POLITECNICO MILANO 1863

School of Architecture Urban Planning and Construction Engineering

Master of Science in Building and Architectural Engineering

# Shaping the Future Workspace: Analyzing the impact of smart-working policies on post-pandemic office energy consumption

Author: **Valentina Brambilla**

| | |
|---|---|
| Student ID: | 995654 |
| Supervisor: | Juan Diego Blanco Cadena |
| Academic Year: | 2022 – 2023 |

# Acknowledgments

First, I extend my deepest gratitude to my supervisor, Juan Diego Blanco Cadena, for his invaluable support and guidance throughout the development of my thesis. His insights have been essential in navigating the challenges of this research.

I am profoundly thankful to my parents for their solid support throughout my academic journey. Their sacrifices have allowed me to pursue unique and enriching life experiences, for which I am eternally grateful.

A special thanks goes to Diego, whose love and support have been my strength in facing the challenges of this last year. His encouragement has been a constant motivation to excel in every challenge.

My appreciation also extends to my classmates, for being by my side through the university's pains and joys. Together, we have tackled challenges, supported one another, and faced sleepless nights working on projects, strengthening our bond.

I particularly want to acknowledge my best friends Giulia and Nicola for their companionship and steady support since day-one. Their presence has been a guiding light in the most critical and happy times of this journey.

My gratitude also extends to Allegra, Lucrezia, and Giovanni for their love, support, and friendship throughout my university journey. Their presence has been a constant source of comfort and strength.

Lastly, I thank all the people I have had the privilege of meeting over the past six years. Sharing a part of this unique life experience without you would not have been the same.

# Abstract

This thesis investigates the impact of smart-working policies on the energy demand in office buildings, incorporating a post-COVID-19 perspective that acknowledges the shift towards hybrid work models. Through the simulation of various occupancy profiles, including those defined by international standards and real-office scenarios, the study explores their impact on energy needs and efficiency, considering the effects of reduced occupancy rates and the optimization of office area while maintaining the same number of employees.
Key findings reveal that occupancy has a more substantial impact on cooling needs than on heating, with reductions in occupancy due to smart-working policies yielding greater benefits in warmer climates by significantly decreasing cooling needs. The study underscores the importance of evaluating both the Energy Use Intensity (EUI) and energy consumption per capita per hour to account for the socio-economic impacts of changing occupancy patterns.
The research further highlights that while reducing occupancy can lead to lower overall energy consumption in the considered climates, maintaining the same office layout and working hours while reducing occupancy results in increased per capita energy consumption. This suggests the need for broader changes to office configurations and operations to achieve energy efficiency. Moreover, area optimization strategies - facilitated by smart systems and flexible office configurations - emerge as effective measures for enhancing energy savings and reducing per capita energy consumption.
The thesis contributes to the understanding of how smart-working policies, accelerated by the pandemic, influence office building energy consumption. It provides valuable insights and tools for future research aimed at developing smart-working policies that optimize the future workplace for employee comfort, productivity, and energy efficiency. This study's comprehensive approach, which integrates energy efficiency with socio-economic considerations, offers a blueprint for navigating the evolving landscape of workplace environments in the post-pandemic era.

**Key-words:** Smart-Working Policies, Occupancy Profiles, Office Buildings, Energy Consumption, EUI, Post-Pandemic

# Abstract in lingua italiana

Questa tesi indaga l'impatto delle politiche di smart-working sulla domanda energetica degli edifici per uffici, incorporando una prospettiva post-COVID-19 che considera lo sviluppo di modelli di lavoro ibridi. Attraverso la simulazione di diversi profili di occupazione, tra cui quelli definiti dagli standard internazionali e quelli definiti da scenari di uffici reali, lo studio esplora il loro impatto sul fabbisogno e sull'efficienza energetica, considerando gli effetti dei tassi di occupazione ridotti e l'ottimizzazione della superficie degli uffici mantenendo lo stesso numero di dipendenti.

I risultati principali rivelano che l'occupazione ha un impatto più sostanziale sul fabbisogno di raffreddamento rispetto al riscaldamento, con riduzioni dell'occupazione dovute a politiche di smart-working che producono maggiori benefici nei climi più caldi, riducendo significativamente il fabbisogno di raffreddamento. Lo studio sottolinea l'importanza di valutare sia l'intensità di utilizzo dell'energia (EUI) sia il consumo energetico per capita per ora, per tenere conto anche degli impatti socio-economici dei cambiamenti nei modelli di occupazione.

La ricerca evidenzia inoltre che, mentre la riduzione dell'occupazione può portare a una riduzione del consumo energetico complessivo nei climi considerati, il mantenimento della stessa disposizione degli uffici e degli orari di lavoro, pur riducendo l'occupazione, comporta un aumento del consumo energetico per capita. Ciò suggerisce la necessità di apportare modifiche più ampie alla configurazione e all'operatività degli uffici per raggiungere l'efficienza energetica. Inoltre, le strategie di ottimizzazione delle aree - supportate da sistemi intelligenti e configurazioni flessibili degli uffici - emergono come misure efficaci per aumentare il risparmio energetico e ridurre il consumo energetico pro capite.

La tesi contribuisce alla comprensione di come le politiche di smart-working, accelerate dalla pandemia, influenzino il consumo energetico degli uffici. Fornisce spunti e strumenti preziosi per la ricerca futura, finalizzata allo sviluppo di politiche di smart-working che ottimizzino il futuro luogo di lavoro per il comfort dei dipendenti, la produttività e l'efficienza energetica. L'approccio complessivo di questo studio, che integra l'efficienza energetica con considerazioni socio-economiche, offre una base per navigare nel panorama in evoluzione degli ambienti di lavoro nell'era post-pandemia.

**Parole chiave:** Politiche di Smart Working, Profili di Occupazione, Edifici per Uffici, Consumo Energetico, EUI (Indice di Utilizzo Energetico), Post-Pandemia

# Contents

# Introduction

Building energy consumption is not just a significant portion of total energy use worldwide; it also accounts for a substantial part of global $CO_2$ emissions. This reality has produced extensive research and development efforts aimed at pioneering energy-efficient technologies designed to curb these consumption levels. Historically, buildings have been engineered for functionality and comfort, often with less emphasis on energy efficiency. However, the climate crisis and rising energy costs have shifted the focus towards sustainability in building design and operation.

The start of COVID-19 towards the end of 2019 introduced extraordinary changes on a global scale, affecting over 200 countries and forcing a radical shift in daily routines. Governments worldwide instituted various measures, including city lockdowns and mandates for remote work and study, in an effort to mitigate virus spread. These measures not only altered the structure of daily life but also induced a reevaluation of workspace utility and design.

In the subsequent post-pandemic era, as restrictions eased and a return to 'normality' became possible, the continuation of remote work practices emerged as a lasting legacy of the pandemic. The forced experiment with remote work revealed numerous advantages, from reduced commute times to increased flexibility, leading many organizations to permanently adopt smart-working policies. This transition, however, has highlighted a mismatch between the design of existing office spaces and their current usage patterns. Offices, traditionally designed for full occupancy during standard working hours, now face periods of underutilization or require adaptations to support hybrid work models.

This discrepancy underscores a pressing issue: most office buildings are being used in ways significantly different from their original design intentions, leading to inefficiencies in energy use. At a time when the global community is struggling with strict energy efficiency targets to combat climate change, understanding how smart-working policies affect office energy consumption becomes vitally important. Addressing this issue is crucial for devising strategies that not only reduce energy consumption but also adapt office environments to the evolving landscape of work practices.

This thesis sets out to explore the impact of reduced occupancy, as a result of smart-working policies, on the energy needs of office buildings. By employing energy simulations of various occupancy profiles—each characterized by distinct people density, schedule, and metabolic rate—the study aims to provide a comprehensive analysis of how these factors influence office energy demand. The profiles, informed by international standards, offer a basis for evaluating energy use across different office layouts, including private offices, open plan offices, and co-working spaces.

Analyzing these simulations through the lens of key performance indices such as the Energy Use Intensity (EUI) and the energy consumption per capita per hour provides valuable insights into the efficiency of different office configurations. This analysis not only drops light on the immediate effects of occupancy changes but also considers the wider socio-economic dimensions of smart-working policies.

Furthermore, the discussion extends to potential optimization strategies that can further enhance energy efficiency and adaptability of office spaces to new working norms. The thesis proposes a suite of tools and methodologies for future research aimed at improve these strategies, thus contributing to the key goal of creating more sustainable, energy-efficient, and employee-friendly office environments. In doing so, it addresses a critical gap in current research, offering a roadmap for navigating the challenges questioned by the shift towards hybrid work models and the requirement for environmental sustainability.

# 1. State of the Art

## 1.1 Energy Consumption in Office Buildings

Considering the commercial buildings sector before the pandemic outbreak the Energy Information Administration (EIA) forecasted an increase in energy consumption. Data indicated a rise in energy consumption per capita within the commercial sector, contrasted with a decline in the residential sector. [1]

This trend underscores the critical importance of harnessing energy efficiency potential within the commercial realm. Despite the wide array of retrofitting opportunities available, existing literature and practices reveal that energy efficiency improvements have been implemented on an ad hoc basis, lacking a systematic approach to decision-making. [2] Furthermore, despite significant energy conservation efforts by developed nations, building energy demand surged by over 20% from 2000 to 2017. This increase is attributed to the expanding floor area of dwellings, modest reductions in energy intensity, and elevated energy demands for services.[3]

The Energy Use Intensity (EUI), calculated as the energy usage per square meter of gross floor area (in $kWh/m^2 \cdot yr$), serves as a pivotal metric for assessing building energy performance. The EUI encompasses energy consumption for cooling, lighting, and plug loads, including additional loads from lifts and escalators.

In office buildings, the predominant energy consumers are space conditioning, lighting, and plug loads for IT equipment, collectively accounting for over 80% of total energy usage. Among these, air conditioning systems emerge as the principal energy consumers, often becoming the focal point of retrofitting efforts, as seen in Figure 1.1, which has been taken from the paper "Using artificial neural networks to assess HVAC related energy saving in retrofitted office buildings" by C. Deb, S. E. Lee, and M. Santamouris. [4]

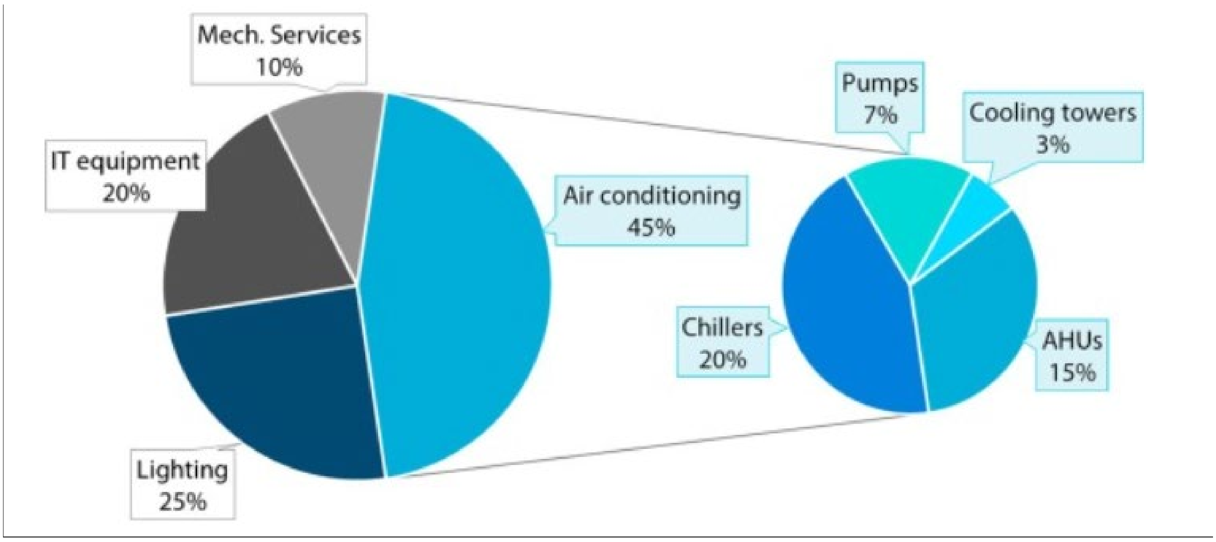



Figure 1.1: Energy breakdown for a typical air-conditioned office building taken from [4].

Annex 53 explores the total energy use in buildings, highlighting that energy consumption is influenced by six main factors categorized into physical and human aspects. These include [5]:

- Physical factors: Climate, Building Envelope and Building Equipment
- Human factors: Maintenance, Occupant Behavior and Indoor environmental Conditions.

It emphasizes that occupant behavior significantly affects energy consumption through interactions with various building systems. Additionally, the climate is noted as a crucial factor directly affecting energy needs, demonstrating the complex interplay between these elements in influencing building energy use. [5][6]

## 1.2 Impact of Occupancy on Building Energy Demand

As anticipated in the previous paragraph, occupancy is a significant factor affecting building energy consumption.

Monitoring studies of identical buildings with similar installations have demonstrated that heating energy consumption can fluctuate by a factor of 2 to 3, attributable only to differences in user behavior. This finding positions the influence of occupant behavior as equal to or even greater than the impact of technological efficiency.[7] In response, the International Energy Agency's Energy in Buildings and Communities Programme initiated Annex 66, aiming to standardize the definition of occupant behavior, develop a quantitative methodology for its simulation in buildings, and clarify its effect on energy usage and indoor environments. Occupant behavior modeling in commercial buildings presents specific challenges due to the high diversity in spatial and functional aspects as can be seen from Figure 1.2 (the image has been taken from Annex 66 official website[1]). Commercial buildings are often controlled by complex environmental systems, with varying degrees of interaction and control between occupants and building or system managers, further complicated by social interactions, mutual influences, and negotiations. Despite the complexity of factors influencing occupant behavior, building energy simulations typically rely on predefined occupancy profiles, focusing on basic parameters such as people density, occupancy schedules, and metabolic rates, thus simplifying the intricate dynamics of actual human behavior.[8]

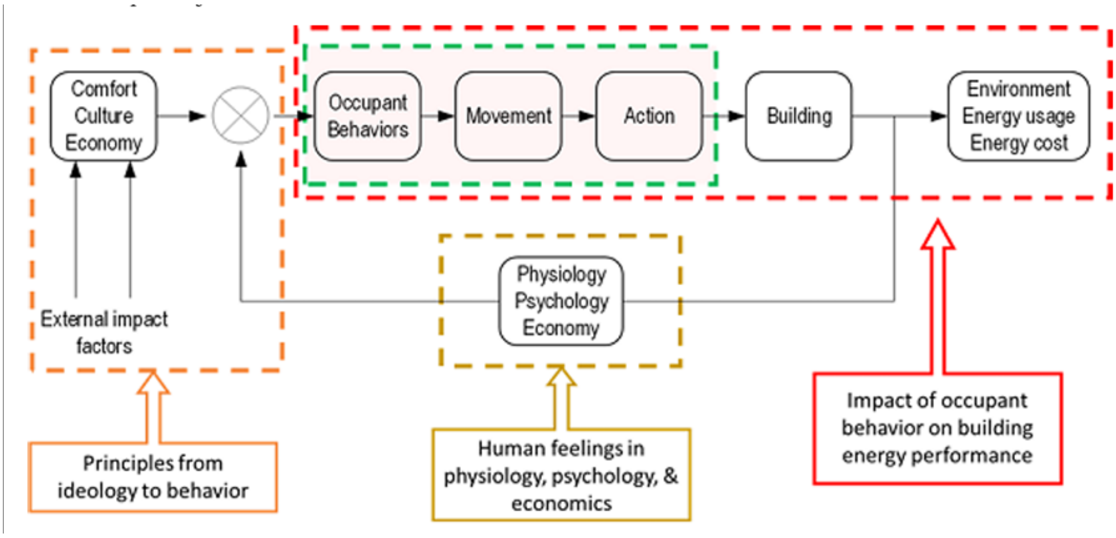



Figure 1.2: Relationship between occupants and building system. Image from Annex 66 official website [8]

In the context of office environments, the behavior of occupants is closely related to the surrounding environment, which has evolved in recent decades due to advancements in office equipment technology. Literature [9] [10] categorizes office spaces into three main types: the private office, where employees of various ranks or teams work in individual rooms, offering traditional workspace configurations; the open plan office, characterized by few or no partitions between employees to enhance communication and the flow of ideas within organizations; and the coworking office, a shared workspace used by individuals from different organizations or those who are self-employed, providing a dynamic alternative to home offices.

In particular, a study [11] examined how these three office layouts, with specific occupancy rates and densities, impact energy consumption, highlighting how different occupancy profiles affects not only the total energy consumption, but also

[1] https://www.annex66.org/

other parameters that include building area and employee's configuration to better understand what the most efficient configuration for the company is.

Below the occupancy inputs (Table 1.1) and the results (Figure 1.3 and Figure 1.4, directly extracted from the paper "Impact of occupants' behaviour on energy consumption and corresponding strategies in office buildings" by Z. Dong, K. Zhao, Y. Hua, Y. Xue, and J. Ge) obtained from the study [11]:

| Occupancy profiles properties from [11] | | | |
|---|---|---|---|
| Typology | People Density | Average Occupancy Rate | Weekly Working Hours |
| [-] | [P/m²] | [-] | [h] |
| Private Office | 0.04 | 0.7 | 50 |
| Open Plan Office | 0.08 | 0.7 | 50 |
| Coworking Office | 0.08 | 0.9 | 112 |

Table 1.1: Occupancy input data used in the simulations in [11]

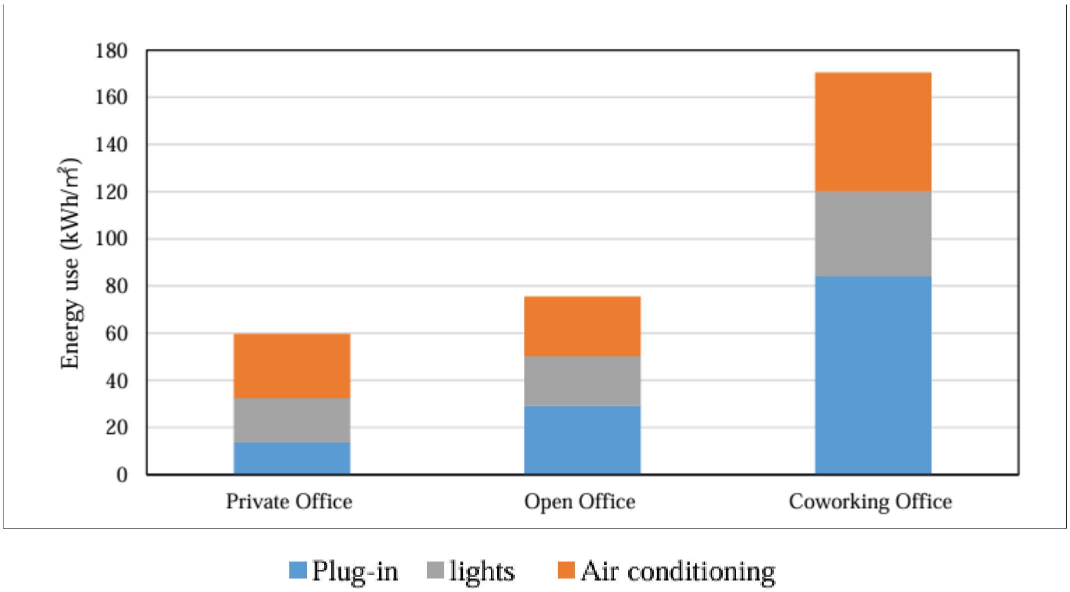



Figure 1.3: Annual building energy consumption per unit of area of three types of office. Image from [11].

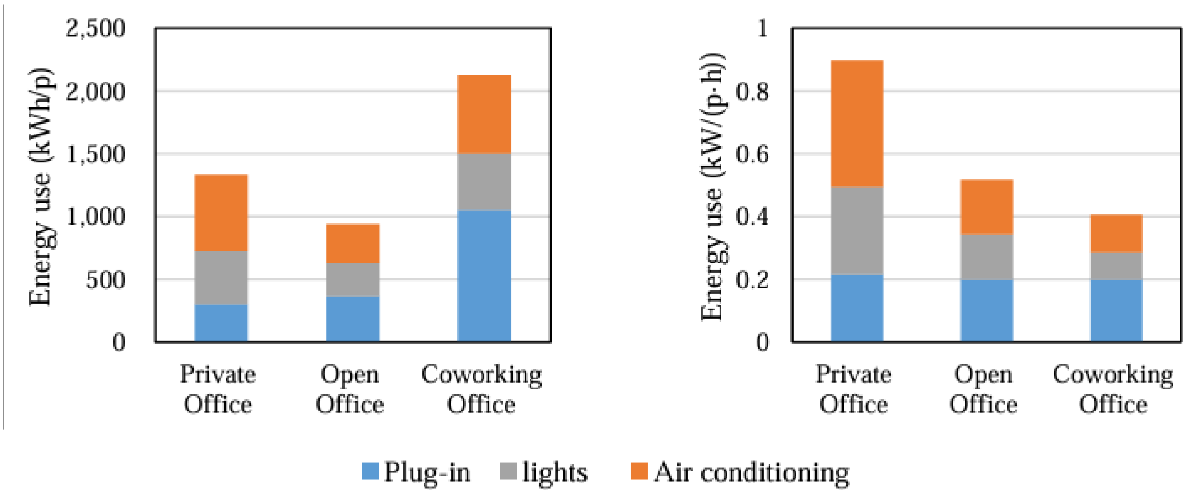



Figure 1.4: Building energy consumption per capita and energy consumption per unit of time per capita. Image from [11].

The analysis reveals that office configurations with higher density, such as open plan offices, exhibit greater annual energy consumption per area unit.

However, when evaluating energy consumption relative to the number of employees, this trend reverses. This discrepancy indicates that neither building energy consumption per area unit nor per capita effectively reflects the actual level of energy consumption. Consequently, the study introduces the metric of building energy consumption per capita per unit of time, under the assumption of equal working efficiency and socio-economic benefits across different office types.

In scenarios where working efficiency and social and economic outcomes are comparable, a lower rate of building energy consumption per unit of time per capita indicates more efficient energy use for generating these benefits. Results show that the energy consumption per capita per unit of time is lowest in coworking offices, suggesting that these spaces are the most efficient in terms of energy use for producing socio-economic benefits.

Moreover, the findings highlight a correlation between higher density and occupancy rates with increased energy consumption per area but decreased consumption per capita per unit of working time. This underscores the benefit of flexible spaces that can accommodate more people over extended periods, including weekends, enhancing their utility and energy efficiency.

## 1.3 COVID-19 Pandemic and Smart-Working policies

Since the initial report of the COVID-19 outbreak in December 2019, the pandemic had impacted over 200 countries and regions by 2020, leading to significant alterations in global human activities. In response, an unprecedented global effort was undertaken to contain the virus's spread, with measures including city lockdowns, work stoppages, bans on gatherings, and mandates for remote work and study. [12], [13]

This situation led most organizations worldwide to implement smart-working policies as a response to the government guidelines and regulations that were intended to maintain the health and safety of employees.

The focus was primarily on promoting social distancing, enhancing ventilation and encouraging the use of open windows, maximizing fresh air intake, and employing improved air filtration systems.[14]

As European countries prepared to ease lockdown restrictions, there were concerns regarding the optimal practices for HVAC systems to ensure healthier and safer work environments. These practices aimed to prevent the virus's spread while adhering to energy consumption and $CO_2$ emission reduction commitments. [15]

In the context of social distancing, remote working emerged as a widely adopted policy during the pandemic for sectors capable of implementing it, transitioning from an emergency response to a more permanent arrangement in the post-pandemic period. This shift has resulted in decreased and more unpredictable building occupancy rates.

