphasis on minimizing heat gain and removing excess heat from indoor spaces. It prioritized strategies applicable to the Northern Hemisphere, particularly Europe, and those suitable for early-stage design implementation. Strategies unrelated to building design—such as surrounding structures, vegetation, or occupant behavior—were excluded, as were strategies that could not be tested in BSim.

Table A.1, shows different strategies found during the literature review, categorized based on three key aspects of the building: the site, the building envelope, and the building systems. For building sites and envelopes, the focus is on striking a balance between minimizing heat gain and controlling direct sunlight in summer, while allowing light and heat penetration during winter. In terms of building systems, the priority is on effectively removing excess heat and providing cooling when passive measures are insufficient.

During the literature review, a special focus was set on the components that have the greatest impact on thermal comfort and energy consumption include the building envelope, which forms the large surface separating the interior from the external environment; the openings, which serve as primary entry points for sunlight and heat; the roof, which can account for up to 70% of the building's heat gain [1]; and the cooling systems, which offer immediate relief when passive strategies are inadequate. In terms of resilience, photovoltaic (PVs) systems enhance energy independence by enabling electricity self-consumption, reducing reliance on external energy networks.

Table A.1: Summary of strategies analyzed in the literature review.

Strategy		Reference
Building site		
Layout	Orientation main facade *North or south orientations to minimize heat gains*	[1]; [14]; [7]
	Air tightness *Compactness and avoidance of thermal bridges*	[1]; [14]; [48]; [49]
	Perimeter/area ratio small *Less area exposed to solar radiation*	[1]
Building envelope		
Facade	Reflective materials *Minimize heat gain with materials with a high solar reflectance index*	[1]; [14]; [48]; [21]; [7]
	High thermal mass materials *Captures heat during the day and releases it at night when it's cooler*	[1]; [13]; [49]
	Green facade *Acts as heat storage and shading*	[14]; [48]; [13]
	Low thermal conductivity *Minimize heat transmission through the building envelope*	[1]; [48]; [19]; [49]
Roof	Reflective materials *Minimize heat gain with materials with a high solar reflectance index*	[1]; [14]; [48]; [49]; [7]
	Green roof *Acts as heat storage and shading*	[14]; [48]; [13]
	Low thermal conductivity *Minimize heat transmission through the building envelope*	[1]; [19]; [49]
Openings	Orientation *North and south orientations to avoid direct sunlight*	[48]; [1]
	WWR[1] *Minimize amount of direct sunlight.*	[1]; [14]; [48]; [7]
	External solar shadings [2] *Minimize amount of direct sunlight, particularly in summer, in south and west facades*	[1]; [48]; [13]; [19]; [49]; [7]
	Glazing properties, g-value & U-value *Minimize heat gain with a low g-value and reducing heat loss with low U-value*	[1]; [13]; [19]; [49]; [7]
Building systems		
Ventilation	Natural ventilation *Single or cross ventilation*	[1]; [48]; [13]; [7]
	Night cooling *Cooling at night when temperatures are lower*	[1]; [14]
	Ventilated roof or facade	[1]; [13]
Cooling	Adiabatic cooling	[48]; [13]
	Geothermal	[48]; [14]
	District cooling	[48]
Electricity	Photovoltaic cells	[48]

1 Included similar strategies such as Openable Window to Floor Area ratio
2 Included similar strategies such as internal solar shadings

Appendix B

Building Envelope and Systems

This annex focuses on the building envelope and systems relevant to the project, specifically outlining a simplified office space model within the BSim building simulation program.

B.1 Baseline

The building envelope constructions comply with ASHRAE requirements adapted for different climate zones and follow common practices across Europe [25]. Details are provided in Table B.1.

The room contains two windows. The area of the larger window (no.1) is based on the minimum industry default specified by [29] for European office buildings. The area of the smaller window (no.2) is determined following the [25] guidelines for surface area requirements for south- and east-facing windows. These guidelines specify that the area of window no.2 must not exceed one-fourth of the total window area, where the total is the sum of the areas of window no.1 and window no.2. Consequently, the area of window no.2 is calculated as one-third of the area of window no.1. Based on these requirements, window no.1 has an area of 7.2 m^2, and window no.2 has an area of 2.4 m^2.

Additionally, the systems and their operational schedules are established in compliance with Danish and European regulations, following standards such as ISO 17772 [27], and ISO 18523 [28], as well as typical practices in Europe [29]. Specifically, set points are determined in accordance with IEQ Category II, and the system schedules are aligned with occupancy hours, operating year-round, Monday to Friday, from 8:00 to 18:00, as defined in [27]. Where specific requirements or established practices in Europe were unavailable, reasonable assumptions were made.

Table B.1: Details on building envelope constructions. Values for different climate zones are differentiated as follows: blue for Copenhagen, orange for Rome, and green for London. N/A indicates that there are no specific requirements.

Element	Parameter	Value	Reference
Roof	U-value	0.18 0.22 0.18	[25]
Ext. walls	U-value	0.51 0.70 0.60	[25]
Windows	U-value	1.76 1.87 1.76	[25]
	g-value	0.38 0.25 0.36	[25]
Int. walls	U-value	0.42	N/A
Int. floor	U-value	0.29	N/A

The following systems are defined in the baseline model, and further described in Table B.2:

- Equipment load: defined according to [27]
- Heating system: designed to effectively meet demand and maintain the desired set point throughout all year.
- Infiltration: defined with a constant ACH defined according to [29], and operating at full capacity during operational hours and at 60% outside of these hours.
- People load: defined for the two scenarios outlined in this paper: normal and double occupancy, based on the minimum defined by [27].
- Mechanical ventilation system: defined with a constant ACH for the minimum ventilation flow according to [27], and equipped with both cooling and heating coils to ensure the setpoint is maintained, operating from one hour before occupancy to one hour after.
- Cooling system: distinct cooling capacities are established for each climate zone to more accurately simulate the cooling requirements in different European locations. The cooling power is determined for each location in the baseline. The set point is set to a higher temperature to ensure activation

occurs only after other passive systems have been utilized. It is available all year.

Table B.2: Details on building systems. Values for different occupancy are differentiated as follows: red for normal occupancy and brown for double occupancy. Values for different climate zones are differentiated as follows: blue for Copenhagen, orange for Rome, and green for London. "Occ. hrs" refers to occupancy hours, which run year-round, Monday to Friday, from 8:00 to 18:00.

System	Parameter	Value	Reference
Equipment	Heat load	0.86 (kW)	[27]
	Control	Occ. hrs	[27]
Heating	Maximum power	100 (W/m^2)	Meets demand
	Set point	20 (°C)	[27]
	Control	Always	
Infiltration	Basic ACH	0.13 (1/h)	[29]
	Control	100% Occ. hrs 60% outside	[29]
People load	Number of people	7.2	[27]
		14.4	Doubled
	Heat generation	0.12 (kW)	[27]
	Moisture generation	0.43 (kg/h)	[27]
	Control	Occ. hrs	[27]
Ventilation	Ventilation flow rate	0.10 (m3/s)	[27]
	Heat. coil max. power	5 (kW)	Maintains 20°C
	Cool. coil max. power	-5 (kW)	Maintains 20°C
	Supply temperature	20 (°C)	[27]
	Control	± 1hr Occ. hrs	[29]
Cooling	Maximum power	-2.5 (kW) -5.5 (kW) -3 (kW)	Typical office today
	Set point	24.5 (°C)	Lower priority
	Control	Occ. hrs	[29]

B.2 Strategies

The defined strategies are tested by adjusting the parameters outlined in Table B.3 relative to the baseline configuration. Unless otherwise specified, all parameters remain consistent with the baseline. Additionally, two new systems are introduced:

- Natural ventilation: Manually operated (active only during operational hours), with a set point of 23°C based on [27]. Each strategy is defined with a maximum air change rate.

- Night cooling: Set to a 19°C set point to cool the zone overnight to a temperature slightly below the desired during occupancy hours. Different activation durations will be tested across strategies.
- External solar shading: Installed on both windows, with varying SC values tested in the strategies. Shading is manually operated and set to a 24°C set point, giving it a lower priority than natural ventilation but higher than mechanical cooling.

Table B.3: Summary of strategies and their variables adjusted in the model relative to the defined baseline. Values for different climate zones are differentiated as follows: blue for Copenhagen, orange for Rome, and green for London. N/A indicates that the system is not present in the model.

	Strategy	Parameter	Baseline	Variables a	Variables b	Variables c
1	Facade/ window orientation	Rotation	0	90°	180°	270°
2	Concrete Cp	Cp (J/kgK) *External walls*	800	1200		
3	WWR	Area (m^2) *Window no.1*	7.2	14.4	3.6	
		Area (m^2) *Window no.2*	2.4	4.8	1.2	
4	Solar shading	SC	N/A	0.5	0.15	0.5
		Control	N/A	manual	manual	automatic
5	g-value	g-value () *Windows*	0.38	0.19		
			0.25	0.125		
			0.36	0.18		
6	U-value	U-value () *Windows*	1.7	0.85		
			1.8	0.9		
			1.7	0.85		
7	Natural ventilation	ACH (1/h)	N/A	2	5	10
8	Night cooling	Control	N/A	7h (22-5h)	4h (1-5h)	

Appendix C

Model Validation

The model was developed to represent a typical European office room accurately. In the absence of an existing case for direct validation, model validation focused on verifying assumptions, comparing outputs to reference data, and ensuring realistic behavior.

