DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

University of Strathclyde Engineering

An hourly analysis of heating and cooling: Energy, thermal comfort and indoor air quality of an aboveground vs. underground small office building in Chicago

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ABSTRACT

Underground constructions have gained traction in the architectural and engineering sectors due to their potential for energy efficiency and sustainability. This research presents a detailed hourly analysis of an aboveground versus an underground small office building in Chicago, focusing on energy demands, thermal comfort, and indoor air quality. Following the ASHRAE guidelines and utilising ESP-r for energy modelling, the study considered key parameters such as infiltration, ventilation rate, and ground properties. Four distinct scenarios were assessed, including a structure of an above and underground small office with and without HVAC systems.

The findings highlighted that the underground model notably surpassed the aboveground in terms of performance. The underground structure reduced humidity levels to 38% post HVAC interventions, whereas the aboveground model only managed a decrease to 57%. In terms of thermal performance, the underground building consumed -772 kWh and -14.3 kWh/m^2 over 1674 hours for sensible cooling, while the aboveground used up 1190 kWh and 22.0 kWh/m^2 across 991 hours, signifying a marked increase in energy consumption. Furthermore, the energy gains during heating for the aboveground model exceeded the underground's by 118.1%, and during cooling, the underground surpassed the aboveground by 162.1%.

Underground buildings highlight significant advantages in energy efficiency and thermal comfort. However, effective ventilation remains a challenge that needs addressing in their design. This research suggests that the construction sector should give more weight to underground building designs as a viable strategy for energy conservation and efficiency.

ACKNOWLEDGEMENT

I'd like to express my heartfelt thanks to my wife and children for their patience and support throughout my studies. Their understanding has been invaluable, and I am deeply grateful.

A big thank you to my supervisor and the Mechanical and Aerospace Engineering team. Their guidance has restored my confidence in engineering and shown me the true potential of this field. The department is a real asset to the engineering world.

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From the bottom of my heart, thank you all.

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ACRONYMS

BWh: Hot Desert Climate

Cfa: Humid Subtropical Climate

Dfb: Humid Continental - Warm Summer

Dwa: Monsoon-influenced Hot-summer Humid Continental Climate

HVAC: Heating, Ventilation, and Air Conditioning

BCE: Building Control Equipment

HMI: Human-Machine Interface

LED: Light Emitting Diode

CO2: Carbon Dioxide

C: Celsius

kWh: Kilowatt-hour

m^2: Square Metre

mm: Millimetre

U-Value: Thermal Transmittance (measure of how effective a building material is as an insulator)

W: Watt

m: Metre

hrs: Hours

ac/h: Air Changes per Hour

%: Percentage

1 INTRODUCTION

1.1 Problem definition

Underground buildings like the ones shown in **Error! Reference source not found.**, have recently gained attention in the fields of architecture and engineering, due to their energy efficient potential and as a solution to address sustainability challenges [1–3]. These structures are built partially or entirely below the ground's surface, utilising the natural thermal properties of soil to create energy-efficient spaces[4,5]. Some examples include underground shopping centers, transportation networks, utility tunnels, and data centers [6–8]. These facilities take advantage of the Earth's insulating properties to create stable interior zone temperatures, reducing the need for energy-intensive heating and cooling systems. The inherent thermal properties of soil act as a natural insulator, maintaining consistent temperatures throughout the year. This built-in insulation significantly reduces the need for energy-intensive heating and cooling systems, resulting in substantial energy savings [4,5,9,10].

A. Underground earth scraper located in Mexico

B. Generic underground office space

Figure 1. Examples of underground buildings [12,70].

With an engineering approach, these buildings have the capacity to transform urban energy consumption, offering practical solutions for sustainable urban development. Insights from underground construction projects worldwide, can provide valuable guidance for urban planners and engineers tackling the challenges of growing populations and environmental sustainability [6–8].

Historical studies analysed energy performance, having adopted a wide range of engineering methods and research endeavours. Evidence within these investigations had shown reductions in energy demand, ranging from 23% to 80%. The studies focused on the optimisation of thermal insulation distribution across underground surfaces; analysis of ground heat transfer within earth-contact structures; the application of specialised 2D thermal analyses tailored to underground building scenarios; utilisation of general-purpose numerical methods for solving 2D heat conduction equations; applying mathematical modelling techniques based on Fourier boundary series; and the integration of 3D finite element simulations with building energy analysis programs [4,5,10–12].

Additionally, practical data that included measurements gathered from pre-existing real world underground constructions was used. The studies incorporated several building typologies, including university buildings, submerged residential court yards; office buildings; two story elementary schools; single story residential buildings; and office dormitories, [Cite]. Geographical locations and climate zones were also considered in many of the cases, such as Dfb (Minnesota, Poland, U.S.), Cfa (Washington, Tennessee, U.S.), BWh (Kuwait), and Dwa (Nanjing, China) [5,11,12] .

Energy performance studies often use methods based on several energy performance compliance codes, depending on the study the country is conducted in. In the United States (U.S.), they adhere to recognised energy patterns including those set by ASHRAE. Founded in 1894, ASHRAE is a global entity dedicated to enhancing human well-being by advocating for environmentally friendly technologies in building design. Its focus areas encompass building systems, energy efficiency, the quality of indoor air, refrigeration, and fostering sustainable practices within the sector. [13–15].

Despite several studies exploring the energy performance and heat transfer characteristics of underground constructions, there are gaps in research and challenges remain. One challenge is the analysis of Hourly Data, where existing research relies on monthly datasets to assess energy consumption and heat loss in underground buildings [11,12,16,17]. However, by not adopting a dynamic dataset, the subtleties of hourly fluctuations may not be captured. Analysis that considers a dynamic approach that includes hourly data, may produce improved correlated energy performance results [18,19].

The intricate dynamics of hourly temperature fluctuations may have a significant influence on the heating, cooling and thermal comfort levels of underground spaces. These fluctuations are instigated by ventilation and internal gains from occupants, lighting, and equipment usage; highlighting the importance of obtaining detailed and timely data to enhance the accuracy of analysis with respect to energy performance [12,18–20].

1.2 Aim

This research provides an analysis for an underground office building studies conforming with ASHRAE guidelines. It aimed to analyse an aboveground small office building and an underground small office building, consolidating annual monthly hourly energy demand for heating and cooling which analysed high and low peak temperatures of both, then compared them to determine which building performed better, which helped determine the feasibility of underground buildings.

1.3 Overview of methodology

This thesis, adopted a methodology for the energy modelling analysis which involved a structured process, show in **Error! Reference source not found.**. In the pre-processing stage, parameters like infiltration, ventilation rate, casual gains, and ground properties were carefully considered. Following this, calculations were carried out across 4 cases that included an above ground and underground small office building with and without HVAC heating, cooling, air-conditioning and ventilation), in a distinct climate: Chicago. These cases adopted model methods that adhered to ASHRAE standards, talked about in section 1.1, when each model was simulated and analysed for annual and hourly energy demand.

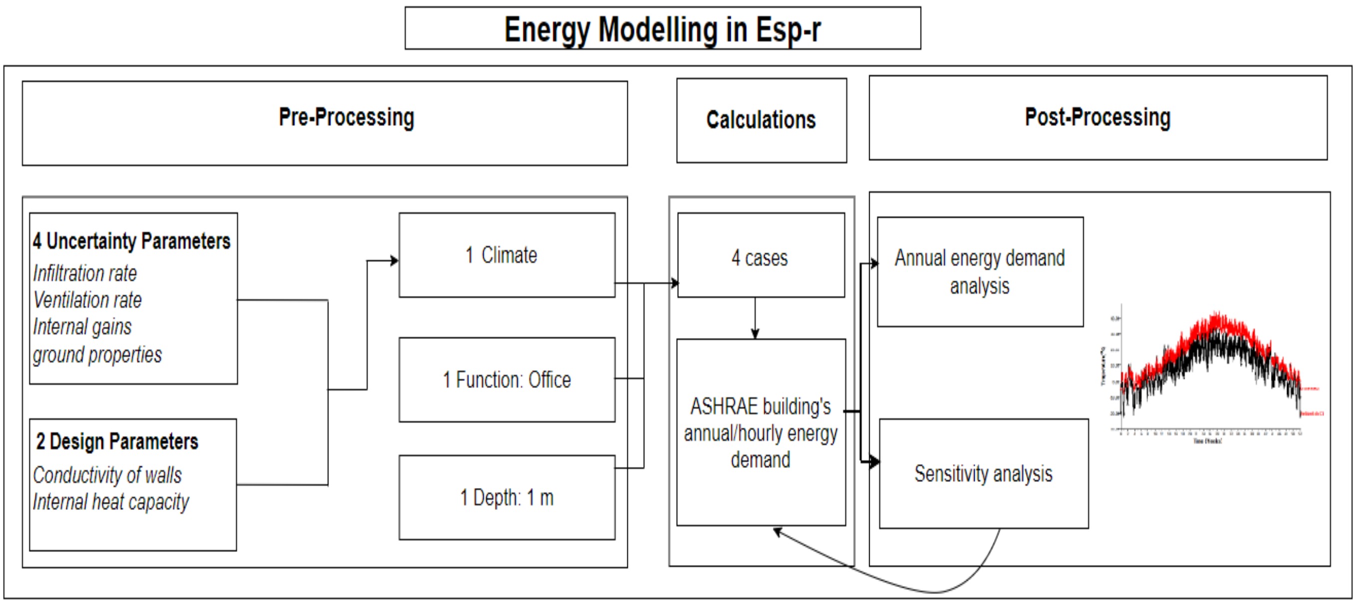

Figure 2. Block diagram of the energy modelling process.

In the post-processing phase, the analysis encompasses annual energy demand evaluation, sensitivity analysis to gauge the model's response to variations, and exploring possibilities for renewable energy integration. This comprehensive approach, from data preparation to rigorous analysis and exploration of energy-efficient options.

1.4 Structure of the dissertation

The structure of the project that assisted the research was:

1. **Literature Review and Data Preparation**

- Conducting a thorough review of existing literature on underground building energy performance studies which confirmed and identified gaps and challenges.
- Obtained and pre-process input parameters including casual gains, ventilation rate and infiltration rates from literature sources. Then they were extrapolated into samples using numerical methods to generate different building input parameter configurations.

2. **Data Analysis and Energy Demand Calculation**

   - Evaluated the calculated annual hourly energy demand for heating and cooling for an underground and aboveground small office building within a temperate climate based on the ASRAE standard.
   - Performed energy modelling calculations for several different cases, which adapted considered heating and cooling which supported the evaluation of the impact of these parameters.

3. **Sensitivity and Uncertainty Analysis**

   - Applied numerical methods to assess the sensitivity and uncertainty of the energy demand calculations based on variable input parameters such as casual gains, infiltration rate, ventilation rate.
   - Analysed the distribution of results and identify relationships between input variables and annual energy demand, which highlighted which parameters had a significant impact.

2 LITERATURE REVIEW: HEATING & COOLING IN ABOVE AND UNDERGROUND BUILDINGS

2.1 Underground building concepts

A large proportion of citizens throughout history have been attracted to the potential for better standards of living that cities have on offer. Whether that be better employment opportunities, healthcare or education, [21–24] . As the influx of people continues to grow within cities, there is even more need necessity to reduce environmental impact caused by urban areas and maximise land use more sustainably. The example shown in **Error! Reference source not found.**, illustrates challenges relating to land scarcity and increasing populations. As a result, urban planners and policymakers are exploring unconventional routes for urban expansion, [1,2,25] . One of these routes lies underground, where the potential of subterranean spaces offers an energy efficient and sustainable solution to the complex problems of modern urban development.

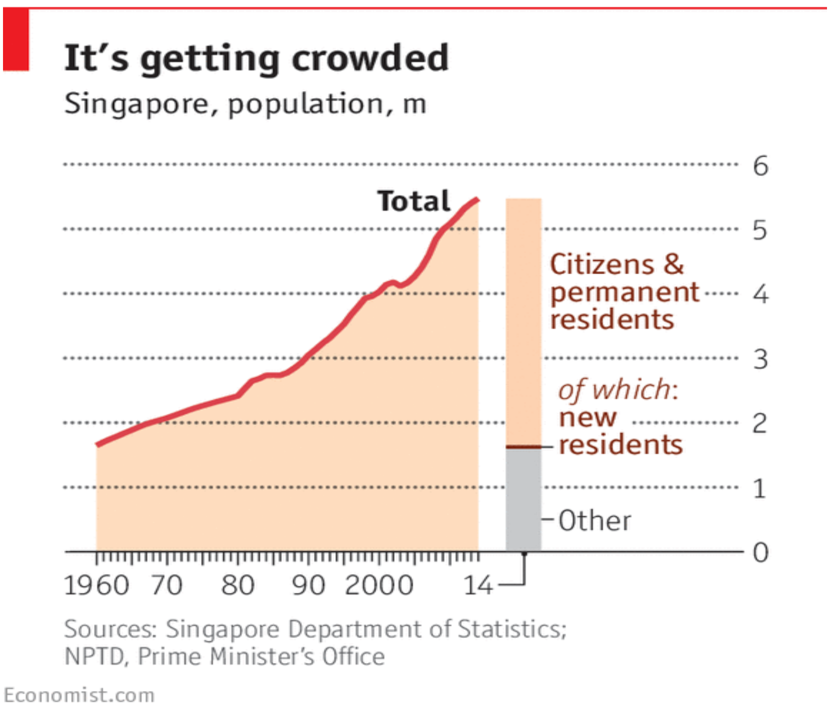

Figure 3. The Economist's stats on overpopulation in Singapore [71] .

The practice of subterranean construction has a longstanding history and historical records show that subterranean structures were designed to withstand extreme climate and environmental challenges dating as far back as the 12th century BCE shown in **Error! Reference source not found.**, [3,26–28]. However, underground construction has highlighted several contentious issues within the engineering and urban planning community. The predominant factor in this is the environmental impact associated with the excavation process. Excavation can disrupt local ecosystems, provoke subsidence, and affect underground water systems raising concerns regarding the ecological repercussions of subterranean development, [29–32]. Additionally, resource allocation is a subject of debate, as there is immense material required for constructing underground buildings. These contentious issues raise questions as to whether the benefits of underground spaces, including enhanced energy efficiency and land utilisation, outweigh the resource-intensive nature of their construction, [33–36].

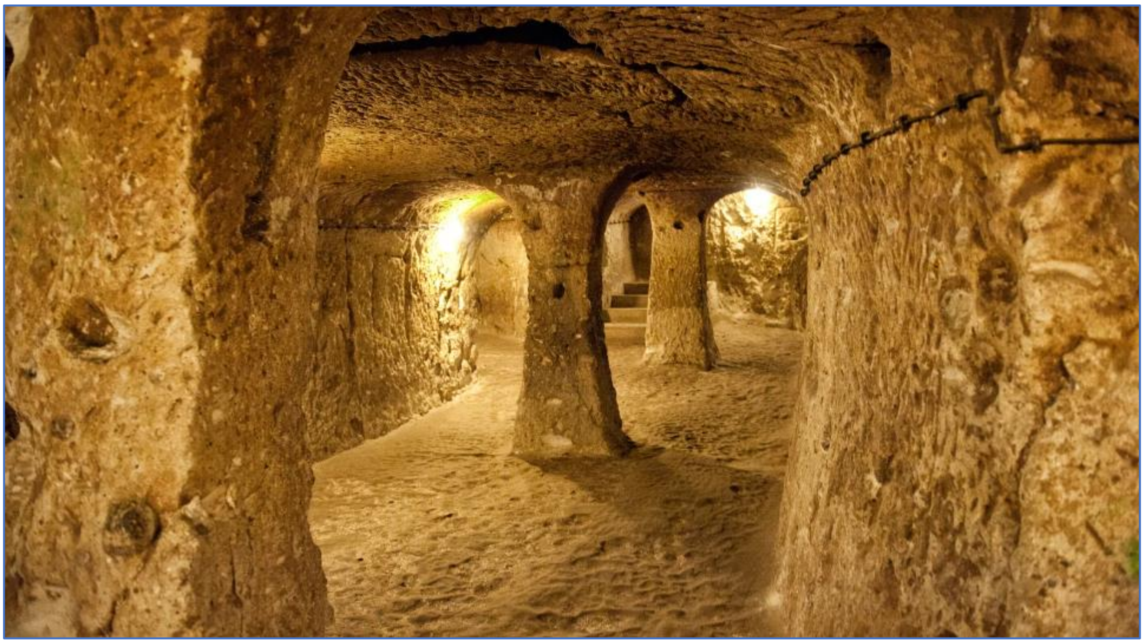

Figure 4. The ancient city of Elengubu, known today as Derinkuyu, Turkey, burrows more than 85m below the Earth's surface, encompassing 18 levels of tunnels built in 1200 BCE [72] .

In more recent history, there has been an increase underground construction which includes shopping complexes, transportation networks, and underground storage facilities. These initiatives have collectively expanded urban living spaces and eased burdens of above ground land utilisation in densely populated cities, [6,33,37–39] . Take for example Singapore, where their country faces a population density challenge. Constrained by the limitations of land reclamation, the Singaporean government have strategically shifted its focus towards subterranean development to accommodate its growing population. Examining case studies, such as underground ammunition storage and largescale industrial storage hubs, underscores the potential of underground spaces, spanning from storage solutions to transportation infrastructure, [6–8,37,40]. Another factor is cost considerations, given that underground construction typically demands higher investments compared to above-ground counterparts due to excavation complexity and the need for structural reinforcement and ventilation systems, [33,35,39].

Urban planners and policymakers are contending with aesthetic concerns and the integration of underground structures into existing urban landscapes, and safety and security pose substantial engineering challenges, particularly in emergency egress planning, ventilation, and structural resilience, [6,33,40,41] . Regulatory frameworks must adapt to accommodate this evolving construction paradigm, which may spark debates about the balance between innovation and regulatory oversight. Public perception plays an influential role in the acceptance and feasibility of underground developments, making it an important aspect to address in advancing the field of subterranean construction.

In contrast, as countries around the world embrace the net-zero carbon emission timeline shown in Figure 5, underground construction is evolving beyond spatial considerations, becoming a conduit for achieving enhanced energy efficiency, [36,42]. Subterranean structures that capitalise on the ground's natural thermal properties offer a convincing solution for sustainably maintaining consistent indoor thermal conditions throughout the year, [5,10,16]. This aligns with global sustainability goals and could present an innovative departure from conventional above-ground architectural norms [43–45] .

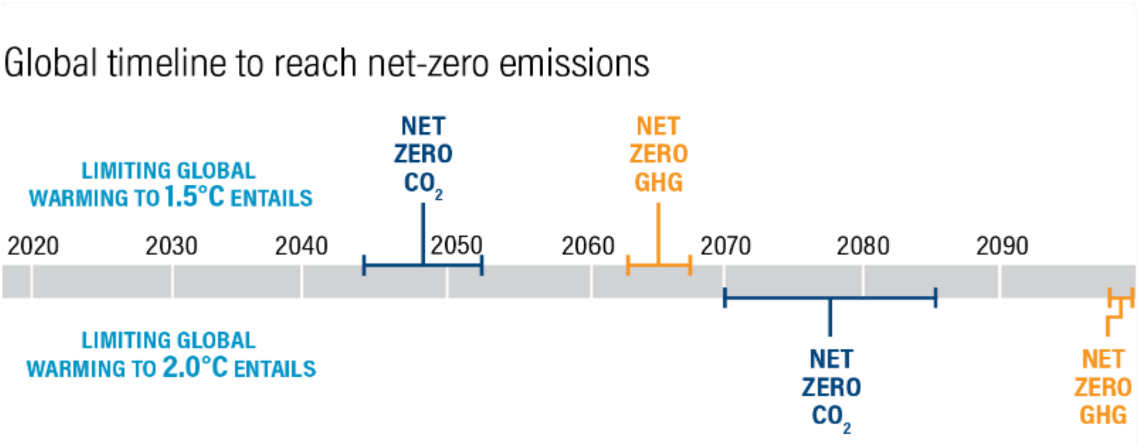

Figure 5. Intergovernmental Panel on Climate Change (IPCC) report net-zero timeline [73].

The exploration of underground structures for commercial and residential has received more interest recently, however the concept of underground buildings remains relatively under-developed due to their constraints. Cities like Mexico City and Shanghai have considered the idea of underground constructions shown in Figure 1 and Figure 6 several years ago due to over population, but these initiatives are still in the concept design stages of development [46,47]. To maximise the capabilities of underground building, it is imperative to examine their distinct advantages, challenges, and potential risks.

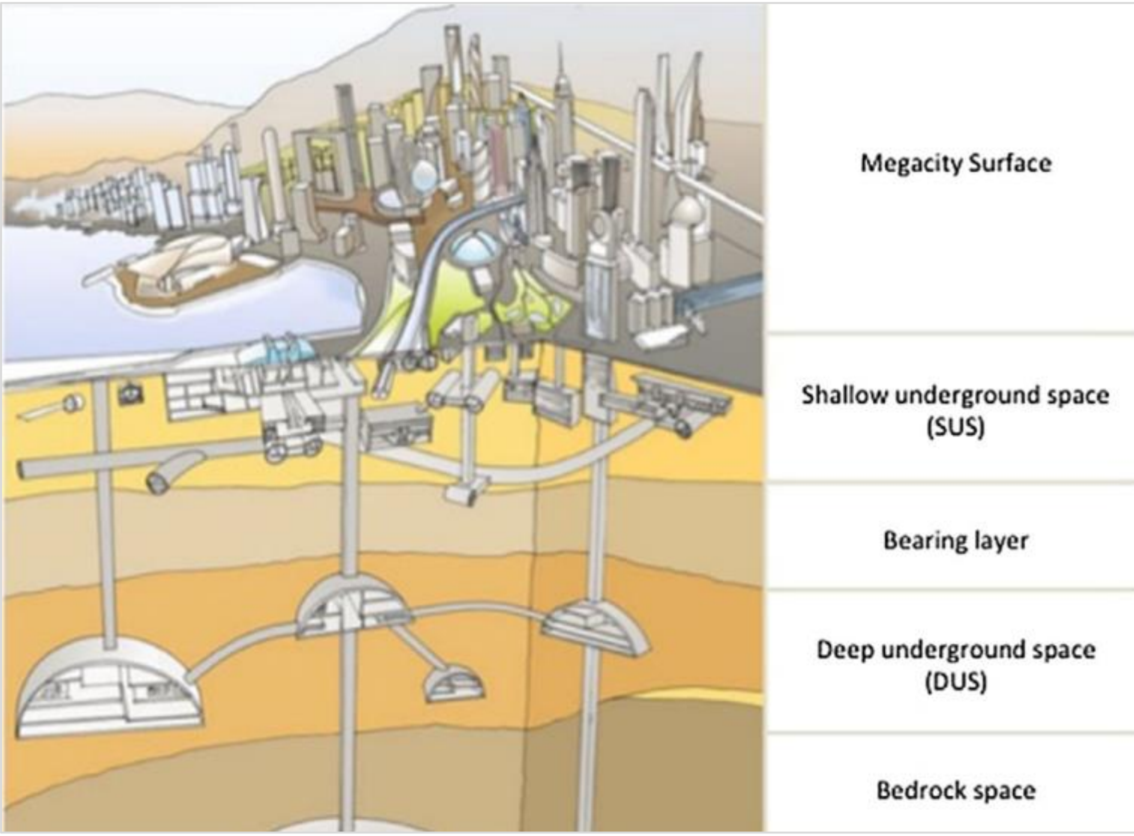

Figure 6. Deep Shanghai Project - Shanghai's megacities underground transport system [74].