The transition to remote working has yielded mixed effects on employee well-being. On one hand, many have appreciated the mandatory work-from-home period, expressing a preference to maintain remote work as their standard mode of operation. On the other hand, challenges such as inadequate home workspaces, childcare responsibilities, and social isolation have adversely affected employees' performance. [16], [17]

In March 2020, the IWG Global Workspace Survey [18] provided insights from 15,000 business professionals across 80 countries on flexible working's key motivations. Findings indicated that approximately half of the workforce spent 2.5 days per week in the office, with 85% attributing enhanced productivity to workplace flexibility. Additionally, four out of five respondents showed a preference for a hybrid workweek, while 65% acknowledged the model's potential to lower logistical costs. Furthermore, 65% of those surveyed reported productivity gains in environments tailored to worker expectations and needs, illustrating the complex interplay between workplace flexibility and employee efficiency.

This shift underscores the importance of studying and analyzing hybrid work trends and their potential effects on energy consumption. Understanding these patterns is vital for developing strategies to manage energy use efficiently in response to changing workplace dynamics. [19]

This situation underscores the challenge of addressing climate change towards the recovery from the COVID-19 crisis, highlighting the ongoing uncertainty in global energy use trends. [20]

## 1.4 Climate Considerations on Post-Pandemic Building Energy Demand

Research consistently indicates that weather conditions significantly influence the energy required for heating and cooling in buildings, with a building's energy consumption being closely tied to local climate. This relationship not only affects the direct energy use of a building but also influences the deployment of energy devices, particularly air conditioning, within the local building infrastructure. [21], [22]

As previously noted in Paragraph 1.1, climate impacts on building energy consumption in two ways: directly affecting the building's energy needs and indirectly by shaping occupant comfort, thereby influencing their behaviors and energy usage patterns.

Climate impacts energy consumption through its influence on occupants' reactions to short-term weather changes and their long-term adaptation strategies. Short-term weather fluctuations prompt immediate adjustments in energy use, increasing heating demands in colder conditions and cooling needs during warmer periods. Over time, these adaptations can lead to technological and structural changes, such as integrating air conditioning systems or modifying buildings to improve energy efficiency, to better cope with climatic demands. [23]

This topic is of interest as it suggests that regions experiencing frequent weather changes may have higher energy requirements. Furthermore, a study [23] analyzing the impact of various climates on high-rise office buildings before and after the pandemic indicated that post-COVID-19 energy consumption trends differ across climate zones.

The assessment considers two scenarios, pre-pandemic and post-pandemic related to HVAC operation due to COVID-19 mitigation guidelines worldwide and in the US. The simulations included a standardized high-rise office building in key IECC [24] climate zones 0 to 8.

In climates ranging from "warm-dry" to "very hot-humid" (zones 0 to 3 according to the IECC [24] ), there is a tendency for energy use intensity and cooling demands to decrease. Conversely, in climates from "mixed-humid" to "subarctic" (zones 4 to 8 according to the IECC), energy use intensity has increased, with a notable divergence: heating requirements have risen, while cooling needs have slightly decreased.

Across all climate zones, energy use intensity for lighting has decreased uniformly (by approximately 35%).

In Figure 1.5 and Figure 1.6 (both directly taken from the study “COVID-19: The impact in US high-rise office buildings energy efficiency” by N. D. Cortiços and C. C. Duarte) are shown the results of the study [23]:

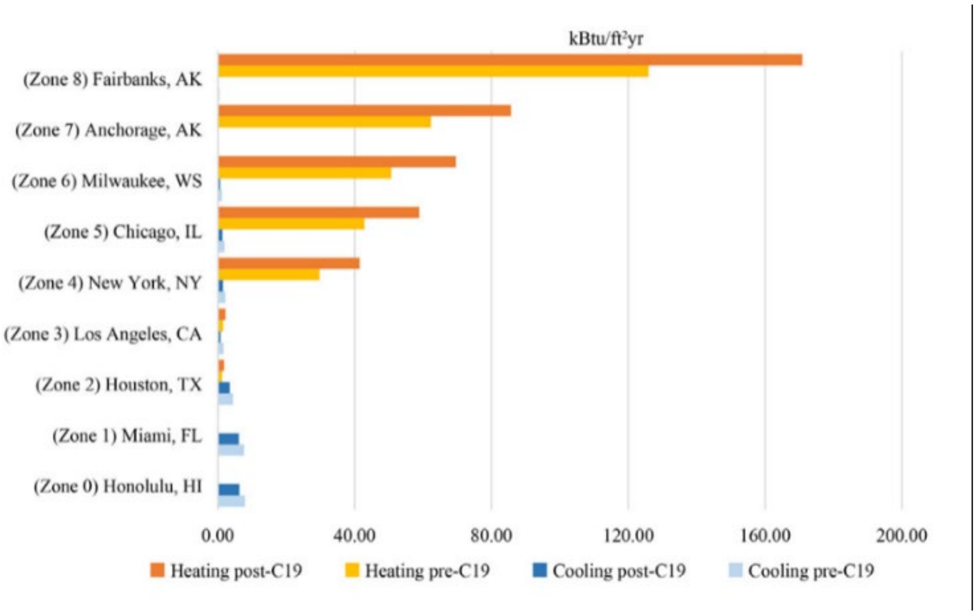



Figure 1.5: Climate zone cooling and heating energy consumption on pre and post pandemic scenarios. Image from [23].

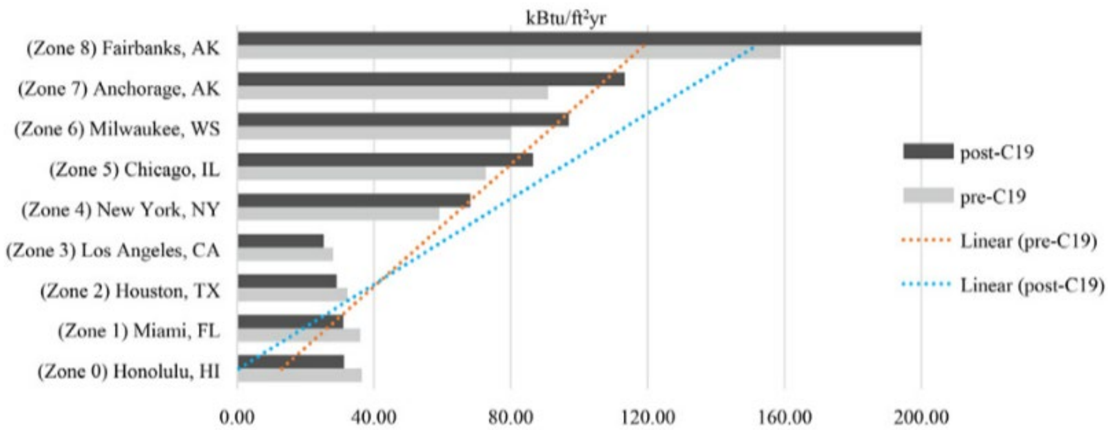



Figure 1.6: Climate zone total energy consumption on pre and post pandemic scenarios. Image from [23].

This research suggests that the pandemic trend tends to favor hot climates while disadvantaging mixed and cold climate, considering energy consumption.

This research give very important insight related to energy consumption trend since in the pre and post pandemic simulations the study consider the same office building but with different HVAC operations used to mitigate the virus in office environments.

# 2. Method

This chapter outlines the methodology employed in the thesis to examine the effects of occupancy profiles on energy demand, aiming to draw conclusions relevant for offices implementing smart-working policies with reduced or variable occupancy rates.

Initially, the process involves validating the thermal model used for the energy simulations with ClimateStudio, a building energy modeling software, against a reference standard. Following model validation, the necessary components for the analysis will be defined, including occupancy profiles, locations, evaluation parameters, and various simulation configurations.

Six occupancy profiles have been selected, three proposed by different international standards, and three real-office configurations, informed by workstation sensor data on a typical workday.

The climates selected for this work has been Denver and London, both have been used to gain deeper insight related to our research question, while the first one have been used also for the model validation.

Finally, we are going to set up the simulations trying to answer this research questions:

1. How do different occupancy profiles will affect energy needs and efficiency while maintaining the same office area?
2. How do reduced occupancy rates of a same profile will affect energy needs and efficiency while maintaining the same office area?
3. How does the office area optimization will affect energy needs and efficiency while maintaining the same number of employees?

This simulation will show us different dynamics that will help to gain insight related to occupancy rates in office buildings.

In Figure 2.1 is summarized the Methodology Workflow that will be detailed in the following paragraphs.

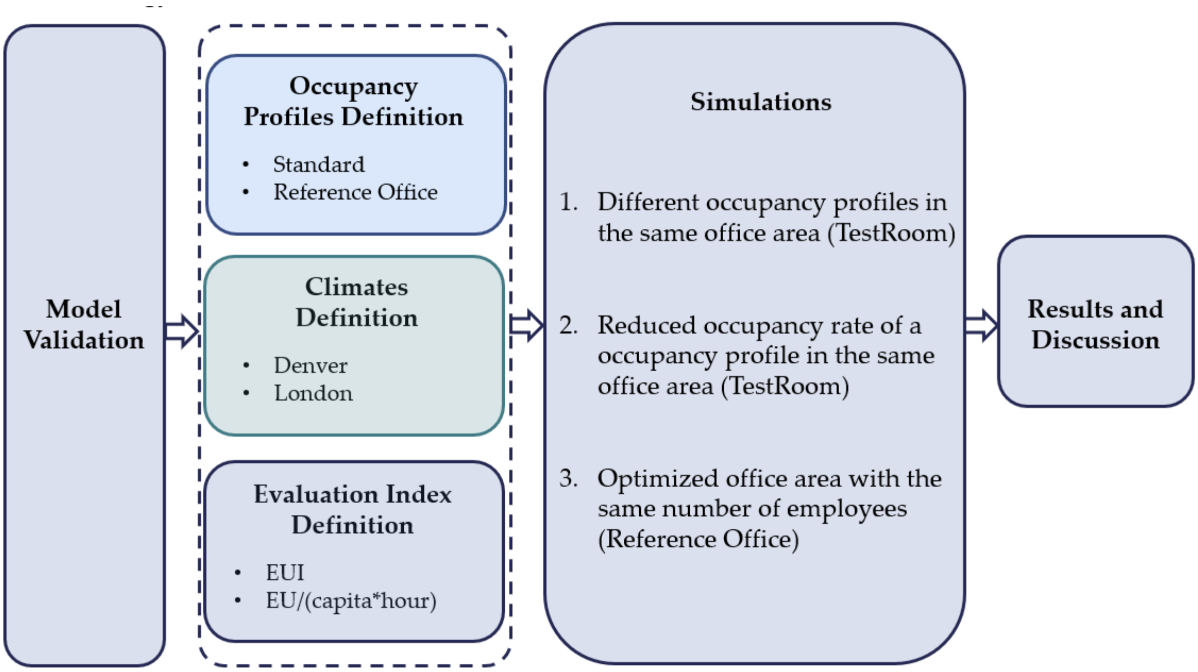



Figure 2.1: Methodology Workflow.

## 2.1 Thermal Model Validation

Prior to launching the simulations, the thermal model underwent validation in compliance with BS EN ISO 52016-1 standard. The test room "BESTest 600FF" [2] was selected as the specific verification case for this process and its properties and the validation data are the same defined by ASHRAE 140-2017 [25].

The geometry of the thermal model has been created in Rhino 7 [3], while all other properties and settings has been defined using ClimateStudio [4] inside Grasshopper [5] environment, a graphical algorithm editor integrated with Rhino's 3-D modeling tools.

Developed by Solemma, ClimateStudio is a graphical user interface for the thermal simulation software EnergyPlus[6] and is well known for allowing users to evaluate and enhance the thermal and daylight performance of buildings even in the early stages of design.

---

[2] Building Energy Simulation Test, test room 600, Free Floating – ASHRAE 140 -2017
[3] https://www.rhino3d.com/
[4] https://www.solemma.com/climatestudio
[5] https://www.grasshopper3d.com/
[6] https://energyplus.net/

The subsequent paragraphs will outline all the validation workflow, geometrical and thermophysical properties of the model and the simulation settings.

### 2.1.1 Validation Workflow

The objective of this validation process is to confirm that the model is accurately calibrated in comparison to the reference model as proposed by the standard [26].

Initially, the validation of climate data will be conducted by comparing the results from the ClimateStudio simulation with the data provided by ISO 52016-1. Upon successful validation of the climate data, the process will proceed to validate the test room. This step is essential for assessing its reliability for subsequent simulations.

The initial step involves creating the geometry in Rhino, modelling the test room components such as wall, roof, floor and window as surfaces, followed by the setup for ClimateStudio in Grasshopper environment.

This Grasshopper workflow includes assigning to the surface their thermophysical properties and linking them to create a thermal zone. After the thermal zone settings and surface properties have been determined, all inputs are integrated into the thermal model creator. This is then connected to the ClimateStudio Energy Simulation Tool, along with the Weather File. The simulation workflow is illustrated in Figure 2.2.

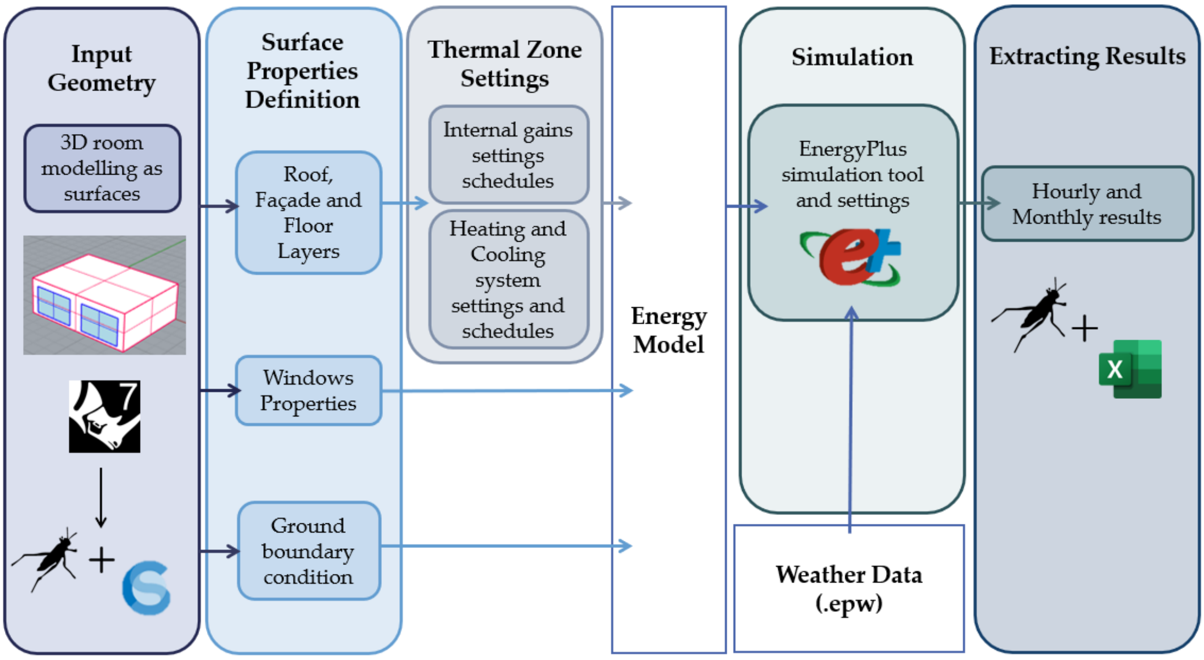



Figure 2.2: ClimateStudio Simulation Workflow

Following the simulation workflow set up, the validation procedure has been developed comparing different envelope modelling strategies to see which one brings to results closer to the reference ones.

The validation procedure involved:

1. **Weather Data Validation:** This step assessed the reliability of the weather data to ensure its accuracy for simulation purposes.
2. **Opaque envelope modelling evaluation:** Three configurations of opaque envelope modeling were simulated, all sharing identical thermophysical properties but differing in mass distribution to evaluate its impact on the outcomes. The internal operative temperature served as the validation parameter for this phase.
3. **Window modelling evaluation:** Similar to the opaque envelope modeling, three window modeling options were analyzed. Each option explored different mass modeling approaches while keeping the thermophysical properties consistent as per the standards. The validation has been done using as validation parameters the internal operative temperature and window solar heat gains.

The detailed modelling procedure will be explained in 2.1.4 and 2.1.5.

The reference value of the validation parameters mentioned above have been obtained as follow:

- **Internal Operative Temperature**: values are reported in results table in the reference standard [26].
- **Window Solar Heat Gains**: which reference values have been calculated using the following formula reported in the same reference standard [26].

$$Q_{sol,w} = (I_{sol,tot} * F_{sh}) * g_{gl,w} * A_w(1 - F_{fr}) * T_a \; [\,Wh\,]$$

Where:

$Q_{sol,w}$ = is the solar gain into the zone from the windows. [Wh]

$I_{sol,tot}$ = is the total south vertical solar radiation from the standard [26]. [Wh/m$^2$]

$F_{sh}$ = is the shading reduction factor for external obstacles for windows, that for this validation is equal to 0 since no external obstacles or elements are considered. [-]

$F_{fr}$ = is the frame area fraction of the window, that for this validation is equal to 0. [-]

$g_{gl,w}$ = is the solar heat gain factor previously defined for the windows. This value is equal to 0.71 and it considers the non-scattering glazing factor equal to 0.9. [-]

$A_w$ = is the total are of the windows equal to 6 m$^2$ for each window, for a total of 12 m$^2$. [m$^2$]

$T_a$ = is the thermal absorption coefficient [-].

The whole validation process is resumed in Figure 2.3.

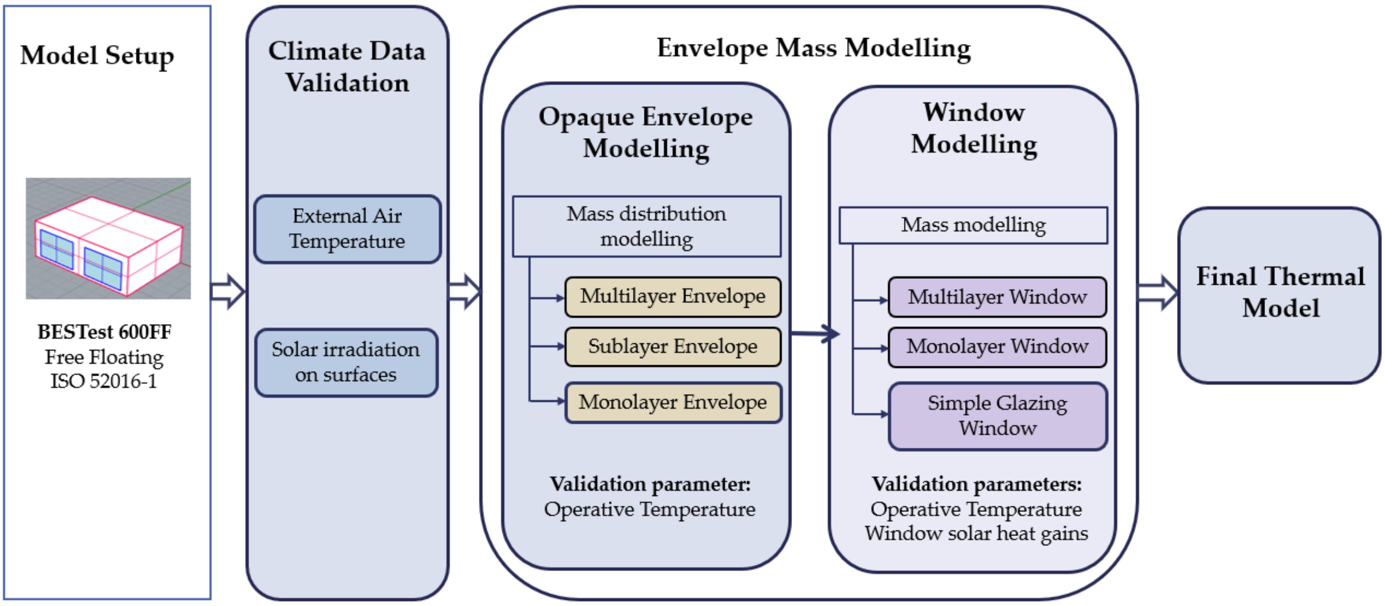



Figure 2.3: Model Validation Workflow

## 2.1.2 Model Description

The test room consists of a single thermal zone composed by a lightweight envelope and two south-oriented windows with no shading systems, for a total area of 48 $m^2$ and a volume of 129.6 $m^3$.

The geometry of the test room is shown in Figure 2.4 (Image directly extracted from the ISO 52016-1 [26] ) while the thermophysical characteristics of the whole envelope are described in Table 2.1, Table 2.2 and Table 2.3.

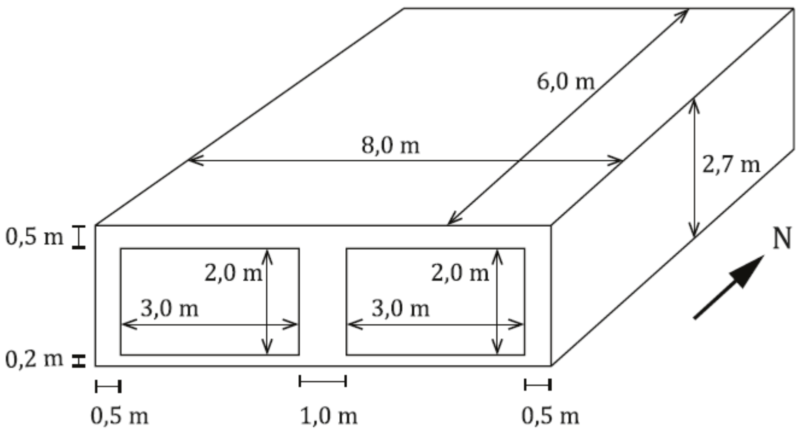



Figure 2.4: Geometry of the test room. [26]

| Opaque Envelope | | | |
|---|---|---|---|
| Structure | Thickness | Thermal resistance | Thermal capacitance |
| [-] | [m] | [$m^2K/W$] | [$kJ/m^2K$] |
| Façade | 0.087 | 1.789 | 14.53 |
| Floor | 1.028 | 25.254 | 19.50[7] |
| Roof | 0.141 | 2.992 | 18.17 |

Table 2.1: Opaque envelope's properties

| Window | | | | |
|---|---|---|---|---|
| Structure | Thermal transmittance | SHGC | Visual transmittance | Frame factor |
| [-] | [$W/m^2K$] | [-] | [-] | [-] |
| Double pane glazing | 2.984 | 0.71 | 0.6 | 0[8] |

Table 2.2: Window's properties

| Solar absorptance | Thermal absorptance |
|---|---|
| [-] | [-] |
| 0.6 | 0.9 |

Table 2.3: Radiative Envelope properties

[7] This value of thermal capacitance doesn't consider the external insulation of the floor that, according to the ISO 52016-1, should be modelled with the lowest density and specific heat allowed by the software.

[8] No frame is considered.

### 2.1.3 Simulation Settings

The simulation settings from the BS EN ISO 52016-1 validation procedure are listed below:

- **Internal heat flow rates**

The total internal heat flow rate shall be 1.453 W/m$^2$ , continuously, 24 hours per day for the full year.

- **Infiltrations**

The infiltration rate shall be 0,41 air changes/h continuously (24 hours per day for the full year), considering that the specified infiltration rates have been adjusted with factor 0,822 to yield mass flows equivalent to those occurring at the specified altitude of the weather station at 1 609 m altitude, which results in 0.5 air changes/h.

- **Humidostat**

There is no humidity control from the system.

- **Ventilation**

There is no ventilation system.

- **Weather Data**

The climatic data utilized for validation was sourced from the reference standard [26] , which is identified as being in Denver-Stapleton (Colorado, USA), as specified in ASHRAE 140.

The EnergyPlus Weather File (.epw) was downloaded from a weather file database[9] and corresponds to the:

**Weather File:** USA_CO_Denver-Stapleton.Intl.AP.724690_TMY.epw

**Location:** Denver – Stapleton, Colorado, USA

**Latitude/Longitude:** 39.76° N, 104.86°W

**Elevation:** 1611 m

Prior to conducting the thermal validation, a procedure to validate the climatic weather file was undertaken to confirm the reliability of the weather file.