The model represents a single office room of 72 m^2 with two windows. Assumptions regarding building envelope construction and systems align with European regulations and common practices (see Subsection 2.1.2 for details).

Validation was conducted for Copenhagen using current weather data and normal occupancy levels. The analysis included:

1 **Annual heat balance**: Figure C.1 displays the yearly heat balance, showing contributions from heating, equipment load, people load, and solar radiation gains, as well as losses due to cooling, infiltration, transmission, and ventilation.

2 **Monthly operative temperature**: Figure C.2 presents the monthly mean operative temperature throughout the year for both occupied hours and all hours.

3 **Daily heat gains and losses**: Figures C.3 and C.4 display daily heat gains and losses during winter and summer, covering equipment and people load, solar radiation, and transmission losses alongside the operative temperature of the room.

4 **Weekly heating and cooling demand**: Figures C.5 and C.6 illustrate the heating and cooling demand over a typical week in winter and summer, showing comparisons with the room's operative temperature.

5 **Weekly ACH and operative temperature**: Figures C.7 and C.8 display weekly

ACH and operative temperature in winter and summer.

Analysis of these performance metrics confirms that the model functions as intended, providing realistic and scalable insights across varied European climates and room configurations.

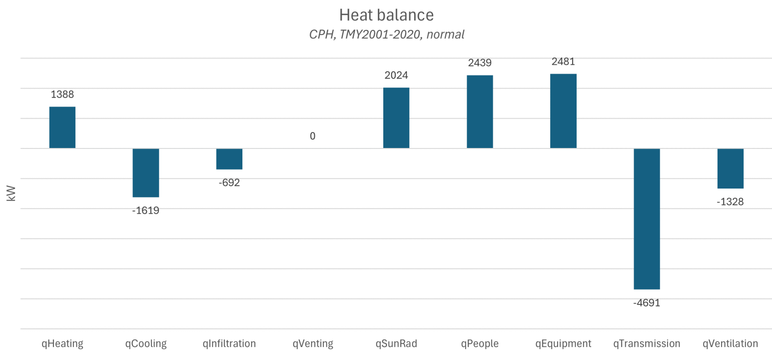


Figure C.1: Heat balance.

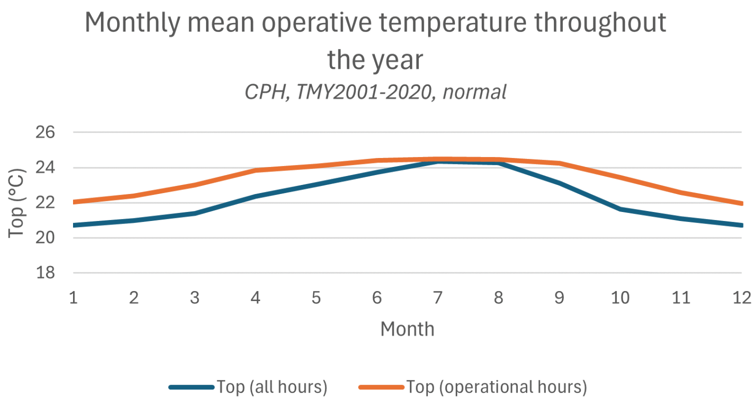


Figure C.2: Monthly mean operative temperature throughout the year.

Several modifications were implemented during the validation to better align the model with a realistic case in the European context.

- **Cooling system set point**: the cooling system temperature set point was set above that of passive systems to ensure delayed activation.
- **Climate-specific cooling capacities**: different cooling capacities were defined for each climate zone, based on the maximum cooling demand identified in the baseline for each location, to make the model more accurate and representative of realistic cases in the European context.
- **Climate-specific envelope specifications**: different building envelope charac-

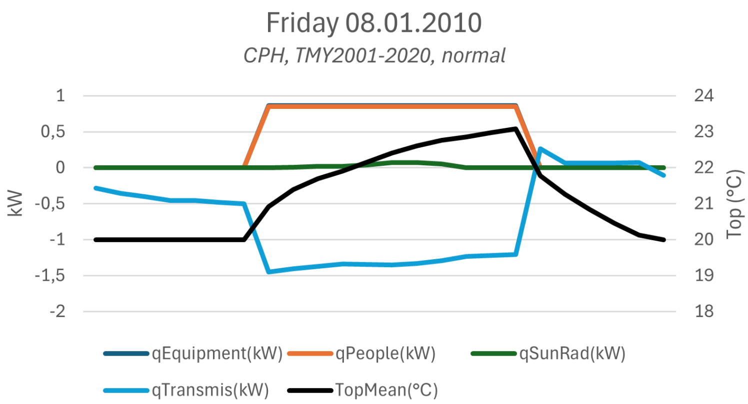


Figure C.3: Daily overview in winter.

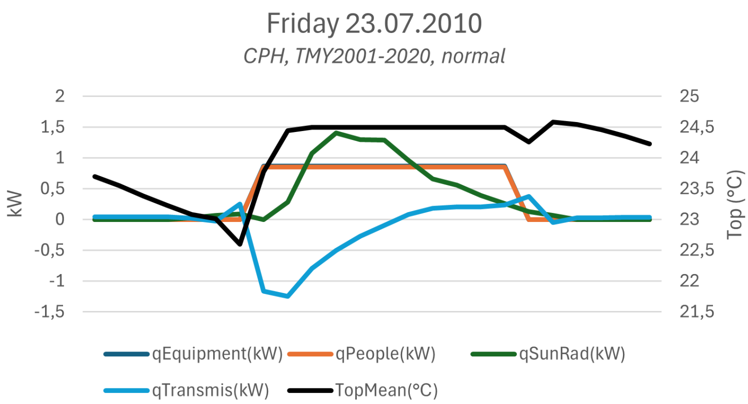


Figure C.4: Daily overview in summer.

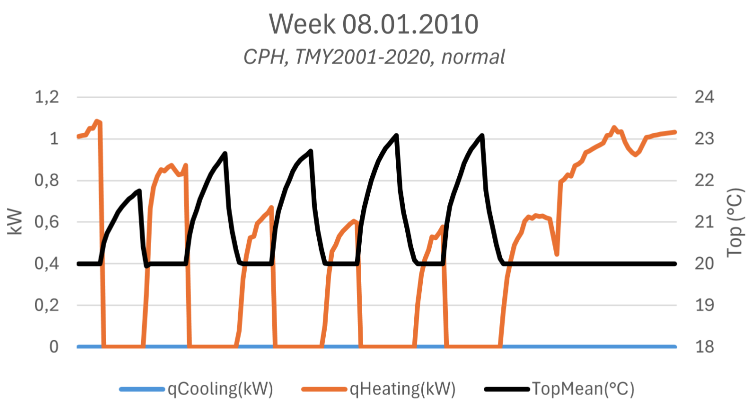


Figure C.5: Weekly overview in winter.

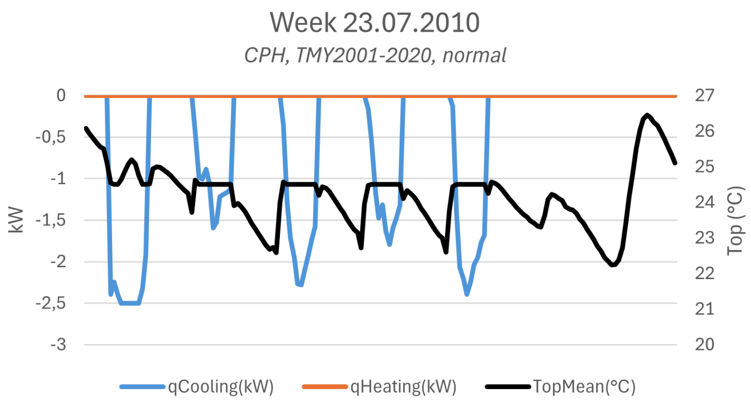


Figure C.6: Weekly overview in summer.

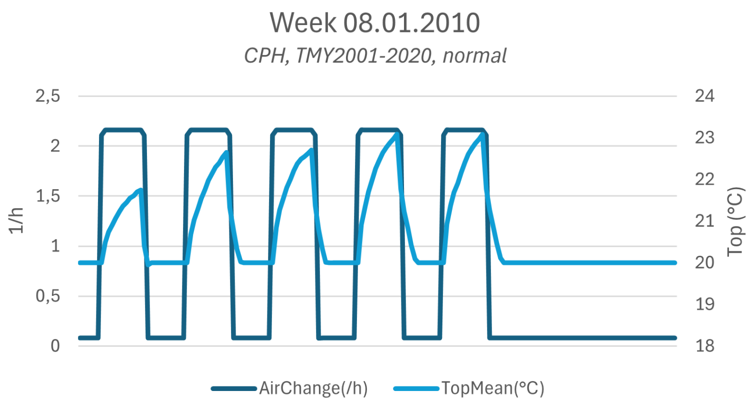


Figure C.7: Weekly ACH and Top overview in winter.

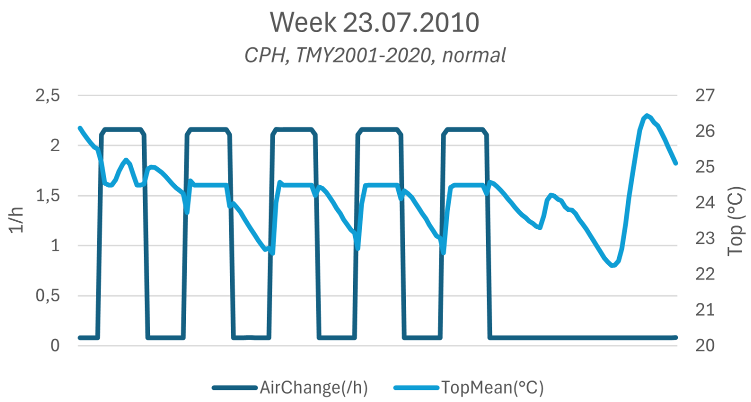


Figure C.8: Weekly ACH and Top overview in summer.

teristics were defined for each climate zone, based on the specifications made by [25], to make the model more accurate and representative of realistic cases in the European context.

