The Impact of Biophilic Design on the Energy Performance and Thermal Comfort of Conventional Apartment Buildings

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Dedication

This dissertation is dedicated to my wife Claudia Schembri Galea and my family for their kindness and continued support.

Authorship Statement

This dissertation is based on the results of the research carried out by myself, in my own composition, and has not been previously presented for any other certified or uncertified qualification.

This research was carried out under the supervision of the tutor Prof. Ing. Daniel Micallef and support of Prof. Ing. Simon Borg.

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Acknowledgements

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Abstract

In Malta, apartment blocks lately have been built without careful consideration of local and international guidelines related to energy performance and thermal comfort. By comparing recent “traditionally” built apartments with biophilic designed apartment, The proposal addressed how biophilic design affect the health and well-being of people trough energy performance and environmental conditions. It showed the benefits of Biophilic design such as retrofitting in the same apartments and a comparison of both scenarios. This study shows a primary focus on thermal comfort analysis that are the result of biophilic design application.

The study used quantitative data collected from data loggers and simulation. To analyse the information obtained, simulation was used to compare different scenarios basically the “traditional” with the “biophilic”. A parametric analysis was performed to optimize and identify the best scenario that affects well-being and energy performance. Results were analysed over a whole year of climate data for the Maltese islands. All results were cross-compared and analysed to provide answers to the research question and objective of this study.

The results showed the benefits of biophilic design in terms of energy performance, thermal comfort and human well-being. This includes 50% reduction in cooling loads and 45% in heating loads for the ground floor scenario, lower CO_2 levels and improved thermal comfort in terms of EN16798-1 adaptive comfort categories. The conclusion presented a holistic approach on how biophilic design can be part of our standards in terms of residential building design.

Keywords: **Biophilic Design, Environmental Design, Energy Performance, Building Simulation and Health and Well-Being**

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Chapter 1 Introduction

In recent years, the rapid construction of apartment blocks in Malta has often proceeded without adequate consideration of both local and international guidelines regarding energy performance and thermal comfort. This neglect has resulted in living environments that fail to improve indoor conditions for human health and well-being.

Considering that the local scenario faces a rapid increase in population thus an increase in demand for apartment blocks, the need for sustainable infrastructure and human centred design is becoming even more essential. One of the most appropriate means to achieve this, is with reinventing the stakeholder's mindset, to include the "Biophilic Design". This design is an opportunity to reintroduce nature into the built environment while integrating nature with the so called "green corridors". Focusing on the merger of the built environment with nature rather than dividing or creating a "gap" in the natural environment. Designing with this approach will not only connect the occupants to nature but it will also benefit from physical and mental health. Whilst also improving the energy performance of the building.

Biophilic design is the integration of natural elements into the built environment, these include light, air, water and vegetation. This is the completely opposite of the current traditional apartments, which are typically constructed under space, time and cost considerations. Apart from the aesthetic, this design approach will result in better energy performance and quality of life.

In this dissertation, the study will compare traditionally built apartments with retrofitting biophilic design. This will show how the biophilic design concept effects the energy performance trough simulation and the human well-being trough the literature review. This study will be also examine how these design strategies can be implemented on already built apartments in urban areas. As a result, the gaps of the current design approach will be identified and highlight how the biophilic design concept can improve our life in two aspects.

The aspects studied includes natural ventilation, natural light and vegetation used as an insulation and air quality. On the other hand, aspects including water and the effect on human quality of life was not studied in a real case scenario but this was evident in the literature review. The biophilic design aspects considered in this study are also passive design aspects as these effect the energy efficiency of the building. Passive design are all the measures that minimise energy use including building form, orientation, thermal mass, shading and ventilation. On the other hand, biophilic design are all the measures related to nature that in this case are natural light, natural ventilation and vegetation. Therefore, not all passive design measures are biophilic.

1.1 Research Question and Hypothesis

The primary research question guiding this study is:

What is the current situation of typical apartments in terms of well-being and energy performance, and how can biophilic design measures be implemented to improve health, well-being, and energy performance in conventional apartment buildings?

The main hypothesis of this dissertation is that an existing apartment or new can easily be redesigned with biophilic approach to improve energy performance and thermal comfort.

Modern apartment buildings in Malta are typically constructed without prioritising local environmental conditions or natural elements that can improve energy efficiency and occupant well-being. By integrating biophilic design elements, this study hypothesizes that there will be a notable improvement in both energy efficiency and indoor thermal comfort.

1.2 Aims and Objectives

Based on the literature review, the following aims and objectives were developed.

1. **To define the existing situation of a typical apartment in terms of energy performance, including natural ventilation and natural lighting, and its effect on health and well-being.**

The initial objective consists of assessing the current energy performance of a traditional apartment in Malta. Including the existing conditions in terms of natural ventilation, light and also the overall thermal comfort and energy demand. This assessment will be carried out through visual analysis, simulation analysis and data logging.

2. **To compare the current existing apartment model with a biophilic-designed apartment, by evaluating the similarities and differences in terms of building performance.**

To achieve this a biophilic design model will be created. The same apartment model will be retrofitted to include the implementation of natural elements, ensuring a true and fair result.

This model will be analysed trough simulation and following a comparison of both results in terms of energy performance and thermal comfort. This will be achieved with the data logging of the existing including temperature, relative humidity and CO2.

3. **To define biophilic design guidelines to improve residential apartment sustainability, well-being, and quality of life in apartments by implementing biophilic design strategies**

Based on the results of both models, this study will identify key factors to inform guidelines and implementation process for biophilic design strategies in both retrofitted and newly designed apartments blocks. These guidelines will focus on sustainability and quality of life with the ultimate goal of developing a prototype design framework for sustainable development in terms of both energy use and occupants' wellbeing.

4. **To identify the advantages and disadvantages of implementing biophilic design**

The final aim will revisit the advantages and disadvantages based on the simulation modelling, with a focus on real-world application

1.3 Structure of Dissertation

CHAPTER	SCOPE
CHAPTER 1 – INTRODUCTION	Introduces the research topic and outlines the aims and objectives, research question, and hypothesis. It provides the context for comparing traditional and biophilic-designed apartments in terms of energy performance and thermal comfort.
CHAPTER 2 – LITERATURE REVIEW	Presents and reviews relevant literature on biophilic design, energy performance, and thermal comfort. Discusses theoretical foundations and previous case studies to establish a framework for the comparative analysis.
CHAPTER 3 – METHODOLOGY	Details the research methods used to assess the energy performance and thermal comfort of the two apartment models. It explains the simulation tools, data collection, and parameters used for evaluation.
CHAPTER 4 – RESULTS AND DISCUSSION	Discusses the findings results from data logging and building simulations. This chapter provides insights into the current condition with the aid of simulation. Here the researcher presents the biophilic design measures simulation results and conducts a comparison of the traditional and biophilic-designed apartments.

	Highlighting also the advantages and disadvantages of biophilic design in terms of energy performance and occupant well-being.
CHAPTER 5 – CONCLUSION	Summarises the study’s key findings, providing recommendations for future research and practical guidelines for applying biophilic design in residential architecture. The chapter also addresses the study's limitations.

Chapter 2 Literature review

2.1 Introduction

The scope and purpose of this literature review is to highlight the main relevant literature on biophilic design, energy performance, and thermal comfort requirements in apartment buildings.

The concept of biophilic design has recently gained significant importance as the reconnection of the built environment with nature. The literature addresses both the sustainability aspects of a building and the well-being of the users. The name of this concept originates from the term biophilia which is *“the inherent human inclination to affiliate with nature”* (Kellert & Wilson, 1993)

This suggests that sustainable design strategies include the incorporation of elements that reconnect people with the natural environment. Consequently, integrating nature into architectural spaces can enhance health, performance, and overall satisfaction. This highlights the importance of balancing energy efficiency with occupant well-being.

Considering local context, being an urbanised country, the incorporation of biophilic principles into apartments is much more required than in other countries since this could be the only effective way to introduce nature within the built environment. This literature review will explore how a biophilic design approach can mitigate local issues raised due to environmental pressures and high energy consumptions, while offering a more sustainable and human-centred approach.

This chapter reviews existing case studies and frameworks that focus on the main principles of biophilic design and their impact on energy performance and well-being.

2.2 Biophilic Design: Principles and Applications

2.2.1 Principles of Biophilic Design

The main principles of biophilic design revolve around the connection between humans and nature through the integration of natural elements into the built environment. This emphasises the human need to connect with natural systems and processes. This design approach is based on the promotion of well-being and sustainability using natural patterns, materials and geometries that create a space (Kellert, Heerwagen, & Mador, 2008).

The three main principles of Biophilic design include:

Reconnect with Nature

This principle refers to the removal of barriers between humans and the natural surroundings. Having a space that supports both the emotional attachment and a sense of place. This is the natural human need that is associated with natural surroundings to sustain mental and physical well-being. According to (Kellert S. R., Nature by design: The practice of biophilic design., 2018), environments that support natural connections promote sensory engagement, emotional stability and overall good health.

Taking into consideration the urbanised setting particularly dense cities, this reconnection will offer stress-reducing experiences and serves as a balance for the disconnection from nature created by the artificial and modern spaces (Zafirah, Ramli, & Ismail, 2021).

Integration of Local Ecosystems

This principle highlights the harmony between the built environment and local ecological systems. This will be achieved by implementing elements such as vegetation or water features that will improve the space’s sensory qualities, sustainability and align with the climate conditions. Biophilic design is not just about adding natural elements but also about the integration with the local ecosystem. Urban green spaces that support biodiversity are spaces which provide natural cooling, restore ecological balance, and enhance urban resilience. Dynamic systems, such as kinetic façades and adaptations to local environmental conditions like sunlight and wind, also contribute to this improvement. These ecologically sensitive strategies will be integrated with advanced technological systems to create more responsive and sustainable environments (Kellert S. R., Nature by design: The practice of biophilic design., 2018).

Evidence-based Strategies

The idea behind this principle is to include data from diverse disciplines including health, psychology and architecture that will prove the impact on human well-being and energy performance. These are used to assess and optimise the impact of these measures. Therefore, a qualitative and quantitative measures of the physiological and psychological benefits of natural light, fresh air and greenery would be available. With the use of this data collection, such studies will clearly demonstrate the contribution in terms of energy savings, productivity and health. This study can be simulated with the use of software including post-occupancy evaluations to showcase such benefits (Kellert S. R., Nature by design: The practice of biophilic design., 2018).

2.2.2 Applications of Biophilic Design

The applications of biophilic design ranges from the interior to the urban landscapes. These include:

Natural light and ventilation

Maximising daylight and airflow within a building is a key aspect of biophilic design. This can be achieved using openable windows, skylights, and thoughtful building orientation. These strategies contribute to the building's energy efficiency and also to the quality of light, enhancing human comfort. By following this approach, thermal comfort is improved while reducing the reliance on artificial systems. Therefore, it is important to optimise the placement of apertures, including skylights, to promote both cross-ventilation and natural lighting, which in turn improves well-being and impacts the building’s overall energy performance. This can be further supported by adaptive systems that regulate daylight and airflow in response to seasonal weather variations.

Dynamic and diffuse lighting

This can be achieved by using reflective surfaces and shading devices that reduce glare, while maintaining a visually pleasing lighting and keeping it energy efficient. Dynamic lighting systems simulate the natural light cycles that help maintain a good human circadian rhythm. These are generally used in spaces with limited access to natural light, like in urban high-rise buildings.

Organic materials and patterns

Using natural materials such as wood, stone and water that will improve the aesthetics and also provide a tangible and visual connection to nature. Patterns that are inspired by natural forms including fractals and biomimicry will enhance emotional engagement and well-being. This method aligns with the harmony between the user and the built environment.

Healing and restorative environments

This includes features such as greenery, water elements and open spaces that improve mental relaxation and the overall quality of life. This is evident in healthcare facilities and residential buildings which include such elements to accelerate the healing, lower anxiety and fosters a sense of calmness.

Energy efficiency through natural processes

Passive design strategies such as ventilation, thermal mass, vegetation for cooling and other natural measures that reduce the use of mechanical systems will make the building more energy efficient. This provides an opportunity for insultation therefore resulting in reducing the urban heat island effects (Ryan, Browning, Clancy, Andrews, & Kallianpurkar, 2015).

2.3 Energy Performance in Buildings and Local Residential Buildings

2.3.1 Energy Performance in Buildings

Buildings are one of the significant contributors to energy use globally, accounting for approximately 40% of energy consumption annually and about 30% of global greenhouse gas emissions. The energy consumption in buildings consists of heating, cooling, lighting and Ventilation and Air Conditioning (HVAC) systems thus making the building sector the primary focus for energy efficient measures.

This has led to climate change that together with the impacts including CO2 emissions, has enhanced energy performance in building with innovative technologies and policy interventions. This means big challenges to achieve energy performance due to technical, behavioural and policy-related factors. Thus, to achieve energy performance in buildings, strategies are required beyond any technical advancements. Energy simulation tools are used to predict or optimise energy use during the design phase or retrofitting. However, these are generally limited by inaccurate assumptions and insufficient data on that building envelope apart from the lack of consideration in terms of occupants behaviour. For example, variations in thermostat settings, natural ventilation measures and occupancy patterns affect the energy consumption of a building (International Organization Standardization, 2022).

This research highlights the requirement of integrating realistic occupant behaviour models to bridge the gap between the predicted and the actual energy usage. The incorporation of both passive and active measures is required to achieve energy efficiency. Passive strategies include insulation, natural ventilation that leads to reduce the use of mechanical use therefore energy demand. Whilst passive strategies reduce the use of mechanical equipment, active strategies include renewable energy technologies such as photovoltaic systems, wind turbines and others. Adding on this is the Life Cycle Assessments (LCA) that shows the importance of embodied energy in materials, especially as operational energy demands decrease in Nearly Zero-Energy Buildings (NZEB). Therefore, to achieve sustainability, one needs to balance operational and embodied energy impact (Mirabella, et al., 2018).

Energy performance in general is directly related to the policy and regulatory frameworks. For instance, European policies such as the Energy Performance of Buildings Directive that promote retrofitting existing buildings to decarbonize the building stock by 2050. Such policies are in place to reduce operational energy demand while on the other hand addressing the environmental impacts of construction materials and their processes.

A holistic approach including simulation tools, behavioural modelling and integrated design strategies are required to improve the energy performance of a building. The operational and embodied energy demands should be addressed within the polices and technologies. The building sector plays a big role in the global efforts in terms of climate change and reduce resource reduction (European Committee for Standardization, 2017).

2.3.2 Energy Performance in Local Residential Buildings

Overview of energy performance developments in Malta

The local climate has historically contributed to low energy demands in residential buildings particularly for heating. On the other hand, overheating during the summer period has shaped the traditional building designs that incorporate high thermal mass and external shading device, stack ventilation and high ceilings. According to the Koppen climate classification, the climate in Malta is hot and dry in Summer and mild and wet in Winter.

The Energy Performance of Buildings Directive (EPBD) 2002/91/EC acted as a turning point that targeted energy efficiency and set minimum performance standards for both new and existing buildings locally. This directive was updated on Directive 2010/31/EU and subsequently amended from Directive (EU) 2018/844. Malta's implementation aligns with the mild climate and unique building stock that includes a mix of vernacular and modern construction. This directive addresses Malta's specific challenges, including summer overheating and low energy requirements in winter that promote energy efficiency.

The main points of the EPBD for Malta include:

1. Minimum Energy Performance Requirements

This includes the energy performance levels required in various building typologies to ensure tailored standards for residential and non-residential buildings that were updated through cost-optimal studies. Including, the building envelope, systems and renewable energy integration.

2. Nearly Zero Energy Buildings (NZEB)

The NZEB targets for new buildings are 75 kWh/m² per year for residential buildings and 220 kWh/m² per year for non-residential buildings.

3. Renovation and Existing Buildings

The energy performance standards apply for minor and major renovations. The Long-Term Renovation strategy was issued in 2020 and targets to reach a 3.3% annual renovation rate by 2030. This aims to reduce energy use by 2050.

4. Energy Performance Certificate (EPC)

This is a mandatory certification for newly built, for sale and rental properties since 2009. This certification ensures transparency and also encourages energy efficiency choice for buyers and tenants.

5. Renewable Energy Integration

This is based on solar renewable energy systems and includes incentives as well as the feed-in tariffs that support the implementation of photovoltaics and other renewable energy sources.

Amended EPBD

This directive was amended in 2023 and included significant updates to Malta's energy performance framework. These changes align with Directive (EU) 2018/844 that updates the previous EU directives on energy performance and efficiency. The regulations include enforcement, clarity and implementation of energy performance measures that focus on residential buildings being built or renovated from 1st July 2024 onwards.

The new minimum energy performance requirements include:

1. Enhanced Energy Standards

This includes the reduction in the energy consumption, waste and contribution to long-term costs savings and environmental benefits.

2. Building Envelope Improvements

This includes measures in relation to insulation standards, glazing requirements and criteria for HVAC systems. These will reduce heat transfer and improve energy efficiency.

3. Integration of Solar Energy

This includes the cost-effectiveness of solar renewable energy in terms of incorporating into new residential buildings. This means analysing the solar potential in every newly built dwelling in terms of orientation and cost-effectiveness. On the other hand, buildings without solar potential require a higher overall energy performance, to ensure consistent progress toward the energy efficiency goals.

4. Technical Building System Enhancements

This includes new requirements in terms of technical systems such as boilers, heat pumps and lighting systems. These include higher efficiency and functionality standards that will reduce consumption while enhancing the building energy efficiency.

Broader Objectives and Impacts

The updated regulations are designed to achieve the following objectives:

Promote Energy Efficiency: The amendments establish ambitious performance benchmarks aimed at reducing energy consumption and operational costs for building owners and occupants.

Support Environmental Sustainability: By encouraging the integration of renewable energy and implementing stricter building standards, these regulations contribute to lowering carbon emissions and align with climate change mitigation strategies.

Improve Indoor Environmental Quality: Enhanced building performance directly benefits the comfort and well-being of occupants, addressing concerns related to both thermal and energy efficiency.

Implementation and Compliance

The regulatory framework is detailed in Technical Document F (2023), which specifies:

Part 1: Requirements for new residential buildings and renovations.
Part 2: Requirements for non-residential buildings and renovations.
Part 3: Requirements for technical building systems in all building types.

By applying energy performance considerations to a diverse range of building typologies, the amendments ensure comprehensive progress in energy efficiency, with a particular emphasis on advancing standards in the residential sector.

Current Energy Performance Requirements

The minimum energy performance requirements, revised in 2016, were based on cost-optimal studies conducted across a range of building typologies. These studies evaluated energy performance levels, focusing on the impact of exposure, building systems, and renewable energy integration. For residential buildings, specific improvements included:

- Enhanced thermal transmittance requirements for walls, roofs, and glazing.
- Measures to mitigate overheating through maximum allowable glazing areas and dynamic simulations that consider shading.

Nearly Zero Energy Buildings (NZEB)

The progression toward NZEB standards is a priority in Malta. The cost-optimal studies revealed that renewable energy systems, such as solar panels, are cost-effective for all building types. For residential buildings, NZEB levels target a primary energy balance of 75 kWh/m² annually, achievable through energy-efficient designs and the integration of renewable energy sources. While these standards are mandatory for new buildings as of 2020, existing buildings undergoing significant renovations are encouraged but not required to meet these standards.

Renovation and Existing Building Stock

Most of Malta's residential buildings are owner-occupied single-family homes, which often lack energy-efficient designs. Renovation efforts focus on retrofitting building envelopes, replacing outdated systems, and integrating renewable energy. Financial incentives and feed-in tariffs have been introduced to encourage the adoption of solar renewables, heat pump systems, and other efficiency measures. Between 2016 and 2020, €55 million was invested in such upgrades, demonstrating substantial energy savings and increased alignment with NZEB goals.

Challenges and Future Directions

Despite progress, challenges persist in mobilising large-scale renovations due to limited financial benefits associated with Malta's mild climate and low energy costs. A Long-Term Renovation Strategy (LTRS) was introduced in 2020, targeting a 3.3% annual renovation rate by 2030. The strategy includes financial support, stronger regulations, and exemplary government-led projects to stimulate investment. These efforts aim to halve energy use across residential and non-residential sectors by 2050.

Current situation in conventional apartments

Considering apartment buildings, energy performance is inefficient since most of the apartments locally rely on electricity in terms of heating, cooling, lighting and ventilation. As a common design approach, the benefits of natural elements such as natural light and natural ventilation are always ignored. Considering the local climate, where the temperature regulation is very important, natural insulation and ventilation strategies are always lacking therefore leading to high energy consumption. Apart from this, the use of building materials also creates inefficiencies as these will not necessarily have the required thermal insulation. This shows that designing without considering the integration of natural elements such as daylight and natural ventilation, the apartment will lack from energy efficiency. Apart from energy efficiency, this will contribute to higher energy bills, environmental issues and also discomfort (Degiorgio & Farrugia, 2020).

2.4 Biophilic Design in relation to Energy Performance

Although biophilic design focuses on the human connection to nature with architectural elements, these elements will also improve the energy performance of the same building. Natural elements, such as daylight, air and vegetation directly contribution to reducing reliance on energy sources thereby affecting the energy performance of the building.

2.4.1 Energy performance benefits when implementing biophilic design measures

Natural light

Optimisation of the window to wall ratios and introducing skylights where possible will reduce the dependence on artificial lighting. Therefore, the Window to Wall Ratio (WWR) both in a newly design building and in retrofitting, will affect the dependence on artificial lighting substantially. This means the increase in daylight factor will affect the energy efficiency of the building. Apart from this, it is very important to have an equal disarticulation of natural light throughout the spaces.

Natural ventilation

Implementing natural ventilation in a building is not only a biophilic design aspect that effects humans however it also improves the indoor air quality (IAQ) and therefore reduce the need of switching on the air conditioners or any other mechanical ventilation systems. Cross ventilation is the most common type of natural ventilation that effects the thermal comfort in terms of cooling therefore making the building more energy efficient (ASHRAE. , 2019).

Vegetation

Vegetation is one off the most biophilic design measures that effect the thermal comfort. Such vegetation can be used to create thermal mass therefore improves the insulation. It reduces the heat transfer, keeping the building cool in summer and warm in winter. This can be achieved by implementing green roofs, green walls and also vegetation as shading.

Natural materials

The use of natural materials such as reflective or colours will affect the daylight inside a building while also contributing to energy efficiency (Ryan, Browning, Clancy, Andrews, & Kallianpurkar, 2015).

2.4.2 EN 15252-1:2017 Standard

The European standard EN 15252-1:2017 - "Energy performance of buildings – Impact of Building Automation, Controls, and Building Management". This standard includes a framework for the assessing of building automation and control systems in terms of energy efficiency of the building.

This was replaced by EN ISO 52120-1:2022 that include an updated framework that assess the contribution of building automation, controls (BACS) and technical building management (TBM) systems for energy performance.

The main aspects of this standard include:

The type of functions

This means a detailed classification of what is considered as control, automation and technical management function that will affect the building energy performance. This will help the users to define which strategies are applicable for the systems being implemented.

Assessment types

This standard includes both detailed and simplified assessments to find the impact of BACS and TBM implementations on the building's energy performance. This is set in order to have initial estimations to assess the benefits and the actual analysis according to the particular building type.

BACSa period efficiency classes, these include:

Class A: High-energy performance BACS and TBM functions.
Class B: Advanced BACS with specific TBM functions.
Class C: Standard BACS
Class D: Non-energy efficient BACS, this include systems that must be retrofitted or eliminated completely in new projects.

The main benefits of BACS and TBM in terms of energy performance include the optimisation of energy use. This includes the demand driven control that adjust system operations according to the occupancy of the building, weather conditions and also real-time indoor environmental quality. Another aspect is the dynamic setpoints that can be set to HVAC and lighting according to real-time data and therefore reduce energy consumptions.

Another important factor is the automated scheduling that ensures such systems operate according to the use therefore reducing the overall energy demand. Another important benefit is the reduction in energy waste. This will be achieved through load management and peak shaving that reduce peak energy demand by improving the energy consumption patterns. Fault detection and diagnostics is another aspect that identifies the leak of efficiency and faults of systems to operate at their maximum efficiency. Zoning and room-level control will exclude overcooling or overheating of different spaces with different uses or unoccupied.

The integration of renewable energy is another factor in terms of BACS and TBM that effect the energy performance. This includes the smart grid interaction, energy storage management and automated energy distribution. This means that the renewable sources will be use according to availability, therefore using the renewable energy before other conventional sources. Also optimising the use of on-site renewable energy in terms of storage management.

2.5 Environmental Modelling

2.5.1 Building Energy Modelling

Building energy modelling is a virtual tool that predicts the building energy consumption and performance based on energy balances at control points. This is beneficial for this study since it can provide a detailed understanding of the building performance as a result of varying design conditions. This can eventually lead to comparing the proposed model with the existing model in terms of energy efficiency and thermal comfort.

The main key inputs for energy building modelling include location, weather data, building geometry, envelope components, building use patterns. In terms of weather data, this is preferably collected from the local MET office or similar. This will generally be in the form of hourly data for the following:

- Air temperature

- Dew point temperature
- Relative Humidity
- Atmospheric pressure
- Global horizontal solar radiation
- Diffuse Horizontal solar radiation
- Direct normal radiation
- Wind Speed
- Wind Direction
- Cloud cover

Building geometry will be explained in the next sub-section. This will mainly include the thermal zoning and scale layouts that are very important to have accurate simulation results. Apart from the geometry, every building element including walls, roofs and glazing will be specified in terms of the properties of materials used. Another important factor are the daily patterns and schedules of the building use, in terms of occupancy, which subsequently effects the lighting and HVAC.

From these conditions, one can generate outputs in terms of peak heating and cooling loads, energy consumption for every mechanical and electrical system, and the energy performance of the building (Garg, Mathur, & Bhandari, 2020).

The geometry is based on the thermal zoning, aspect ratio, adjacent conditions, floor multipliers and the model itself. Thermal zoning includes splitting the building layout into different zones according to the heat gains and losses.

Thermal Zoning

Thermal zoning is used to group space with the same thermal conditions, occupancy schedule and HVAC requirements. Thermal zoning is essential to reduce simulation complexity and run-time while keeping the accuracy of the model. This will also help in making the HVAC system design more efficient. One can easily notice areas of high energy demand therefore this will affect optimisation of the system accordingly.

Aspect Ratio

Aspect ratio is the ration of the building in terms of length to width. This will affect the exposure of the building in terms of ventilation and daylight. The higher the aspect ratio (elongated building) the more exterior surface area, meaning higher heat gains and losses. This means that low aspect ratio leads to less energy demands due to less exterior surfaces.

Floor multiplier and zone multiplier

This is used to decrease simulation time when having a block of same layouts on different floors. Therefore, instead of modelling each floor, using the floor multiplier to create identical floors as a single unit.

Surface adjacency settings

This is used to define the interaction of building surfaces with the adjacent environment. This can be used both vertical and horizontal. Therefore, one needs to define the ground underneath a floor accordingly. For example, “adiabatic” means that there is no heat exchange. It is very important to use real ground temperature for accurate simulation (Garg, Mathur, & Bhandari, 2020).

2.5.2 Ventilation

Natural Ventilation

For modelling of natural ventilation, one can use two methods, these include the scheduled ventilation and calculated ventilation. Scheduled ventilation is pre-defined maximum air change rate per zone with a fixed schedule. On the other hand, calculated ventilation is generally based on window openings, cracks, buoyancy and wind-driven pressure differences. This means that one can define the best schedule for opening windows, the impact of the sizes and the temperature controlled automatic windows.

One can also note the impact of wind speed on ventilation, this means that by adjusting the speed, one can see the improvements in ventilation rates. Windows can be modelled as open based on temperature control mode. This means that one can model windows to open when the indoor temperature is higher than outdoor plus setpoint. Whereas the scheduled ventilation can be altered to different hours of the day to note the difference.

2.5.3 Daylight

Daylight is one of the most important aspects in energy modelling, as this can affect the energy consumption (due to direct solar radiation), human comfort and lighting efficiency. One can analyse daylight penetration, illuminance levels and also energy saving aspects with daylight reactive settings. Daylight availability and illuminance metrics

Useful daylight and illuminance (UDI) are the percentage of time that the daylight level is between 100 and 2000 lux. This is the average lux level required for sufficient illumination and control of glare. Therefore, when modelling such area with a percentage of window to wall ratio (WWR) one can identify the percentage of floor area that is in line with the UDI target. On the other hand, there is the daylight factor (DF). This is the proportion of external light that effects the indoor spaces. For example, 2% is suitable for general office tasks. One has to keep in mind that the DF effects the cooling loads required.

WWR will affect energy performance, since as you increase WWR, cooling loads will increase accordingly. For a typical double-glazed window with a WWR between 10 to 90%, this will mean lighting reduction of up to 42% but increase cooling loads to more than 50%. This can be mitigated by shading control. Such shading control includes overhands and fins. A typical 1m overhand with side fins can improve the UDI by 20%. This means reducing glare while also increase the energy performance. (Garg, Mathur, & Bhandari, 2020).

Daylight sensors and lighting controls are another factor for in the daylight simulation. This is generally set according to the real-time daylight availability. It is very important that such controls are in place to maximize the efficiency. This can be achieved by setting the linear dimming or stepped control. Linear dimming reduces artificial light in parallel with daylight availability. On the other hand, stepped control will adjust the levels in fixed steps according to the sensor readings preset.

To achieve maximum daylight while having the optimum energy savings, one needs to consider the window placement, glass type and daylight control and sensors positions. Such conditions can be achieved with the following parameters. For window positioning, south-facing for maximum daylight, glass type double-glazing with low-E and placing sensors in 2 different extreme positions, to have a uniform control (Garg, Mathur, & Bhandari, 2020).

2.5.4 Vegetation on Walls and Green Roofs

Vegetation on walls and green roofs can be simulated to see the effect in terms of energy consumption being heating and cooling. As a normal practice, vegetation will act as an insulation therefore enhance thermal comfort and improve energy performance of a building. The simplest way to model such vegetation is by considering it as an insulation being as a green roof or green wall.

This can be created by including new construction configurations for both walls and roofs. Such vegetation modelling will be assigned by using custom wall and roof configurations. In terms of internal vegetation such as indoor trees and other small plants, these can be modelled as part of internal gains or moisture sources. This must be user defined; therefore, properties of such vegetation should be gathered before implementing such variables. The vegetation will affect the surface heat transfer, indoor humidity levels and microclimate around the building envelope (Garg, Mathur, & Bhandari, 2020).

2.6 Thermal Comfort Standards for Residential Buildings

Thermal comfort standards in residential buildings include several different established standards that define the best indoor environmental conditions. These include ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy, ISO 7730: Ergonomics of the Thermal Environment, EN 15251: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings, CIBSE Guide A: Environmental Design.

2.6.1 ANSI / ASHRAE standard 55

This standard includes indoor thermal environmental factors and human factors that produce the thermal conditions acceptable for different scenarios. It includes the main environmental factors: temperature, thermal radiation, humidity, air speed, activity and clothing as insulation. This standard also provides different criteria for both mechanical and natural conditioned spaces. This guideline if used for design, commissioning and testing of buildings with HVAC and existing thermal environments (SimScale. (n.d.). ASHRAE 55 and ISO 7730, n.d.).

The main thermal comfort models include the Predicted Mean Vote (PMV) and the Adaptive Model. PMV was developed by P.O Fanger, this model is the average thermal sensation which derived from a large group's vote in a particular environment. This includes factors such as metabolic rate and other environmental factors mentioned above. On the other hand, the adaptive model considers the occupants in naturally ventilated space that can adapt for a range of temperatures. This range of temperatures considers the difference in the actual temperature between indoor and outdoor environments (ANSI/ASHRAE Standard 55-2020, 2020).

This standard also covers the comfort zone methods, local thermal discomfort, elevated air speed and evaluation in existing buildings. Comfort zone methods are based on the psychrometric chart in terms of temperature and humidity according to the indoor activity. Also, the use of the PMV model to confirm the conditions in terms of environmental and personal. The local thermal discomfort is related to the radiant temperature, draft, difference in air temperature and floor surface temperatures (International Organization for Standardization, 2005).

The elevated air speed is the increase in air movement that is created by the increase in heat loss from the body that will determine the acceptable air speeds in relation to temperature. One can use this standard to evaluate the conditions of existing buildings in terms of thermal comfort (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE Standard 55-2010). , 2010).

2.6.2 ISO 7730: Ergonomics of the Thermal Environment

This standard includes analytical determination and interpretation of thermal comfort by calculating the PMV and Predicted Percentage of Dissatisfied (PPD) indicators and local thermal comfort criteria. This means the general thermal feeling and degree of discomfort of a person exposed to thermal environments.

The main purpose of this standard is to forecast the thermal feeling and level of discomfort by the user in adequate thermal environments. The PPD is a percentage estimate of dissatisfied individuals by means of a quantitative measure of thermal discomfort. Similar to ANSI/ASHRAE Standard 55, this standard considers local thermal comfort criteria to limit discomfort from these factors. This is utilised for evaluating thermal environments and specifies the criteria for acceptable thermal conditions across various contexts. When compared to other standards, this is very similar to ASHRAE. These standards serve as the foundation for designing or evaluating environments focused on occupant comfort and well-being (International Organization for Standardization. , 2023).

2.6.3 EN 15251: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings

This standard was in place to define the criteria required for indoor environmental quality (IEQ) in terms of building design and energy performance of newly designed or existing. This includes indoor air quality, thermal comfort, lighting, and acoustics. This standard provides a framework for creating comfortable and energy-efficient indoor spaces. This standard establishes a comprehensive framework for the design of systems and the calculation of energy performance across multiple sectors, including residential, commercial, educational, and healthcare applications (European Committee for Standardization EN15251, 2007).

In terms of air quality, this standard includes ventilation requirements according to the perceived air quality including occupant density and building use. This results to the effect and impact of air cleaning systems. In terms of thermal comfort, this standard includes both mechanical and natural ventilation system, that considers adaptive models. This also include the local thermal discomfort factor as the other standards. Finally in terms of lighting and acoustics, this shows the illuminance levels and availability of natural light and also the acoustic in terms of background noise levels in dB and reverberation times (Seppänen & Kurnitski, 009).

This standard is categorised in 4 different levels of indoor environments, these include:
Category I – high level – sensitive
Category II – normal level
Category III – moderate level
Category IV – low level (period of the year)

2.6.4 CIBSE (Chartered Institution of Building Services Engineers) Guide A: Environmental Design

This guide is a useful tool for environmental design in the built environment, which emphasises on energy efficiency. This is applicable for any type of building, but it is very well known for residential buildings in terms of thermal comfort that goes hand in hand with the energy performance (Chartered Institution of Building Services Engineers Guide A, 2016).

Thermal Comfort Criteria for Residential buildings

Recommended internal temperature ranges are found in this guide for different building typologies and room functions. In terms of residential buildings, the main focuses are the number of habitants and usage patterns. It is important to note that this guide include the following parameters that effect thermal comfort.

- Air temperature
- Mean radian temperature
- Air movement
- Humidity
- Clothing insulation
- Metabolic rate

Similar to other standards, this guide references PMV and PPD concerning comfort levels used in designing HVAC systems for commercial and residential environments. An example for temperature is the recommended summer internal temperature of 23 to 25°C for living areas and slightly cooler for bedrooms. On the other hand, recommended winter conditions internal temperature is 21°C. These examples are based on adaptive comfort principles with natural ventilation. This means that habitants will adjust their clothing and ventilation according to the change in weather.

This document highlights the basic assessment criteria for naturally ventilated residential building to eliminate the risk of overheating. This includes having internal temperature not more than 28°C for more than 1% occupied hours per year and the use of adaptive comfort models when indoor temperature is simultaneous changing with the average outdoor temperatures. This method is commonly used for mediterranean climates and where passive design strategies are required in terms of thermal comfort.

In terms of natural ventilation, this is considered as the main source of ventilation for residential dwellings. According to this guide, the main recommendations include cross-ventilation wherever possible and having an air speed in the range of 0.1 and 0.8m/s for thermal comfort without the effect of currents. These are the basic values for openable windows and ventilation paths.

Finally, energy efficiency hand in hand with comfort is of utmost importance for this guide. This guide specifies the importance of energy performance goals. These include the use of passive design measures, simulation modelling for thermal comfort with natural resources. And climate-based design such as orientation, shading and materiality accordingly to the local conditions. One can conclude that this guide aims to combine the occupant needs with the climate and sustainability goals.

2.7 Biophilic Design Research for Residential Buildings

In this section, the existing unofficial guidelines will be portrayed as found during the research and to set a framework for incorporating such elements in my study on existing scenarios in Malta. In this section it will be discussed how biophilic design guidelines will affect sustainability, energy performance and well-being of inhabitants.

Biophilic design is now considered as a vital strategy in residential buildings. This is due to the fact that such design will enhance the quality of life of the inhabitants since these will be directly connected with nature. It will also be improving their well-being, health and the building's energy performance. According to the review of such research, it was very clear that biophilic design is the integration of nature into the build environment both with physical and experienced elements. Due to the increase of urbanisation and other health challenges, the home is now considered as a multifunctional space that required the need for connection with nature.

According to "The 14 Patterns of Biophilic Design" (Ryan, Browning, Clancy, Andrews, & Kallianpurkar, 2015), it was defined that biophilic design for residential buildings is divided into three main categories. These include nature in the space, natural analogues and nature of the space. These categories are then divided into different patterns. These patterns are listed in the table below with examples for each pattern for both newly designed residential buildings and retrofitted. One can immediately notice that in some case such interventions can be applied in both newly built and retrofitted buildings.

Table 1 - The 14 Patterns of Biophilic Design " (Ryan, Browning, Clancy, Andrews, & Kallianpurkar, 2015)

Category	Pattern	Architecture Design (New)	Retrofitted
Nature in the Space	Visual Connection with Nature	Incorporate large operable apertures and balconies that are oriented towards natural vistas such as gardens, the sea, or expansive green areas.	Modifications may include or expand apertures, indoor vegetation near existing windows, or replace opaque panels with transparent glazing.
	Non-Visual Connection with Nature	Utilize natural soundscapes such as water features and ventilation to create air circulation and introduce natural scents.	Incorporate indoor water features, natural ventilation, and aromatic plants.
	Thermal and Airflow Variability	Cross-ventilation layout, operable shading devices, and flexible thermal zones.	Openable apertures or solar chimney systems in case of penthouse level apartments.
	Presence of Water	Integrate fountains or water walls in courtyards or indoor atriums.	Add small fountains or aquariums in living areas.
	Dynamic and Diffuse Light	Use skylights, clear glass apertures, and light shelves to allow daylight variability.	Install daylight tubes and use sheer curtains to diffuse light.

	Connection with Natural Systems	Integrate seasonal gardens and ensure rainwater is visible.	Use planters with seasonal plants and change finishes to natural material or colours.
	Non-Rhythmic Sensory Stimuli	Design for exposure to natural motion such as trees through skylights and use wind-responsive elements like kinetic screens.	Install blinds that move with air, place plants near airflow, and use adjustable lighting.
Natural Analogues	Material Connection with Nature	Use timber flooring, stone surfaces, and exposed natural materials.	Replace plastic or metal finishes with wood laminates or natural finish wall panels.
	Biomorphic Forms and Patterns	Architectural elements mimic organic shapes like arches and spiral stairs.	Apply feature wall with or furniture with natural patterns.
	Complexity and Order	Design interiors with layered spatial and visual elements.	Arrange wall art or shelves in natural sequences.
Nature of the Space	Refuge	Include reading corners and window seating surrounded by plants.	Use furniture or curtains to create quiet corners or semi-enclosed green spaces indoors.
	Prospect	Enhance living rooms or balconies with extended outward views.	Use transparent railing such as glass and open layouts.
	Mystery	Incorporate curved corridors or framed views through layers.	Utilise hanging plants or screens to deliberately obscure full views.
	Risk	Use of glass floors, bridges, or exposed balconies.	Utilise dramatic overlooks or lightwells to create a sense of visual depth.

From these interventions, the research will be looking into the ones that relate to energy performance rather than biophilic design on its own. These interventions include those related to natural light, natural ventilation and thermal comfort. From this framework, one can also define the scale of interventions from as simple as a change in materiality to as complicated as a structural intervention. Therefore, one needs to evaluate this when considering biophilic design for retrofitting existing apartments (Nitu, Gocer, Wijesooriya, Vijapur, & Candido, 2022).

According to this framework, the main key guidelines of biophilic design in relation to energy performance include:

- Daylight optimisation and natural ventilation - Balancing natural light, natural ventilation and heat gains from openings
- Indoor and outdoor vegetation - green roofs and living walls to enhance thermal comfort as a mean of insulation
- The use of natural materials and textures can also influence thermal comfort
- Other factors that will not affect energy performance, but the human well-being include:
    - The importance of spaces for refuge and prospect spaces – balance between enclosed areas and openness trough views
      Spaces that enhance multi-sensory experiences such as sound, smell and touch, so called as the use of biomorphic forms.

This shows that biophilic design is related to climate conditions and the human lifestyle. It was also mentioned that such applications will improve mental, clarity, sleep quality, mood and cognitive function in the residents. (Nitu, Gocer, Wijesooriya, Vijapur, & Candido, 2022)

According to (Beiruti, Al-Kodmany, & Kassem, 2023), as a minimum requirement to residential buildings in terms of biophilic design and based on contextual and post-pandemic adaptation, a “home” must include these three main pillars:

- Physical and psychological restoration
- Flexible work and resting zones
- Connection to natural rhythms and elements

This study shows biophilic indicators that are based on garden design, privacy-sensitive outdoor space and context awareness in terms of materiality. It also shows that cultural sensitivity should be considered when implementing biophilic applications.

In terms of guidelines, one must keep in mind that biophilic applications must be in line with scalability and affordability in terms of retrofitting and housing blocks. It is very important that such applications are place-based design therefore although a guideline can be established, as a design process, this is very site/ building specific. Therefore, every application must be considered in that scenario. This will also mean that in newly designed buildings, the integration of biophilia should be considered from the beginning to maximise the opportunities in terms of energy performance and effectiveness for the user experience.

2.8 Challenges and Opportunities in Implementing Biophilic Design

2.8.1 Challenges

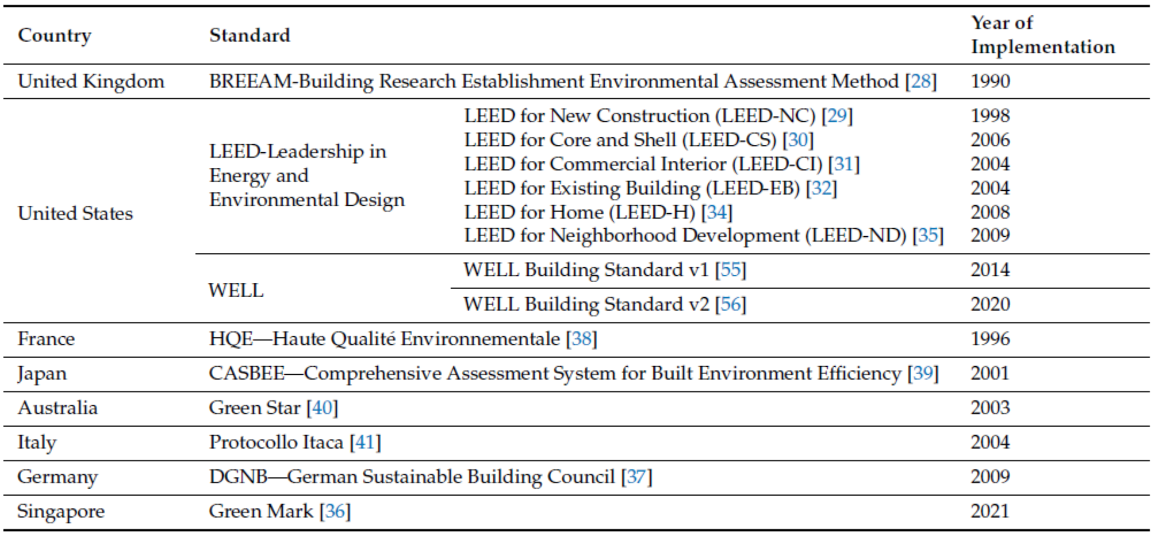
When considering the challenges of implementing Biophilic Design in residential buildings, the main common factors are based on costs, retrofitting implementation and maintenance.

Knowledge and Regulations

According to (Aranda-Castilla, Neila-González, & Pérez, 2023), it is very evident that lack of comprehensive frameworks or policies in place is another challenge that hinders the implementation of biophilic design practices. This will obviously mean lack of supportive regulations that are the basis of every standard in this industry. Although there are many EU regulations that cover energy efficiency and renewable energy, one cannot find any regulations related to nature-based design guidelines.