With respect to the heating and cooling element of underground buildings, like above ground buildings, there are several crucial parameters that are required to be analysed comprehensively to assess the energy performance and thermal comfort. These include thermal insulation, geological conditions, climate data, heat gain, ventilation systems, building, indoor thermal comfort, heating and cooling control strategies, energy efficiency measures, and renewable energy integration [14,48].

2.2 Environmental impact of underground buildings and above ground buildings

2.2.1 Environmental effects induced by excavation

Environmental considerations are important factor to consider, even when conducting model simulations for above and underground construction, ensuring that both construction practices and the surrounding environment remain safe and undisturbed, even in the concept stages [49–51]. In the study [30], the researchers investigated the intricate dynamics of groundwater seepage and soil deformation during excavation processes. With reference to Figure 7 ,utilising a 3D finite element method approach, founded on Biot's consolidation theory and the nonlinear Duncan-Chang's model, they developed a program to investigate the coupling effects of these two factors.

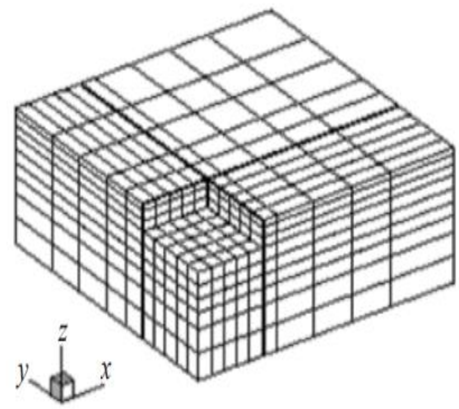

Figure 7. Mesh of finite elements designed for the 3-D finite method for analysing the environmental effects induced by excavation [30].

Their findings highlighted the fundamental role of water head difference variations during excavation. Specifically, neglecting this variation led to discrepancies in predicting porewater pressure distributions and resulted in underestimated pit deformations. By thoroughly examining the distribution patterns of soil displacements (both horizontal and vertical) around the excavation pit and excess porewater pressure, the study offered an insight into the environmental effects around excavation sites.

2.3 Energy modelling techniques and tools for buildings

Energy modelling techniques help figure out how much energy a building will use, whether it's built above the ground or below it and traditionally follow a distinct pattern, shown in Figure 8.

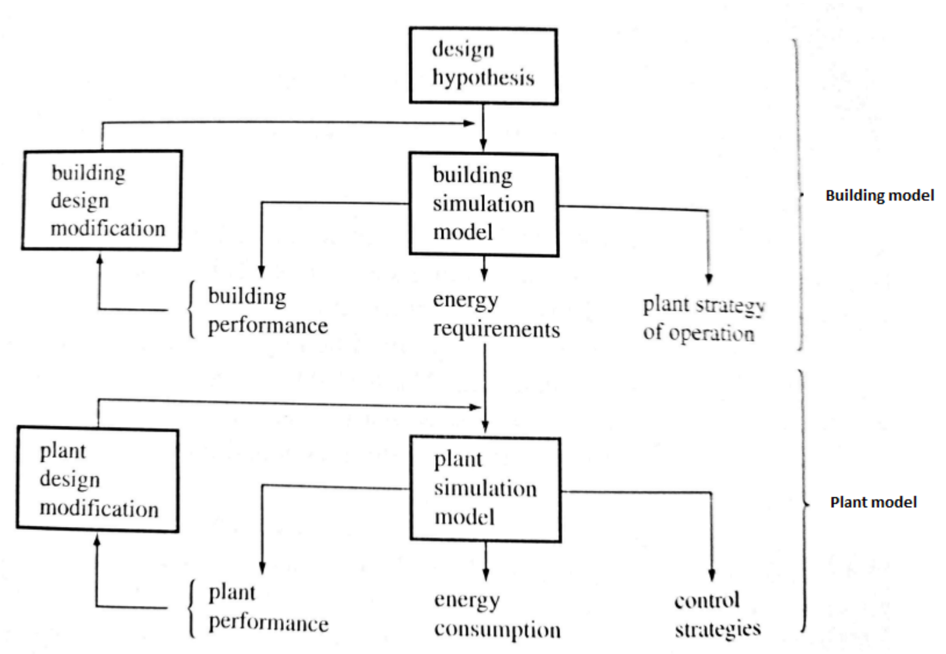

Figure 8. The traditional diagram of modelling a building and plant system taken from Joseph Clarke's "Energy simulation in building design" [53] **.**

Sections 2.2.1 and 2.2.3 help form an understanding that these techniques are especially important before a building is constructed. By adopting them, architects and engineers can make plans that reduce energy demand and cost when thinking about the long-term lifecycle of the project [25,35,52]. Additionally, the techniques are also useful for older buildings, where to make a traditional building more energy efficient, these techniques could potentially demonstrate how it can be done. Simply, they are like a handbook for making sure buildings are made as efficient as far as reasonably possible.

2.3.1 Joseph Clarke's energy simulation in building design book, second edition

Referencing [53], according to Joseph Clarke, understanding and predicting the energy performance of buildings hinges on effective energy modelling techniques. He outlines that contemporary simulation programs, predominantly employ either response function methods or numerical approaches that encompass finite difference or finite volume. While the former is tailored for linear differential equations with static parameters, the latter showcases versatility, addressing both linear and non-linear equation systems that exhibit temporal variation. The essence of these methods lies in their emphasis on the conservation of energy, ensuring model integrity, and accommodating all flow paths. As the field evolves, the integration of innovative technologies such as neural networks and genetic algorithms emerges, paving the way for sophisticated energy use predictions.

2.3.2 Advances in research for underground buildings: Energy, thermal comfort, indoor quality

As mentioned in section 2.1, there is a rising trend towards underground building research, shown in Figure 9.

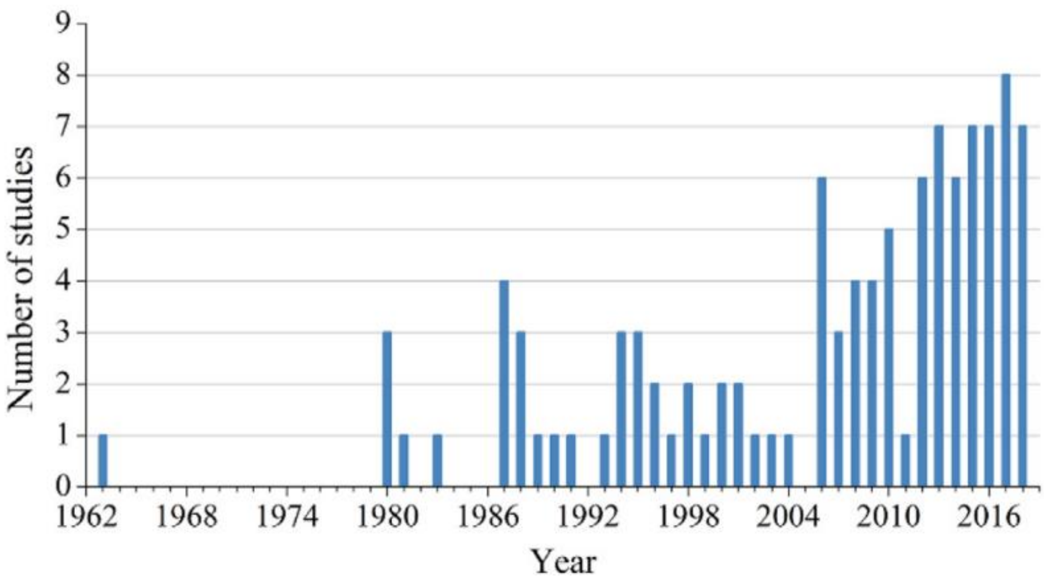

Figure 9. A number of studies completed on energy, thermal comfort and indoor air quality of underground buildings [11] .

This article researches the energy efficiency, thermal comfort, and indoor air quality of these structures. Key findings found that energy modelling of underground buildings commonly adopt the finite difference method when modelling and conducting simulations and analysis. However, when evaluating indoor air quality and thermal comfort, it was found that onsite experiments were preferred.

One challenge identified is the simulations' accuracy in predicting heat transfer through the ground, suggesting that these models need refining. The research also emphasizes the need for a balanced approach, focusing not just on energy efficiency but also ensuring that underground spaces provide a comfortable and healthy environment for occupants.

2.3.3 ESP-r: integrated simulation tool for design of building and systems

Within this study, an energy modelling software package called ESP-r , adopted the numerical and integrated methods described in Joeseph Clarkes book [53,54] . Referencing [55], the paper in this section states that ESP-r is a powerful state-of-the-art simulation tool, which the designers used for designing buildings and its heating and cooling systems. This software helps designers understand how a building will perform, supporting their design decisions based on the most efficient design choices. The structure of the ESP-r design tool is shown in Figure 10.

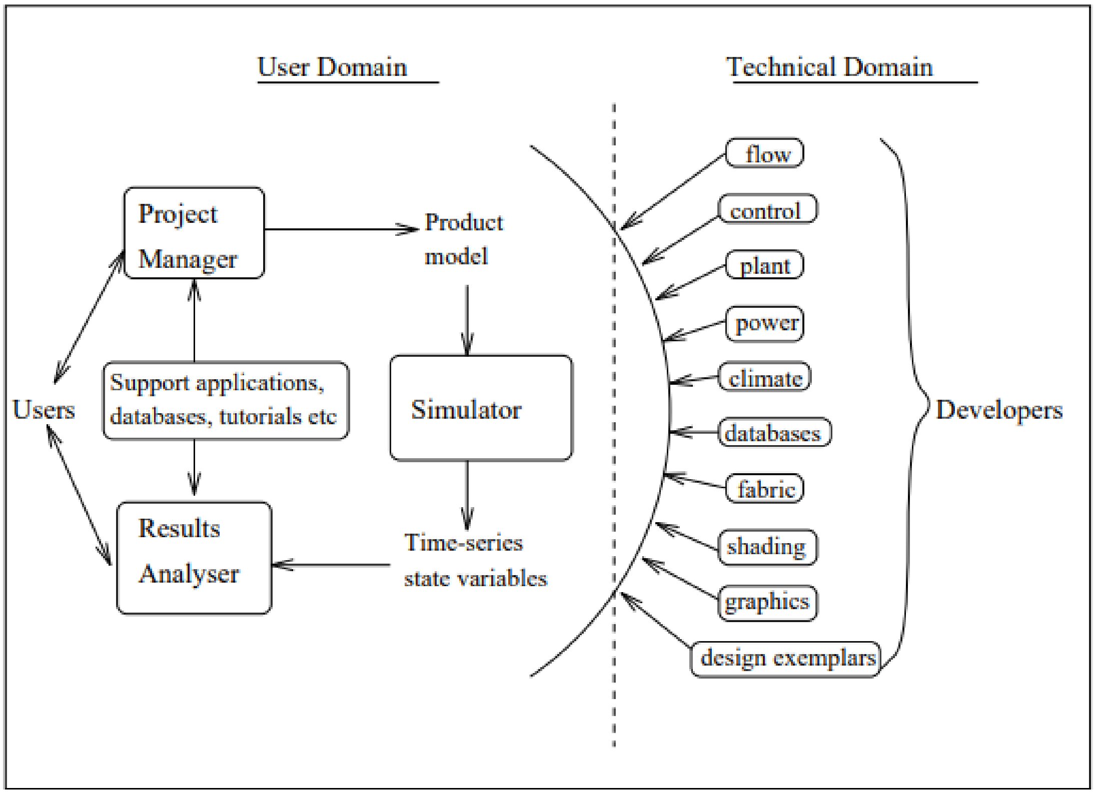

Figure 10. Structure of the ESP-r energy modelling software [54].

Additionally, the paper talks about three real-life examples: designing a new office, creating a unique area for a zoo, and turning an old church into a concert hall shown in Figure 11 and Figure 12 illustrates an example of its temperatures being simulated. In all these projects, ESP-r helped the design teams make informed decisions to ensure the buildings operated efficiently. The main point of the article was that tools like ESP-r are fundamental for making buildings that are both energy-efficient and sustainable. From this, ESP-r is a tool that gives designers a better understanding of how their designs will work.

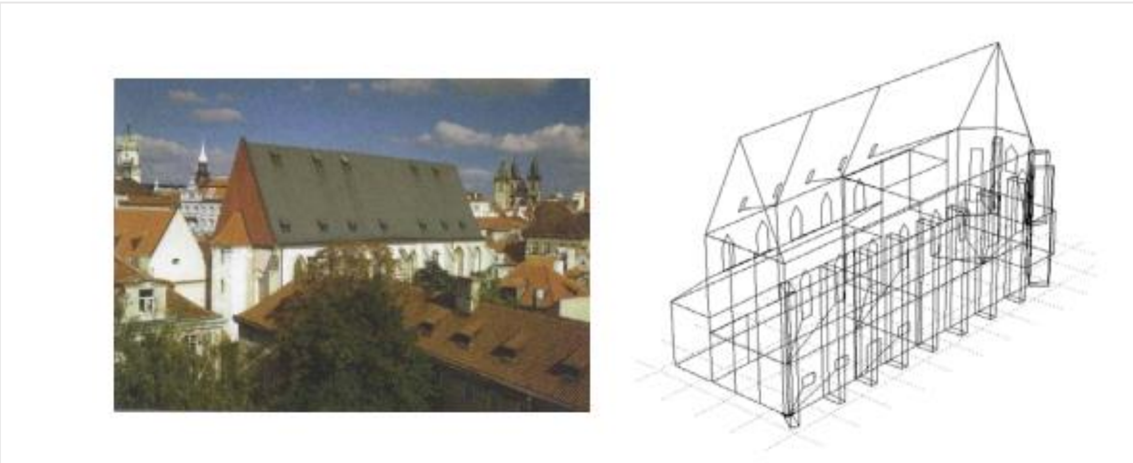

Figure 11. Image of the old church, modelled in ESP-r [55].

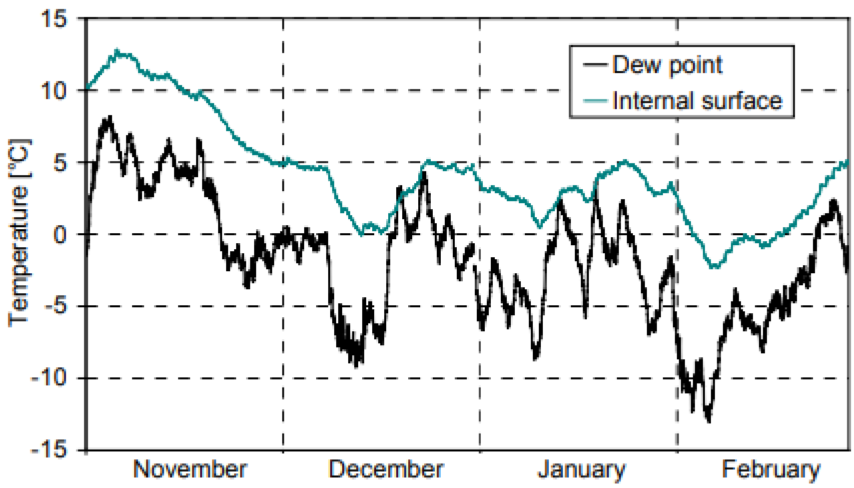

Figure 12. The old church's Internal surface temperature on the north wall and dew point temperature being simulated[55] .

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2.4 Energy performance in above and underground buildings

As mentioned, energy performance in underground buildings has begun to grow in interest as a potentially viable prospect for modern sustainable architecture. With respect to energy modelling, there are key parameters that affect the energy efficiency of buildings and is a topic of interest that has several studies adopting principles and practices that govern energy modelling practices and projects, reviewed in sections 2.3.1 to 2.4.6.

2.4.1 Heating and cooling of buildings: Principles and practice of energy efficient design

This book [48] ,explores the principles integral to the design of energy efficient and sustainable buildings. This resource highlights foundational thermal science, e.g. heat flow through a plane wall shown in figure; emphasising the significance of human thermal comfort, indoor air quality, and solar radiation in the context of building performance.

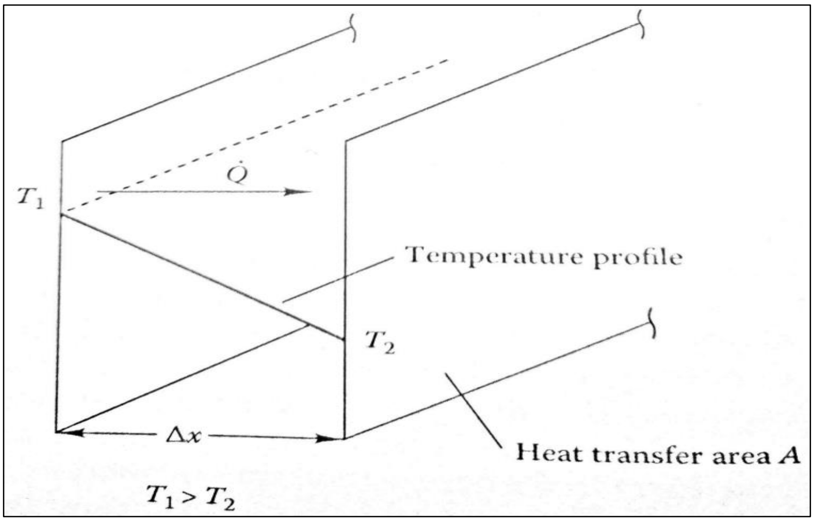

Figure 13. An extracted heat flow diagram from the heating and cooling literature[48] .

Additionally, it brings to the forefront the role of factors like infiltration, natural ventilation, and steady-state heat flows in influencing the heating and cooling dynamics of a building. This literature provides the essential mathematical equations that guide these processes and the book emphasises the key parameters that can impact the energy performance of a building.

For energy modelling analysis, this textbook offers valuable insights that help bridge the gap between theoretical knowledge and practical application within this thesis, especially when assessing the thermal comfort and indoor air quality of both aboveground and underground office structure.

2.4.2 Heating and cooling energy demand in underground buildings: Potential for saving in various climates and functions.

This article investigated into the potential energy savings offered by subterranean structures across different climates and functional uses [12]. This research highlighted that underground buildings are not just beneficial in terms of energy conservation but also present an innovative approach to land use.

To comprehensively evaluate the energy dynamics, the study employed monthly energy calculations over a year for both aboveground and underground buildings. With it's investigative methods shown in the method overview in Figure 14, this analysis was not limited to a single climate or building function but encompassed various scenarios, offering a broad understanding of energy implications. Importantly, the study also factored in the potential impact of varying assumptions on energy consumption, ensuring robust and reliable findings.

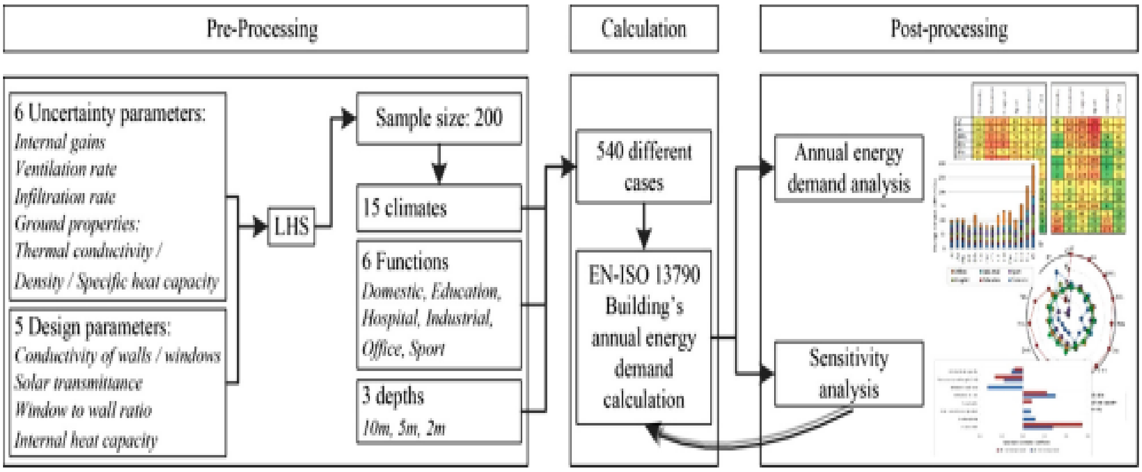

Figure 14. An example method overview of investigative procedures for underground simulation and analysis [12].

The results showed that a significant number of cases (11%), underground buildings demonstrated minimal additional energy requirements. The study also found that how deep the building was underground didn't change the energy use much, with only about 2 kWh/m2y difference on average. The parameters influencing energy usage varied depending on the specific climate and the intended use of the building. This highlighted that while underground buildings hold potential for energy efficiency, the extent of their effectiveness is influenced by external factors, necessitating a nuanced understanding of their energy performance in different settings. The conclusion of the study highlighted that it adopted monthly datasets for further work, and it identified that for further work, hourly data may be useful to investigate the intricate and erratic temperature fluctuations that monthly data may miss.

2.4.3 Moisture flow modelling within the ESP-r integrated building performance simulation system

This paper by Joseph Clarke takes a closer look at how moisture affects buildings. Moisture isn't just about wet patches or mould, shown in Figure 15 ; it is a fundamental parameter to consider because it impacts air quality, how warm or cold a place feels (thermal comfort) [12,48], and even how quickly a building wears down.