- **Simplified systems**: ventilation and infiltration were simplified by establishing a constant ACH, while the heating system maintained a fixed setpoint for all hours.
- **Ventilation system coils**: initially, the ventilation system included only a heat recovery unit, which was insufficient to achieve the defined setpoint. To address this, cooling and heating coils were added to the system.

The analysis of the above key performance metrics shows the correct function of the model, and proofs that the simplified model provides realistic and scalable insights.

Appendix D

Scoring System Definition

The scoring system for each KPI was defined by establishing maximum, acceptable minimum, and average values based on specific assumptions, and where possible, existing benchmarks or available data. This section explores the assumptions and parameters considered and provides a rationale for them.

HE and OEF

In the absence of a common standard for acceptable and unacceptable HE levels in a room across the three locations, it was assumed that the optimal scenario occurs when HE is 0%. On the other hand, a HE higher than 5% was considered unacceptable, meaning that if more than 5% of the operational hours during the summer exceed 26°C, the scenario is deemed unacceptable and assigned a score of 0 points. The 5% threshold was established in accordance with [35], which specifies a permissible range of deviation within thermal comfort limits between 3% and 6%.

The thresholds for acceptable and unacceptable OEF levels were determined based on the definition of the KPI, which is the ratio between IOD and AWD. The maximum and minimum acceptable values for these parameters, and consequently for the OEF, were calculated and set as boundaries. The highest performance (10 points) is achieved when IOD equals 0, indicating no temperatures above 26°C, resulting in an OEF of 0. The lowest performance (0 points) corresponds to the maximum OEF, which is determined as follows:

- The maximum acceptable IOD occurs when the comfort temperature (26°C) is exceeded by 0.5°C for 5% of the summer operational hours, resulting in an IOD of 0.3.

- The minimum AWD for each location across all weather events, which is provided in Table D.1.

These values are summarized in Table D.1.

Table D.1: Determination of the maximum and minimum OEF for each location.

	Copenhagen	**Rome**	**London**
Lower IOD		0	
Higher IOD		0.3	
Lower AWD	2.31	5.27	2.86
Minimum OEF		0	
Maximum OEF	0.011	0.005	0.009

AHD

The average energy consumption for each location was calculated using actual total energy consumption data (kWh) and floor area data (m^2), allowing for the determination of the average energy use in kWh/m^2 for each location. The determination of the average AHD for each location can be seen in Table D.2. Several assumptions and considerations were made due to data availability:

- The data refers to residential buildings, which differ from the project's focus; however, it was the most reliable data available and aligned well with the project results.
- The data are from 2020, except for energy consumption in UK, which is from 2019, as this was the latest data available.
- Floor area data for the UK were unavailable from the same source. To maintain consistency, floor area data from another EU country with a comparable population and energy consumption (France) were used, rather than relying on data from a different source.

This average energy consumption was scored with 2.5 points; while the highest score for AHD is achieved when the room has zero energy consumption. The minimum, average, and maximum values are presented in Table D.3

GWP

The GWP scoring framework is based on its mathematical formula, incorporating the considerations outlined above along with new assumptions. The carbon footprint assessment is performed by multiplying the relevant elements included in the calculation by their respective emission factors. These elements include the energy

Table D.2: Determination of the average AHD for each location.

Country	Floor area [m^2]	Energy consumption [kWh]	**Energy consumption per floor area** [kWh/m^2]
Denmark	3.42E+08	4.97E+10	145.5
UK	3.10E+09	4.44E+11	143.2
Italy	3.36E+09	3.57E+11	106.0

Table D.3: Determination of the maximum and minimum AHD for each location.

	Copenhagen	**Rome**	**London**
Minimum AHD (kWh/m^2)	0		
Average AHD (kWh/m^2)	145.5	105.9	143.2
Maximum AHD (kWh/m^2)	194.1	141.3	190.9

used in the room (for heating, ventilation, and cooling) and specific building components such as windows and solar shading mechanisms. Since this calculation is based on current conditions, the emission factors will be considered as constant. Consequently, the maximum and minimum values for the GWP scoring system are derived from the maximum and minimum quantities of the assessed elements, as seen in Table D.4. The assumptions made in this process are as follows:

- The emission factors for the elements are those described in Table 3.5 for each location. Since the breakdown of energy consumption by source (ventilation, heating, and cooling) is unavailable, the emission factors for these will be averaged.
- The minimum score corresponds to the scenario where, energy demand is zero (as described for AHD in Table D.3); the window area is the minimum established according to Artelia [29] (WWR=10% for the longest window); and there are no solar shadings mechanisms installed.
- The maximum score corresponds to the scenario where, energy demand is at its maximum acceptable (calculated above for AHD in Table D.3); the window area is the maximum specified as default by Artelia [29] (WWR=65% in the longest window); and there are solar shading mechanisms covering the entire window area.

Δrec

The Δrec scoring framework is derived from its mathematical equation, as shown in Equation 2.3. The minimum score is assigned when the temperature difference is smallest and the recovery time is longest, while the maximum score is achieved with the highest temperature difference and the shortest recovery time.

Table D.4: Determination of the maximum and minimum GWP for each location.

	Copenhagen	**Rome**	**London**
Emission factors (kgCO_2eq./FU)			
Heat (kWh)	0.07	0.20	0.20
Electricity (kWh)	0.05	0.27	0.17
Windows (m^2)	235.81	235.81	235.81
Solar shadings [1] (m^2)	87.76	107.02	98.27
Minimum amounts[2]			
Energy[3] (kWh)	0	0	0
Windows (m^2)	4.8	4.8	4.8
Solar shadings (m^2)	0	0	0
Maximum amounts[2]			
Energy[3] (kWh)	698622.16	508690.12	687416.46
Windows (m^2)	31.2	31.2	31.2
Solar shadings (m^2)	31.2	31.2	31.2
Minimum GWP per year	22.63	22.63	22.63
Maximum GWP per year	1040.25	2604.77	2751.91

1 Emission factors for automatic shading mechanisms.

2 For a period of 50 years.

3 Energy based on maximum and minimum AHD over 50 years for the room area.

- The smallest temperature difference occurs when the peak temperature during a HW equals the defined threshold (28°C), resulting in a temperature difference and Δrec of zero.
- The largest temperature difference occurs when the HW reaches the highest recorded temperature, as detailed for each location in Table 3.4.
- An acceptable recovery time is assumed to be when the threshold is reached within 24 hours.

Based on the above, the acceptable thresholds for the shock recovery rate are displayed in Table D.5.

Table D.5: Determination of the maximum and minimum Δrec for each location.

	Copenhagen	**Rome**	**London**
Lower T_{max} [°C]		28	
Lower Δ_T [°C]		0	
Higher T_{max} [°C]	35	41	39
Higher Δ_T [°C]	7	13	11
Lower $\Delta_{t,rec}$ [hours]		24	
Minimum Δrec		0	
Maximum Δrec	0.29	0.54	0.46

Appendix E

Outdoor Conditions

This section provides a detailed analysis of the HW studied characterization. The detection method defined by [42] identifies a HW when the Spic threshold (99.5th percentile) is reached. The HW begins when temperatures exceed the Sdeb threshold (97.5th percentile) and ends when they drop below the Sint threshold (95th percentile) or remain below the Sdeb threshold for three consecutive days. These thresholds are derived from the historical multiyear period for each location and are outlined in Table E.1. Using these thresholds, the HWs for each location are identified.

For Copenhagen:

- Historical period: The HW lasts 21 days, from July 13th to August 2nd, reaching a maximum temperature of 31°C and an average temperature of 22.4°C.
- Mid-term: The HW spans 25 days, from July 9th to August 2nd, with a maximum temperature of 32°C and an average temperature of 21.7°C.
- Long-term: The HW lasts 54 days, from July 2nd to August 24th, reaching a maximum temperature of 35°C with an average temperature of 23.6°C.

For London:

- Historical period: The HW lasts 19 days, from July 4th to July 23nd, reaching a maximum temperature of 35°C and an average temperature of 23.9°C.
- Mid-term: The HW spans 19 days, from July 21st to August 8th, with a maximum temperature of 39°C and an average temperature of approximately 25.4°C.
- Long-term: The HW lasts 41 days, from July 4th to August 13th, reaching a maximum temperature of 39°C with an average temperature of 24.8°C.

For Rome:

- Historical period: The HW lasts 16 days, from July 17th to August 1st, reaching a maximum temperature of 34°C and an average temperature of 27.6°C.
- Mid-term: The HW spans 44 days, from July 12th to August 24th, with a maximum temperature of 37°C and an average temperature of 27.8°C.
- Long-term: The HW lasts 96 days, from June 16th to September 19th, reaching a maximum temperature of 41°C with an average temperature of 30.2°C.

The DoS is calculated as the product of a HW severity and duration, as defined in Equation 2.7. Severity is based on the the daily average dry bulb temperature during the HW ($T_{db,HW}$) and the daily average dry bulb temperature for the same period from TMY data ($T_{db,TMY}$). The duration is determined by dividing the HW duration (t_{HW}) by the duration of the longest HW across any time period (historical, mid-term, or long-term), highlighted in Table E.2 with an asterisk. Detailed calculations and results for DoS are presented in Table E.2.