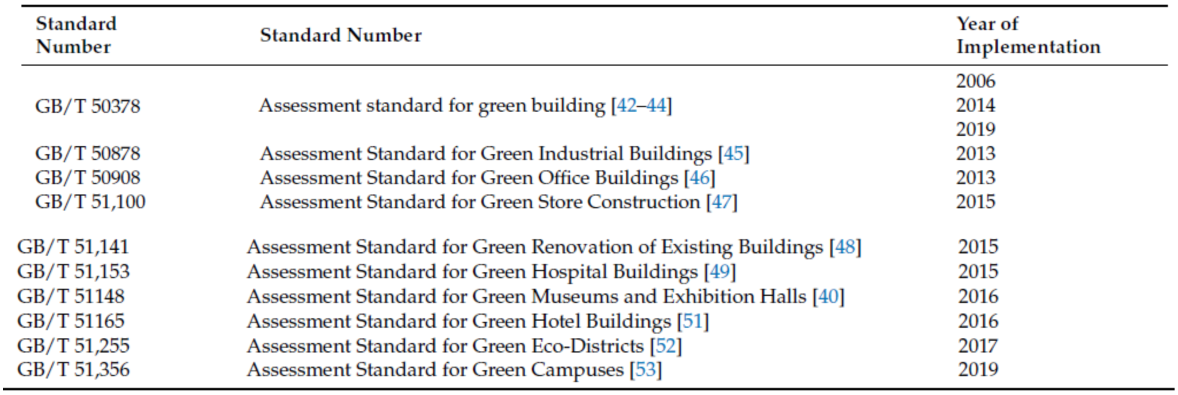
In the table below one can find existing standards that include biophilic architecture but not related to residential buildings.

Table 2 - Composition of Global Evaluation Standards for Biophilic Architecture (Castellanos & Roa-Fuentes, 2024)



Country	Standard		Year of Implementation
United Kingdom	BREEAM-Building Research Establishment Environmental Assessment Method [28]		1990
United States	LEED-Leadership in Energy and Environmental Design	LEED for New Construction (LEED-NC) [29]	1998
		LEED for Core and Shell (LEED-CS) [30]	2006
		LEED for Commercial Interior (LEED-CI) [31]	2004
		LEED for Existing Building (LEED-EB) [32]	2004
		LEED for Home (LEED-H) [34]	2008
		LEED for Neighborhood Development (LEED-ND) [35]	2009
	WELL	WELL Building Standard v1 [55]	2014
		WELL Building Standard v2 [56]	2020
France	HQE—Haute Qualité Environnementale [38]		1996
Japan	CASBEE—Comprehensive Assessment System for Built Environment Efficiency [39]		2001
Australia	Green Star [40]		2003
Italy	Protocollo Itaca [41]		2004
Germany	DGNB—German Sustainable Building Council [37]		2009
Singapore	Green Mark [36]		2021

Table 3 - Composition of China Evaluation Standards for Biophilic Architecture (Castellanos & Roa-Fuentes, 2024)



Standard Number	Standard Number	Year of Implementation
GB/T 50378	Assessment standard for green building [42–44]	2006 2014 2019
GB/T 50878	Assessment Standard for Green Industrial Buildings [45]	2013
GB/T 50908	Assessment Standard for Green Office Buildings [46]	2013
GB/T 51,100	Assessment Standard for Green Store Construction [47]	2015
GB/T 51,141	Assessment Standard for Green Renovation of Existing Buildings [48]	2015
GB/T 51,153	Assessment Standard for Green Hospital Buildings [49]	2015
GB/T 51148	Assessment Standard for Green Museums and Exhibition Halls [40]	2016
GB/T 51165	Assessment Standard for Green Hotel Buildings [51]	2016
GB/T 51,255	Assessment Standard for Green Eco-Districts [52]	2017
GB/T 51,356	Assessment Standard for Green Campuses [53]	2019

Apart from this, it was also mentioned that there is a lack of knowledge and education on biophilic principles in all professional sectors in the construction industry. This will obviously result in inconsistencies and unprofessional applications (Aranda-Castilla, Neila-González, & Pérez, 2023). A lack of understanding of biophilic design benefits and methods among architects, planners, contractors, and developers is a big challenge and is the first thing that needs to be addressed to start implementing such design. As one can note, this knowledge gap will imply on the design decisions and budgeting. From the figure 1 below, one can notice the comparison between the articles published per year and their actual review. In figure 2, the published papers on the subject per country is depicted which shows a lack of published papers around Europe.

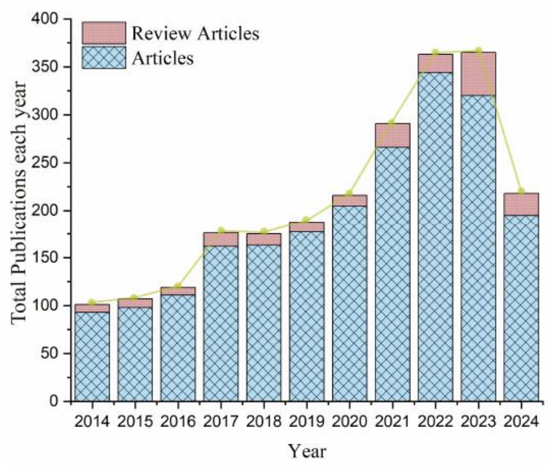


Figure 1 - Comparison between articles published per year and actual review (Castellanos & Roa-Fuentes, 2024)

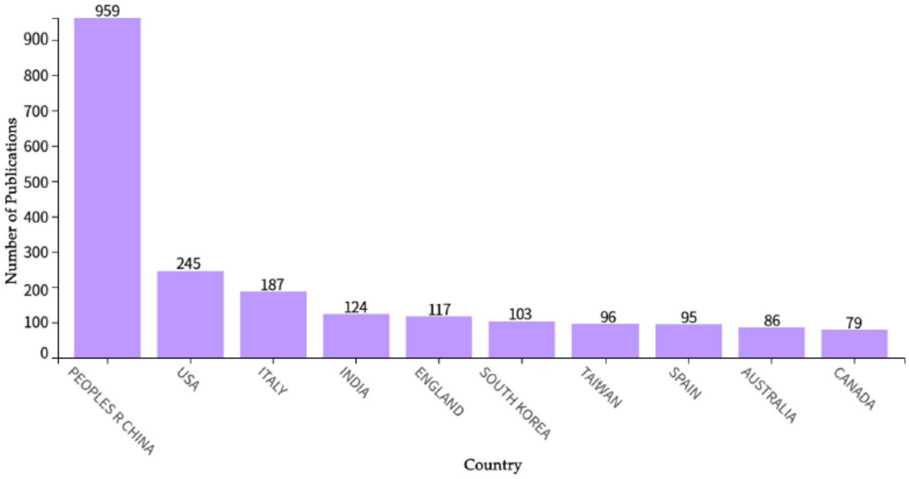


Figure 2 - Published papers around Europe (Castellanos & Roa-Fuentes, 2024)

Implementation Costs

In terms of affordability and costs, this is another challenge due to the misconception that the implementation of biophilic design elements including greenery, natural materials and passive design strategies are expensive in residential building developments. Such extra costs could include the specialized design and construction techniques to be used to achieve such implementation. Although there is well known evidence that such implementation will impact on less running costs, such as heating and cooling.

Maintenance

Another factor mentioned is the maintenance of such natural elements. This is always a challenging factor when considering green walls and green roofs. Although maintenance is required for such green applications, this might not be a lot when compared with the benefits in terms of thermal comfort. The most important thing is that the installation is done properly, and training is given to the occupants that will be maintaining such systems. On the other hand, the choice of materiality and passive design strategies will not necessarily mean that maintenance will increase.

Space and Structure

The final limitation in terms of retrofitting is the space and structural stability. This can mean that higher costs are required to implement such biophilic design measures in an existing building but not always the case. Retrofitting can be more limited in terms of implementation but there are a lot of measures that one can implement into existing building without effecting the structural integrity of the building. Therefore, interventions such as widening of the apertures and installation of green roofs might be not feasible for retrofitting buildings but surly ideal for new buildings. In terms of newly designed apartment blocks in densely built environment like Malta, there is usually not enough space for making such interventions as a common area such as a central courtyard. Although one cannot forget that the roof could be easily designed as a green roof and given to the residents as a common space rather than kept by the owner. This does not mean that small interventions could not be design in a limited area.

Perceptions

As everyone knowns, biophilic design are perceived as a decorative thing rather than integration of an architectural design project that is also beneficial in terms of the energy performance of the building and human wellbeing. This perception causes people to view such interventions as separate or superficial rather than as a proper design integration (Aranda-Castilla, Neila-González, & Pérez, 2023).

2.8.2 Opportunities

Biophilic design opportunities are various and can be achieved from both newly built and retrofitted projects.

Wellbeing

The most important aspect is the wellbeing and mental health benefits. According to all the research reviewed, biophilic design has an important role to the human wellbeing. Simple natural elements such as daylight, natural ventilation and nature views lead to the reduction of stress, improve sleep and helps the mood. (Lau, Gou, & Liu, 2021) (Ali, Al-Maiyah, & Cook, 2021). It was also mentioned that post pandemic period, this factor is even more important since people are now using their home for more functions. Exposure to elements such as daylight, natural materials, and vegetation is associated with improved mental clarity, reduced anxiety, and enhanced quality of life. Research indicates that in densely populated countries such as Malta, where access to natural environments is restricted, residential spaces can serve as compensatory areas for individuals to engage with nature. Apart from this, it will also affect the concentration, focus and productivity, this is very relevant in terms of remote workspace or study rooms.

Another important factor of the wellbeing is the sleeping and circadian rhythm. Biophilic design measures such as natural light and ventilation will help the circadian rhythm therefore lead to better quality of sleep. This also shows that natural light is always the best option when compared to artificial light, apart from the fact that this will also affect the energy performance of the building. Lastly in terms of wellbeing it was also found that the sense of attachment to the home will increase. This is since natural elements in a building will lead to more calming and liveable environments. One cannot forget to mention the vulnerable section of people that are important as the rest. These include the children and the elderly; from a study it was shown that such sector will also benefit in terms of wellbeing having nature inside their home when they will have limited access to outdoor green spaces. This is another important opportunity that will makes the designed space for everyone.

Environmental performance

Another opportunity in implementing biophilic design strategies is the passive environmental performance, therefore the scope of my research. This opportunity is also of major importance since energy performance is one of the most important factors in now a day building design. As already mentioned, nearly all the measures that one can implement in terms of biophilic design, will affect the energy performance of the building. This is since all strategies are related to nature being the light, ventilation and vegetation (thermal comfort). Such natural elements will eventually reduce the reliance on mechanical systems therefore energy loads that will eventually lead to improvement aligned with the SDG (Suleiman, Mohd-Nasir, & Wahab, 2023).

From the same article, it was shown that biophilic design is increasing in acknowledgment in terms of its contribution in relation to the energy efficiency of residential buildings. This demonstrates that biophilic design not only improves occupant well-being but also reduces energy demand by integrating passive environmental control and renewable technologies.

One of the more effective opportunities is the thermal comfort when introducing green roofs or green walls. These will reduce the need for cooling loads as this will act as a natural means of insulation. The vegetation layer is a thermal buffer and will reduce the indoor temperature therefore the need of mechanical cooling systems. These systems are generally classified into 3 types being extensive, intensive and semi-intensive. The difference is in the depth of the soil therefore will differ the kind of vegetation that can grow in such environments. Extensive systems are generally less than 200mm of soil with large area, while intensive will be more than 1m depth of soil with a smaller area. The plant selection varies but are generally shallow rooted. As an average guideline of the difference in temperature when implementing such system, one can use the following table:

Table 4 - Green Roof Types (Castellanos & Roa-Fuentes, 2024)

Green Roof Type	Typical Soil Depth	Temperature Reduction	Notes
Extensive	< 200 mm	15°C to 30°C	Lower weight, moderate insulation
Semi-Intensive	200–1000 mm	Moderate (context-specific)	Mix of grasses, shrubs
Intensive	> 1000 mm	Higher than 30°C (assumed)	High thermal mass, highest cooling

The main layers of a green roof include vegetation, drainage layer, insulation and waterproofing. It is important to mention that both green roofs and green walls are aligned with the aims of the sustainable development goals. These include SDG 11 – reducing urban heat islands, enhancing air quality, and improving urban aesthetics. Also, SDG 13 – climate change mitigation through carbon sequestration and improving energy performance, SDG 15 – fostering biodiversity and SDG 6 – managing stormwater runoff.

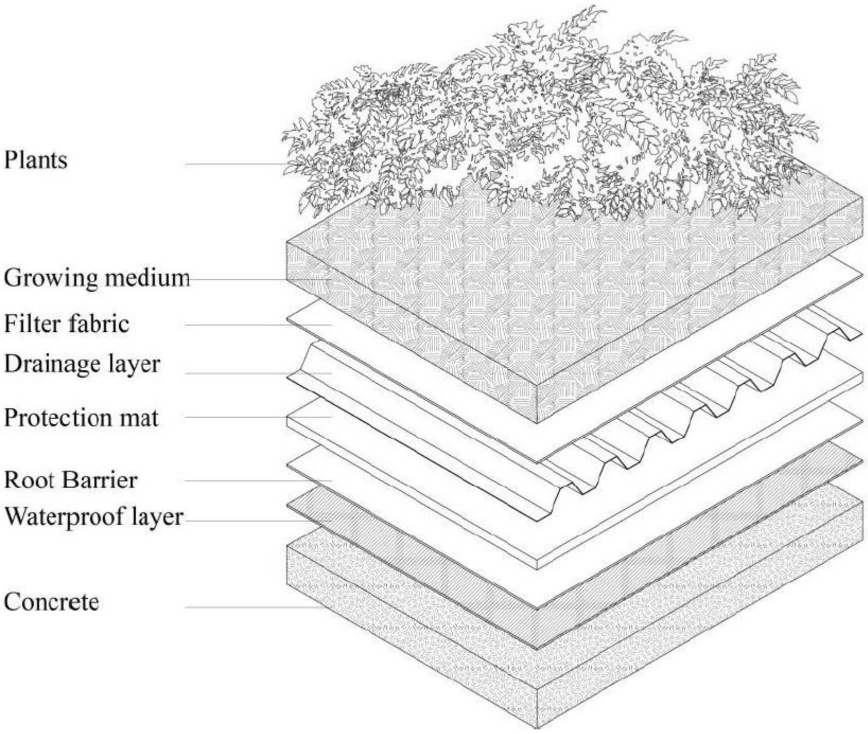


Figure 3 - Green Roof layers (Castellanos & Roa-Fuentes, 2024)

On the other hand, green walls can vary from different types as shown in figure 4.

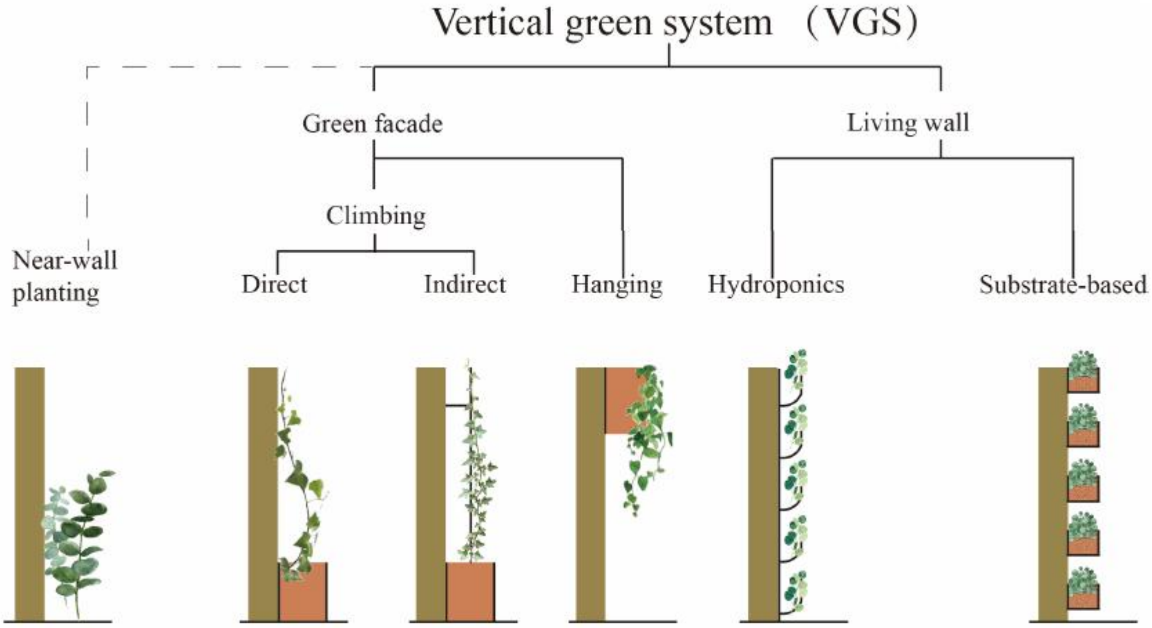


Figure 4 - Vertical Green Systems (Castellanos & Roa-Fuentes, 2024)

These green walls can be simple as just planting next to a wall and can be also more complicated as hydroponics. Each of these have an effect of the thermal comfort but with different values. Apart from thermal comfort, these will also reduce the energy consumption therefore making the building more energy efficient. The main effect in terms of passive energy include shading and thermal insulation, evaporative cooling and also as a wind barrier.

Apart from this as the effect of double wall, the layer of vegetation separated from the building facade will create an insulation air layer. This also depends on the type of plant, density, climatic condition, orientation and overall facade design. Using thick layers of vegetation with suitable plants like Philodendron, which are less effective at reducing CO_2 levels compared to other species, and Tradescantia, which has demonstrated the strongest cooling effect through transpiration, can be beneficial. Apart from this, another important factor is the correct placement and orientation that will affect the building in terms of solar heat gains. In terms of temperature, the following results can be obtained:

Table 5 – Vertical Green Systems Performance (Castellanos & Roa-Fuentes, 2024)

Condition	**Performance Result**
Temperature reduction (summer)	Up to **20°C** cooler compared to bare walls
Temperature reduction (winter)	Up to **8°C** cooler compared to bare walls
Passive energy savings range	**5% to 50%** (typically **20% to 30%**)
Reduction in solar radiation with 5 leaf layers	Up to **86%** reduction
Indoor temperature reduction in green-facade-shaded offices	**3.5°C to 5.6°C** cooler

This can be very effect in retrofitted building where insulation external or internal is not possible and to create a sense of nature while enhancing the energy efficiency of the building.

The main types include near wall planting, green facades and living walls. Green facades include two types, climbing and hanging. For climbing, a system of tendrils and twining stems is needed to ascend the walls without any support. There are generally without or very low maintenance like Boston ivy or English ivy. On the other hand, one can find the indirect climbers require structures for support. These are generally separated from the building facade, therefore no risk of structural problems. The other type is the hanging; these will generally be installed on roofs or balconies that will hang down.

Living walls require more maintenance than other types because they include plants that grow in modular containers or hydroponic systems attached to facades. These systems will be generally integrated with irrigation that will also include fertilisation.

Dual performance with Photovoltaic Systems

Green roofs can serve as an opportunity to increase the performance of photovoltaics. This is since green roofs will help the cooling effect of the photovoltaic panels therefore improving their efficient and lifetime. Therefore, one can consider that biophilic design will go hand in hand with sustainable systems. Another sustainability benefit is the stormwater management. This is required for the mentioned vegetation systems that can be directly connected with a stormwater storage.

Another improvement is natural ventilation and airflow. Green courtyards, internal atriums and just openable windows increase natural ventilation therefore will help reducing the reliance on mechanical ventilation systems such as air conditions. According to the same paper, integrating natural cross ventilation and green shading affects indoor temperature and energy savings. As mentioned previously natural light is also considered as a biophilic design element. This will reduce the need of artificial lighting. According to this article having a maximum daylight can save up to 20% of the energy consumption required for lighting. Apart from this having the opportunity to create visual comfort and occupant satisfaction.

Biophilic design enhances place-making by incorporating local ecological and cultural identities. Especially in multi-residential environments, the integration of shared green spaces, green roofs, and natural material palettes can strengthen community bonds and enhance social cohesion (Aranda-Castilla et al., 2023). Research indicates that even low-cost solutions like indoor plants, window views, and natural textures can be impactful. These measures can lead to broader biophilic acceptance in residential retrofits (Zafirah et al., 2021).

Conclusion

One can conclude that biophilic design has more opportunities than challenges. This must be the way forward for architectural design as with one factor one can combine all the requirements to have a liveable space with multiple benefits that effect the human wellbeing while using passive design strategies that can be compounded with sustainability. Therefore, biophilic design can be considered to be a holistic approach towards sustainable in all ways residential building. This includes social, environmental and economic sustainability. This means that the concept of biophilic design as being an and approach geared towards aesthetics is fundamentally flawed. Rather it is a comprehensive design approach that synergises architecture, building engineering, ecology, psychology and the overall effect on the urban planning acting as a green corridor leading to a broader perspective. Thus, it supports climate, natural resources, and human activities across all levels of residential and urban life, which is essential for designing in a sustainable manner. The effective integration of biophilic design in residential buildings depends on overcoming obstacles such as cost perception, knowledge deficiencies, and spatial limitations. Research suggests its potential to improve well-being, support sustainability objectives, and develop resilient living environments. Future design guidelines should consider cultural relevance, affordability, and adaptive strategies to encourage scalable and inclusive adoption.

2.9 Specific Case Studies Applications to Apartments

This chapter discusses various international case studies that shows how biophilic design strategies can be successful in local climate conditions and residential building such as apartments. These case studies found from (Terrapin Bright Green, 2014) shows how these applications are reliable for our local environment.

2.9.1 Khoo Teck Puat Hospital in Singapore – Healing through nature - CPG Consultants (lead) and RMJM (design consultant) - 2010

Figure 5 - Khoo Teck Puat Hospital in Singapore

The first case study is the Khoo Teck Puat Hospital in Singapore. Although this is a hospital, such strategies can be easily implemented in apartment blocks. The main elements of this hospital include large internal gardens and terraces, that increase natural ventilation and daylight (Terrapin Bright Green, 2014). The green elements in this case study shows a significant impact on the urban heat island effect and the internal microclimate. In case of Malta, semi-arid climate, such strategies could be easily implemented in residential buildings. The primary objective of this project was to align with Singapore's Garden City strategy and enhance healthcare through nature. This includes promoting recovery, reducing stress, and improving overall comfort for both staff and visitors. The main elements used include natural light and ventilation by introducing large openable windows and open-air corridors creating the "logga" effect. This will mean the reduction of artificial lighting and air conditioning. Another key element was the greenery, the importance of having local plants. These include both vertical and horizontal gardens. Apart from this one can also note the large pond that can be implemented in a central common outdoor space in a block of apartments. It was also mentioned that such measures can also lead to increase the sense of community and social interaction that is something very missing in the apartment blocks. This example helped patients feel better and connect with nature and each other (Kishnani, 2017).

2.9.2 Sidwell Friends School in Washington D.C – Andropgon Associates – 2007

Figure 6 - Sidwell Friends School in Washington D.C - Renewable energy & Biophilic design elements

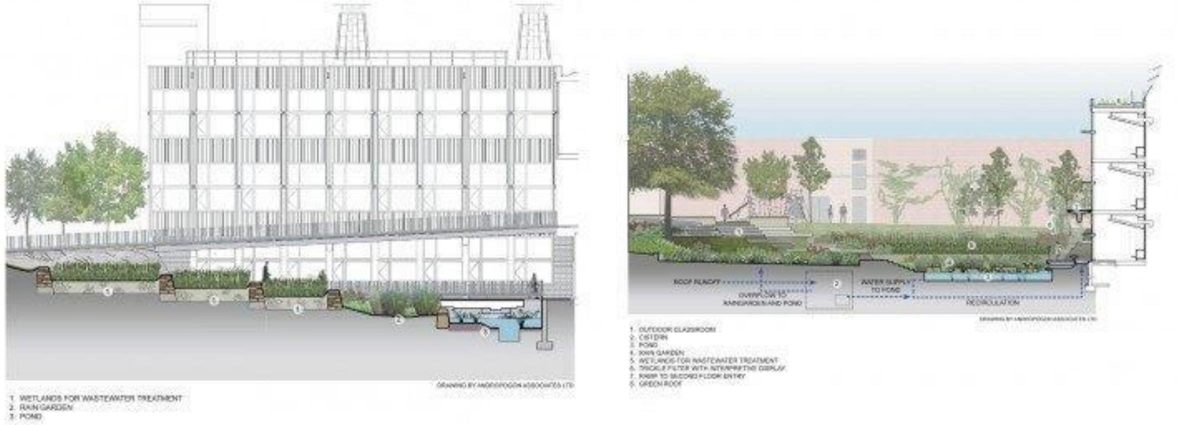


Figure 7 - Elevation showing shading devise and surrounded gardens

This case study includes green roofs, rain gardens and the maximization of natural light to reduce the artificial lighting demand. The green roofs impacts on the reduction of mechanical systems. On the other hand, the effect of maximization of natural light also assisted natural cross ventilation. The rain gardens include the water collection of overflows with native aquatic plants such as water lilies and pickerel rushes (Andropogon Associates, 2007)

2.9.3 Verde Project in the Bronx, New York - Dattner Architects (New York) and Grimshaw Architects (London/New York) – 2012

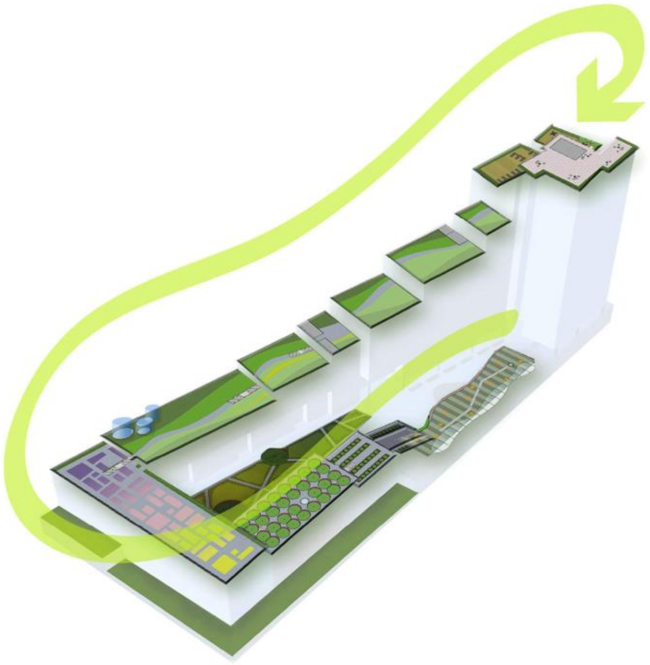


Figure 8 - Verde Project in the Bronx, New York – green roof

Figure 9 - Internal squarish layouts - enhance cross ventilation

Figure 10 - Internal Layouts

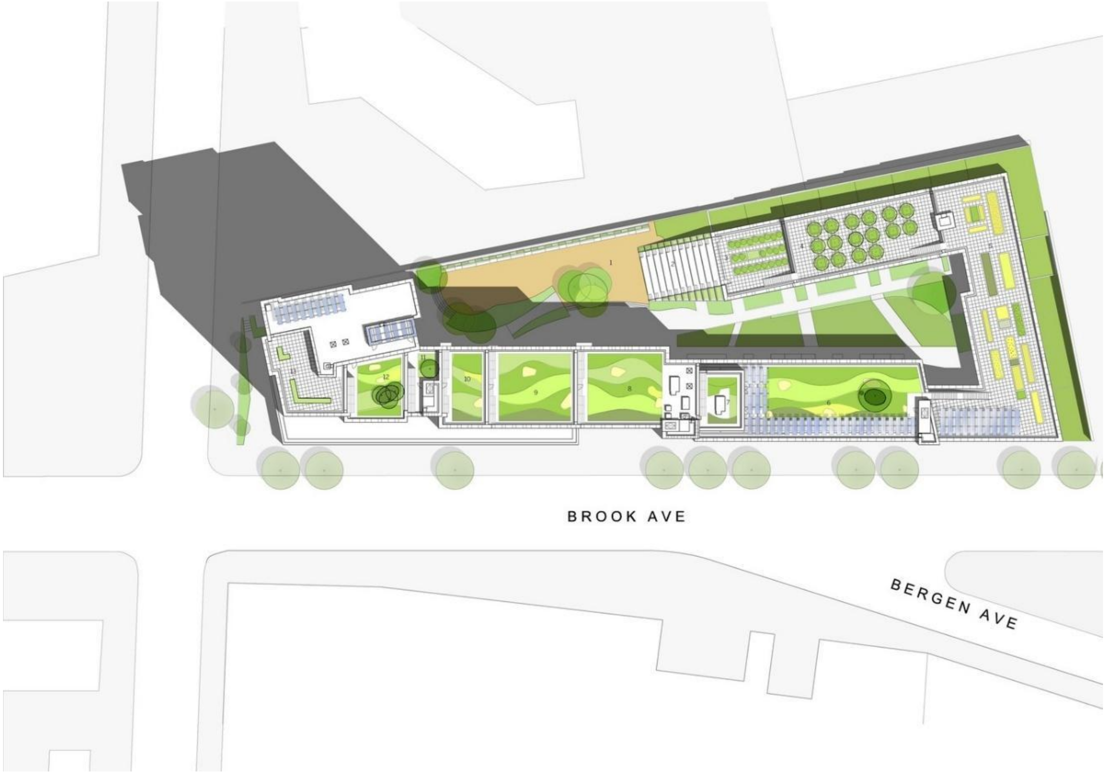


Figure 11 - Green Roof Plan

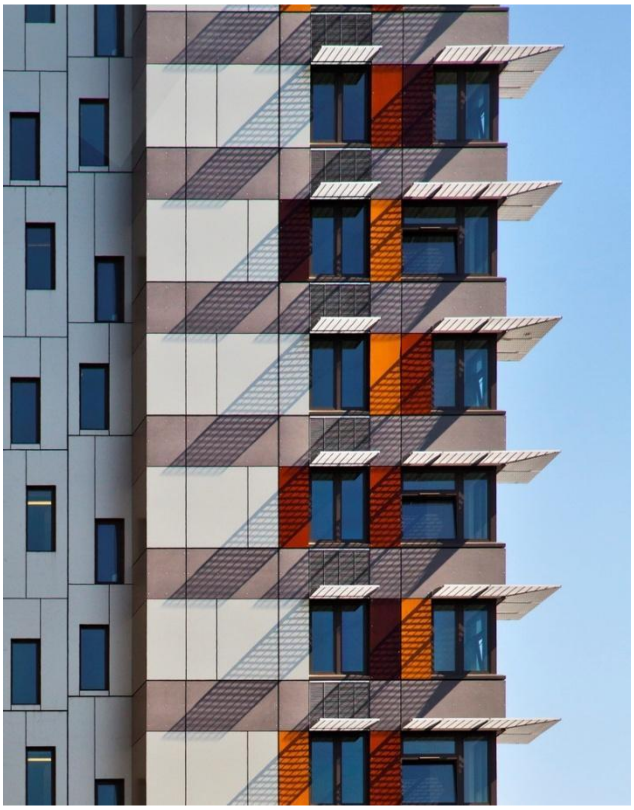


Figure 12 - Shading Device with facade

Figure 13 - Green roof

This is a block of apartments includes green roofs as a community gardens natural ventilation trough the internal layouts and building orientation. This aimed to lower energy bills and enhanced community health. These elements were designed without increasing construction costs. Such model can be easily implemented in Malta if apartment blocks are built with an urban strategy rather than as individual plots (Grimshaw & Dattner Architects, 2014).

2.9.4 Phipps Centre for Sustainable Landscapes in Pittsburgh - Phipps Centre for Sustainable Landscapes in Pittsburgh - 2012

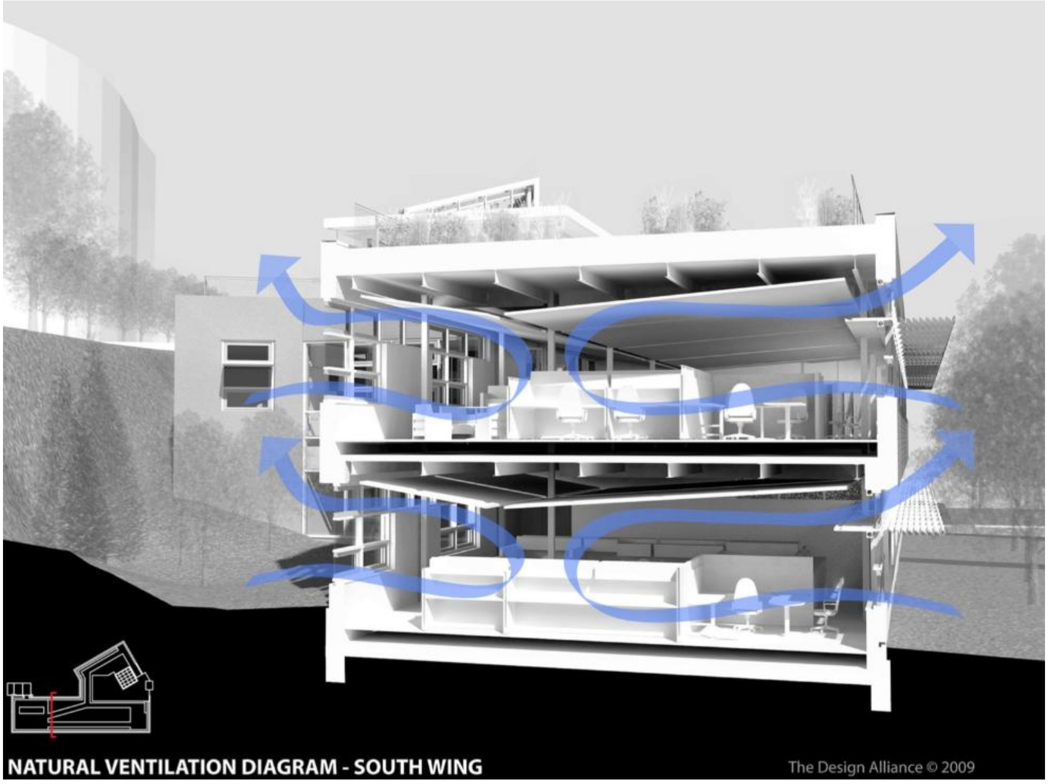


Figure 14 - Natural cross ventilation

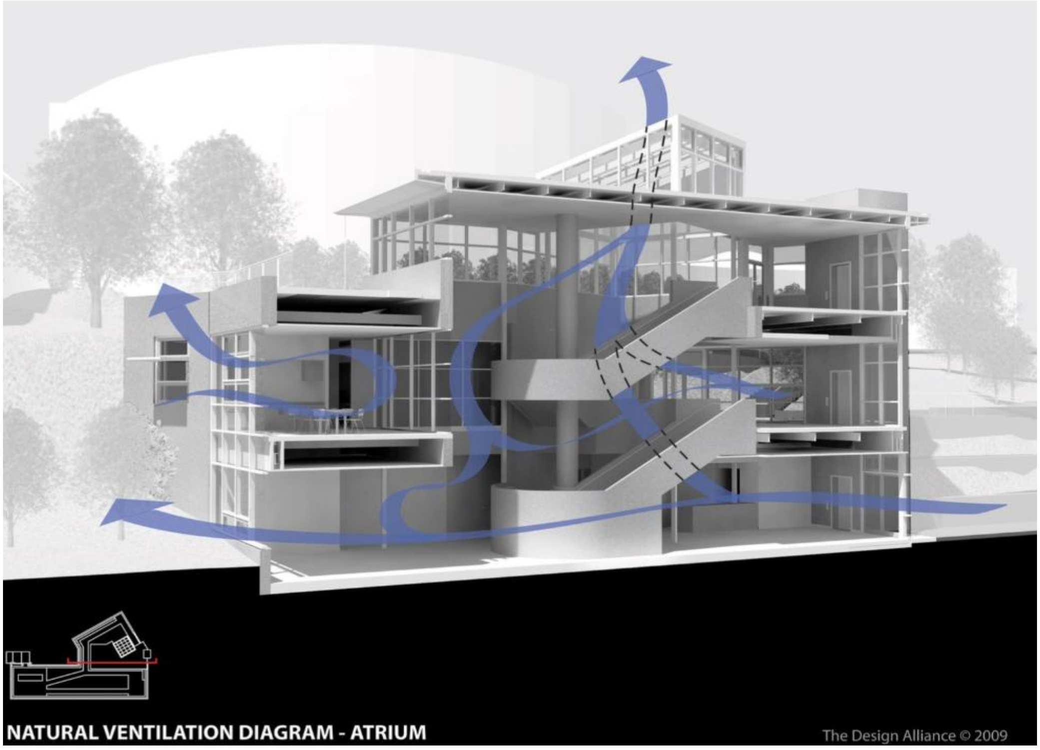


Figure 15 - Cross ventilation and atrium effect

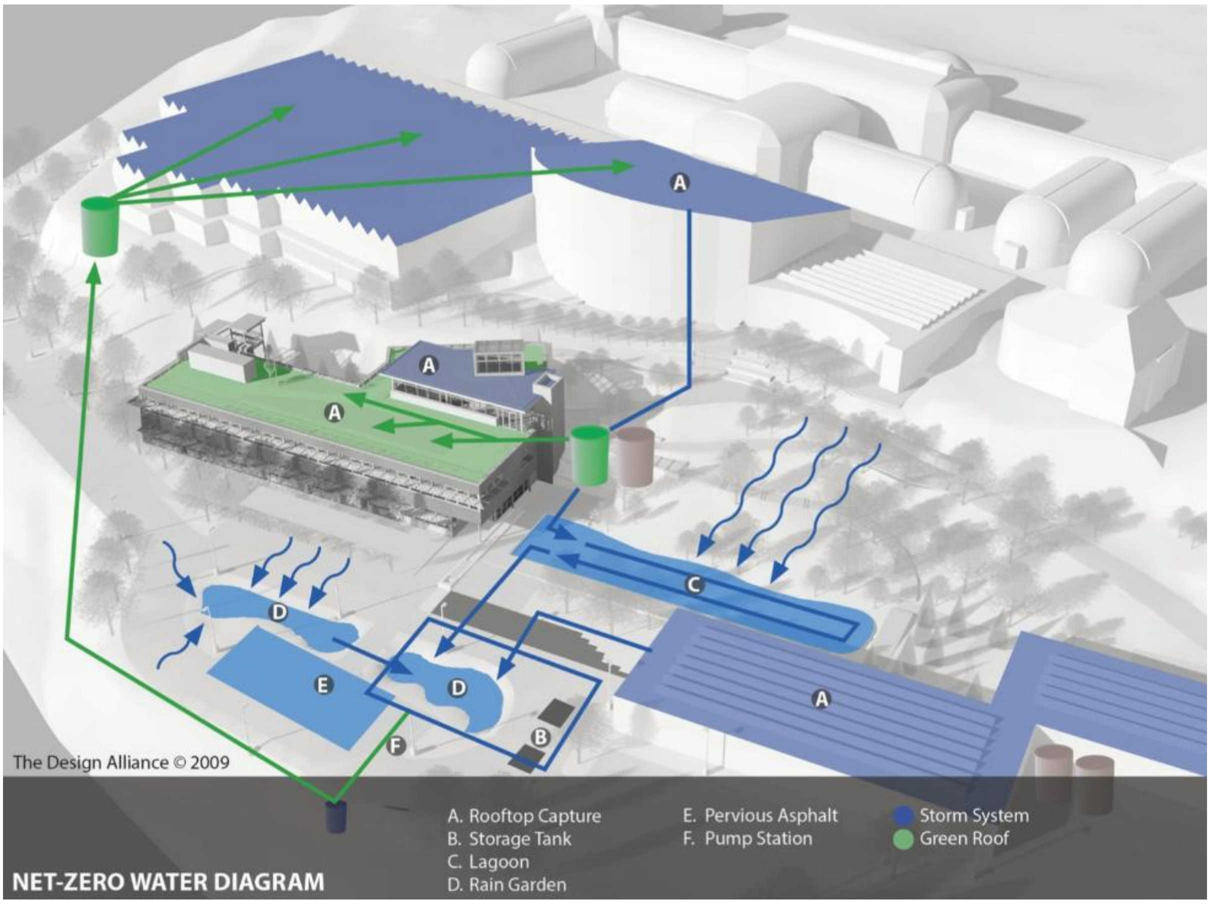


Figure 16 - Sustainable systems and biophilic design integration

Figure 17 - Natural Materials and shading

This building is one of the most building certified for energy efficiency and renewable energy. This building is net-zero energy performance with passive design, landscaping and the use of natural materials. This building includes natural shading, canopies, cross ventilation, vegetation and glazed areas for natural light (Phipps Conservatory and Botanical Gardens, 2012).

In Table 4. one can see these case studies and how these can be potentially applied locally.

Table 6 - Case Studies with Potential Application in Malta

Case Study	**Key Biophilic Strategies**	**Potential Application in Malta**
Khoo Teck Puat Hospital, Singapore	Internal gardens, vegetated facades, natural ventilation	Integrate greenery in residential courtyards and facade designs to enhance passive cooling and microclimate management
Sidwell Friends School, Washington D.C.	Green roofs, daylight maximisation, rain gardens	Promote green roof systems and daylight-optimized layouts in new housing and school projects to improve energy performance
Via Verde Project, Bronx, New York	Community gardens, green roofs, natural ventilation	Integrate green roofs and communal green areas into affordable housing schemes to boost community health and reduce energy costs
Phipps Center for Sustainable Landscapes, Pittsburgh	Full biophilic integration, net-zero energy strategies	Use natural shading, cross-ventilation, and passive cooling designs in residential retrofits and new eco-developments

The Bosco Verticale project in Milan, Italy, is a pioneering high-rise residential complex with vertical forests on its façade. This design cools the area, improves air quality, and enhances biodiversity. An example is the Eco-Luxury Apartments in Melbourne, Australia, which incorporate natural ventilation corridors, planting, and natural materials to create an urban living environment that connects to local ecosystems (Kellert S. R., Nature by design: The practice of biophilic design., 2018).

In Malta, traditional limestone architecture establishes a material connection to the local environment. Using indigenous materials alongside enhanced ventilation corridors could support cultural identity and improve environmental performance in modern apartment retrofits and new developments. These case studies show that biophilic design can enhance sustainability, energy efficiency, and liveability in apartment buildings.

2.10 Monitoring Energy Performance and Thermal Comfort

2.10.1 Monitoring of energy performance in general

Energy performance and thermal comfort monitoring is very important in order to achieve a sustainable and human comfort architecture. This is done in order to understand the energy consumption patterns, indoor environmental quality and also user experience. This monitoring is required to enhance energy efficiency and human well-being. Recent studies have focused on using monitoring systems to assess design interventions in homes and schools.

Nowadays this is done by integration monitoring system that are generally found in large buildings to assess the operational performance in terms of energy. (González-Torres, Cuerda, Alonso, & Llorente, 2023) indicate that real-time monitoring enables the continuous assessment of electrical consumption, indoor temperature, humidity levels, and air quality, providing data for optimising building management systems (BMS).

This monitoring includes the use of smart meters, environmental sensors and data software that will eventually facilitate the analysis of the users' behaviours patterns in relation to the energy use. Evaluation of resident interaction within retrofitted residential buildings is necessary to ascertain how post-occupancy affects energy performance.

According to (Elnaklah, Costanzo, Fosas, & Mourshed, 2023), longitudinal monitoring is crucial for capturing changes in a building's overall performance. Even if it is instructive, short-term monitoring is crucial for identifying the main pathways for thermal comfort and energy demand in relation to various climatic seasons. According to this paper, a minimum of one year monitoring full cycle is required to identify the anomalies and to account for the different patterns of usage, weather conditions and mechanical systems schedules. This approach is very important for environmental climates like Malta, as the different seasons will impact on the cooling and heating needs.

Another important factor mentioned in the literature is the role of indoor environment quality monitoring in terms of thermal comfort. The main parameters include operative temperature, air velocity, relative humidity and mean radiant temperature as per standards including ISO 7730 and EN 15251. Monitoring these variables helps understand occupant satisfaction better, linking energy efficiency with human-centric design.

In real scenarios, this study shows that wireless sensor network and the internet of things helped a lot in the feasibility of building monitoring systems. This shows that such monitoring can be cheap. Apart from this, sensors in a building can be scalable according to the area and these will record real time data in different zones as may require. This data will be then used to examine it in terms of any irregularities and to forecast patterns of energy consumption. Qualitative data in terms of experience from the residents should be added to the monitoring systems as these will be the real experience of the users. This will show a more thorough understanding of building performance and the relationship between the built environment and the human behaviour to combine objective environmental data with subjective comfort impressions.

One can say that monitoring energy performance and thermal comfort is a fundamental element of modern sustainable building method. This approach facilitates the design decisions, using adaptive design strategies, and encourages environments that are both energy-efficient and accommodated to occupant needs therefore biophilic design. Implementing complete monitoring frameworks in the residential sector could significantly contribute to achieving the dual objectives of environmental sustainability and human well-being (Azhar, Arif, & Khan, 2023).

2.10.2 CIBSE Standard: Monitoring indoor environmental quality (TM68: 2022)

According to CIBSE standards for monitoring of energy performance and thermal comfort, this is an essential practice in terms of sustainable building design. This document includes a detailed guidelines on the processes, technologies and required consideration in terms of indoor environmental quality (IEQ). This is specifically for thermal comfort in terms of energy use.

Reliable monitoring in terms of energy performance is considered as critical to assess the operational efficiency of a building in relation to the design expectations. Post occupancy monitoring guide the facility managers for large scale buildings or person responsible for the energy use in case of residential buildings individually owned (the owner), the architect in terms of building passive design strategies and the engineer in terms of mechanical systems to determine the inefficiencies and success or failure in terms to the energy performance of the building. Therefore, smart meters, sub metering and data logging is essential to assess the building in terms of heating, cooling, lighting and ventilation systems, both natural and mechanical. With such data one can easily analyse the energy demand patterns and identify any future trends of overuse or deficit of building systems. This is important to optimize such systems in a way that these will be kept at their maximum efficiency and potentially improve them in terms of both passive design and active systems. Apart from having thermal comfort in terms of well-being. These guidelines also mention that such monitoring should include air temperature, operating temperature, relative humidity, air speed and mean radiant temperature as already discussed in the previous paper. Such parameters are in line with international standards already mentioned that also allow for the user perspective of thermal comfort. Therefore, it is very important that such monitoring will not include just air temperature but all other factors that affect the environment and the human comfort.