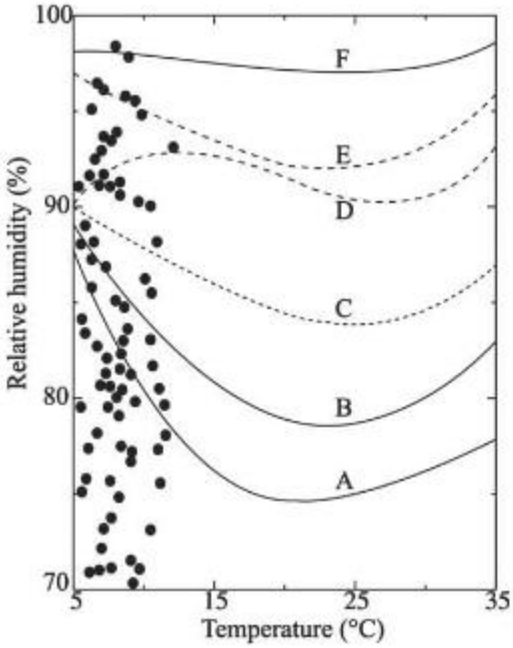

Figure 15. Mould growth isopleths with ESP-r predictions for the illustrated mould-infested house superimposed [75].

To understand this better, the methods in this study, adopted the use of ESP-r to model how moisture moves inside buildings. This model worked alongside other models that predicted things like heat, electricity, air movement, and light. The mathematics behind it comes from Fick's second law, which describes how moisture spreads, and another method to track energy movement. The findings in this article underline that when designing buildings, understanding how moisture behaves is key to saving energy and ensuring the building lasts.

2.4.4 Underground soil and thermal conductivity materials-based heat reduction for energy-efficient building in tropical environments

While this article [10] , investigates a tropical climate, the study specifically examined heat reduction in buildings (above ground), using underground soil and thermal conductivity materials. It provided fundamental insight into how materials behave when submerged in soil. The study looked into how underground soil and materials that conduct heat (like aluminium pipes) could help, with an example of a pipe submerged in the soil shown in Figure 16 . The idea was to use the soil as a way to reduce heat, pulling heat away from a building.

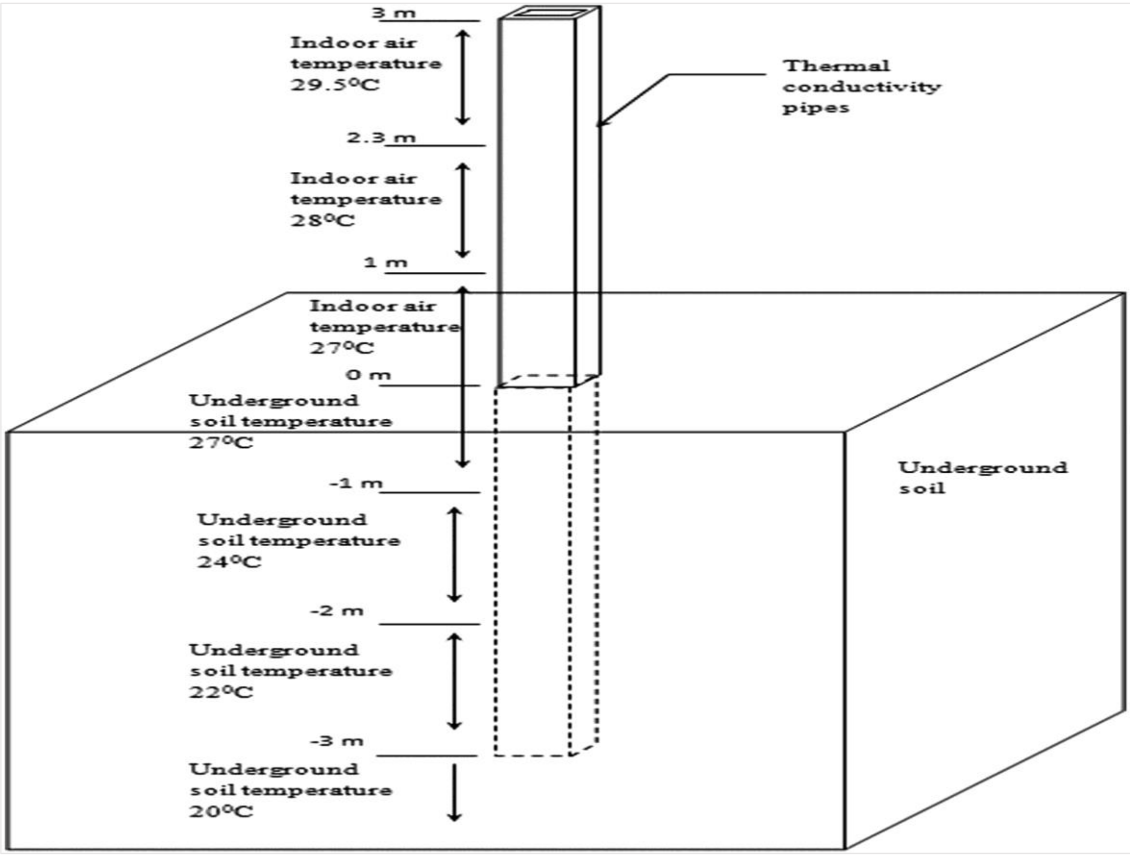

Figure 16. Temperature distribution around the pipe above and below the ground and also temperatures of underground soil .

To test this, a model was set up and then simulated using a tool called ANSYS 11, simulating both a room and the ground temperatures. With respect to Figure 14, heat-conducting pipes were placed on the inner walls of the building, making sure the pipes of reached the ground. As a result, the ground absorbed the heat from the room through these pipes, which lowered the temperature inside by about 3°C. This method had shown that it could be paired with other cooling systems, offering a potential way to make an underground building more efficient. However, it is important to note that the study used a small building model and had a few limitations in its design. When comparing this to energy modelling for underground versus above-ground buildings, it was important to understand how materials, like soil and the pipes, how they interact with heat and how they can play an influential role in the design of energy-efficient structures.

2.4.5 Thermal modelling and temperature control of a house

HVAC systems, shown in Figure 17 are systems that are responsible for the heating, ventilation, and air conditioning of buildings and may significantly impact energy consumption [48]. In this paper [56], the authors highlight the need to optimise HVAC system performance.

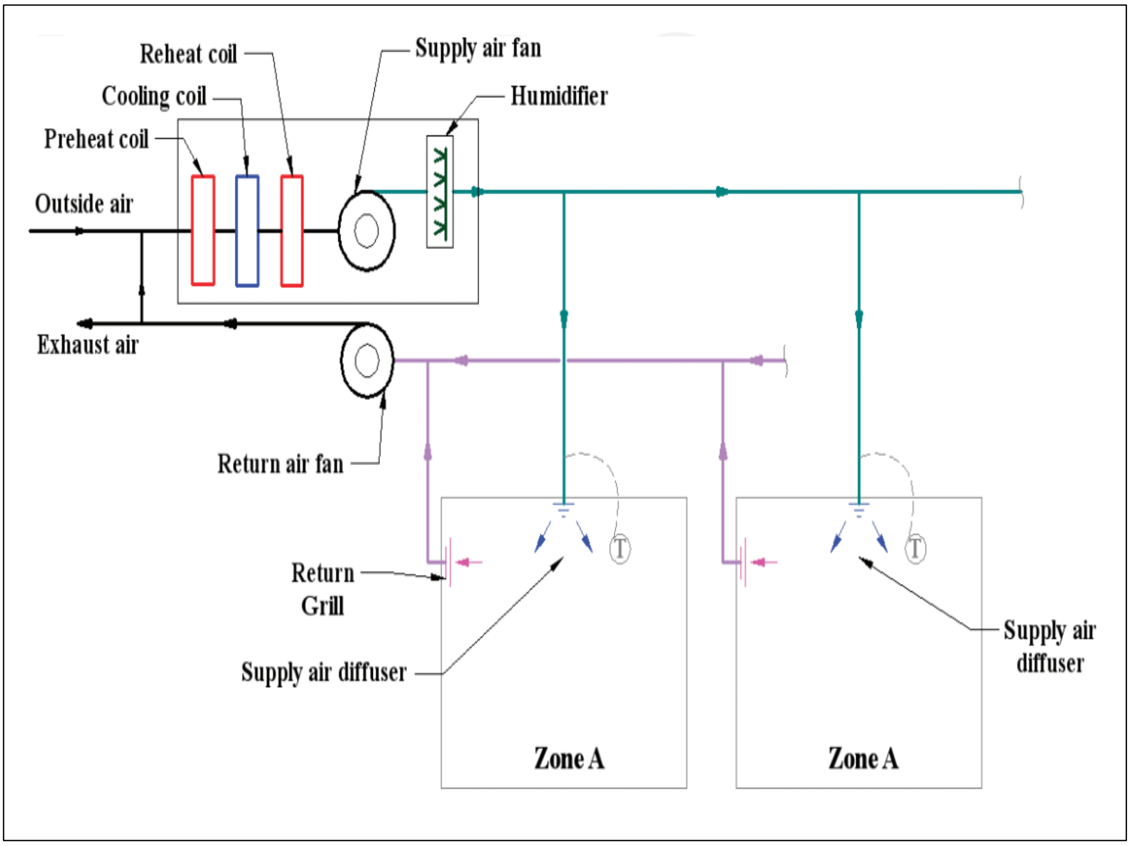

Figure 17. An example of a typical HVAC system for single zone like a small office building[76] .

The study employs mathematical models to represent the building's thermal behaviour and use automatic control techniques to adjust thermal zone temperatures and humidity. External environmental factors, such as solar radiation and ambient temperature, are incorporated into the model. Additionally, the study considers occupant behaviour and electrical appliances in its simulation. The end goal of this comprehensive modelling was to reduce energy usage.

2.4.6 Modelling and simulation of an HVAC system for energy analysis and management of commercial buildings

A commercial building's energy consumption is heavily influenced by their HVAC systems. This study [57], investigates the significance of energy demand. The authors highlighted that among the various energy consuming components of commercial buildings, the HVAC system is the primary consumer.

They employed mathematical models to simulate parameters such as outdoor temperature, outdoor relative humidity, wind speed and direction, global solar radiation and atmospheric pressure; and analyse real-time energy consumption and process parameters of the HVAC system, where the approach they used in their model helped them identify factors that could reduce the energy demand of such HVAC system.

While the paper introduced a software application with an HMI for system adjustments, the core lesson for heating and cooling studies, is that HVAC systems are highly influential in energy delivered within an energy model. Addressing parameters that influence the HVAC system, can optimise the system and can lead to substantial energy savings and demand reduction in buildings.

2.5 Key parameters influencing building energy performance

With reference to sections 2.4.1 to 2.4.6, upon reviewing these papers, it was identified that they are several key parameters that influence building performance including natural influences (solar irradiance, the wind, neighbouring structures trees etc.), soil interaction with materials, internal gains (casual gains such as occupants, equipment etc.), thermal mass (as the mass/size of a building increases, the thermal mass also increases), with more being highlighted in the heating and cooling book stated in section 2.4.1 [14,48] . The reviewed papers in section 2.5.1 to 2.5.1 highlight the importance of understanding internal gains, ventilation and humidity.

2.5.1 The importance of internal heat gains for building and cooling design

This paper [58], used an energy modelling package called "Design Builder v4" to calculate heat dissipation from sources such as lighting devices, electrical equipment, and occupants. The temperature observations of a residential building were conducted over three weeks using calibrated hobo data loggers shown in Figure 18.

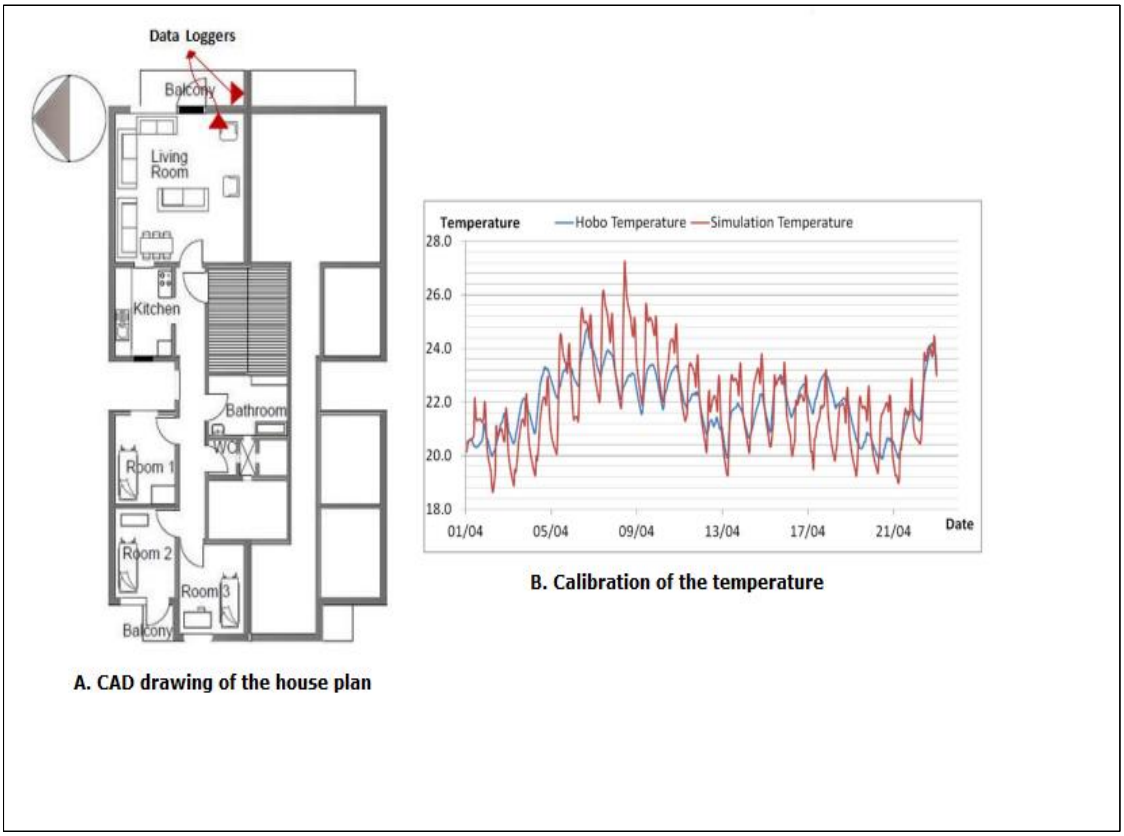

Figure 18. The location of the building and its structure defined using CAD drawings and the calibrated temperatures using the hobo data loggers [58].

To provide accurate results, a detailed schedule was prepared based on operation time and occupancy. The location of the building and its structure were defined using CAD drawings, and material properties, crucial for cooling load calculations, were determined. The main sources of internal loads included occupants, lighting devices, and electrical equipment. The paper cites research indicating that an adult man emits heat ranging from 80 W (while sleeping) to 570 W (during heavy work). Lighting devices, especially LED lights, while being energy efficient, still contribute significantly to internal heat due to the conversion of electric power to heat. The research further discussed the effect of different internal heat sources on cooling load, observing their individual contributions.

From the paper, it could be seen that a comprehensive understanding of internal heat gains was crucial for designing energy efficient buildings. Whilst technological advancements such as LED lighting offer energy savings, the resultant heat production needs to be accounted for in cooling load calculations. Occupancy changes, efficient electrical equipment, and suitable lighting devices are factors that influence a building's cooling load.

2.5.2 Estimation of natural ventilation rates in an office room with 145mm-diameter circular openings using the occupant-generated tracer-gas method

Natural ventilation is a technique to ensure optimal indoor air quality in a building. Such ventilation methods help dilute a range of contaminants produced by occupants, emissions from building materials, or moisture arising from an occupant's activities. This is especially in environments where heating and cooling is a necessity. Striking a balance between energy consumption and maintaining a healthy indoor atmosphere via proper ventilation is important [12,14,48,59].

This research paper [59], employed the occupant-generated carbon dioxide (CO2) tracer gas decay technique to estimate the ventilation rates in an office room located in Seoul, South Korea, across different seasons, shown in figure. A key aspect of this method was that it allowed for real-time computation of ventilation rates by monitoring the indoor and outdoor CO2 concentrations, eliminating the need for an external tracer gas. The study specifically utilised 145mm-diameter circular openings in fixed glass for natural ventilation, shown in Figure 19.

Figure 19. Scenario 1 and 2 with the 145mm diameter circular openings on the windows and the CO2 sensors within the building to estimate natural ventilation rates[59].

Two core findings were evident. First, the indoor CO2 levels were an effective metric to gauge and found that the deterioration rate in indoor air quality was higher when windows were kept shut in an occupied office space. Secondly, it was perceived that the estimated ventilation rates oscillated based on various environmental conditions, even if the openings for ventilation were consistent. Specifically, in scenarios of mild wind conditions, the temperature gradient was a dominant influence on the estimated ventilation rates, while in cases with minimal temperature differences, wind speed took precedence. The study highlighted the potential hazards of compromised indoor air quality in office settings, which might lead to health issues or degrade the work environment. The adopted methods and findings in this paper helped develop an understanding the significance of ventilation and infiltration in maintaining a healthy indoor environment.

2.5.3 Heat and moisture transfer investigation of surface building materials

When designing buildings that are efficient and sustainable, it's important to know how building materials manage indoor humidity. This study [60], used energy modelling numerical methods to see how certain building materials, which can absorb moisture help control indoor humidity changes. The numerical simulations incorporated data from the NORDTEST method, a known test on how building materials manage moisture, shown in Figure 20.

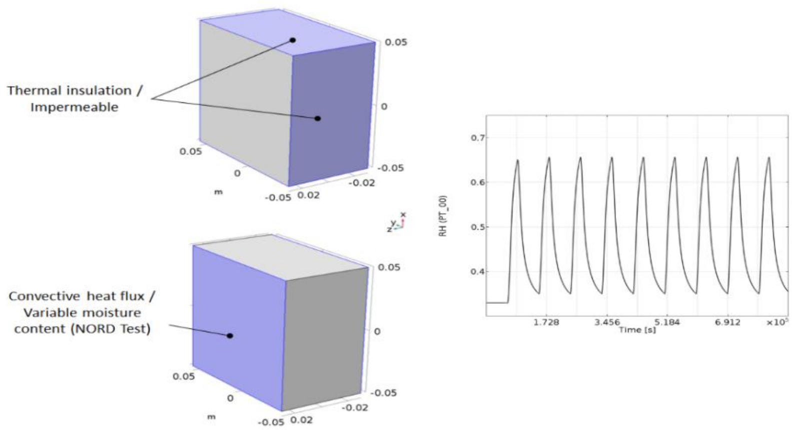

Figure 20. Model and numerical simulations incorporated data from the NORDTEST method [60].

This research focused on charts called sorption isotherm curves. These charts show how much moisture a material can hold at different humidity levels. By using these charts and some mathematical calculations, the study looked at how porous the materials are. They also looked at how temperature and humidity change together. The main point of the study was to see how these materials can help control indoor humidity without using energy. This means that using the right building materials can help save energy and make indoor spaces more comfortable.

2.5.1 Experimental study of influence of thermal mass on comfort and cooling energy demand in residential buildings

In this study [61], thermal mass in building design has been investigated to discern its potential impact on indoor temperatures and cooling energy demands, especially during extreme weather conditions. The research was conducted on two real scale energy efficient single family buildings that were similar in most respects except for the construction of their external and internal walls. One used lightweight skeletal construction while the other employed traditional masonry construction, shown in Figure 21.

Figure 21. Location map of laboratory buildings B1 and B2 in The Science and Technology Park[61] .

Results from the study highlighted that increasing the building's thermal mass led to a reduction of the average indoor temperature by approximately 2.8°C during a heatwave. This reduction reached a maximum of 3.4°C during the peak heat times. By switching from a lightweight structure to cellular concrete, the study observed a significant drop in the duration of indoor temperatures exceeding 28°C, reducing it from 18.6 days to just 8 hours in an exceptionally warm month.

Additionally, the research found consistent cooling effects from the thermal mass throughout the 14-day heatwave, resulting in a notable decrease in cooling energy demand by up to 75% at a set point temperature of 26°C. This study emphasised the importance of considering the material and design considerations, particularly thermal mass, to optimise thermal comfort and reduce energy consumption in residential settings.

2.6 Conclusion of literature review

The literature review conducted highlighted several factors that influence the energy performance of buildings for above and underground buildings. Thermal comfort is a primary concern, and it's influenced by factors such as air ambient temperature, radiant temperature, humidity, and air velocity. Maintaining the right balance in these factors ensures the comfort of the occupants, but also has a direct impact on the energy efficiency of the building.

Ventilation is another important parameter. Proper ventilation management is essential to prevent energy losses and maintain indoor air quality. Internal gains, referred to as casual gains from sources like appliances and occupants, can influence the energy balance in a building. Proper management of these gains is essential for improved energy performance. Natural elements such as solar irradiance, wind patterns, and ground interactions also play a significant role in a building's energy dynamics. Ground interactions, specifically, are essential to consider. The way building materials interact with soil can influence the thermal properties of a building, potentially impacting its energy consumption.

The role of thermal mass in building design emerges as a fundamental parameter. As building materials increase in size, the thermal mass of the materials also increases. By leveraging the heat storage capacity of construction materials, buildings can achieve significant reductions in cooling energy demand. The potential to harness thermal mass for enhanced energy efficiency and occupant comfort highlights the intricate interplay between material properties and building performance.

The importance of humidity is evident in both the comfort level of occupants and its effect on heating and cooling requirements. Advances in material science, especially with porous hygroscopic materials, have shown promise in controlling indoor humidity passively, pointing to the significance of selecting the right materials in construction. One fundamental insight from the literature is the need for energy modelling before constructing buildings. Energy performance models can help anticipate potential energy performance issues, leading to more efficient and sustainable construction practices.

HVAC systems play an important role in maintaining and improving desired indoor conditions and indoor air quality. The efficiency and design of these systems directly influence a building's energy consumption and occupant comfort. Optimising HVAC systems and integrating controls, could help reduce energy demand.

These points highlight the importance of a comprehensive approach to building design and operation. From the materials used, to the natural environment it's placed in, plays an influential role in a building's energy performance, whether that be above or below ground. This newfound knowledge during the literature review, has been foundational and will help as this thesis explores methods to enhance both energy efficiency and occupant comfort.