- **Thermostat**

The BESTest 600FF is a Free Floating case, which means there is no temperature control.

---

[9] https://climate.onebuilding.org/

In the occupancies simulations the thermostat has been set to 27°C for cooling and 20°C continuously, in order to evaluate the energy needs for cooling and heating.

This thermostat setting is the same adopted by the testroom BESTest 600 as well described in the same standard [26].

### 2.1.4 Opaque Envelope Modelling

Given the thermal capacitance of walls, roofs, and floors, various modeling techniques that retain the original thermophysical properties but employ different mass modeling configurations are evaluated:

- **Standard Modelling: Multilayer Envelope**
  This approach serves as the reference model due to its straightforward application: the properties of walls are modeled and integrated into ClimateStudio, maintaining the original layers and properties specified in Appendix A – TestRoom properties.

- **Mass Distribution and Sublayers Modelling: Sublayer Envelope**
  This technique consists in modeling the façade and roof as monolayer components with the same total thickness and thermophysical properties but divided into four identical sublayers. This method ensures even distribution of internal mass and aligns with the standard mass distribution (Appendix A – TestRoom properties). It is presented as a viable alternative in the standard [26] and warrants examination for its impact on results.
  The flooring must be carefully modelled since the external insulation layer should be modeled as a non-mass element, a configuration not supported by ClimateStudio. Moreover, according to the standard, mass distribution should be concentrated on the internal side of the floor. Consequently, the floor is modeled to one-quarter of its original thickness (to concentrate mass at the internal node as per the standard [26]) while preserving the same thermophysical properties.
- **Mass Distribution Modelling: Monolayer Envelope**
  This modelling strategy is close linked to the previous modelling strategy, since we have a unique material that compose the building construction, but in this case the elemnt is not divided in the sublayers. The floor has been kept modelled in the same way as in the previous modelling strategy.

  In the Appendix B – ClimateStudio Modelling Configurations are shown the detailed modelling configuration inside the software of the different modelling strategies.

### 2.1.5 Window Modelling

The Grasshopper ClimateStudio workflow proposes different ways of modelling the windows construction:

- **Simple Glazing Window**
  This is the most simple way of modelling a window since it just requires the essential thermal and visual properties such as:
  - Thermal transmittance of the whole window
  - Solar heat gain coefficient
  - Visible Light Transmittance

  The mass of the window construction is not considered.

- **Build Window from Scratch**
  This method allows to insert all the layers of a glazing, including all the physical and thermal properties of every layer, air gap included.
  The standard reference [26] only provided the basic thermal properties of the window, but the window layers information can be extracted from the ASHRAE 140 – 2017 [25], to which the reference standard is referred.

Considering these window modelling option, three window modelling configurations have been defined:

- **Simple Glazing Window**
  The window has been defined with the properties specified in paragraph 2.1.2 with the "Simple Glazing Window" modelling workflow.

- **Multilayer Window**
  This window configuration considers the same thermophysical properties defined before, with the addition of the layers thickness, which include two clear glass panes divided by an air gap.
  The specific of each layer are explained in the Appendix B – ClimateStudio Modelling Configurations.

- **Monolayer Window**
  Following the previous opaque envelope modelling, this window model is composed by a single clear glass with the same thickness and thermal properties of the previous models.
  The specific of the layer are explained in the Appendix B – ClimateStudio Modelling Configurations.

## 2.2 Occupancy Profiles Definition

Determining an accurate occupancy model is challenging due to its stochastic nature. In many simulations, occupant activities are typically represented by fixed schedules, which overlook the significant uncertainty inherent in human behavior. Consequently, most building energy simulations utilize Standard Profiles that outline general trends in occupancy, density, and metabolic rate. These Standard Profiles are detailed in international standards such as ASHRAE 90.1, ISO 17772-1, and ISO 18523, and they will be described and applied in the subsequent analysis.

Furthermore, this analysis will incorporate a real open-plan office occupancy profile, obtained through sensor data, and propose three different office configurations. These configurations consider the same number of people distributed across various office areas.

For each profile identified, it was necessary to supply the following input parameters for ClimateStudio:

- **Metabolic Rate [met]:** the rate of transformation of chemical energy into heat and mechanical work by metabolic activities of an individual, per unit of skin surface area, expressed in units of "mets". One met is equal to 58.2 W/$m^2$, which is the energy produced per unit skin surface area of an average person seated at rest [27].

  In general, the metabolic rate for offices activities is between 1.0 (reading, seated) and 1.7 (walking about) [28].

  Additionally, EnergyPlus assume a body area of 1.8 $m^2$ per person[29], which means that for each profile the occupant heat production will depend on the defined value of metabolic rate.

- **People density [People/$m^2$]:** refers to the number of individuals that can occupy a specific area, measured in persons per square meter (persons/$m^2$).

  In this instance the people density represents the number of workstations divided by the office area.

- **Occupancy Schedule:** It is a defined timetable that outlines the expected occupancy patterns of a specific area, with values determined on an hourly basis. These values can range from 0 (indicating the area is empty) to 1 (indicating the area is completely full) or expressed in percentage.

To simplify the analysis of all occupancy profiles, a unique yearly schedule has been defined. This schedule starts with Sunday as the first day of the year and includes only one holiday (December 25$^{th}$).

### 2.2.1 Standard Profiles

The occupancy profiles described below represent occupancy trend related to office buildings proposed by international standards. Even if all profiles are valid to simulate the occupancy in building energy simulations, they have different characteristics that might be more suitable depending on the office typology considered.

As already commented in the State of the Art (Paragraph 1.2) the literature mainly divides the office typologies in private office, open plan office and co-working.

For the purpose of this work, it is possible to associate to each standard profile an office typology. Below, the standards profiles will be described and in Table 2.6 and Table 2.7 will be resumed all the occupancy profiles with all the schedules, properties and assigned office typology based on the definitions given by the literature. [9]

- **ASHRAE 90.1**

The ASHRAE Standard 90.1 [30] is a comprehensive document that sets forth the minimum requirements for energy-efficient design in buildings except low-rise residential structures. It covers a wide range of criteria, including building envelope, HVAC systems, water heating, power usage, and lighting, aiming to reduce energy consumption while maintaining comfortable and functional indoor environments. [30]

The standard proposes schedules and internal loads, by building type, to be used in the building energy simulations.

The operation time of this schedule is from 6 a.m. to midnight in the weekdays, while on Saturdays from 6 a.m. to 7 p.m. and on Sundays from 6 a.m. to 6 p.m.. The schedule is resumed in the Chart 2.1.

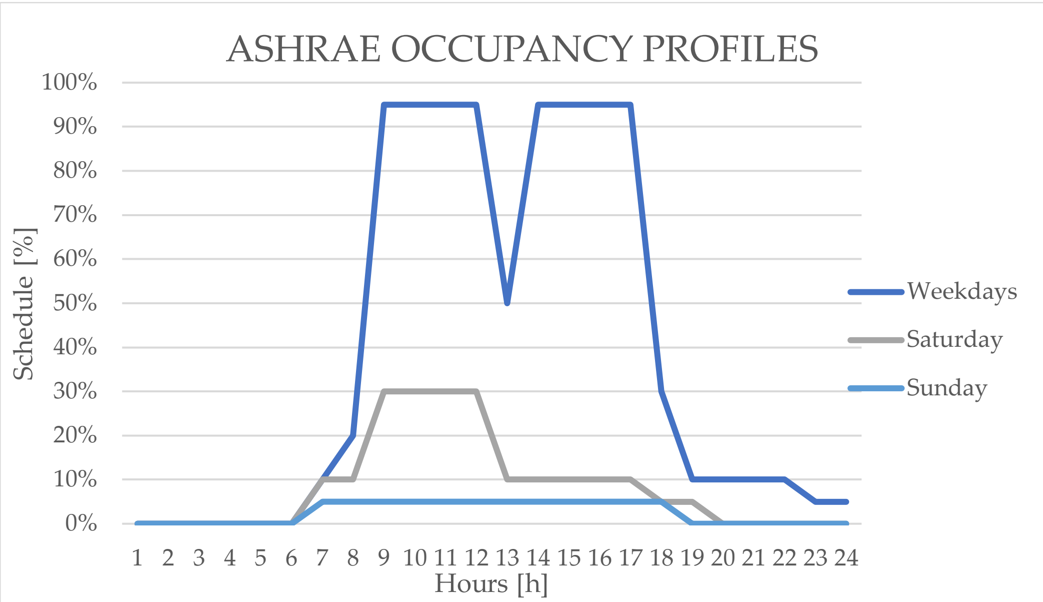



Chart 2.1: ASHRAE 90.1 – Occupancy Schedule.

This schedule indicates a highly flexible behavior of occupants, including presence during the weekends and extending beyond conventional office hours, up to midnight on weekdays. Therefore, it can be assumed that this schedule likely represents a co-working space or an office with extensive flexibility policies for its employees.

- **ISO 17772-1**

The BS EN ISO 17772-1 [31] specifies requirements for indoor environmental parameters for building system design and energy performance calculations. This standard focuses on the indoor environmental input parameters for the design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics.

The considered occupancy profile can be found in the Annex N and it describes an occupancy profiles configuration for a landscaped office that can be used as input to calculations of energy use in a building, when a standard calculation is made.

The operation time of this schedule is from 7 a.m. to 6 p.m. and it considers only weekdays. The schedule is resumed in the Chart 2.2.

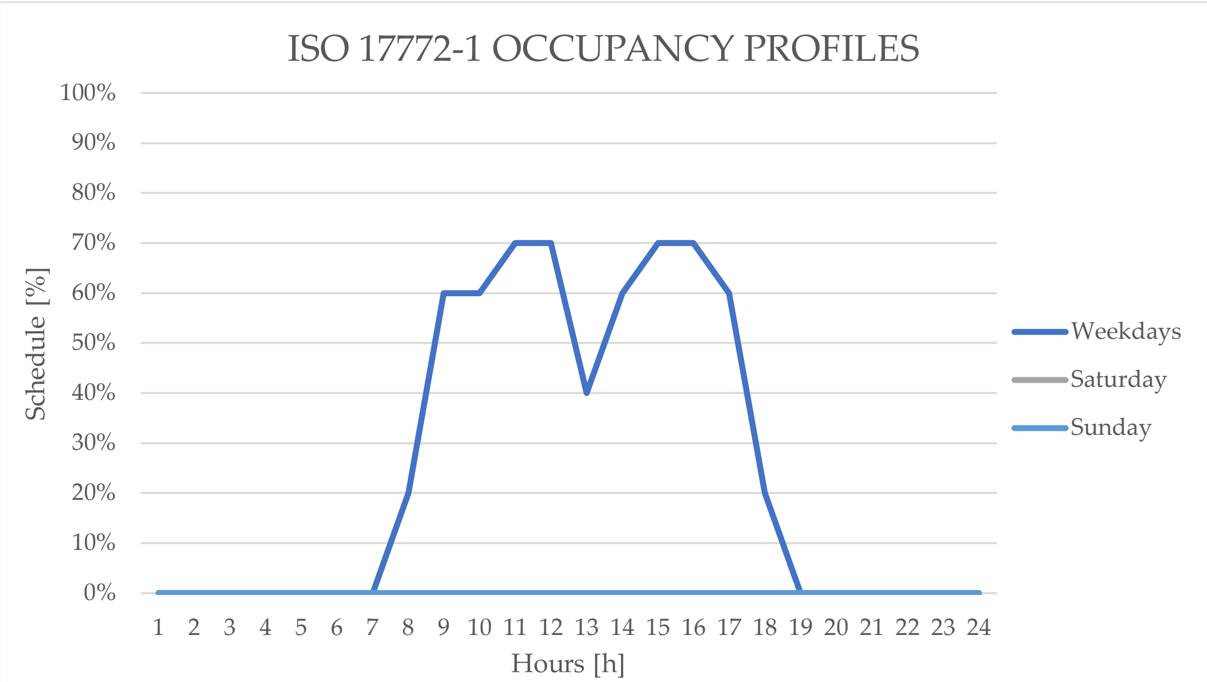



Chart 2.2: ISO 17772-1 - Occupancy Schedule.

The schedule illustrates the dynamics within a landscaped office, similar to an open-plan setting. This office environment is characterized by not being fully occupied but operates exclusively on weekdays, from early morning through to the evening.

- **ISO 18523-1**

ISO EN 18523-1 [32] is a standard dedicated to outlining the formats for presenting the schedule and condition of building, zone, and space usage, which serves as essential input data for energy calculations in non-residential buildings. It categorizes buildings and zones based on distinct schedules to facilitate these calculations.

Within the context of this research, the focus will be on the "Office building" category, specifically selecting the "Office Room" zone. The detailed schedule for this category is provided in Annex D of the standard, encompassing schedules and settings for air conditioning, lighting, equipment, and domestic hot water. However, this study will exclusively utilize the people occupancy schedule and people heat gain.

The chosen profile more closely aligns with a standard office room configuration rather than an open-plan office setup. This is due to its occupancy schedule, which shows a rate that reaches 100% for the majority of the day. Therefore, this profile is characterized by a higher occupancy rate, attributed to the continuous presence of employees in the office.

The operation time of this schedule is from 8 a.m. to 9 p.m. and it considers only weekdays. The schedule is resumed in the Chart 2.3.

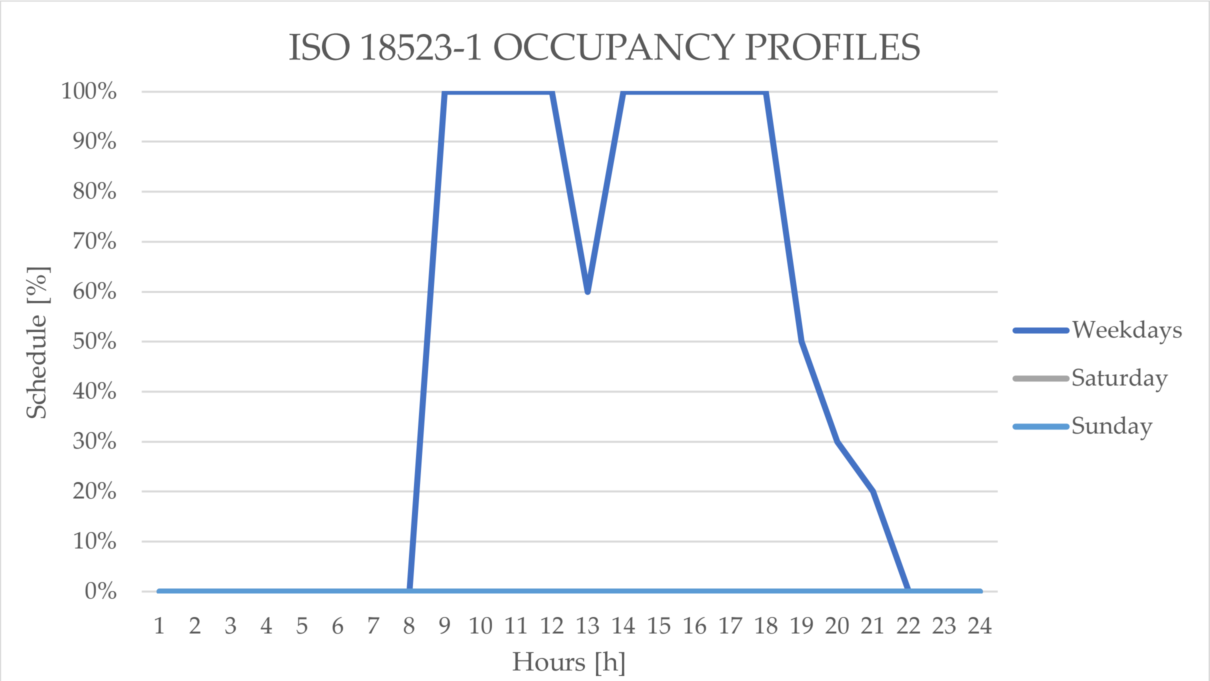



Chart 2.3: ISO 18523-1 – Occupancy Schedule.

This schedule could correspond to a private office, as it exhibits the highest occupation rate throughout the day compared to other profiles. This pattern suggests the characteristics of a small office space shared by a few employees.

### 2.2.2 Smart-Working Occupancy Trends

The COVID-19 pandemic, which swept across the globe in early 2020, led to unprecedented changes in human behavior and economic activities and a significant reduction in energy consumption was observed worldwide. This phenomenon was primarily due to lockdown measures, social distancing policies, and a temporary halt in industrial activities, which collectively contributed to altering the conventional patterns of energy use.

In office and educational buildings the occupancy has suffered a drastic decrease, which in most of the case led to an energy consumption reduction, but as many studies highlighted [33], despite the apparent saving, the energy consumption per capita increases, significantly translating into lower energy efficiency.

According to Strategic Regional Research Alliance of the city of Toronto [34] between May 2020 and May 2022 the average office occupancy were never above 20%, with an average of 10% and, according to a Savills article [35] , we have assisted to a occupancy recovery in June 2022 of 61% and of 79% in February 2023 (out of the 70% occupancy measured in 2019 [35]).

In Table 2.4 the occupancy trend considered:

| Covid-19 Occupancy Trend | | |
|---|---|---|
| Time | Occupancy* | Source |
| May 2020 – May 2022 | 10% | SRRA [34] |
| June 2022 | 61% | Savills [35] |
| February 2023 | 79% | Savills [35] |

*As a percentage of pre-covid occupancy.

Table 2.4: Occupancy Trend Percentage.

To evaluate the effects of occupancy variations, a simulation of one of the standard profiles will be conducted. This approach aims to gain insights into how these variations influence the overall energy demand across two distinct climate conditions.

### 2.2.3 Reference Office

The reference office occupancy profile is derived from an actual office located in London. This profile outlines the number of employees attending the office, the available workstations, and their spatial distribution within the office area. The occupancy schedule and density have been determined based on these input data.

The office spans a single floor, featuring a central core flanked by two open-plan office spaces, one facing east and the other west. Under normal circumstances, the office is fully utilized, with most workstations occupied. However, the occupancy rate provided reflects a significantly reduced trend, accounting for a post-pandemic scenario where most employees work remotely.

Two additional occupancy profiles have been developed to explore the strategy of closing one office wing (either east or west) to accommodate only a portion of the employees on-site. This approach, coupled with the adoption of flexible working policies, is anticipated to reduce office energy consumption by limiting the area in use.

This reference office will serve as the baseline for assumptions regarding strategies to enhance energy efficiency. Specifically, the analysis will focus on the impact of flexible working policies that result in fewer employees being physically present in the office and the potential for reduced operational costs.

In Figure 2.5 a scheme that explain office configurations explained above.

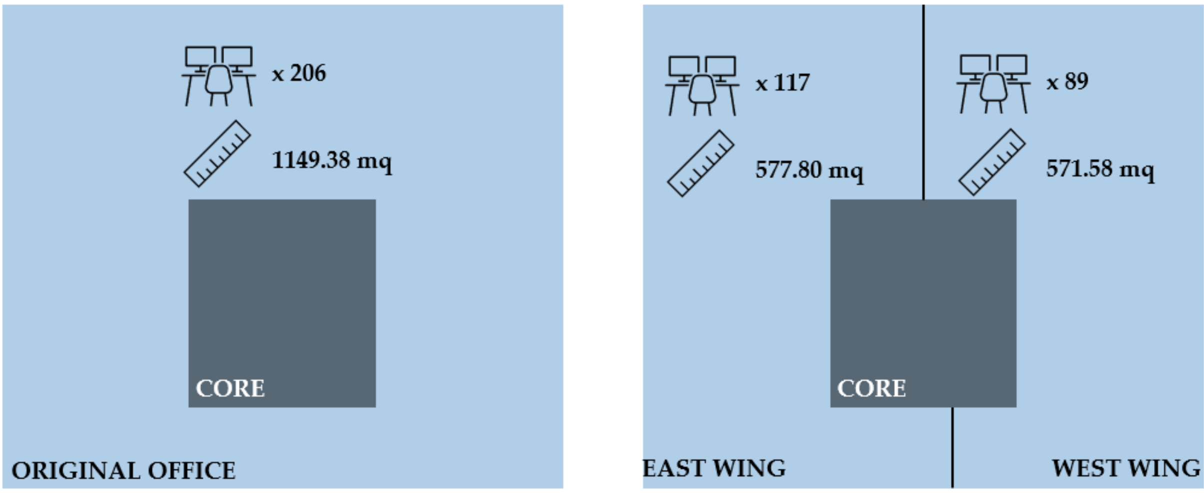



Figure 2.5: Reference Office Configurations

The only data that was missing from the reference office occupancy profile was the metabolic rate, that has been assumed equal to 1.2 (from ASHRAE Standard 55 Table 5-1) which consider the office activity of seating during office work.

The operation time of this schedule is from 8 a.m. to 10 p.m. and it considers only weekdays.

Below the fixed number of the employees coming to the office obtained from the occupancy sensor (Table 2.5), used for the calculation of the different occupancy rates in the different office configurations, represented in Chart 2.4.

| Reference Office - Number of employees | | | |
|---|---|---|---|
| Hour | Weekday | Saturday | Sunday |
| [h] | [P] | [P] | [P] |
| 8-9 | 28 | 0 | 0 |
| 9-10 | 57 | 0 | 0 |
| 10-11 | 66 | 0 | 0 |
| 11-12 | 68 | 0 | 0 |
| 12-13 | 69 | 0 | 0 |
| 13-14 | 63 | 0 | 0 |
| 14-15 | 71 | 0 | 0 |
| 15-16 | 72 | 0 | 0 |
| 16-17 | 73 | 0 | 0 |
| 17-18 | 69 | 0 | 0 |
| 18-19 | 52 | 0 | 0 |
| 19-20 | 42 | 0 | 0 |
| 20-21 | 38 | 0 | 0 |
| 21-22 | 33 | 0 | 0 |

Table 2.5: Reference Office – Number of Employees.

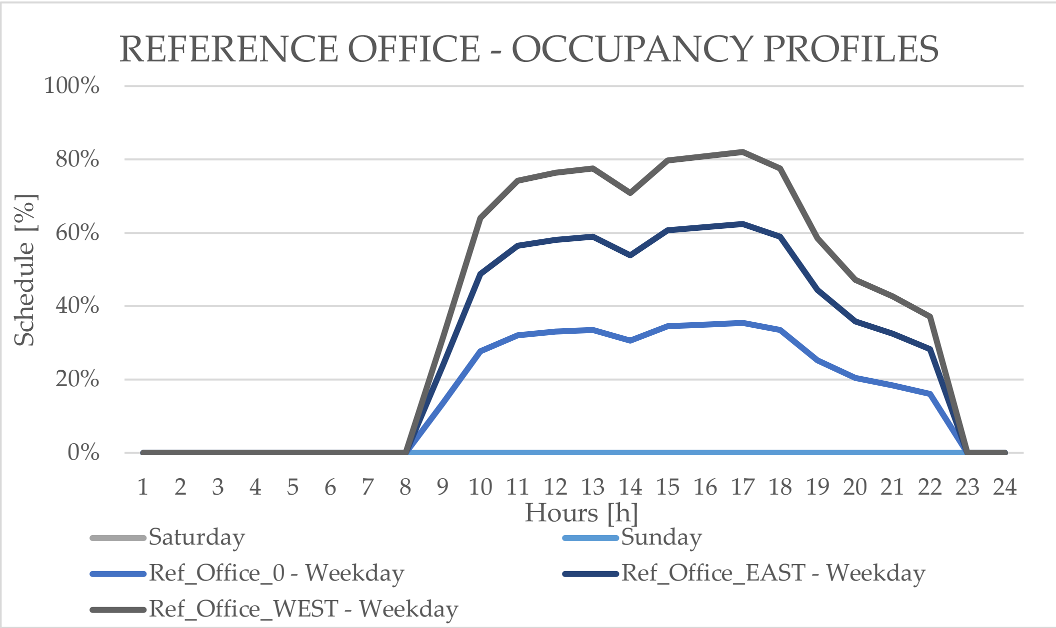



Chart 2.4: Reference Office - Occupancy Schedules.