This document emphasis the need of integrated monitoring that include data of energy performance while having scheduled thermal comfort measures in place. This means that such monitoring of current situation will have a clear picture of the current design strategies in that building zone. Therefore, one can determinate if the current design is achieving the intended outcomes in terms of occupant thermal comfort.

In terms of data collection, these guidelines recommend the use of wireless sensors that works on a cloud-based management system therefore having the data collection, storage and analysis on one system. This will facilitate the results therefore the implementation of improvements if required. As already mentioned, these guidelines confirm the need for at least 1 year data collection to have a clear picture of the ongoing trends in that building in all different and extreme scenarios in terms of season. It also shows that the energy performance of a building depends on the user behaviour and actions, this means that both quantitative and qualitative feedback is essential to optimize the monitoring. Such data will be managed and actioned by means of dashboards, trend analysis and comparable benchmarks.

Moving on to data interpretation and analysis, this should be done on both technical and non-technical levels. This guideline can be utilized to create a customized framework for the monitoring of energy performance and thermal comfort of that building (CIBSE TM68, 2022).

Chapter 3 Methodology

3.1 Introduction

With the aid of a building energy modelling tool based on Design Builder® and Energy+, a comparison between existing apartments scenarios at various levels and different orientation with same apartments with biophilic design interventions were carried out to achieve the scope of this research. Design builder® with the aid of Energy+ plugin is a simulation software that can be used for any simulation of buildings both existing and proposed to analyse various parameters in relation to energy performance, HVAC sizing, daylighting, natural ventilation and human comfort analysis.

This will consist of the modelling of these apartments to establish the ideal biophilic design parameters in terms of human comfort including thermal, visual and acoustics and indoor air quality (CO_2). These results will be presented by combining measures rather than showing the outcome for each parameter separately since the main scope of this study was the impact of such multitude of measures as whole on energy performance and thermal comfort and not to study the effect of each individual measure.

The simulations were validated using measurements from a CO2 and temperature/humidity sensor. The meter used was MRC, CO2-9914SD. (MRC Laboratory Instruments , 2025)

3.2 Measured Data

It is important to mention that the following uncertainty analysis was considered for the results error bar based on the meter specifications and standard reference. This include +/- 1.3 for the temperature that it is based on the summation of +/- 0.8 from the meter specifications and another +/- 0.5 for the weather station (Aguilar, Auer, Brunet, Peterson, & Wieringa, 2003). For the CO_2 readings a +/- 40 PPM was taken based on the meter (MRC, CO2-9914SD) specifications.

This will consist of placing the sensors in 2 accessible apartments being one top floor penthouse and one ground floor maisonette to monitor existing conditions for a period of time. These two extremes were chosen to have a comprehensive data across the climatic conditions. Top floor Penthouse monitoring period was from the 10th February to the 8th March 2025 and ground floor maisonette monitoring period was from the 9th March 2025 to the 7th April 2025. Since the weather data available for the simulations was for 2024, validation of temperature profiles was carried out using the temperature difference between outdoors and indoors. This assumption is realistic since the building's thermal resistance will remain the same for the purpose of validating the data gathered and the latter is proportional to the change in temperature.

Such a validation also enabled the calibration of model parameters such as air infiltration rate that is difficult to define. For the validation of temperature, the temperature difference $\Delta T = T_2 - T_1$ was used. Hourly data was taken from the position marked in red on the plans on the next page.

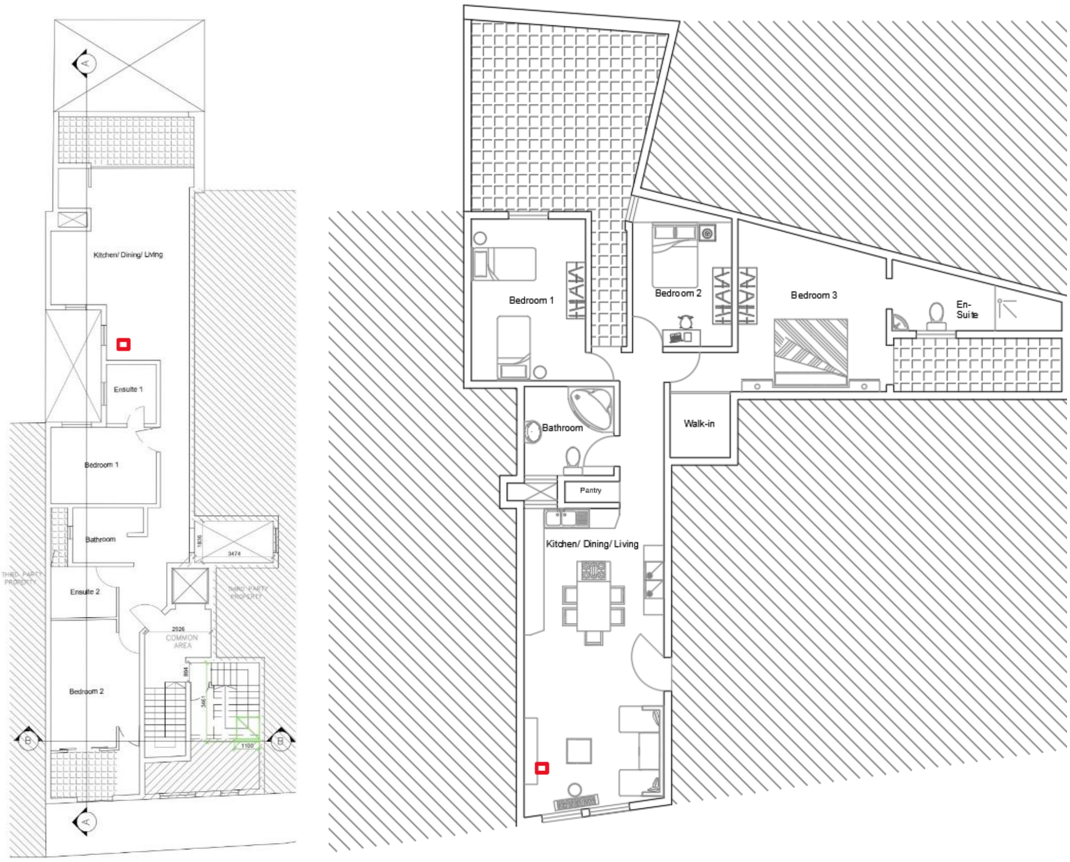


Figure 18 - Existing Plans - Position of Sensor

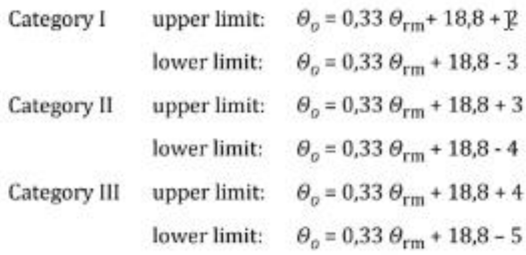
For the validation of CO^2 the same resolution was kept (hourly).

3.3 Standard Parameters

According to EN 16798-01 the table below based on the level of expectation of a residential apartment, indoor environment quality was used to assess the mean air temperature. This means that according to EN 16798-01, the results will be considered as adaptive comfort in a set of ranges.

Table 7 - Categories of indoor environmental quality (European Committee for Standardization EN 16798-1, 2019)

Category	**Level of expectation**
IEQ_{I}	High
IEQ_{II}	Medium
IEQ_{III}	Moderate
IEQ_{IV}	Low
NOTE In the tables only the category numbers are used without the IEQx symbol.	



Category I upper limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 + 2$

lower limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 - 3$

Category II upper limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 + 3$

lower limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 - 4$

Category III upper limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 + 4$

lower limit: $\Theta_o = 0{,}33\ \Theta_{rm} + 18{,}8 - 5$

(European Committee for Standardization EN 16798-1, 2019)

The adaptive comfort was worked out using the following equation:

$$\Theta_{rm} = (1-\alpha).\left\{\Theta_{ed-1} + \alpha.\Theta_{ed-2} + \alpha^{2}\Theta_{ed\text{-}3}\right\}$$

where

Θ_{rm} = Outdoor Running mean temperature for the considered day (°C).

$\Theta_{ed\text{-}1}$ = daily mean outdoor air temperature for previous day

α = constant between 0 and 1 (recommended value is 0,8)

$\Theta_{ed\text{-}i}$ = daily mean outdoor air temperature for the *i-th* previous day

3.4 Case 1 – Penthouse

Case 1 - Hortensia Court, Triq san pawl, Saint Paul’s Bay

Figure 19 - Site Plan

Site Location & Context

This site is located in Saint Paul’s bay, around 100 meters away from the sea. The site is facing south and has around 8 meters of façade. This site is found in a main road next to a bus stop and other day to day amenities. This is a block of apartments, built in 2010.

As architectural features, it includes stone masonry walls in the façade, brickwork internally. Iron railing and aluminium apertures.

In terms of environmental factors, the front has a lot of sunlight due to the south facing. With regards to natural ventilation, if apertures are open, there is cross ventilation. The site topography is very flat. The external environment can be considered as polluted due to the presence of a main road.

Site Analysis

From the visual site analysis, the following information was obtained:

Table 8 - Visual Site Analysis

	Kitchen/Dining /Living	**Bedroom 1**	**Ensuite 1**	**Bathroom**	**Bedroom 2**	**Ensuite 2**
Daylight:						
Size of windows: m²	12.24	1.44	1.08	0.6	3.84	3.50
Type of windows:	Double Glazing with aluminum frame	Double Glazing with aluminum	Double Glazing with aluminum	Double Glazing with aluminum	Double Glazing with aluminum	Double Glazing with aluminum
Shading devices (curtains/blinds/ external shading):	Blinds & Curtains	Roller Blinds	Roller Blinds	Frosted glazing	Blinds & Curtains	Frosted glazing
Obstructions of windows (blocking sunlight)	No	4.5m shaft	Yes small shaft (2.2m)	Yes small shaft (0.7m)	No	Yes small shaft (2.4m)
Reflectivity of walls/ceilings/floors	Medium	Medium	Medium	Medium	High	Medium
Air:						
Availability of natural ventilation (openable windows/cross-ventilation)	Cross-ventilation	50% openable aperture	50% openable aperture	50% openable aperture	openable aperture	50% openable aperture
Mechanical cooling and heating	Yes	Yes	No	No	Yes	No
Visual barriers affective the airflow	No	No	No	No	No	No
Indoor air pollution (cooking)	Yes	No	Yes	Yes	No	Yes
Presence of odours	No	No	No	No	No	No
Plants:						
Indoor plants	Low	No	No	No	No	No
Evaluate potential space for plants (windowsills, shelves, balconies, walls)	High	High	Low	Low	High	Low
Availability of natural light for plants	High	Medium	Low	Low	High	Low
Water:						
Any water features	No	No	No	No	No	No
Opportunities/space to incorporate water elements	Yes	No	No	No	No	No
Sound:						
Existing soundproof measures (window glazing or any insulation)	Double glazing and roof insulation	Double glazing and roof insulation	Double glazing and roof insulation	Double glazing and roof insulation	Double glazing and roof insulation	Double glazing and roof insulation
Potential for introducing sound-absorbing materials or designs	Yes	Yes	N/A	N/A	Yes	N/A
Natural sound (birds, wind, water)	No	No	No	No	No	No
General:						
Health and well-being						
Occupant feedback – lighting, temperature and air quality	Good	Good	Good	Good	Good	Good
Any complaints or issues						
Assess space for psychological well-being (clutter, openness)	No	No	No	No	No	No
Energy performance						
Lighting type	LED	LED	LED	LED	LED	LED
Insulation type	XPS (roof)	XPS (roof)	XPS (roof)	XPS (roof)	XPS (roof)	XPS (roof)
Appliance energy efficiency	Yes	Yes	N/A	N/A	Yes	N/A
Energy consumption (bills)	High	High	High	High	High	High
Considering structural condition, the existing structure looks structurally sound.	Good	Good	Good	Good	Good	Good

Natural light

From the visual site analysis, it was noted that this penthouse has good access to natural light, mainly in the open plan and bedroom 2. Both areas include a double-glazing aperture with minimal obstructions. On the other hand, the other rooms have limited day light since the apertures are limited in terms of area and having limited distance from the aperture to the wall of the shaft.

Natural Ventilation and thermal comfort

In terms of natural ventilation, this is available when the apertures are open, but some of these are only 50% openable since these are sliding windows. Natural cross ventilation is only available in the open plan. It was also noted that air conditioning is installed in all habitable areas primarily used for cooling in summer.

Occupants feedback

From the occupant's perspective, the indoor air quality is good in general with no presence of odours.

Energy performance

According to the occupant's feedback, it was noted that although there is double glazing, XPS insulation and LED lighting system, the energy consumption is considered as high. Therefore, in this analysis a comparison is made between the existing case and the case with biophilic implementation to maximize the well-being while providing a better energy performance solution.

Biophilic opportunities

From the site inspection, one can immediately identify opportunities for biophilic interventions already mentioned:

1. Apertures and shading for Natural ventilation and natural light. Apertures can be implemented through
    a. Size
    b. Shading (overhang)

2. Plants/ vegetation – the implementation of a green roof, green and indoor plants

In this case, since this is a penthouse level, all opportunities are applicable and can be implemented on the DesignBuilder® software to compare the difference in terms of energy performance. On the other hand, one can also integrate indoor plants that will enhance the human wellbeing based on but will not be modelled for this purpose. Also, one can investigate the opportunity of including water features that will again impact on the wellbeing but not necessarily on the energy performance, therefore will not be assessed in this analysis. The water features can be considered with the wall of the corridor. In terms of indoor plants, these are applicable for all areas. In the implementation of such biophilic considerations, one can also can enhance natural soundscapes.

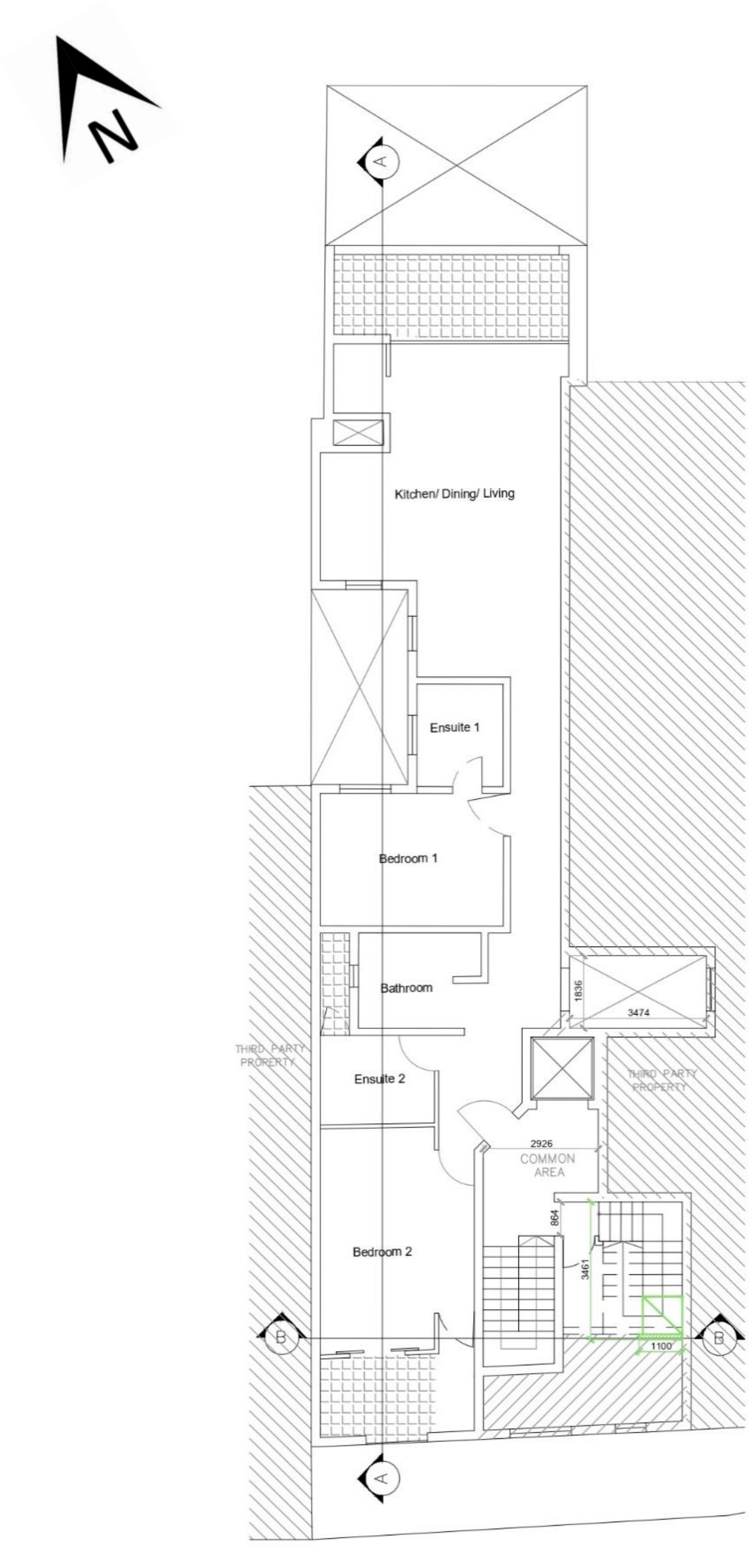


Figure 20 - Existing Penthouse level Plan

3.5 Case 2 – Ground Floor Maisonette

Case 2 – Avery Court, Triq San Pawl, St.Paul's Bay

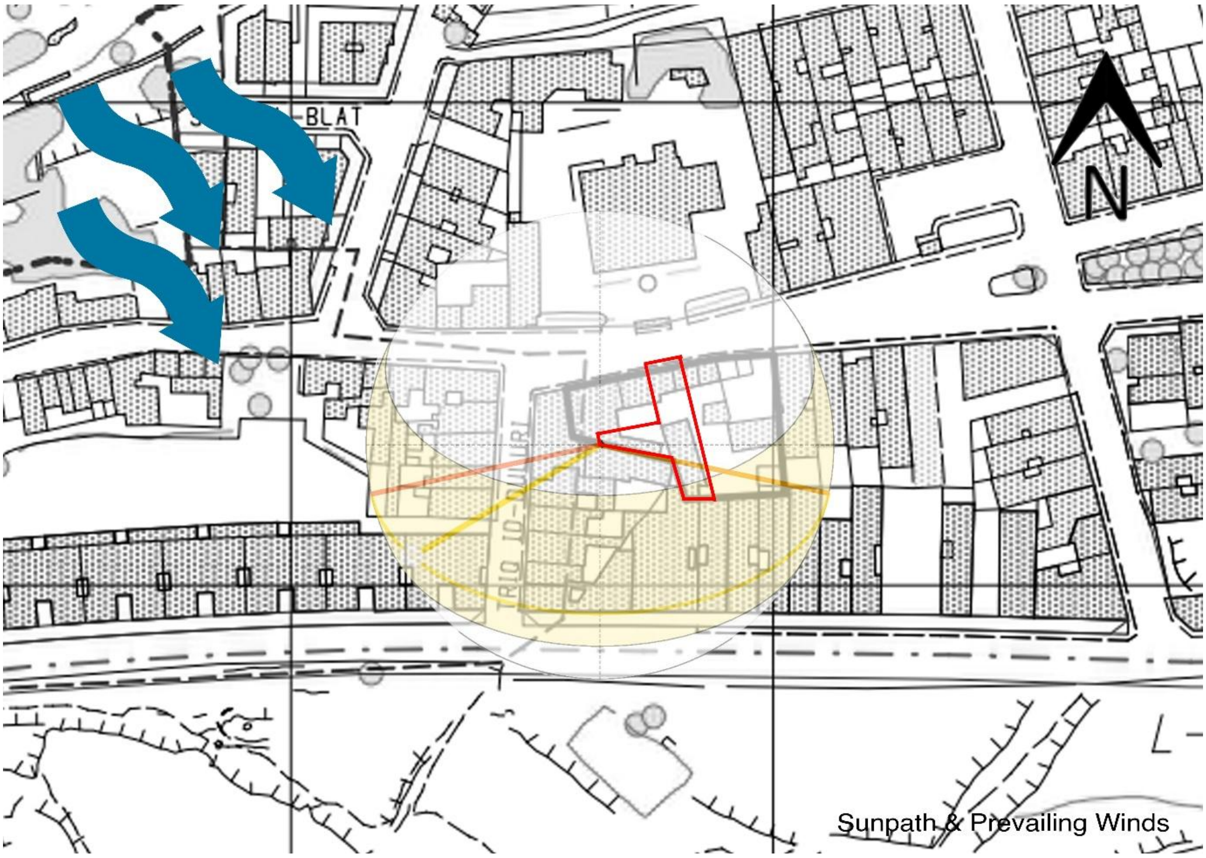


Figure 21 - Site Plan

Site Location & Context

This site is located in Saint Paul's bay, around 160 meters away from the sea. The site is facing north and has around 6 meters of façade. This site is found in a main road next to opposite to a restaurant. This is a block of apartments, built in 2022.

As architectural features, it includes stone cladding walls in the façade, brickwork internally. Iron railing and aluminium apertures.

In terms of environmental factors, the front has nearly no sunlight due to its orientation. With regards to natural ventilation, if apertures are open, there is cross ventilation. The site topography is a bit slope. The external environment can be considered as fairly polluted due to fair traffic.

Site Analysis

From the visual site analysis, the following information was obtained:

Table 9 - Visual Site Analysis

	Kitchen/Dining /Living	**Bedroom 1**	**Bedroom 2**	**Bathroom**	**Bedroom 3**	**Ensuite**
Daylight:						
Size of windows: m^2	5.04	1.44	0.96	2.12	2.54	1.44
Type of windows:	Double Glazing with aluminum frame	Double Glazing with aluminum	Double Glazing with aluminum	Double Glazing with aluminum	Double Glazing with aluminum	Double Glazing with aluminum
Shading devices (curtains/blinds/ external shading):	Horizontal Blinds & Curtains	Horizontal Blinds	Horizontal Blinds	Frosted glazing & roller blinds	Blinds & Curtains	Frosted glazing & roller blinds
Obstructions of windows (blocking sunlight)	No	5.6m backyard	Yes small shaft (0.53m)	Yes small shaft	4.7m backyard	Yes small shaft (1.6m)
Reflectivity of walls/ceilings/floors	High	Medium	Medium	Low	Low	Low
Air:						
Availability of natural ventilation (openable windows/cross-ventilation)	Cross-ventilation	50% openable aperture	50% openable aperture	50% openable aperture	50% openable aperture	50% openable aperture
Mechanical cooling and heating	Yes	Yes	Yes	No	Yes	No
Visual barriers affective the airflow	No	No	No	No	No	No
Indoor air pollution (cooking)	Yes	No	No	Yes	No	Yes
Presence of odours	No	No	No	No	No	No
Plants:						
Indoor plants	Yes	No	No	No	No	No
Evaluate potential space for plants (windowsills, shelves, balconies, walls)	High	High	High	High	High	Low
Availability of natural light for plants	High	High	Medium	Low	Low	Low
Water:						
Any water features	No	No	No	No	No	No
Opportunities/space to incorporate water elements	Yes	No	No	Yes	No	Yes
Sound:						
Existing soundproof measures (window glazing or any insulation)	Double glazing	Double glazing	Double glazing	Double glazing	Double glazing	Double glazing
Potential for introducing sound-absorbing materials or designs	Yes	Yes	Yes	N/A	Yes	N/A
Natural sound (birds, wind, water)	No	Yes	Yes	No	No	No
General:						
Health and well-being						
Occupant feedback – lighting, temperature and air quality	Good	Good	Good	Good	Good	Good
Any complaints or issues						
Assess space for psychological well-being (clutter, openness)	No	No	No	No	No	No
Energy performance						
Lighting type	LED	LED	LED	LED	LED	LED
Insulation type	Double glazing	Double glazing	Double glazing	Double glazing	Double glazing	Double glazing
Appliance energy efficiency	Yes	Yes	Yes	N/A	Yes	N/A
Energy consumption (bills)	Medium	Medium	Medium	Medium	Medium	Medium
Considering structural condition, the existing structure looks structurally sound.	Good	Good	Good	Good	Good	Good

Natural light

From the visual site analysis, it was noted that this ground floor maisonette has good access to natural light, mainly in the open plan and bedroom 1. Both areas include a double-glazing apertures with minimal obstructions. On the other hand, the other rooms have limited day light since the apertures are limited in terms of area and having limited distance from the aperture to the wall of the shaft. It was also noted that all apertures include internal shading device such as horizontal blinds and curtains, this ensures control of natural light as may be required.

Natural Ventilation and thermal comfort

In terms of natural ventilation, this is available when the apertures are open, but some of which are only 50% openable since these are sliding windows. Natural cross ventilation is only available in the open plan and bedroom 3. It was also noted that air conditioning is installed in all habitable areas primarily used for cooling in summer.

Occupants feedback

From the occupant's perspective, the indoor air quality is good in general with no presence of odours.

Energy performance

It was noted that the only factors that can affect the energy performance are the double glazing, double wall façade and the LED lighting fixtures. Therefore, in this analysis a comparison will be made between the existing and biophilic implementation to maximize the well-being while providing a better energy performance solution.

Biophilic opportunities

From this visual inspection, one can immediately identify opportunities for biophilic interventions already mentioned:

1. Apertures and shading for Natural ventilation and natural light. Apertures can be implemented through
    a. Size
    b. Shading (overhang)

2. Plants/ vegetation – the implementation of a green walls and indoor plants

In this case, since this is a ground floor level, some of the biophilic interventions that were used for the penthouse are not applicable. The applicable interventions listed will be implemented on the DesignBuilder® software to compare the difference in terms of energy performance. On the other hand, one can also integrate the same interventions mentioned in the other scenario.

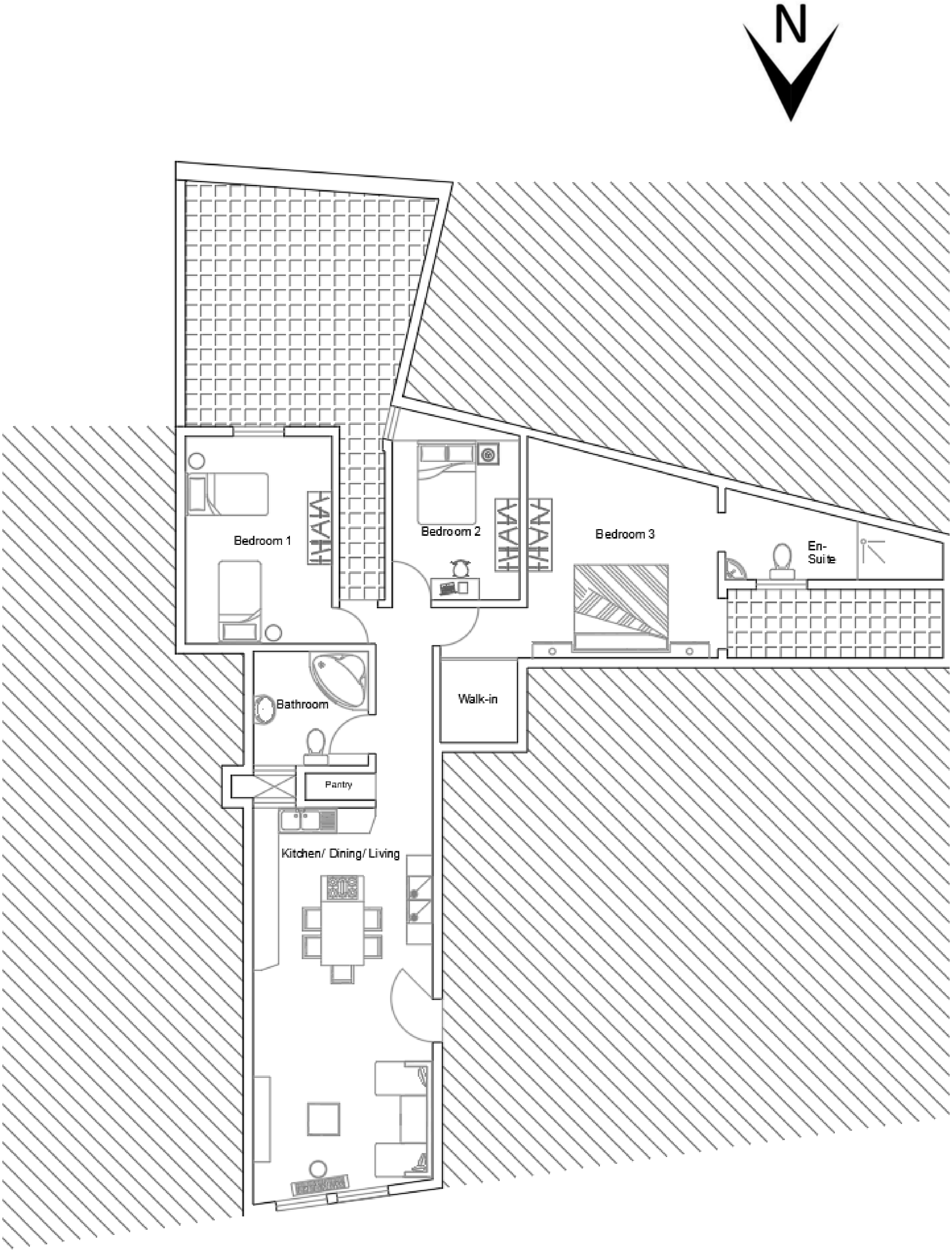


Figure 22 - Existing Ground floor maisonette plan

3.6 Building Energy Models

This study includes 2 different existing scenarios for a penthouse and a ground floor maisonette as follows:

Scenario 1: No HVAC and calculated ventilation

The simulation will include:

1. Indoor mean air temperature
2. CO_2 Levels

This model will be optimized through biophilic design measures:

1. Apertures and shading for Natural ventilation and natural light. Apertures can be implemented through
    a. Size
    b. Shading (overhang)

2. Plants/ vegetation – the implementation of a green roof, green walls and indoor plants

This will result in:

1. Minimise discomfort hours (adaptive) that requires the use of mechanical ventilation
2. Minimise energy consumption

A comparison of these will be done to show the advantages and disadvantages of such measures.

Scenario 2: HVAC on

1. Heating and Cooling load comparison between existing and biophilic measures

3.6.1 Design Builder for both existing scenarios

Table 10 - Materials Properties

Section	***Description***	***R (m²K/W)***	***d (m)***	***λ (W/mK)***	***ρ (kg/m³)***	***cp (J/kgK)***	***Details***	***Source***
External walls	230mm double thickness HCB*	0.27	0.23	0.86	1345	1000	230mm double thickness HCB, uncoated	SBEM-mt
Roof	Concrete roof/floor slab	0.111	0.15	1.35	2000	1000	Cast concrete	AD-L2 (2002 Edition)
Roof	Flooring screed	0.12	0.05	0.41	1200	1000	Flooring screed. 50mm is a typical thickness	AD-L2 (2002 Edition)
Roof	XPS Polystyrene 50mm		0.05	0.03	35	1400		
Intermediate floors	Concrete, dense, 150mm	0.078	0.15	1.93	2400	1000	Concrete block, high density	AD-L2 (2002 Edition)
Intermediate floors	Flooring screed	0.12	0.05	0.41	1200	1000	Flooring screed. 50mm is a typical thickness	AD-L2 (2002 Edition)

Intermediate floors	Ceramic tiles	0.008	0.01	1.3	2300	1000	Ceramic tiles	SBEM-mt

Apertures: Existing apertures are all double glazing. The properties included 3mm clear glazing, 13mm air gap and 3mm clear glazing.

Light: LED from the standard section of the design builder as this will not affect this study.

Third party buildings more known as adjacent building for design builder, these were created as a component block with 3-adiabatic type since this is the most ideal when having property next, above or below the building being modelled.

The activities were set accordingly to the room as a standard in the design builder.

Airtightness was considered to 0.2 ac/h, this was achieved by various trials and errors to calibrate the model in terms of CO^2 and temperature.

3.6.2 Penthouse existing scenario

For the activity in the kitchen/ dining/ living the following calculation was worked out. Assuming 1.5 people – (1 person at most of the day, 2 persons later in the evening – average 1.5). Therefore 1.5 divide by area of 34.7m^2 for the occupancy density of 0. 043.This was also worked out for the whole penthouse of 102.5m^2, giving an occupancy density of 0.0146.

3.6.3 Ground floor maisonette existing scenario

For the activity in the kitchen/ dining/ living the following calculation was worked out. Assuming 1.5 people – (1 person at most of the day, 2 persons later in the evening – average 1.5). Therefore 1.5 divide by area of 38.05m^2 for the occupancy density of 0. 039.This was also worked out for the whole penthouse of 120.96m^2, giving an occupancy density of 0.0124.

3.6.4 Penthouse with biophilic design measures

The following interventions were implemented into the existing model:

Table 11 - Biophilic Interventions for the Penthouse

Biophilic Intervention	***Description of Intervention***	***Implementation in DesignBuilder®***	***Layer/Material Details***
Natural Ventilation	North- and south-facing openings sized for airflow	Aperture size: Bedroom 2 south window set to 2.5m x 2.5m; Kitchen/Dining/Living north opening height increased to 2.5m	Set window size and operability for ventilation.
Shading Devices (Overhang)	External horizontal overhang on façade	Overhang of 1.5m added above openings (likely modelled in shading or geometry settings)	Adjust in the openings tab
Green Roof	Vegetated roof surface acting as insulation	Added as roof construction with layers: soil substrate, drainage, filter membrane, root barrier, insulation, waterproof membrane	Vegetation layer Soil/substrate (150–200mm) XPS insulation Waterproofing membrane
Green Walls	North and south facades with green walls	Defined as wall construction or added as attached construction with layers for simulation	Vegetation layer Support frame Moisture barrier
Indoor Green Walls	North and south facades with green walls	Defined as wall construction or added as attached construction with layers for simulation	Water vapour Leaves Air gap Stem Air gap
Indoor Vegetation	Use of internal plants to provide thermal mass	Modelled under **Catering** in Activity tab	Not Applicable

Apertures

In terms of apertures these were enlarged as follows:

Bedroom 2 – opening south dimensions were increased from 2.12 by 1.2 to 2.5 by 2.5m

Kitchen/Dining/Living – opening north dimension was increase in height from 2.12 to 2.5m

Apart from this a general 1.5m overhang shading was placed with every aperture. In terms of glazing this remained double glazing.

Green Roof

Green roof layers were set as follows:

Table 12 - Green Roof Properties of each layer

Layer Name	*Material*	*Typical Thickness (m)*	*Conductivity (W/m·K)*	*Density (kg/m³)*	*Specific Heat (J/kg·K)*	*Notes*
Vegetation Layer	Native Sedum/Herbs/Grasses	0.1	0.20	300	1500	Based on Malta-native and CIBSE-recommended low-root vegetation
Growing Medium (Substrate)	Extensive Roof Soil Mix	0.08–0.15	0.25–0.40	800–1000	1500	Malta standard recommends lightweight

						blends with drainage compatibility
Filter Fabric	Geotextile layer	0.003	0.04	250	1250	Prevents clogging; per Malta and CIBSE guidance
Drainage Layer	Lightweight aggregate/plastic	0.04–0.06	0.30–1.20	400–600	1000	Drainage panels or gravel layer
Protection Layer	Recycled textile mat	0.01	0.25	1000	1000	Recommended under drainage layer (KS11)
Root Barrier	HDPE or bitumen-polymer	0.003	0.40	950	1800	Required for root resistance (Malta green roof standard draft)
Waterproofing Membrane	Bituminous / PVC	0.005	0.17	1400	1900	CIBSE and Malta: ensure watertightness
Thermal Insulation	XPS or EPS panels	0.08–0.12	0.035	35–45	1400	CIBSE: outside insulation in

						inverted green roofs
Structural Roof Deck	Reinforced concrete	0.20	1.70	2300	1000	Structural base as in most Maltese flat roofs

For the vegetation layer the follow settings on the green roof tab were set:

Table 13 - Vegetation Layer Settings

Parameter	**Value**
Moisture diffusion calculation method	1-Simple
Height of plants (m)	0.1000
Leaf area index (LAI)	2.7000
Leaf reflectivity	0.30
Leaf emissivity	0.950
Minimum stomatal resistance (s/m)	100.000
Max volumetric moisture content at saturation	0.500
Min residual volumetric moisture content	0.010
Initial volumetric moisture content	0.150

Green Walls

The walls set to green walls for this model include the north and south facing walls that in this case are the back and front facades.

For the green wall layers, the following layers were inputted:

Table 14 - Green Wall Layers

Layer	Material	Thickness (m)
Outermost	Green Wall Vegetation Panel	0.1
Layer 2	Cement/plaster/mortar - cement	0.02
Layer 3	Blockwork	0.23
Layer 4	Air Gap	0.003
Layer 5	Stem	0.015
Layer 6	Air Gap	0.003
Layer 7	Leaves	0.001
Innermost	Water Vapour	0.002

The properties for these materials are listed below: (Yoshimi & Altan, 14-16)

Table 15 - Green Wall Vegetation Panel Properties

Property	Value
Thickness	0.10 m (typical)
Conductivity	0.35 W/m-K
Density	500 kg/m³
Specific Heat	1600 J/kg-K
Thermal Resistance (R)	0.29 m²·K/W

Table 16 - Air Gap Properties

Property	Value
Thickness	0.003m
Conductivity	5.56 W/m-K
Density	1.3 kg/m³
Specific Heat (J/kg·K)	1004 J/kg-K

Table 17 - Stem Properties

Property	Value
Thickness	0.0150 m
Conductivity	0.1400 W/m-K
Density	110.00 kg/m³
Specific Heat	1880.00 J/kg-K

Table 18 - Leaves Properties

Property	Value
Thickness	0.0010 m
Conductivity	0.4000 W/m-K
Density	533.00 kg/m³
Specific Heat	100.00 J/kg-K

Table 19 - Water Vapor Properties

Property	Value
Thickness	0.0020 m
Conductivity	5.5600 W/m-K
Density	0.60 kg/m³
Specific Heat	1966.00 J/kg-K

Indoor Plants

The indoor plants used for this analysis were Ficus Benjamina. This is a common plant that can grow to standard size indoor plant with low maintenance. In terms of properties to insert in the design builder, the following data was obtained from (Berger, Essah, & Blanusa, 2024).

Table 20 - Indoor Plants Properties

Property	***Value / Description***	***Reference***
Sensible Heat Gain	1.0 – 1.5 W per plant (estimated, based on typical energy balance models for indoor plants)	Estimated from general plant thermodynamics; not directly measured in source (Berger, Essah, & Blanusa, 2024)
Latent Heat Gain (Transpiration)	3.8 – 6.3 W per plant during active daytime periods (corresponds to 35–58 g H_2O/day)	(Berger, Essah, & Blanusa, 2024)
Transpiration Rate	0.56 – 5.09 mmol H_2O $m^{-2} \cdot s^{-1}$ (varies with VPD, temperature, and light)	(Berger, Essah, & Blanusa, 2024)
CO_2 Absorption	Approx. 315 ppm reduction per 24 hours per room-sized volume (group-based estimation)	Not quantified in (Berger, Essah, & Blanusa, 2024); estimate based on prior chamber studies [e.g., (Gubb, Blanusa, Griffiths, & Pfrang, 2019)]
Transpiration Schedule	**Active period**: 08:00 – 18:00 (natural daylight hours) **Peak transpiration**: 10:00 – 16:00	(Berger, Essah, & Blanusa, 2024)

CO_2 concentration during the day and night was not considered since the amount was very small and it is considered as negligible. This can be verified in the graph below. If this was to be considered, this will be inserted as scheduled at night from 7:00-19:00 since the rest of the time is absorption of CO_2 as per table above.

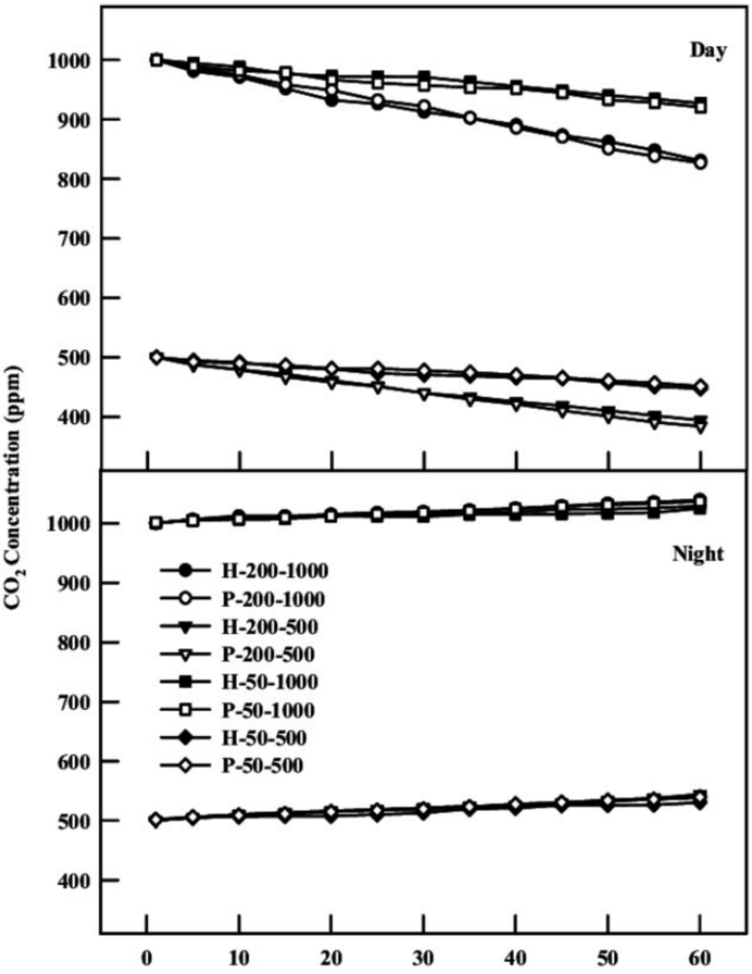


Figure 23 - Changes of CO2 concentration during day and night by Ficus benjamina L. in an airtight chamber treated with the combinations of 500 or 1000 ppm CO2 and 50 or 200 µmol · m -2 · s -1 light intensity. The plant was grown in an 18 cm pot (diameter) containing hydroball (H) or peatmoss (P). (Yang, Pennisi, Son, & Kays, 2009)

In terms of inserting the indoor plants in Design Builder®, these were inserted in each zone as per the proposed drawings as per figure 23 under the activity tab as "Catering" (DesignBuilder Software Ltd, n.d.). This decision was taken based on the most applicable input that one can choose from in Design Builder® as the data for an indoor plant is very similar to this. Also, one needs to mention that fuel was assumed as natural gas so that this will not affect the energy consumption. To input this data the following calculations were done for each zone with plants according to the number of plants designed in that zone.

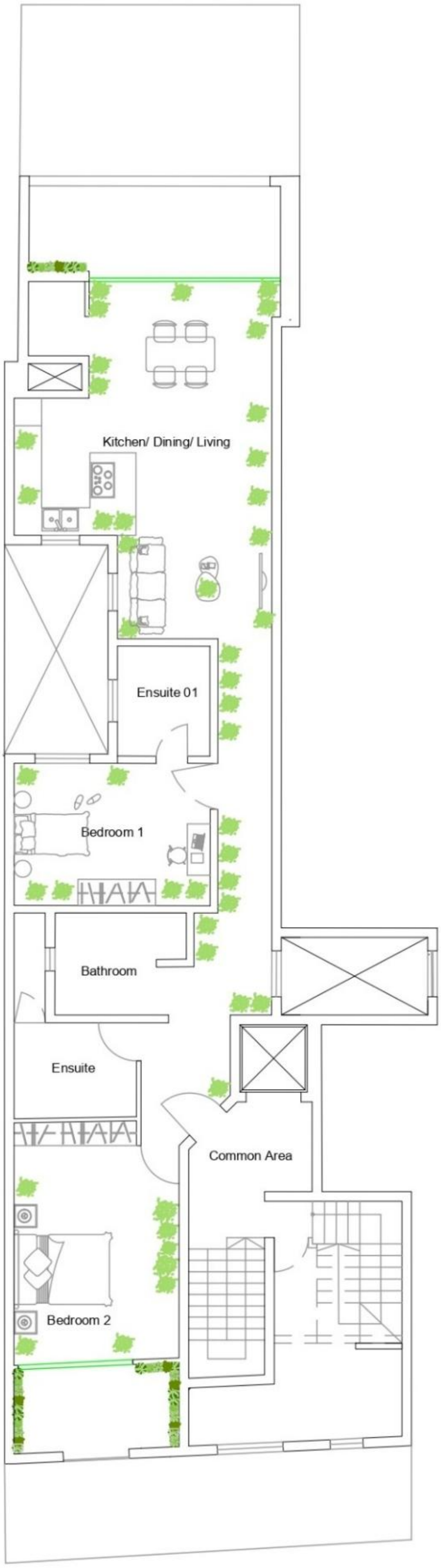


Figure 24 - Proposed Biophilic measures including green walls, enlarged apertures in green and indoor plants (green roof on top) NTS

This was done in the case of the penthouse layout:

Table 21 - Calculations for Indoor Plants

Kitchen/ Dining/ Living			
Total Gains from 20 Plants:	W	Quantity	
Sensible:	1	20	20
Latent:	3.8	20	76
Total			96
Area	34.7	m^2	
total gains/area: density			**2.77**
Fraction loss: (no power is being released)			0
Latent fraction: latent/total			0.79
Radiant fraction: (radiation = convection)			0.104
Bedroom 1			
Total Gains from 6 Plants:	W	Quantity	
Sensible:	1	6	6
Latent:	3.8	6	22.8
Total			28.8
Area	13.28	m^2	
total gains/area: density			**2.17**
Fraction loss: (no power is being released)			0
Latent fraction: latent/total			0.79
Radiant fraction: (radiation = convection)			0.104
Bedroom 2			
Total Gains from 8 Plants:	W	Quantity	
Sensible:	1	8	8
Latent:	3.8	8	30.4
Total			38.4
Area	18.33	m^2	
total gains/area: density			**2.09**
Fraction loss: (no power is being released)			0

Latent fraction: latent/total			0.79
Radiant fraction: (radiation = convection)			0.104
Corridor			
Total Gains from 13 Plants:	W	Quantity	
Sensible:	1	13	13
Latent:	3.8	13	49.4
Total			62.4
Area	16.23	m^2	
total gains/area: density			**3.84**
Fraction loss: (no power is being released)			0
Latent fraction: latent/total			0.79
Radiant fraction: (radiation = convection)			0.104

An example of the inputted data is shown in the table below:

Table 22 - Kitchen/ Dining/ Living Inputted Data

Property	**Value**
Power density (W/m²)	2.77
Schedule	Indoor Plants – Ficus benjamina
Fuel	2–Natural gas
Fraction lost	0.000000
Latent fraction	0.790000
Radiant fraction	0.104000
CO2 generation rate	0.000000000

It is important to note that radiant fraction was calculated by 1 minus the latent, the answer will be divided by 2 as the radiant fraction and convection are equal and according to design builder the total had to be 1. As per data shown before regarding the schedule, the schedule from 8:00 to 18:00 was set for the indoor plants.