3 MATERIALS and METHODS

3.1 Energy modelling software adopted and validation

With reference to Figure 2, for the purposes of the numerical experiments performed, a system called ESP-r has been used. Briefly highlighting the history of ESP-r and the reason for adopting the software... From 1974 to 1977 Dr Joe Clarke developed the initial prototype as part of his doctoral research. Then, over the period 1977 to 1980, with funding from the (then) UK Science and Engineering Research Council (SERC), ESP-r was refined in a number of respects: the system was streamlined and documented, validation trials commenced, multi-zone processing was implemented and a graphics orientated user interface was established.

With respect to validation, the ESP-r software [54], is a system that has been developed over 20 years, which is widely used in research within the University of Strathclyde's Energy Systems Research unit (ESRU). Continuous activities within this department ensure that ESP-r is continuing to evolve, in terms of further validation, technical extensions and user interface improvements. As part of its research portfolio, ESRU has continued to evolve ESP-r - most notably within the framework of the UK Department of Energy's (now Trade and Industry) Passive Solar Programme, the CEC's PASSYS project (a 10 member country concerted action in Passive Solar Architecture), a SERC funded project to establish an intelligent front-end for the package and within a number of ongoing projects concerned with plant and control simulation.

Whilst absolute declarations of validity are not possible; each numerical experiment performed was validated against similar sample models within the ESP-r system, a literature review on peer reviewed journals on similar work was conducted, and the fact that the UK government funds worked supported by ESP-r, ensures that validity of work has gone as far as reasonably possible.

3.2 Method Overview

With reference to Figure 2, this study was conducted using numerical methods covered in the ESRU Introduction to ESP-r (and it's related materials) and Joseph Clarke's "Energy Simulation in Building Design" [53,62].

3.3 Model Assumptions

The models will be simulated against climate data recorded in Chicago in 2001 and will be assumed to be present day. The design assumes two single zone offices, one above and one underground, which are both south facing for consistency of simulations and will operate between the hours of 0800hrs to 1800hrs.

To evaluate the energy demand for heating and cooling within the adapted design model; basic thermal science laws, equations and principles for convection, conduction, radiation, solar radiation is considered as they influence Esp-r's calculations of resultant temperatures and casual gains e.g., steady-state heat flows. For the purposes of this study only, it will be assumed that ASHRAE will be used [13,14]. Therefore, any selection of composition properties including materials (including U-values) and operation (casual gains and ventilation) of the building, will adhere to the ASHRAE standards [13,14,48] .

ESP-r will use numerical methods and apply fundamental equations and methodologies for integrated simulation [53]. Specifically, ESP-r will model human thermal comfort, indoor air quality, solar radiation, casual gains, infiltration, and natural ventilation [12,48]. Additionally, it will simulate steady-state heat flows as well as heating and cooling design load calculations. Ventilation will be considered infiltration as Esp-r recognises natural ventilation as infiltration. ESP-r will account for material specifications when selecting materials from its modelling software and performs calculations for several considerations.

3.4 Generic testbench model

With reference to section 2 and 3.2, prior to analysing energy modelling performance for the models in Figure 23 and , it was important to establish a robust foundation to ensure accuracy and reliability of results. The testbench model, derived from Esp-r's pre-built training model packages shown in Figure 22 (including building orientation and dimensions), served as a preliminary step in this study's methodology to accomplish this. Primarily, the test bench acted as a diagnostic tool, which allowed for identification and rectification of potential software operational anomalies. This ensured that the software performed as it should have throughout the study [53,62].

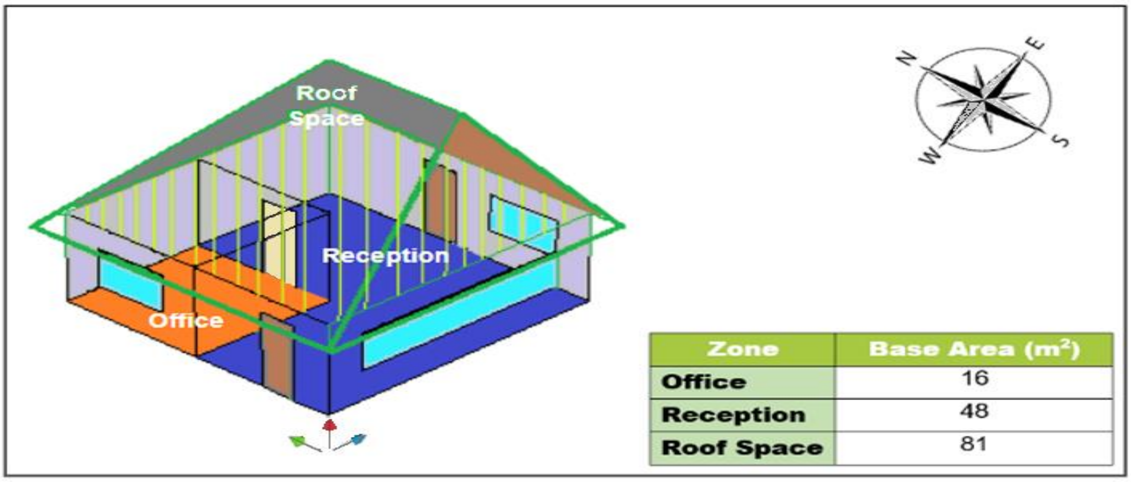

Figure 22. ESP-r's basic training model within the software package [62].

Additionally, it provided an opportunity to become familiar with the software and the modelling process. Conducting the test bench prior to base model evaluations offered a calibrated starting point, ensuring that all subsequent analyses and adaptations to the base model were built upon a sound and validated framework. By adopting the testbench, it minimised errors and streamlined the evaluation process.

To ensure the reliability and functionality of the base model, a basic two zone office test model with pre-set materials, thermal properties, casual gains, heating and cooling settings was utilised within Esp-r's model library [54,62], which meant that sensible heat and cooling values could be used against Esp-r's weather data for Chicago . The test model served to assess if the software operated as it should, thus allowing for a systematic evaluation of the base model's performance. Prior to test benching the training model, building composition, operational details and HVAC were inspected, then test simulations for annual/hourly temperatures, floor surface flux, sizing of heat and cooling, and energy delivered were conducted.

3.4.1 Testbench model – Building composition .

Referencing sections 2.3.1 and 2.4.1, the building composition (roof omitted), is shown in Table 1. Referencing section 3.3, building dimensions and orientation is shown in Figure 22. ESP-r's basic training model within the software package [62].. The building's walls consist of multiple layers, with layer 1 being the outermost and layer 8 the innermost.

Table 1. Testbench model - Building materials.

Materials	Layer	Thickness (mm)	U-Value-horizontal/up/down		
			External Wall		
Brown brick	External 1	100	0.393	0.397	0.387
Glass wool	2	75	0.393	0.397	0.387
Air gap	3	50	0.17	0.17	0.17
Breeze block	Internal 4	100	0.393	0.397	0.387
			Internal Walls		
White gypboard	External 1	13	1.186	1.230	1.113
Gap	2&4	50	0.17	0.17	0.17
Block inner	3	100	1.186	1.230	1.113
White gypboard	Internal 5	13	1.186	1.230	1.113
			Ceiling		
Glass wool	External 1	100	0.333	0.336	0.329
Ceiling mineral	Internal 2	50	0.333	0.336	0.329
			Floor		
Earth	Ext. 1,2,3,4,5	200	0.946	0.974	0.911
Red granite	6	100	0.946	0.974	0.911
Concrete	7	50	0.946	0.974	0.911
Cement screed	Int. 8	50	0.946	0.974	0.911

		Glazing			
Plate glass	1&3	6	2.811	3.069	2.527
Gap	2	12	0.17	0.17	0.17
		Internal & External Doors			
Oak	1	25	3.316	3.682	2.928

3.4.2 Testbench model – Building operations.

Casual gains were investigated and recorded in Table 2.

Table 2. Casuals Gain for the testbench model.

Period	Type	Sensible Heat (W)	Latent Heat (W)
12am-9am	Occupants	0	0
9am-5pm	Occupants	180	100
5pm-12am	Occupants	0	0
12am-9am	Lights	0	0
9am-5pm	Lights	200	0
5pm-12am	Lights	0	0

Upon inspecting the casual gains, in the same menu, ventilation and infiltration was inspected and recorded as 24hrs per day with an infiltration rate of 0.5 ac/h and ventilation rate of 2.0 ac/h in the reception zone.

3.4.3 Testbench Model - Heating and cooling

When inspecting the heating and cooling system, it was found that there was a heating and cooling control system included. There was a 3kw heating system, however, the cooling value was set to 0, meaning cooling would not activate when hitting the maximum setpoint. Although this was a testbench model, it was important to ensure that changing the heating and cooling values would produce results and operate as expected.

Therefore, it was essential to consider the sizing of the cooling system to determine whether the test model would adjust the thermal comfort levels according to the sizing of the heating and cooling system. The heating control system setpoint was set to 24℃ and the cooling system setpoint was set 21℃ to ensure that thermal comfort remained within acceptable limits adhering to ASHRAE standards [13,14,48]. The heating and cooling system sizes were then simulating a range of 0W to 16kW.

3.5 Above ground model -No HVAC

With reference to the architecture of the modern building on the right of Figure 23, was deemed an innovative design and functional aesthetically. Depicting an above-ground model adjacent with that image inspired the design of the above ground model on the left in ESP-r. The model showcased a building with a south-facing orientation to improve passive solar heating and its structural design without any windows, was intentional to help maintain consistent internal temperatures [63] . The walls, doors, floor and roof have been configured to react with ambient dry bulb temperatures, aligning with the objective of creating an energy-efficient space. Additionally, the floor was set to adiabatic to analyse the behaviour of the surface flux characteristics [53,62,64].

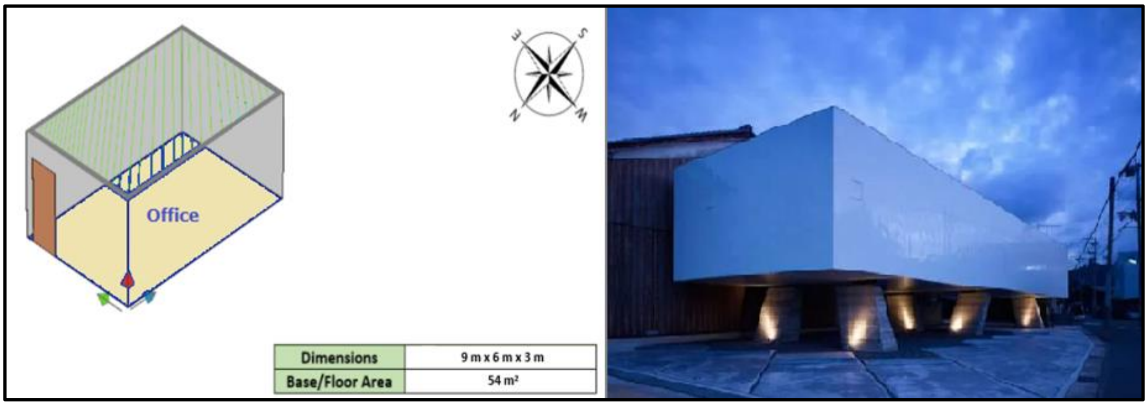

Figure 23. ESP-r Aboveground model and an image that inspired the design [77].

With more in depth consideration into the architectural anatomy of the building, it was essential to grasp how each component contributed to the building's overall energy efficiency and structural integrity. The subsequent section 3.4.1 outlines the composition of the building, elaborating on the layering of construction materials.

3.5.1 Above ground model – Building composition

With reference to **Error! Reference source not found.**, the dimensions (9m x 6m x 3m) of the above ground building designed to emulate a small office with no windows. **Error! Reference**

source not found., describes and illustrates an example of how the construction materials layers look like when describing them in **Error! Reference source not found.**, [54].

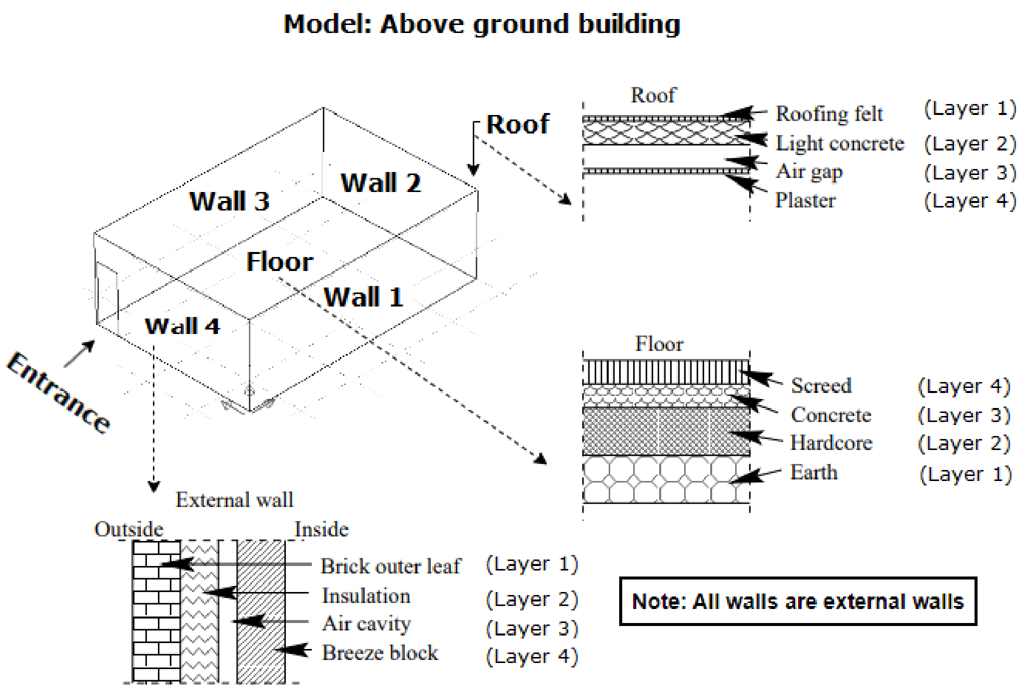

Figure 24. An illustrative description of the composition of the materials for the above ground model [54].

To evaluate the above-ground building model, a methodical approach was adopted to understand the interplay of various construction materials. Referring to Figure 24, each component of the building, from the walls to the roof and floor, had distinct layers of materials. The walls comprise four primary layers: a brick outer leaf (Layer 1), insulation (Layer 2), an air cavity (Layer 3), and a breeze block (Layer 4). The layered composition aimed to replicate real-world constructions, providing a balance of thermal insulation and structural integrity.

When examining the materials' interactions with the environment, a critical factor was the ambient conditions they would encounter. The chosen reference environment was Chicago's dry bulb temperatures. This decision means that the external layers of the building, particularly the roof, walls, and entrance doors, were exposed to the temperature fluctuations typical of this region. Conversely, the floor was treated differently. Given its contact with the ground and the natural insulation the earth provides, it was designated as adiabatic, implying that it neither gains nor loses heat. This distinction ensures a realistic representation of how above-ground buildings interact with their surroundings, providing valuable data for energy performance analyses. With reference to **Error! Reference source not found.** and **Error! Reference source**

not found., the materials and their U-values used to construct the walls, ceiling, floor and door are stated in Table 3 [13,14,48].

Table 3. Above ground model - Building materials.

Materials	Layer	Thickness (mm)	U-Value-horizontal/up/down		
		External Wall			
Brown brick	External 1	100	0.393	0.397	0.387
Glass wool	2	75	0.393	0.397	0.387
Air gap	3	50	0.17	0.17	0.17
Breeze block	Internal 4	100	0.393	0.397	0.387
		Internal Walls			
White gypboard	External 1	13	1.186	1.230	1.113
Gap	2&4	50	0.17	0.17	0.17
Block inner	3	100	1.186	1.230	1.113
White gypboard	Internal 5	13	1.186	1.230	1.113
		Ceiling			
Glass wool	External 1	100	0.333	0.336	0.329
Ceiling mineral	Internal 2	50	0.333	0.336	0.329
		Roof			
Roofing felt	External 1	12	1.799	1.902	1.678
Concrete	2	50	1.799	1.902	1.678
Gap	3	50	0.17	0.17	0.17
Ceiling plaster	Internal 4	8	1.799	1.902	1.678
		Floor			
Earth	Ext. 1,2,3,4,5	200	0.946	0.974	0.911
Red granite	6	100	0.946	0.974	0.911
Concrete	7	50	0.946	0.974	0.911
Cement screed	Int. 8	50	0.946	0.974	0.911
		Entrance Door			

Oak	1	25	3.316	3.682	2.928

3.5.2 Above ground model – Building operations

Casual gains were quantified by monitoring the heat contributions from distinct sources within the office environment. This was done using calibrated sensors in the operation control menu, designed to detect and differentiate between sensible and latent heat emissions. The difference in values for a single occupant stem from two primary mechanisms: direct body warmth and moisture release. With reference section 2.5.1, sensible heat was measured from the direct warmth that the occupant may emit due to bodily functions, whereas latent heat was gauged from the moisture output, primarily through breathing and perspiration [48,58]. The data used to simulate this during is presented in Table 4. After configuring the casual gains values, ventilation and infiltration were scheduled for the office hours between 0800hrs-1800hrs on weekdays at between rates of 0.5 ac/h and 3.0 ac/h.

Table 4. Casuals Gain for the above ground model.

Period	Type	Sensible Heat (W)	Latent Heat (W)
8am-9am	Occupant	50	30
9am-12pm	Occupant	90	45
12pm-2pm	Occupant	50	25
2pm-6pm	Occupant	0	0
8am-6pm	Lights	8	0
8am-6pm	Equipment	5	0

3.5.3 Above ground model – Heating and cooling omission

Reference section 2.4.1 and 2.4.4, to assess the above ground building's energy characteristics, the initial model omitted any heating or cooling systems. This allowed for clarity of the building's natural capacity to retain heat and cool down without external influence [48,62]. Establishing this baseline was crucial, as it would later serve as a reference when introducing heating and cooling systems in the simulation process.

With reference to sections 3.4.1 to 3.4.2, for the HVAC settings confirmed to be inactive, the model was tested against Chicago's yearly weather patterns. The was to show how the office's internal temperatures reacted to outside conditions. By analysing the data over the year, particularly the highest and lowest temperature peaks, a closer look into hourly trends revealed if the temperatures maintained the comfort levels set by ASHRAE standards [14,48]. Lastly, the energy consumption was simulated to confirm there was no demand.

3.6 Above ground model - HVAC

3.6.1 Above ground model – Building operations adaptations

In relation to Figure 23 detailed in section 3.4, the base energy model underwent certain modifications to enhance its thermal performance. Specifically, heating and cooling systems were integrated to address the any observed discrepancies with the ASHRAE-prescribed thermal comfort thresholds [14,48]. The ventilation and infiltration rate were simulated from a range of 3.0 ac/h down to 1.5 ac/h, with increment reductions of 0.5 ac/h to better align with HVAC system optimisation in section 3.5.2. Throughout this modification, the casual gains attributed to office equipment, occupants, and lighting were maintained at the same values.

3.6.2 Above ground model – Heating and cooling addition

Utilising zone loop options within the Esp-r software, a HVAC control system with an example shown in Figure 25, was implemented for the purpose of moderating the thermal and indoor air quality environment of the above ground model [12,48,60]. To prevent incorrect set-points that could reduce thermal comfort, it was important to consider the setpoint for heating and cooling. Considering this, the setpoint was systematically adjusted to 22°C to 24°C respectively [48,65]. This adjustment was driven by the objective to maintain acceptable temperature that assures thermal comfort without excess energy consumption.

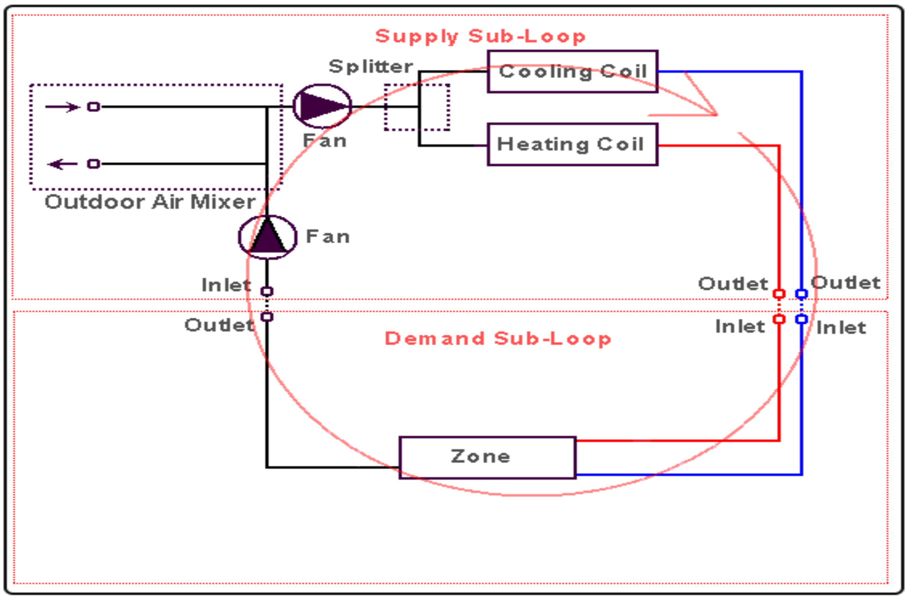

Figure 25. An example of how the HVAC system for single zone like a small office building would be set-up.

Subsequent to initial setup, the system's power capacity was evaluated using simulations ranging from 0W to 5000W, increasing in 500W increments. This method was chosen to pinpoint the most suitable system size, ensuring the building's thermal conditions complied with the ASHRAE standards for thermal comfort [14,48]. After the appropriate HVAC system was identified, temperatures during office hours were assessed, and the energy requirements for sensible heating and cooling were examined.

3.6.3 Above ground model – Energy balance

Referring to the diagram Figure 26, to allow for a better understanding of how efficiently the system operated and where improvements might be needed, it became imperative to undertake an evaluation of the energy balance.

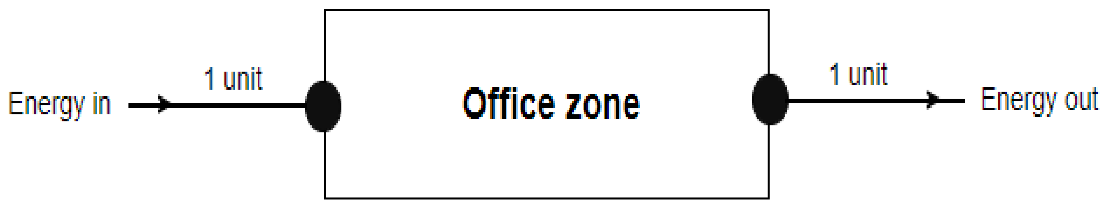

Figure 26. Schematic representation of energy flow into and out of the Office zone.