### 2.2.4 Occupancy Profiles Summary

In the following page (Table 2.6 and Table 2.7) are resumed the detailed schedules of all the considered occupancy profiles, including occupancy properties needed for the energy simulations such as people density and metabolic rates and other characteristics such as weekly working hours that are useful for the post process analysis.

| Occupancy Profiles Properties | | | | | |
|---|---|---|---|---|---|
| Occupancy Profile | Office Type | People Density | Metabolic Rate | Heat Production per Person | Weekly Working Hours |
| [-] | [-] | [P/m²] | [met] | [W/P] | [h] |
| ASHRAE | Co-Working | 0.05 | 1.26 | 132 | 115 |
| ISO 17772 | Open Plan Office | 0.06 | 1.14 | 119 | 55 |
| ISO 18523 | Office Room | 0.1 | 1.14 | 119 | 65 |
| Ref_Office_0 | Open Plan Office | 0.18 | 1.2 | 125.7 | 70 |
| Ref_Office_EAST | | 0.20 | | | |
| Ref_Office_WEST | | 0.16 | | | |

Table 2.6: Occupancy profiles properties.

| Hourly occupancy rate schedule [%] | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Hours of the day** | | | 6-7 | 7-8 | 8-9 | 9-10 | 10-11 | 11-12 | 12-13 | 13-14 | 14-15 | 15-16 | 16-17 | 17-18 | 18-19 | 19-20 | 20-21 | 21-22 | 22-23 | 23-24 |
| **Standard** | **ASHRAE** | **Weekday** | 10 | 20 | 95 | 95 | 95 | 95 | 50 | 95 | 95 | 95 | 95 | 30 | 10 | 10 | 10 | 10 | 5 | 5 |
| | | **Saturday** | 10 | 10 | 30 | 30 | 30 | 30 | 10 | 10 | 10 | 10 | 10 | 5 | 5 | 0 | 0 | 0 | 0 | 0 |
| | | **Sunday** | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **ISO 17772** | **Weekday** | 0 | 20 | 60 | 60 | 70 | 70 | 40 | 60 | 70 | 70 | 60 | 20 | 0 | 0 | 0 | 0 | 0 | 0 |
| | **ISO 18523** | **Weekday** | 0 | 0 | 100 | 100 | 100 | 100 | 60 | 100 | 100 | 100 | 100 | 100 | 50 | 30 | 20 | 0 | 0 | 0 |
| **SmartWorking** | **ISO 18523 (79%)** | **Weekday** | 0 | 0 | 79.0 | 79.0 | 79.0 | 79.0 | 47.4 | 79.0 | 79.0 | 79.0 | 79.0 | 79.0 | 39.5 | 23.7 | 15.8 | 0 | 0 | 0 |
| | **ISO 18523 (61%)** | **Weekday** | 0 | 0 | 61.0 | 61.0 | 61.0 | 61.0 | 36.6 | 61.0 | 61.0 | 61.0 | 61.0 | 61.0 | 30.5 | 18.3 | 12.2 | 0 | 0 | 0 |
| | **ISO 18523 (10%)** | **Weekday** | 0 | 0 | 10 | 10 | 10 | 10 | 6 | 10 | 10 | 10 | 10 | 10 | 5 | 3 | 2 | 0 | 0 | 0 |
| **ReferenceOffice** | **Original** | **Weekday** | 0 | 0 | 14 | 28 | 32 | 33 | 33 | 31 | 34 | 35 | 35 | 33 | 25 | 20 | 18 | 16 | 0 | 0 |
| | **East** | **Weekday** | 0 | 0 | 24 | 49 | 56 | 58 | 59 | 54 | 61 | 62 | 62 | 59 | 44 | 36 | 32 | 28 | 0 | 0 |
| | **West** | **Weekday** | 0 | 0 | 31 | 64 | 74 | 76 | 78 | 71 | 80 | 81 | 82 | 78 | 58 | 47 | 43 | 37 | 0 | 0 |

Table 2.7: Occupancy profile schedules

## 2.3 Climates

Before evaluating the impact of occupancy profiles on the energy needs of the test room, it is crucial to identify the expected energy demand trends in the selected locations. To this end, an initial investigation into the climate typologies of these locations will be conducted. This will be followed by calculating the annual heating and cooling degree days, providing an initial insight into the anticipated energy demand trends. Afterwards, the energy needs of the test room will be calculated without any occupancy profiles to establish a baseline case.

This approach facilitates a clearer understanding of how occupancy profiles might influence energy requirements.

As already seen in the literature (Paragraph 1.4) climate plays a key role in determining the building energy needs and to explore the relationship between occupancy and office energy demand in a post-pandemic context, analyzing a single climate would not be sufficient. This is due to observations that the pandemic has impacted energy consumption differently across various locations.

For this study, Denver and London have been chosen: Denver, as it is recommended for model validation, and London, because it houses the reference office for this research. The selected locations are detailed below, considering their distinct climatic conditions to provide a comprehensive analysis.

- **Denver**

**Location:** Denver – Stapleton, Colorado, USA

**Latitude/Longitude:** 39.76° N, 104.86°W

**Elevation:** 1611 m

Denver is characterized by a Cold Semi-Arid climate (type BSk according to the Köppen Climate Classification [36] and zone 5 according to IECC climate zone [24]). This classification indicates that Denver falls under a dry climate category (B) due to its limited precipitation throughout the year. The "S" denotes a semi-arid or steppe climate, highlighting that the area receives more precipitation than arid regions, but still not enough to classify it as a wet climate. The "k" in the classification specifies that Denver experiences cold conditions, but not extremely harsh winter conditions.

Key features of Denver's climate include low annual precipitation, which manifests as snow during the winter months and leads to relatively dry summers. The region is also known for its significant temperature variations between seasons, with hot summers and cold winters, providing a distinct seasonal contrast. Furthermore, Denver's unique geographical location at the base of the Rocky Mountains contributes to rapid weather changes, making the local climate dynamic and sometimes unpredictable. [37]

- **London**

**Location:** London City AP – England - GBR

**Latitude/Longitude:** 51.505° N, 0.055°E

**Elevation:** 5 m

London is classified under the Oceanic climate category (Cfb) according to the Köppen-Geiger classification [36] , and it also falls within zone 4 (mixed humid) (based on the European climate zones [38]). This specific climate type is distinguished by several key characteristics. The "C" in the classification denotes a mild temperate climate, indicating that there is no dry season and that summers are warm. The "f" further emphasizes that London does not experience a significant dry season at any time of the year, ensuring a relatively consistent distribution of precipitation. Additionally, the "b" categorizes London's summers as warm.

Key features of London's Oceanic climate include moderate temperatures throughout the year, which means the city avoids extreme cold or heat. This temperate nature is coupled with relatively stable yet high humidity levels, contributing to the overall mild climate. Precipitation in London is fairly evenly distributed across all months, although there is a tendency for increased rainfall during the autumn and winter months. [39]

To gain a deeper insight into the two climates and their potential effects on energy needs, the calculation of annual heating and cooling degree days for both locations has been conducted.

According to literature (Paragraph 1.1), air conditioning typically accounts for a significant portion of energy consumption. Therefore, to assess climates with varying energy demands, the degree day method has been chosen for evaluating the selected climates.

Heating Degree Days (HDD) and Cooling Degree Days (CDD) are defined as the sum of the differences between the daily average outdoor temperature and the reference temperature. Values where the average temperature falls below the reference are classified as HDD, whereas those exceeding it are identified as CDD.

The calculation will follow the methodology outlined in EN ISO 15927-6 [40].

$$HDD_{annual} = \Sigma_1^{365}(T_{ref} - T_{daily\,mean})$$

$$CDD_{annual} = \Sigma_1^{365}(T_{daily\,mean} - T_{ref})$$

The daily average outdoor temperature has been obtained from the hourly outdoor temperature from the weather data file, while a reference temperature of 18°C has been selected for this purpose.

## 2.4 Efficiency Evaluation Indexes

In order to evaluate the energy efficiency of the different occupancy profiles above defined, it has been decided to use two evaluation indexes, that will allow to have a more comprehensive understanding of the impact of occupants in offices, not only from the direct impact on energy need but also considering office variable that are considered valuable resources.

For this purpose, we are going to consider two evaluation indexes:

- EUI (Energy Use index), used in many contexts in particular refurbishment to evaluate efficiency improvement of a building, and is defined by the ratio between the total annual energy consumption of building and the gross building area.

$$EUI_{year} = \frac{Energy\ Consumption_{total}\ [kWh]}{Gross\ Area\ [m^2]}$$

- EU/(capita*hour) (Total Energy Use per capita per hour), has been proposed by the literature [11] and outlined in the State of the Art of this thesis (Paragraph 1.2).
  This parameter allows to evaluate energy consumption out of two important variables: time and number of people in the office, considered relevant socio-economical resources of the office.

$$EU/(P * h)_{year} = \frac{Energy\ Consumption_{total}\ [kWh]}{P_{max} * h_{year}\ [p * h]}$$

  Where:
  $P_{max}$ is the peak number of people in the office considered during the working week.
  $h_{year}$ is the number of hours when the office is open, regardless, which considers the number of hours during all the year were the occupancy rate is different from 0.

# 3. Results

## 3.1 Thermal Model Validation

The subsequent chapter details the outcomes of the climate data validation, followed by the results of validating the test room.

### 3.1.1 Weather Data Validation

As a first step of the validation process we have been validating the climatic data, to assure that the climatic data from the selected weather data file are as expected. Below the results related to the external air temperature and the incident solar radiation. First the monthly data and following the hourly data related to January 4$^{th}$, the date used in ISO 52016-1 for the thermal model validation.

- External Air Temperature

| Monthly External Air Temperature | | | |
|---|---|---|---|
| Month | ISO_52016-1 | ClimateStudio | Error |
| [-] | [°C] | [°C] | [%] |
| Jan | -23.3 | -23.3 | 0% |
| Feb | -24.4 | -24.4 | 0% |
| Mar | -23.3 | -23.3 | 0% |
| Apr | -23.3 | -23.3 | 0% |
| May | -23.3 | -23.3 | 0% |
| Jun | -23.3 | -23.3 | 0% |
| Jul | -23.3 | -23.3 | 0% |
| Aug | -23.9 | -23.9 | 0% |
| Sept | -22.8 | -22.8 | 0% |
| Oct | -20 | -20 | 0% |
| Nov | -16.7 | -16.7 | 0% |
| Dec | -16.1 | -16.1 | 0% |

Table 3.1: Monthly External Air Temperature Validation

| External Air Temperature - January 4th | | | |
|---|---|---|---|
| Hour | ISO_52016-1 | ClimateStudio | Error |
| [h] | [°C] | [°C] | [%] |
| 1 | -23.3 | -23.3 | 0% |
| 2 | -24.4 | -24.4 | 0% |
| 3 | -23.3 | -23.3 | 0% |
| 4 | -23.3 | -23.3 | 0% |
| 5 | -23.3 | -23.3 | 0% |
| 6 | -23.3 | -23.3 | 0% |
| 7 | -23.3 | -23.3 | 0% |
| 8 | -23.9 | -23.9 | 0% |
| 9 | -22.8 | -22.8 | 0% |
| 10 | -20 | -20 | 0% |
| 11 | -16.7 | -16.7 | 0% |
| 12 | -16.1 | -16.1 | 0% |
| 13 | -15 | -15 | 0% |
| 14 | -11.7 | -11.7 | 0% |
| 15 | -12.8 | -12.8 | 0% |
| 16 | -14.4 | -14.4 | 0% |
| 17 | -16.7 | -16.7 | 0% |
| 18 | -20 | -20 | 0% |
| 19 | -20 | -20 | 0% |
| 20 | -19.4 | -19.4 | 0% |
| 21 | -20 | -20 | 0% |
| 22 | -19.4 | -19.4 | 0% |
| 23 | -18.9 | -18.9 | 0% |
| 24 | -18.9 | -18.9 | 0% |

Table 3.2: Daily External Air Temperature Validation.

- Incident Solar Radiation - Horizontal

| Horizontal Incident Solar Radiation - January 4th | | | |
|---|---|---|---|
| Hour | ISO_52016-1 | ClimateStudio | Error |
| [h] | [W/m²] | [W/m²] | [%] |
| 1 | 0.0 | 0.0 | 0% |
| 2 | 0.0 | 0.0 | 0% |
| 3 | 0.0 | 0.0 | 0% |
| 4 | 0.0 | 0.0 | 0% |
| 5 | 0.0 | 0.0 | 0% |
| 6 | 0.0 | 0.0 | 0% |
| 7 | 0.0 | 0.0 | 0% |
| 8 | 22.8 | 22.0 | -3% |
| 9 | 166.1 | 167.9 | 1% |
| 10 | 284.0 | 288.0 | 1% |
| 11 | 466.9 | 476.2 | 2% |
| 12 | 503.8 | 515.9 | 2% |
| 13 | 483.8 | 498.3 | 3% |
| 14 | 403.8 | 419.8 | 4% |
| 15 | 276.5 | 292.5 | 6% |
| 16 | 131.5 | 144.9 | 10% |
| 17 | 13.3 | 17.3 | 29% |
| 18 | 0.0 | 0.0 | 0% |
| 19 | 0.0 | 0.0 | 0% |
| 20 | 0.0 | 0.0 | 0% |
| 21 | 0.0 | 0.0 | 0% |
| 22 | 0.0 | 0.0 | 0% |
| 23 | 0.0 | 0.0 | 0% |
| 24 | 0.0 | 0.0 | 0% |

Table 3.3: Horizontal Solar Radiation Validation.

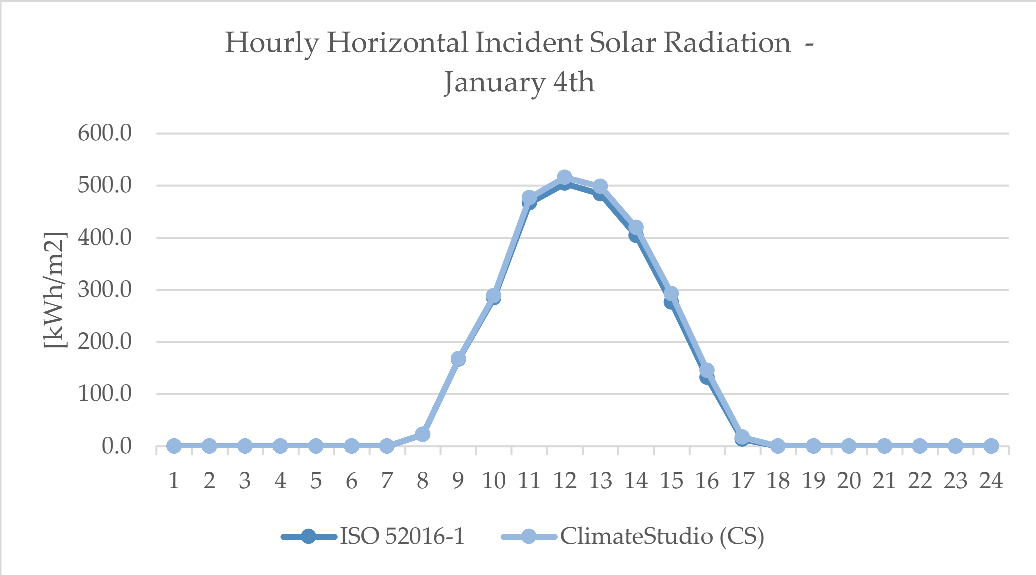



Chart 3.1: Hourly Horizontal Incident Solar Radiation.

- Incident Solar Radiation – Vertical – South
-

| South Vertical Incident Solar Radiation - January 4th | | | |
|---|---|---|---|
| Hour | ISO_52016-1 | ClimateStudio | Error |
| [h] | [W/m²] | [W/m²] | [%] |
| 1 | 0.0 | 0.0 | 0% |
| 2 | 0.0 | 0.0 | 0% |
| 3 | 0.0 | 0.0 | 0% |
| 4 | 0.0 | 0.0 | 0% |
| 5 | 0.0 | 0.0 | 0% |
| 6 | 0.0 | 0.0 | 0% |
| 7 | 0.0 | 0.0 | 0% |
| 8 | 44.8 | 27.6 | -38% |
| 9 | 308.3 | 386.3 | 25% |
| 10 | 558.2 | 583.2 | 4% |
| 11 | 944.0 | 948.7 | 0% |
| 12 | 988.3 | 981.4 | -1% |
| 13 | 961.2 | 955.4 | -1% |
| 14 | 861.1 | 856.6 | -1% |
| 15 | 690.5 | 687.4 | 0% |
| 16 | 466.4 | 464.4 | 0% |
| 17 | 87.4 | 92.1 | 5% |
| 18 | 0.0 | 0.0 | 0% |
| 19 | 0.0 | 0.0 | 0% |

| | | | |
|---|---|---|---|
| 20 | 0.0 | 0.0 | 0% |
| 21 | 0.0 | 0.0 | 0% |
| 22 | 0.0 | 0.0 | 0% |
| 23 | 0.0 | 0.0 | 0% |
| 24 | 0.0 | 0.0 | 0% |

Table 3.4: South-Vertical Solar Radiation Validation.

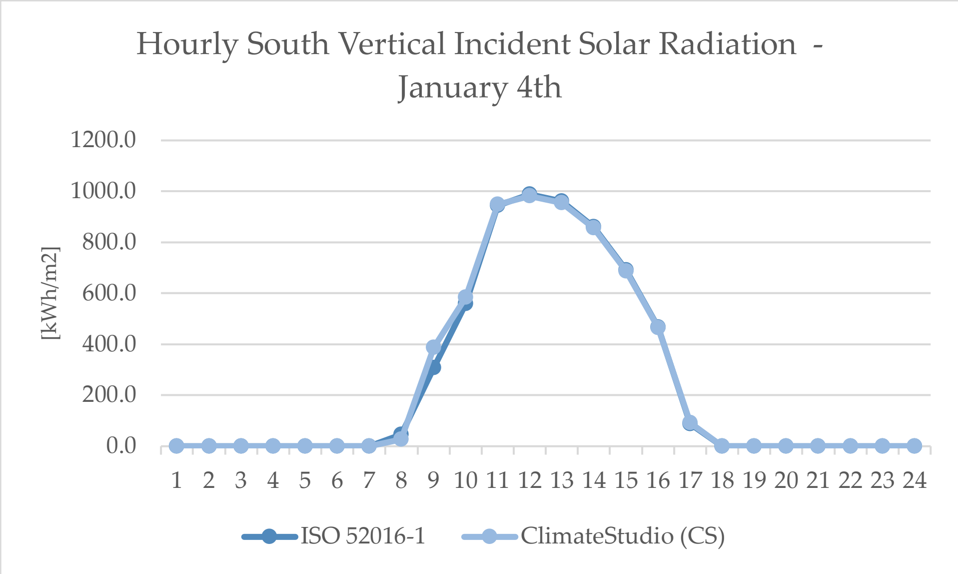



Chart 3.1: Hourly South Vertical Incident Solar Radiation.

The results achieved are quite positive: there is an excellent alignment between the hourly and monthly external air temperature values, demonstrating a perfect match. Similarly, the solar irradiation values exhibit a consistent trend, with most errors being less than 10%. There are a few instances where the discrepancies are slightly larger, but still below 40%. These outliers may be attributable to conversion variances between the data sourced from the Denver weather file and that from the ISO 52016-1 standard.

### 3.1.2 Test Room Validation

The validation process for the thermal model now progresses to the examination of opaque envelope modeling configurations. The results related to the specified validation parameter, which in this instance is the internal operative temperature, are outlined below.

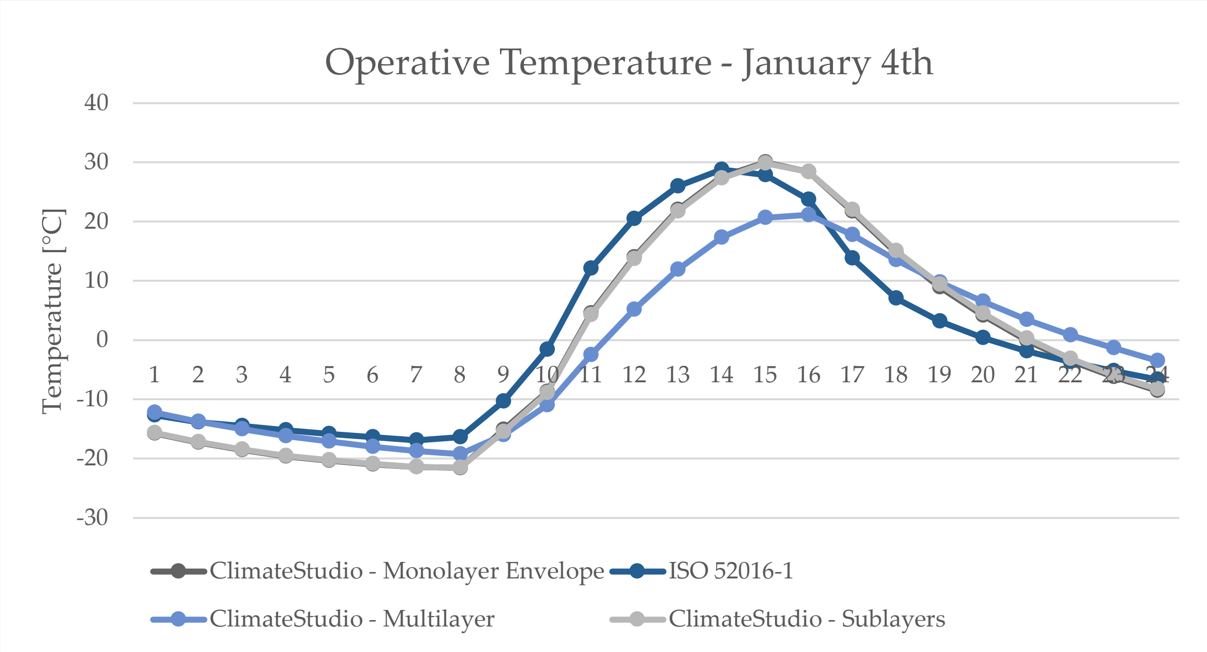



Chart 3.2: Daily Operative Temperature – January 4th – Opaque Envelope Modelling Results

| OPAQUE ENVELOPE MODELLING | | | | | | | |
|---|---|---|---|---|---|---|---|
| Hour | ISO 52016-1 | Multilayer | Error | Sublayer | Error | Monolayer | Error |
| [h] | [°C] | [°C] | [%] | [°C] | [%] | [°C] | [%] |
| 1 | -12.7 | -12.2 | 4% | -15.6 | 23% | -15.8 | 24% |
| 2 | -13.8 | -13.8 | 0% | -17.2 | 24% | -17.3 | 25% |
| 3 | -14.5 | -15.0 | 4% | -18.4 | 27% | -18.5 | 28% |
| 4 | -15.2 | -16.1 | 6% | -19.5 | 28% | -19.6 | 29% |
| 5 | -15.8 | -17.1 | 8% | -20.3 | 28% | -20.3 | 29% |
| 6 | -16.4 | -18.0 | 9% | -20.9 | 27% | -21.0 | 28% |
| 7 | -16.9 | -18.7 | 11% | -21.4 | 27% | -21.4 | 27% |
| 8 | -16.4 | -19.2 | 17% | -21.5 | 31% | -21.5 | 31% |
| 9 | -10.3 | -16.0 | 55% | -15.5 | 50% | -15.1 | 46% |
| 10 | -1.6 | -11.0 | 585% | -8.8 | 453% | -8.7 | 446% |
| 11 | 12.1 | -2.5 | 121% | 4.3 | 65% | 4.6 | 62% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 12 | 20.5 | 5.1 | 75% | 13.7 | 33% | 14.0 | 32% |
| 13 | 26 | 11.9 | 54% | 21.7 | 16% | 22.0 | 15% |
| 14 | 28.8 | 17.3 | 40% | 27.4 | 5% | 27.6 | 4% |
| 15 | 27.9 | 20.7 | 26% | 29.8 | 7% | 30.0 | 8% |
| 16 | 23.7 | 21.2 | 11% | 28.4 | 20% | 28.4 | 20% |
| 17 | 13.8 | 17.8 | 29% | 22.0 | 59% | 21.7 | 57% |
| 18 | 7.1 | 13.5 | 90% | 15.1 | 113% | 14.7 | 107% |
| 19 | 3.2 | 9.8 | 205% | 9.4 | 193% | 9.0 | 180% |
| 20 | 0.4 | 6.5 | 1521% | 4.5 | 1028% | 4.1 | 935% |
| 21 | -1.9 | 3.5 | 283% | 0.3 | 116% | 0.0 | 99% |
| 22 | -3.7 | 0.9 | 124% | -3.1 | 15% | -3.4 | 7% |
| 23 | -5.2 | -1.3 | 74% | -5.9 | 13% | -6.2 | 18% |
| 24 | -6.6 | -3.5 | 48% | -8.2 | 25% | -8.5 | 29% |
| | | **Average error [%]** | **142%** | **Average error [%]** | **101%** | **Average error [%]** | **95%** |