The peak temperature reached during the HW and the time taken from the start of the HW to reach this temperature are shown in Table E.3.

Table E.1: Temperature thresholds for the historical multiyear period for the three locations.

Threshold	**Copenhagen**	**Rome**	**London**
Percentile 95 (Sint)	18.73	25.66	20.53
Percentile 97.5 (Sdeb)	20.07	26.42	21.88
Percentile 99.5 (Spic)	22.41	27.90	24.32

Table E.2: Calculation of DoS for the three climates across the three time periods. ∗*asterisk* identifies the maximum duration of the HW for across the time periods.

Climate location	**Period**	**Avg Tdb,HW** (C)	**Avg Tdb,TMY** (C)	**Duration** (days)	**doS**
Copenhagen	Historical	22.4	17.2	21	0.12
	Mid-term	21.7	18.5	25	0.08
	Long-term	23.6	19.4	54*	0.21
Rome	Historical	27.6	25.3	16	0.02
	Mid-term	27.8	25.4	44	0.04
	Long-term	30.2	27.8	96*	0.09
London	Historical	23.9	18.2	20	0.13
	Mid-term	25.4	19.9	19	0.13
	Long-term	24.8	22.0	41*	0.12

Table E.3: Determination of the peak temperature reached during the HW (Max Tdb,HW) and the time taken from the start of the HW to this peak (t until Max Tdb,HW).

Climate location	Period	Max Tdb,HW (C)	t until Max Tdb,HW (h)
Copenhagen	Historical	31	230
	Mid-term	32	352
	Long-term	35	1024
Rome	Historical	34	157
	Mid-term	37	470
	Long-term	41	1480
London	Historical	35	111
	Mid-term	39	254
	Long-term	39	279

Appendix F

Evaluation of Results

F.1 Evaluation of HE

Copenhagen

Copenhagen, performance peaked during the HT and LT scenarios under normal occupancy, with multiple strategies consistently achieving a perfect score of 10. However, strategy 3a (larger window area) stood out for its poor performance, scoring 0 points across all climate events.

In the EX scenario, the average performance declined to 6.7 points compared to 9.4 for HT and LT under normal occupancy. The top-performing strategies included 1b (north-facing façade), 3b (smaller window area), 4b and 4c (solar shading), 5a (improved window g-value), and 8a and 8b (night cooling). All strategies, except for 3a and 6a (halved U-value), outperformed the baseline.

The HW scenario proved the most challenging, with the room highly susceptible to overheating, resulting in an average score of 1.5. Despite this drop, strategies 1b, 3b, and 5a stood out by scoring above the medium threshold (5), with 4b, 4c and the 8-series also outperforming the baseline.

Under double occupancy, HT and LT scenarios saw a significant reduction in average scores from 9.4 to approximately 6.5, aligning with results from EX. Strategies 1b, 1c (east-facing facade), 3b, 4b, 4c, 5a, and 8a performed well under double occupancy. Strategies under LT conditions showed the most improvement relative to the baseline, particularly 1b, 1c, 3b and 5a.

Across all weather events, the most consistently high-performing strategies were 1b, 3b, and 5a. Strategies 4c, 8a, and 8b also performed strongly across most scenarios. In contrast, strategy 3a performed the worst, with a consistent score of 0 across all climate events, followed by 6a, which only performed adequately under HT and LT with normal occupancy.

The increase in average temperatures across the different weather events, as detailed in Section 3.1, is reflected in the HE results. Interestingly, despite higher temperatures in, reduced solar radiation during LT explains why strategy 3a, which is highly influenced by solar radiation due to its large window area, exhibited lower HE under LT compared to HT.

Rome

Section 3.1 reveals rising average temperatures across HT, LT, and HW, accompanied by a decline in solar radiation. Combined with the higher cooling capacity in Rome (5.5 kWh, compared to 2.5 kWh in Copenhagen), this helps explain the less pronounced drop in mean scores across weather events compared to Copenhagen. It also accounts for the limited performance variability among strategies, except during the HW event, where differences became more noticeable.

In Rome, all strategies performed above average across the three weather events. The top-performing strategies included 1a, 1b, 2a, 3b, 5a, 8a, and 8b, while strategy 3a struggled under most conditions, consistent with its performance in Copenhagen.

London

Results in London followed a pattern similar to Copenhagen. Under normal occupancy, all strategies performed well during HT and LT, except for strategy 3a, which scored 0.

Double occupancy led to increased HE, with strategy 3a continuing to score 0 points, while strategy 1a under LT also showed significant decrease. However, strategies such as 1b, 3b, 5a, and the 8-series demonstrated notable improvements compared to the baseline.

During the HW event, the average score dropped to 5.7 points, compared to 9.6 and 9.0 for HT and LT, respectively, under normal occupancy. Despite this decline, strategies 1b, 3b, and 5a achieved a very good performance. Conversely, strategies 1a, 1c, 3a, and 6a performed worse than the baseline.

Overall, the best-performing strategies across all scenarios were 1b, 3b, 5a, 8a, and 8b, which showed significant improvements compared to the baseline, particularly during HW. The poorest-performing strategies were 3a and, to a lesser extent, 1a, both of which often performed worse than the baseline.

F.2 Evaluation of OEF

Copenhagen

The OEF displays trends similar to HE, as both indicators assess room overheating. While OEF measures the degrees exceeding 26°C, HE evaluates the number of hours surpassing this threshold.

Under normal occupancy, the HT and LT scenarios achieve the highest average performance across strategies, with a mean score of 9.4. Double occupancy during HT and LT, as well as the EX scenario, exhibit moderate performance, with average scores ranging from 7.2 to 7.5. In contrast, the HW scenario demonstrates the lowest performance, with an average score of just 1.5. Notably, HT and LT scenarios perform similarly under both normal and double occupancy conditions.

The strategies that consistently perform best across scenarios are 1b, 3b, 5a, and 8a. Additionally, for all scenarios except HW, strategies 1c, 4-series, 5a, and the 8-series also exhibit strong performance. Conversely, strategies 1a, 3b and 6a perform worse than the baseline, with strategy 3b consistently scoring 0 across all scenarios.

Rome

In Rome, the OEF for the three tested weather events reflects strong performance, with a slight decrease from HT (mean score of 9.9) to LT and HW (mean score of 8).

During HT, all strategies, except 3a, achieved scores close to 10 points. In the LT and HW scenarios, strategies 1b, 2a, 3b, 5a, 8a, and 8b maintained excellent performance. However, strategies 3a, 1c, and 6a performed worse than the baseline, with 3a showing the largest negative difference.

London

In London, HT and LT scenarios under normal occupancy exhibit similar results, achieving high performance across most strategies, except for strategy 3a, which performs poorly.

Under double occupancy, the LT scenario shows a greater impact on overheating compared to HT, with a mean score of 6.7 across strategies, compared to 8.2 for HT. The HW scenario produces results comparable to LT under double occupancy. Across these scenarios, the top-performing strategies are 1b, 3b, 5a, 8a, and 8b.

All these strategies show the greatest improvement compared to the baseline during the HW scenario, followed by LT and HT. Notable differences in performance include the 4-series strategies, which improve compared to the baseline under HT but perform worse under LT and HW. This discrepancy may be explained by the variation in solar radiation across events, as highlighted in Section 3.1. Solar radiation increases during the HW event, whereas it decreases during LT, resulting in a more pronounced impact of solar shading (4-series strategies) during HW.

F.3 Evaluation of AHD

The AHD represents energy consumption for heating, cooling, and ventilation. Analyzing the performance of thermal comfort (via HE and OEF) and the performance in terms of AHD, the strategy performance can be determined. Poor thermal comfort, indicated by increased overheating, results in higher AHD values due to elevated cooling energy requirements. However, caution is necessary when interpreting results. Some strategies may achieve favorable thermal comfort (low overheating) not through passive measures but by relying heavily on cooling energy, significantly impacting AHD.

Copenhagen

AHD results in Copenhagen align with thermal comfort trends across scenarios, though with slightly reduced mean scores. While thermal comfort scores are well above average, AHD scores are generally above average, indicating that thermal comfort is achieved using a reasonable amount of energy.

Under normal occupancy, scenarios HT, LT and EX exhibit similar average AHD performance across strategies, scoring approximately 7–7.5 points. In contrast, scenarios HT and LT under double occupancy, as well as HW, show lower average scores of 6.5–6.7. This suggests that the impacts of LT and EX weather events are comparable to HT, while double occupancy exacerbates overheating, similar to HW conditions.

Performance differences across strategies are minimal, closely matching the average performance in each scenario. The most effective strategies are 1b, 1c, 3b, 4b, 5a, 7a, 7b, and 7c. The 7-series strategies show a significant improvement over the baseline, particularly under double occupancy. Conversely, strategy 3a consistently performs worse than the baseline in all scenarios, followed by 8a, which scores slightly below baseline performance.

Rome

In Rome, thermal comfort results are excellent, but AHD scores are notably low, indicating that thermal comfort is achieved predominantly through high energy consumption. For normal occupancy, the mean AHD values for scenarios HT, LT, and HW are 4.5. 2.6, and 2.4, respectively. Regardless of strategies, the room performs below average in HT and fails completely in LT and HW scenarios.