3.6.5 Ground floor maisonette with biophilic design measures

the biophilic design measures for this maisonette include the following:

Table 23 - Biophilic Interventions for the Ground Floor Maisonette

Biophilic Intervention	***Description of Intervention***	***Implementation in DesignBuilder®***	***Layer/Material Details***
Natural Ventilation	North- and south-facing openings sized for airflow	Aperture size: Bedroom 1 south window set to 2.5m x 2.5m; Kitchen/Dining/Living north height increased to 2.5m and width 3m	Set window size and operability for ventilation.
Shading Devices (Overhang)	External horizontal overhang on façade	Overhang of 1.5m added above openings (likely modelled in shading or geometry settings)	Adjust in the openings tab
Green Walls	North and south facades with green walls	Defined as wall construction or added as attached construction with layers for simulation	Vegetation layer Support frame Moisture barrier
Indoor Green Walls	North and south facades with green walls	Defined as wall construction or added as attached construction with layers for simulation	Water vapour Leaves Air gap Stem Air gap
Indoor Vegetation	Use of internal plants to provide thermal mass	Modelled under **Internal Thermal Mass** in Construction tab	----

Apertures

In terms of apertures these were enlarged as follows:

Bedroom 1 – opening south dimensions were increased from 1 by 1.2 to 2.5 by 2.5m

Kitchen/Dining/Living – opening north dimension was increase from 2 windows 1 by 1.2 to one window 2.5 by 3m.

Apart from this a general 1.5m overhang shading was placed with every aperture. In terms of glazing this remained double glazing as the penthouse model.

Green Walls

The same settings used in the penthouse model are adopted here.

Indoor Plants

Same properties used in the penthouse model but different quantities of plants and zones according to the maisonette layout.

This was done in the case of the ground floor maisonette proposed drawings as per figure 24:

Figure 25- Proposed Biophilic measures including green walls, enlarged apertures in green and indoor plants NTS

Table 24 - Calculations for Indoor Plants

Kitchen/ Dining/ Living			
Total Gains from 15 Plants:	W	Quantity	
Sensible:	1	15	15
Latent:	3.8	15	57
Total			72
Area	38.05	m^2	
total gains/area: density			**1.89**
Fraction loss: (no power is being released)			0
Latent fraction: latent/total			0.79
Radiant fraction: (radiation = convection)			0.104
Bedroom 1			
Total Gains from 6 Plants:	W	Quantity	
Sensible:	1	6	6
Latent:	3.8	6	22.8
Total			28.8
Area	16.73	m^2	
total gains/area: density			**1.72**
Fraction loss: (no power is being released)			0
Latent fraction: latent/total			0.79
Radiant fraction: (radiation = convection)			0.104
Bedroom 2			
Total Gains from 5 Plants:	W	Quantity	
Sensible:	1	5	5
Latent:	3.8	5	19
Total			24
Area	12.55	m^2	
total gains/area: density			**1.91**
Fraction loss: (no power is being released)			0
Latent fraction: latent/total			0.79
Radiant fraction: (radiation = convection)			0.104

Bedroom 3			
Total Gains from 9 Plants:	W	Quantity	
Sensible:	1	9	9
Latent:	3.8	9	34.2
Total			43.2
Area	23	m^2	
total gains/area: density			**1.88**
Fraction loss: (no power is being released)			0
Latent fraction: latent/total			0.79
Radiant fraction: (radiation = convection)			0.104

Corridor			
Total Gains from 10 Plants:	W	Quantity	
Sensible:	1	10	10
Latent:	3.8	10	38
Total			48
Area	10.87	m^2	
total gains/area: density			**4.42**
Fraction loss: (no power is being released)			0
Latent fraction: latent/total			0.79
Radiant fraction: (radiation = convection)			0.104

3.6.6 Heating and Cooling consumption

Finally, the HVAC was considered on to monitor the energy consumption for cooling and heating. This was done with the same settings for all models. These settings include:

Template: Fan coil unit (4 pipe), air cooled chiller.

- Heated on with a CoP of 3
- Cooled on with a CoP of 3
- Electricity from grid
- Schedule as a common area for domestic use.

Typical CoP values were used.

Then a comparison between the existing and the biophilic designed layouts was done. The most important exercise for this was the difference between the existing and the proposed retrofitted biophilic designed layouts. It is important to mention that the adaptive CEN Standard 15251 was ticked as on for all output data on Design Builder®.

3.6.7 Summary of interventions in biophilic design (including lighting, thermal comfort and energy performance)

The interventions intended to be used for this analysis include:

- Daylight
- Air
- Plants

These are essential elements to improve the indoor environment quality and enhance the well-being of the building occupants. These elements will also contribute to a sustainable building in terms of energy performance and reducing the environmental impact.

Daylight

Natural light is one of the main key elements in biophilic design. This can be achieved by means of large apertures, skylights and other open spaces that allow daylight to filter into the building interior. This will obviously reduce the reliance on artificial light therefore will improve energy efficiency. This has to be implemented with adaptive shading systems that will optimize daylight while reduce heat gain or glare. These elements will affect thermal comfort and visual well-being. (Parsaee et al., 2019), (Kellert, Heerwagen, & Mador, 2009).

Air:

Natural ventilation can be achieved through openable apertures, atriums and cross-ventilation. These strategies enhance air quality and also create a connection between the indoor and outdoor environment. This can be further enhanced by including vegetation such as green walls or vertical gardens. This leads to better air quality by naturally filtering the pollutants and also improving oxygen levels which leads to healthier indoor spaces (Wijesooriya & Brambilla, 2021), (Park, Kim, Yoo, Oh, & Son, 2010).

Plants:

Plants can be integrated into the built environment in different ways, such as green roofs, internal or external vertical gardens, and landscaping. Apart from improving the air quality and reduce the urban heat island effect plus being an insulation, the presence of greenery has been shown to enhance psychological well-being. This includes the reduction of stress and improve cognitive function. Therefore, such measures will lead to a sustainable building (Wijesooriya & Brambilla, 2021), (Park, Kim, Yoo, Oh, & Son, 2010).

Chapter 4 Results and Discussion

4.1 Introduction

In this chapter, all the results are discussed, including the existing monitoring in 2 different scenarios and the simulations for the existing and biophilic interventions. The simulation findings are analysed in terms of thermal comfort standards, energy performance and human well-being criteria. This will also include the evaluation of the performance of typical apartments' scenarios including the most extreme cases being the top floor level and the lowest floor level compared to the same apartments' scenarios with biophilic improvements.

This chapter will also show the impact of natural elements such as ventilation, daylight, vegetation and materiality, in terms of energy efficiency and thermal comfort. This will include quantitative data from design builder simulations and monitoring with data logger based on the research in the literature reviewed. The main aim is to identify the potential of the biophilic implementation to bridge the gap between the sustainability and human-centred architecture approach for both retrofitting and new development.

4.2 Validation with Existing Data

4.2.1 Temperature Difference

4.2.1.1 Ground Floor Maisonette

To make sure that the simulation model is optimized with real data, the temperature data collected from the kitchen/ dining/ living of the ground floor maisonette was compared with simulated results of the same space.

The data sets from the data logger (2025) and the simulation (2024 based on weather data availability) were analysed over a period of one month between the 9th of March and 7th of April. Apart from this a further detail was done by assessing four specific days to make sure that the data had the same trend daily. As explained in the methodology, some finetuning was required to make the model optimized as possible to the real data, such as the air infiltration.

Figure 26 shows the temperature difference between outdoor and indoor environments on the whole month on an hourly basis. From these results, it was noted that the indoor temperature remained constant when compared to the outdoor temperature. This is also since the adjacent and upper apartments of this floor acts as a buffer from solar exposure. It is important to note that the measured data and the simulation are very similar and follow the same pattern with changes that are within the range of +/-3°C. This shows that the model is very valid.

To have a more detailed analysis, four days were chosen to be compared in detail. From figure 27 (10th March) the measured data and the simulation shows a good similarity with a similar pattern. This is reflected in all the data sets compared for the other 3 days. Overall, there was a limited margin of variation but with a similar pattern. Another example was figure 29 (24th March), this shows a constant variation therefore having similar indoor environment conditions. Considering that the temperature difference remained within a range of 2.5°C for the simulation, showing the accuracy of the model and therefore the results.

From this analysis, it was concluded that the energy model's is credible and confirm that the existing case is accurately modelled in terms of thermal performance to the existing maisonette.

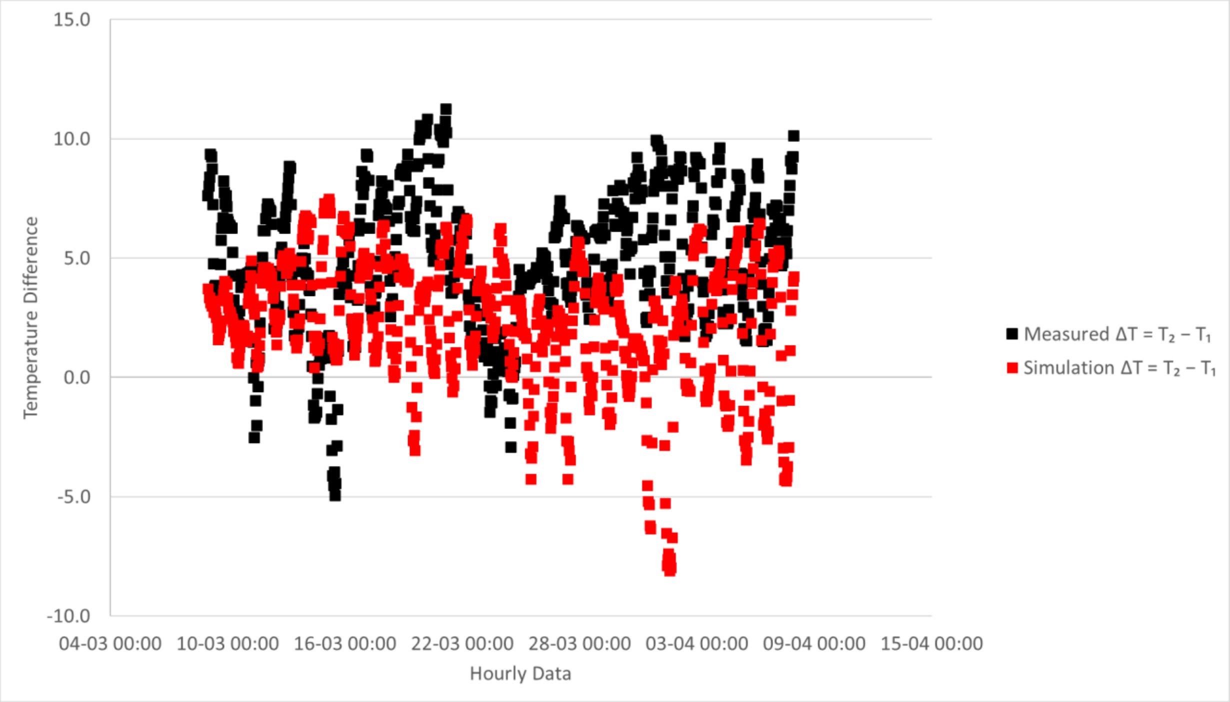


Figure 26 - Temperature Difference between outdoor and indoor results for a period of 1 month from the 9th of March to the 7th of April - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the ground floor Maisonette Results

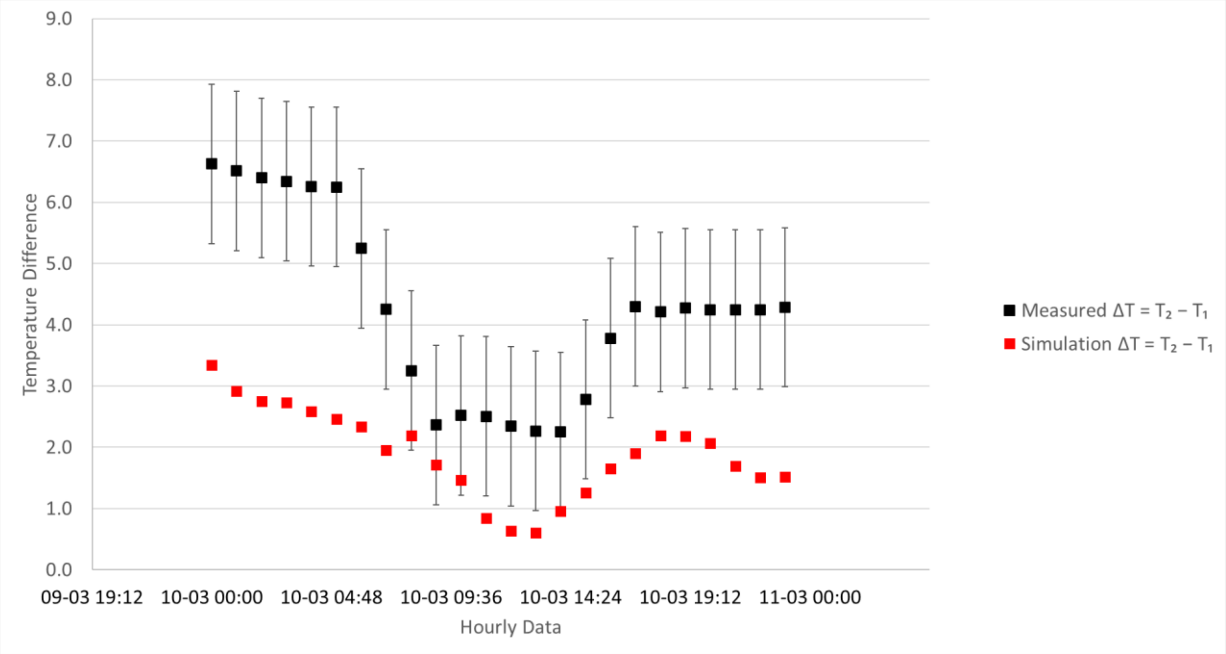


Figure 27 - Temperature Difference between outdoor and indoor results for a period of 1 day (10th of March) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the ground floor Maisonette

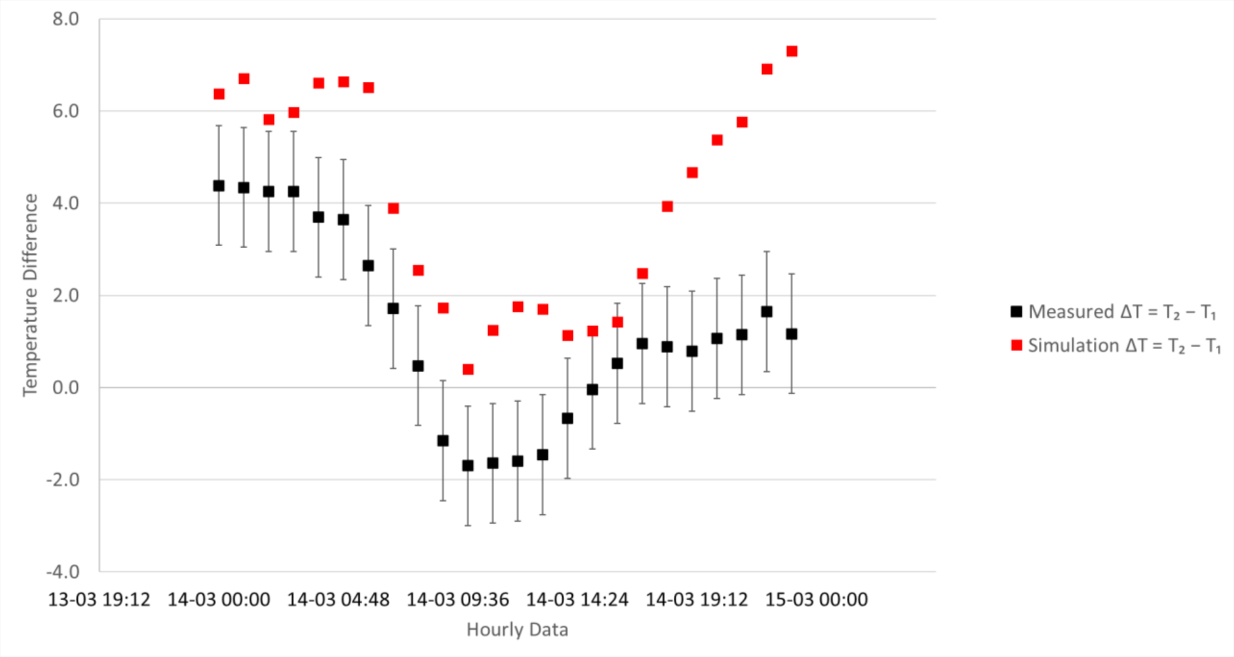


Figure 28 - Temperature Difference between outdoor and indoor results for a period of 1 day (14th of March) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the ground floor Maisonette

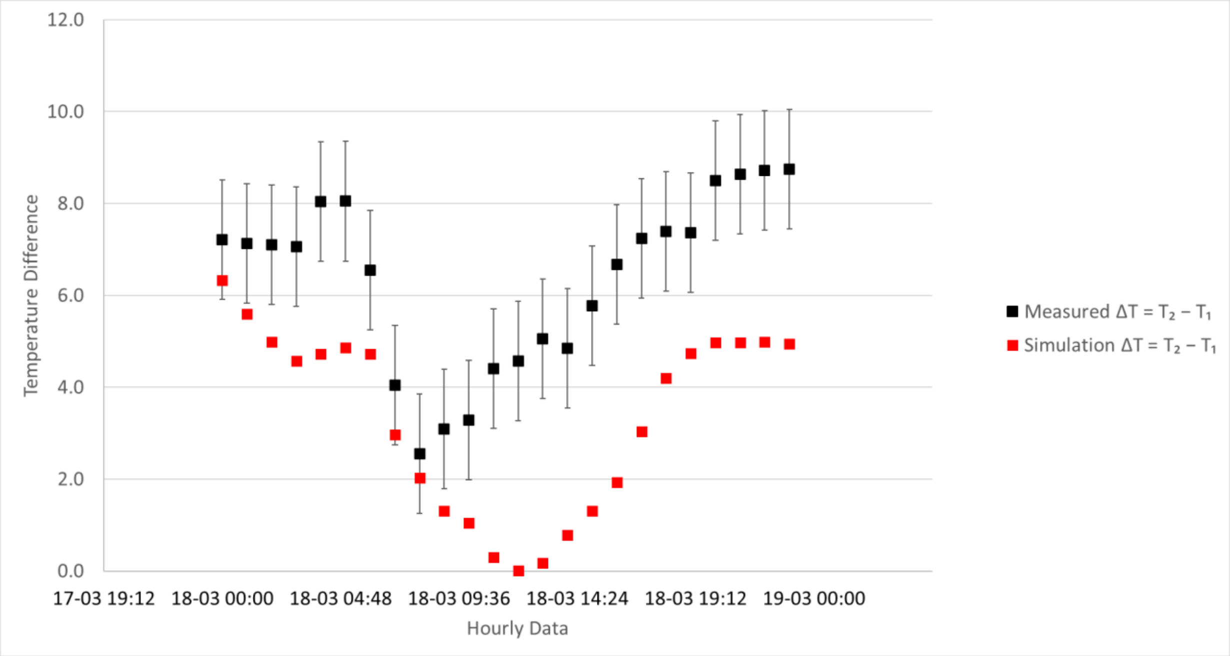


Figure 29 - Temperature Difference between outdoor and indoor results for a period of 1 day (18th of March) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the ground floor Maisonette

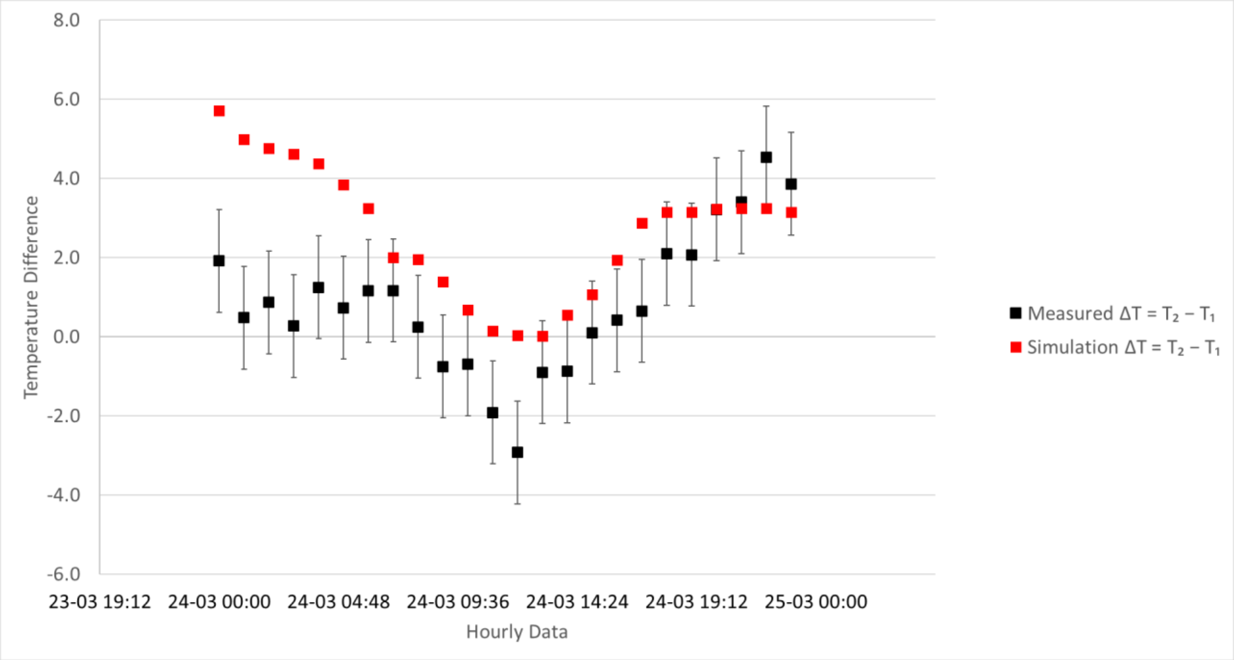


Figure 30 - Temperature Difference between outdoor and indoor results for a period of 1 day (24th of March) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the ground floor Maisonette

4.2.1.2 Penthouse

The same process was done for the penthouse. The data sets from the data logger (2025) and the simulation (2024 based on weather data availability) were analysed over a period of one month between the 10th of February and 8th of March. The area used for this analysis was the kitchen/ dining/ living area therefore the simulation compared with was of the same zone. When compared with the ground floor, one can note that on an average, the temperature differences are higher, and the ranges shifted to high temperatures that are within the range of +/-6°C. This is since the penthouse is more exposed to the external considering the full roof.

As the other model, I also focused on 4 days to analyse in detail these results. From figure 32 (12th February) the temperature difference is very accurate as some of the hours are nearly the same or within the range of the error bar from the measured data. Similarly to figure 33 (13th February) the temperature difference is nearly the same, showing a negligible difference. This will also confirm that the model was verified and can be used for this analysis. This will also confirm that such biophilic implementations can be easily assessed when compared to the existing scenarios.

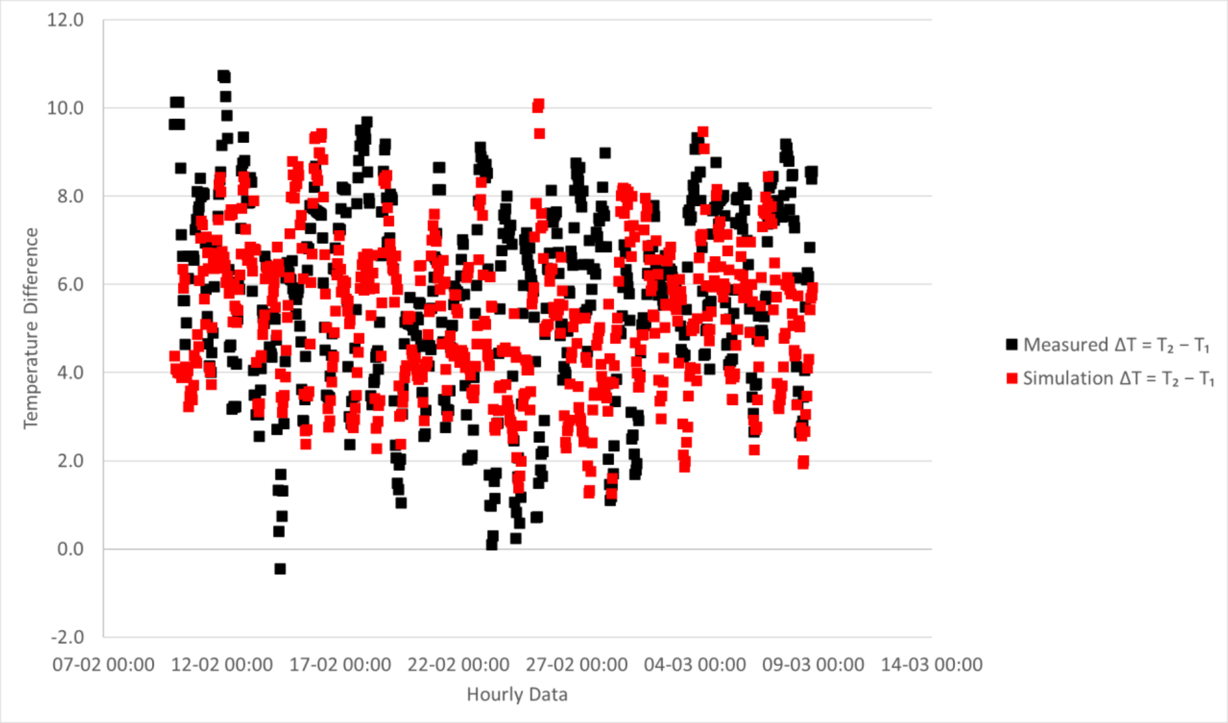


Figure 31 - Temperature Difference between outdoor and indoor results for a period of 1 month from the 10th of February to the 8th of March - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the Penthouse

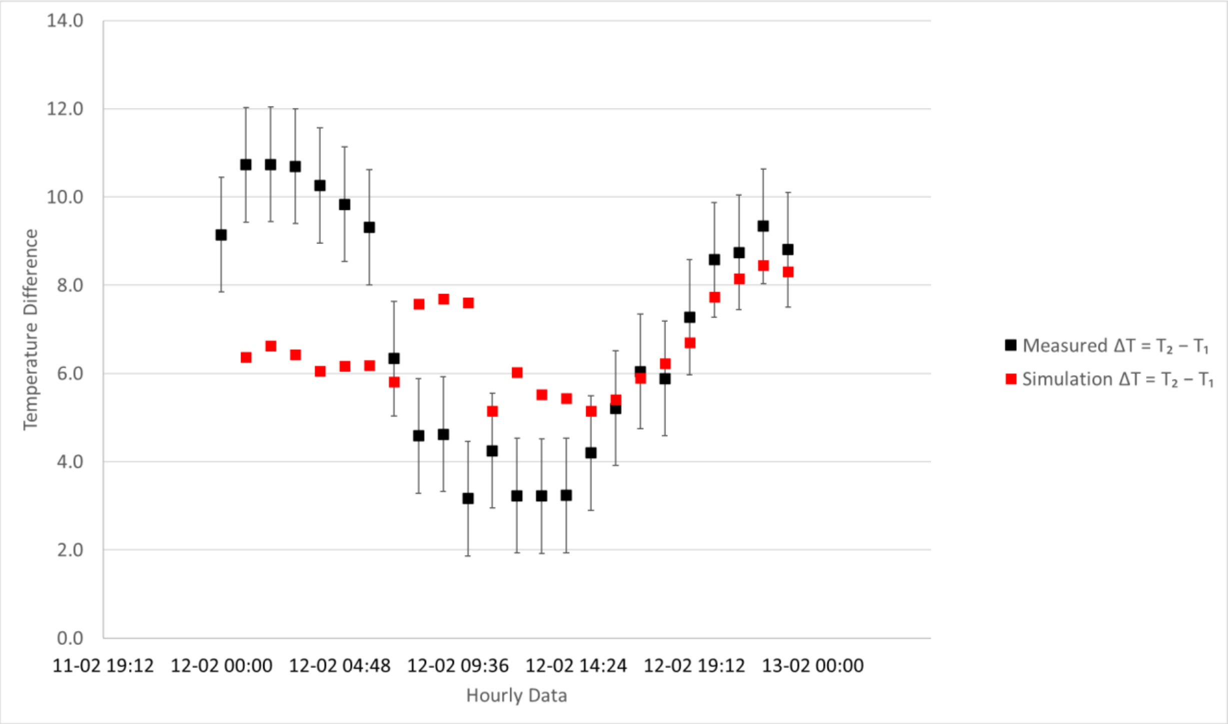


Figure 32 - Temperature Difference between outdoor and indoor results for a period of 1 day (12th of February) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the Penthouse

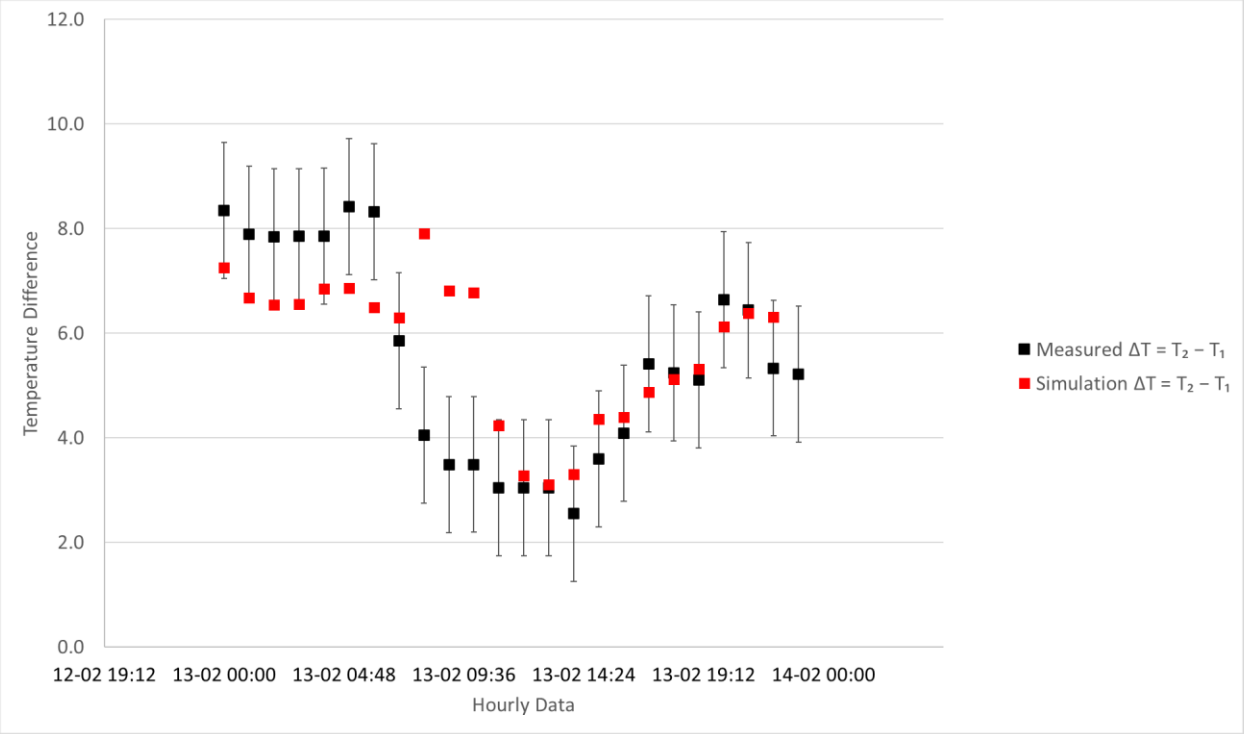


Figure 33 - Temperature Difference between outdoor and indoor results for a period of 1 day (13th of February) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the Penthouse

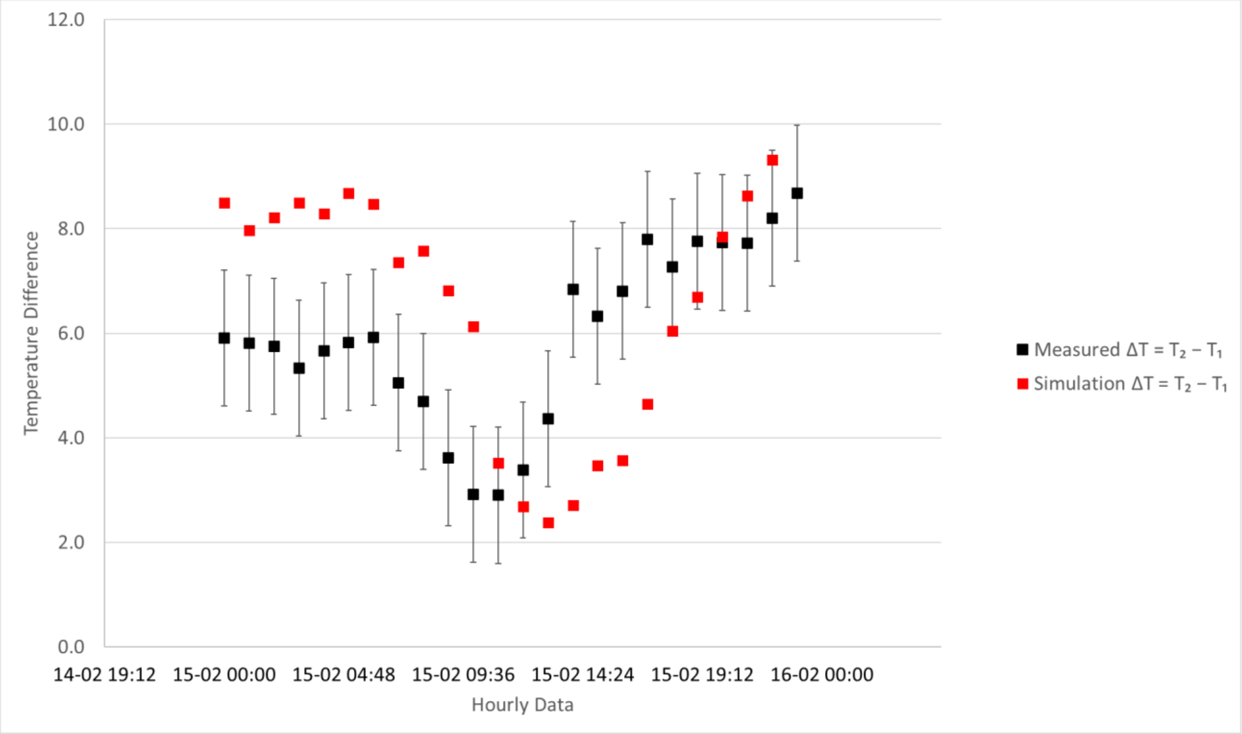


Figure 34 - Temperature Difference between outdoor and indoor results for a period of 1 day (15th of February) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the Penthouse

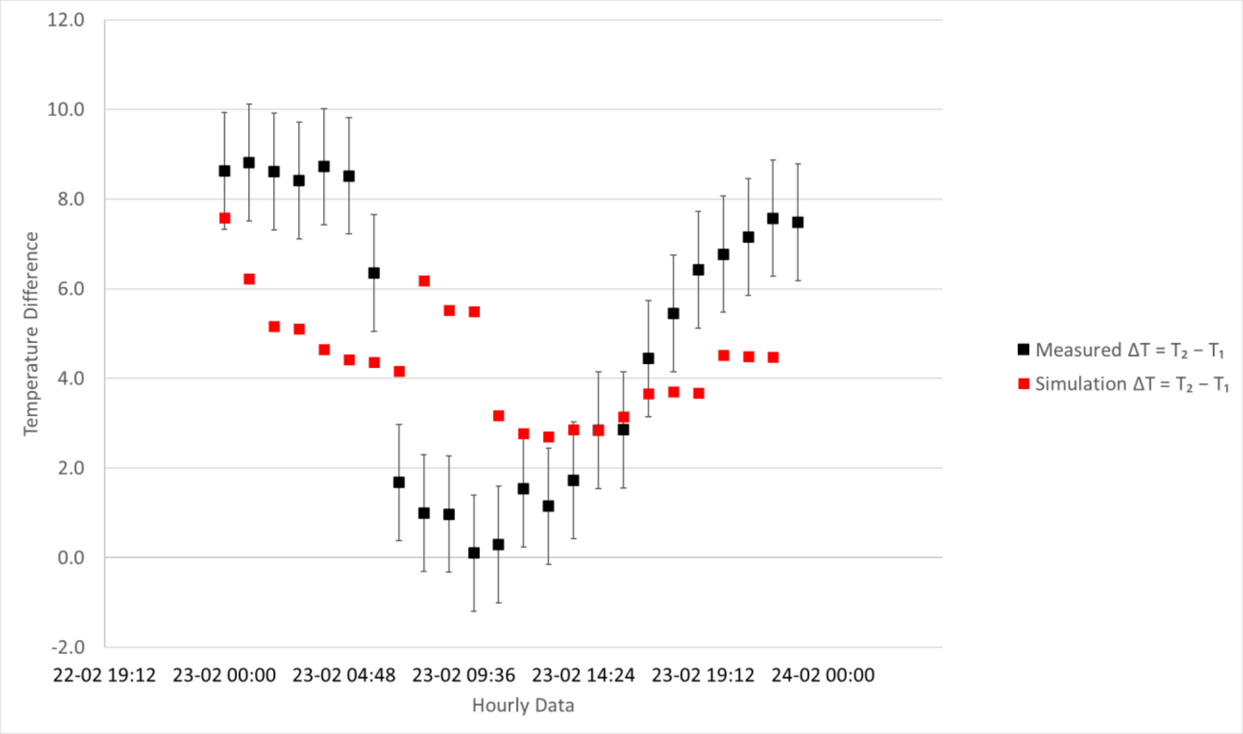


Figure 35 - Temperature Difference between outdoor and indoor results for a period of 1 day (23rd of February) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the Penthouse

4.2.2 CO_2 in ppm

4.2.2.1 Ground Floor Maisonette

The same validation process was carried out for the CO_2 to assess the indoor air quality and validate the simulation model. This includes hourly data of CO_2 levels measured from the ground floor maisonette compared to the simulation. The same zone (kitchen/ dining/ living area) was used for this analysis. This space was chosen since it is the most occupied there representative for the living patterns in this existing maisonette.

Figure 36 shows a one-month comparison between from the 9th March to the 7th April. The measured data levels range from 500ppm to a peak of around 2500ppm depending on the occupancy as specified in the methodology. Compared to the simulation that confirms that the model was validated since the ranges are within the same values but will not peak more than around 800ppm. This is since the occupancy was set with a timetable as explained in the methodology and ventilation was not considered.

To have a detailed analysis of this data, 4 days were chosen to prove that the patterns and values are within the same range. As one can note in figure 37 (13th March) the simulation and the measured data are nearly identical except from some of the hours, but the patterns are very consistent. This shows a morning rise in CO_2 due to the occupancy schedule with a peak at mid-day. This shows that the set occupancy and the infiltration rates in the model are like the existing scenario. Similarly to this can be observed in figure 38 (18th March) where the patterns and values are very consistent except from such instances that in real life could be some conditions that were not predictable. This also shows the effect of limited natural ventilation for both the measured and the model.

In figure 39, one can also observe that the CO_2 are very constant and most of them below 900ppm. Some changes in CO_2 from the measured data are due to instances where the apertures being opened or other instances of higher occupancy that was not considered in the model.

To conclude, the measured data and the simulation shows a high level of correlation between with differences in the range of +/-50ppm. This shows that the existing simulation in very accurate and can be used for testing the biophilic implementation including natural ventilation.