Table 3.5: Daily Operative Temperature – January 4th – Opaque Envelope Modelling Results

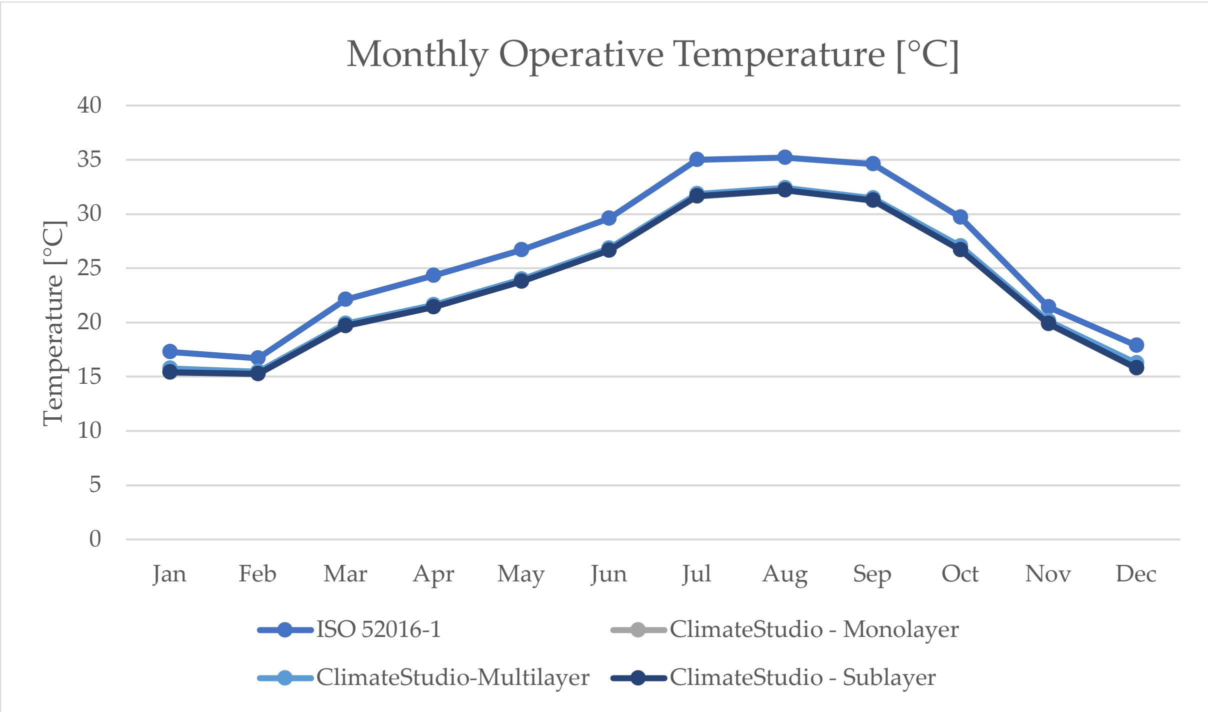



Chart 3.3: Monthly Operative Temperature – Opaque Envelope Modelling Results

| OPAQUE ENVELOPE MODELLING | | | | | | | |
|---|---|---|---|---|---|---|---|
| Month | ISO 52016-1 | Multilayer | Error | Sublayer | Error | Monolayer | Error |
| [-] | [°C] | [°C] | [%] | [°C] | [%] | [°C] | [%] |
| 1 | -12.7 | 15.8 | 9% | 15.4 | 11% | 15.4 | 11% |
| 2 | -13.8 | 15.5 | 7% | 15.3 | 9% | 15.2 | 9% |
| 3 | -14.5 | 19.9 | 10% | 19.7 | 11% | 19.7 | 11% |
| 4 | -15.2 | 21.6 | 11% | 21.4 | 12% | 21.4 | 12% |
| 5 | -15.8 | 24.0 | 10% | 23.8 | 11% | 23.8 | 11% |
| 6 | -16.4 | 26.8 | 9% | 26.6 | 10% | 26.6 | 10% |
| 7 | -16.9 | 31.9 | 9% | 31.6 | 10% | 31.6 | 10% |
| 8 | -16.4 | 32.4 | 8% | 32.2 | 9% | 32.2 | 9% |
| 9 | -10.3 | 31.5 | 9% | 31.2 | 10% | 31.2 | 10% |
| 10 | -1.6 | 27.0 | 9% | 26.7 | 10% | 26.7 | 10% |
| 11 | 12.1 | 20.1 | 6% | 19.9 | 7% | 19.9 | 7% |
| 12 | 20.5 | 16.2 | 9% | 15.8 | 12% | 15.8 | 12% |
| | | **Average error [%]** | **9%** | **Average error [%]** | **10%** | **Average error [%]** | **10%** |

Table 3.6: Monthly Operative Temperature – Opaque Envelope Modelling Results

Reviewing the results for the three opaque envelope modeling scenarios, it is noted that the monthly operative temperatures align, with low average error (around 10%) yet there are significant discrepancies in the hourly operative temperatures. Among these, the monolayer configuration exhibits the lowest average error. Consequently, the validation process will proceed using the monolayer opaque envelope configuration.

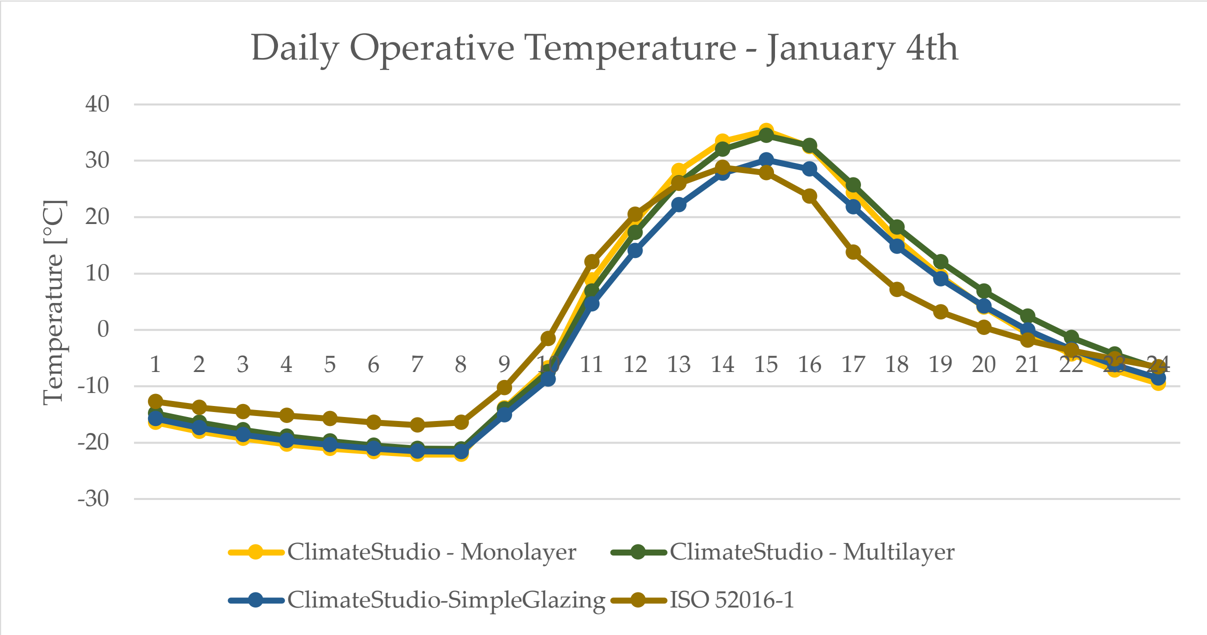



Chart 3.4: Daily Operative Temperature – January 4th – Window Modelling Results

| WINDOW MODELLING | | | | | | | |
|---|---|---|---|---|---|---|---|
| Hour | ISO 52016-1 | Simple Glazing | Error | Multilayer | Error | Monolayer | Error |
| [h] | [°C] | [°C] | [%] | [°C] | [%] | [°C] | [%] |
| 1 | -12.7 | -15.8 | 24% | -14.8 | 16% | -16.3 | 29% |
| 2 | -13.8 | -17.3 | 25% | -16.4 | 19% | -17.9 | 30% |
| 3 | -14.5 | -18.5 | 28% | -17.8 | 23% | -19.2 | 32% |
| 4 | -15.2 | -19.6 | 29% | -18.9 | 24% | -20.2 | 33% |
| 5 | -15.8 | -20.3 | 29% | -19.8 | 25% | -21.0 | 33% |
| 6 | -16.4 | -21.0 | 28% | -20.5 | 25% | -21.6 | 32% |
| 7 | -16.9 | -21.4 | 27% | -21.0 | 24% | -22.1 | 30% |
| 8 | -16.4 | -21.5 | 31% | -21.1 | 29% | -22.0 | 34% |
| 9 | -10.3 | -15.1 | 46% | -14.1 | 37% | -13.8 | 34% |
| 10 | -1.6 | -8.7 | 446% | -7.4 | 365% | -6.8 | 325% |
| 11 | 12.1 | 4.6 | 62% | 6.8 | 44% | 8.7 | 28% |
| 12 | 20.5 | 14.0 | 32% | 17.2 | 16% | 19.0 | 7% |
| 13 | 26 | 22.0 | 15% | 26.0 | 0% | 28.1 | 8% |
| 14 | 28.8 | 27.6 | 4% | 32.0 | 11% | 33.3 | 16% |
| 15 | 27.9 | 30.0 | 8% | 34.5 | 24% | 35.1 | 26% |
| 16 | 23.7 | 28.4 | 20% | 32.7 | 38% | 32.4 | 36% |
| 17 | 13.8 | 21.7 | 57% | 25.7 | 86% | 24.2 | 76% |
| 18 | 7.1 | 14.7 | 107% | 18.2 | 156% | 16.0 | 125% |
| 19 | 3.2 | 9.0 | 180% | 12.0 | 276% | 9.4 | 195% |
| 20 | 0.4 | 4.1 | 935% | 6.8 | 1611% | 4.0 | 903% |
| 21 | -1.9 | 0.0 | 99% | 2.4 | 225% | -0.6 | 68% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 22 | -3.7 | -3.4 | 7% | -1.3 | 64% | -4.3 | 17% |
| 23 | -5.2 | -6.2 | 18% | -4.3 | 17% | -7.1 | 36% |
| 24 | -6.6 | -8.5 | 29% | -6.9 | 4% | -9.5 | 43% |
| | | **Average error [%]** | **95%** | **Average error [%]** | **132%** | **Average error [%]** | **92%** |

Table 3.7: Daily Operative Temperature – January 4th – Window Modelling Results

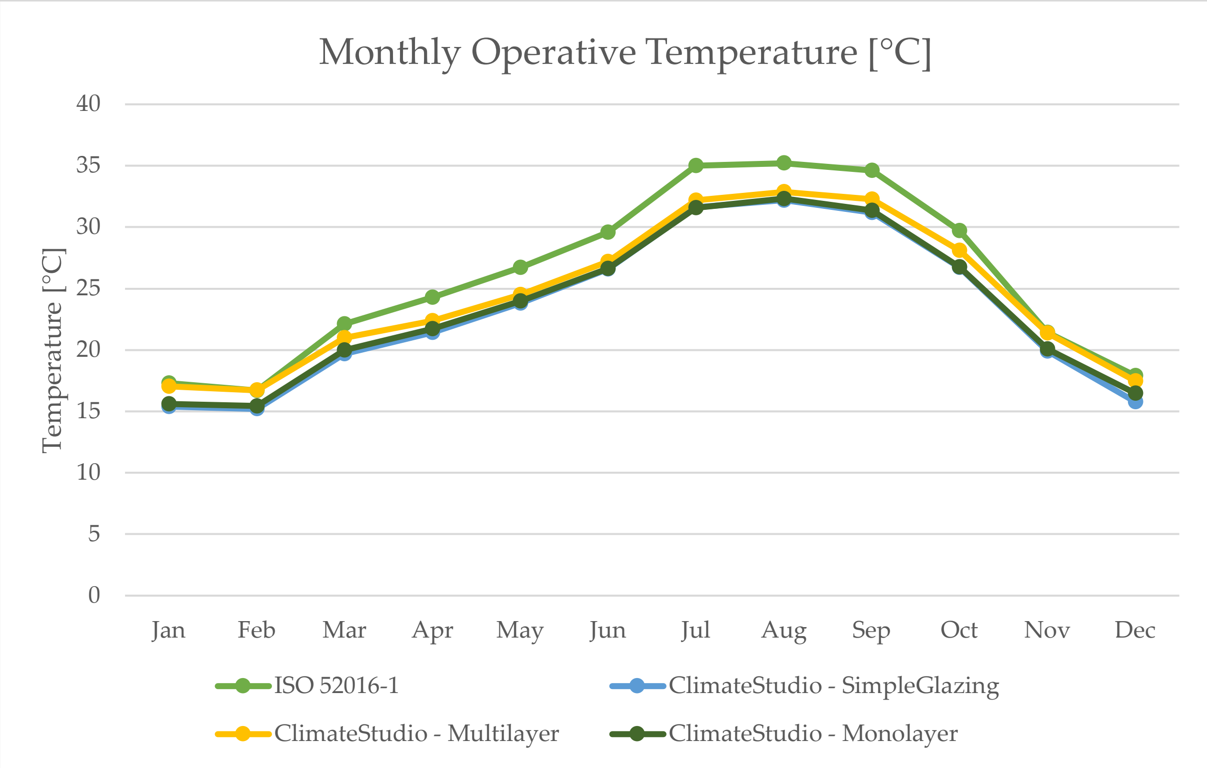



Chart 3.5: Monthly Operative Temperature – Window Modelling Results

| WINDOW MODELLING | | | | | | | |
|---|---|---|---|---|---|---|---|
| Month | ISO 52016-1 | Simple Glazing | Error | Multilayer | Error | Monolayer | Error |
| [h] | [°C] | [°C] | [%] | [°C] | [%] | [°C] | [%] |
| 1 | -12.7 | 15.4 | 11% | 17.1 | 1% | 15.6 | 10% |
| 2 | -13.8 | 15.2 | 9% | 16.7 | 0% | 15.4 | 8% |
| 3 | -14.5 | 19.7 | 11% | 21.0 | 5% | 20.0 | 10% |
| 4 | -15.2 | 21.4 | 12% | 22.4 | 8% | 21.7 | 11% |
| 5 | -15.8 | 23.8 | 11% | 24.5 | 8% | 24.0 | 10% |
| 6 | -16.4 | 26.6 | 10% | 27.2 | 8% | 26.6 | 10% |
| 7 | -16.9 | 31.6 | 10% | 32.2 | 8% | 31.6 | 10% |
| 8 | -16.4 | 32.2 | 9% | 32.9 | 7% | 32.3 | 8% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9 | -10.3 | 31.2 | 10% | 32.2 | 7% | 31.4 | 9% |
| 10 | -1.6 | 26.7 | 10% | 28.1 | 5% | 26.8 | 10% |
| 11 | 12.1 | 19.9 | 7% | 21.4 | 0% | 20.1 | 6% |
| 12 | 20.5 | 15.8 | 12% | 17.5 | 2% | 16.5 | 8% |
| | | **Average error [%]** | **10%** | **Average error [%]** | **5%** | **Average error [%]** | **10%** |

Table 3.8: Monthly Operative Temperature – Window Modelling Results

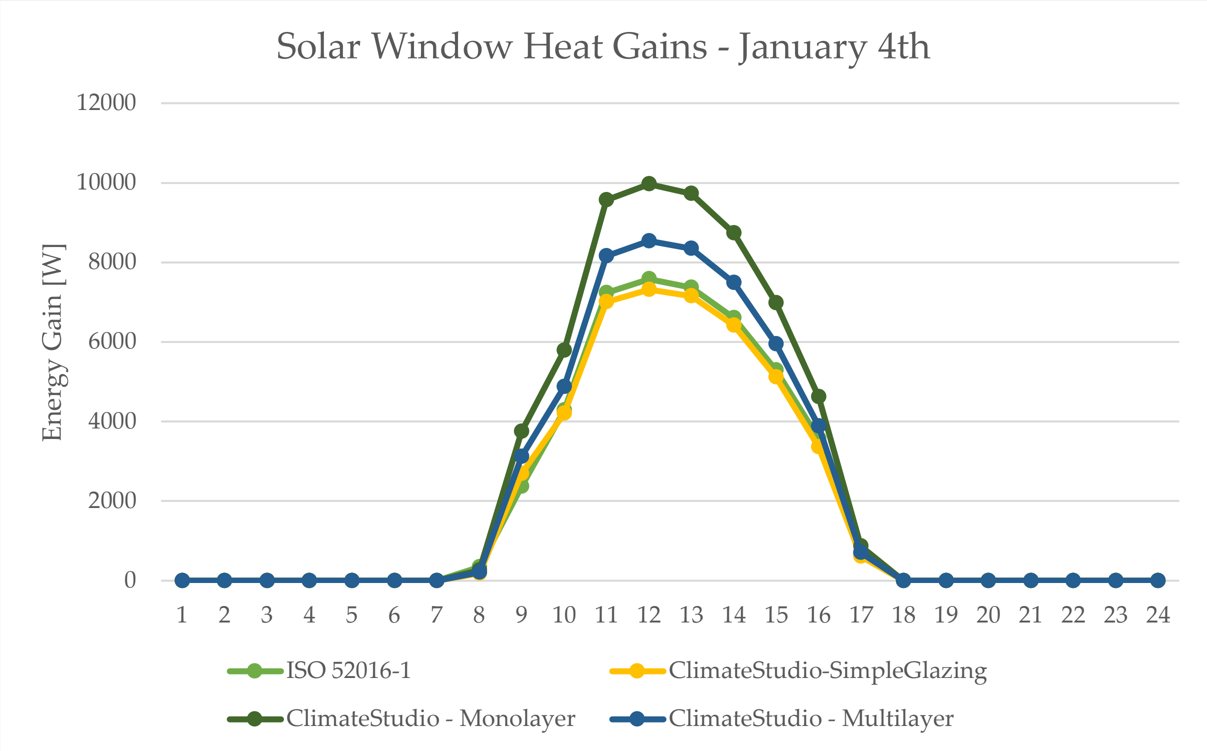



Chart 3.6: Daily Solar Window Heat Gains – January 4th – Window Modelling Results

| WINDOW MODELLING | | | | | | | |
|---|---|---|---|---|---|---|---|
| Hour | ISO 52016-1 | Simple Glazing | Error | Multilayer | Error | Monolayer | Error |
| [h] | [W] | [W] | [%] | [W] | [%] | [W] | [%] |
| 1 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 2 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 3 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 4 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 5 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 6 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 7 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 8 | 343.4 | 182.5 | 47% | 212.9 | 38% | 258.6 | 25% |
| 9 | 2364.3 | 2682.8 | 13% | 3111.9 | 32% | 3746.7 | 58% |
| 10 | 4280.6 | 4200.8 | 2% | 4878.9 | 14% | 5782.8 | 35% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 11 | 7238.9 | 7001.1 | 3% | 8160.8 | 13% | 9569.2 | 32% |
| 12 | 7578.0 | 7315.6 | 3% | 8537.8 | 13% | 9964.4 | 31% |
| 13 | 7370.3 | 7151.1 | 3% | 8346.7 | 13% | 9727.2 | 32% |
| 14 | 6602.9 | 6417.2 | 3% | 7483.6 | 13% | 8729.2 | 32% |
| 15 | 5294.9 | 5120.3 | 3% | 5946.4 | 12% | 6972.2 | 32% |
| 16 | 3576.0 | 3358.9 | 6% | 3882.8 | 9% | 4623.6 | 29% |
| 17 | 670.4 | 607.6 | 9% | 708.8 | 6% | 872.3 | 30% |
| 18 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 19 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 20 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 21 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 22 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 23 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| 24 | 0 | 0 | 0% | 0 | 0% | 0 | 0% |
| | | **Average error [%]** | **4%** | **Average error [%]** | **7%** | **Average error [%]** | **14%** |

Table 3.9: Daily Solar Window Heat Gains – January 4th – Window Modelling Results

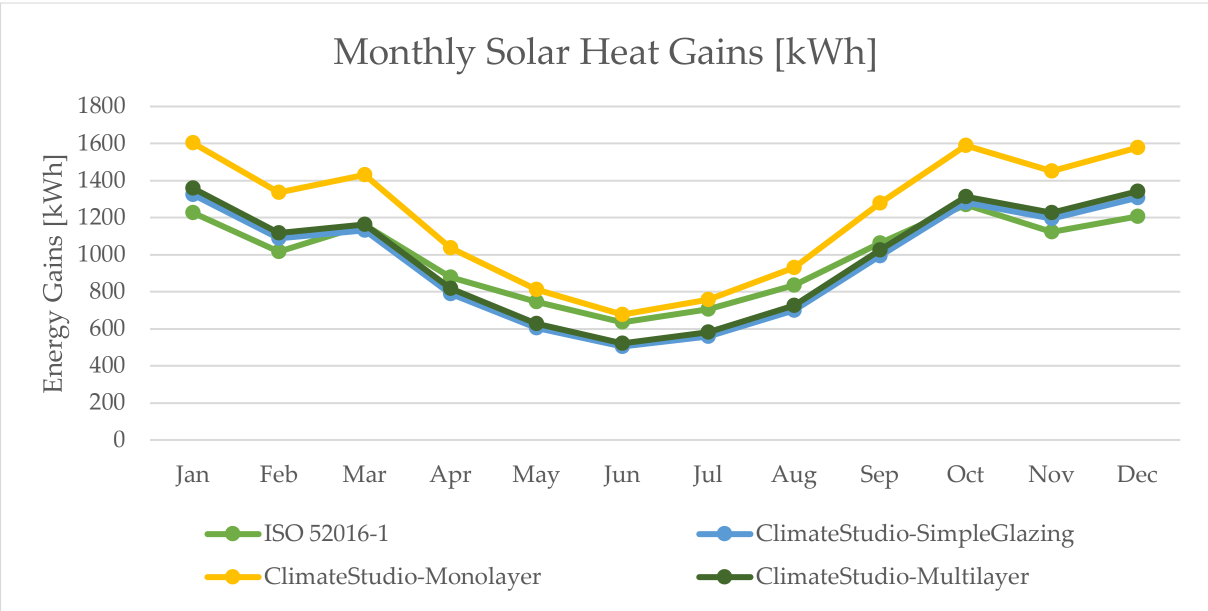



Chart 3.7: Monthly Solar Window Heat Gains – Window Modelling Results

| WINDOW MODELLING | | | | | | | |
|---|---|---|---|---|---|---|---|
| Month | ISO 52016-1 | Simple Glazing | Error | Multilayer | Error | Monolayer | Error |
| [h] | [kWh] | [kWh] | [%] | [kWh] | [%] | [kWh] | [%] |
| 1 | 1226.1 | 1324.4 | 8% | 1358.6 | 11% | 1602.6 | 31% |
| 2 | 1017.5 | 1089.2 | 7% | 1116.7 | 10% | 1335.1 | 31% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3 | 1160.9 | 1131.7 | 3% | 1163.3 | 0% | 1430.9 | 23% |
| 4 | 877.2 | 790.1 | 10% | 817.5 | 7% | 1035.6 | 18% |
| 5 | 744.6 | 606.0 | 19% | 628.1 | 16% | 811.7 | 9% |
| 6 | 634.9 | 504.6 | 21% | 521.4 | 18% | 676.8 | 7% |
| 7 | 704.7 | 560.0 | 21% | 580.3 | 18% | 757.0 | 7% |
| 8 | 835.8 | 698.3 | 16% | 724.5 | 13% | 931.2 | 11% |
| 9 | 1062.8 | 994.6 | 6% | 1025.0 | 4% | 1277.6 | 20% |
| 10 | 1269.8 | 1280.4 | 1% | 1313.4 | 3% | 1587.8 | 25% |
| 11 | 1124.1 | 1195.4 | 6% | 1226.3 | 9% | 1452.1 | 29% |
| 12 | 1205.4 | 1306.8 | 8% | 1341.3 | 11% | 1576.6 | 31% |
| | | **Average error [%]** | **10%** | **Average error [%]** | **10%** | **Average error [%]** | **20%** |

Table 3.10: Monthly Solar Window Heat Gains – Window Modelling Results

In the validation of window modeling, which considers two parameters, the average errors in monthly values for both parameters do not exceed 10%, indicating a satisfactory level of accuracy. However, notable discrepancies are observed in the hourly operative temperatures, with the monolayer window configuration and simple glazing showing the closest alignment. A precise match is also noted in the hourly solar heat gains with the simple glazing configuration, highlighting its effectiveness in accurately admitting the desired amount of energy into the room. Taking these findings into account, the monolayer opaque envelope emerges as the most compatible modeling configuration with standard results, featuring walls and a roof with evenly distributed mass, except for the roof where the mass is concentrated on the inside. For window modeling, the simple glazing option, which focuses solely on key thermal properties without considering mass, is identified as the optimal choice.