The impact of strategies relative to the baseline is less pronounced in HT than in LT and HW; showing higher improvements during the LT. Across all scenarios, most strategies outperform the baseline, with exceptions for 3a and, to a lesser extent, 6a.

The top-performing strategies include 1b, 5a, and the 7-series, with strategy 7c demonstrating the most significant improvement compared to the baseline.

London

AHD results in London mirror those observed in Copenhagen, following thermal comfort trends but with slightly reduced mean scores. Thermal comfort is achieved using an acceptable amount of energy, yielding above-average AHD performance.

Under normal occupancy, scenarios HT and LT achieve average scores of 7.3–7.6. Under double occupancy, scenarios exhibit lower average scores of 6–6.5, slightly below the HW scenario under normal occupancy (6.7).

Performance differences across strategies is minimal in general and align closely with scenario averages, except for double occupancy that has a biggest improvement compared to the baseline. All strategies outperform the baseline except for 3a. The best-performing strategies are 3b, 5a, and the 7-series, particularly 7c, which delivers the largest improvement over the baseline. Strategies 6a and 8a perform the same as the baseline but score lower under double occupancy.

F.4 Evaluation of Recovery Rate

The recovery rate measures the temperature decrease in degrees per hour during a heat wave, indicating how quickly a room returns to comfortable conditions after an episode of high temperatures. A higher recovery rate means better performance. Comparing results across the three locations, Copenhagen achieves the highest recovery rate score, followed by Rome and London, with scores of 2.8, 2.6, and 2.2. respectively. These scores, however, remain low, indicating that, on average, rooms do not recover within a day, as defined in Section 2.5.

In Copenhagen, strategy 3a demonstrates the best recovery rate, effectively reducing high temperatures in a relatively short time. Strategies 1b, 4a, 4b, 8a, and 8b also perform well. Conversely, strategy 2a reduces the recovery rate compared to the baseline. Strategies 1c, 4c, 6a, 7a, 7b, and 7c show minimal differences from the baseline.

For Rome, strategies 1a and 3a deliver the highest recovery rates, followed by 1b and 5a. In contrast, strategy 2a negatively impacts the recovery rate compared to the baseline. Other strategies, including 1c, 4a, 4b, 4c, 6a, 7a, 7b, 7c, 8a, and 8b, show negligible differences from the baseline.

In London, many strategies decrease the recovery rate relative to the baseline, with strategies 5a, 3b, and 1a showing the most significant negative impacts. Strategies 4a, 4b, and 8a exhibit relatively significant improvements. Strategies 1c, 4c, 6a, 7a, 7b, 7c, and 8b perform similarly to the baseline, with minimal variation.

F.5 Evaluation of GWP

The evaluation of the carbon footprint of the proposals considers both the elements included in each strategy (e.g., increased window area or shading mechanisms) and the energy required for their operation, as reflected in the AHD.

In Copenhagen, the average carbon footprint across scenarios ranges from 7.2 to 7.6, indicating a strong performance driven by Copenhagen's favorable AHD results. The top-performing strategies are 3b and the 7-series. For normal occupancy under HT and EX scenarios, strategy 3b delivers the most significant improvement compared to the baseline. Under double occupancy in HT scenarios, the 7-series strategies, particularly 7c and 7b, show the greatest impact. The poorest performer is strategy 3a, a trend consistent across all locations. The success of strategies 3b and the 7-series can be attributed to reduced window area and lower energy demand for 3b, and the absence of additional elements combined with low energy demand for the 7-series.

In Rome, the top strategies are 7b and 7c, followed by 1b, 3b, 5a, and 7a. These strategies significantly reduce the GWP compared to the baseline. Conversely, the lowest-performing strategies are 3a and 6a.

In London, the best-performing strategies are the 7-series, followed by 3b. These strategies have a greater impact in normal occupancy scenarios compared to double occupancy. Under normal occupancy, all strategies except 3a outperform the baseline. However, under double occupancy, strategies 3a, 4a, 4c, 6a, and 8a fall below baseline performance.

Table F.1: HE (%) and score per strategy in Copenhagen.

	C-HT-n	**C-HT-d**	**C-LT-n**	**C-LT-d**	**C-EX-n**	**C-HW-n**	*Mean*
Base.	0.0%	3.6%	0.0%	4.2%	3.9%	7.4%	
	10.0	**2.8**	**10.0**	**1.7**	**2.2**	**0.0**	*4.4*
1a	0.0%	5.8%	0.0%	4.8%	2.1%	8.0%	
	10.0	**0.0**	**10.0**	**0.5**	**5.8**	**0.0**	*4.4*
1b	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	
	10.0	**10.0**	**10.0**	**10.0**	**10.0**	**6.8**	*9.5*
1c	0.0%	0.0%	0.0%	0.2%	1.4%	5.1%	
	10.0	**10.0**	**10.0**	**9.7**	**7.2**	**0.0**	*7.8*
2a	0.0%	2.4%	0.0%	3.2%	2.4%	7.8%	
	10.0	**5.2**	**10.0**	**3.7**	**5.2**	**0.0**	*5.7*
3a	12.2%	43.5%	9.8%	42.2%	36.5%	32.4%	
	0.0	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	*0.0*
3b	0.0%	0.0%	0.0%	0.0%	0.0%	2.2%	
	10.0	**10.0**	**10.0**	**10.0**	**10.0**	**5.7**	*9.3*
4a	0.0%	0.7%	0.0%	1.4%	1.0%	5.5%	
	10.0	**8.7**	**10.0**	**7.2**	**8.0**	**0.0**	*7.3*
4b	0.0%	0.1%	0.0%	1.3%	0.4%	4.3%	
	10.0	**9.8**	**10.0**	**7.3**	**9.2**	**1.3**	*7.9*
4c	0.0%	0.6%	0.0%	0.7%	0.0%	4.2%	
	10.0	**8.8**	**10.0**	**8.6**	**10.0**	**1.7**	*8.2*
5a	0.0%	0.0%	0.0%	0.0%	0.0%	2.1%	
	10.0	**10.0**	**10.0**	**10.0**	**10.0**	**5.8**	*9.3*
6a	0.0%	6.4%	0.2%	5.8%	5.5%	8.0%	
	10.0	**0.0**	**9.7**	**0.0**	**0.0**	**0.0**	*3.3*
7a	0.0%	1.6%	0.0%	1.5%	2.6%	7.3%	
	10.0	**6.8**	**10.0**	**7.0**	**4.8**	**0.0**	*6.4*
7b	0.0%	1.4%	0.0%	1.3%	2.1%	7.2%	
	10.0	**7.1**	**10.0**	**7.5**	**5.8**	**0.0**	*6.8*
7c	0.0%	1.4%	0.0%	1.2%	2.0%	7.2%	
	10.0	**7.1**	**10.0**	**7.7**	**6.0**	**0.0**	*6.8*
8a	0.0%	0.2%	0.0%	0.7%	0.0%	3.8%	
	10.0	**9.7**	**10.0**	**8.7**	**10.0**	**2.3**	*8.4*
8b	0.0%	0.8%	0.0%	0.8%	0.0%	4.2%	
	10.0	**8.5**	**10.0**	**8.3**	**10.0**	**1.7**	*8.1*
Mean	*9.4*	*6.7*	*9.4*	*6.3*	*6.7*	*1.49*	

Table F.2: HE (%) and score per strategy in Rome.

	R-HT-n	**R-LT-n**	**R-HW-n**	***Mean***
Base.	0.0%	0.7%	1.0%	
	10.0	**8.7**	**8.0**	*8.9*
1a	0.0%	0.5%	0.7%	
	10.0	**9.0**	**8.7**	*9.2*
1b	0.0%	0.3%	0.6%	
	10.0	**9.5**	**8.8**	*9.4*
1c	0.3%	0.9%	1.4%	
	9.5	**8.2**	**7.2**	*8.3*
2a	0.0%	0.3%	0.4%	
	10.0	**9.3**	**9.2**	*9.5*
3a	0.4%	**1.7%**	1.9%	
	9.2	**6.7**	**6.2**	*7.3*
3b	0.0%	0.5%	0.5%	
	10.0	**9.0**	**9.0**	*9.3*
4a	0.0%	0.7%	0.9%	
	10.0	**8.7**	**8.2**	*8.9*
4b	0.0%	0.6%	0.9%	
	10.0	**8.8**	**8.2**	*9.0*
4c	0.0%	0.7%	0.9%	
	10.0	**8.7**	**8.2**	*8.9*
5a	0.0%	0.3%	0.5%	
	10.0	**9.3**	**9.0**	*9.4*
6a	0.1%	0.7%	1.0%	
	9.8	**8.7**	**8.0**	*8.8*
7a	0.0%	0.7%	1.0%	
	10.0	**8.7**	**8.0**	*8.9*
7b	0.0%	0.7%	1.0%	
	10.0	**8.7**	**8.0**	*8.9*
7c	0.0%	0.7%	1.0%	
	10.0	**8.7**	**8.0**	*8.9*
8a	0.0%	0.3%	0.6%	
	10.0	**9.3**	**8.8**	*9.4*
8b	0.0%	0.4%	0.7%	
	10.0	**9.2**	**8.7**	*9.3*
Mean	*9.9*	*8.8*	*8.2*	

Table F.3: HE (%) and score per strategy in London.