Referencing section 2.3.1 and 2.4.1, in the above-ground model's energy balance analysis, the focus was on understanding the flow of energy within the office zone. As illustrated in Figure 26, the model was conceptualised as an 'Office zone' where energy is both received (Energy in) and dispensed (Energy out) in equal units. The objective was to determine the quantity and nature of energy entering the zone (energy delivered), whether it was utilised for heating, cooling, or other functionalities [48,62,66]. By monitoring this energy transition, it provided a clearer understanding into the system's efficiency and highlighted areas that might need adjustments or enhancements. This approach ensured that every unit (kWh) of energy was accounted for, ensuring a balanced and efficient energy flow throughout the system.

3.7 Underground building – No HVAC

Figure 27 illustrates an underground building primarily submerged 1 meter below the ground level, leaving it entirely out of view from the surface.

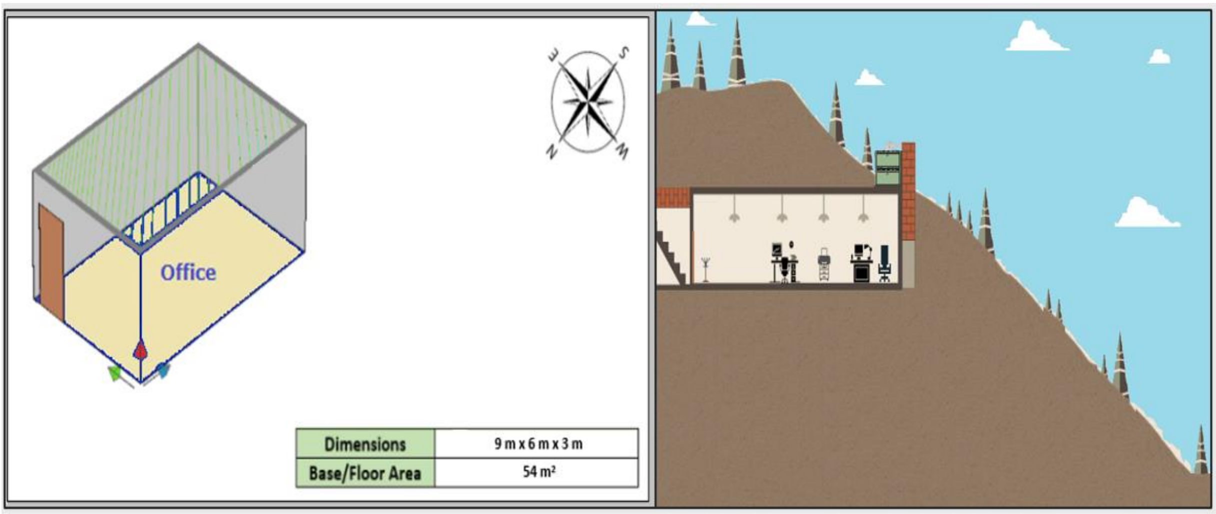

Figure 27. ESP-r underground model on the left inspired by the drawing on the right.

This model adopts a rectangular form, with specific dimensions spanning 9 meters in length, 6 meters in width, and 3 meters in height. As a result, its total floor area calculates to 54 square meters. For the sake of maintaining consistent results across the study, the underground structure mirrors the shape of its above-ground counterpart.

3.7.1 Underground model – Building composition

For a spatial perspective on the construction of the underground building, Figure 28 describes and illustrates the structural layout and material composition of the underground building. perspective.

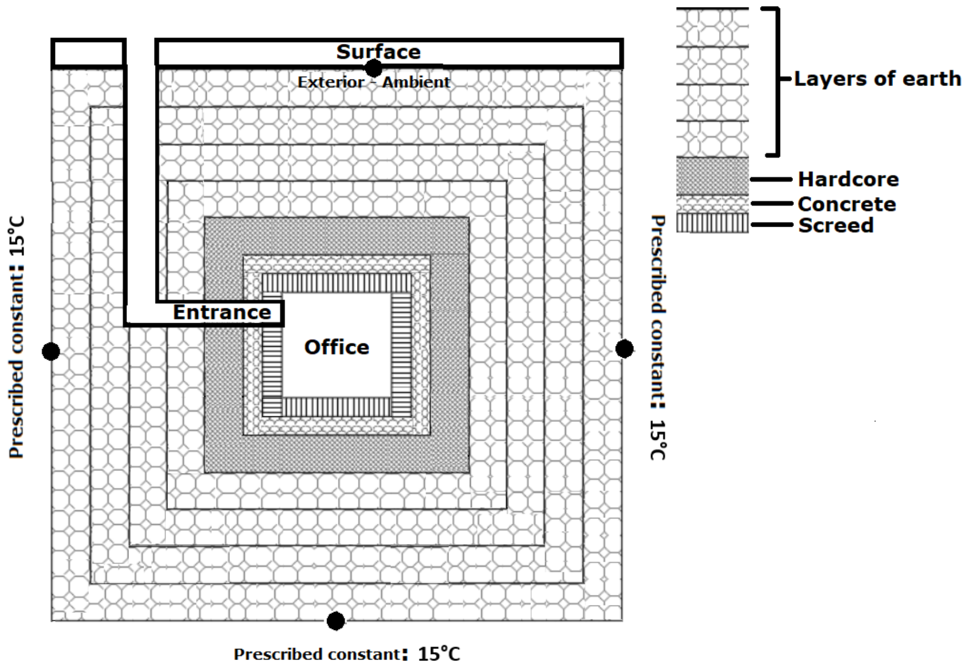

Figure 28. Schematic Representation of the Layered Underground Building Composition.

With reference to the building material described in Figure 24 and Figure 28 provided depicts the structural configuration of the underground building, highlighting its layered composition and positioning relative to the surface. Considering the insights from section 2.4.4 and additional readings [4,9,67,68], a prescribed static temperature of 15 degrees Celsius was adopted for the modelling process. This temperature was chosen to represent the consistent underground temperature prevalent at the given depth. The accurate representation of the building's material layers – such as hardcore, concrete, and screed – was fundamental, given their significant roles in dictating the building's thermal behaviour. When integrating this model into the modelling software, these layers were essential for correctly simulating the ground's thermal characteristics. The specific materials chosen for the walls, ceiling, floor, and base, founded on their thermal attributes, are expanded upon in Table 5.

Table 5. Underground model building materials

Materials	Layer	Thickness (mm)	U-Value-horizontal/up/down		
		Floor, walls & ceiling			
Earth	Ext. 1,2,3,4,5	200	0.946	0.974	0.911
Red granite	6	100	0.946	0.974	0.911
Concrete	7	50	0.946	0.974	0.911
Cement screed	Int. 8	50	0.946	0.974	0.911
		Entrance Door			
Oak	1	25	3.316	3.682	2.928

The selection of materials for each layer seen in Table 5, including hardcore, concrete, and screed, was essential because of their direct impact on the building's thermal performance. These materials, with their inherent thermal mass, influence how the building absorbs, stores, and releases heat [9,10,61,69]. Considering the ESP-r model, accurately representing these layers was important to simulate the ground's thermal attributes effectively.

3.7.2 Underground model - Building operations

During office hours, internal temperatures are influenced by factors such as occupants, lighting, and equipment. This holds true whether the building was situated above or below ground. Although underground spaces have unique thermal behaviours due to the insulating properties of the surrounding soil and limited solar irradiation, the heat generated from occupants, lights, and equipment remained constant.

Thus, the underground model adopted the same casual gains as described for the above-ground model in section 3.4.2. Ventilation rates were initially set 3.0 ac/h within office hours. The rate was iteratively reduced and simulated step sizes of 0.5 ac/h, to identify the most suitable ventilation rate adhering to ASHRAE standards [14,48,59]. The objective was to ensure a consistent air flow during operational hours underground, promoting acceptable thermal comfort, good air quality, and reduced humidity levels.

3.7.3 Underground model – Heating and cooling

In the preliminary assessment of the underground model, there was no integrated heating and cooling system, mirroring the conditions of the above-ground model. The approach for introducing the heating and cooling components was consistent with the methodology detailed in section 3.4.3.

3.8 Underground building – HVAC

3.8.1 Underground model – Building operations adaption

Referring to section 3.5.1 and in concordance with the data from Figure 27 highlighted in section 3.6, the model of the underground structure underwent modifications to enhance its thermal efficacy. Recognising the inherent thermal behaviour of underground construction, where external temperature variations have a diminished impact due to absence of reduced infiltration and solar irradiation, the focus shifted towards improving internal comfort, particularly ventilation.

To mitigate any disparities from the ASHRAE's thermal comfort standards, as outlined in sections 4.1.1 and 4.1.2, integrated heating and cooling systems were introduced. Drawing parallels with section 3.6.2, initial ventilation rates were set at 3.0 ac/h during operational hours. This rate was methodically adjusted in increments of 0.5 ac/h to achieve optimal conditions. Throughout this calibration process, the thermal contributions from office equipment, occupants, and lighting were consistently maintained.

3.8.2 Underground model – Heating and cooling addition

Similar to section 3.5.2 . the HVAC control system, as illustrated as an example in within the zone loop options. Considering the unique insulation properties of being underground, the heating and cooling set points were varied from 20°C and 22°C respectively. The rationale behind this range was to identify the comfortable temperature range that both meets ASHRAE standards for thermal comfort and reduces energy usage. In considering energy efficiency, like the above ground building, the controls were systematically adjusted, where these settings were iteratively simulated to find the balance between maintaining comfort and conserving energy in the underground space.

3.8.3 Underground model – Energy balance

Drawing from Figure 26 and aligning with the methodology detailed in section 3.5.3, an analysis of the energy balance for the underground structure was conducted to gain insights into its performance efficiency. Recognising the distinct characteristics of subterranean structures, it became imperative to determine the primary avenues of energy consumption, be it for heating, cooling, or other essential functions.

4 RESULTS

4.1 Generic testbench model

4.1.1 Testbench model - annual temperatures

The annual temperatures for the office and reception are shown in Figure 29.

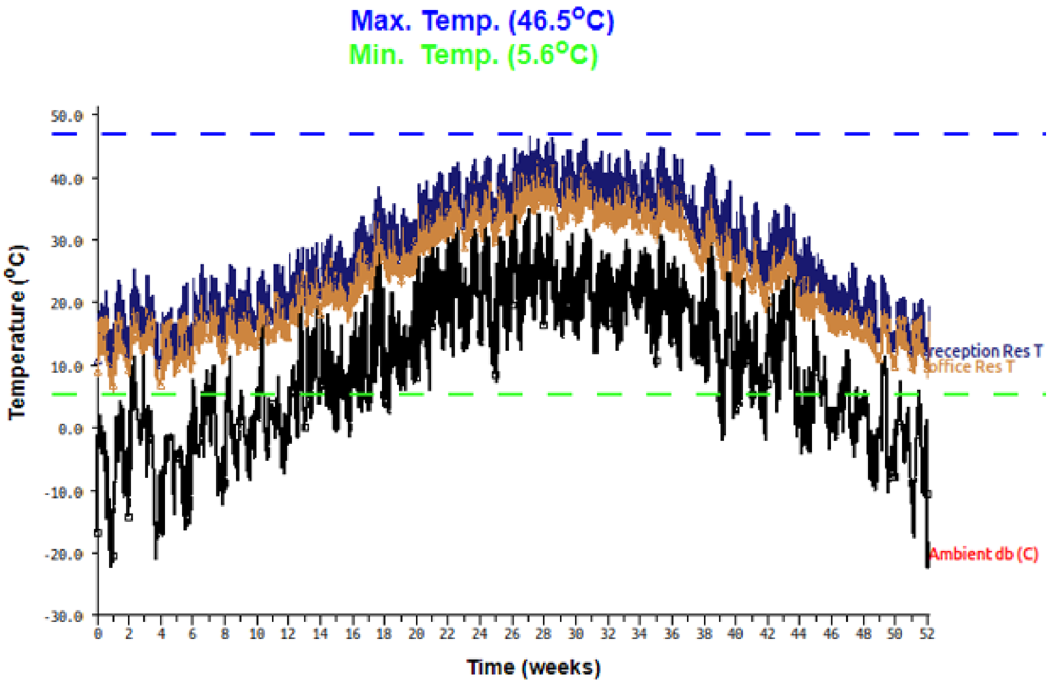

Figure 29. Comparative annual temperature trends: Office, Reception, and Chicago's ambient temperatures.

In Figure 29, aligned with insights from section 2, it was observed that there were dynamic temperature shifts spanning across summer, autumn, and winter. The coldest point in the office transpired between January 8th and 14th, registering at 5.6°C. Conversely, the peak warmth was captured between July 8th and 14th, soaring to 46.5°C. These readings indicated that the internal thermal comfort was occasionally outside the recommended ASHRAE benchmarks.

4.1.2 Testbench model – Hourly temperatures vs. casual gains

Figure 30 and Figure 31 show illustrate the hourly temperature profiles and causal gains of the testbench model. The data captures extremes from Chicago's annual weather dataset, highlighting the warmest conditions experienced in the reception and the coldest conditions observed in the office.

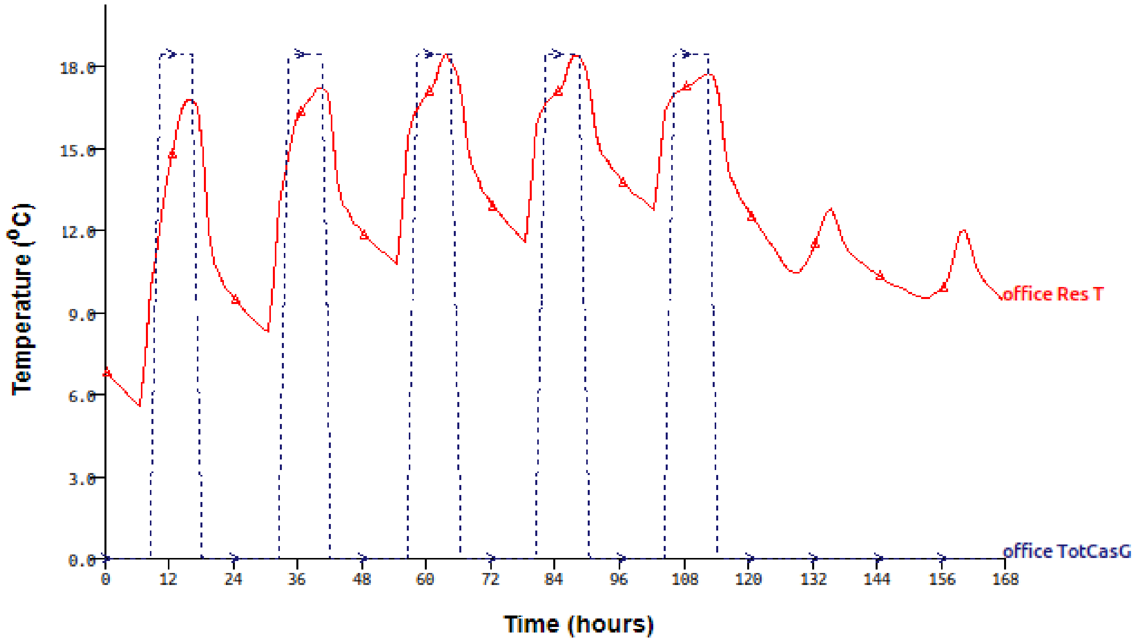

Figure 30. Hourly temperature trends and causal gains for the office during Chicago's coldest period.

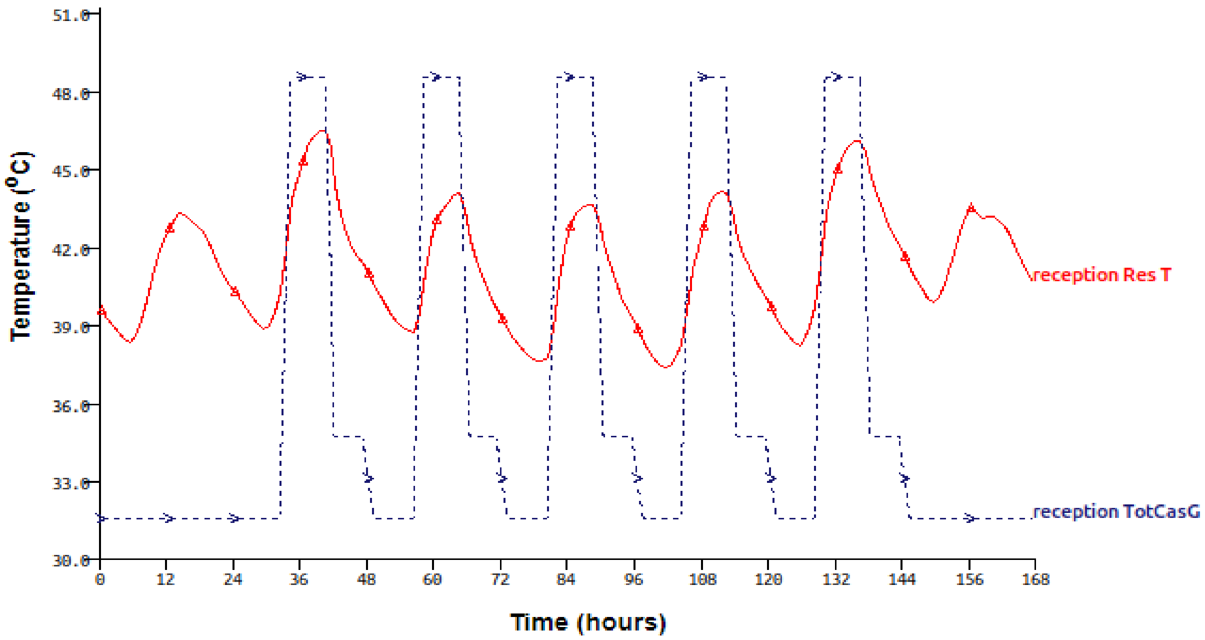

Figure 31. Hourly temperature fluctuations and causal gains for the reception during Chicago's warmest phase

Referring to sections 2.4.1, 2.4.2, and 3.3.2, along with observations from Figures 30 and 31, it becomes apparent that peaks of solar irradiance significantly amplify solar heat gains through the glazing. These temperature spikes can be attributed to thermal bridging and radiative heat transfer, especially through areas like walls, building envelopes, and architectural corners, which typically exhibit lower thermal resistance.

A deeper analysis of the temperature profiles revealed a consistent trend, regardless of whether it was during office hours or after. Notably, there was an absence of cooling, which was further corroborated when assessing the annual energy data for both cooling and heating demands. This analysis underscored the fact that only the sensible heating exhibited non-zero values, as presented in Table 6.

Table 6. Energy demand overview for heating and cooling

Zone	Sensible Heating		Time Required
	(kWh)	(kWh/m^2)	(hours)
Office	993.8	20.7	1266.0
Reception	1146.4	71.7	1656.0
Total	2140.2	113.1	1580
Zone	**Sensible Cooling**		**Time Required**
	(kWh)	(kWh/m^2)	(hours)
Office	0	0	0
Reception	0	0	0
Total	0	0	0

The graphical data in Figure 30 and Figure 31 further emphasised the significant role of causal gains in dictating peak temperatures and the overall energy demand. Reducing these gains effectively would lower the demand for sensible heating. Conversely, if any cooling demand was observed (a parameter value exceeding zero), it would signify the presence of a cooling mechanism. However, the recorded temperature drops can be attributed more to external temperature declines, making the outdoor environment cooler than both the office and reception areas.

4.1.3 Testbench model – Floor surface flux

The surface flux and its effects on the reception and office area can be seen in Figure 32.

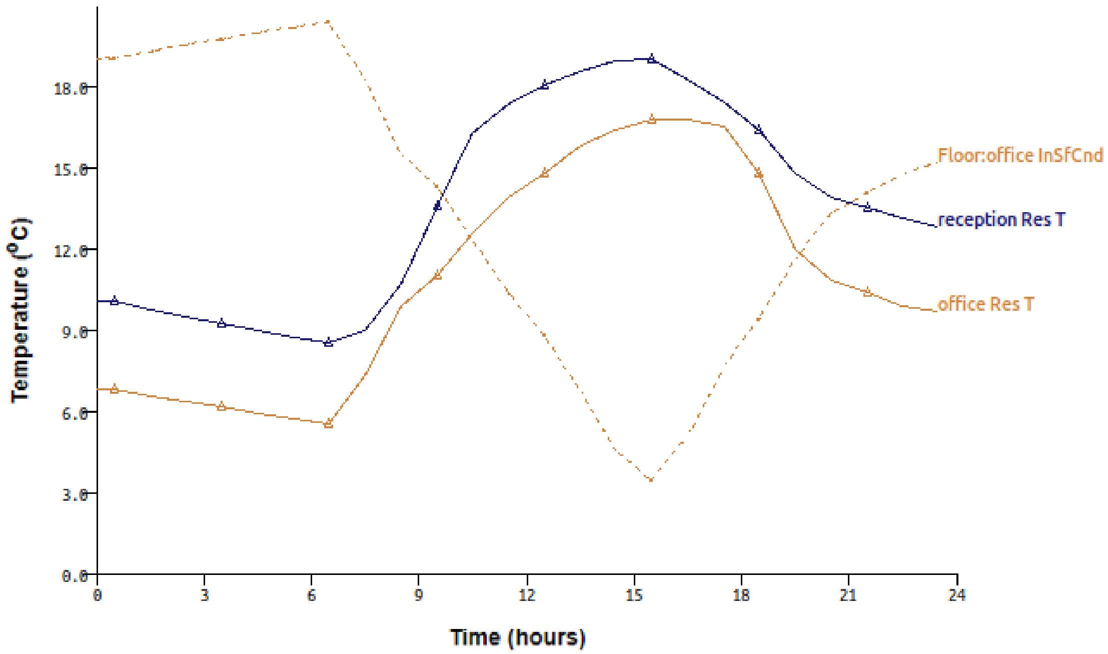

Figure 32. Daily variation of floor surface flux and its impact on reception and office temperatures.

In the results shown in Figure 32, the inside surface flux of the floor by conduction represented the way heat traveled within the floor. The floor was thought of as having a series of layers. The heat movement from the top layer or node 1 (closest to the rooms) to the layer beneath (closest to the ground) was specifically observed. This movement indicated the amount of energy that was flowing.