## 3.2 Climate and energy need analysis

Prior to initiating building energy simulations, the calculation of degree days is undertaken to gain preliminary insights into the expected energy requirements for these climates.

The following Table 3.10 presents the results obtained from this calculation.

| Degree Days | | |
|---|---|---|
| **Location** | **HDD ($T_{ref}$ = 18°C)** | **CDD ($T_{ref}$ = 18°C)** |
| **Denver** | 3379 | 352 |
| **London** | 2238 | 86 |

Table 3.11: Denver and London annual heating and cooling degree days

It is observable that Denver has a higher total number of degree days, suggesting higher energy needs compared to London. Simultaneously, both locations exhibit characteristics of cold climates. These parameters will aid in the analysis, providing a more comprehensive understanding of the results obtained from the simulations.

In Chart 3.7, Chart 3.8 and Chart 3.9 a shown the results of the energy needs of the two locations, without any occupancy profile.

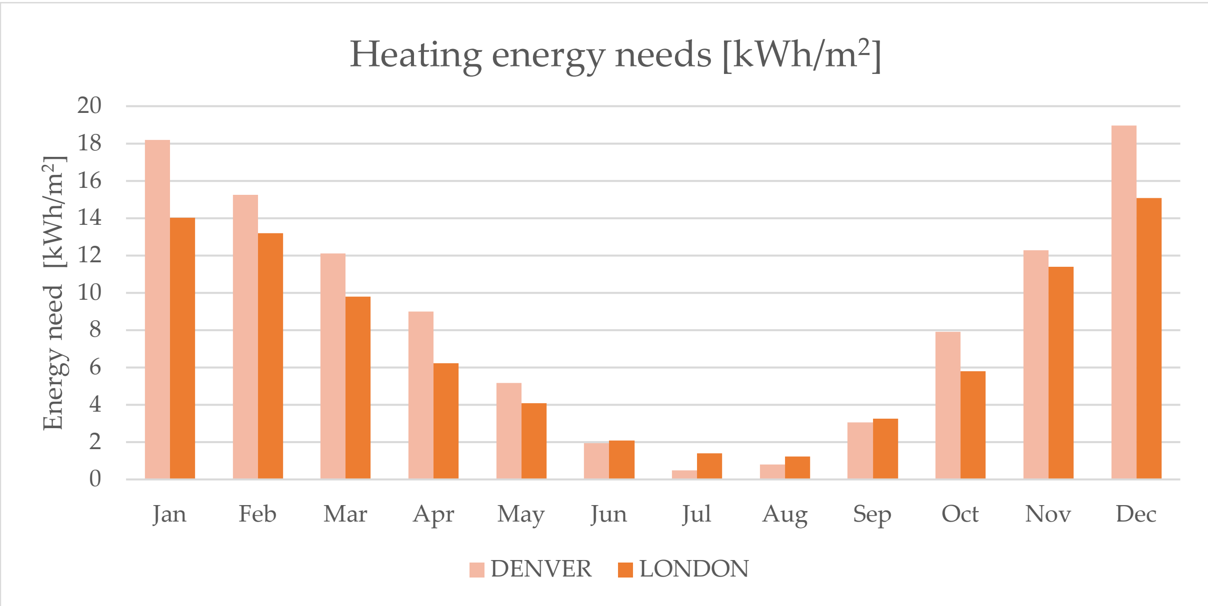



Chart 3.8: Monthly heating energy needs comparison – Denver and London

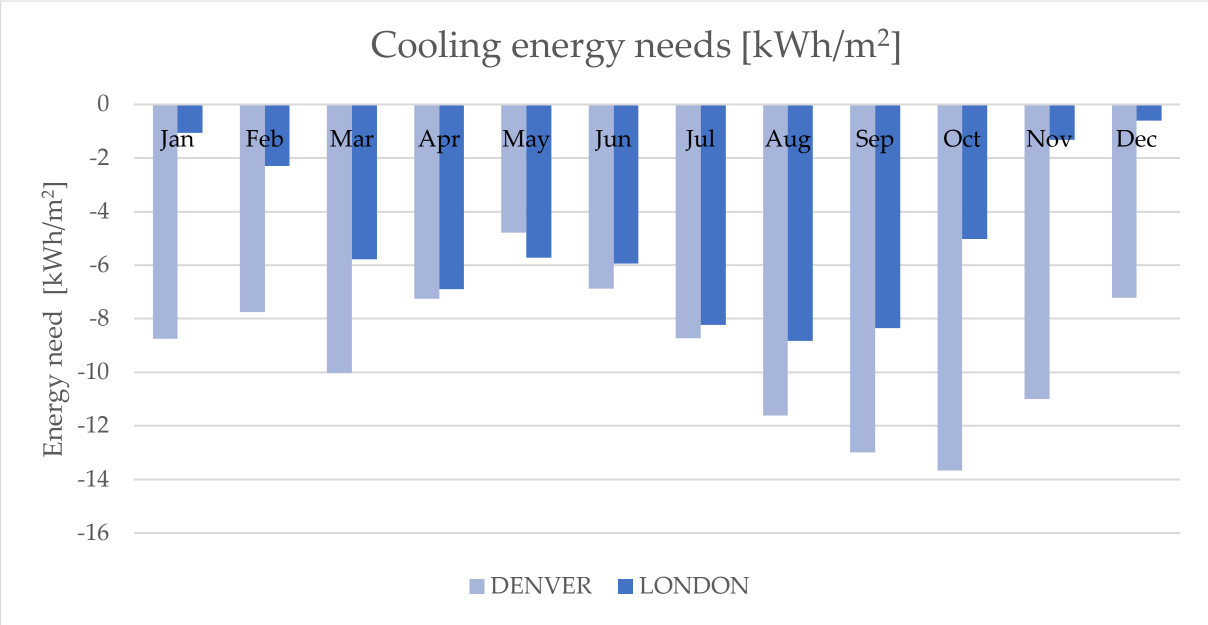



Chart 3.9: Monthly cooling energy needs comparison – Denver and London

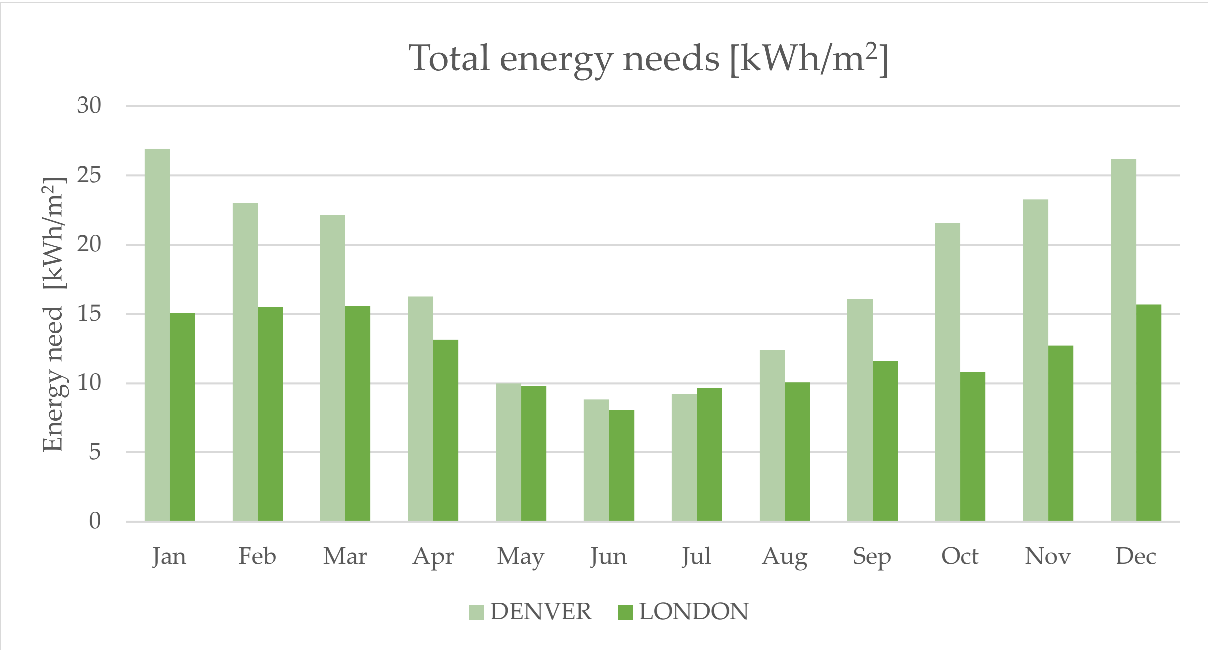



Chart 3.10: Monthly total energy needs comparison – Denver and London

It is evident that Denver has higher energy needs than London, a fact aligned with the degree days calculation. In both locations, heating loads show similar patterns, with Denver experiencing higher values for most of the year, except during the summer when London's heating needs surpass Denver's. On the other hand, cooling loads exhibit distinct behaviors; London's cooling demand peaks in the summer and diminishes in the winter, adhering to the expected cooling season. Denver, however, maintains high and consistent cooling loads throughout the year. These findings will inform the subsequent discussion of the results.

## 3.3 Full occupancy profiles analysis

| DENVER | | | | | | | |
|---|---|---|---|---|---|---|---|
| Occupancy Profile | People Heat Gain | Heating Need | | Cooling Need | | Total Energy Need | |
| [-] | [kWh/m²] | [kWh/m²] | [%] | [kWh/m²] | [%] | [kWh/m²] | [%] |
| No People | 0 | 111.16 | - | 116.04 | - | 227.2 | - |
| ASHRAE | 16.63 | 109.36 | -1.62 | 121.76 | 4.93 | 231.12 | 1.73 |
| ISO 17772 | 11.14 | 110.07 | -0.98 | 120.4 | 3.76 | 230.47 | 1.44 |
| ISO 18253 | 32.8 | 108 | -2.84 | 127.76 | 10.10 | 235.76 | 3.77 |
| Reference office_0 | 22.69 | 108.59 | -2.31 | 123.16 | 6.14 | 231.75 | 2.00 |
| Reference office_EAST | 44.56 | 106.3 | -4.37 | 130.05 | 12.07 | 236.35 | 4.03 |
| Reference office_WEST | 45.73 | 106.18 | -4.48 | 130.41 | 12.38 | 236.59 | 4.13 |

Table 3.12: Test RoomOffice - Energy Needs Results - Denver

| LONDON | | | | | | | |
|---|---|---|---|---|---|---|---|
| Occupancy Profile | People Heat Gain | Heating Need | | Cooling Need | | Total Energy Need | |
| [-] | [kWh/m²] | [kWh/m²] | [%] | [kWh/m²] | [%] | [kWh/m²] | [%] |
| No People | 0 | 87.59 | | 60.04 | | 147.63 | |
| ASHRAE | 16.63 | 84.41 | -3.63 | 64.41 | 7.28 | 148.82 | 0.81 |
| ISO 17772 | 11.14 | 85.54 | -2.34 | 63.34 | 5.50 | 148.88 | 0.85 |
| ISO 18253 | 32.8 | 81.76 | -6.66 | 69.1 | 15.09 | 150.86 | 2.19 |
| Reference office_0 | 22.69 | 83.28 | -4.92 | 65.39 | 8.91 | 148.67 | 0.70 |
| Reference office_EAST | 44.56 | 79.55 | -9.18 | 71.07 | 18.37 | 150.62 | 2.03 |
| Reference office_WEST | 45.73 | 79.35 | -9.41 | 71.38 | 18.89 | 150.73 | 2.10 |

Table 3.13: Test RoomOffice - Energy Needs Results – London

The degree days calculation correctly anticipates that Denver would have higher energy needs. What stands out, however, is the unexpected finding that Denver's cooling requirements exceed its heating demands, challenging the typical expectation for a cold climate. This contrasts with established energy consumption patterns categorized by climate.

In Denver, cooling and heating needs show very similar values, suggesting that despite the balanced proportion of cooling and heating loads, the impact of people on cooling is more pronounced.

Considering the three standards occupancy profiles we can observe that in both climates the Private Office (ISO 18523) is the office configuration with the highest energy needs, while the co-working (ASHRAE) results to be the best solution in London but not in Denver, where the Open Plan Office is the profile with lower total energy needs.

More in general, in Denver the higher is the people gain, the higher the energy consumption, but this is not what happens in London: both cities have the same people gain but in London the case with the higher energy need is the ISO 18523, while in Denver the case with the highest energy need is the Reference office_WEST.

This variance may be attributed to the ratio between heating and cooling needs in the two cities. In Denver, the gap between cooling and heating is relatively low (about 5 kWh/m² in the baseline case), contrasting with London, where a more significant difference exists between the two loads.

In conclusion, given the same occupancy profile in an identical office setting, locations with initially lower energy demands are less significantly impacted by the same increase in occupancy considering the total energy needs. Additionally, the occupancy has, in both locations a greater impact on cooling needs.

| DENVER | | | | | |
|---|---|---|---|---|---|
| Occupancy Profile | EUI | | Annual Working Hours | Max n° of people | EU/(P*h) |
| [-] | [kWh/m²] | [%] | [h] | [$P_{max}$] | [kWh/P*h] |
| No People | 239.93 | - | - | - | - |
| ASHRAE | 243.85 | 1.63 | 5996 | 2 | 0.98 |
| ISO 17772 | 243.2 | 1.36 | 2868 | 2 | 2.04 |
| ISO 18253 | 248.5 | 3.57 | 3389 | 5 | 0.70 |
| Reference office_0 | 244.48 | 1.90 | 3650 | 3 | 1.07 |
| Reference office_EAST | 249.09 | 3.82 | 3650 | 6 | 0.55 |
| Reference office_WEST | 249.32 | 3.91 | 3650 | 7 | 0.47 |

Table 3.14: Test RoomOffice - EUI and energy use per capita per hour – Denver

| LONDON | | | | | |
|---|---|---|---|---|---|
| Occupancy Profile | EUI | | Annual Working Hours | Max n° of people | EU/(P*h) |
| [-] | [kWh/m²] | [%] | [h] | [$P_{max}$] | [kWh/P*h] |
| No People | 160.36 | - | - | - | - |
| ASHRAE | 161.54 | 0.74 | 5996 | 2 | 0.65 |
| ISO 17772 | 161.61 | 0.78 | 2868 | 2 | 1.35 |
| ISO 18253 | 163.6 | 2.02 | 3389 | 5 | 0.46 |
| Reference office_0 | 161.4 | 0.65 | 3650 | 3 | 0.71 |
| Reference office_EAST | 163.34 | 1.86 | 3650 | 6 | 0.36 |
| Reference office_WEST | 163.46 | 1.93 | 3650 | 7 | 0.31 |

Table 3.15: Test RoomOffice - EUI and energy use per capita per hour - London

The evaluation now shifts to the two indices of the profiles applied to the test room office.

The total energy usage includes both the total energy needs and the energy consumed by the equipment, which is maintained constant as per the simulation settings (Paragraph 2.1.3). The Energy Use Intensity (EUI) exhibits the same pattern as the total energy needs, as previously discussed. The energy use per person-hour (EU/(P*h*)) serves as an indicator of energy utilization, considering socio-economic variables such as the number of people in the office and the time spent.

The profile with the lowest Energy Use Intensity (EUI) varies between the two locations: in London, it is the Reference Office_0, whereas in Denver, it is represented by ISO 17772 (Standard – Open Plan Office). In opposition, when considering energy use per capita per hour, the ReferenceOffice_WEST profile exhibits the lowest values in both locations. This discrepancy underscores the necessity of evaluating both indices to determine the most efficient occupancy profile, highlighting that the optimal strategy may differ based on geographical location and the specific metric under consideration.

## 3.4 Smart-Working occupancy reduction impact

| DENVER | | | | | | | |
|---|---|---|---|---|---|---|---|
| Occupancy Profile | People Heat Gain | Heating Need | | Cooling Need | | Total Energy Need | |
| [-] | [kWh/m²] | [kWh/m²] | [%] | [kWh/m²] | [%] | [kWh/m²] | [%] |
| ISO 18253 | 32.8 | 108 | - | 127.76 | - | 235.76 | - |
| ISO 18523 (10%) | 3.28 | 110.8 | 2.59 | 117.25 | -8.23 | 228.05 | -3.27 |
| ISO 18523 (61%) | 20.00 | 109.13 | 1.05 | 123.26 | -3.52 | 232.39 | -1.43 |
| ISO 18523 (79%) | 25.91 | 108.59 | 0.55 | 125.32 | -1.91 | 233.91 | -0.78 |

Table 3.16: Smartworking trend - Energy needs - Denver

| LONDON | | | | | | | |
|---|---|---|---|---|---|---|---|
| Occupancy Profile | People Heat Gain | Heating Need | | Cooling Need | | Total Energy Need | |
| [-] | [kWh/m²] | [kWh/m²] | [%] | [kWh/m²] | [%] | [kWh/m²] | [%] |
| ISO 18253 | 32.8 | 81.76 | - | 69.1 | | 150.86 | |
| ISO 18523 (10%) | 3.28 | 86.92 | 6.31 | 60.9 | -11.87 | 147.82 | -2.02 |
| ISO 18523 (61%) | 20.00 | 83.86 | 2.57 | 65.53 | -5.17 | 149.39 | -0.97 |
| ISO 18523 (79%) | 25.91 | 82.86 | 1.35 | 67.15 | -2.82 | 150.01 | -0.56 |

Table 3.17: Smartworking trend - Energy needs - London

Reducing people gains leads to a decrease in heating demand while cooling demand benefits. This pattern affirms the significant role of people gains in overall energy consumption, highlighting that a decrease in people gains can lead to a reduction in total energy demand. Furthermore, as previously analyzed, people gains have a more pronounced effect on cooling needs.

| DENVER | | | | | |
|---|---|---|---|---|---|
| Occupancy Profile | EUI | | Annual Working Hours | Max n° of people | EU/(P*h) |
| [-] | [kWh/m²] | [%] | [h] | [$P_{max}$] | [kWh/P*h] |
| ISO 18253 | 248.5 | | 3389 | 5 | 0.70 |
| ISO 18523 (10%) | 240.78 | -3.11 | 3389 | 1 | 3.41 |
| ISO 18523 (61%) | 245.12 | -1.36 | 3389 | 3 | 1.16 |
| ISO 18523 (79%) | 246.64 | -0.75 | 3389 | 4 | 0.87 |

Table 3.18: SmartWorking Trend - EUI and energy use per capita per hour - Denver

| LONDON | | | | | |
|---|---|---|---|---|---|
| Occupancy Profile | EUI | | Annual Working Hours | Max n° of people | EU/(P*h) |
| [-] | [kWh/m²] | [%] | [h] | [$P_{max}$] | [kWh/P*h] |
| ISO 18253 | 163.6 | | 3389 | 5 | 0.43 |
| ISO 18523 (10%) | 160.56 | -1.86 | 3389 | 1 | 2.09 |
| ISO 18523 (61%) | 162.12 | -0.90 | 3389 | 3 | 0.71 |
| ISO 18523 (79%) | 162.75 | -0.52 | 3389 | 4 | 0.53 |

Table 3.19: SmartWorking Trend - EUI and energy use per capita per hour – London

Analyzing the Energy Use Intensity (EUI) and energy use per capita per hour produces significant findings. As anticipated, the EUI decreases alongside energy needs, given the model's assumption of constant equipment loads. However, examining energy use per capita per hour reveals a contrasting trend: significantly reducing the maximum number of occupants in the office causes a marked increase in this index. This is particularly revealing as it demonstrates the extent of energy inefficiency in the building resulting from simply reducing occupancy without implementing other significant improvements. Essentially, the decrease in energy use is not as impactful as the reduction in the number of people. This analysis leads to the conclusion that while reducing occupancy lowers energy consumption due to decreased cooling needs, the per capita energy consumption does not decrease proportionately, resulting in a significant rise in energy use per capita.

## 3.5 Reference Office optimization

| DENVER | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Occupancy Profile | Area | People Heat Gain | Heating Need | | Cooling Need | | Total Energy Need | |
| [-] | [m²] | [kWh] | [kWh] | [%] | [kWh/] | [%] | [kWh] | [%] |
| ReferenceOffice_0 | 1149.38 | 26079.43 | 124811.17 | | 141557.64 | | 266368.82 | |
| ReferenceOffice_EAST | 577.8 | 26079.43 | 61420.14 | -50.8 | 75142.89 | -46.9 | 136563.03 | -48.7 |
| ReferenceOffice_WEST | 571.58 | 26079.43 | 60690.36 | -51.4 | 74539.75 | -47.3 | 135230.11 | -49.2 |

Table 3.20: Reference Office Area Optimization – Energy needs – Denver

| LONDON | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Occupancy Profile | Area | People Heat Gain | Heating Need | | Cooling Need | | Total Energy Need | |
| [-] | [m²] | [kWh] | [kWh] | [%] | [kWh] | [%] | [kWh] | [%] |
| ReferenceOffice_0 | 1149.38 | 26079.43 | 95720.37 | | 75157.96 | | 266368.82 | |
| ReferenceOffice_EAST | 577.8 | 26079.43 | 45963.99 | -52.0 | 41064.25 | -45.3 | 136563.03 | -48.7 |
| ReferenceOffice_WEST | 571.58 | 26079.43 | 45354.87 | -52.6 | 40799.38 | -45.7 | 135230.11 | -49.2 |

Table 3.21: Reference Office Area Optimization – Energy needs - London

Energy needs were calculated by multiplying the per unit area energy needs, derived from test room simulations, by the corresponding office area. The results are quite positive, with heating needs showing greater improvement than cooling needs. In both locations, the ReferenceOffice_WEST emerged as the most efficient in terms of lowest energy needs. These findings underscore the effectiveness of area optimization as a strategy to decrease the conditioned area, thereby confirming its validity in enhancing energy efficiency.

| DENVER | | | | | | | |
|---|---|---|---|---|---|---|---|
| Occupancy Profile | EUI | | Total Energy Use | | Annual Working Hours | Max n° of people | EU/(P*h) |
| [-] | [kWh/m²] | [%] | [kWh] | [%] | [h] | [$P_{max}$] | [kWh/P*h] |
| ReferenceOffice_0 | 244.48 | | 281000.42 | | 3650 | 73 | 1.05 |
| ReferenceOffice_EAST | 249.09 | 1.89 | 143924.20 | -48.8 | 3650 | 73 | 0.54 |
| ReferenceOffice_WEST | 249.32 | 1.98 | 142506.33 | -49.3 | 3650 | 73 | 0.53 |

Table 3.22: Reference Office Optimization – EUI and energy use per capita per hour – Denver

| LONDON | | | | | | | |
|---|---|---|---|---|---|---|---|
| Occupancy Profile | EUI | | Total Energy Use | | Annual Working Hours | Max n° of people | EU/(P*h) |
| [-] | [kWh/m²] | [%] | [kWh] | [%] | [h] | [$P_{max}$] | [kWh/P*h] |
| ReferenceOffice_0 | 161.4 | | 185509.93 | | 3650 | 73 | 0.70 |
| ReferenceOffice_EAST | 163.34 | 1.20 | 94377.85 | -49.1 | 3650 | 73 | 0.36 |
| ReferenceOffice_WEST | 163.46 | 1.28 | 93430.47 | -49.6 | 3650 | 73 | 0.35 |

Table 3.23: Reference Office Optimization – EUI and energy use per capita per hour – London

The Energy Use Intensity (EUI) exhibits a declining trend, which correlates with observations from profile analyses indicating a direct relationship between higher people gain per square meter and increased EUI levels.