	L-HT-n	**L-HT-d**	**L-LT-n**	***L-LT-d***	**L-HW-n**	***Mean***
Base.	0.0%	1.4%	0.2%	***2.0%***	2.7%	
	10.0	**7.2**	**9.7**	***6.0***	**4.7**	*7.5*
1a	0.0%	1.0%	0.4%	***3.1%***	3.3%	
	10.0	**8.0**	**9.2**	***3.8***	**3.5**	*6.9*
1b	0.0%	0.0%	0.1%	***0.6%***	0.3%	
	10.0	**10.0**	**9.8**	***8.8***	**9.3**	*9.6*
1c	0.0%	0.8%	0.3%	***1.3%***	3.5%	
	10.0	**8.5**	**9.5**	***7.3***	**3.0**	*7.7*
2a	0.0%	1.4%	0.2%	***1.8%***	2.4%	
	10.0	**7.2**	**9.7**	***6.5***	**5.2**	*7.7*
3a	3.5%	**23.3%**	6.0%	***29.2%***	22.8%	
	3.0	**0.0**	**0.0**	***0.0***	**0.0**	*0.6*
3b	0.0%	0.0%	0.1%	***0.4%***	0.3%	
	10.0	**10.0**	**9.8**	***9.2***	**9.3**	*9.7*
4a	0.0%	0.8%	0.3%	***1.8%***	2.3%	
	10.0	**8.3**	**9.3**	***6.5***	**5.5**	*7.9*
4b	0.0%	0.5%	0.3%	***1.8%***	1.7%	
	10.0	**9.0**	**9.3**	***6.5***	**6.7**	*8.3*
4c	0.0%	0.3%	0.3%	***1.7%***	1.7%	
	10.0	**9.3**	**9.3**	***6.7***	**6.7**	*8.4*
5a	0.0%	0.0%	0.0%	***0.2%***	0.2%	
	10.0	**10.0**	**10.0**	***9.7***	**9.7**	*9.9*
6a	0.0%	1.9%	0.3%	***2.1%***	3.0%	
	10.0	**6.2**	**9.3**	***5.8***	**4.0**	*7.1*
7a	0.0%	1.4%	0.2%	***1.8%***	2.5%	
	10.0	**7.2**	**9.7**	***6.3***	**5.0**	*7.6*
7b	0.0%	1.4%	0.2%	***1.7%***	2.4%	
	10.0	**7.2**	**9.7**	***6.7***	**5.2**	*7.7*
7c	0.0%	1.4%	0.2%	***1.6%***	2.4%	
	10.0	**7.2**	**9.7**	***6.8***	**5.2**	*7.8*
8a	0.0%	0.1%	0.1%	***1.0%***	1.6%	
	10.0	**9.8**	**9.8**	***8.0***	**6.8**	*8.9*
8b	0.0%	0.0%	0.0%	***0.7%***	1.0%	
	10.0	**10.0**	**10.0**	***8.7***	**8.0**	*9.3*
Mean	*9.6*	*7.9*	*9.0*	6.7	5.7	

Table F.4: OEF (-) and score per strategy in Copenhagen.

	C-HT-n	**C-HT-d**	**C-LT-n**	***C-LT-d***	**C-EX-n**	***C-HW-n***	***Mean***
Base.	0.0E+00	6.0E-03	0.0E+00	*6.4E-03*	6.0E-03	*2.3E-02*	
	10.0	**4.4**	**10.0**	***4.1***	**4.5**	***0.0***	*5.5*
1a	0.0E+00	1.2E-02	0.0E+00	*9.5E-03*	3.4E-03	*2.4E-02*	
	10.0	**0.0**	**10.0**	***1.3***	**6.8**	***0.0***	*4.7*
1b	0.0E+00	0.0E+00	0.0E+00	*0.0E+00*	0.0E+00	*1.9E-03*	
	10.0	**10.0**	**10.0**	***10.0***	**10.0**	***8.2***	*9.7*
1c	0.0E+00	0.0E+00	0.0E+00	*3.4E-05*	2.5E-03	*1.4E-02*	
	10.0	**10.0**	**10.0**	***10.0***	**7.7**	***0.0***	*7.9*
2a	0.0E+00	3.3E-03	0.0E+00	*4.0E-03*	2.5E-03	*2.0E-02*	
	10.0	**7.0**	**10.0**	***6.3***	**7.7**	***0.0***	*6.8*
3a	3.7E-02	3.1E-01	2.6E-02	*2.6E-01*	2.0E-01	*1.6E-01*	
	0.0	**0.0**	**0.0**	***0.0***	**0.0**	***0.0***	*0.0*
3b	0.0E+00	0.0E+00	0.0E+00	*0.0E+00*	0.0E+00	*3.5E-03*	
	10.0	**10.0**	**10.0**	***10.0***	**10.0**	***6.8***	*9.5*
4a	0.0E+00	5.7E-04	0.0E+00	*2.0E-03*	9.3E-04	*1.6E-02*	
	10.0	**9.5**	**10.0**	***8.1***	**9.1**	***0.0***	*7.8*
4b	0.0E+00	1.1E-05	0.0E+00	*1.9E-03*	3.8E-04	*1.2E-02*	
	10.0	**10.0**	**10.0**	***8.3***	**9.6**	***0.0***	*8.0*
4c	0.0E+00	3.1E-04	0.0E+00	*4.3E-04*	0.0E+00	*1.0E-02*	
	10.0	**9.7**	**10.0**	***9.6***	**10.0**	***0.5***	*8.3*
5a	0.0E+00	0.0E+00	0.0E+00	*0.0E+00*	0.0E+00	*3.2E-03*	
	10.0	**10.0**	**10.0**	***10.0***	**10.0**	***7.0***	*9.5*
6a	0.0E+00	1.2E-02	4.0E-05	*1.2E-02*	1.1E-02	*2.6E-02*	
	10.0	**0.0**	**10.0**	***0.0***	**0.0**	***0.0***	*3.3*
7a	0.0E+00	3.3E-03	0.0E+00	*1.7E-03*	3.6E-03	*2.2E-02*	
	10.0	**6.9**	**10.0**	***8.4***	**6.7**	***0.0***	*7.0*
7b	0.0E+00	2.9E-03	0.0E+00	*1.2E-03*	2.9E-03	*2.1E-02*	
	10.0	**7.4**	**10.0**	***8.9***	**7.3**	***0.0***	*7.3*
7c	0.0E+00	2.8E-03	0.0E+00	*9.9E-04*	2.7E-03	*2.1E-02*	
	10.0	**7.4**	**10.0**	***9.1***	**7.5**	***0.0***	*7.3*
8a	0.0E+00	9.7E-05	0.0E+00	*4.7E-04*	0.0E+00	*7.8E-03*	
	10.0	**9.9**	**10.0**	***9.6***	**10.0**	***2.8***	*8.7*
8b	0.0E+00	5.6E-04	0.0E+00	*9.1E-04*	0.0E+00	*1.0E-02*	
	10.0	**9.5**	**10.0**	***9.2***	**10.0**	***0.5***	*8.2*
Mean	*9.4*	*7.2*	*9.4*	*7.2*	*7.5*	*1.5*	

Table F.5: OEF (-) and score per strategy in Rome.

	R-HT-n	**R-LT-n**	**R-HW-n**	*Mean*
Base.	0.0E+00	9.1E-04	1.1E-03	
	10.0	**8.1**	**7.8**	*8.6*
1a	0.0E+00	5.4E-04	7.4E-04	
	10.0	**8.9**	**8.4**	*9.1*
1b	0.0E+00	2.3E-04	4.8E-04	
	10.0	**9.5**	**9.0**	*9.5*
1c	1.7E-04	1.3E-03	1.9E-03	
	9.6	**7.3**	**6.0**	*7.6*
2a	0.0E+00	2.9E-04	4.1E-04	
	10.0	**9.4**	**9.1**	*9.5*
3a	7.0E-04	2.8E-03	2.9E-03	
	8.5	**4.1**	**3.8**	*5.5*
3b	0.0E+00	3.5E-04	4.9E-04	
	10.0	**9.3**	**9.0**	*9.4*
4a	0.0E+00	8.6E-04	9.8E-04	
	10.0	**8.2**	**7.9**	*8.7*
4b	0.0E+00	8.3E-04	9.2E-04	
	10.0	**8.2**	**8.1**	*8.8*
4c	0.0E+00	8.2E-04	9.1E-04	
	10.0	**8.3**	**8.1**	*8.8*
5a	0.0E+00	3.1E-04	4.8E-04	
	10.0	**9.3**	**9.0**	*9.4*
6a	1.6E-06	9.8E-04	1.1E-03	
	10.0	**7.9**	**7.7**	*8.5*
7a	0.0E+00	8.9E-04	1.1E-03	
	10.0	**8.1**	**7.8**	*8.6*
7b	0.0E+00	8.9E-04	1.1E-03	
	10.0	**8.1**	**7.7**	*8.6*
7c	0.0E+00	8.9E-04	1.1E-03	
	10.0	**8.1**	**7.7**	*8.6*
8a	0.0E+00	4.0E-04	5.9E-04	
	10.0	**9.2**	**8.8**	*9.3*
8b	0.0E+00	4.7E-04	6.7E-04	
	10.0	**9.0**	**8.6**	*9.2*
Mean	*9.9*	*8.3*	*7.9*	

Table F.6: OEF (-) and score per strategy in London.