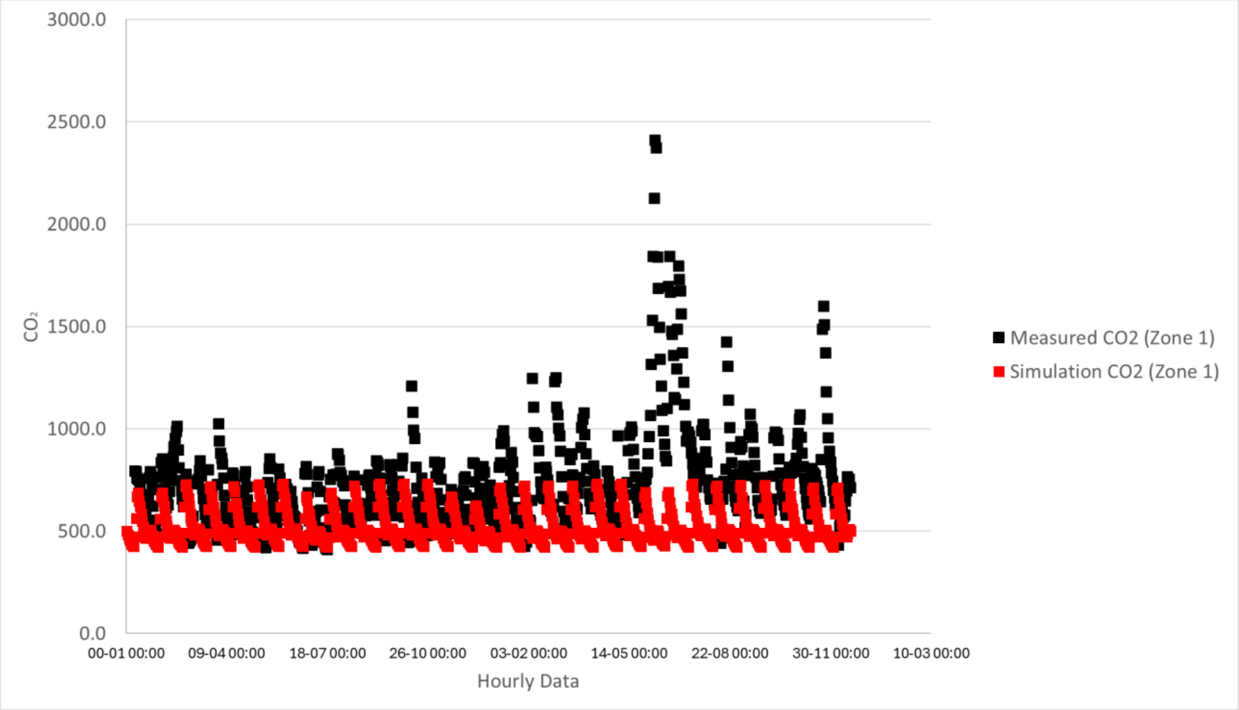


Figure 36- CO_2 results for a period of 1 month from the 9th of March to the 7th of April - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the ground floor Maisonette

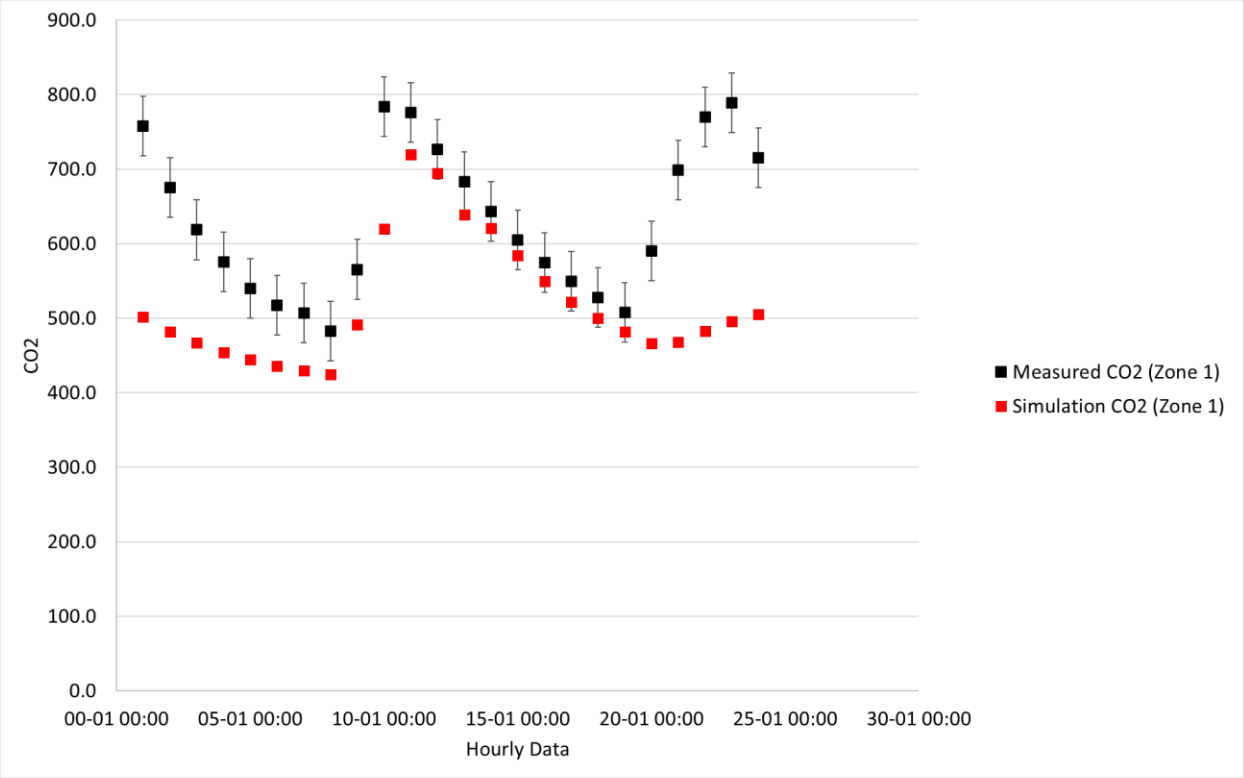


Figure 37 - CO_2 results for a period of 1 day (13th March) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the ground floor Maisonette

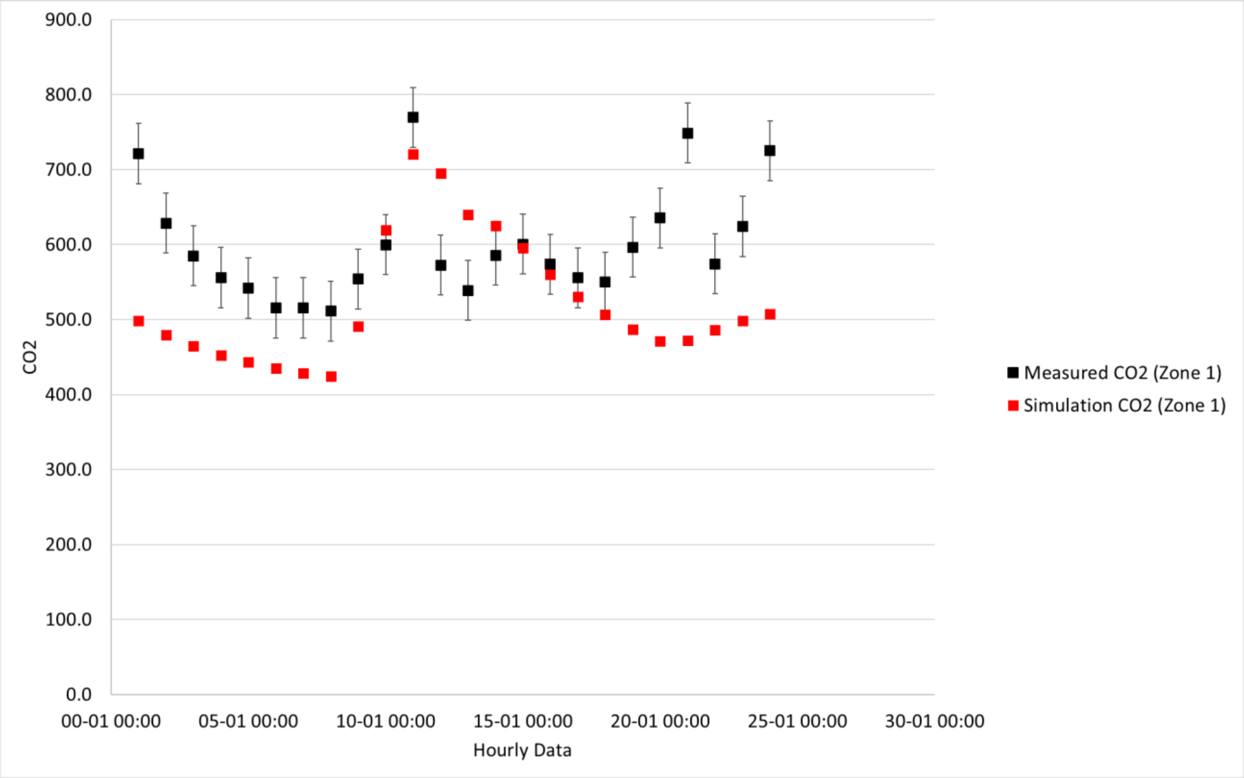


Figure 38 - CO^2 results for a period of 1 day (18th March) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the ground floor Maisonette

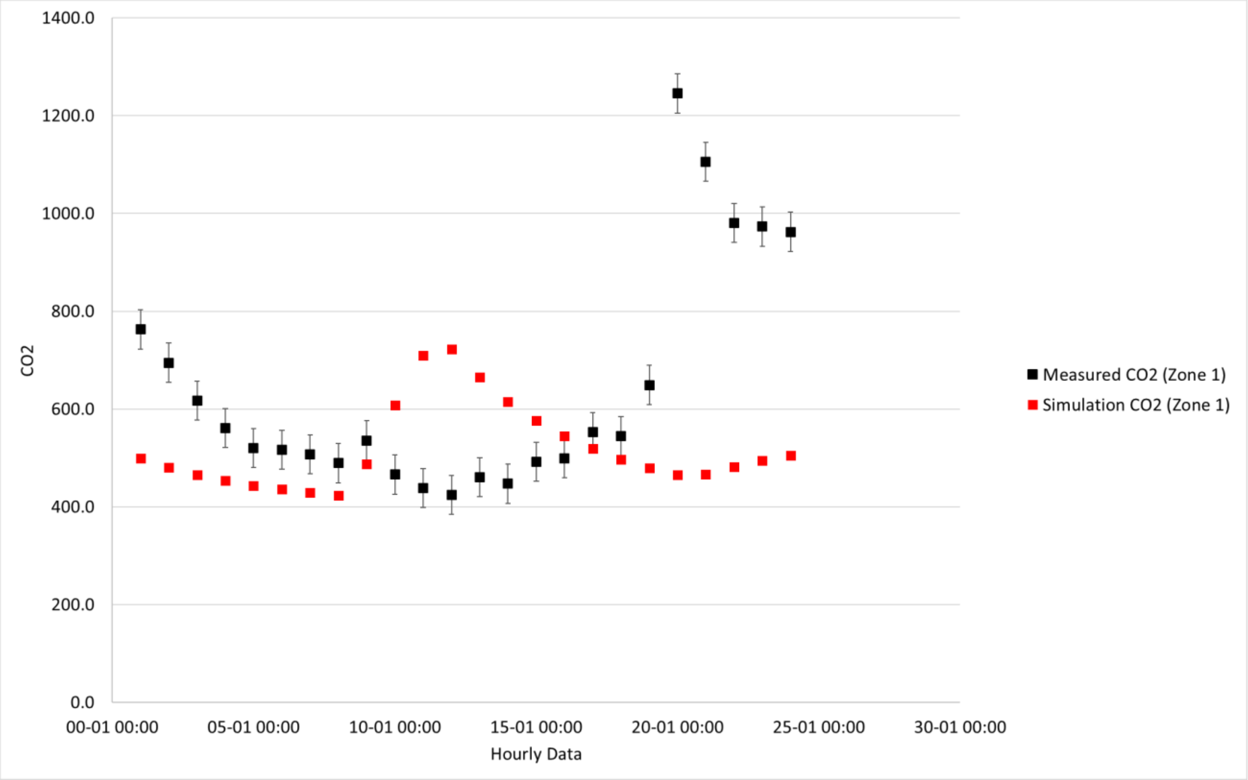


Figure 39 - CO_2 results for a period of 1 day (25th March) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the ground floor Maisonette

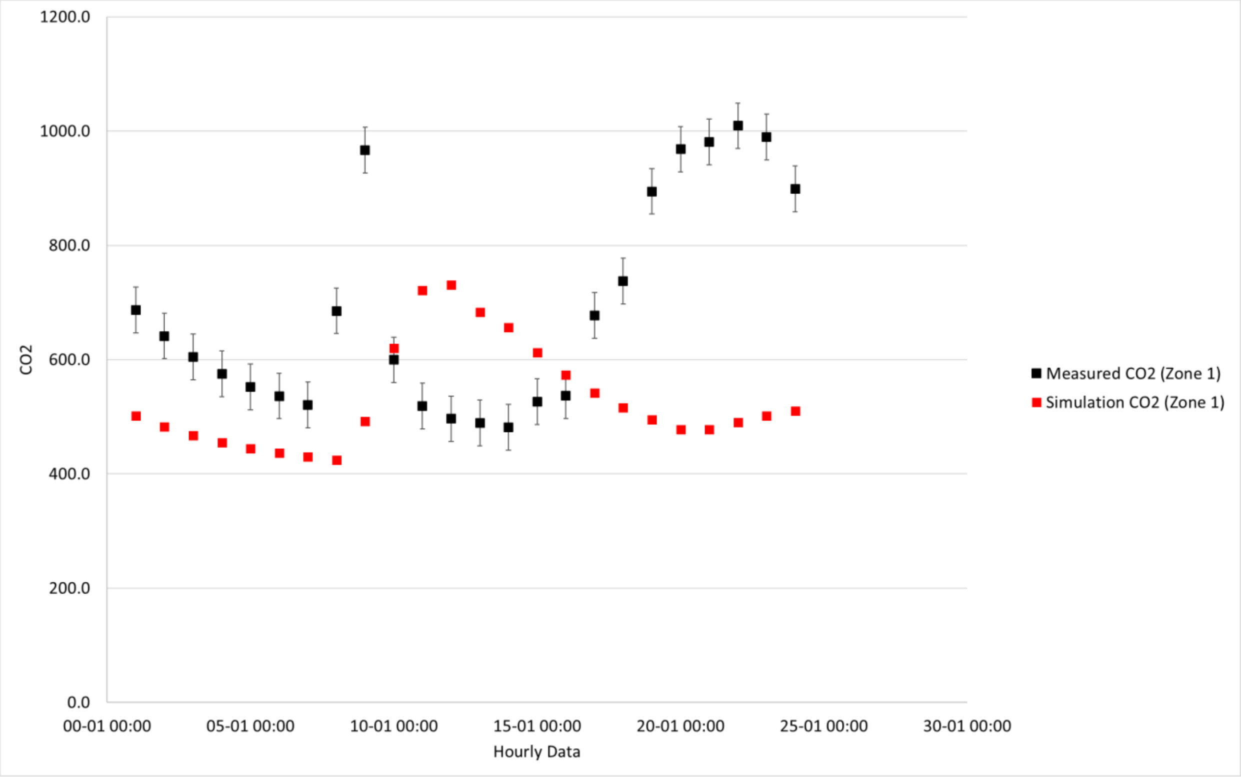


Figure 40 - CO_2 results for a period of 1 day (29th March) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the ground floor Maisonette

4.2.2.2 Penthouse

The same validation was done for the penthouse. The measured period was between the 10th February and the 8th March. As the ground floor maisonette, same zone was used for this analysis.

Figure 41 shows the results of one-month comparison. The measured data levels range from 450ppm to a peak of around 1050ppm depending on the occupancy as specified in the methodology. Compared to the simulation that confirms that the model was validated since the ranges are within the same values but will not peak more than around 800ppm. Same as the ground floor, the occupancy was set with a timetable as explained in the methodology and ventilation was not considered.

To have a detailed analysis of this data, 4 days were chosen to prove that the patterns and values are within the same range. As one can note in figure 42 (12th February) the simulation and the measured data are nearly identical with same patterns and ranges. As the ground floor, the results of one typical day shows a morning rise in CO_2 due to the occupancy schedule with a peak at mid-day and drop to the night. This also shows that the set occupancy and the infiltration rates in the model are like the existing scenario.

Similarly to this can be observed in figure 43 (19th February) where the patterns and values are very consistent except from such instances. This also shows the effect of limited natural ventilation for both the measured and the model.

To conclude, the measured data and the simulation shows a high level of correlation between with differences in the range of +/-50ppm or less. This shows that the existing simulation in very accurate and can be used for testing the biophilic implementation including natural ventilation. One can also mention that the simulation patterns are very accurate when comparing the different days of simulation, while the measured will change in some instances due to existing situations that were not defined.

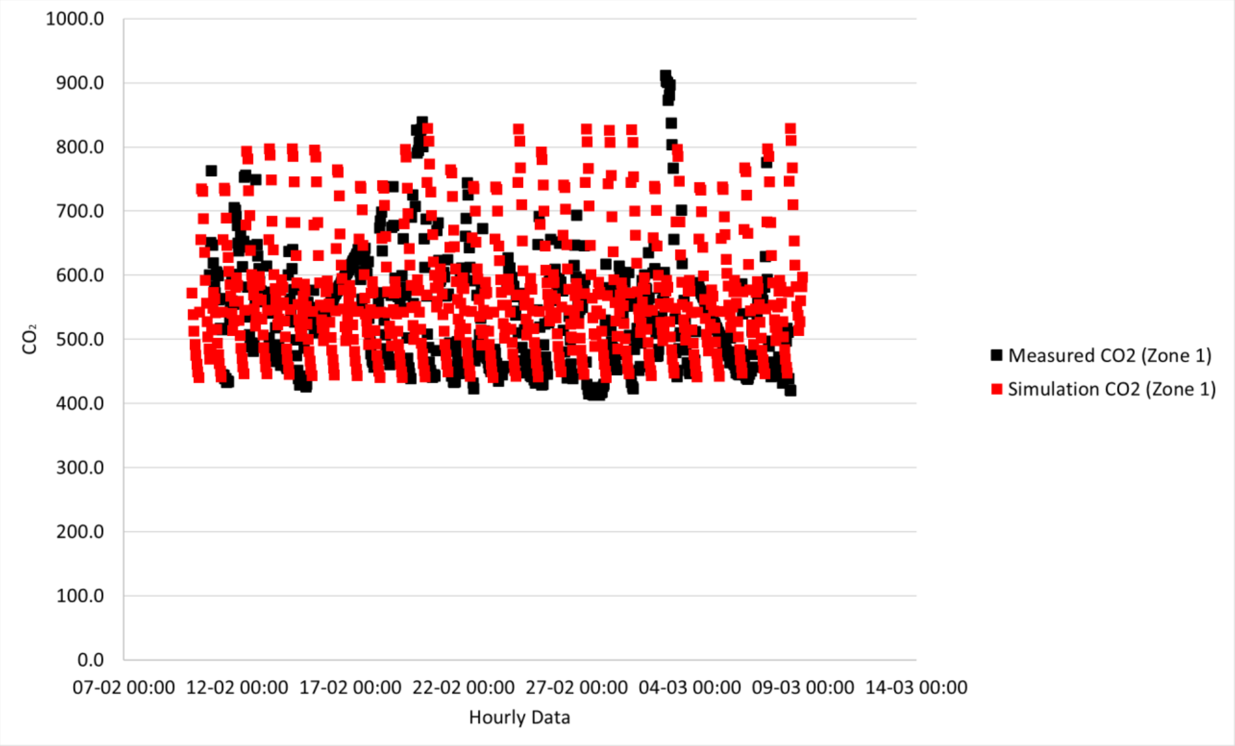


Figure 41 – CO_2 results for a period of 1 month from the 10th of February to the 8th of March - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the Penthouse

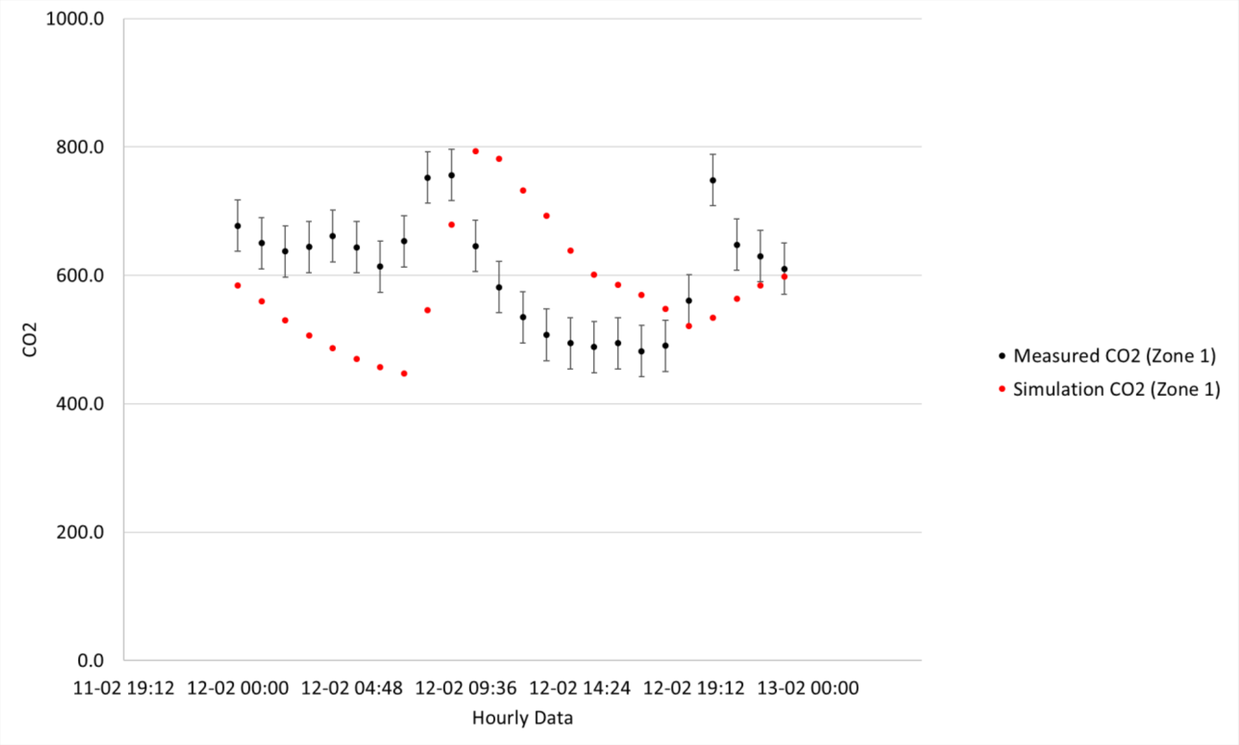


Figure 42 - CO_2 results for a period of 1 day (12th February) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the Penthouse

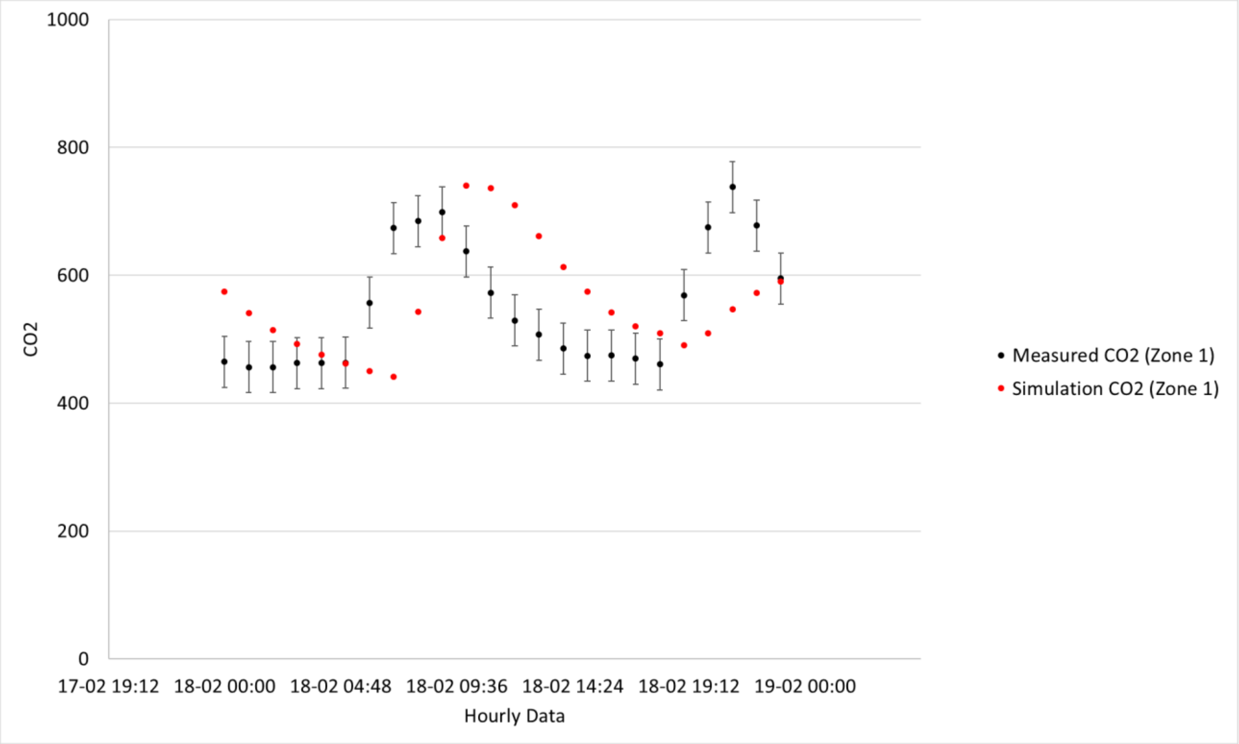


Figure 43 - CO_2 results for a period of 1 day (19th February) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the Penthouse

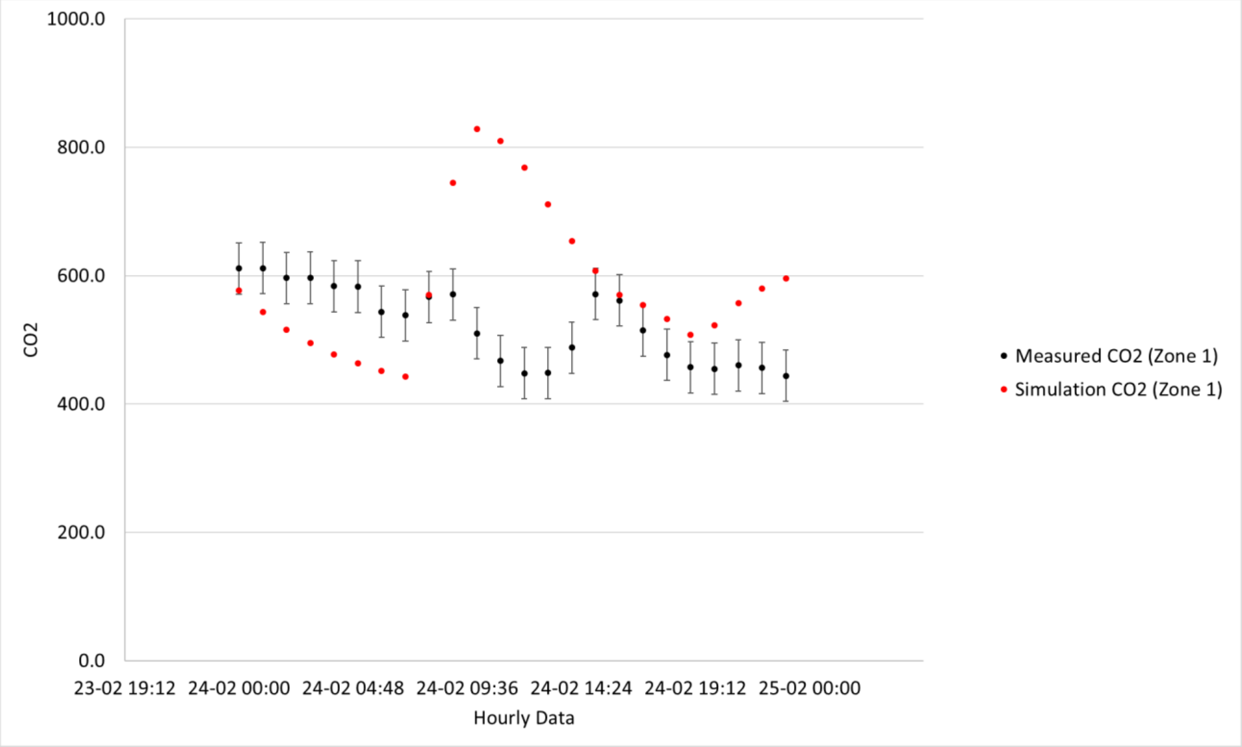


Figure 44 - CO_2 results for a period of 1 day (24th February) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the Penthouse

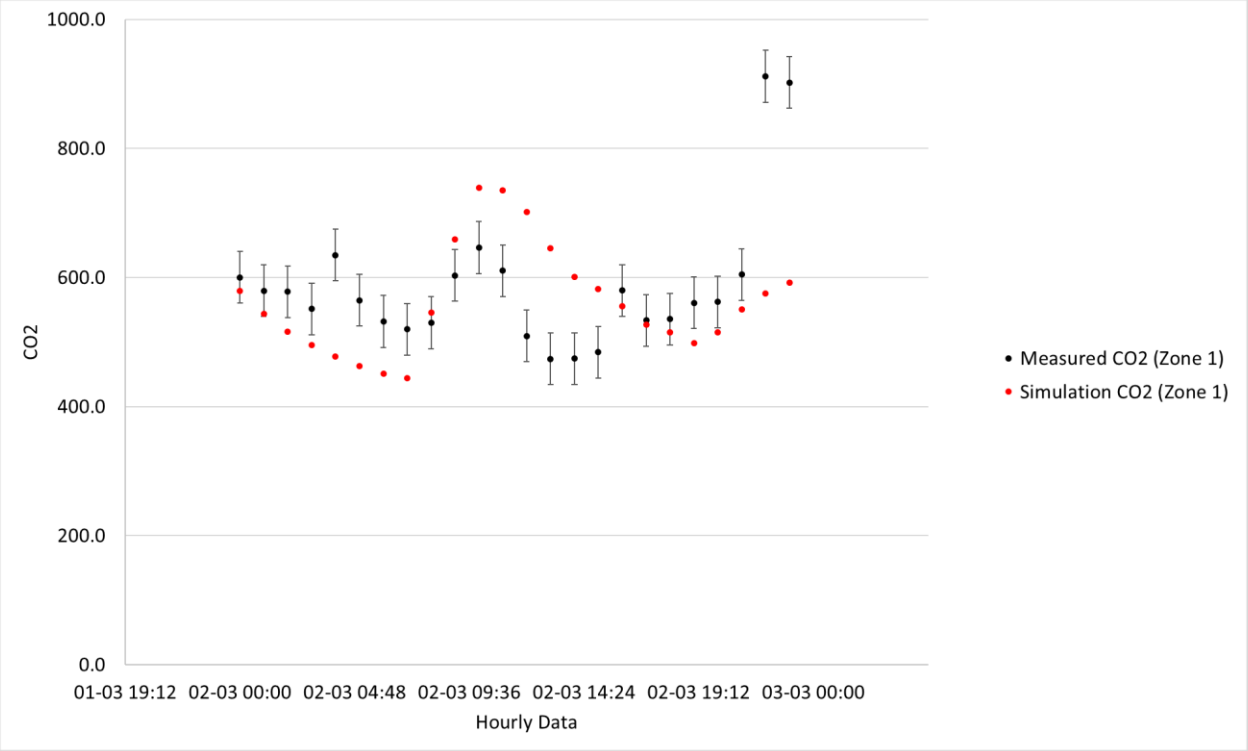


Figure 45 - CO_2 results for a period of 1 day (2nd March) - Comparison between the measured (2025) and simulation (2024) hourly data of the kitchen/dining/living of the Penthouse

4.3 Adaptive Comfort Analysis

4.3.1 Ground Floor Maisonette

In this section a comparison of simulation results over a full year for each zone between the existing conditions and the biophilic design implementations. From these results one can immediately notice that the existing scenario was within the adaptive comfort zone when considering category II and III. On the other hand, for Category I, that is considered as the highest level of expectation therefore the most ideal temperature in terms of comfort, one can immediately notice that with the implementation of the biophilic measures, the temperature nearly satisfied this zone. This shows that the implementation of the biophilic design measures in the ground floor was successful in terms of temperature comfort.

From the first zone (Kitchen/ Dining/ Living area as the most living space, this shows a high improvement with biophilic design implementation. For category I, a good effect is very visible from 74.86% to nearly 100%. On the other hand, the other categories did not change much since these were already 100%. This clearly shows that for the whole year the adaptive comfort is reached.

On the other hand, considering the bedrooms, these also shows same improvement in category I. Bedroom 1 achieved 100% from 90.88%, bedroom 2 achieved almost 100% from 79.28%, while bedroom 3 achieved almost 95% from 80.66%. although same biophilic design measures were implemented one can note that bedroom 3 positioning and availability to natural ventilation is different, also the fact that the green wall was not implemented in that areas since it is not south facing. Overall, this also shows that the biophilic design implementation have a positive impact on thermal comfort. These improvements show increase in natural airflow and controlled solar heat gains from the openable and size of the apertures and the shading.

In the other rooms including the bathroom, ensuite, walk-in and pantry, no specific interventions were implemented, therefore one can see the effect from the results. For the bathroom it shows there was improvement in category I, from 72.1% to 97.51%, this is since this is in the same area of the kitchen/ dining/ living. On the other hand, a very minimal change (from 54.14% to 54.70%) can be observed in the ensuite, as discussed before this is next to bedroom 3 where changes were very minimum except from the indoor plants effect. The walk-in is near the corridor and the bedroom 3, this area is very enclosed and is not affected from the external environment. As the bathroom, there was a good effect in the pantry, this is since this is next to the main area and the corridor.

Finally, from the results of the corridor, one can observe a good performance in category I from 88.12% to 100%, apart from the cumulative thermal effect, indoor plants were introduced in this area. One can conclude that the biophilic measures have a significant effect to the adaptive comfort, almost always reaching category I. This means that the thermal conditions improved to a high quality.

For ease of reference, the following legend was used for the following results:

– – Category I upper
– – Category I lower
– – Category II upper
– – Category II lower
– – Category III upper
– – Category III lower
🟥 Kitchen/Dining/Living Existing
🟦 Kitchen/Dining/Living Biophilic

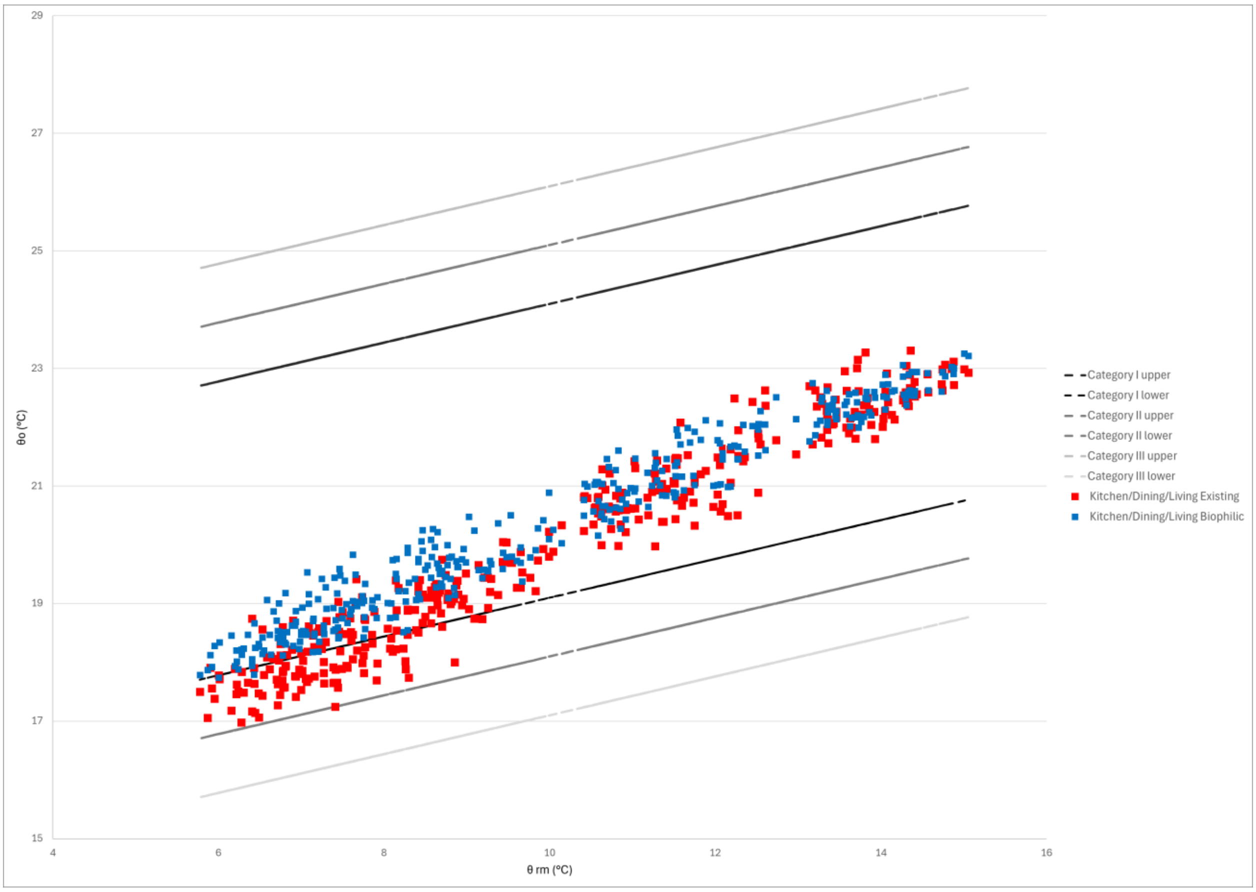


Figure 46- Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the kitchen/dining/living of the ground floor Maisonette also compared with the categories of the adaptive comfort as per EN 16798-1

Table 25 - Kitchen/ Dining/ Living Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	74.86%	100.00%	100.00%
Biophilic	99.17%	100.00%	100.00%

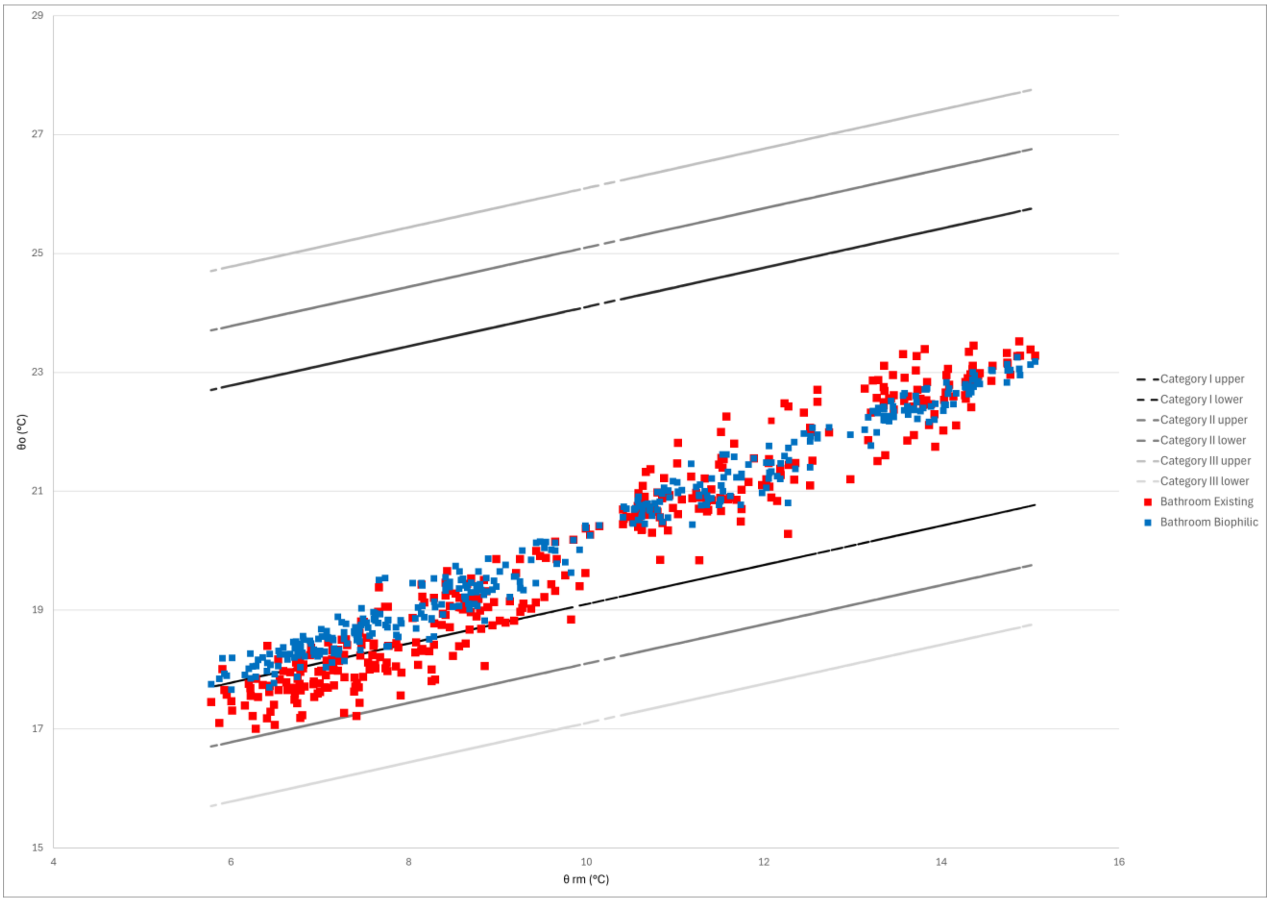


Figure 47 - Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bathroom of the ground floor Maisonette also compared with the categories of the adaptive comfort as per EN 16798-1

Table 26- Bathroom Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	72.10%	100.00%	100.00%
Biophilic	97.51%	100.00%	100.00%

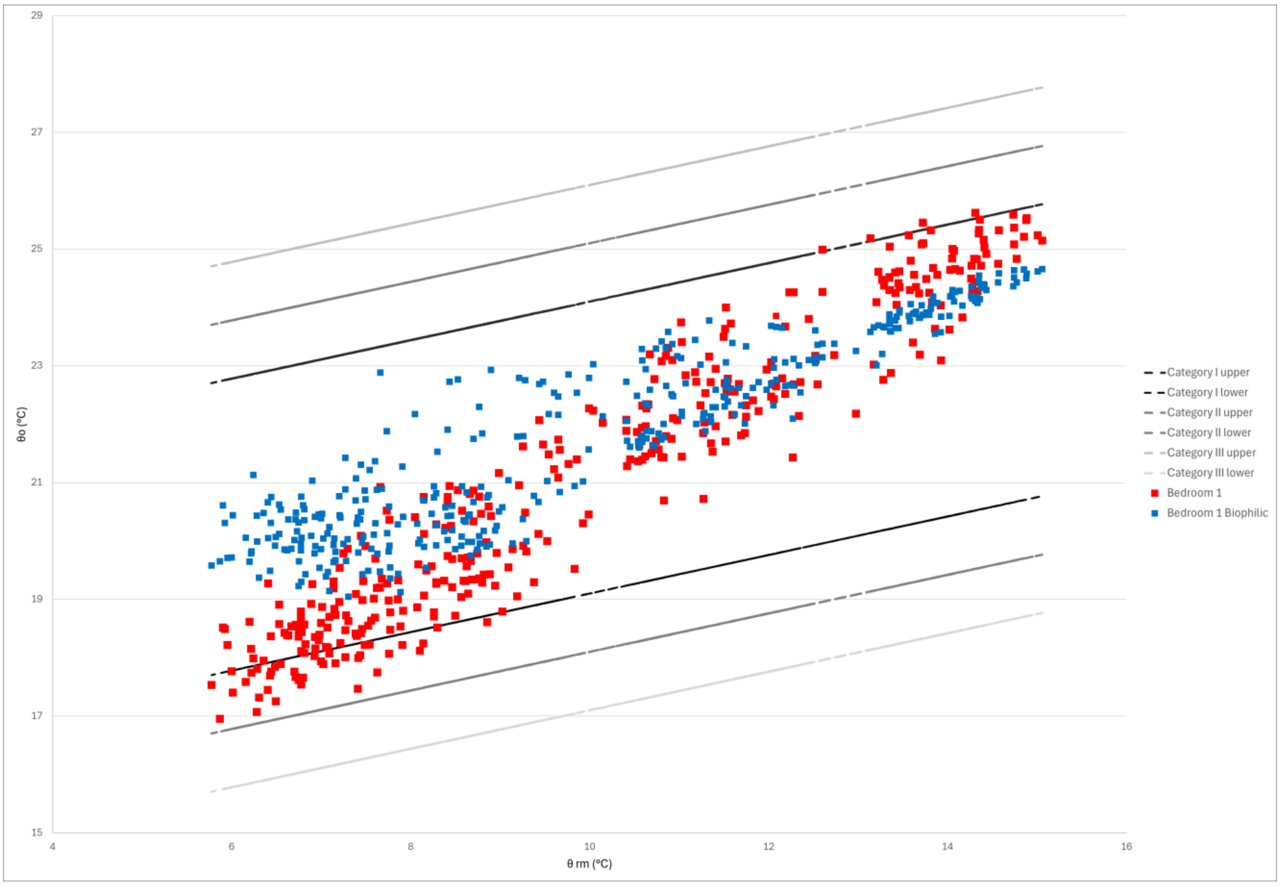


Figure 48 - Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bedroom 1 of the ground floor Maisonette also compared with the categories of the adaptive comfort as per EN 16798-1

Table 27 – Bedroom 1 Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	90.88%	100.00%	100.00%
Biophilic	100.00%	100.00%	100.00%

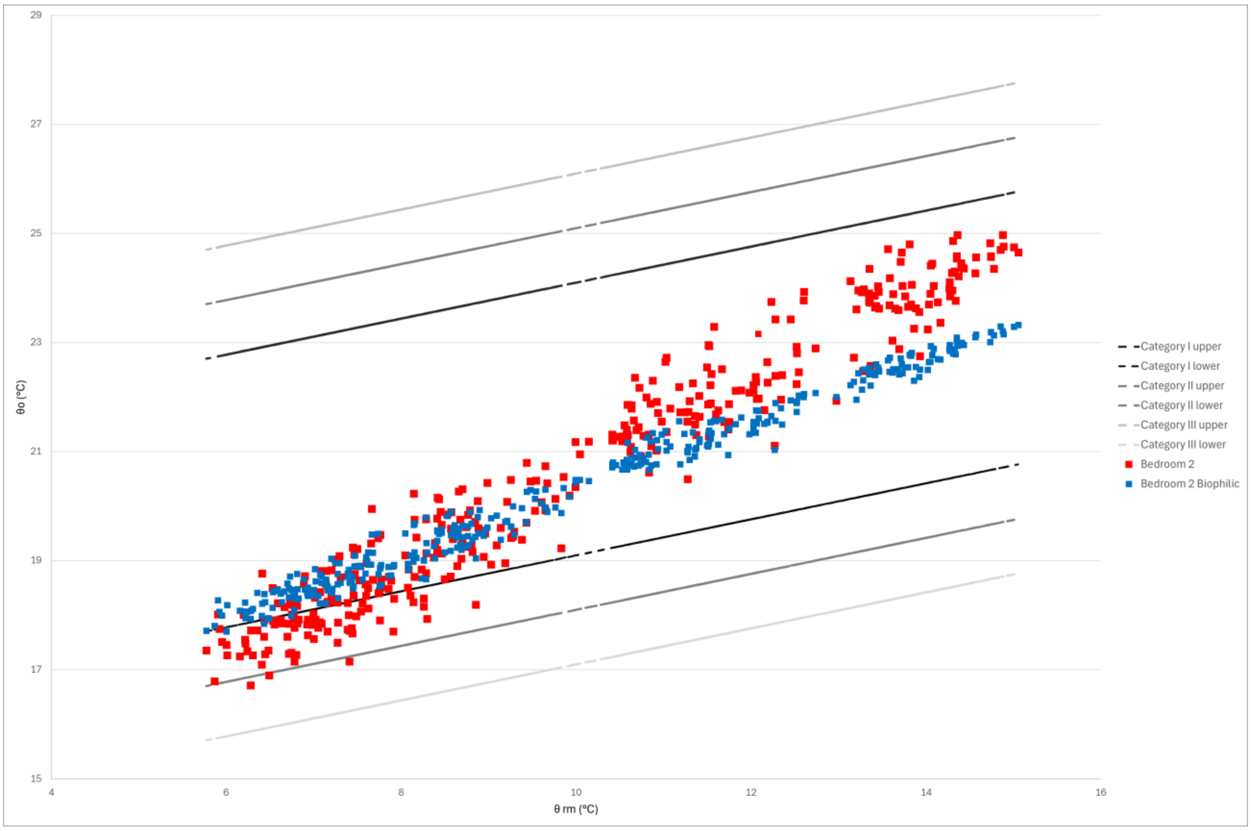


Figure 49 - Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bedroom 2 of the ground floor Maisonette also compared with the categories of the adaptive comfort as per EN 16798-1