However, applying the EUI across the total area of three distinct office configurations reveals the significant impact of area optimization. Similarly, this optimization is evident in the energy use per capita per hour metrics. This is a result of the consistency in the number of people and working hours with the reducing of the office area, which decreases the overall energy consumption, thereby enhancing per capita energy efficiency. This highlights the pivotal role of spatial optimization in achieving energy efficiency in office environments.

# 4. Discussion

The Energy Use Intensity (EUI) index is widely used to assess building energy performance and compare various configurations. However, in the context of office buildings, it's essential to consider a wider range of variables. Strategies aimed at enhancing the efficiency of office buildings must take into account socio-economic implications, making the energy per capita per hour index a useful metric for gaining deeper insights into the effectiveness of specific office configurations.

In the post-pandemic era, smart-working policies have caused a rapid decrease in office occupancy, challenging the conventional design of office buildings that did not anticipate hybrid working models.

The consequences of this phenomena are different and based on the location, since, as already seen in the literature, office building energy consumptions mainly depends on air conditioning and ventilation, which strongly depends on the climates. This highlights the complexity of managing office building energy consumption in adapting to emerging work practices.

From the analysis, the following conclusions can be drawn:

- Cooling loads are more significantly affected by people gains than heating loads, indicating that reductions in occupancy due to smart-working policies will primarily decrease cooling demands, with a less pronounced effect on heating loads.

- The impact of occupancy variations is more pronounced in buildings with higher total energy needs, a correlation that can be anticipated through degree day calculations as a comparative measure between different climates.
- In climates like London or Denver, the energy savings resulting from reduced occupancy do not offset the socio-economic advantages observed in simulations of smart-working profiles.
- Area optimization yields significant energy savings in both climates, underscoring the importance of considering spatial dimensions as a critical factor.
- In general, it is important to observe both energy related parameter, together with time and human resources when considering an office building.

These key findings offer valuable insights for developing strategies to enhance efficiency in existing office buildings.

The analysis reveals that Denver experiences significant cooling needs throughout the year, including the winter months, with heating demands peaking during the winter season, with lower values in summer. In contrast, London's total energy needs remain relatively stable year-round, as cooling and heating demands balance each other each month and both follow the season (high heating needs in winter, lower in summer, high cooling load in summer, lower in winter)

For the reference office, various strategies can be adopted depending on the company's culture and type. A general approach could involve utilizing only one wing of the office during months of peak energy demand and potentially closing the office entirely for specific weeks or months, depending on organizational needs.

Given the significant impact of occupancy on cooling demands, implementing area optimization strategies during the warmest months could be an effective approach. This approach, coupled with promoting higher rates of smart-working, not only aids in reducing energy consumption but also supports employee well-being and satisfaction by allowing employees to manage vacations and work schedules more flexibly.

In addition, over recent decades, the four-day working week (4DWW) has gradually gained popularity, with literature highlighting benefits such as increased productivity and job satisfaction. [41] [42] Despite these advantages, few companies have adopted this program but integrating the 4DWW with area optimization could offer a novel approach. By maintaining the office at full capacity for three days a week (Tuesday to Thursday) and reducing the utilized office area on Mondays and Fridays, employees could enjoy the benefits of the 4DWW while the company remains operational for five days. This strategy not only supports flexible working arrangements but also results in significant energy savings, with a potential reduction in energy for 40% of the monthly working days.

Furthermore, a recent study [43] suggests the use of dynamic space configuration technologies for post-pandemic offices, such as semi-autonomous mobile partitions to adaptively adjust open-plan office layouts. This aligns with sustainability goals by optimizing natural resource use and minimizing dependence on artificial lighting and HVAC systems. An integrated approach could involve an HVAC system that operates solely in occupied office areas, making spatial configuration a versatile option for energy savings, including lighting and appliances.

Another study [44] deploy IoT sensors across office spaces to continuously monitor occupancy and environmental conditions. These data are used to adjust HVAC, lighting, and other systems in real-time, ensuring they operate efficiently and only when needed, thereby reducing unnecessary energy consumption.

These two studies showcase progressive technologies that can lead the transformation of hybrid offices in the future.

Finally, it is essential to foster energy-saving awareness among office staff, since has highlighted in the literature [8] occupants' voluntary actions can have a huge impact on energy consumptions.

# 5. Conclusions

The primary aim of this study is to analyze and provide significant insights into how smart-working policies impact the energy demand in office buildings. To this end, various occupancy profiles have been simulated, including three defined by international standards that mirror the behaviors of employees across different office layouts—specifically, private offices, open plan offices, and co-working spaces. Additionally, three profiles are associated with a real office, taking into account three distinct area configurations.

The research was structured around three main analyses, each designed to address specific questions. These questions were formulated to steer the study toward generating meaningful conclusions.

1. How do different occupancy profiles affect energy needs and efficiency in a same office?

Generally, occupancy has a more significant impact on cooling than on heating needs. The reduction in occupancy resulting from smart-working policies is more beneficial in warmer climates, where a more substantial decrease in cooling needs is observed. However, it's also critical to consider the total energy needs, which are influenced by the severity of the climate, measurable through degree days. Climates with higher degree days, indicating more extreme seasons, are likely to be more significantly affected by changes in occupancy rates.

This trend is supported by literature [23], which has documented a reduction in cooling consumption in warmer climates and an increase in heating demand in colder climates.

2. How do reduced occupancy rates of a same profile will affect energy needs and efficiency while maintaining the same office area?

Following the analysis, it is observed that in cities such as Denver and London, the adoption of smart-working policies resulting in reduced occupancy leads to decreased energy consumption. However, maintaining the same office layout and working hours while reducing occupancy significantly increases energy consumption per capita. This suggests that without broader changes to office configuration and operation, reducing occupancy alone may not be an efficient solution from a more comprehensive perspective.

3. How does the office area optimization will affect energy needs and efficiency while maintaining the same number of employees?

Optimizing the area of an office, while maintaining reduced occupancy due to smart-working policies, leads to significant energy savings and a reduction in energy consumption per capita per hour. This outcome underscores the effectiveness of such a strategy in enhancing energy efficiency.

All these outputs are quite interesting and provide a first global understanding of how smart-working policies, that have been implemented in many offices after the COVID-19 pandemic outbreak, have affected and will affect office buildings energy consumption.

Evaluating different cases and profiles to determine the most effective one cannot rely solely on the Energy Use Intensity (EUI) as it fails to account for the socio-economic impacts, such as the number of people attending the office and their working hours. Therefore, the analysis of occupancy profiles has included both the EUI and the energy consumption per capita per hour, incorporating a socio-economic dimension into the assessment. This dual evaluation approach ensures a comprehensive understanding of each profile's implications on both energy efficiency and the socio-economic aspects of the company.

Many strategies have been already proposed by previous studies that can be applied in old and new offices, which mainly includes smart systems and flexible office configurations, which allows the office area adjustment based on employees needs and HVAC system efficiency, but for the companies is also very important to define a strategies that aligns with the company working needs and purpose, such as the short working week (4DWW) or strategic use of the building in key period of the year (summer months were flexibility is more appreciated and cooling needs higher).

Hybrid work is increasingly becoming a fundamental aspect of the new way of working, underscoring the necessity to explore and refine smart-working policies. This is crucial for creating solutions that are both energy-efficient and cost-effective, thereby meeting environmental and energy conservation goals.

The objective of this study is to offer insights and tools for forthcoming research to devise smart-working policies. These policies aim to sculpt the future workplace in a way that prioritizes employee comfort, enhances productivity, and optimizes building energy usage.

# 6. Limitations

This study encompasses several limitations, being a broad examination of the effects of smart-working policies on the energy consumption of office buildings.

The simulations, due to their simplified nature, omit several significant factors critical to energy consumption, such as ventilation, which is a significant factor during the cooling season.

The analysis assumes an idealized system framework, neglecting the real-world performance efficiencies of HVAC systems, potentially leading to underestimated energy consumptions.

Additionally, the analysis does not account for various constant energy consumption elements that significantly contribute to energy consumption, such as elevators and Building Management System (BMS) components.

The study utilizes a simplified and lightweight building envelope model, which does not accurately reflect the higher thermal inertia typical of the climates under consideration. This higher thermal inertia usually moderates temperature extremes, a factor particularly relevant in the case of Denver.

For a more detailed understanding, it would be optimal to simulate the necessity of simulating additional climates, with different cooling and energy trends and values. Analyzing only two climates does not provide a thorough analysis or understanding of the phenomenon.

Future research should include a more detailed office modelling, including the systems and a specific envelope, and wider range of climates, in order to offer a more comprehensive overview of energy consumption trends in diverse environmental contexts.

# 7. Bibliography


[1] US Department of Energy, "2011 Buildings Energy Data Book," 2012.

[2] T. Nikolaou, D. Kolokotsa, and G. Stavrakakis, "Review on methodologies for energy benchmarking, rating and classification of buildings," *Advances in Building Energy Research*, vol. 5, no. 1, pp. 53–70, May 2011, doi: 10.1080/17512549.2011.582340.

[3] "Perspectives for the clean energy transition. The critical role of buildings," 2019.

[4] C. Deb, S. E. Lee, and M. Santamouris, "Using artificial neural networks to assess HVAC related energy saving in retrofitted office buildings," *Solar Energy*, vol. 163, pp. 32–44, Mar. 2018, doi: 10.1016/j.solener.2018.01.075.

[5] H. Yoshino, T. Hong, and N. Nord, "IEA EBC annex 53: Total energy use in buildings—Analysis and evaluation methods," *Energy Build*, vol. 152, pp. 124–136, Oct. 2017, doi: 10.1016/j.enbuild.2017.07.038.

[6] M. Bonte, F. Thellier, and B. Lartigue, "Impact of occupant's actions on energy building performance and thermal sensation," *Energy Build*, vol. 76, pp. 219–227, Jun. 2014, doi: 10.1016/j.enbuild.2014.02.068.

[7] K. Gram-Hanssen, "Efficient technologies or user behaviour, which is the more important when reducing households' energy consumption?," *Energy Effic*, vol. 6, no. 3, pp. 447–457, Aug. 2013, doi: 10.1007/s12053-012-9184-4.

[8] "ANNEX66." Accessed: Dec. 17, 2023. [Online]. Available: https://www.annex66.org/

[9] C. Bodin Danielsson and T. Theorell, "Office Employees' Perception of Workspace Contribution: A Gender and Office Design Perspective," *Environ Behav*, vol. 51, no. 9–10, pp. 995–1026, Nov. 2019, doi: 10.1177/0013916518759146.

[10] A. Pouwels, "Open Plan Offices - The new ways of working - The advantages and disadvantages of open office space Open Plan Offices - The new ways of working," 2020. doi: 10.2861/104979.

[11] Z. Dong, K. Zhao, Y. Hua, Y. Xue, and J. Ge, "Impact of occupants' behaviour on energy consumption and corresponding strategies in office buildings," *IOP Conf Ser Earth Environ Sci*, vol. 294, no. 1, p. 012076, Jul. 2019, doi: 10.1088/1755-1315/294/1/012076.

[12] F. Benita, "Human mobility behavior in COVID-19: A systematic literature review and bibliometric analysis," *Sustain Cities Soc*, vol. 70, p. 102916, Jul. 2021, doi: 10.1016/J.SCS.2021.102916.

[13] L. Mi *et al.*, "How does COVID-19 emergency cognition influence public pro-environmental behavioral intentions? An affective event perspective," *Resour Conserv Recycl*, vol. 168, p. 105467, May 2021, doi: 10.1016/J.RESCONREC.2021.105467.

[14] J. L. Santarpia *et al.*, "Aerosol and surface contamination of SARS-CoV-2 observed in quarantine and isolation care," *Sci Rep*, vol. 10, no. 1, p. 12732, Jul. 2020, doi: 10.1038/s41598-020-69286-3.

[15] N. D. Cortiços and C. C. Duarte, "Energy efficiency in large office buildings post-COVID-19 in Europe's top five economies," *Energy for Sustainable Development*, vol. 68, pp. 410–424, Jun. 2022, doi: 10.1016/j.esd.2022.04.006.

[16] Y. Xiao, B. Becerik-Gerber, G. Lucas, and S. C. Roll, "Impacts of Working From Home During COVID-19 Pandemic on Physical and Mental Well-Being of Office Workstation Users," *J Occup Environ Med*, vol. 63, no. 3, pp. 181–190, Mar. 2021, doi: 10.1097/JOM.0000000000002097.

[17] G. A. O'Rourke, "Workplace strategy: a new workplace model," *Asia Pacific Journal of Human Resources*, vol. 59, no. 4, pp. 554–566, Oct. 2021, doi: 10.1111/1744-7941.12288.

[18] "THE IWG GLOBAL WORKSPACE SURVEY," 2019.

[19] H. Davidsson, S. K. Chowdary, N. Gentile, B. Berggren, and J. Kanters, "Energy use of buildings in relation to occupancy rates," *J Phys Conf Ser*, vol. 2069, no. 1, p. 012217, Nov. 2021, doi: 10.1088/1742-6596/2069/1/012217.

[20] B. J. van Ruijven, E. De Cian, and I. Sue Wing, "Amplification of future energy demand growth due to climate change," *Nat Commun*, vol. 10, no. 1, p. 2762, Jun. 2019, doi: 10.1038/s41467-019-10399-3.

[21] G. Henderson, "Home air conditioning in Europe-how much energy would we use if we became more like American households?"

[22] M. Auffhammer and E. T. Mansur, "Measuring climatic impacts on energy consumption: A review of the empirical literature," *Energy Econ*, vol. 46, pp. 522–530, Nov. 2014, doi: 10.1016/j.eneco.2014.04.017.

[23] N. D. Cortiços and C. C. Duarte, "COVID-19: The impact in US high-rise office buildings energy efficiency," *Energy Build*, vol. 249, p. 111180, Oct. 2021, doi: 10.1016/j.enbuild.2021.111180.

[24] M. C. Baechler, T. L. Gilbride, P. C. Cole, M. G. Hefty, and K. Ruiz, "Guide to Determining Climate Regions by County PREPARED BY Pacific Northwest National Laboratory," 2015. [Online]. Available: www.buildingamerica.gov

[25] "ASHRAE 140 - Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs," 2017. [Online]. Available: www.ashrae.org

[26] *BS EN ISO 52016-1 - Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads*. 2017.

[27] *ASHRAE Standard 55 -Thermal Environmental Conditions for Human Occupancy*. 2023. Accessed: Feb. 24, 2024. [Online]. Available: https://ashrae.iwrapper.com/ASHRAE_PREVIEW_ONLY_STANDARDS/STD_55_2023

[28] "ASHRAE Standard 55 -Thermal Environmental Conditions for Human Occupancy - Addendum G," 2013. [Online]. Available: www.ashrae.org

[29] "Engineering Reference," 2018.

[30] "ASHRAE Standard 90.1 - Energy Standard for Buildings Except Low-Rise Residential Buildings,"Building Envelope Trade-Off Schedules and Loads"," 2020, Accessed: Feb. 24, 2024. [Online]. Available: https://web.ashrae.org/90_1files/

[31] *EN ISO 17772-1 - Energy performance of buildings-Indoor environmental quality BSI Standards Publication*. 2017.

[32] *BS EN ISO 18523-1 - Energy performance of buildings-Schedule and condition of building, zone and space usage for energy calculation BSI Standards Publication*. 2017.

[33] S. Tavakoli, W. Loengbudnark, M. Eklund, A. Voinov, and K. Khalilpour, "Impact of COVID-19 Pandemic on Energy Consumption in Office Buildings: A Case Study of an Australian University Campus," *Sustainability 2023, Vol. 15, Page 4240*, vol. 15, no. 5, p. 4240, Feb. 2023, doi: 10.3390/SU15054240.

[34] "SRRA - Strategic Regional Research Alliance - Occupancy Index", Accessed: Feb. 24, 2024. [Online]. Available: https://srraresearch.org/covid/category/Occupancy%20Index

[35] "Spotlight: European Office Occupancy Rates - Savills Real Estate," Nov. 2023, Accessed: Feb. 24, 2024. [Online]. Available: https://www.savills.com/research_articles/255800/353641-0

[36] H. E. Beck, N. E. Zimmermann, T. R. McVicar, N. Vergopolan, A. Berg, and E. F. Wood, "Present and future Köppen-Geiger climate classification maps at 1-km resolution," *Sci Data*, vol. 5, no. 1, p. 180214, Oct. 2018, doi: 10.1038/sdata.2018.214.

[37] "MetroDenverEDC." Accessed: Mar. 11, 2024. [Online]. Available: https://www.metrodenver.org/live-here/climate

[38] "European climate zones and bio-climatic design requirements," 2016. [Online]. Available: www.pvsites.eu

[39] "ClimateData.org." Accessed: Mar. 11, 2024. [Online]. Available: https://en.climate-data.org/europe/united-kingdom/england/london-1/

[40] B. Standard, *Hygrothermal performance of buildings-Calculation and presentation of climatic data Part 6: Accumulated temperature differences (degree-days) (ISO 15927-6:2007)*. 1592.

[41] T. T. Campbell, “The four-day work week: a chronological, systematic review of the academic literature,” *Management Review Quarterly*, Apr. 2023, doi: 10.1007/s11301-023-00347-3.

[42] Z. Spicer and J. Lyons, “Small Town, Short Work Week: Evaluating the Effects of a Compressed Work Week Pilot in Zorra, Ontario, Canada,” *State and Local Government Review*, vol. 55, no. 1, pp. 73–81, Mar. 2023, doi: 10.1177/0160323X221115358.

[43] B. Vinh and D. Nguyen, “The Adaptive Architectural Layout: How the Control of a Semi-Autonomous Mobile Robotic Partition was Shared to Mediate the Environmental Demands and Resources of an Open-Plan Office,” *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI ’24), May 11â•ﬁ16, 2024, Honolulu, HI, USA*, vol. 1, 2024, doi: 10.1145/3613904.3642465.

[44] L. Babun, A. K. Sikder, A. Acar, and A. S. Uluagac, “IoTDots: A Digital Forensics Framework for Smart Environments,” Sep. 2018.

# Appendix A – TestRoom properties

| Structure | $D$<br>m | $\lambda$<br>W/(m·K) | $R$<br>m²·K/W | $\kappa_{m;op}$<br>J/(m²·K) | $\rho$<br>kg/m³ | $c$<br>J/(kg·K) |
|---|---|---|---|---|---|---|
| **External wall (inside to outside)** | | | | | | |
| Plasterboard | 0,012 | 0,160 | 0,075 | 9576 | 950 | 840 |
| Fiberglass quilt | 0,066 | 0,040 | 1,650 | 665 | 12 | 840 |
| Wood siding | 0,009 | 0,140 | 0,064 | 4293 | 530 | 900 |
| Total surf-surf | | | 1,789 | | | |
| For application of ISO 52016-1:<br>- Class specific heat capacity<br>- Class of distribution | | | | Very light<br>Evenly (D) | | |
| **Floor (inside to outside)** | | | | | | |
| Timber flooring | 0,025 | 0,140 | 0,179 | 19500 | 650 | 1200 |
| Insulation [a] | 1,003 | 0,040 | 25,075 | 0 [b] | 0 [b] | 0 [b] |
| Total surf-surf | | | 25,254 | | | |
| For application of ISO 52016-1:<br>- Class specific heat capacity<br>- Class of distribution | | | | Very light<br>Internal (I) | | |
| **Roof (inside to outside)** | | | | | | |
| Plasterboard | 0,010 | 0,160 | 0,063 | 7980 | 950 | 840 |
| Fiberglass quilt | 0,1118 | 0,040 | 2,794 | 1127 | 12 | 840 |
| Roofdeck | 0,019 | 0,140 | 0,136 | 9063 | 530 | 900 |
| Total surf-surf | | | 2,992 | | | |
| For application of ISO 52016-1:<br>- Class specific heat capacity<br>- Class of distribution | | | | Very light<br>Evenly (D) | | |

[a] To reduce uncertainty regarding testing the other aspects of simulating the building envelope, the floor insulation (below the actual floor construction) has been made very thick in the test case description, with the purpose to effectively decouple the floor thermally from the ground.

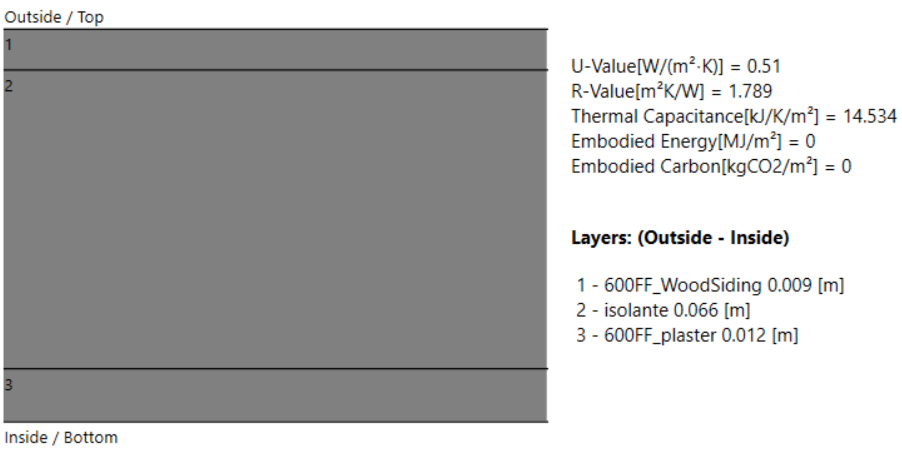
For the application of this document this means that the floor plus insulation is modelled as an opaque construction to outdoor air; this implies that the thermal resistance of the floor has to be used in the calculations instead of the effective thermal resistance ($R_{c;f;eff}$) in case of a ground coupled floor. To ensure that the thermal mass of the actual floor is modelled as part of the actual floor and not distributed over the actual floor and the artificial thick thermal insulation layer, the thermal resistance of the thick thermal insulation layer is imposed on the first (most outdoor) conductance which does not take part in the attribution of the thermal mass of the Class I type of construction (see 5.6.7.2); so: $h_1$ **= 0,04 W/(m²·K).**

[b] Underfloor insulation has the minimum density and specific heat the program being tested will allow, but not < 0. For the application of this document the density, specific heat and specific heat capacity of the underfloor insulation are assumed to be zero.