	L-HT-n	**L-HT-d**	**L-LT-n**	***L-LT-d***	**L-HW-n**	*Mean*
Base.	0.0E+00	2.2E-03	2.9E-04	***3.4E-03***	4.0E-03	
	10.0	**7.4**	**9.7**	***6.1***	**5.4**	*7.7*
1a	0.0E+00	9.5E-04	6.6E-04	***6.7E-03***	4.8E-03	
	10.0	**8.9**	**9.2**	***2.3***	**4.5**	*7.0*
1b	0.0E+00	0.0E+00	7.6E-05	***6.7E-04***	3.4E-04	
	10.0	**10.0**	**9.9**	***9.2***	**9.6**	*9.8*
1c	0.0E+00	9.7E-04	5.3E-04	***2.7E-03***	7.2E-03	
	10.0	**8.9**	**9.4**	***6.9***	**1.8**	*7.4*
2a	0.0E+00	1.9E-03	1.9E-04	***2.8E-03***	3.2E-03	
	10.0	**7.9**	**9.8**	***6.8***	**6.4**	*8.2*
3a	1.3E-02	1.1E-01	1.1E-02	***1.1E-01***	9.8E-02	
	0.0	**0.0**	**0.0**	***0.0***	**0.0**	*0.0*
3b	0.0E+00	0.0E+00	8.6E-05	***5.7E-04***	2.8E-04	
	10.0	**10.0**	**9.9**	***9.4***	**9.7**	*9.8*
4a	0.0E+00	1.1E-03	6.7E-04	***4.2E-03***	3.4E-03	
	10.0	**8.8**	**9.2**	***5.2***	**6.1**	*7.8*
4b	0.0E+00	5.3E-04	6.7E-04	***4.0E-03***	2.3E-03	
	10.0	**9.4**	**9.2**	***5.4***	**7.3**	*8.3*
4c	0.0E+00	2.3E-04	5.1E-04	***3.7E-03***	1.9E-03	
	10.0	**9.7**	**9.4**	***5.8***	**7.8**	*8.6*
5a	0.0E+00	0.0E+00	0.0E+00	***1.4E-04***	2.9E-05	
	10.0	**10.0**	**10.0**	***9.8***	**10.0**	*10.0*
6a	0.0E+00	3.7E-03	4.7E-04	***4.3E-03***	5.0E-03	
	10.0	**5.7**	**9.5**	***5.1***	**4.2**	*6.9*
7a	0.0E+00	2.1E-03	1.4E-04	***2.3E-03***	3.5E-03	
	10.0	**7.6**	**9.8**	***7.3***	**6.0**	*8.1*
7b	0.0E+00	2.2E-03	8.0E-05	***1.9E-03***	3.3E-03	
	10.0	**7.5**	**9.9**	***7.8***	**6.3**	*8.3*
7c	0.0E+00	2.2E-03	8.0E-05	***1.8E-03***	3.1E-03	
	10.0	**7.5**	**9.9**	***7.9***	**6.5**	*8.4*
8a	0.0E+00	5.8E-06	3.7E-05	***8.3E-04***	1.1E-03	
	10.0	**10.0**	**10.0**	***9.1***	**8.8**	*9.6*
8b	0.0E+00	0.0E+00	0.0E+00	***3.7E-04***	3.9E-04	
	10.0	**10.0**	**10.0**	***9.6***	**9.6**	*9.8*
Mean	*9.4*	*8.2*	*9.1*	*6.7*	6.5	

Table F.7: AHD (kWh/m^2) and score per strategy in Copenhagen.

	C-HT-n	**C-HT-d**	**C-LT-n**	**C-LT-d**	**C-EX-n**	**C-HW-n**	*Mean*
Base.	54.13	71.30	52.40	72.98	61.87	65.94	
	7.2	**6.3**	**7.3**	**6.2**	**6.8**	**6.6**	*6.7*
1a	54.83	69.42	52.17	70.98	59.11	66.15	
	7.2	**6.4**	**7.3**	**6.3**	**7.0**	**6.6**	*6.8*
1b	49.81	63.03	47.17	65.11	52.13	61.32	
	7.4	**6.8**	**7.6**	**6.6**	**7.3**	**6.8**	*7.1*
1c	51.06	65.71	48.59	67.57	56.39	63.25	
	7.4	**6.6**	**7.5**	**6.5**	**7.1**	**6.7**	*7.0*
2a	53.06	69.11	51.27	70.81	61.15	64.87	
	7.3	**6.4**	**7.4**	**6.4**	**6.8**	**6.7**	*6.8*
3a	76.81	88.96	72.83	87.71	80.76	86.38	
	6.0	**5.4**	**6.2**	**5.5**	**5.8**	**5.5**	*5.8*
3b	43.78	61.56	42.70	64.55	50.80	55.65	
	7.7	**6.8**	**7.8**	**6.7**	**7.4**	**7.1**	*7.3*
4a	51.07	68.28	49.71	70.45	57.90	63.09	
	7.4	**6.5**	**7.4**	**6.4**	**7.0**	**6.7**	*6.9*
4b	49.22	65.86	48.13	68.47	55.17	61.32	
	7.5	**6.6**	**7.5**	**6.5**	**7.2**	**6.8**	*7.0*
4c	50.95	68.14	49.65	70.36	57.38	62.97	
	7.4	**6.5**	**7.4**	**6.4**	**7.0**	**6.8**	*6.9*
5a	48.22	63.54	45.86	65.55	53.46	59.88	
	7.5	**6.7**	**7.6**	**6.6**	**7.2**	**6.9**	*7.1*
6a	51.58	72.33	50.89	74.48	60.53	63.29	
	7.3	**6.3**	**7.4**	**6.2**	**6.9**	**6.7**	*6.8*
7a	43.56	52.49	42.08	53.60	52.16	59.07	
	7.8	**7.3**	**7.8**	**7.2**	**7.3**	**7.0**	*7.4*
7b	40.10	45.07	38.53	46.44	46.23	56.32	
	7.9	**7.7**	**8.0**	**7.6**	**7.6**	**7.1**	*7.7*
7c	39.44	43.45	37.79	44.68	44.21	55.74	
	8.0	**7.8**	**8.1**	**7.7**	**7.7**	**7.1**	*7.7*
8a	57.22	75.11	54.70	76.95	62.29	69.06	
	7.1	**6.1**	**7.2**	**6.0**	**6.8**	**6.4**	*6.6*
8b	52.94	70.64	51.46	72.28	60.18	65.03	
	7.3	**6.4**	**7.3**	**6.3**	**6.9**	**6.6**	*6.8*
Mean	*7.37*	*6.62*	*7.47*	*6.54*	*7.05*	*6.73*	

Table F.8: AHD (kWh/m^2) and score per strategy in Rome.

	R-HT-n	**R-LT-n**	**R-HW-n**	***Mean***
Base.	81.57	112.45	114.09	
	4.2	**2.0**	**1.9**	***2.7***
1a	76.75	102.68	105.86	
	4.6	**2.7**	**2.5**	***3.3***
1b	70.44	90.55	95.41	
	5.0	**3.6**	**3.2**	***4.0***
1c	77.81	97.73	102.22	
	4.5	**3.1**	**2.8**	***3.4***
2a	80.36	112.48	113.90	
	4.3	**2.0**	**1.9**	***2.8***
3a	104.89	140.63	140.04	
	2.6	**0.0**	**0.1**	***0.9***
3b	71.64	98.75	101.53	
	4.9	**3.0**	**2.8**	***3.6***
4a	79.33	105.51	108.41	
	4.4	**2.5**	**2.3**	***3.1***
4b	77.97	100.82	104.55	
	4.5	**2.9**	**2.6**	***3.3***
4c	79.29	104.52	107.49	
	4.4	**2.6**	**2.4**	***3.1***
5a	71.63	96.31	99.90	
	4.9	**3.2**	**2.9**	***3.7***
6a	83.44	115.63	116.23	
	4.1	**1.8**	**1.8**	***2.6***
7a	70.70	96.61	101.08	
	5.0	**3.2**	**2.8**	***3.7***
7b	66.90	90.00	96.47	
	5.3	**3.6**	**3.2**	***4.0***
7c	66.37	88.81	95.62	
	5.3	**3.7**	**3.2**	***4.1***
8a	86.31	111.78	114.57	
	3.9	**2.1**	**1.9**	***2.6***
8b	80.12	110.24	112.23	
	4.3	**2.2**	**2.1**	***2.9***
Mean	*4.48*	*2.61*	*2.38*	

Table F.9: AHD (kWh/m^2) and score per strategy in London.