Table 28 – Bedroom 2 Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	79.28%	99.45%	100.00%
Biophilic	98.90%	100.00%	100.00%

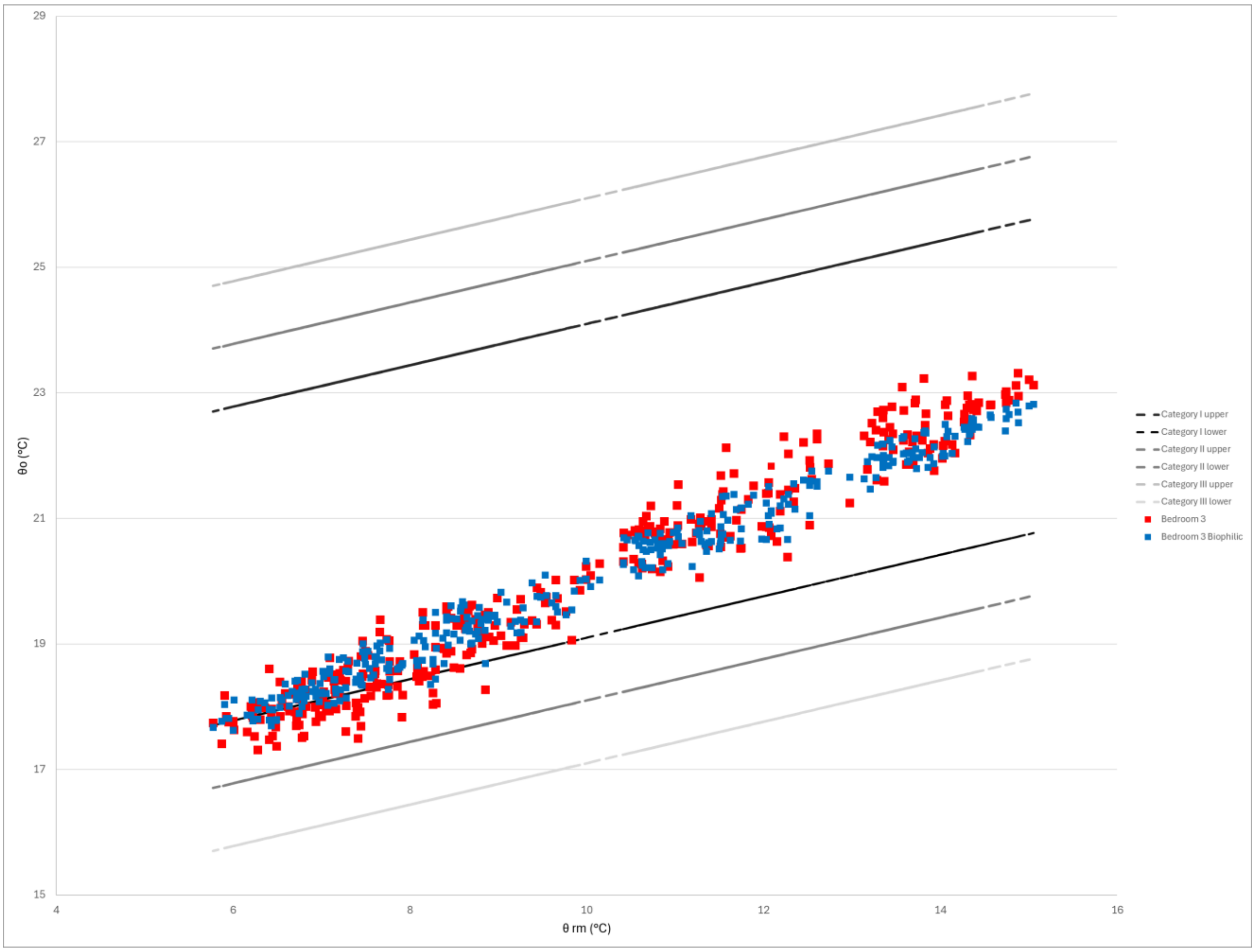


Figure 50 - Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bedroom 3 of the ground floor Maisonette also compared with the categories of the adaptive comfort as per EN 16798-1

Table 29 – Bedroom 3 Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	80.66%	100.00%	100.00%
Biophilic	94.48%	100.00%	100.00%

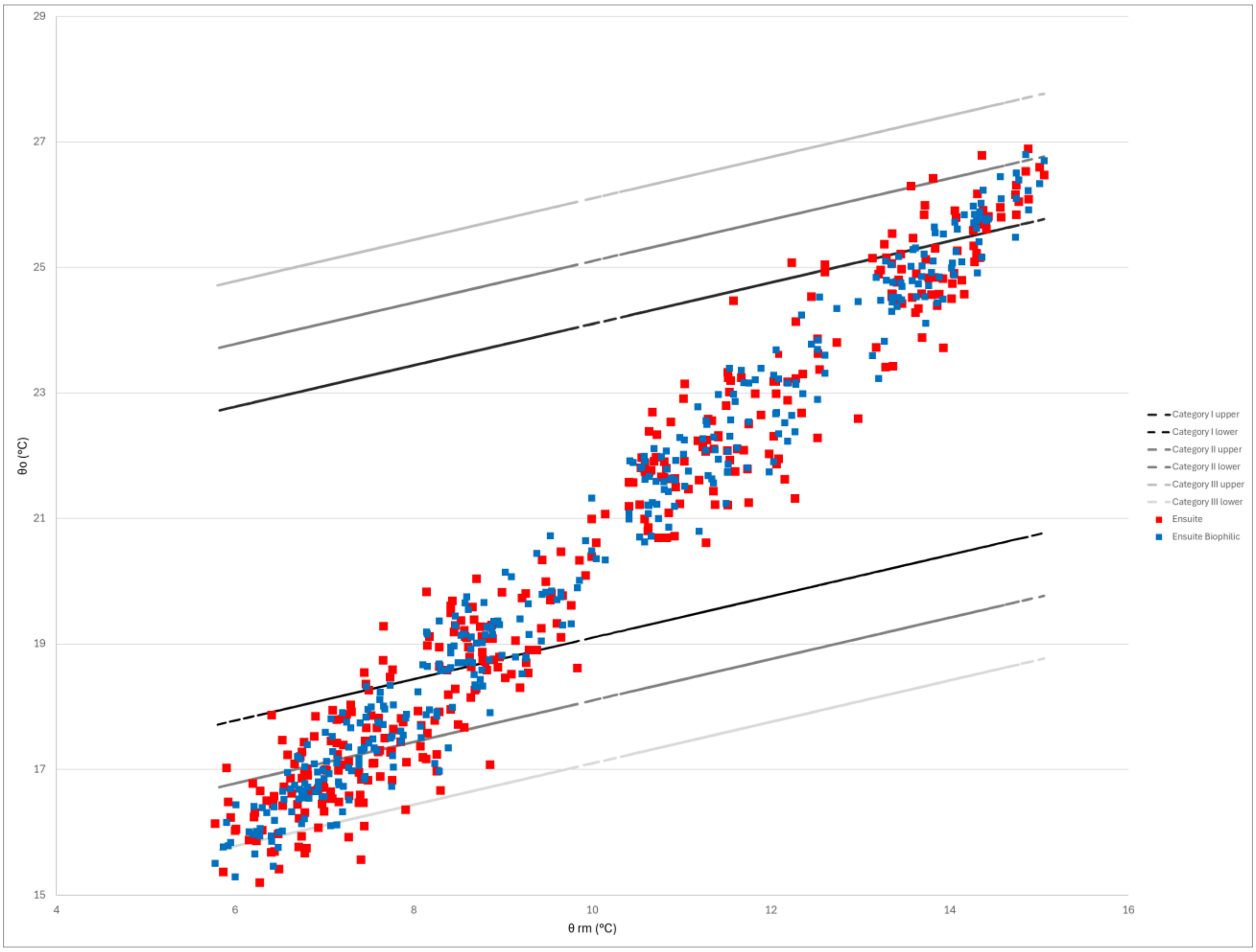


Figure 51 - Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the ensuite of the ground floor Maisonette also compared with the categories of the adaptive comfort as per EN 16798-1

Table 30 – Ensuite Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	54.14%	76.80%	95.86%
Biophilic	54.70%	79.56%	97.79%

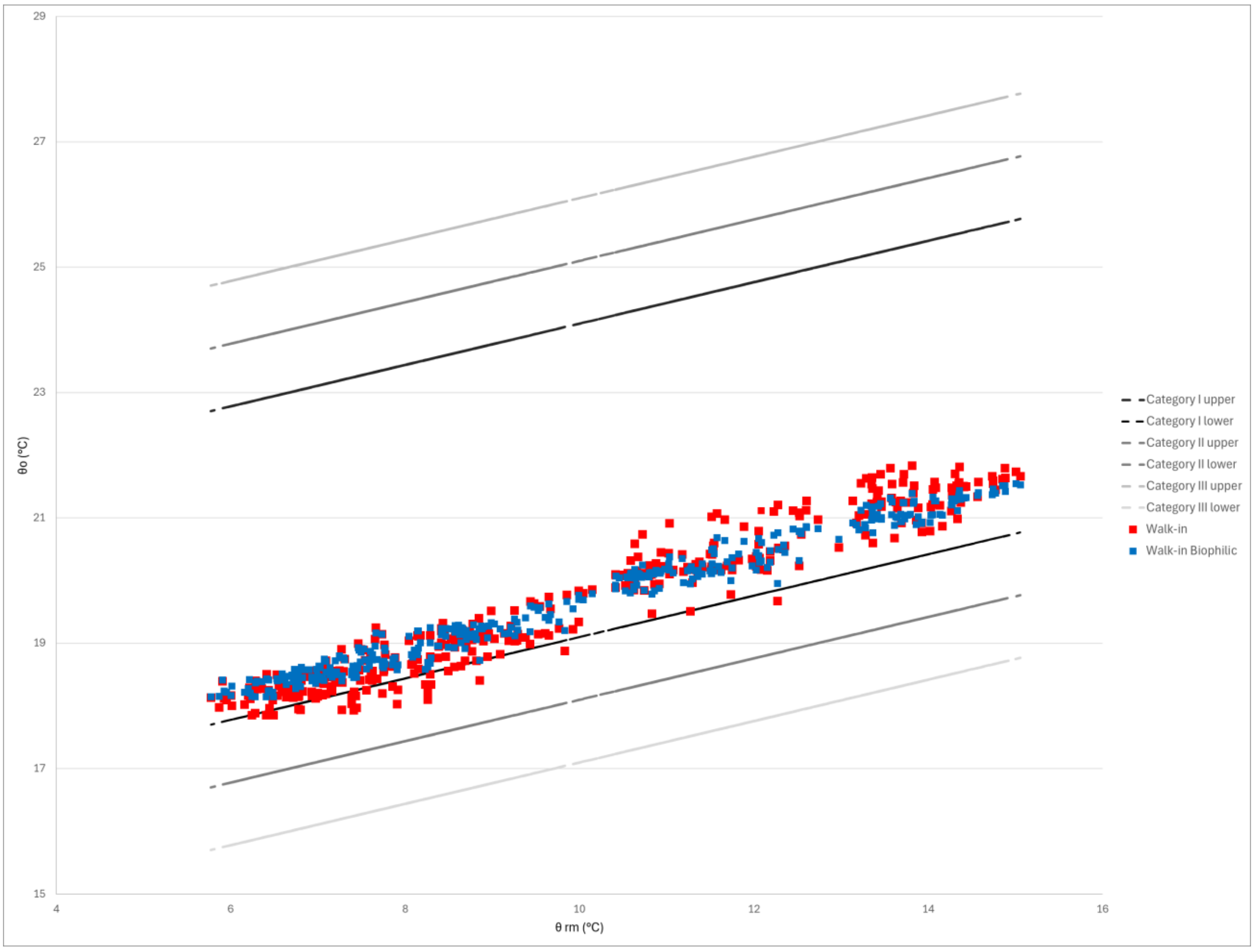


Figure 52 - Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the walk-in of the ground floor Maisonette also compared with the categories of the adaptive comfort as per EN 16798-1

Table 31 – Walk-in Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	96.13%	100.00%	100.00%
Biophilic	100.00%	100.00%	100.00%

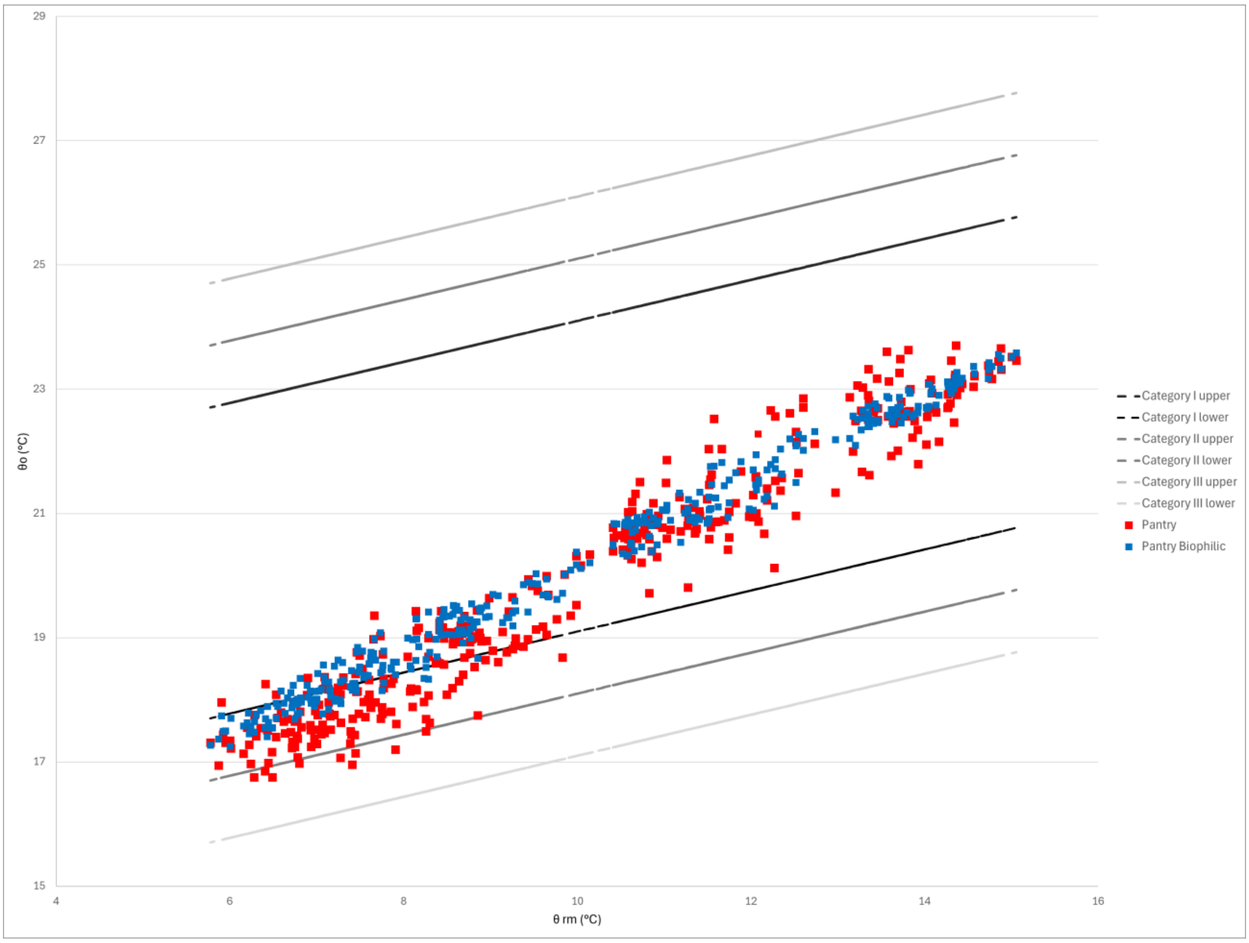


Figure 53 - Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the pantry of the ground floor Maisonette also compared with the categories of the adaptive comfort as per EN 16798-1

Table 32 – Pantry Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	67.96%	99.72%	100.00%
Biophilic	81.49%	100.00%	100.00%

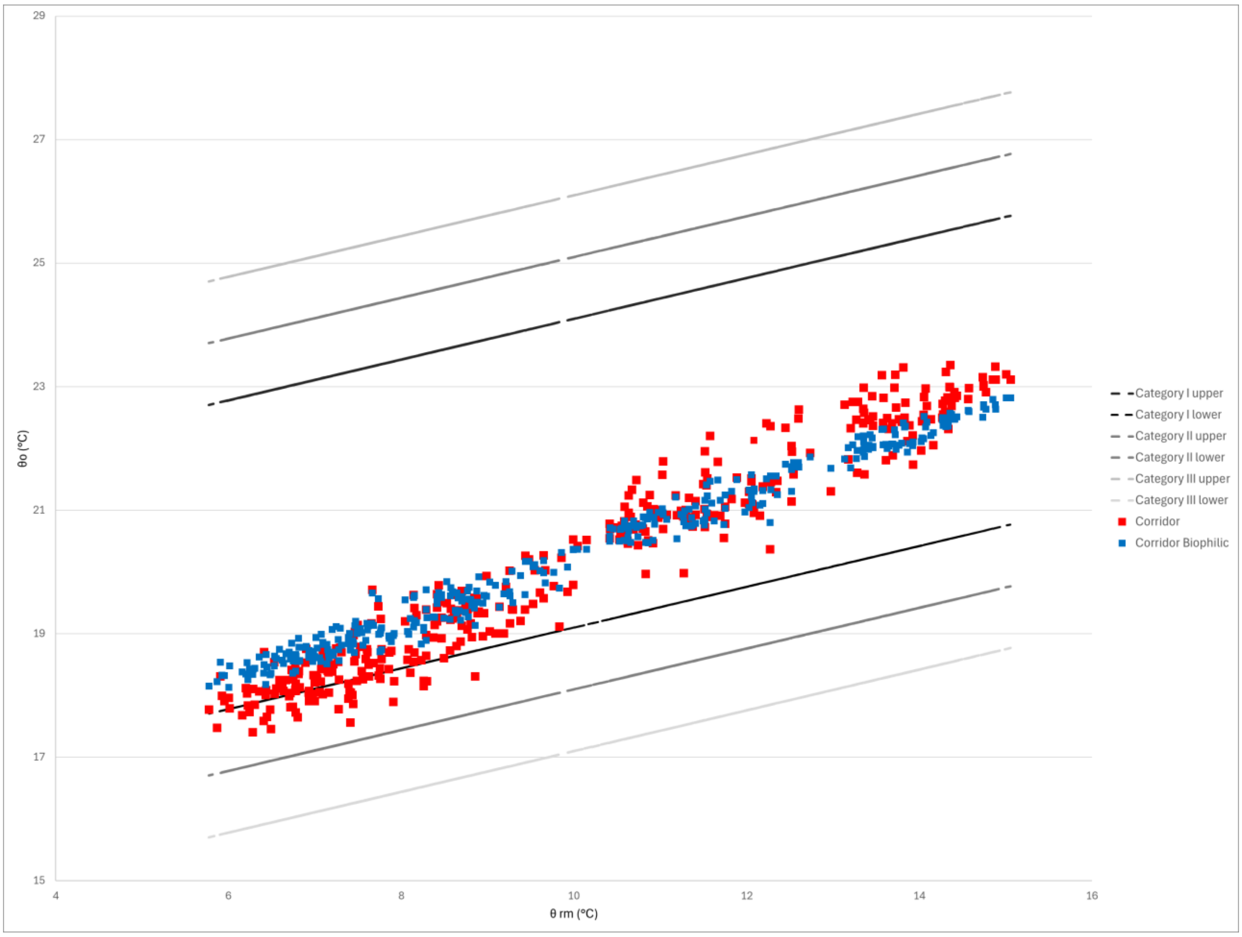


Figure 54 - Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the corridor of the ground floor Maisonette also compared with the categories of the adaptive comfort as per EN 16798-1

Table 33 – Corridor Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	88.12%	100.00%	100.00%
Biophilic	100.00%	100.00%	100.00%

4.3.2 Penthouse

As the previous case, a comparison of the simulation results over a full year for each zone as existing conditions and with biophilic design implementations for the penthouse will be analysed. From these results one can immediately notice that the existing scenario is far from the adaptive comfort categories. Also, although one can see an improvement in terms of temperature within the adaptive comfort categories, this is not as high as the ground floor. As one may know the penthouse is a completely different scenario when compared to the ground floor, therefore this was expected.

Considering the kitchen/ dining/ living, this shows very low improvement but there still is an improvement. One must consider that the existing roof was already with a standard insulation therefore the green roof did not make that difference. The results shows that there was a shift from category III to category II and I as these increased while category III decreased and this is a positive result. The results shows that in category I from 37.02% increased to 37.85%, category II increased from 45.3% to 47.79% nearly 50% and category III decreased from 52.49% to 51.93%. This shows that nearly 50% of the year the results are in the adaptive comfort zone. This also conclude that passive means are not enough to reduce thermal loads at penthouse levels.

Moving to the bedrooms, a similar effect was noted but this time higher results. From category III almost 65% from 62% for both bedrooms while also improving the other categories with a similar trend. This means that all the categories increased therefore the temperatures were shifted similarly. For bedroom one, category I from 29.83% to 32.32% and category II from 42.54% to 54.42% while bedroom 2 category I from 29.28% to 32.32%, and category II from 44.48% to 54.97%. In category 2, the improvement was very high as it reaches nearly 10%. This shows that in these zones, the biophilic implementation were more effective, this is due to the fact of the orientation and positioning of the zones.

For the areas that no specific interventions were implemented except for the green roof that covers all the roof area, these areas still showed improvements that this confirms the effectiveness of the green roof. For example, the bathroom, category I from 29.56% to 33.70%

and category II from 42.54% to 55.25%. This shows more than 13% increase for category II that is very effective. Similar improvements were shown in the ensuite. On the other hand, one can note a slightly less improvement in the ensuite 01, this is due to the fact the orientation is more to the south. The improvements in Category I from 29.56% to 33.43% and Category II from 43.37% to 55.80%. For the corridor, one can note a similar improvement of around 10% in category II, from 40.06% to 49.17%.

Although the improvements might seem less than the ground floor overall as a percentage difference, some of them are even high, this shows that the only difference in the implementation of biophilic interventions that was the green roof, had a positive impact to the thermal comfort. For the top floor level, the effectiveness is quite high overall when considering category II and III that are quite sufficient for a residential building. This also shows that in case of a penthouse, one needs to have both passive and active system in certain period of the year.

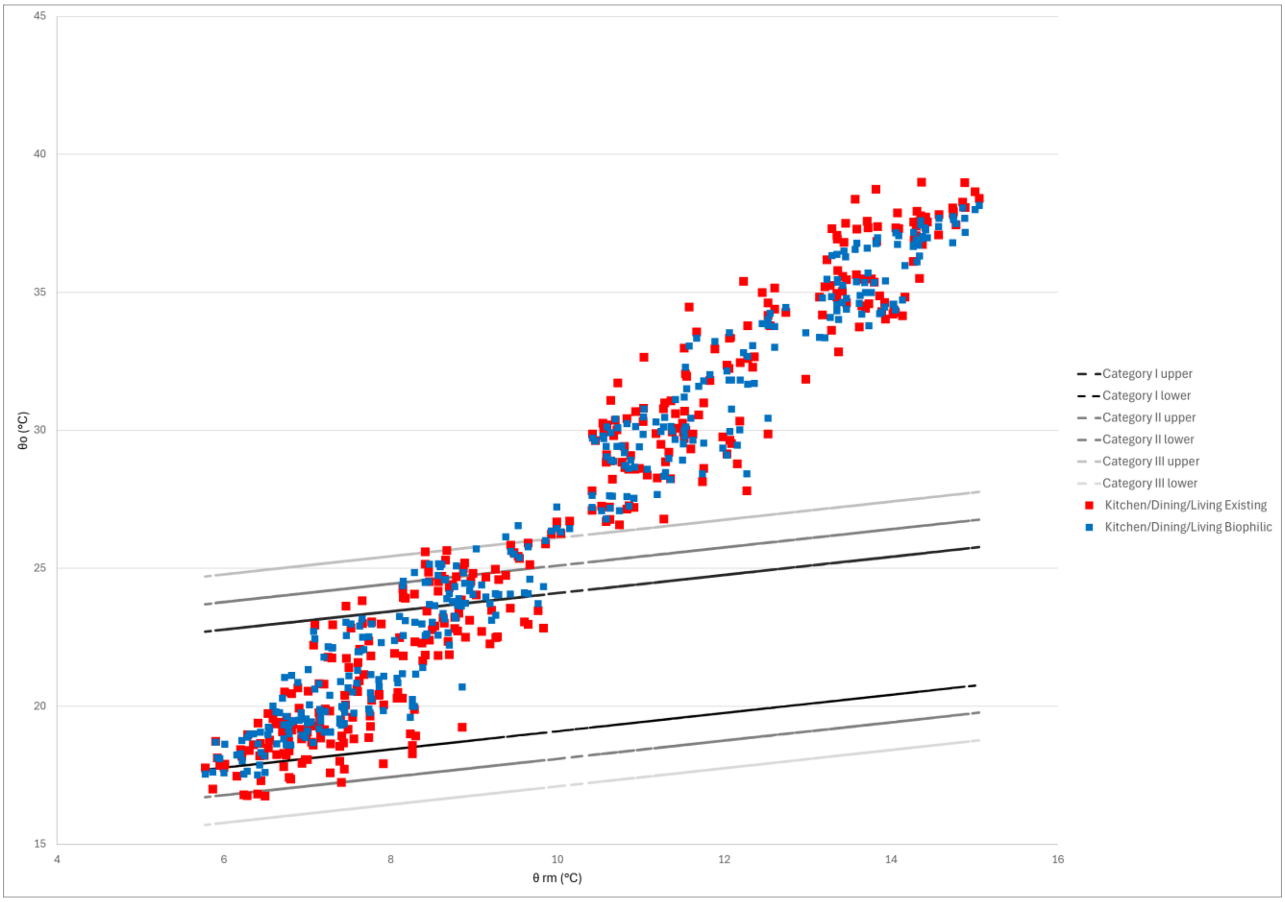


Figure 55 – Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the kitchen/ dining/ living of the Penthouse also compared with the categories of the adaptive comfort as per EN 16798-1

Table 34 - Kitchen/ Dining/ Living Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	37.02%	45.30%	52.49%
Biophilic	37.85%	47.79%	51.93%

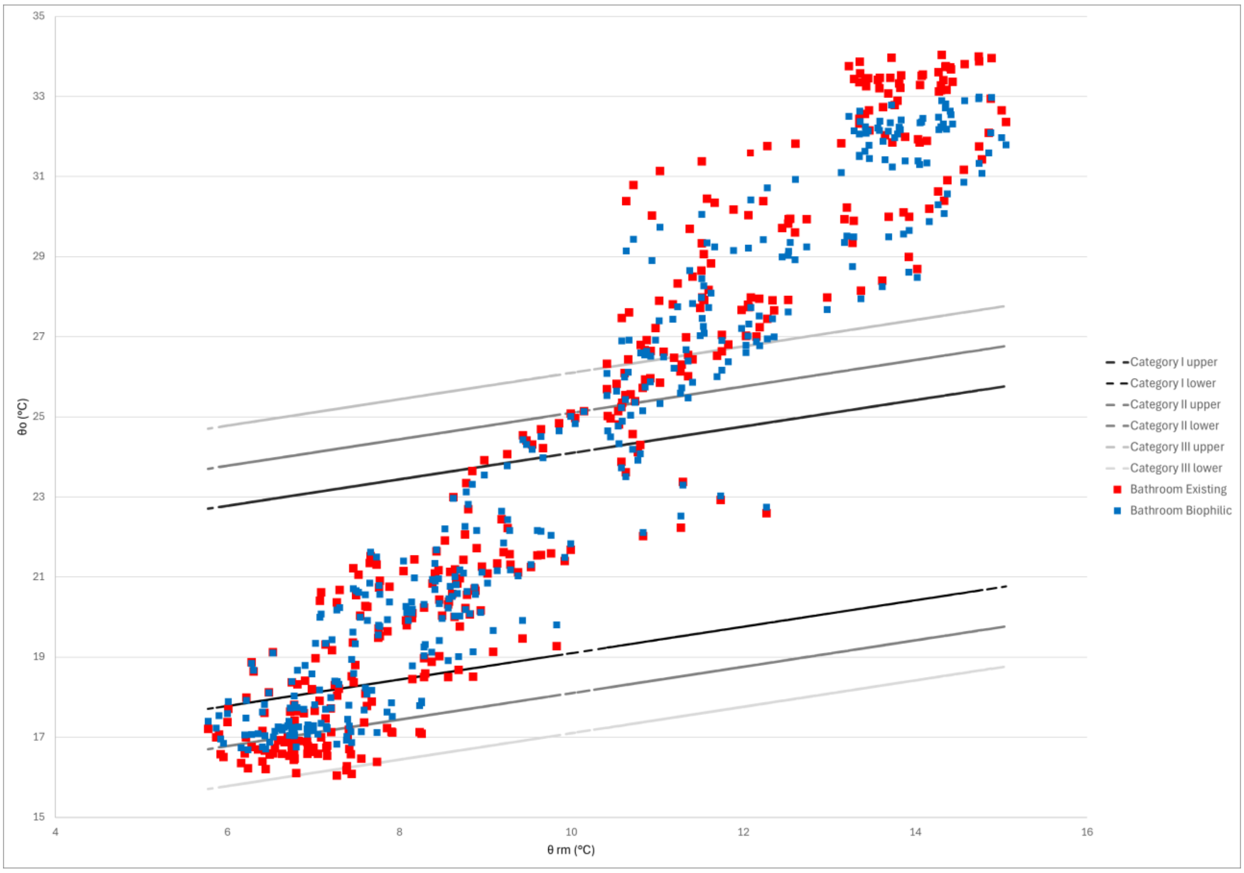


Figure 56 – Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bathroom of the Penthouse also compared with the categories of the adaptive comfort as per EN 16798-1

Table 35- Bathroom Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	29.56%	42.54%	62.15%
Biophilic	33.70%	55.25%	64.64%

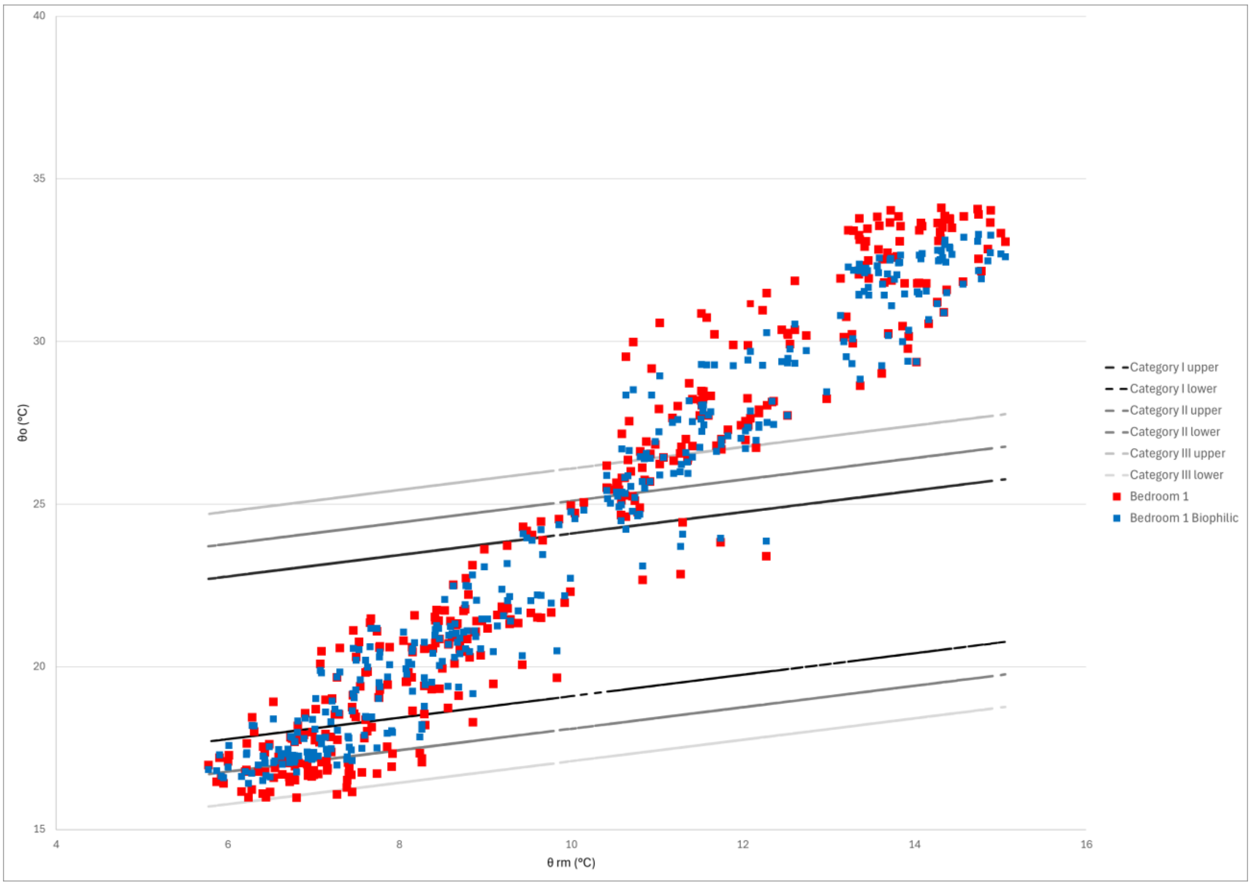


Figure 57 – Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bedroom 1 of the Penthouse also compared with the categories of the adaptive comfort as per EN 16798-1

Table 36 – Bedroom 1 Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	29.83%	42.54%	61.88%
Biophilic	32.32%	54.42%	64.09%

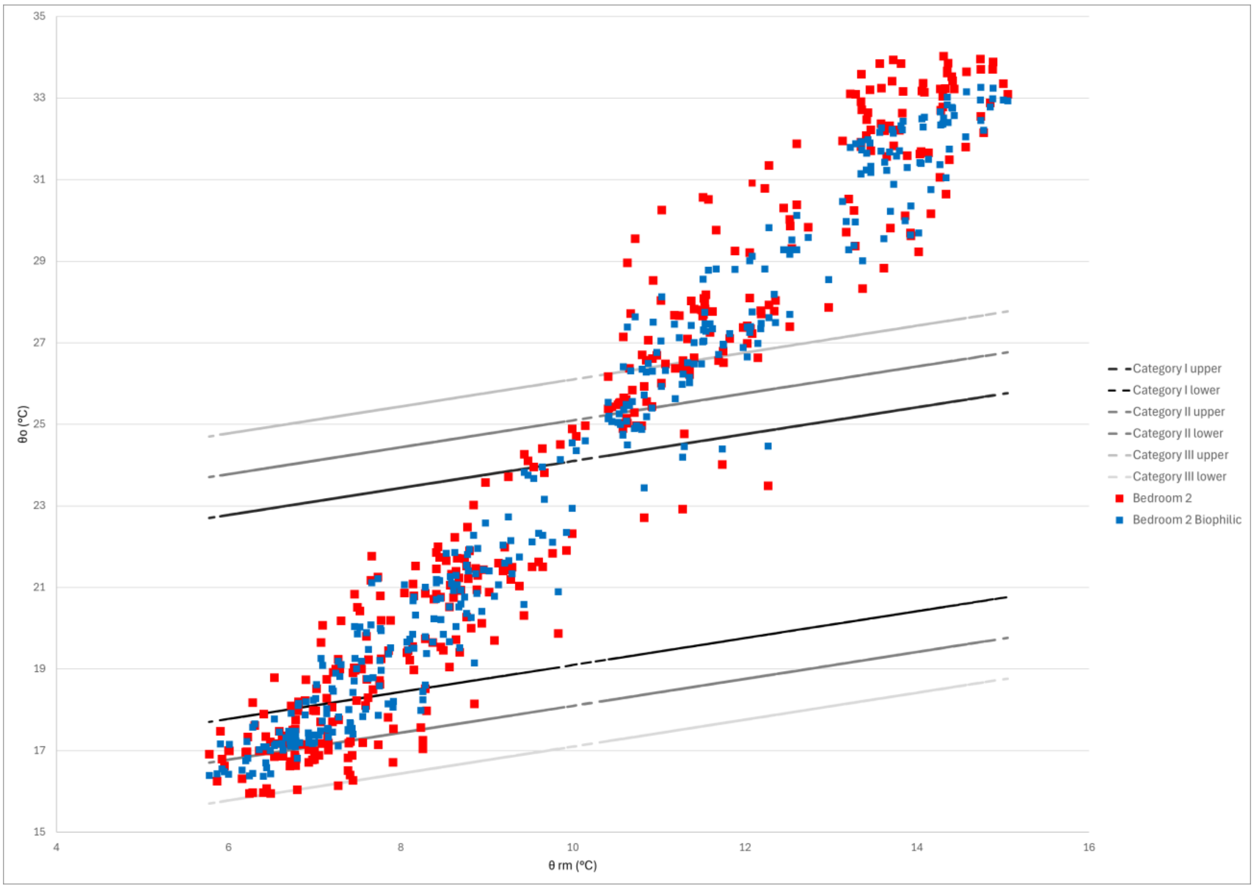


Figure 58 – Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bedroom 2 of the Penthouse also compared with the categories of the adaptive comfort as per EN 16798-1

Table 37 – Bedroom 2 Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	29.28%	44.48%	61.60%
Biophilic	32.32%	54.97%	65.19%

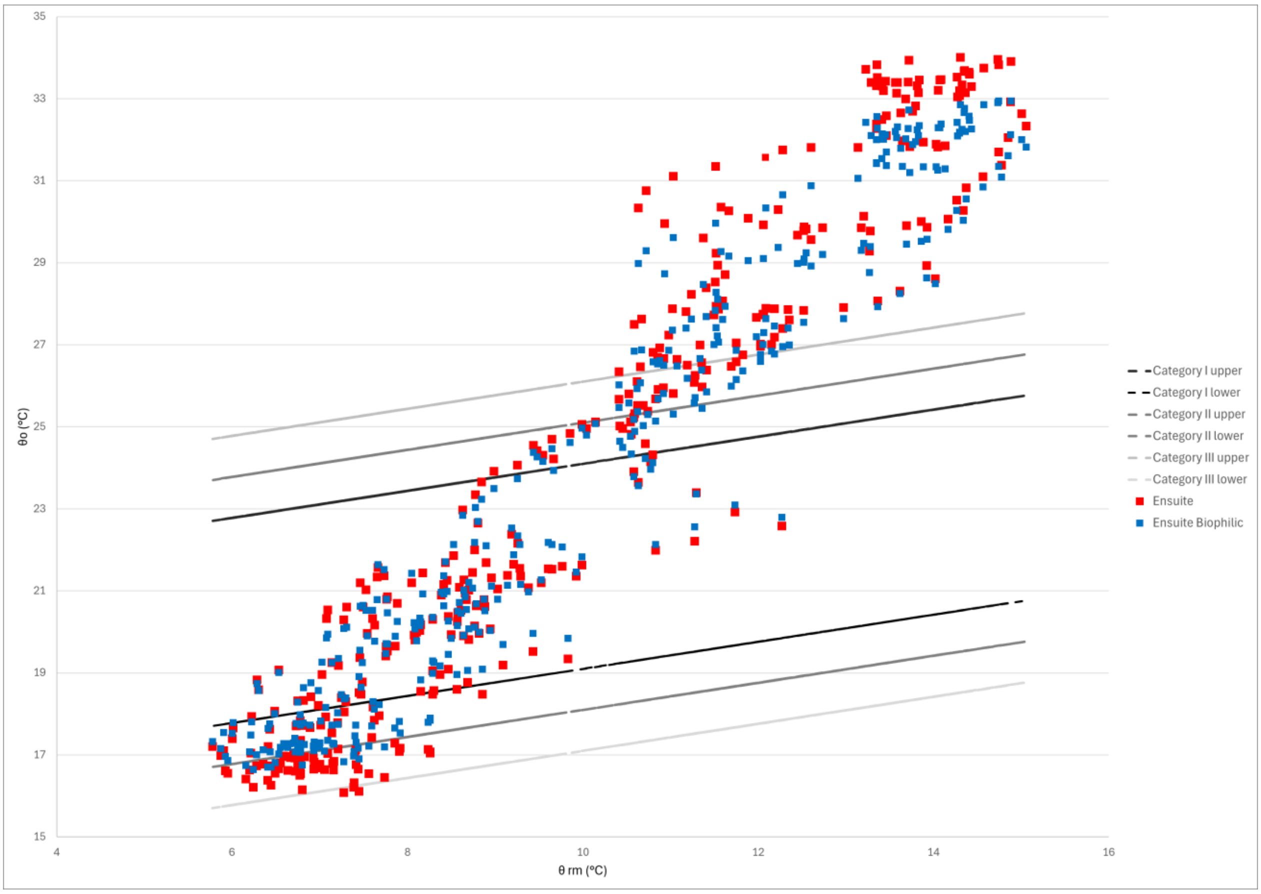


Figure 59 – Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the ensuite of the Penthouse also compared with the categories of the adaptive comfort as per EN 16798-1

Table 38 - Ensuite Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	29.56%	43.37%	62.15%
Biophilic	33.43%	55.80%	64.64%

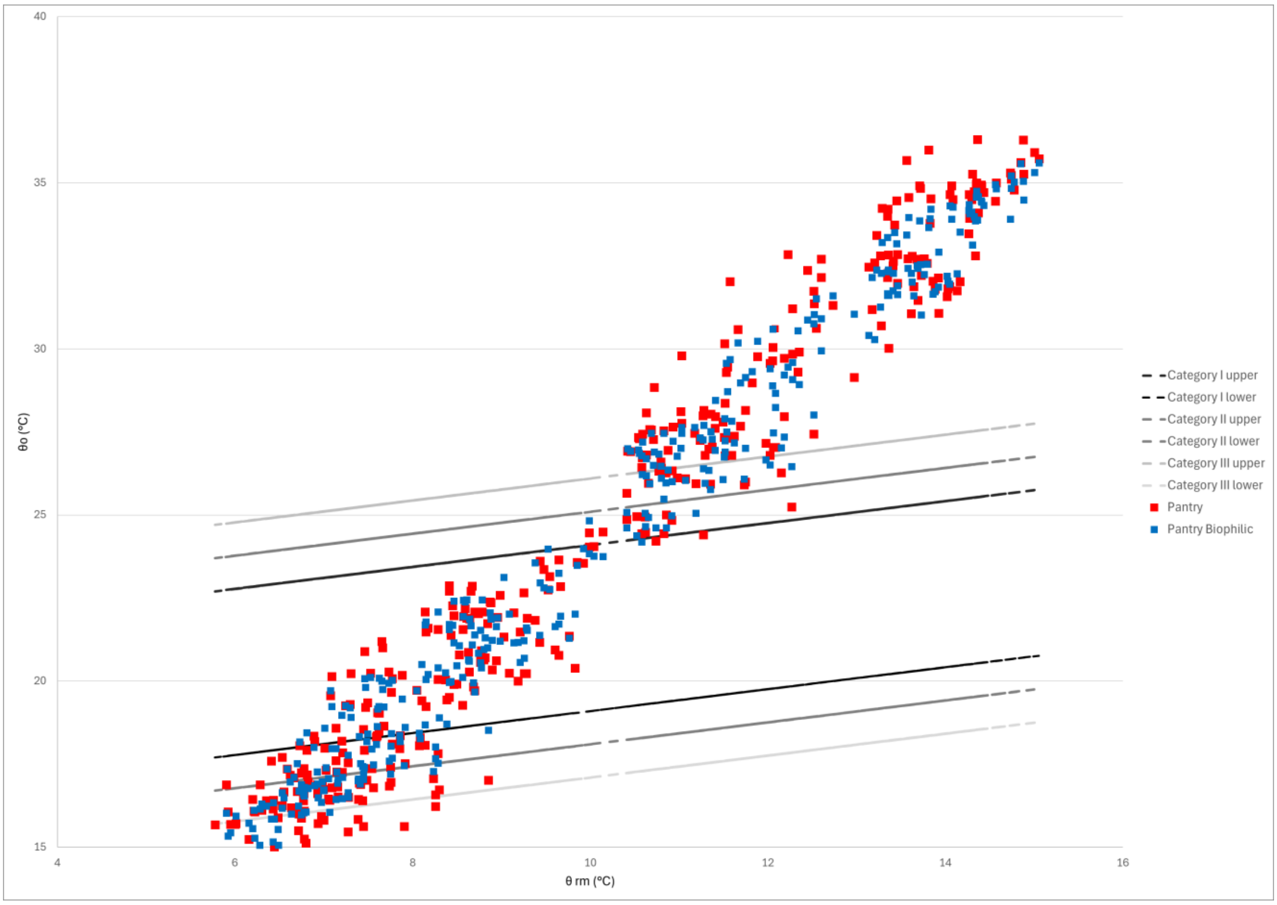


Figure 60 – Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the pantry of the Penthouse also compared with the categories of the adaptive comfort as per EN 16798-1

Table 39 - Pantry Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	25.97%	36.19%	53.04%
Biophilic	27.62%	38.95%	56.91%