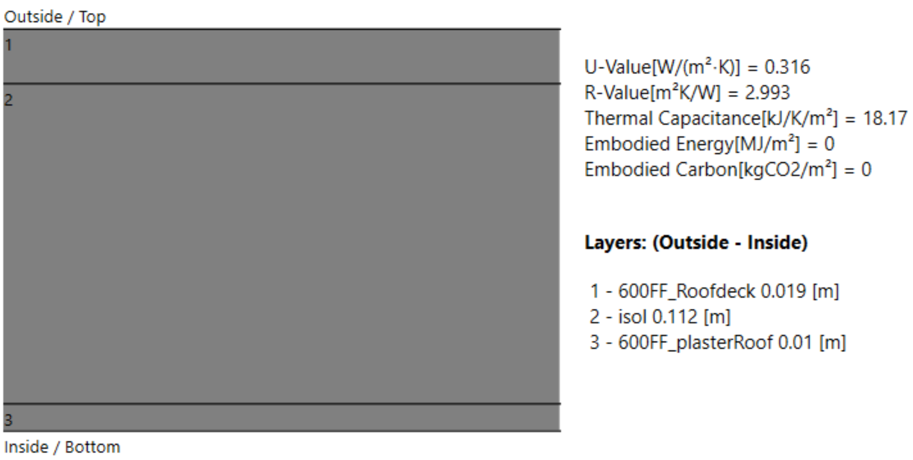
# Appendix B – ClimateStudio Modelling Configurations

## Multilayer Opaque Envelope Configuration

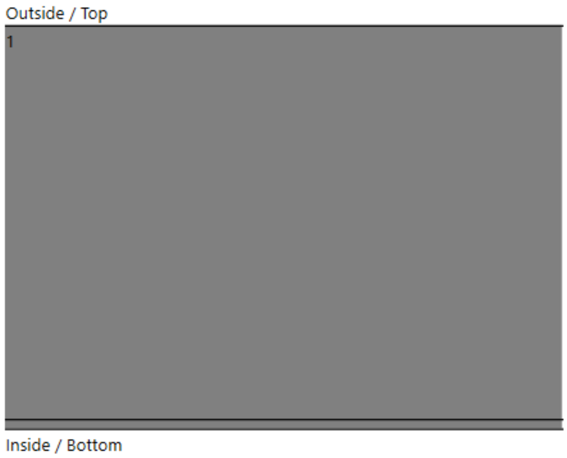
- **Façade:**




- **Roof**



- **Floor**



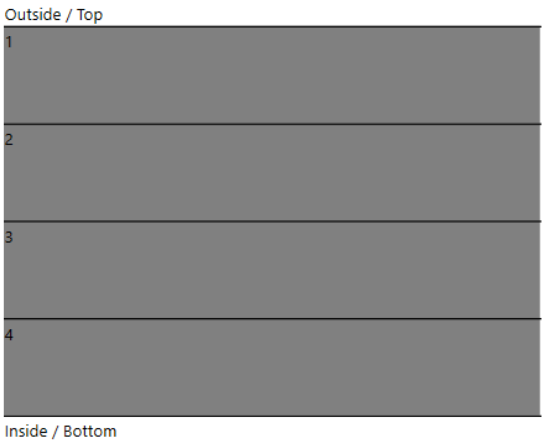

U-Value[W/(m²·K)] = 0.039
R-Value[m²K/W] = 25.254
Thermal Capacitance[kJ/K/m²] = 20.503
Embodied Energy[MJ/m²] = 0
Embodied Carbon[kgCO2/m²] = 0

**Layers: (Outside - Inside)**

1 - isola 1.003 [m]
2 - 600FF_Timberflooring 0.025 [m]

# Sublayers Opaque Envelope Configuration

- **Façade**

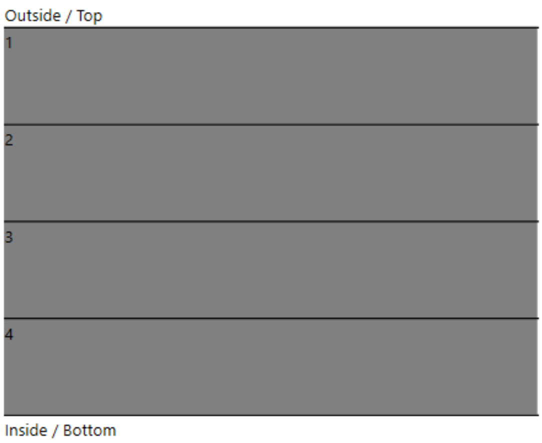



U-Value[W/(m²·K)] = 0.51
R-Value[m²K/W] = 1.79
Thermal Capacitance[kJ/K/m²] = 14.534
Embodied Energy[MJ/m²] = 0
Embodied Carbon[kgCO2/m²] = 0

**Layers: (Outside - Inside)**

1 - FACADE_x4LAYER 0.022 [m]
2 - FACADE_x4LAYER 0.022 [m]
3 - FACADE_x4LAYER 0.022 [m]
4 - FACADE_x4LAYER 0.022 [m]

- **Roof**

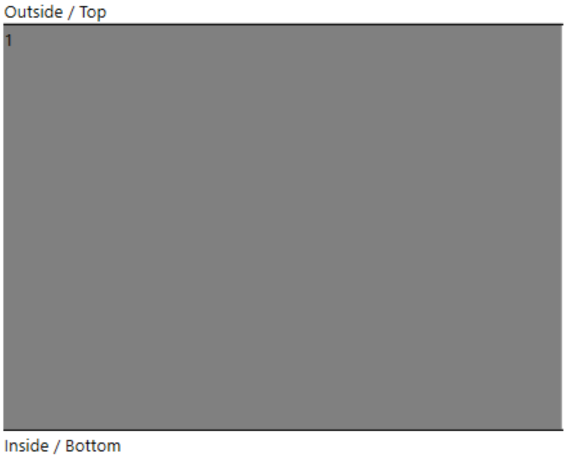



U-Value[W/(m²·K)] = 0.317
R-Value[m²K/W] = 2.989
Thermal Capacitance[kJ/K/m²] = 18.17
Embodied Energy[MJ/m²] = 0
Embodied Carbon[kgCO2/m²] = 0

**Layers: (Outside - Inside)**

1 - ROOF_x4LAYER 0.035 [m]
2 - ROOF_x4LAYER 0.035 [m]
3 - ROOF_x4LAYER 0.035 [m]
4 - ROOF_x4LAYER 0.035 [m]

- **Floor**



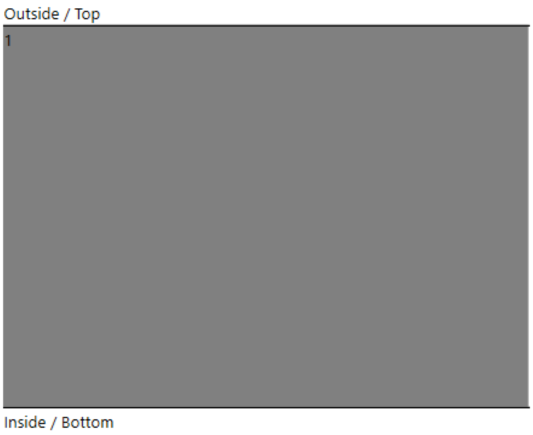

U-Value[W/(m²·K)] = 0.039
R-Value[m²K/W] = 25.221
Thermal Capacitance[kJ/K/m²] = 19.5
Embodied Energy[MJ/m²] = 0
Embodied Carbon[kgCO2/m²] = 0

**Layers: (Outside - Inside)**

1 - x4_iso 0.257 [m]

# Monolayer Opaque Envelope Configuration

- **Façade**

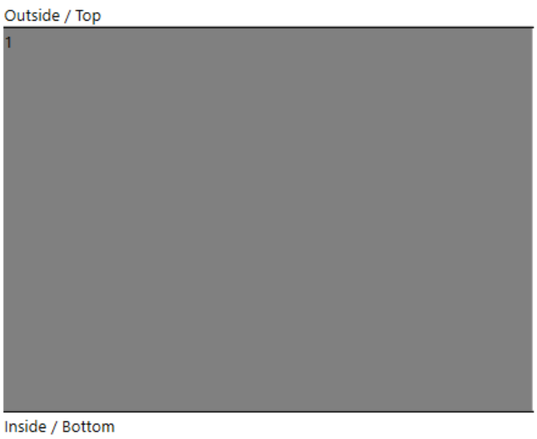



U-Value[W/(m²·K)] = 0.51
R-Value[m²K/W] = 1.79
Thermal Capacitance[kJ/K/m²] = 14.534
Embodied Energy[MJ/m²] = 0
Embodied Carbon[kgCO2/m²] = 0

**Layers: (Outside - Inside)**

1 - FACADE_LAYER 0.087 [m]

- **Roof**

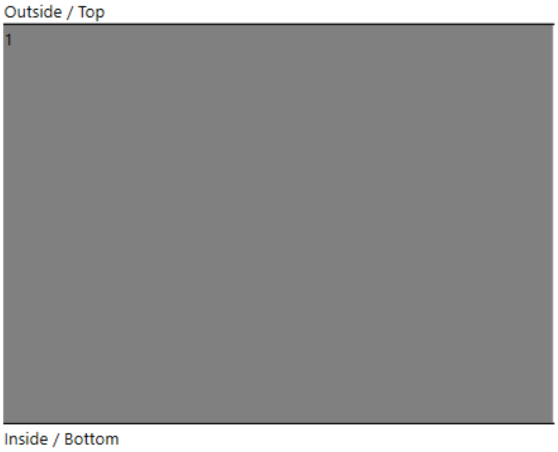



U-Value[W/(m²·K)] = 0.317
R-Value[m²K/W] = 2.989
Thermal Capacitance[kJ/K/m²] = 18.17
Embodied Energy[MJ/m²] = 0
Embodied Carbon[kgCO2/m²] = 0

**Layers: (Outside - Inside)**

1 - ROOF_LAYER 0.141 [m]

- **Floor**

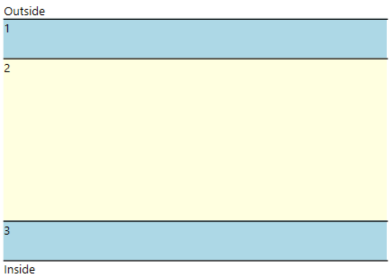



U-Value[W/(m²·K)] = 0.039
R-Value[m²K/W] = 25.221
Thermal Capacitance[kJ/K/m²] = 19.5
Embodied Energy[MJ/m²] = 0
Embodied Carbon[kgCO2/m²] = 0

**Layers: (Outside - Inside)**

1 - x4_iso 0.257 [m]

- **Multilayer Window**




**IDF_GLASS**

U-Value[W/(m²·K)] = 2.984
SHGC = 0.71
TVIS = 0.6
Embodied Energy[MJ/m²] = 238.125
Embodied Carbon[kgCO2/m²] = 14.446

**Layers: (Outside - Inside)**

1 - GLASS_LAYER 3.175 [mm]
2 - AIR_13 13 [mm]
3 - GLASS_LAYER 3.175 [mm]

- **Monolayer Window**


**IDF_GLASS_monolayer**

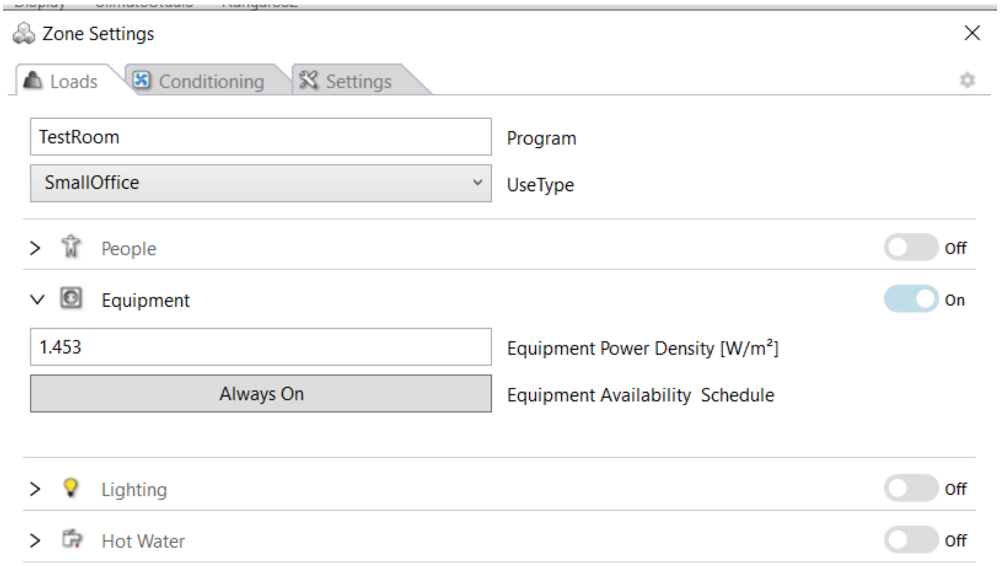
U-Value[W/(m²·K)] = 2.984
SHGC = 0.71
TVIS = 0.6
Embodied Energy[MJ/m²] = 725.625
Embodied Carbon[kgCO2/m²] = 44.021

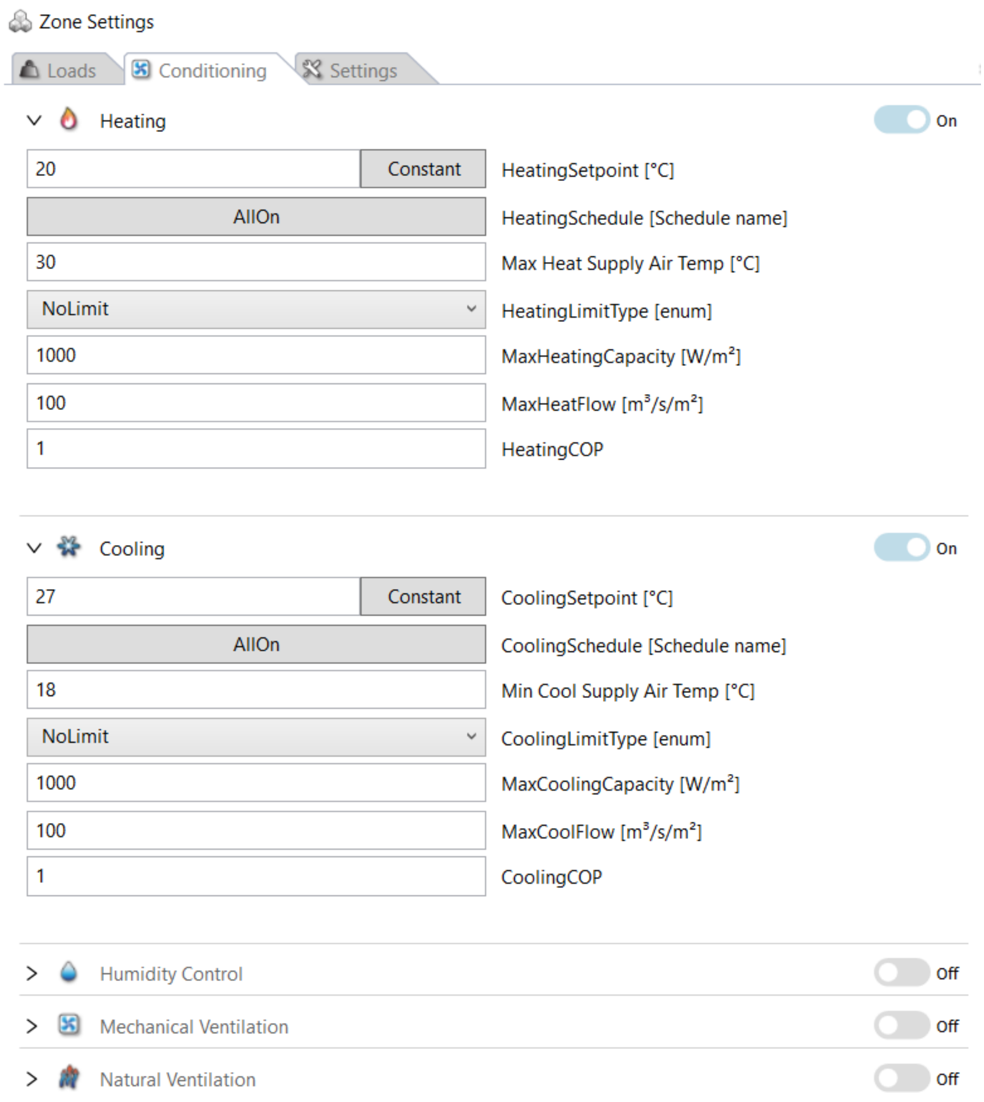
**Layers: (Outside - Inside)**

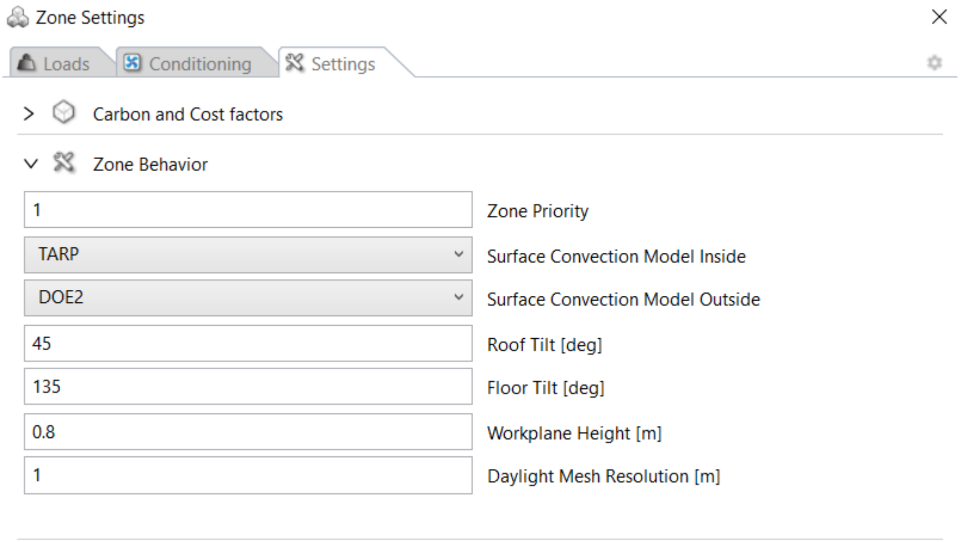
1 - GLASS_LAYER 19.35 [mm]

# Simulation Settings

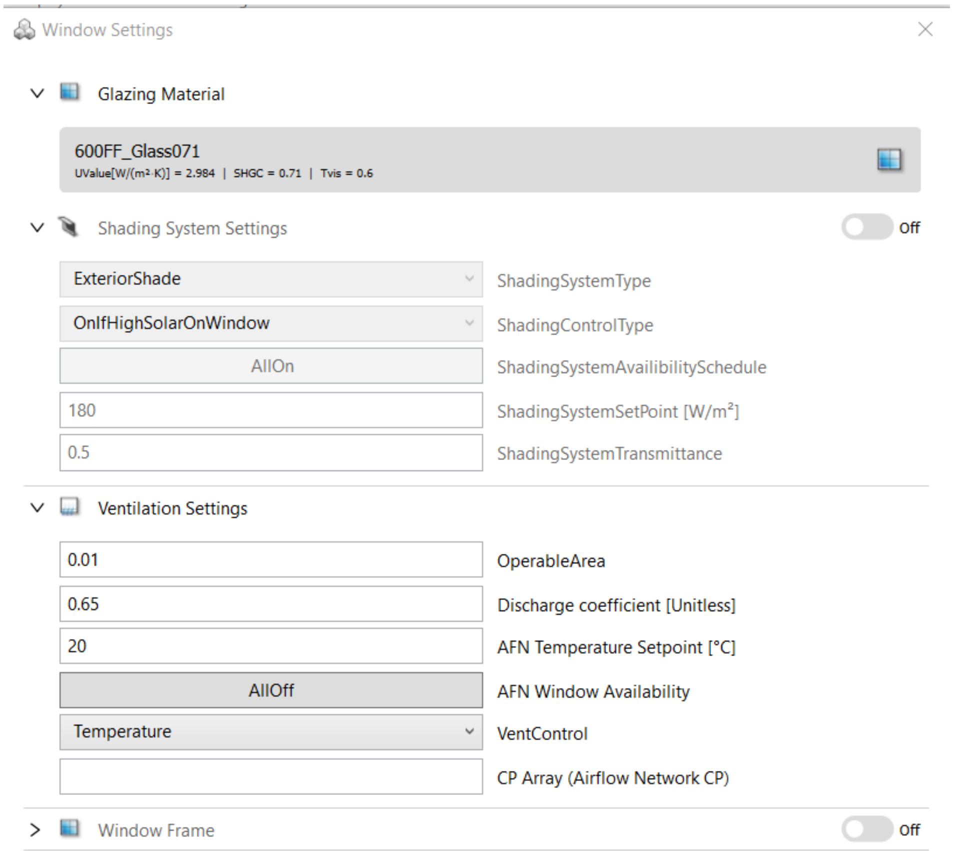
- **Zone settings**



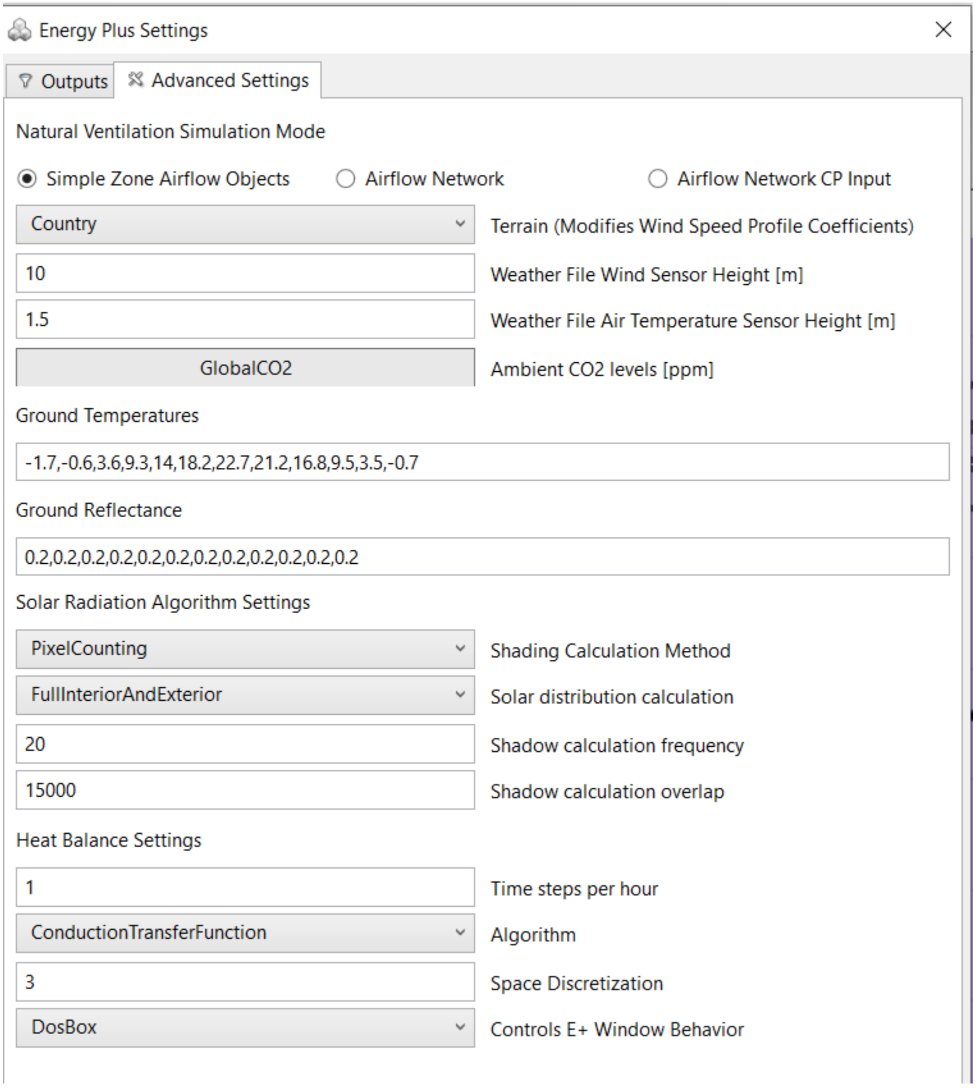






- ## Window Settings



- ## Simulation Settings



# List of Figures

# List of Tables

# List of Charts