During certain periods of the day, as demonstrated, the floor, being warmer than the room's air, gave off its heat to the room. But when the heating system was turned on and the room's air became warmer than the floor, the heat started moving from the air back into the floor. On the graph, this change was marked by a downward trend. The pattern continued to evolve after the heating was turned off.

4.1.4 Testbench model – Changes to cooling system values

As a result of Table 6, five distinct cooling system sizes were evaluated, as depicted in Figure 33.

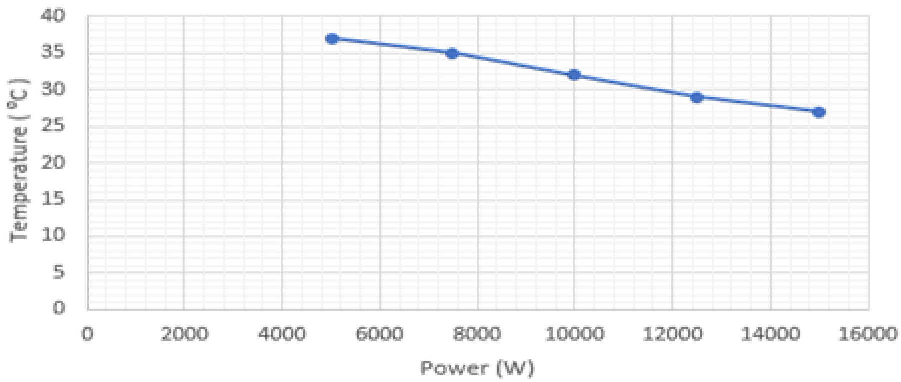

Figure 33. Cooling temperatures achieved across various cooling system power ratings.

The graph in Figure 33 highlights the importance of correctly sizing the heating and cooling system for a given indoor environment. Referencing section 2.4.1 and 2.4.6, ensuring the system's dimensions matched its requirements was vital for delivering realistic energy values during simulations. An undersized system size could have resulted in inefficient energy utilisation, disrupting the simulated environment's stability.

For instance, when the cooling system was not configured (set to null), peak temperatures went unchecked. Conversely, an oversized heating system could lead to energy wastage and frequent on-off cycles. By adhering to ASHRAE's recommended setpoints and choosing the 15kW cooling system, the testbench successfully mimicked an environment with thermal comfort ranges between 19°C and 27°C. It was evident that the temperature spikes surpassing the blue line corresponding to non-operational office hours.

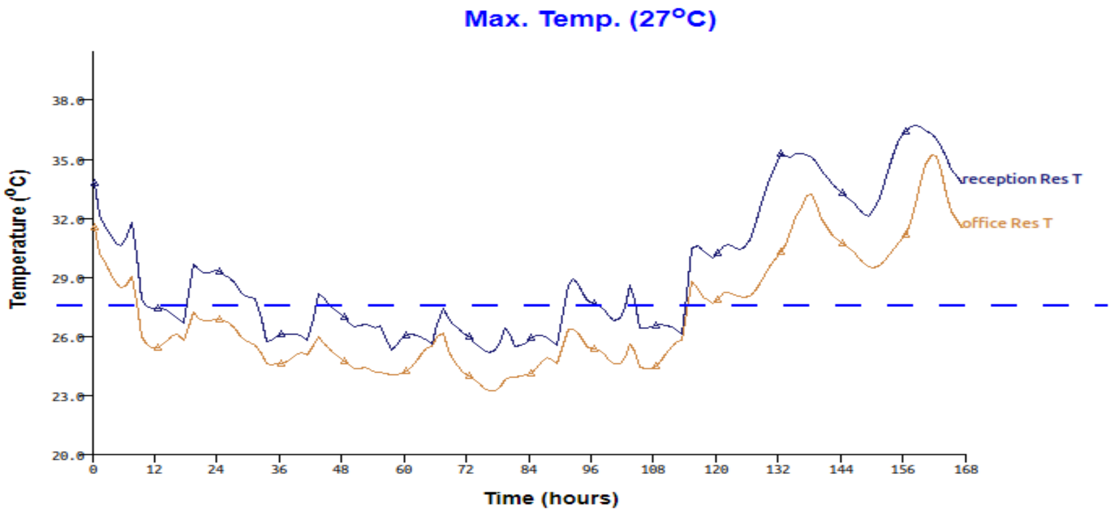

Figure 34. Temperature variations over time: A Comparison with office in the hottest operational hours in the summer.

4.1.5 Testbench model – Energy demand

Upon the integration of the cooling system, there was a noticeable rise in the total energy demand for both heating and cooling, as detailed in **Table 7**.

Table 7. Total energy demand for heating and cooling upon adapting the cooling system.

Zone	Sensible Heating		Time Required
	(kWh)	(kWh/m^2)	(hours)
Reception	993.8	20.7	1266.0
Office	1146.4	71.7	1656.0
Total	2140.2	113.1	1580
Zone	Sensible Cooling		Time Required
	(kWh)	(kWh/m^2)	(hours)
Reception	-3372.1	-70.3	1432.0
Office	-488.3	-30.5	1040.0
Total	2140.2	33.4	2472.0

As observed in Figure 22, the initial heating system was equipped with a 3kW capacity, however, lacked a cooling counterpart. The introduction of a 15kW cooling system and an evaluation of the combined heating-cooling dynamics resulted in the findings summarised in Table 7. Emphasising this energy demand was integral as it highlighted parameters that may need to be improved e.g., buildings materials.

With the evaluation of the testbench model, inclusive of its annual, hourly, and surface flux temperature metrics, revealed that the adapted cooling system efficiently upheld thermal comfort as per ASHRAE benchmarks. As seen in Table 7, the cooling statistics underwent a transition from a scenario with no cooling to the presented figures. This smooth transition and consistent performance signify the reliability and efficiency of the testbench's operational dynamics.

4.2 Above ground model – No HVAC

4.2.1 Above ground model – Annual temperatures

The graph in Figure 35 captures the yearly temperature shifts within the above ground model, benchmarked against the ambient temperatures observed in Chicago.

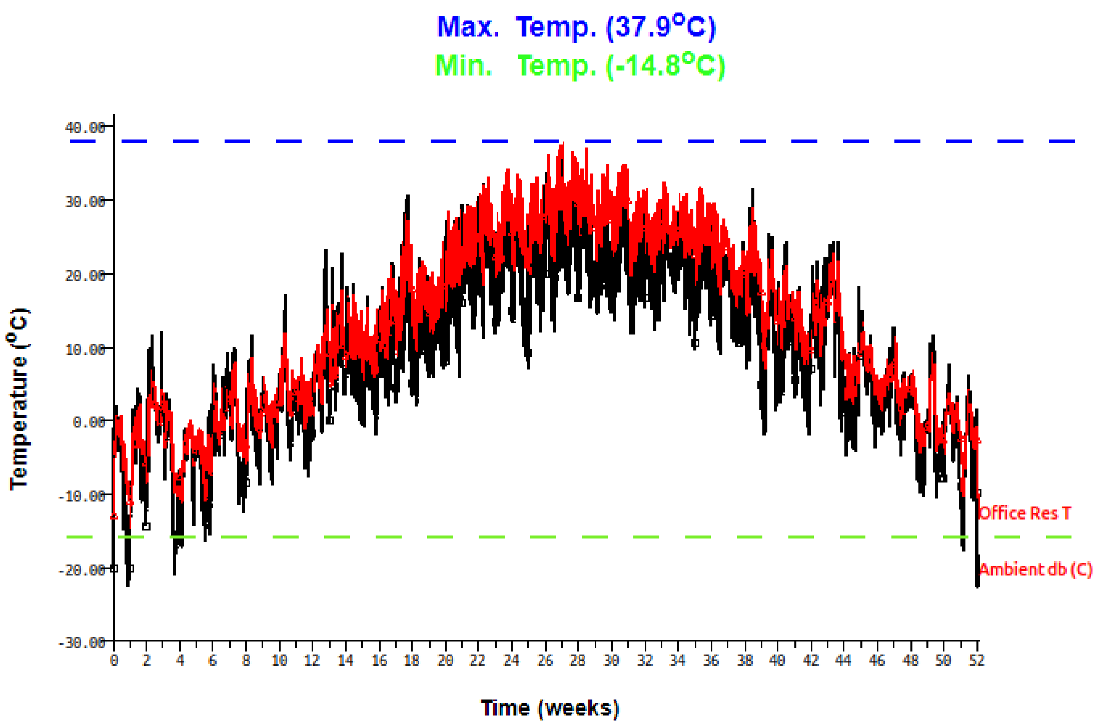

Figure 35. Annual temperature variations in the above ground model without HVAC, compared to Chicago's ambient conditions.

Analysing Figure 35, the graph depicts a clear cyclical trend, mirroring Chicago's characteristic seasonal variations. With reference to 2.4.1, as the fundamentals of thermodynamics dictate, heat naturally transitions from hotter to cooler zones. This was evident in the office's temperature trends with Chicago's ambient conditions, particularly during the height of summer and the depths of winter. A closer examination of the data showed that the office's internal temperatures peaked at 37.9°C in the summer and plummeted to a -14.8°C in the winter. These values exceed the comfort thresholds set by the ASHRAE for optimal indoor conditions.

The pronounced spikes during summer months were largely be attributed to direct solar exposure, amplifying the building's internal heat levels. While solar irradiation was a primary factor, the building materials as discussed in section 3.4.1 also play a pivotal role. They absorb and gradually release heat, intensifying the building's internal warmth, especially during persistent sunny spells. Conversely, in the absence of a heating mechanism, colder external conditions lead to a noticeable drop in internal temperatures, highlighting the need for efficient HVAC system to ensure consistent indoor comfort.

4.2.2 Above ground model – Hourly temperatures

Referring to Figure 36, Figure 37 and section 4.2.1, the hourly temperatures were derived from the annual weather data presented in Figure 35. The data showcases extreme temperature variations with the coldest temperatures observed during the week of 8th to 14th January and the hottest temperatures recorded between 9th and 15th July.

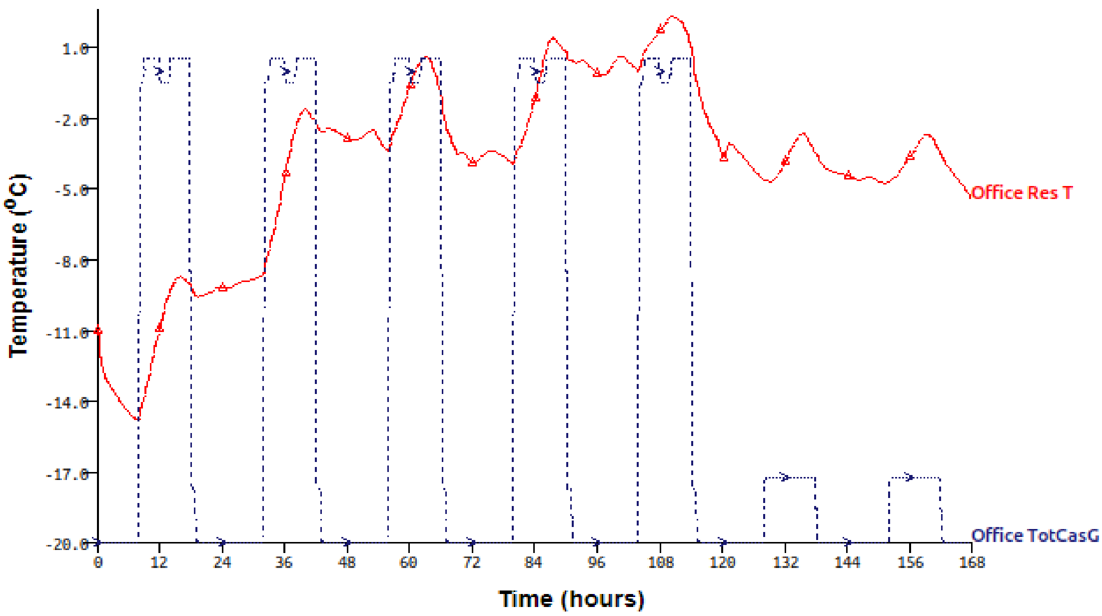

Figure 36. Hourly temperature trends in the above ground model during the coldest week (8th to 14th January). The chart highlights the extremities in temperature fluctuations, depicting the building's response to Chicago's ambient conditions.

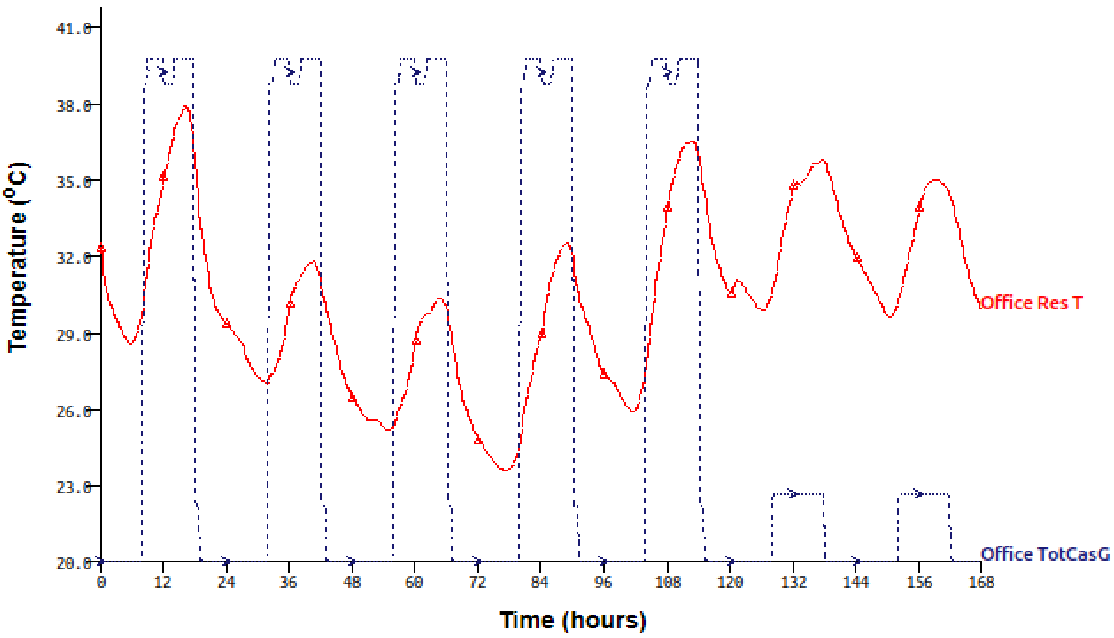

Figure 37. Hourly Temperature Variations in the Above Ground Model during the Hottest Week (9th to 15th July). The data illustrates the building's temperature dynamics in relation to Chicago's peak summer conditions.

Referencing the literature in section 2, observing the coldest temperatures recorded on the graph in Figure 36, during the colder winter months, the thermal dynamics of a building have been impacted by various factors. One of the prominent influences is solar irradiance; even in winter, the solar irradiance has warmed up the surfaces, i.e. walls, roof etc. This heat directly contributed to a building's interior temperature. Conversely, convection is also evident when the temperatures out with office hours decreased. Infiltration influenced a reduction heat from the structure's outer surface, causing a decrease in the internal temperatures . Similarly by conduction, the heat from the building's inside transferred to its colder exterior, leading to a further reduction in inside temperatures. Referring to the peak temperatures shown in Figure 37 and with reference to Figure 35, during the warmer summer months, various factors played a role in elevating the building's temperatures. Solar irradiance was a significant factor.

In summer, the increased solar irradiance resulted in an increase in the amount of solar energy absorbed by the building's surfaces, such as walls and roofs. This absorbed energy, in turn, raised the temperature inside the building. However, post office hours, the cooling effect of convection became more apparent as the indoor-outdoor temperature difference increased. Additionally, as the outdoor temperatures spike, the heat within the building escaped through conduction, transferring from the warmer interior to the cooler exterior. Although the effects of infiltration in summer may have been less, it still caused some warmer outdoor air to penetrate the building, marginally affecting the internal temperature.

With respect to casual gains, they are unintentional heat sources that have a large influence inside the building and has impacted its thermal environment. These gains have come from the occupant, lighting, and equipment shown Table 8.

Table 8. Annual casual gains for the office.

Office casual gains distribution (kWh)			
Type	Cond+Rad	Conv	Time required (hours)
Occupant	226.2	113.1	2925.0
Lights	1236.5	618.3	3741.3
Equipment	702.0	351.0	2665.0
Total	**2165.0**	**1082.0**	

Referencing section 2.5.1, the occupant has introduced sensible heat from the warmth of their body and the activities they perform. The lighting has emitted sensible heat when it has been in use. The office electrical equipment has also produce sensible heat during operation, hence it was important to consider this for both sensible and latent casual gains when designing the building's thermal management system, in this case, heating, cooling and ventilation.

4.2.3 Above ground model – Floor surface flux

The surface flux and its effects on the office area can be seen in Figure 38. Daily variations of floor surface flux in the above ground model. The graph illustrates the relationship between surface flux (BaseOfficeHclSrd) and office temperature (Office ResT) over a 24-hour period, showcasing the influence of floor surface flux..

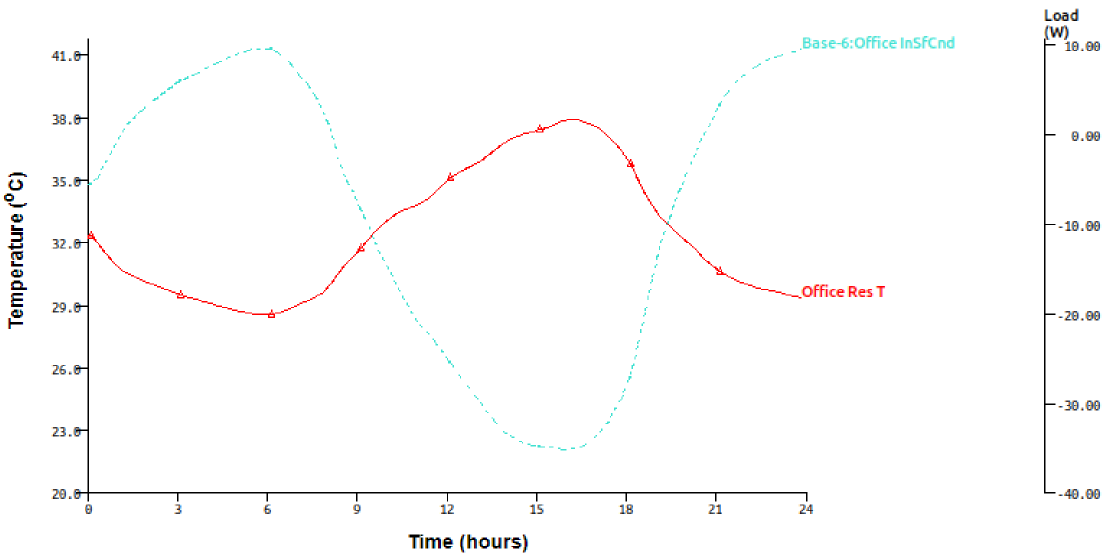

Figure 38. Daily variations of floor surface flux in the above ground model. The graph illustrates the relationship between surface flux (BaseOfficeHclSrd) and office temperature (Office ResT) over a 24-hour period, showcasing the influence of floor surface flux.

Referencing Figure 38 and section 3.4, the inside surface flux of the above-ground building by conduction illustrates the intricate characteristics thermal dynamics taking place over a 24-hour period. The flux graph illustrates the rate at which heat energy traversed between the floors nodes. Specifically, the movement of heat from the exterior node (closest to the outer environment) to the subsequent inner node (closer to the building's interior) was quantitatively captured. This movement signified the actual energy flux or the transfer of thermal energy between these nodes.

From the graph, throughout the course of the day on the 9th of July (hottest day of the year) there were periods when the external building surface became hotter than its immediate inner layer. This was largely influenced by the direct solar radiation combined with ambient atmospheric conditions. During these intervals, the exterior, laden with heat, transmitted this excess energy inward, which was demonstrated as an upward trend on the graph.

Conversely to this, if it was in the context of the 8th of January (coldest day of the year), things would transpire differently. The exterior surface would be considerably cooler. With reference to section 2.4.1 and 3.2, heat would have then flow from a region of higher temperature to one of lower temperature. This means that the building's internal heat would tend to move outwards to the outside colder environment . This would result in a more pronounced downward trend in the graph during most hours, indicating the building's attempt to maintain its internal thermal equilibrium vs. the outside cold environment. Soil, as a semi-infinite medium, had a distinct influence in this process. Its properties like thermal inertia and depth played crucial roles.

4.2.4 Above ground model – Relative humidity

In this conducted simulation, an analysis was performed on annual and hourly temperatures as outlined in sections 4.2.1 and 4.1.2. The data revealed that the relative humidity throughout the year, reaching a peak of 100% and a low of 18.6%, with an average of 58.1%. While this average lies within the acceptable range of 30%-60% set by ASHRAE standards, the extremes deviate from this recommended range.

These deviations would have had implications in energy modelling performance. Elevated humidity levels, approaching or exceeding 100%, can lead to the onset of dew point conditions, where moisture in the air condenses. This not only has the potential to damage building materials but can also foster the growth of mould and mildew, which can degrade indoor air quality. With respect to lower end, excessive low humidity can cause materials to dry out and become brittle and can adversely affect occupant comfort. Maintaining relative humidity within the recommended ASHRAE range was important to consider for the longevity of the building structure, optimising energy use, and ensuring a healthy indoor environment.

4.2.5 Above ground model - Energy demand

Following the analysis of the data presented in sections 4.2.1 through 4.2.4, the energy delivered with respect to energy contributions for sensible heating and cooling was inspected, shown in Table 9.

Table 9. Energy delivered for heating and cooling evaluation for the above ground building.

Model type	**Sensible heating**		**Time required**
	(kWh)	(kWh)/m^2)	(hours)
Single-zone base model	0	0	0
Model type	**Sensible cooling**		**Time required**
	(kWh)	(kWh)/m^2)	*(hours)*
Single-zone base model	0	0	0

In the evaluation of sensible heat and cooling demand, it was observed that no energy was delivered from heating or cooling systems, as anticipated. The absence of these systems directly impacts several key parameters. Without heating or cooling systems, the annual and hourly resultant temperatures were primarily influenced by external environmental factors and internal gains, with no active control to moderate them. This meant that during hot periods, there was no system in place to remove excess heat, leading to higher indoor temperatures. Conversely, in colder periods there was no mechanism to introduce heat, causing indoor temperatures to drop.