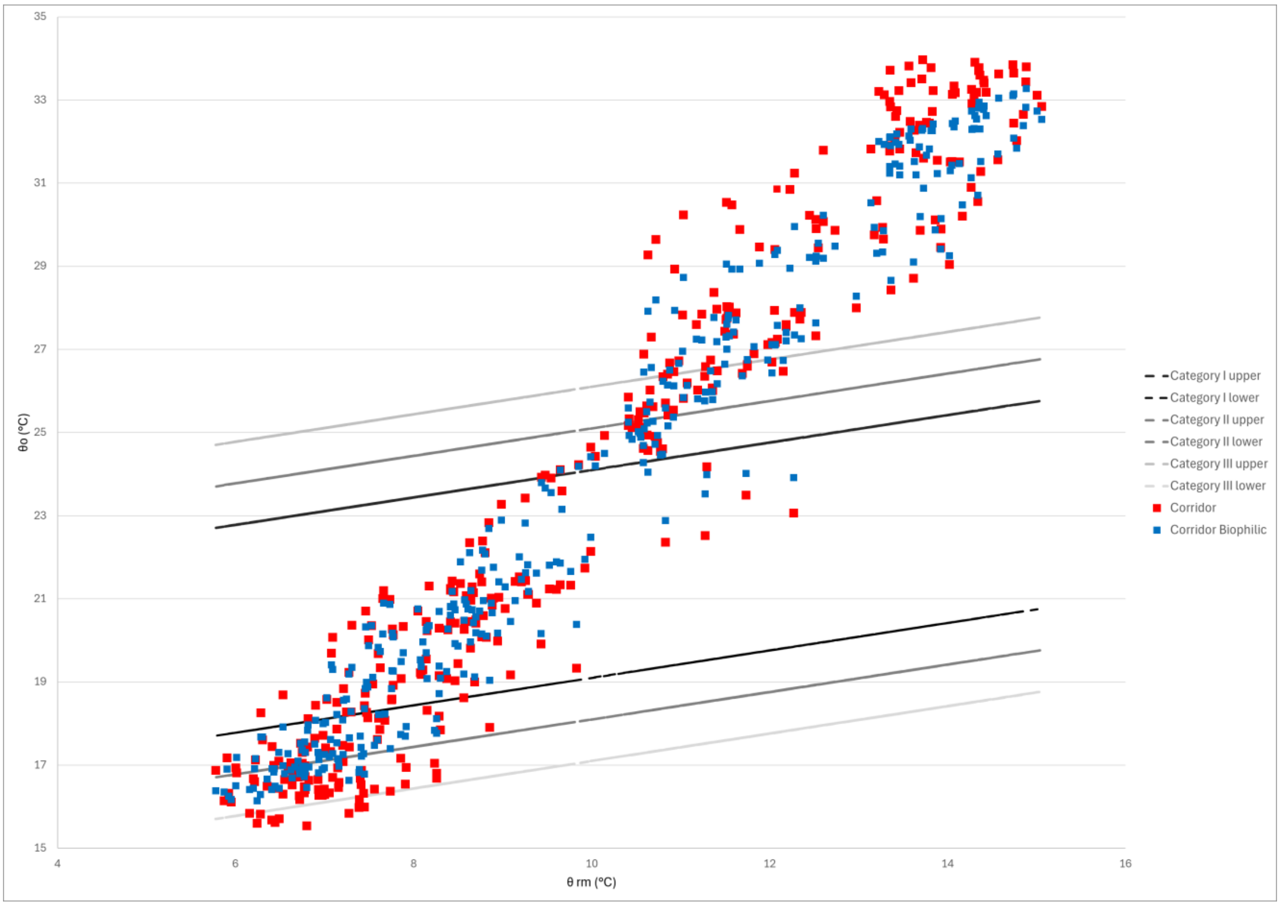


Figure 61 – Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the corridor of the Penthouse also compared with the categories of the adaptive comfort as per EN 16798-1

Table 40 - Corridor Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	27.62%	40.06%	61.88%
Biophilic	30.66%	49.17%	65.75%

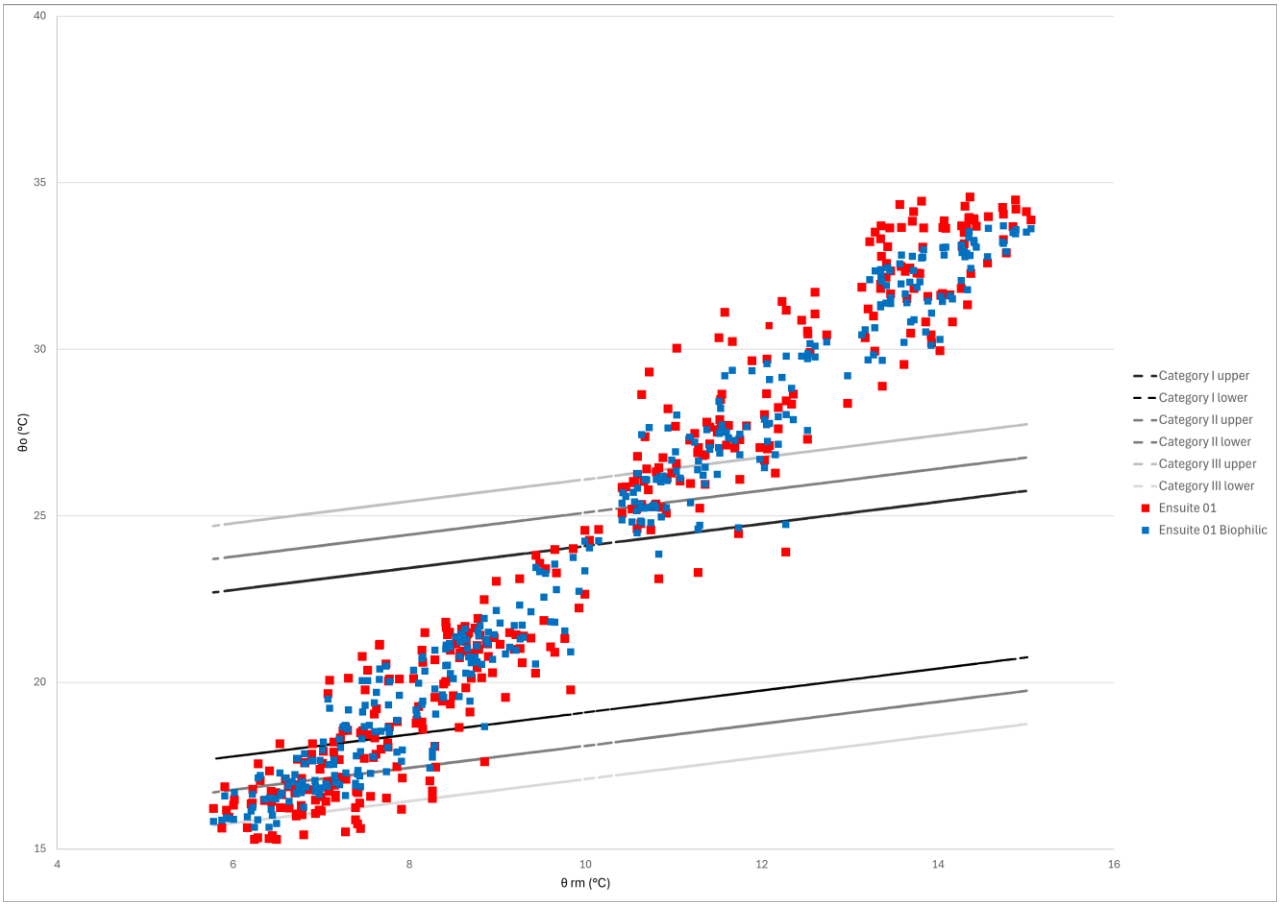


Figure 62 – Temperature results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the ensuite 01 of the Penthouse also compared with the categories of the adaptive comfort as per EN 16798-1

Table 41 – Ensuite 01 Percentage amount within the Categories

	Category I	*Category II*	*Category III*
Existing	27.07%	38.40%	58.84%
Biophilic	29.56%	43.37%	64.92%

4.4 CO_2 Analysis in ppm

4.4.1 Ground Floor Maisonette

In this section, the results of annual CO_2 concentration for every zone on the ground floor maisonette are discussed. A comparison is made with the existing scenario using the biophilic implementation. These results will show the effect of natural ventilation and occupants comfort level. The main effect on these results is the natural ventilation implementations consisting of the openable apertures and increasing the dimensions of the existing north and south apertures.

Starting from the kitchen/ dining/ living area, as the mostly active space and the schedule of occupancy was specifically inputted for this area, a good reduction of CO_2 is very visible (Figure 63). This shows that the introduction of openable apertures and increase in size, increase cross ventilation therefore lowered the CO_2. From the positioning of the apertures one can notice that cross ventilation is very effective. This confirms that the biophilic natural implementation can also affect the indoor air quality.

Considering the bedrooms, one can also see a difference in CO_2 levels except for bedroom 2. This is due to the fact of the orientation of the apertures, therefore there was an effect on the CO_2 from the indoor plants. The corridor showed nearly no effect since there is no cross ventilation since it was modelled as a separate zone from the kitchen/ dining/ living. Finally, the zones where no specific biophilic measures were considered, the effect is nearly negligible. Overall, one can conclude that there is a positive impact of biophilic measures to the indoor air quality, mostly evident in the most occupied areas. Although areas without biophilic measures were not considered as effective, these will also influence the overall indoor environment.

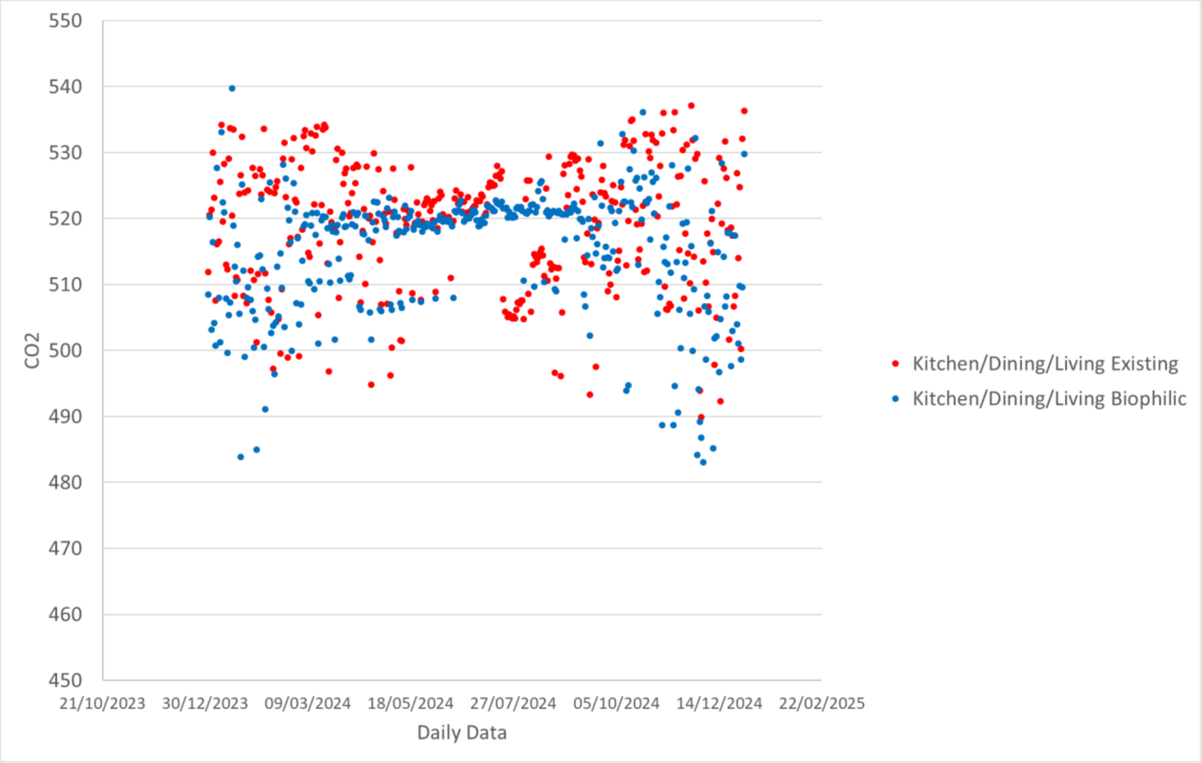


Figure 63 – CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the kitchen/dining/living of the ground floor Maisonette

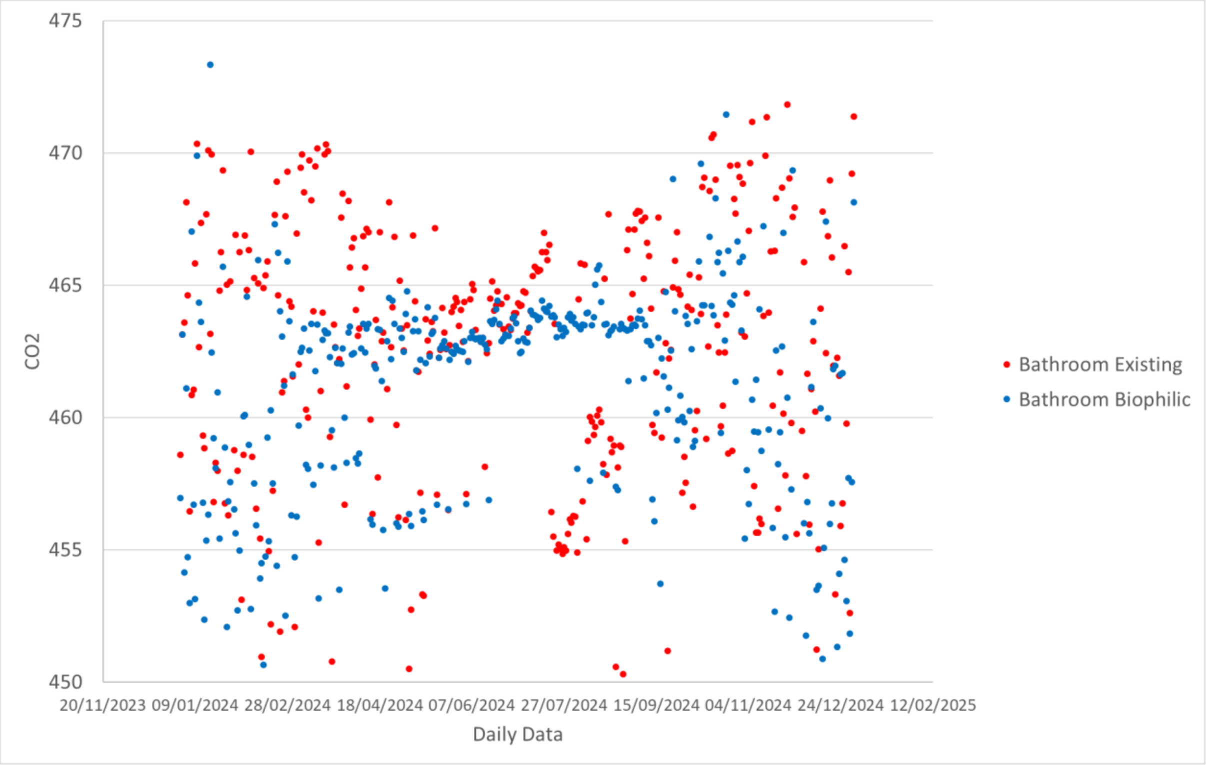


Figure 64 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bathroom of the ground floor Maisonette

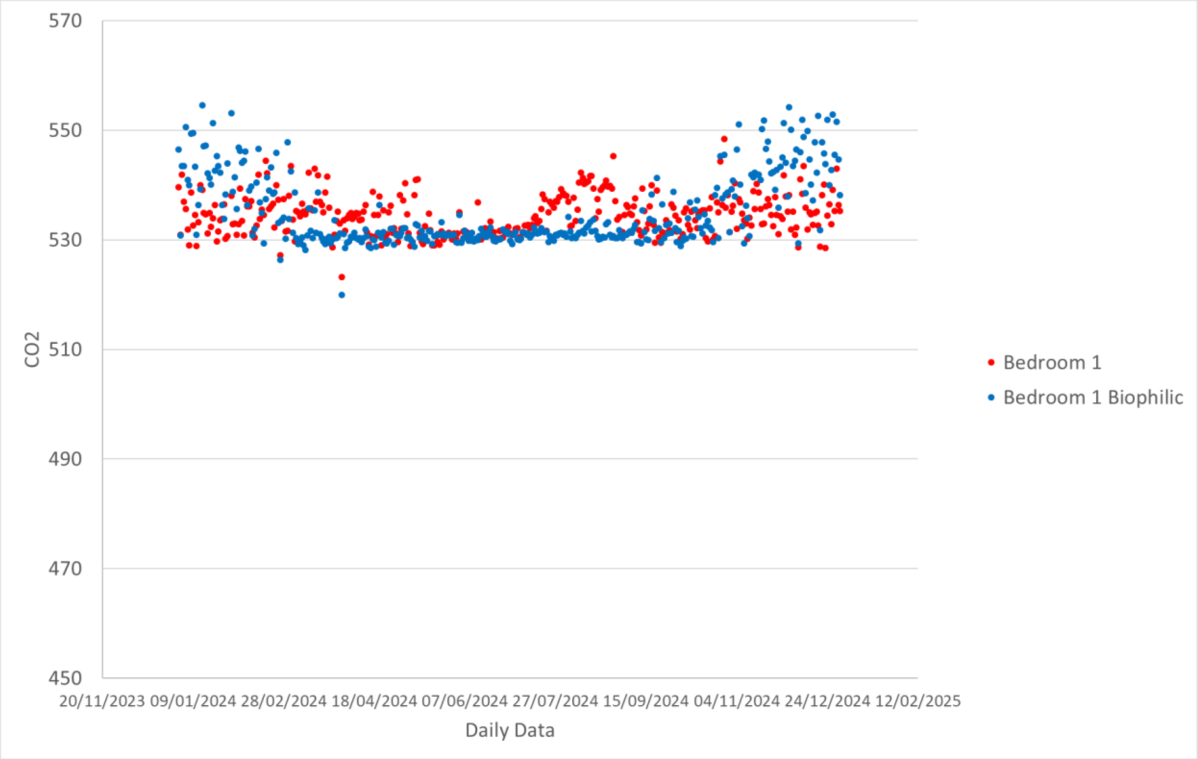


Figure 65 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bedroom 1 of the ground floor Maisonette

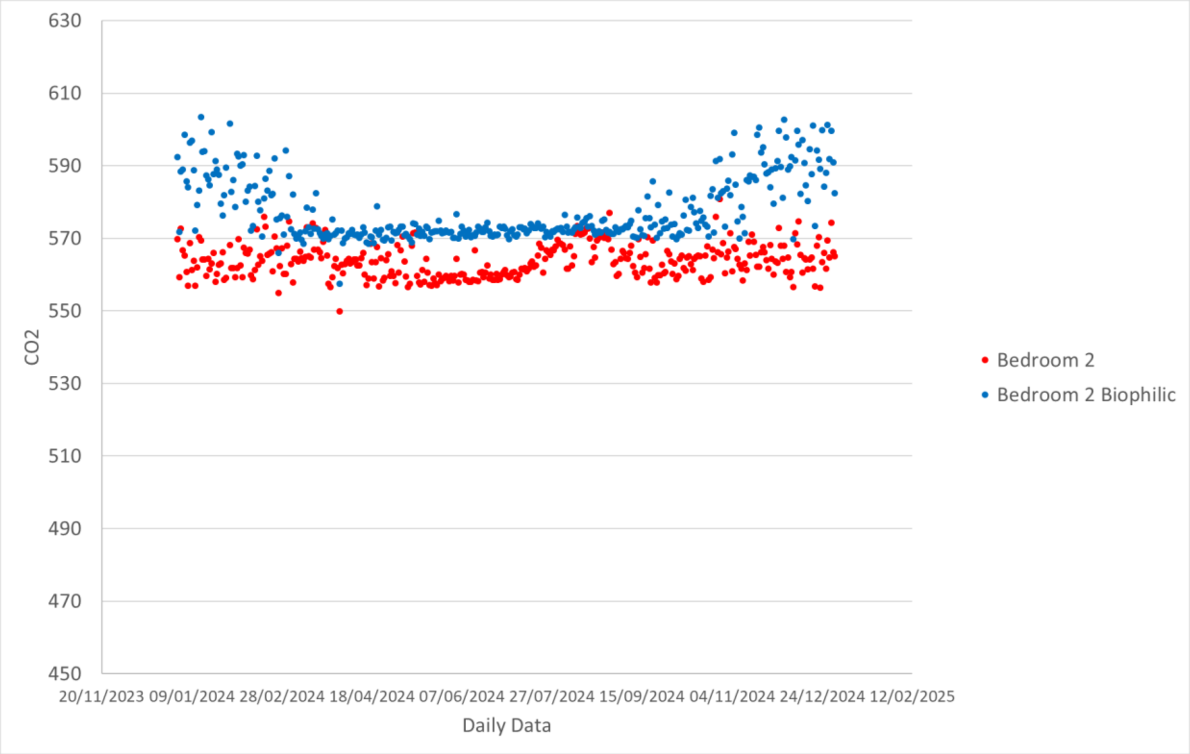


Figure 66 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bedroom 2 of the ground floor Maisonette

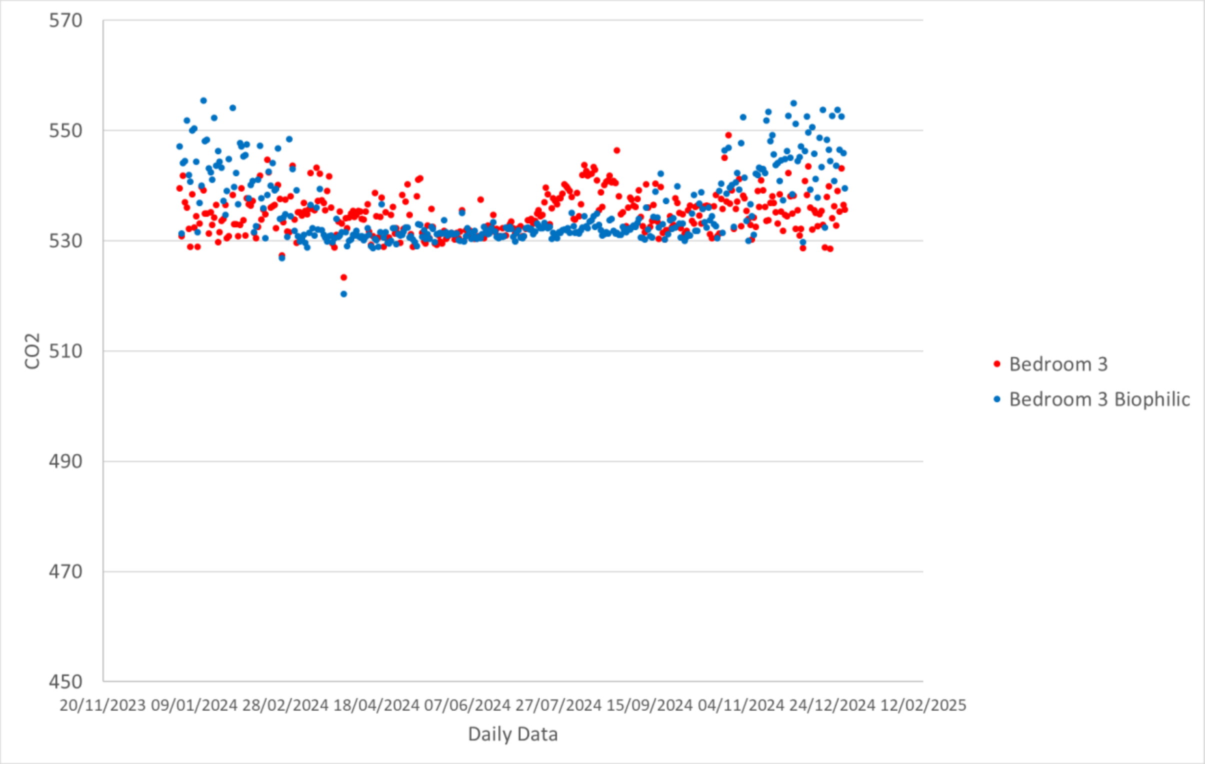


Figure 67 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bedroom 3 of the ground floor Maisonette

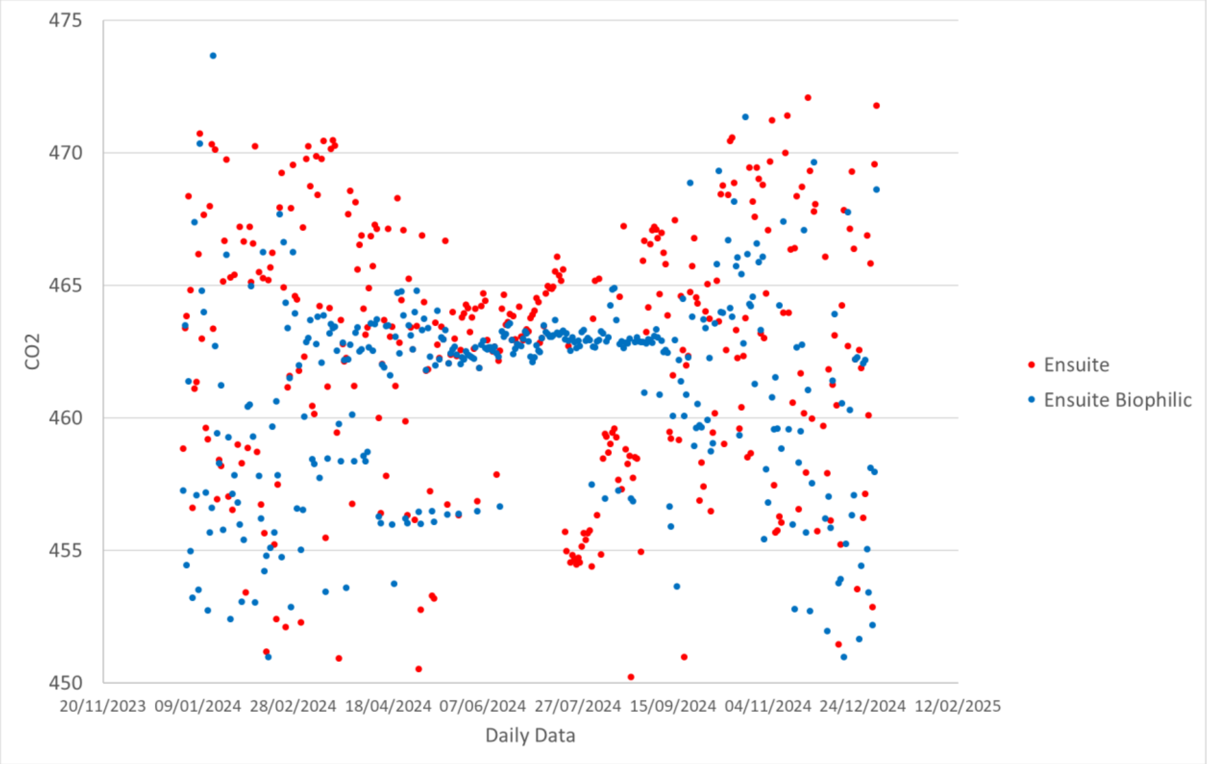


Figure 68 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the ensuite of the ground floor Maisonette

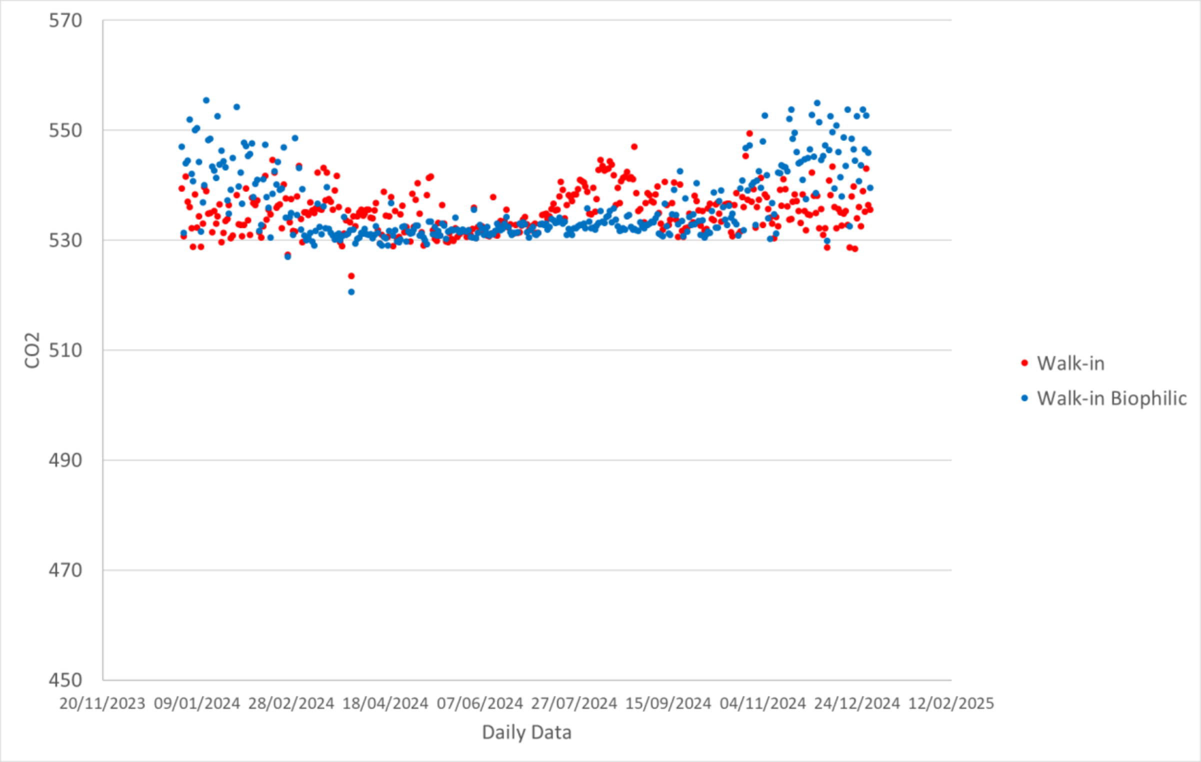


Figure 69 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the walk-in of the ground floor Maisonette

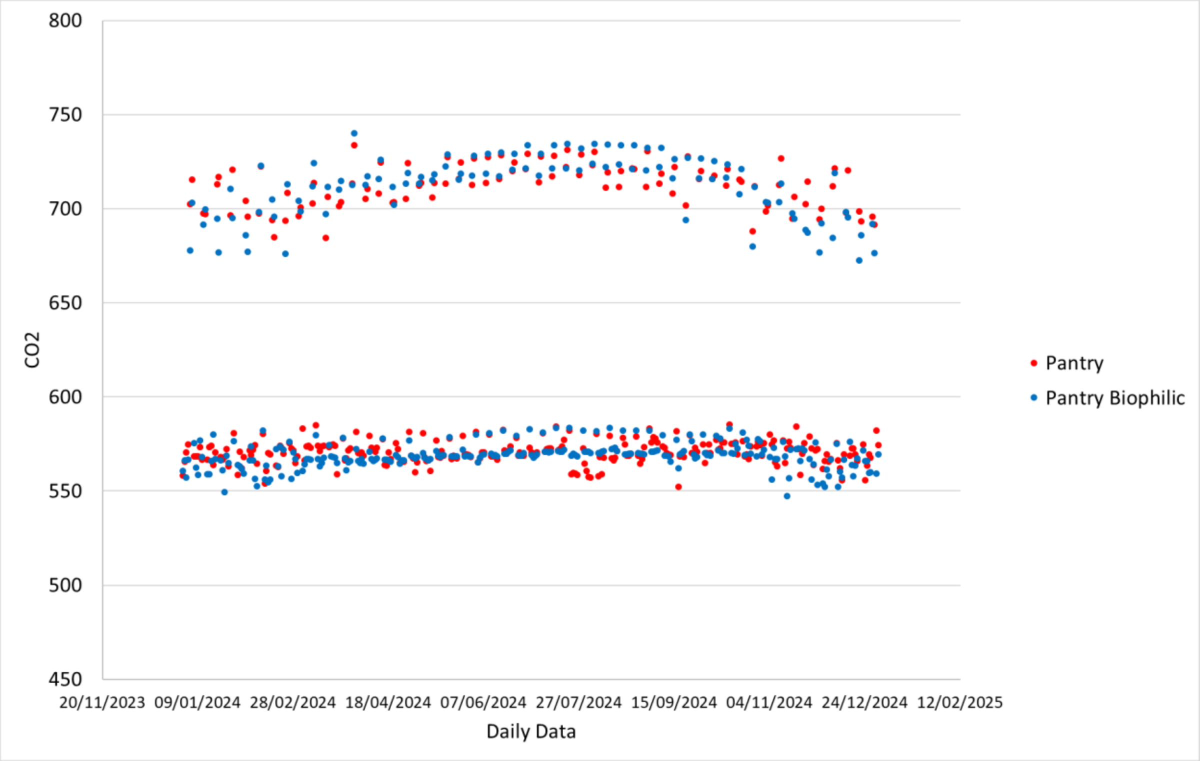


Figure 70 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the pantry of the ground floor Maisonette

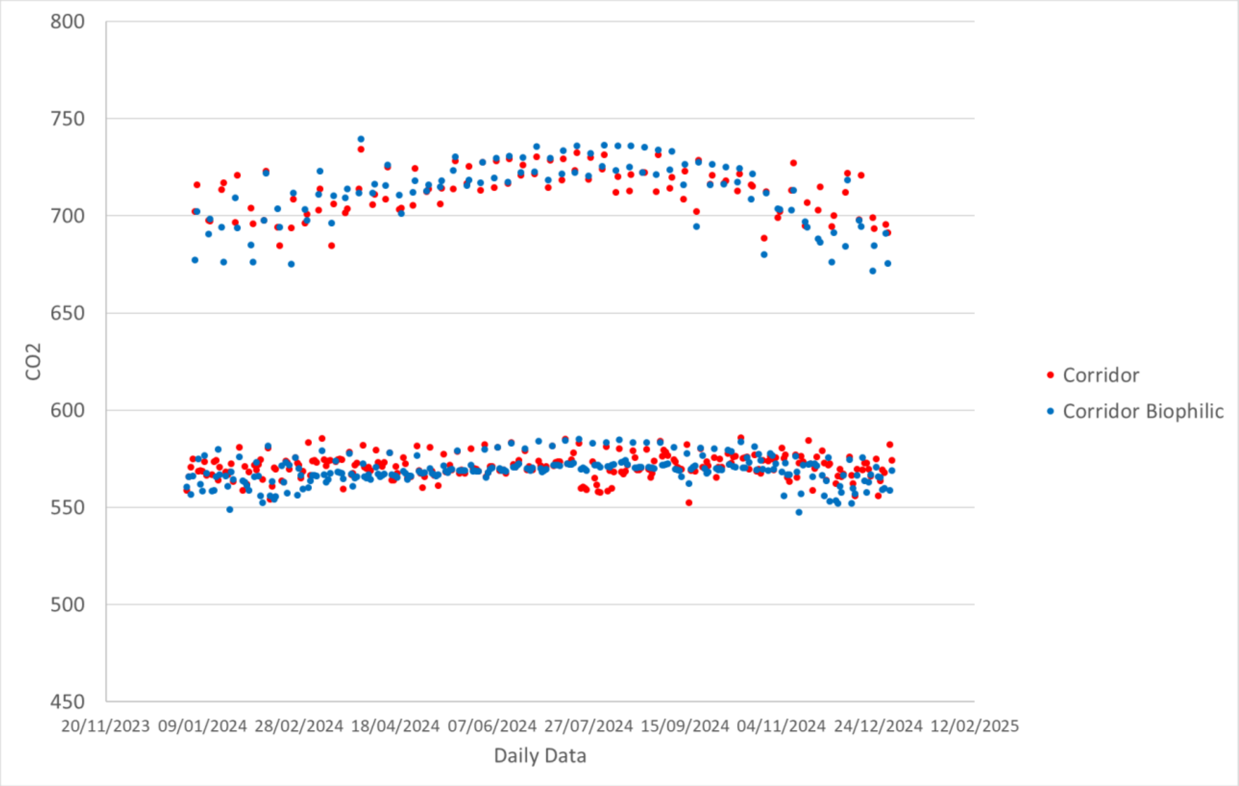


Figure 71 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the corridor of the ground floor Maisonette

4.4.2 Penthouse

Similarly to the results of the ground floor maisonette, the same effect was reflected in the penthouse. Considering the kitchen/ dining/ living (figure 72), this shows a significant improvement nearly 100ppm difference. The effect of natural ventilation from larger openable apertures shows an increase in cross ventilation, these areas also include apertures that enhance cross ventilation. This was mostly during the schedule when the areas are occupied.

When compared to the same space at ground floor, there was a better reduction, and this is very important to note. This is because of wind and solar gains exposure that can benefit or not the airflow. In this case it shows that the wind effect was of a higher impact than the solar gains exposure. This can also be verified since the kitchen/ dining/ living space is affected by the prevailing wind. Considering both bedroom, these also shows a significant improvement as shown in figure 74 and 75. These show an improvement of around 50ppm.

In the areas were no specific biophilic interventions were done, has shown negligible improvement. This can also be seen in the corridor, that as the ground floor maisonette, this was assumed to be another separate zone from the kitchen/ dining/ living. According to ANSI/ASHRAE Standard 62.1-2019: Ventilation for acceptable indoor air quality, the results are in line with the range of 400–1,000 ppm. Overall, one can see a good impact in the improving air quality with biophilic measures. This is mostly due to the natural ventilation effect.

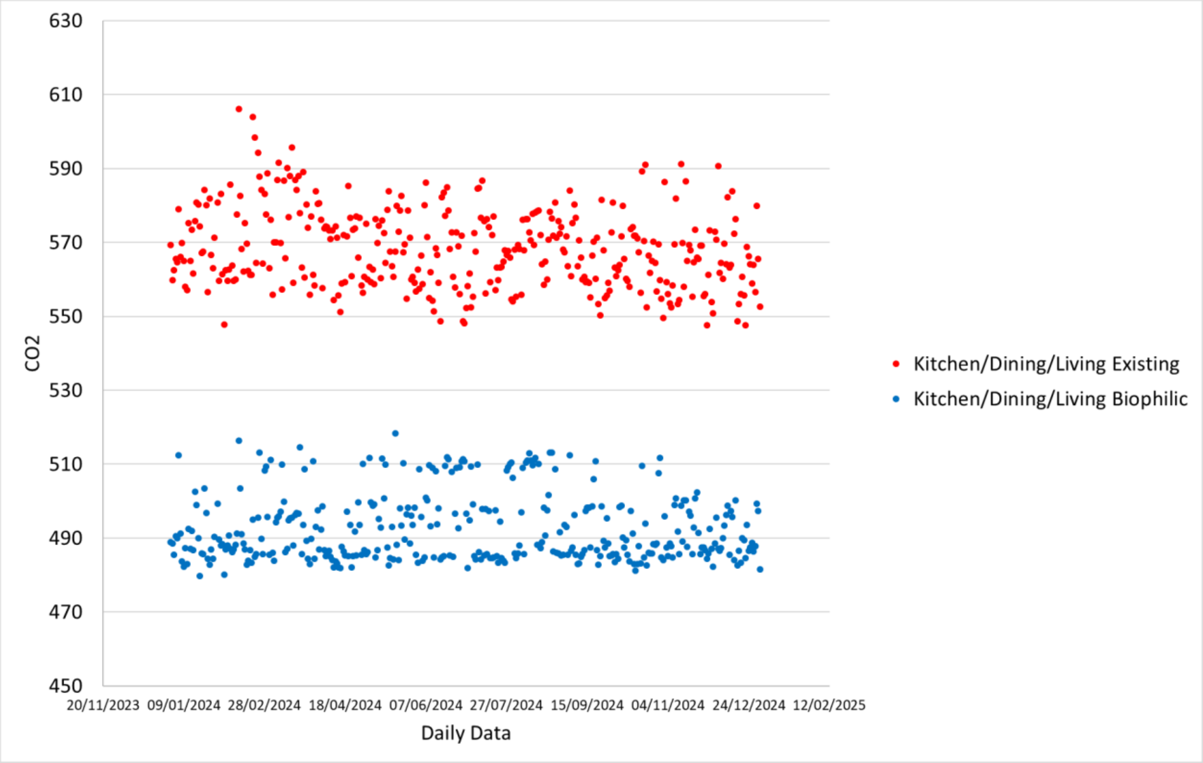


Figure 72 – CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the kitchen/ dining/ living of the Penthouse

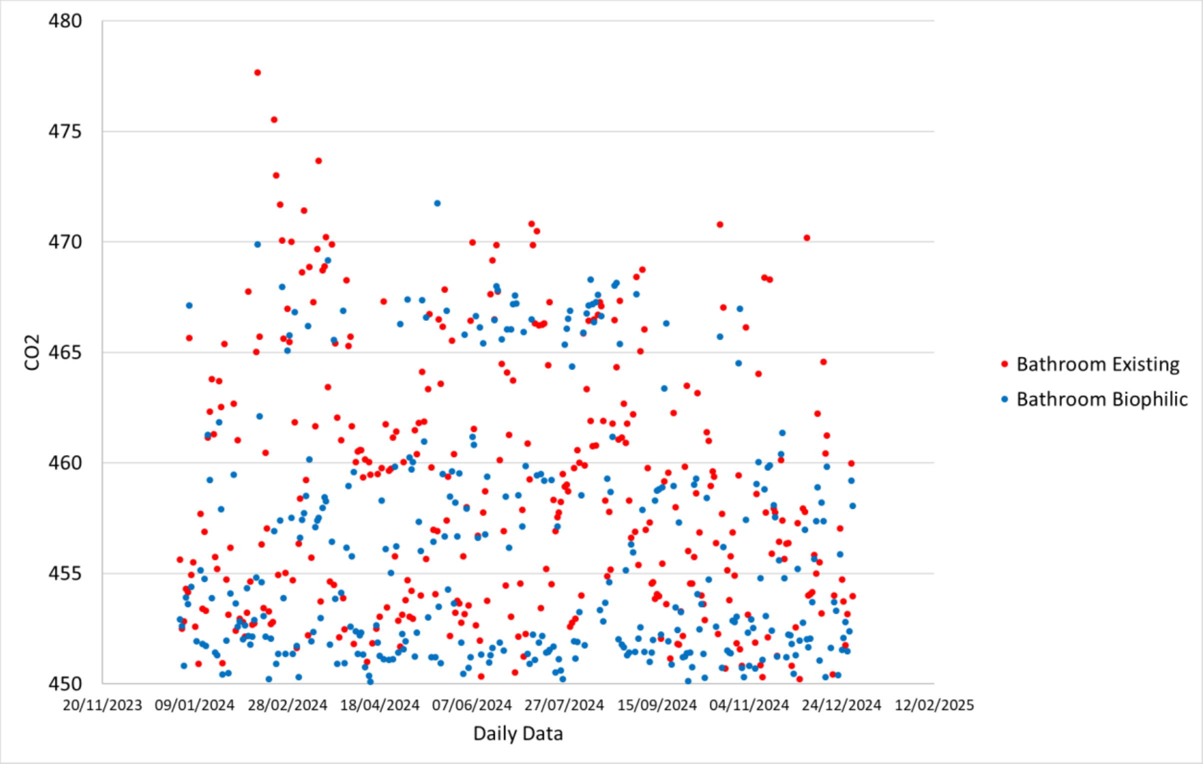


Figure 73 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bathroom of the Penthouse

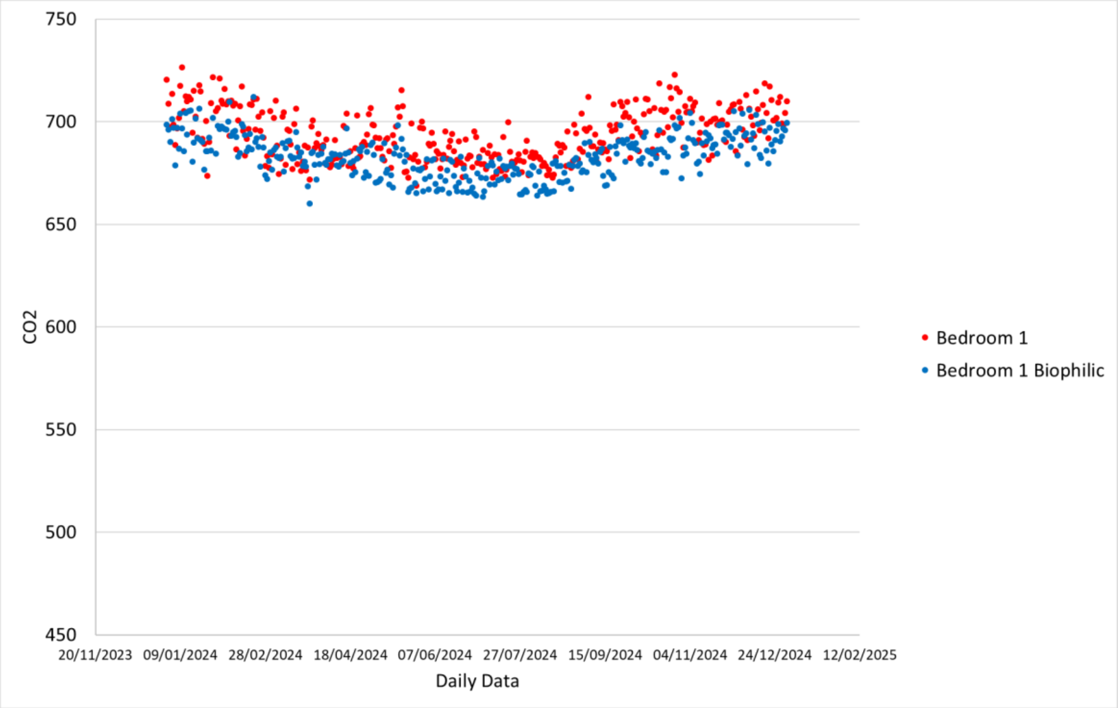


Figure 74 - CO$_2$ results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bedroom 1 of the Penthouse