	L-HT-n	**L-HT-d**	**L-LT-n**	**L-LT-d**	**L-HW-n**	*Mean*
Base.	47.96	72.15	53.66	80.98	65.72	
	7.5	**6.2**	**7.2**	**5.8**	**6.6**	*6.6*
1a	48.63	71.37	53.59	79.79	65.02	
	7.5	**6.3**	**7.2**	**5.8**	**6.6**	*6.7*
1b	44.33	65.33	49.25	74.01	58.86	
	7.7	**6.6**	**7.4**	**6.1**	**6.9**	*6.9*
1c	46.56	68.73	51.54	77.06	62.34	
	7.6	**6.4**	**7.3**	**6.0**	**6.7**	*6.8*
2a	47.51	71.33	53.24	80.27	65.47	
	7.5	**6.3**	**7.2**	**5.8**	**6.6**	*6.7*
3a	69.03	91.17	72.79	97.31	83.98	
	6.4	**5.2**	**6.2**	**4.9**	**5.6**	*5.7*
3b	40.58	64.86	46.56	74.28	57.19	
	7.9	**6.6**	**7.6**	**6.1**	**7.0**	*7.0*
4a	46.61	71.00	52.51	80.05	63.73	
	7.6	**6.3**	**7.2**	**5.8**	**6.7**	*6.7*
4b	45.24	69.08	51.23	78.41	62.08	
	7.6	**6.4**	**7.3**	**5.9**	**6.7**	*6.8*
4c	46.54	70.91	52.37	79.88	63.42	
	7.6	**6.3**	**7.3**	**5.8**	**6.7**	*6.7*
5a	42.11	63.71	47.16	72.60	57.80	
	7.8	**6.7**	**7.5**	**6.2**	**7.0**	*7.0*
6a	47.35	74.40	54.01	83.47	65.86	
	7.5	**6.1**	**7.2**	**5.6**	**6.6**	*6.6*
7a	38.75	50.53	44.57	59.40	57.61	
	8.0	**7.4**	**7.7**	**6.9**	**7.0**	*7.4*
7b	35.25	42.74	40.57	50.80	53.66	
	8.2	**7.8**	**7.9**	**7.3**	**7.2**	*7.7*
7c	34.08	40.30	39.17	47.64	52.38	
	8.2	**7.9**	**7.9**	**7.5**	**7.3**	*7.8*
8a	48.57	73.27	54.00	81.79	65.49	
	7.5	**6.2**	**7.2**	**5.7**	**6.6**	*6.6*
8b	46.65	70.80	52.67	79.92	64.12	
	7.6	**6.3**	**7.2**	**5.8**	**6.6**	*6.7*
Mean	*7.61*	*6.51*	*7.32*	*6.06*	*6.72*	

Table F.10: Recovery rate (°C/h) and score per strategy across all locations.

	C-HW-n	**R-HW-n**	**L-HW-n**
Base.	0.07	0.12	0.11
	2.5	**2.2**	**2.3**
1a	0.08	0.19	0.09
	2.6	**3.5**	**1.9**
1b	0.10	0.16	0.10
	3.3	**2.9**	**2.1**
1c	0.07	0.12	0.11
	2.5	**2.3**	**2.3**
2a	0.06	0.10	0.10
	2.1	**1.8**	**2.1**
3a	0.12	0.19	0.10
	4.3	**3.4**	**2.2**
3b	0.08	0.14	0.06
	2.7	**2.6**	**1.4**
4a	0.09	0.12	0.12
	3.2	**2.2**	**2.7**
4b	0.09	0.12	0.13
	3.2	**2.2**	**2.7**
4c	0.08	0.12	0.11
	2.6	**2.2**	**2.3**
5a	0.09	0.16	0.05
	2.9	**2.9**	**1.2**
6a	0.07	0.12	0.11
	2.5	**2.2**	**2.4**
7a	0.07	0.12	0.11
	2.5	**2.2**	**2.3**
7b	0.07	0.12	0.11
	2.6	**2.2**	**2.3**
7c	0.07	0.12	0.11
	2.6	**2.2**	**2.3**
8a	0.09	0.12	0.12
	3.1	**2.2**	**2.6**
8b	0.09	0.12	0.10
	3.1	**2.2**	**2.3**
Mean	*2.84*	*2.58*	*2.21*

Table F.11: GWP ($kgCO_2eq./year$) and score per strategy across all locations.

	C-HT-n	C-HT-d	C-EX-n	R-HT-n	L-HT-n	L-HT-d
Base.	267.75	320.95	285.16	1594.48	651.88	937.42
	7.6	**7.1**	**7.4**	**3.9**	**7.7**	**6.7**
1a	273.06	316.17	277.34	1493.05	664.67	932.20
	7.5	**7.1**	**7.5**	**4.3**	**7.7**	**6.7**
1b	260.32	297.17	255.51	1360.42	617.78	862.75
	7.7	**7.3**	**7.7**	**4.8**	**7.8**	**6.9**
1c	262.74	305.17	269.39	1508.48	642.47	902.21
	7.6	**7.2**	**7.6**	**4.2**	**7.7**	**6.8**
2a	262.97	311.31	281.64	1574.40	645.76	926.49
	7.6	**7.2**	**7.5**	**4.0**	**7.7**	**6.7**
3a	407.91	443.23	408.53	2070.78	968.91	1230.58
	6.2	**5.9**	**6.2**	**2.1**	**6.5**	**5.6**
3b	202.84	258.18	218.83	1385.05	535.92	823.16
	8.2	**7.7**	**8.1**	**4.7**	**8.1**	**7.1**
4a	273.19	326.37	287.29	1567.29	653.08	941.74
	7.5	**7.0**	**7.4**	**4.0**	**7.7**	**6.6**
4b	266.84	317.85	277.72	1541.05	636.77	918.55
	7.6	**7.1**	**7.5**	**4.1**	**7.8**	**6.7**
4c	274.02	326.37	285.78	1570.07	655.59	943.89
	7.5	**7.0**	**7.4**	**4.0**	**7.7**	**6.6**
5a	250.94	296.26	258.12	1396.53	585.98	838.50
	7.8	**7.3**	**7.7**	**4.7**	**7.9**	**7.0**
6a	249.37	317.36	273.54	1638.29	634.82	957.28
	7.8	**7.1**	**7.5**	**3.7**	**7.8**	**6.6**
7a	233.03	259.82	253.03	1379.83	545.19	682.99
	7.9	**7.7**	**7.7**	**4.7**	**8.1**	**7.6**
7b	221.09	234.45	232.36	1305.66	503.52	590.42
	8.0	**7.9**	**7.9**	**5.0**	**8.2**	**7.9**
7c	218.74	228.78	225.28	1295.30	489.39	560.97
	8.1	**8.0**	**8.0**	**5.1**	**8.3**	**8.0**
8a	285.32	341.90	291.26	1658.25	664.42	958.42
	7.4	**6.9**	**7.4**	**3.7**	**7.7**	**6.6**
8b	264.36	319.84	280.12	1563.30	637.07	922.68
	7.6	**7.1**	**7.5**	**4.0**	**7.8**	**6.7**
Mean	*7.6*	*7.2*	*7.5*	*4.2*	*7.8*	*6.9*

Appendix G

Sustainability Impact Calculation

The sustainability impact assessment includes evaluating the energy consumption impact alongside the contributions of specific elements such as windows and solar shading mechanisms. A more detailed explanation of this assessment is provided below:

Energy Consumption

The impact of energy consumption for space heating, cooling, and ventilation is evaluated under Module B6, which represents operational energy use over the building's life cycle. The energy source and corresponding emission factors vary by location. Details of these considerations and the projected emission factors over a 50-year period are provided in Table G.1. The total environmental impact of energy usage is calculated by multiplying the energy consumption for heating, cooling, or ventilation (over a 50-year period) of each strategy, by the projected emission factor for each of the three locations.

Windows

Changes in glazing area, whether increased or reduced, influence several life-cycle modules, including the product stage (Modules A1 – "Raw material supply," A2 – "Transport," and A3 – "Manufacturing"), the use stage (Module B4 – "Replacement"), the end-of-life stage (Modules C3 – "Waste processing" and C4 – "Disposal"), and Module D (benefits from reuse, recovery, and recycling). This data will be sourced from the manufacturer's EPD.

As outlined in 3.2.2, a single EPD will be applied to all windows across different locations and strategies tested in this project, disregarding variations in glazing properties. The selected EPD, provided by the Aluminium Spanish Association

Table G.1: Emission factors for energy used for heating, cooling and ventilation in the three locations

	Energy source	Emission factor [1] (kg CO_2eq./kWh)
Heating		
Denmark	District heating [39]	0.072 [2]
United Kingdom	Natural gas [39]	0.202 [3]
Italy	Natural gas [39]	0.199 [4]
Cooling and ventilation		
Denmark	Electricity	0.049 [2]
United Kingdom	Electricity	0.168 [5]
Italy	Electricity	0.267 [6]

1 Projected emission factor for a reference period of 50 years (2024-2074).

2 BR18 Appendix 2, Table 8 "Emission factors for electricity, district heating and gas" [26].

3 Based on UK's 2023 conversion factors [50].

4 Based on ecoinvent [51] emission factors.

5 Based on UK's 2023 conversion factors [50] and future projections [52].

6 Based on ecoinvent [51] emission factors and projected Italy's 2050 GHG emissions [53].

(AEA) [46], represents a composite of products from various manufacturers rather than a specific product. It reflects a window with glazing properties similar to those tested in this project. The product's specified lifetime in the EPD is 30 years, which will be used to calculate Module B4 – "Replacement."

External Solar Shading Mechanisms

The implementation of solar shading mechanisms affects all life-cycle modules, including the product stage (Modules A1 – "Raw material supply," A2 – "Transport," and A3 – "Manufacturing"), the use stage (Module B4 – "Replacement" and Module B6 – "Operational energy use" for automated systems), the end-of-life stage (Modules C3 – "Waste processing" and C4 – "Disposal"), and Module D (benefits from reuse, recovery, and recycling). Relevant data will be sourced from the manufacturer's EPD.

As detailed in 3.2.2, a single EPD will be used for all strategies involving solar shading mechanisms, disregarding variations in solar coefficients. The selected EPD represents external venetian blinds with aluminum slats, provided by Griesser [47], and accounts for a range of solar transmission coefficients.

The control mechanism, whether manual or automated, will be considered as it affects Module B6 – "Operational energy use". If automatic, in the EPD, energy consumption is specified as 50 kWh/m^2 for standby mode and 3 kWh/m^2 during operation within the reference use period. The total energy consumption of 53 kWh/m^2 is calculated over the reference period of 30 years, scaled to the 50-year study period, and then multiplied by the electricity emission factor specific to each location.

The product’s specified lifetime is 30 years, which will be used to calculate Module B4 – "Replacement."

STUDENT REPORT

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