This natural fluctuation also affected the surface flux, as there was a more pronounced transfer of heat between the building's interior and the external environment due to the lack of temperature regulation. Similarly, humidity levels varied significantly as there was no system to dehumidify or humidify the air, that would lead to potential discomfort and the issues previously discussed. Without a heating or cooling system, there was an increased reliance on casual gains, like solar irradiance or equipment use to influence indoor temperatures. In reality and out with the simulation, these gains would be unpredictable and could further contribute to temperature and humidity variations.

4.3 Above ground model - HVAC

4.3.1 Above ground model - Heating and cooling

The sizing of both the heating and cooling systems can be seen in Figure 39 and Figure 40.

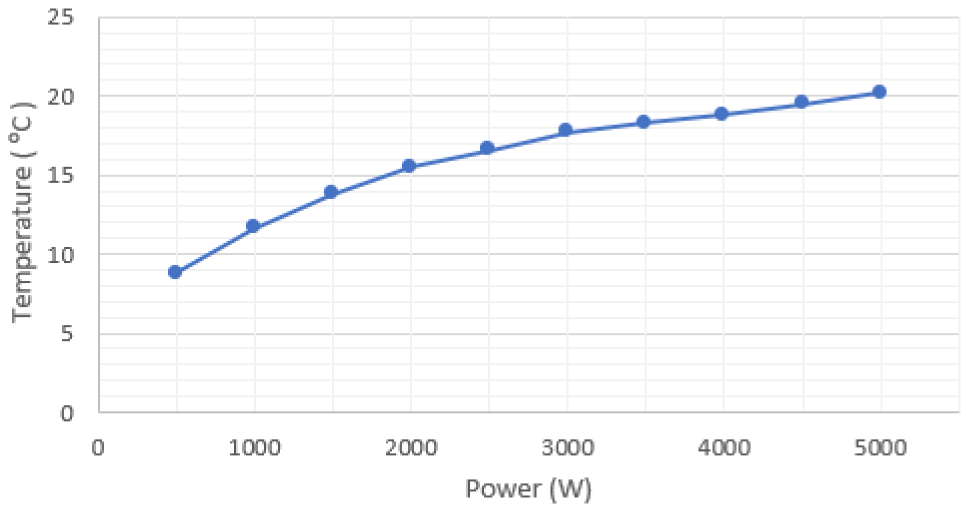

Figure 39. Heating system performance - relationship between power (W) and achieved indoor temperature (°C).

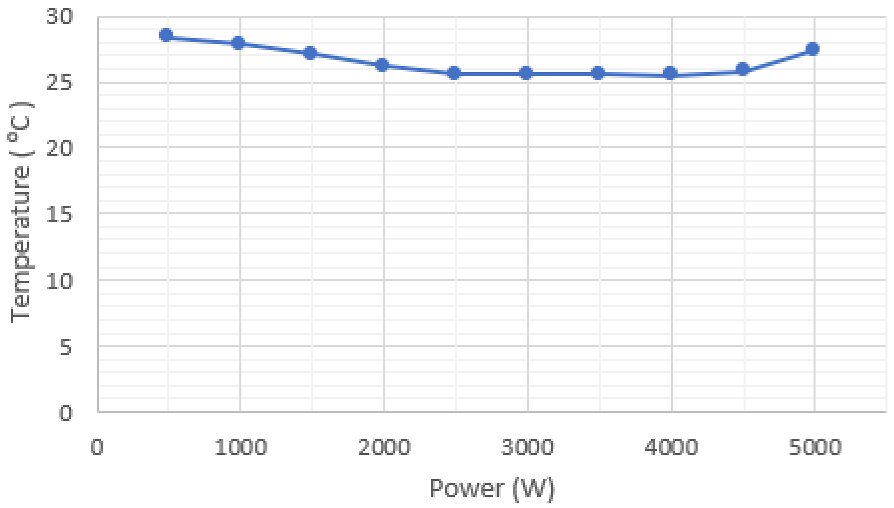

Figure 40. Cooling system performance - correlation between power (W) and reduced indoor temperature (°C).

In examining the graphs figures Figure 39 and Figure 40 , the heating sizing seen that a capacity 5kW power rating emerged as the most suitable . This selection was based on its demonstrated capability to reduce the models highest temperatures in the year and it consistently maintained office hour thermal comfort levels at an acceptable level, shown in figure Figure 41.

It’s important to note that ventilation rates played a highly influential role in determining this system size. The analysis illustrated that as the ventilation rate was systematically decreased, the system's performance in maintaining thermal comfort improved, leading to the identification of an appropriate ventilation rate.

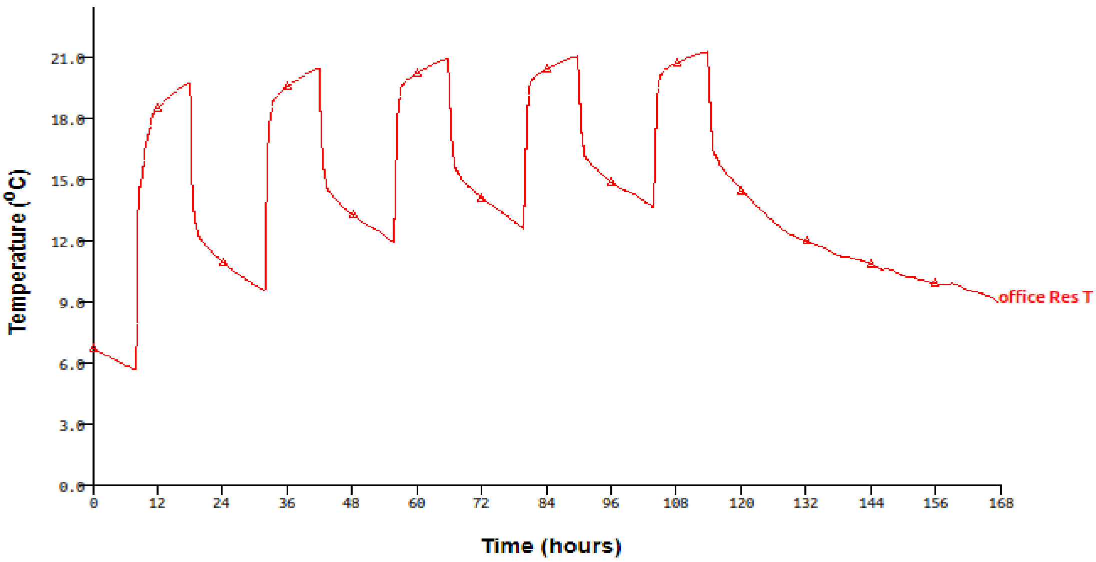

Figure 41. Performance of a 5kW heating system: This graph displays the temperature variations in the office over time, highlighting the efficacy of the 5kW heating system in maintaining consistent indoor temperatures.

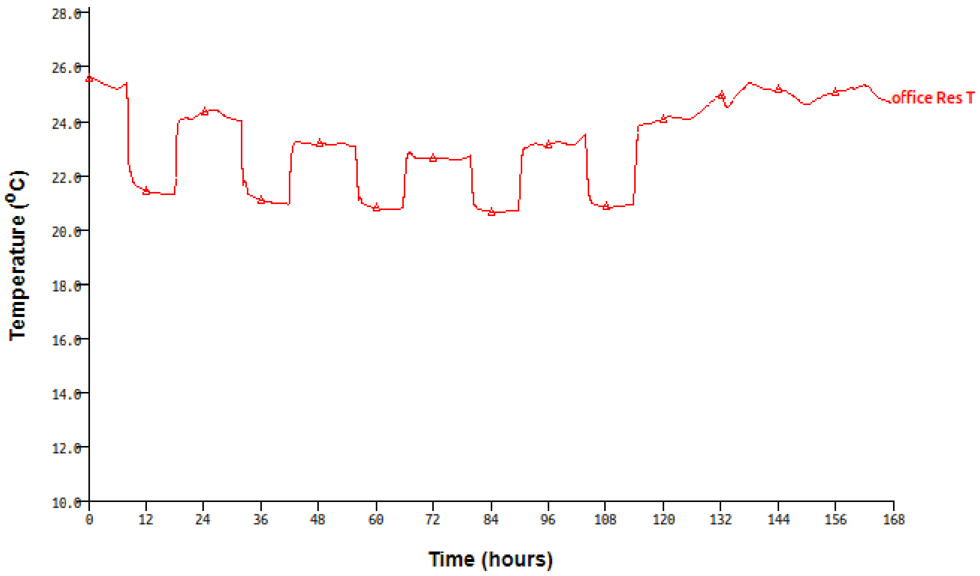

Figure 42. Performance of a 3kW cooling system: Demonstrated is the cooling system's ability to stabilize the office temperature across a duration, showcasing the effectiveness of the 3kW cooling setup.

For cooling, a 3kW system was chosen, where it maintained thermal comfort levels consistently between 21°C and 22°C, shown in figure. This decision was influenced by occasional unforeseen temperature spikes; while a 2kW system met the basic requirements, it occasionally surpassed acceptable thermal comfort limits. Interestingly, there was an observed counterintuitive behaviour; increasing the system size beyond the optimal point had a counterproductive effect on thermal performance. This suggested that simply increasing system capacity did not guarantee improved performance and could, in certain circumstances, deteriorate the thermal comfort conditions.

In relation to the relative humidity for the above ground building, as detailed in section 4.4.2, there were observable periods when the peak humidity levels only decreased to 80%, marking a 20% improvement. Simultaneously, the minimum humidity values rose to 36%. The mean humidity experienced a minor reduction, settling at 57%. This is aligned with the ASHRAE standards, which recommend a range of 30% to 60% for relative humidity. From an energy modelling perspective, it's worth noting that achieving a significant reduction in peak relative humidity levels may be challenging due to inherent building characteristics and external climatic factors.

4.3.2 Above ground model – Energy demand

Following the comprehensive evaluation of the HVAC system's modifications and its subsequent impact on indoor thermal conditions, the energy delivered for both sensible heating and cooling was quantified and recorded in Table 10.

Table 10. New annual heating and cooling Energy demand after model adaptations.

Model type	**New sensible heating**		**Time required**
	(kWh)	(kWh)/m^2)	(hours)
Above ground model	3121.9	57.8	1637
Model type	**New sensible cooling**		**Time required**
	(kWh)	(kWh)/m^2)	*(hours)*
Single-zone base model	-434.8	-8.1	825

The data presented for the single-zone base model in Chicago in Table 10 demonstrates the heating and cooling energy requirements. For heating, the model demands a substantial energy input of 3121.9 kWh over a duration of 1637 hours. In contrast, the cooling requirement registers at -434.8 kWh, achieved over a shorter span of 825 hours. The energy demand per square meter for heating is 57.8 kWh/m², while for cooling, it's -8.1 kWh/m². Section 4.3.3 connects Table 11 in greater contract.

4.3.3 Above ground model – Energy balance

Table 11 presents a breakdown of the energy gains and losses in terms of kilowatt-hours (kWh) and the totals tie up with the energy delivered in Table 10.

Table 11. Energy demand balancing for the above ground model after heating and cooling addition.

Type	**Heating Period (kWh)**		**Cooling Period (kWh)**	
	Gain	*Loss*	*Gain*	*Loss*
Infiltration & ventilation	0.4	-810.5	26.4	-43.1
Occupants	62.6	0.0	31.7	0.0
Lighting	346.9	0.0	174.3	0.0
Equipment	216.8	0.0	109.0	0.0
Storage	30.2	-98.4	1.6	-2.8
Material components external	0.03	-1738.3	92.4	-12.3
Material components internal	0.24	-1131.8	66.0	-8.4
Plant	3121.9	0.0	0.0	-434.8
Total	3779	-3779	501.4	-501.4

With reference to Table 11 ,the above ground model reveals a clear heating demand of 3121.9 kWh, substantially higher than its cooling demand, which is registered at -434.8 kWh. This pronounced difference can be directly attributed to the prevailing climatic conditions of Chicago, characterised by extended cold periods that necessitate rigorous heating.

A closer analysis of the energy balance table offers insights into the primary avenues of energy losses and gains. Notably, the significant energy loss of -810.6 kWh during the heating period is predominantly due to infiltration and ventilation. Here, 'infiltration' is defined as the uncontrolled influx of external air into the building through gaps and openings in the building envelope. 'Ventilation', on the other hand, represents the controlled introduction of outside air for maintaining indoor air quality. These substantial losses suggest potential inefficiencies in the building's envelope and the ventilation system, warranting further investigation and rectification.

Consistent energy gains are observed from internal sources such as occupants, lighting, and equipment. However, external and internal materials of the building depict marked heat losses of -1738.3 kWh and -1131.8 kWh, respectively, during the heating cycle. These losses underscore the vital role that construction materials and insulation play in a building's energy dynamics. For optimal energy performance and efficiency, it's imperative to focus on improving insulation properties and sealing potential gaps that contribute to infiltration.

4.4 Underground model- No HVAC

4.4.1 Underground model – Annual temperatures

Figure 43 shows the annual resultant temperatures of the Chicago base model versus the outside ambient dry bulb temperatures.

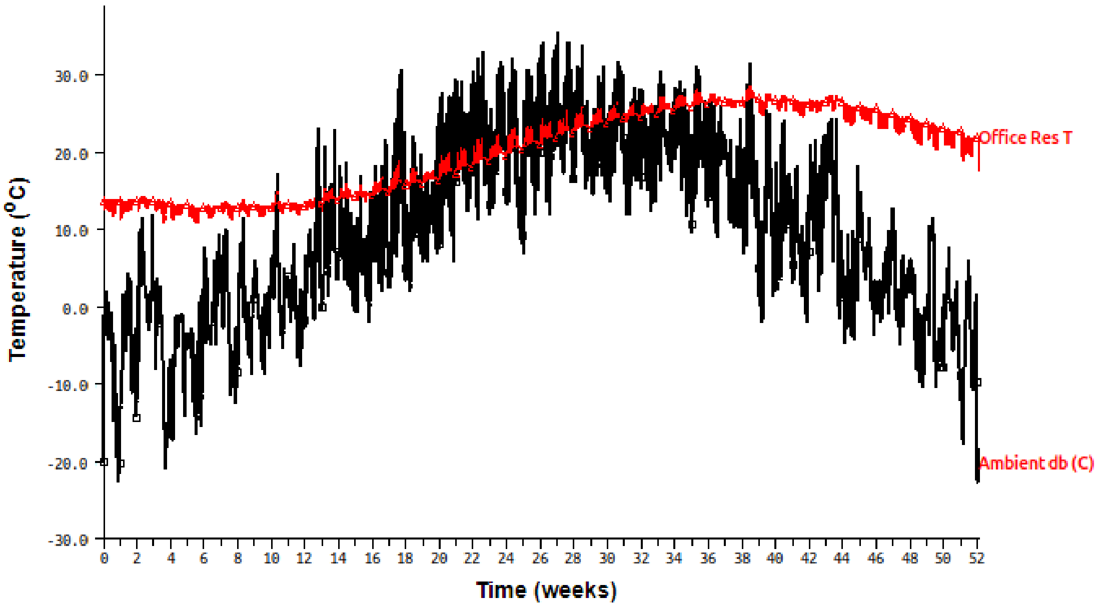

Figure 43. Annual temperature profile of the underground model: The graph contrasts the internal office temperatures (red) with Chicago's external ambient dry bulb temperatures (black), highlighting the temperature fluctuations experienced over the year.

Referencing Figure 43, both the ambient dry bulb and the office space temperatures show fluctuations throughout winter, summer, and autumn. These temperature variations were primarily due to factors such as conduction, convection, as detailed in section 4.1.4. Being underground, the model was less influenced by infiltration and solar radiation compared to a building situated above ground. With respect to ASHRAE standards for thermal comfort, the minimum temperature occurred 26th January at 10.7°C and the maximum temperatures was recorded 25th September, where both were out with the acceptable limits of between 19°C and 27°C.

The underground office model was exposed to the thermal properties of the surrounding materials, primarily the earth's layers seen in Figure 28, and construction elements like concrete and screed. The Soil had unique behaviours when it came to thermodynamics. Its high heat capacity meant it stored a large amount of heat energy, and its low thermal conductivity ensured slow transfer of this heat. The soil's buffering effect was evident when inspecting the recorded resultant temperatures. Despite daily or seasonal fluctuations in ambient temperatures, the earth either absorbed or released heat, which lead to a moderated temperature experience within the underground office. This was driven by the earth's ability to resist sudden temperature changes, serving as a thermal buffer.

In both winter and summer, the prescribed static temperature was set at 15°C. This consistent static temperature illustrated the building's buffering capacity. The underground office model’s consistent temperature can be attributed to the earth's depth-dependent thermal gradient; deeper regions of the earth maintain a relatively stable temperature, unaffected by seasonal changes.

The construction materials of the office, like concrete and screed, augmented this temperature stability. These materials offered extra layers of thermal resistance, ensuring the heat transfer into and out of the office was gradual. The collective thermal attributes of the soil and building materials ensured the underground office saw minimal temperature shifts, offering a more consistent thermal environment than results observed in above-ground models

4.4.2 Underground model - Hourly temperatures

As outlined in Figure 44, Figure 45 and discussed in section 4.2.1, the temperatures on an hourly time series were extrapolated from the annual weather data detailed in section 4.4.1. This data highlights pronounced temperature fluctuations, with high and low peak temperatures recorded during the hours within week of 19th to 26th January (winter) at 10.7 ℃, and between 19th and 26th September (summer) at 26.5 ℃.

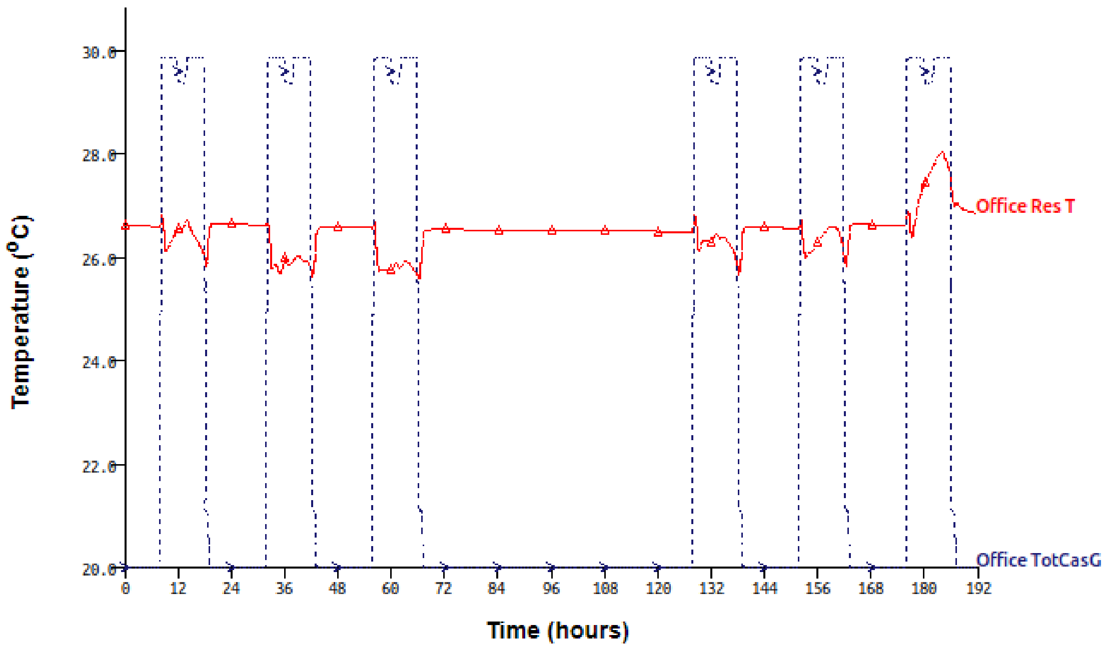

Figure 44. Summer hourly temperature profile for the underground model: The chart displays the office resultant temperatures (red) contrasting with casual gains (blue) over a week's duration in July.

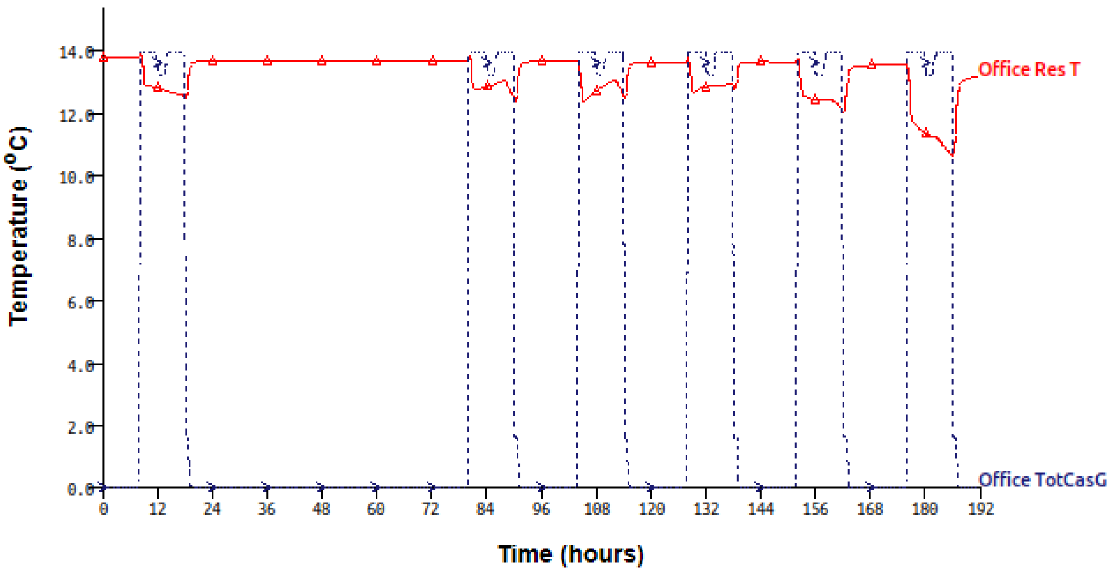

Figure 45. Winter hourly temperature profile for the underground model: The graph contrasts the office resultant temperatures (red) with casual gains (blue) across a week's span in February.

Reviewing the temperatures of the underground office space and with respect to section 2.5, casual gains was factor that can be seen in figure Figure 44 with the temperature spike on the far right. Between 19th to 26th September, shows consistent temperature changes. However, there's no clear temperature drop between 1200hrs and 1400hrs, which was attributed to lunch breaks. Between 19th January to 26th January, shows a similar pattern but at a lower temperature range. Even in colder conditions, the effects of casual gains are evident through the repeated temperature fluctuations.