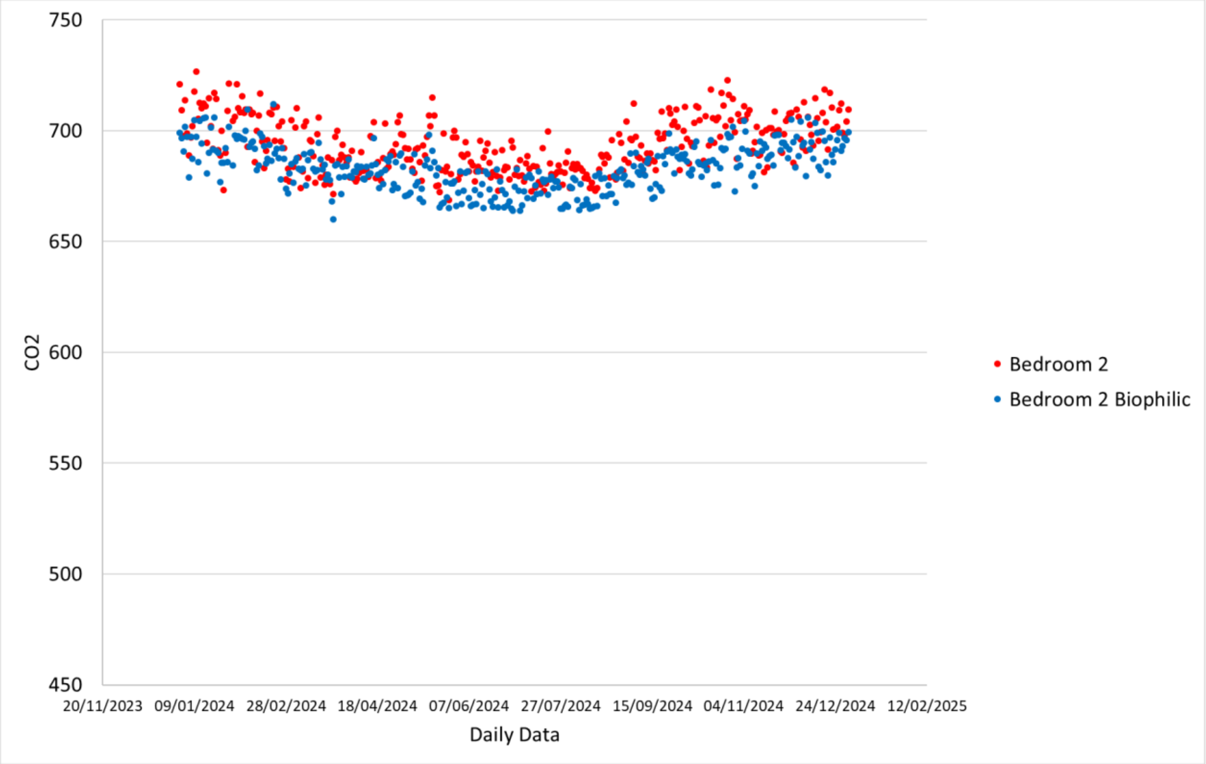


Figure 75 - CO$_2$ results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the bedroom 2 of the Penthouse

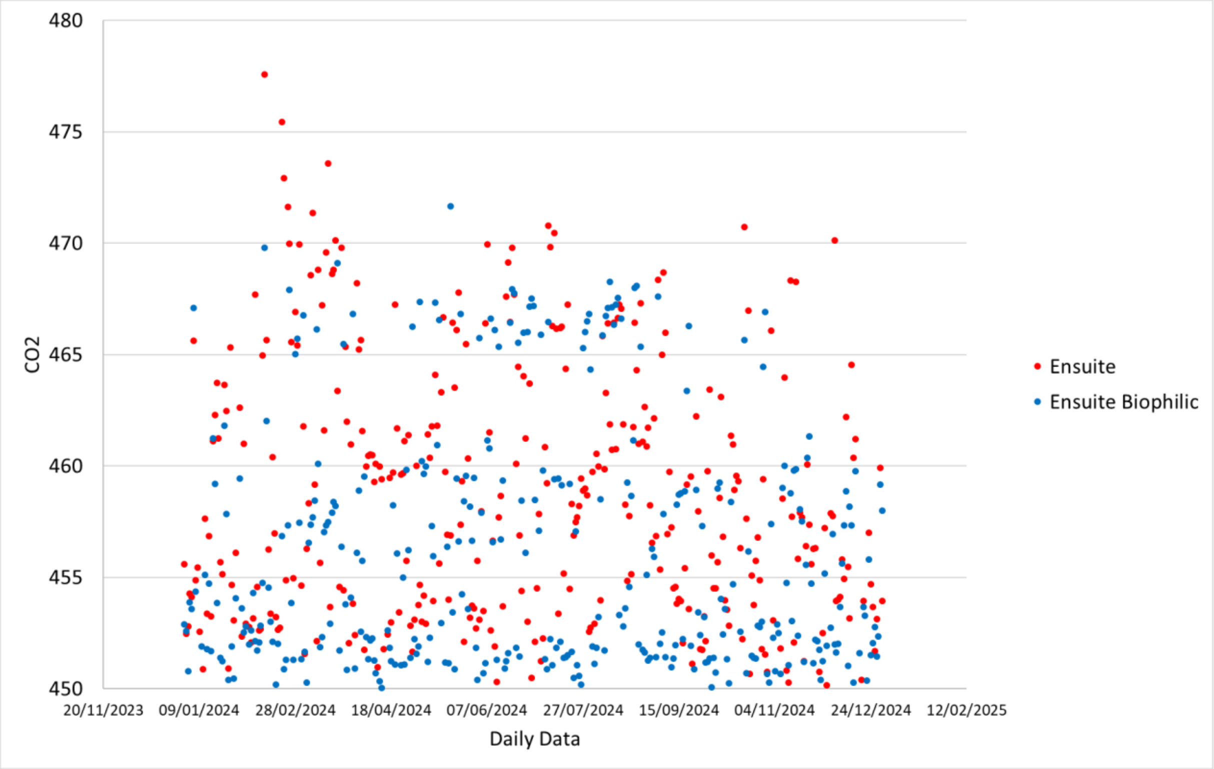


Figure 76 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the ensuite of the Penthouse

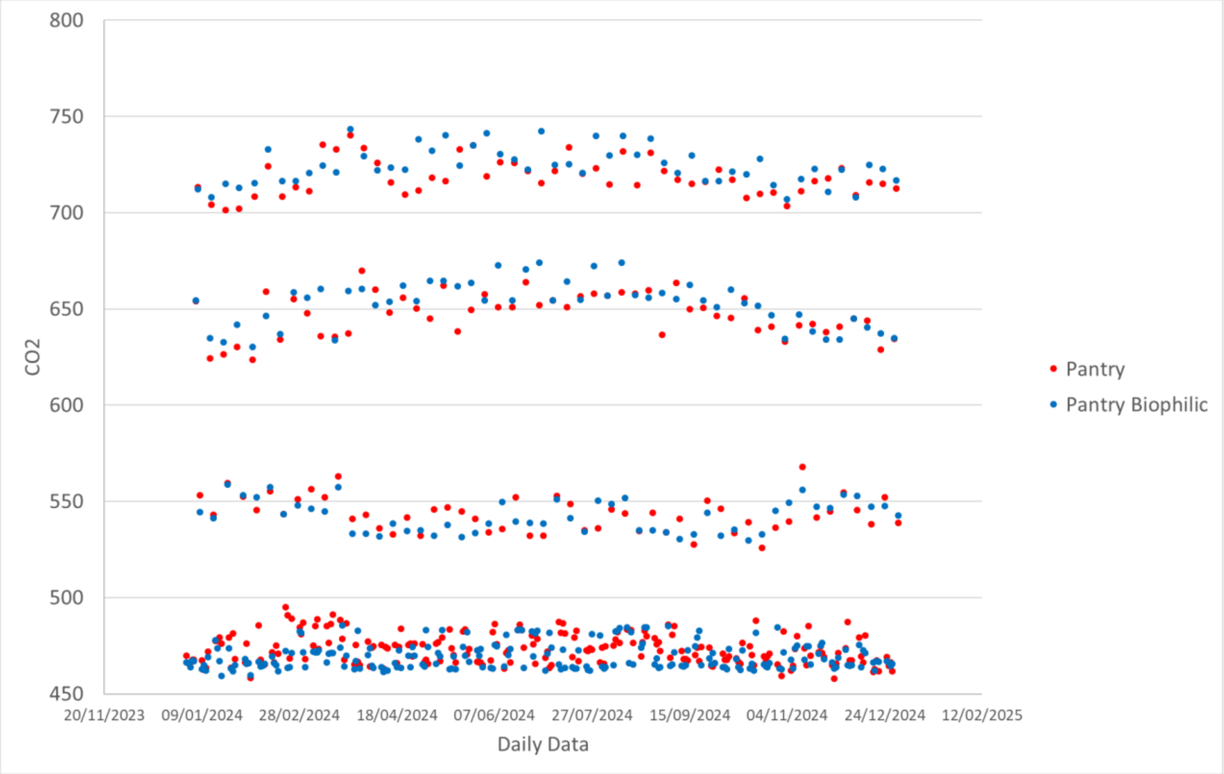


Figure 77 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the pantry of the Penthouse

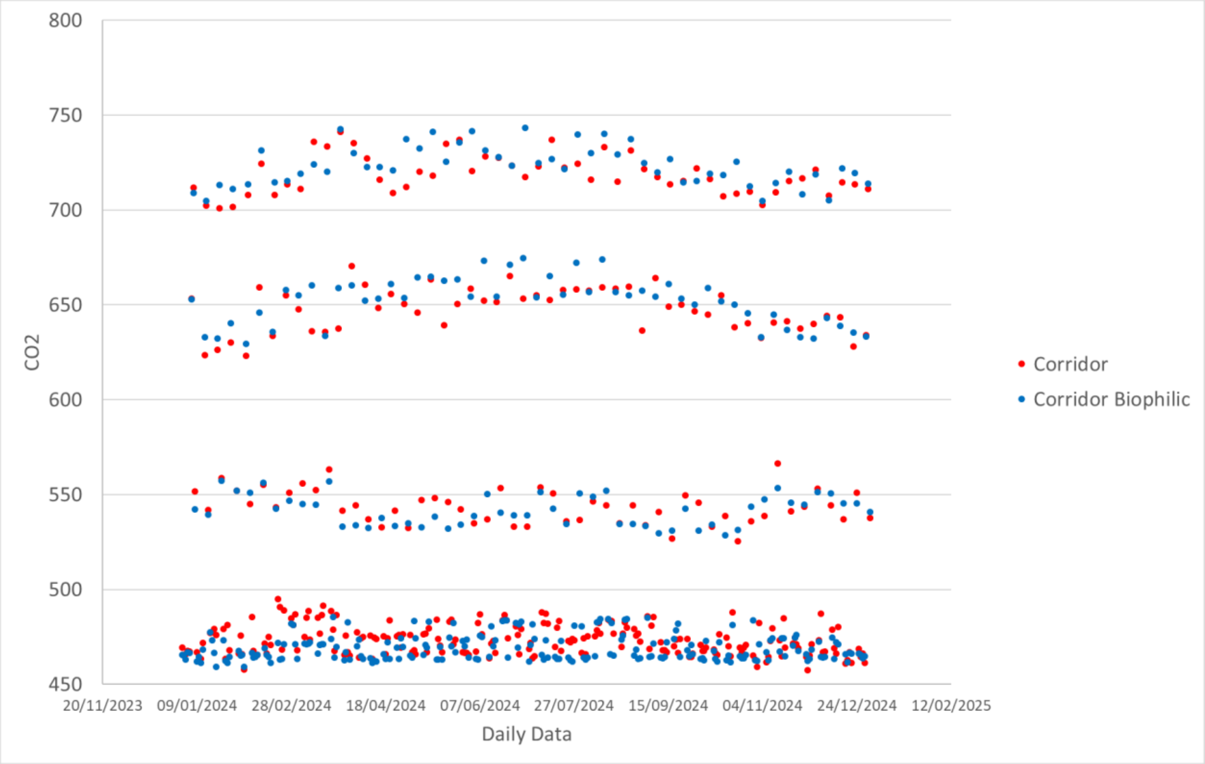


Figure 78 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the corridor of the Penthouse

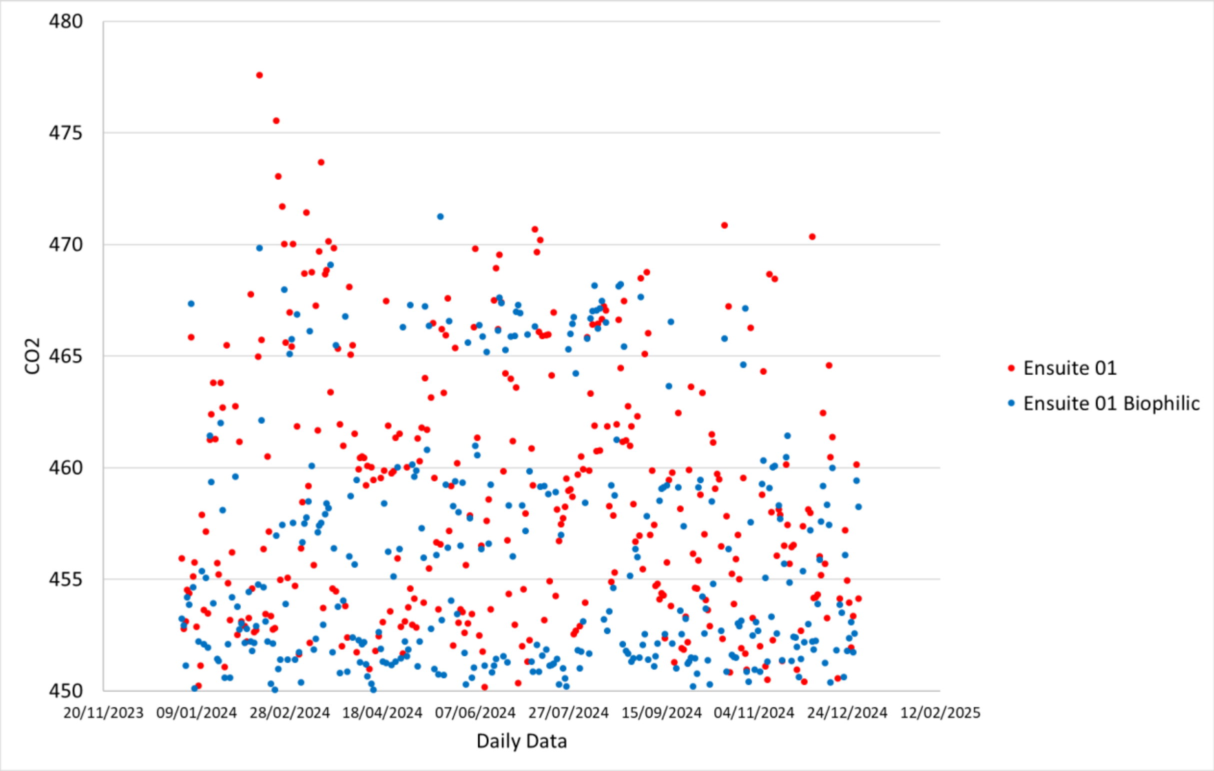


Figure 79 - CO_2 results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of the ensuite 01 of the Penthouse

4.5 Heating and Cooling Load Comparisons

4.6.1 Ground Floor Maisonette

In this section a discussion on the impact of the biophilic measures in terms of cooling and heating loads on a yearly basis. This analysis shows a full year 2024, presented daily load patterns for cooling and heating and total kWh consumption.

Considering the cooling load patterns in figure 80, this shows the consumption in the summer period from mid-June to mid-September for both the existing and the biophilic. One can observe that in the biophilic there are times that the cooling is not in use. Overall, as a total consumption the cooling load of the existing is 32.17kWh while the biophilic model reduced the amount by nearly 50% that amounts to 16.20kWh. This confirms the improvement in passive thermal effect and shows the effect of biophilic implementations that will also result in energy efficiency apart from the associated aspect of human well-being. This means that the active cooling system in this case the HVAC will be used for half the amount when compared to the existing scenario.

On the other hand, when comparing the heating loads, one can see a 45% reduction from 377.75kWh to 207.77kWh. while one assumes that the biophilic measures are associated with cooling, these results shows that it also effects the heating loads therefore keeping the internal temperature stable during winter months from November till April.

Comparing the cooling loads with and without indoor plants, to assess the effectiveness of the plants, a set of simulations was carried out without plants while keeping all the biophilic implementations mentioned in the methodology. The difference is negligible, only reducing the cooling loads by 0.1kWh. Although the number of plants was not that large, one can conclude that the indoor plants will not affect the overall cooling load consumption as from the properties one can notice that these will produce heat.

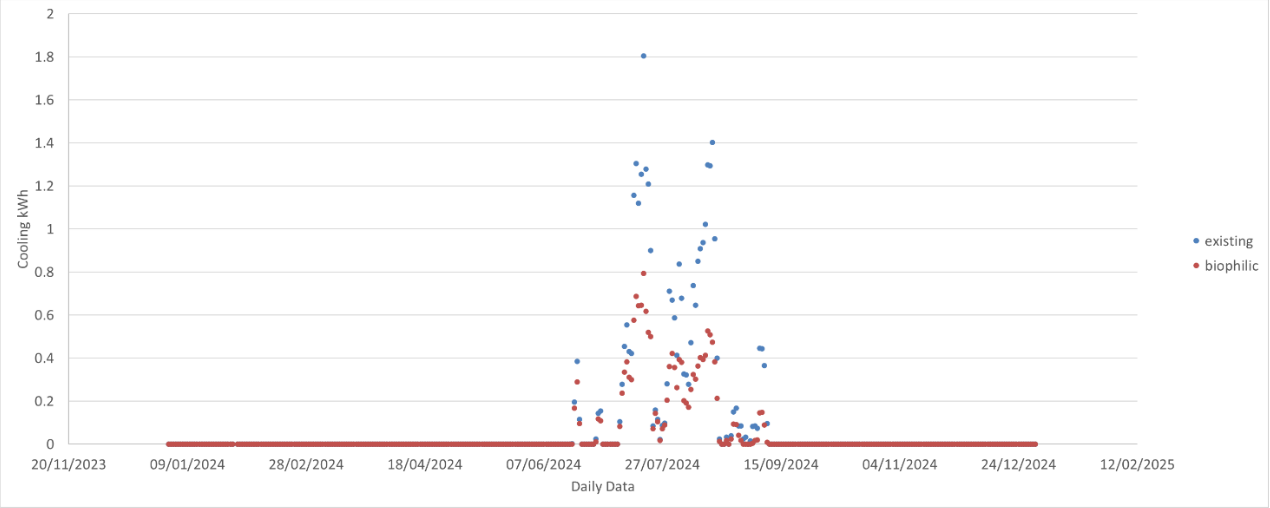


Figure 80 – Cooling load (kWh) results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of ground floor Maisonette

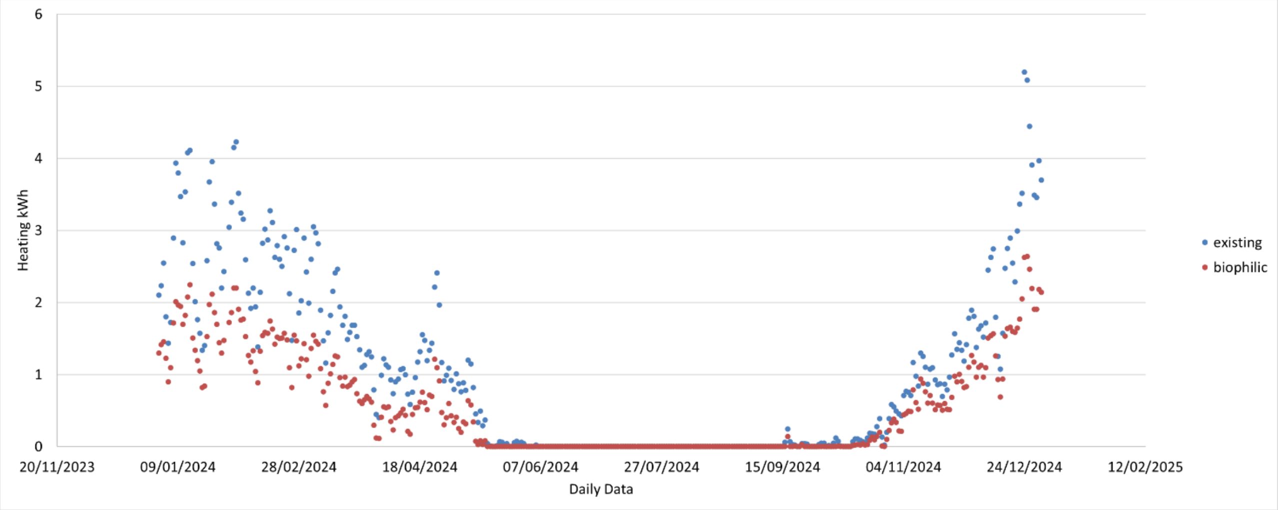


Figure 81 – Heating load (kWh) results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of ground floor Maisonette

Table 42 – Total cooling and heating load for both existing and biophilic implementations simulations of ground floor Maisonette

	Cooling (kWh)	*Heating (kWh)*
Existing	32.17	377.75
Biophilic	16.20	207.77

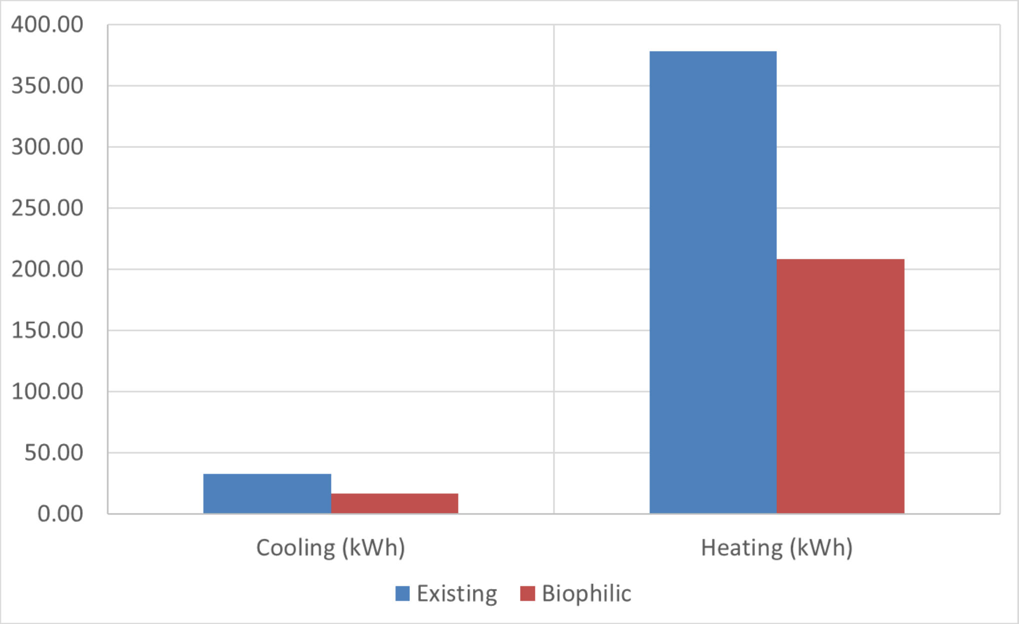


Figure 82 - Total cooling and heating load for both existing and biophilic implementations simulations of ground floor Maisonette

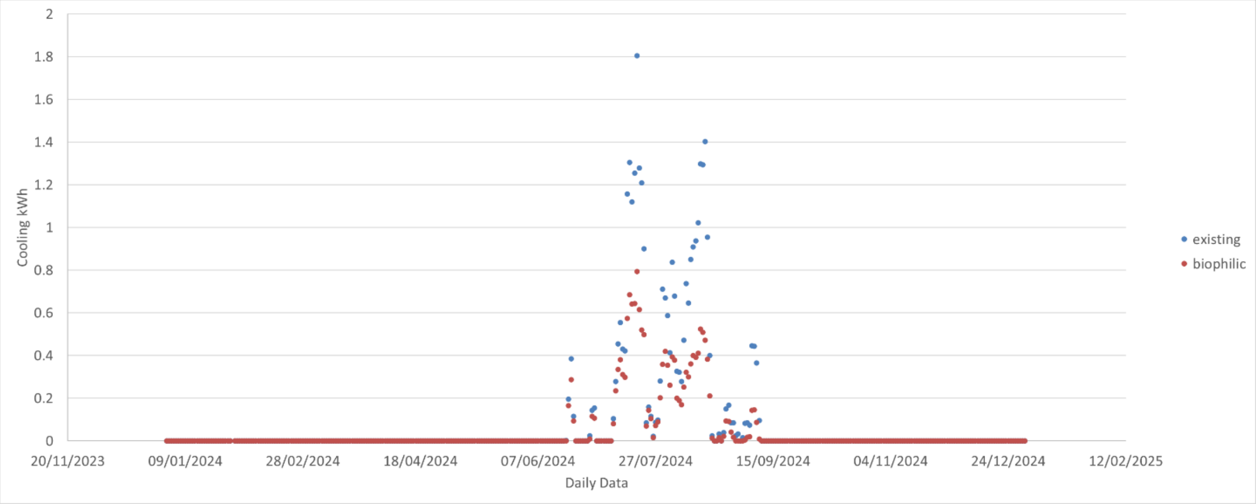


Figure 83 - Cooling load (kWh) results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation (without plants) simulations daily data of ground floor Maisonette

Table 43 – Total cooling and heating load for both existing and biophilic implementations (without plants) simulations of ground floor Maisonette

	Cooling (kWh)	*Heating (kWh)*
Existing	32.17	377.75
Biophilic	16.10	207.77

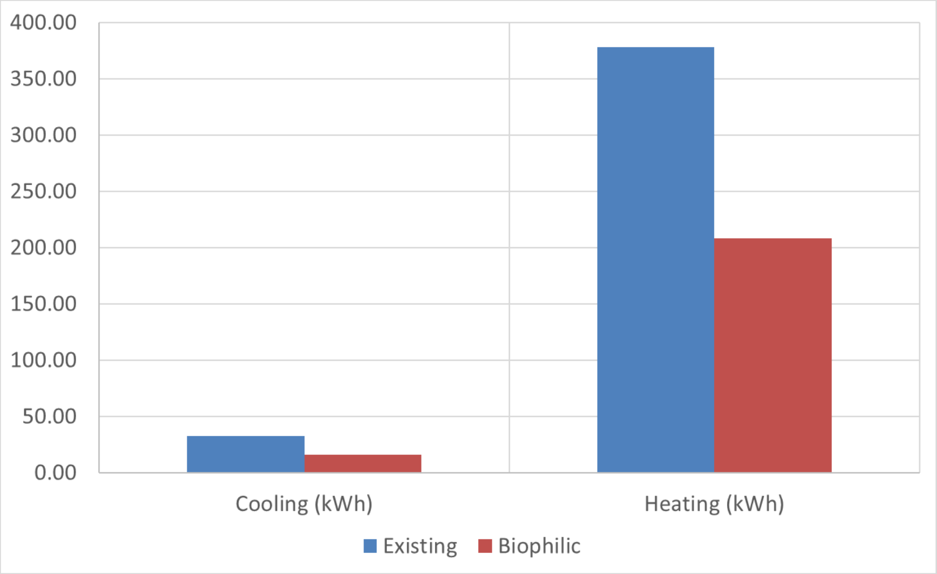


Figure 84 – Total cooling and heating load for both existing and biophilic implementations (without plants) simulations of ground floor Maisonette

4.6.2 Penthouse

The same analysis was carried out for the penthouse. Since the penthouse have full exposure to solar radiation therefore the external temperatures, the results are very different when compared to the ground floor.

This results in no effect when comparing the cooling loads but a very minimal increase in kWh from 1749.30 kWh to 1773.44 kWh (Table 44). This shows that the effect of heat from the indoor plants resulted into a slight increase in cooling loads. This result continues to confirm when simulating the same scenario without the indoor plants, this is since the loads decrease from 1773.44 kWh to 1704.03 kWh. Apart from this, one can also mention the fact that improve natural ventilation and daylight with increased apertures size, this will increase solar gains therefore more cooling will be required. One can comment that biophilic implementations must be well balanced to avoid such situations.

On the other hand, heating loads shows a significant decrease from 223.42 kWh to just 84.22 kWh, this confirms the results and discussion on the cooling load, therefore such insulation acts as a barrier from the outside temperature but will also affect the control of the internal temperature. As explained, this effect will allow passive solar gains that will decrease the heating loads in winter.

Overall, the biophilic implementation will affect more the heating loads rather than the cooling loads in the penthouse case. But as already mentioned, the effect without indoor plants shows a good decrease in cooling.

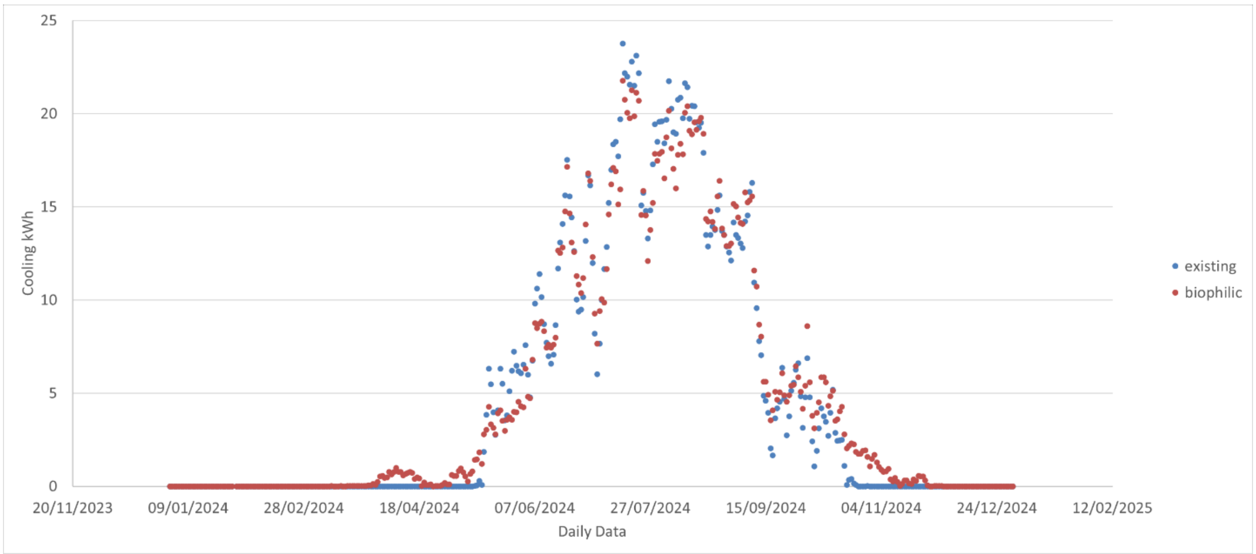


Figure 85 – Cooling load (kWh) results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of Penthouse

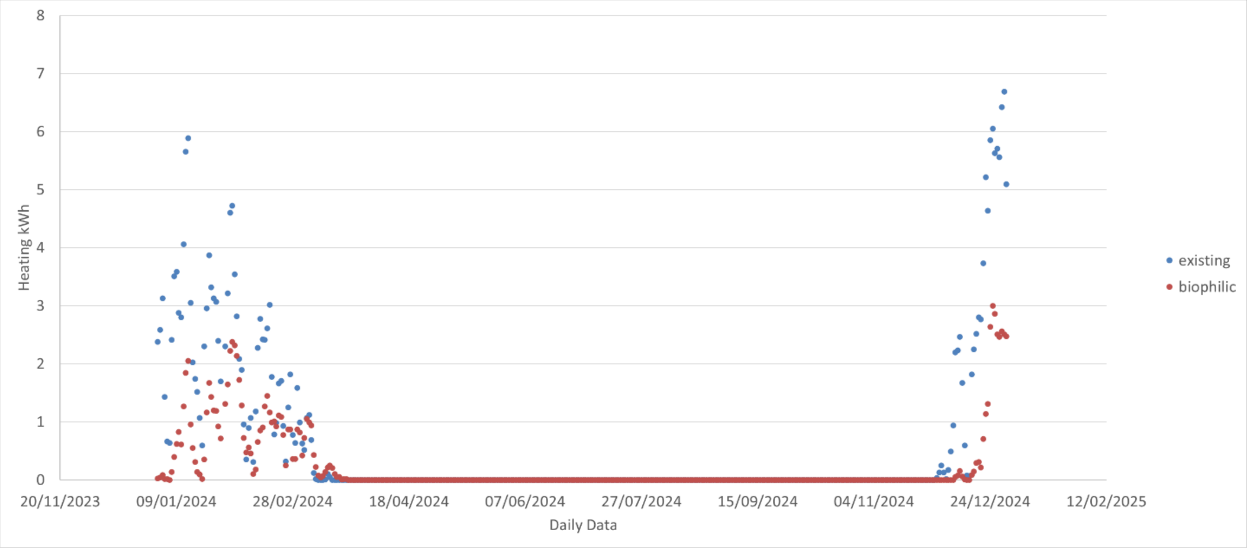


Figure 86 – heating load (kWh) results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation simulations daily data of Penthouse

Table 44 – Total cooling and heating load for both existing and biophilic implementations simulations of Penthouse

	Cooling (kWh)	*Heating (kWh)*
Existing	1749.30	223.42
Biophilic	1773.44	84.22

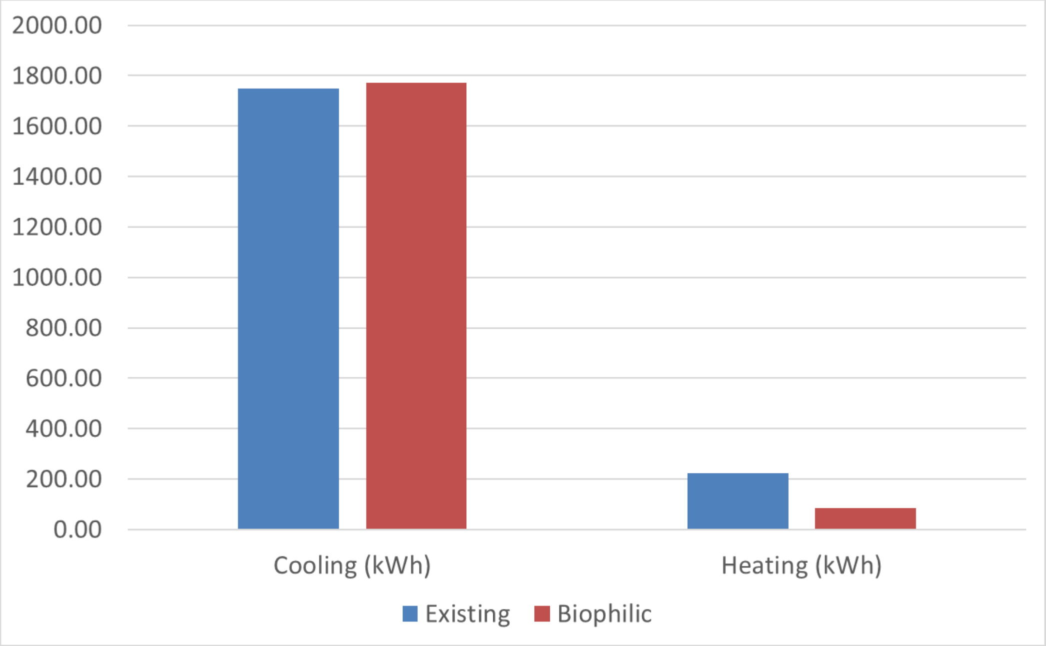


Figure 87 – Total cooling and heating load for both existing and biophilic implementations simulations of Penthouse

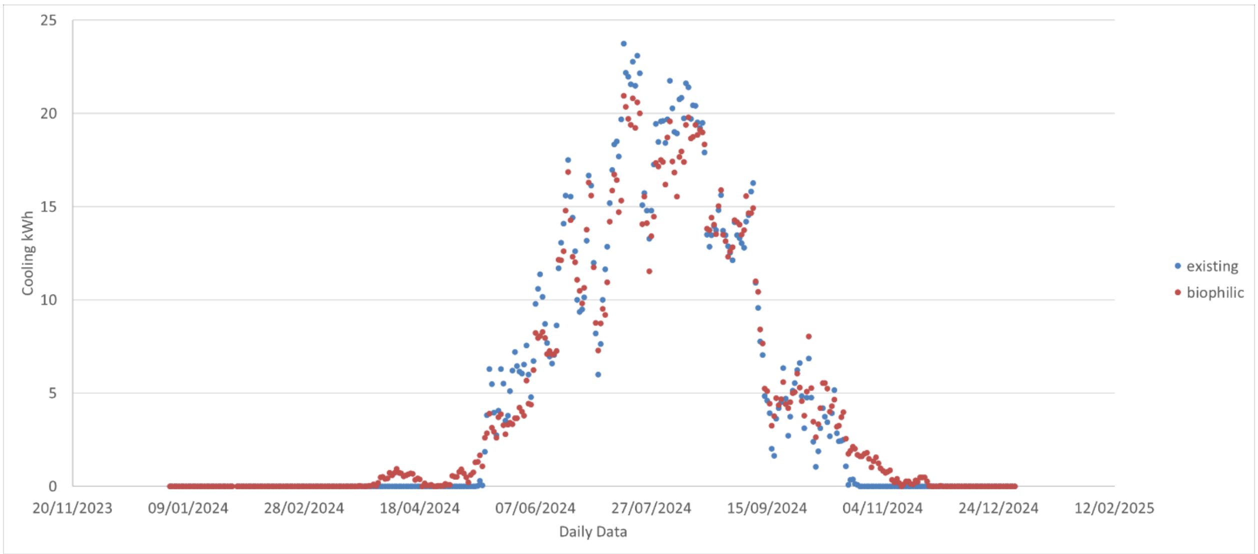


Figure 88 – Cooling load (kWh) results for a period of 1 year (2024) - Comparison between the existing and biophilic implementation (without plants) simulations daily data of Penthouse

Table 45 – Total cooling and heating load for both existing and biophilic implementations (without plants) simulations of Penthouse

	Cooling (kWh)	*Heating (kWh)*
Existing	1749.30	223.42
Biophilic	1704.03	84.22

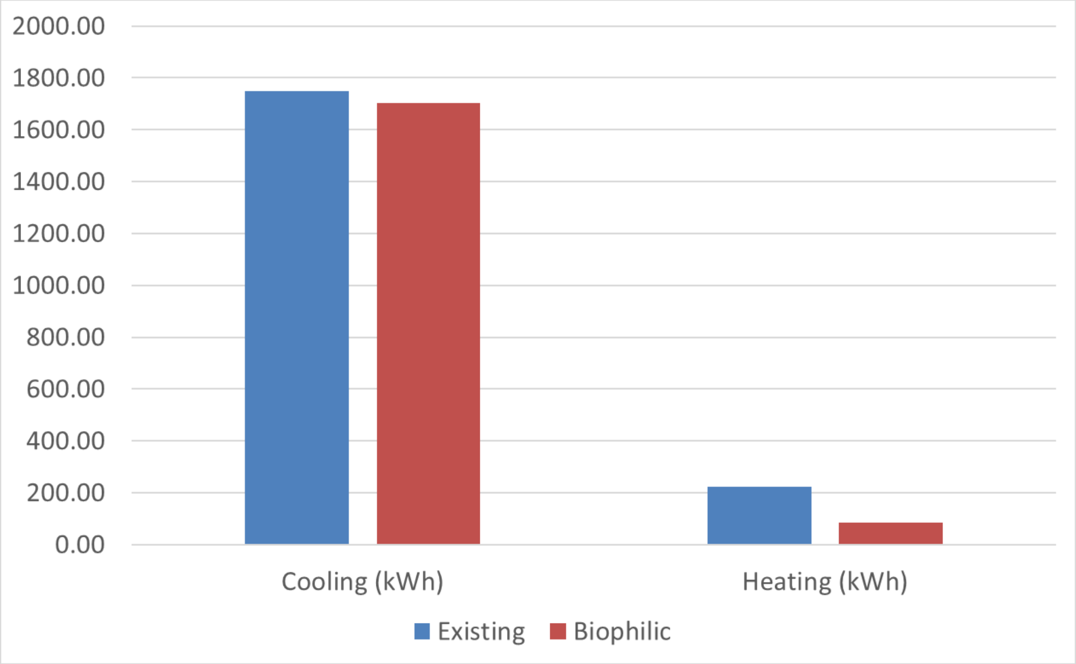


Figure 89 – Total cooling and heating load for both existing and biophilic implementations (without plants) simulations of Penthouse

4.6 Analysis of the advantages and disadvantages of Biophilic Design Measures

From the implementation of biophilic design measures in two different extreme scenarios being the ground floor and the topmost level, I can mention the main advantages and disadvantages in terms of thermal performance, indoor air quality, adaptive comfort and energy consumption.

4.6.1 Advantages

Thermal comfort

From the adaptive comfort analysis, important improvements were found mostly in the ground floor. This was effective for both scenarios having a substantial increase in category I for ground floor and good increase in category II and III for the topmost level. This shows that thermal comfort for ventilation and solar control is effective and controls internal temperature while decrease discomfort. This is one of the objectives of this dissertation.

Reduction in energy consumption

Heating and cooling loads in the ground floor reductions were very evident, having a decrease of 50% in cooling and 45% in heating. This is one of the dissertation objectives that biophilic design improve energy performance. On the other hand, the penthouse shows a slight decrease, but this is since this case is more complex in terms of cooling, but there was a substantial reduction on heating loads.

Improved indoor air quality

CO_2 levels show a constant result of lower rates. This shows that natural ventilation that is part of the biophilic design aspects effect the indoor air quality.

Human well-being

Finally, the human well-being although not tested in simulations or measured, from the literature review, it was very evident that biophilic design reduce stress, improve quality of life and well-being in general.

4.6.2 Disadvantages

- Limited cooling loads decrease for the upper levels
- Minimal impact with indoor plants
- Design complexity in retrofitting

Chapter 5 Conclusion

This research shows the performance of a typical existing ground floor apartment and top floor apartment and that of the same apartment with biophilic design measures that can improve the overall energy performance and thermal comfort. The research in this study found that the existing residential design standards both locally and on EU level, lack from promoting human well-being in relation to energy efficiency. This shows that there is a gap in the standards for residential buildings in terms of biophilic design aspects when compared to commercial buildings. This shows another gap between the energy efficiency compliance with the user human well-being, and these must go hand in hand (Ruparathna, Hewage, & Sadiq, 2016).

From this study, the researcher found that biophilic design is the way forward to close this gap. The findings indicate that each natural element affecting the built environment contributes to human well-being and may thus be regarded as a component of biophilic design. This means that thermal comfort, indoor air quality and energy performance are all related to natural elements which are part of the biophilic design. This also shows that passive design has high impact on the environment that not only led to adaptive comfort levels or energy consumption but by addressing the fundamental challenges of creating a truly liveable space.

This research provides a foundation for updating residential design standards, offering a pathway for improvements in both new and retrofitted apartment buildings. This can be achieved by including adaptive comfort and well-being in residential building codes, incentives for passive biophilic design measures and create pilot projects to raise awareness, projects that can be evaluated through user experience.

In terms of guidelines for our local scenario, the method used for this study could be implemented for existing buildings to ensure that retrofitted measures are feasible in terms of energy consumption, quality of life and initial costs. This suggested study can be based on a minimum of one year to have the full spectrum of data and one can compare a whole year of measured data with a whole year of simulation. Apart from the guidelines found in the literature to select the applicable biophilic design measures, for implementation, the method used for this study can be applied to on any existing residential apartment locally.

As a conclusion, the biophilic design is surely not just an aesthetic or theoretical information but a real-life approach to enhance sustainable buildings while also improving quality of life. This should be the future standard for residential building.

5.1 Limitations

Due to time limitations and simulation limitations, the following biophilic design aspects were not modelled. From research evidence these are two important factors that affect the human well-being in the built environment. Other factors include post-occupancy feedback for the quality of life aspect, since such measures were only simulated and not implemented in real life scenario.

Water: (Secondary)

Water can be integrated into the built environment in different ways, such as fountains, ponds, and rainwater harvesting systems. The function of these features includes the cooling of the indoor environment through evaporation, which means reducing energy consumption. Apart from this, water affects the sensory experience of the building which is a secondary element that helps the psychological well-being (Wijesooriya & Brambilla, 2021), (Park, Kim, Yoo, Oh, & Son, 2010).

Sound: (Secondary)

Acoustic design considerations such as the sound of leaves, water and birds are also part of the biophilic design experience. These sensory elements can affect the well-being however not affect the energy performance.

5.2 Recommendation for Future Research

Future recommendations include incorporating elements such as water features and natural sounds, which are essential components of biophilic design. These can be evaluated through surveys of occupants living in spaces with and without these features. Additionally, if time was not a constraint, a more comprehensive assessment could be conducted by comparing the experiences of occupants living in traditional apartments versus those in spaces that actively incorporate biophilic design principles examined fin this study.

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