With respect to the temperature peak in Figure 44, this could indicate a day when the ventilation system might have been off which further demonstrates the influences of casual gains. Without ventilation, the heat from internal sources such as equipment, lighting, and occupants can build up, leading to higher temperatures.

Both graphs highlight the effect of casual gains on the office's temperature. The temperature increases during office hours because of heat gains and then decreases after office hours. Without regular use of cooling or ventilation, it was identified that the office cannot effectively manage the increase in temperature from internal heat sources.

4.4.3 Underground model – Floor surface flux

The surface flux and its effects on the office area can be seen in Figure 46.

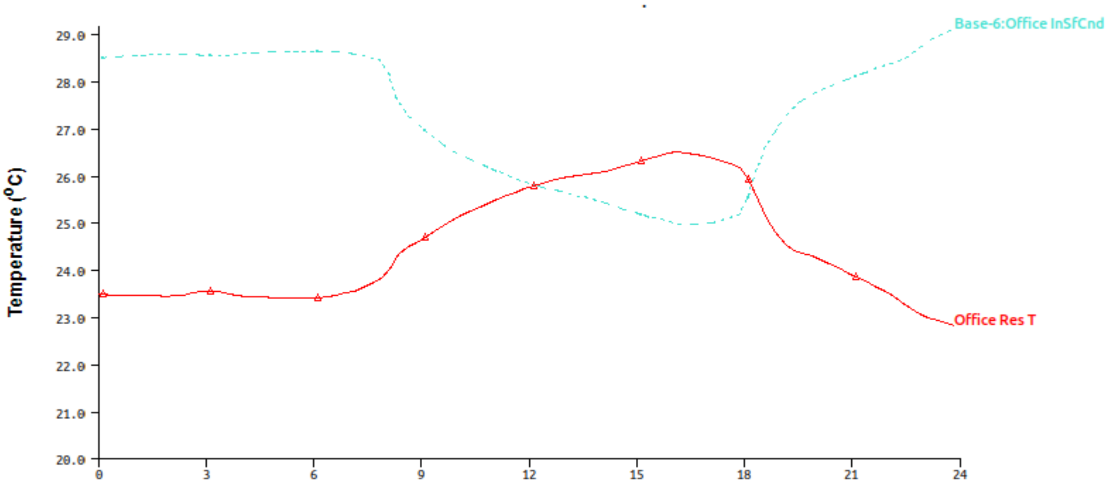

Figure 46. 24-hour temperature profile of the underground model's floor surface flux: The graph showcases the office resultant temperature (red solid line) in relation to the base office inside conduction (blue dashed line) over the course of a day in September.

Referring to Figure 46, the inside surface flux of the underground building, due to conduction, illustrated the thermal interactions that occurred over a 24-hour period on 19th September. The graph pinpointed the rate at which thermal energy moves between the floor nodes. In particular, the heat transfer from the outermost node (closest to the surface of the ground) to the subsequent inner node (more interior to the underground building) was effectively captured. This represented the actual energy movement or the heat transfer between these nodes. From the graph, during the day, there are moments when the outer layer of the building's floor became warmer than its immediate inner layer. A significant reason for this is the absorption of solar radiation by the ground above, which then conducted heat downward. At these times, the outer layer warmed up and drove excess energy inward, seen as a rise in the graph.

However, due to the building's underground nature, there were pronounced differences compared to the above ground model. Being underground at a depth of 1m ensured that the building was shielded from the direct effects of atmospheric temperature fluctuations. This meant that throughout the day, temperature changes were more gradual and buffered by the surrounding soil. A point worth highlighting is that the walls of the underground model displayed a similar pattern as the floor, due to the same materials and construction techniques were used in the simulation for both walls and floor. They behaved in a comparable way to thermal changes with respect to the floor. The soil, as a dense medium surrounding the building provided a buffering effect (as mentioned in section 4.4.1), minimising fast rates of temperature changes and creating a more stable internal environment. This was evident in the relatively steady nature of the graph compared to more fluctuating trends seen in above ground model.

4.4.4 Underground model - Relative humidity levels

When assessing the relative humidity, it was found that the maximum value was 100% with a minimum of 7.7% and an average value of 60.34%. With reference to section 2.8.5, the ASHRAE standard stated that humidity levels must be designed at 65% or less. These values were above acceptable limits. Referencing section 2.4.1 and 2.4.3, this meant there was a significant increase of the risk of mould growth, material degradation and discomfort and potential health concerns for occupants.

4.4.5 Underground model – Energy demand

Drawing from the discussions in section 4.2.5 and employing the same analytical techniques, the results confirmed that the underground model had neither heating nor cooling present. This outcome aligned with observations for the above-ground structure, indicating that the energy demands were primarily shaped by external environmental conditions and internal gains. The lack of heating or cooling systems meant the temperatures within the space responded naturally to these influences, without any mechanisms to actively regulate them.

4.5 Underground model - HVAC

4.5.1 Underground model – Heating and cooling addition

The sizing of both the heating and cooling systems can be seen in Figure 47 and Figure 48.

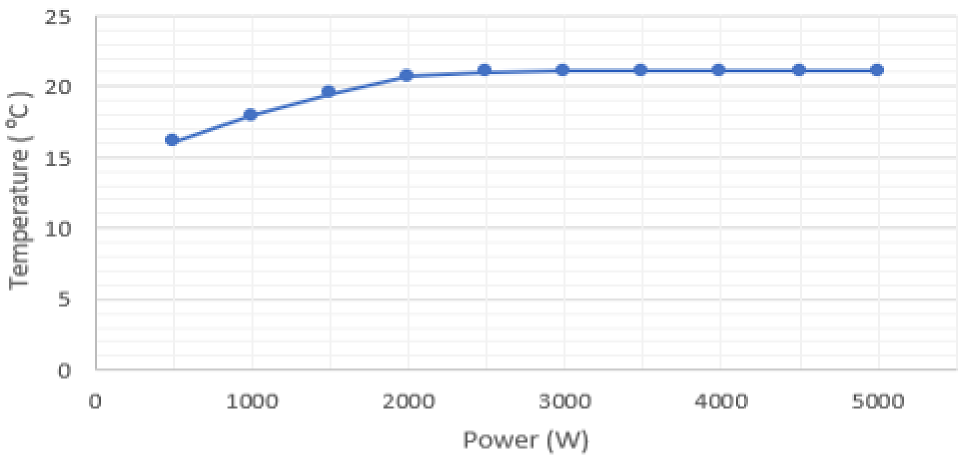

Figure 47. Relationship between system power and maximum heating temperature: This graph illustrates the correlation of HVAC system size, measured in wattage (W), to the maximum temperature achieved during heating.

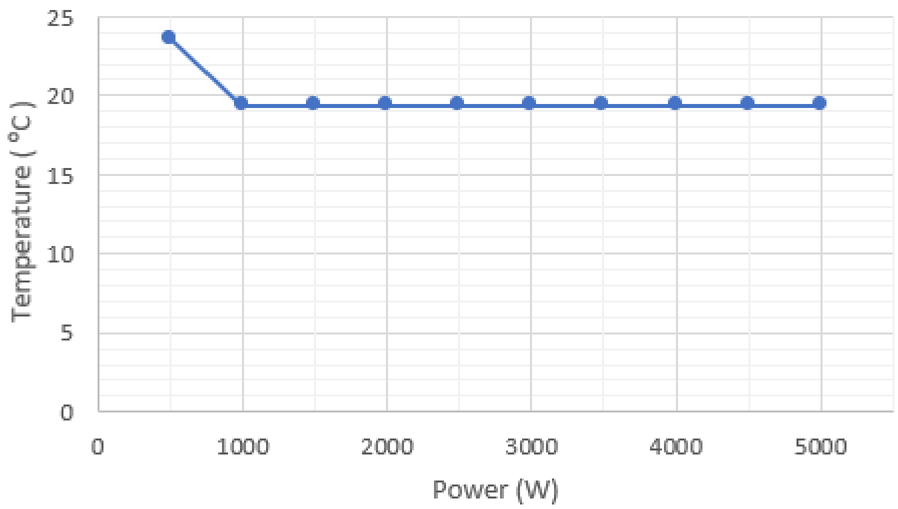

Figure 48. Relationship between System Power and maximum cooling temperature: Displaying the consistency of the HVAC system's cooling performance across various power outputs, indicating the system's efficiency in maintaining desired temperatures.

With reference to Figure 47 and Figure 48, the performance of various heating and cooling systems were evaluated. For the heating system, a setpoint of 22°C was established, while the cooling system had a setpoint of 20°C. The data revealed that, regardless of the heating system size, the temperatures consistently stabilised around 21.1°C. In contrast, the cooling system's efficacy varied with its size. The 500W cooling system was determined the most suitable, as it maintained temperatures within the ASHRAE recommended thermal comfort levels of between 19°C and 27°C, while other systems, despite achieving a cooling of 19.4°C, offered no significant advantage.

In the context of the underground model after HVAC installation, there were notable changes in the annual relative humidity levels. The humidity levels fluctuated through the year and at its peak, the humidity experienced a marginal decline, settling at 93% from an initial 100%, indicating a 7% enhancement. On the lower end, the humidity dropped significantly to 3%, a decrease from the earlier 8%. Most importantly, the average relative humidity exhibited a considerable reduction, averaging at 38% compared to the previous 60%. These outcomes can be attributed to the efficiency and effectiveness of the HVAC system in regulating moisture levels. The underground environment inherently retains more moisture, but with the implementation of the HVAC, there was enhanced moisture extraction and control, leading to these improved humidity levels.

The Figure 49 and Figure 50 provide a detailed temporal assessment of temperature variations. Without the intervention of the cooling system, internal gains would push temperatures beyond the comfort range, peaking around 24°C during office hours.

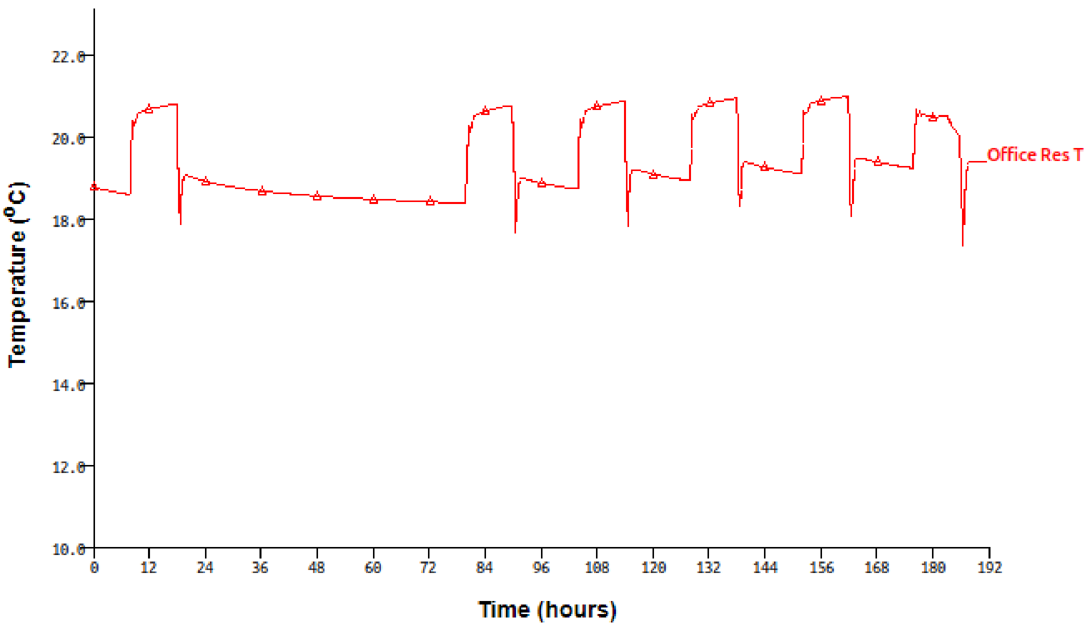

Figure 49. Temperature Trend for over 1 week with 2.5 kW heating system

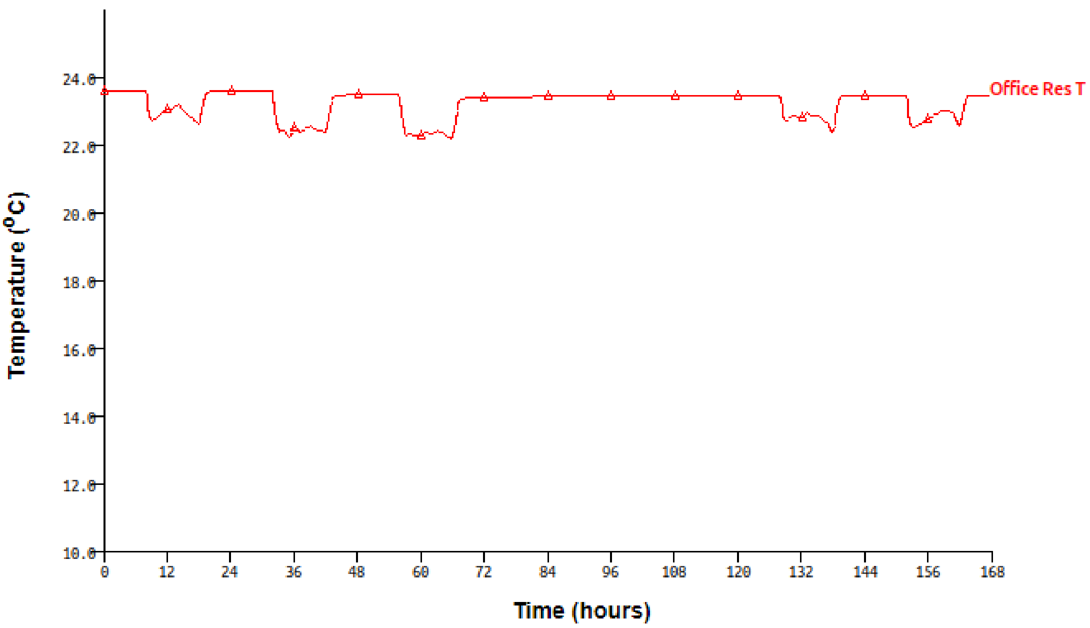

Figure 50. Temperature trend for over 1 week with 500 W cooling system.

With reference to section 2.4 and 2.5, these spikes were be attributed to casual gains from equipment, lighting, and occupants, and thermal inertia which to be expected underground spaces, shown in Figure 49 by the minor falls and rises in the graph. Conversely, without the heating the indoor environment would experience sharp decreases in temperatures, emphasising the importance of an effective heating solution, especially during colder periods. Fortunately, casual gains provided a supplementary heat source, offsetting some of the heating demand. Ventilation also played an influential role in stabilising the indoor temperature, minimising fluctuations. While the selected 500W cooling and 2500W heating systems were deemed suitable for this scenario, the building's inherent thermal mass, coupled with the effects of ventilation at 1.5 ac/h (after several iterations with reference to section 3.7.1) and casual gains, played a key role in maintaining a comfortable indoor environment.

4.5.2 Underground model – Energy demand

After checking the changes made to the HVAC system and seeing how they affected the indoor temperatures, the energy used for heating and cooling was listed in **Table 12**.

Table 12. New annual heating and cooling Energy demand after model adaptations.

Model type	**New sensible heating**		**Time required**
	(kWh)	(kWh)/m^2)	(hours)
Underground office model	1190.0	22.0	991.0
Model type	**New sensible cooling**		**Time required**
	(kWh)	(kWh)/m^2)	*(hours)*
Underground office model	-772.0	-14.3	1674

With reference to Table 12, the energy delivered for the heating phase requires an energy input of 1190.0 kWh, distributed over 991 hours, leading to a heating demand of 22.0 kWh/m². Conversely, the cooling phase demonstrates a demand of -772.0 kWh, which is spread over a prolonged duration of 1674 hours, resulting in a cooling demand of -14.3 kWh/m². This behaviour indicates that although the underground structure demands lesser energy for heating compared to above-ground models, it sustains a prolonged cooling duration. With respect to section 2.4 and 2.5, this extended cooling period could be attributed to the inherent thermal inertia of the underground environment. A significant aspect of the underground model's energy dynamics is the reduced infiltration. Due to its subterranean nature, it experiences little to no air infiltration, which greatly influences its energy demand. The stable ground temperature around the building aids in moderating its internal temperature, leading to a minimised heating requirement but an extended cooling timeframe.

4.5.3 Underground model – Energy balance

Table 13 presents a breakdown of the energy gains and losses in terms of kilowatt-hours (kWh) and the totals tie up with the energy delivered in Table 12.

Table 13. Energy demand balancing for the underground model after heating and cooling addition.

Type	Heating Period (kWh)		Cooling Period (kWh)	
	Gain	*Loss*	*Gain*	*Loss*
Infiltration & ventilation	0.00	-1603.4	115.5	-473.13
Occupants	40.4	0.0	67.6	0.0
Lighting	211.6	0.0	349.9	0.0
Equipment	132.3	0.0	218.7	0.0
Storage	17.74	-23.7	33.9	-11.9
Material components external	139.8	-104.8	0.0	0.0
Material components internal	0.00	0.0	533.7	-61.70
Plant	1190.0	0.0	0.0	-772..0
Total	1731.9	-1731.9	1318.8	-1318.8

The energy demand balancing as observed in Table 13, provides clear findings into the energy dynamics of the small office model. With zero energy loss due to infiltration during the heating period, the model reiterates the benefits of an underground design in limiting external air infiltration. However, ventilation results in a significant energy loss of -1603.4 kWh during the heating period. It is evident that the main energy gains during the heating and cooling periods come from internal sources: lighting contributes 211.6 kWh and 349.9 kWh respectively, and equipment accounts for gains of 132.3 kWh and 218.7 kWh. Material interactions also influence the model's energy performance. Specifically, the external material components show a gain of 139.8 kWh and a loss of -104.8 kWh during the heating period. The building's interaction with the surrounding soil plays a significant influential role as the thermal mass of soil acts as a buffer, tempering extreme temperature fluctuations and consequently aiding the building materials in providing consistent internal temperatures. As the plant system compensates with an addition of 1190.0 kWh during the heating period and a subtraction of -772.0 kWh during the cooling period, a holistic approach to optimizing building material properties, enhancing the ventilation strategy, and understanding soil-building interactions can lead to improved energy efficiency in underground structures.

4.6 Summary of results

Summarising the results on indoor air quality and relative humidity, the underground model demonstrated a distinct advantage over its above ground counterpart. Post implementation of HVAC control measures (ventilation, heating, cooling), the underground model achieved a marked reduction in average humidity, reducing from 60% to 38%. In contrast, the above-ground model, even after a 20% peak improvement, only decreased its average humidity to 57%. As discussed in section 2.4 and 2.4.3, the enhanced efficiency of the underground structure can be credited to its natural moisture retention, optimising the HVAC system's moisture extraction. However, one concern for underground buildings remains: ensuring effective ventilation to maintain air quality, which can be challenging given its design.

Referencing sections 2.4 and 2.5 and evaluating the thermal performance, the underground structure presented improved energy efficiency over the above ground design. For sensible cooling, the underground system recorded -772 kWh and -14.3 kWh/m^2 over 1674 hours, while the above ground structure required 1190 kWh and 22.0 kWh/m^2 across 991 hours. This indicated a 65% increase in energy usage for the above-ground system, despite operating for 68% less time. With reference to section 4.3.3 and 4.5.3, he above-ground model's total energy gains during the heating period were 3779 kWh, significantly exceeding the underground's 1731.9 kWh by 118.1%. In the cooling phase, the underground model logged gains of 1318.8 kWh, surpassing the above-ground model's 501.4 kWh by 162.1%.

With reference to the models in section 4.2 and 4.4 , although these results have identified the energy efficient potential of an underground building when compared with above ground building, it was fundamental to consider the importance of the unique thermal mass properties in shaping the energy efficiency dynamics of the specific underground and above ground small office models. Thermal mass pertains to a material's ability to absorb, store, and then release significant amounts of heat.

An important point to highlight with reference to 2.5.1 was those buildings with a high thermal mass, can regulate temperature fluctuations, absorbing surplus heat during the day and gradually releasing it at night, thus ensuring more consistent indoor temperatures. As the models in this study were relatively small when compared to larger buildings, the results may be somewhat different. It was crucial to understand that these results are exclusive to the defined dimensions of the above and underground models in these findings. In larger buildings, the impact of thermal mass could potentially be more pronounced, either augmenting the observed benefits or introducing complexities not evident in this study. Overall, underground buildings, as evidenced by the study, offer a range of advantages over their above ground counterparts.

5 FINAL REMARKS

5.1 Conclusion

Based on the study's data, underground buildings offer distinct advantages in terms of energy efficiency and indoor thermal comfort. Their ability to naturally regulate indoor humidity and use thermal mass properties significantly contributes to their energy-saving potential. However, challenges like ventilation need careful consideration in underground designs. Despite these concerns, the potential benefits of underground construction are evident. As the world seeks sustainable construction solutions and energy conservation, the results from this study present a strong case for considering underground buildings. The construction industry would benefit from these findings, where refining the underground building designs and adopting these methods could promote a more energy-efficient future.

5.2 Limitations of this study

This study encountered multiple limitations which are pivotal in contextualising its results. Central to these was the model's specific dimensions, a modest 9m x 6m x 3m, representing a total area of just 54m^2. Such a constrained size might not encapsulate the intricacies of larger or varied building structures.

Additionally, the study was restricted to just one depth for the underground building, and the same building shape was maintained throughout the analysis, which might not reflect the diversity of actual construction scenarios. There's also the matter of the number of occupants, which was kept constant, potentially not reflecting varied occupancy scenarios in real life settings. The study's concentration on a single climate in its hourly analyses could be seen as a limitation, potentially skewing results away from broader applicability.

Only four parameters were chosen for the analysis, out of a vast array of key parameters that influence energy performance, which might not present a comprehensive view of real-world scenarios. Sensitivity analyses were not conducted extensively; changes in insulation properties, for instance, were not explored. Given the use of the Esp-r software, limitations might arise from a combination of the software's intrinsic constraints and a lack of exhaustive expertise on the user's part.

The study's time-bound nature could have omitted key data insights which might emerge over extended periods. An important point is, since only one individual was involved in the entire analysis, the possibility of user error or oversight could not have been completely ruled out. While the modelling process accounted for multiple uncertainty and design parameters, real-world applications might present unforeseen challenges not represented in this study.

5.3 Direction for future investigations

For future studies, it would be beneficial to undertake more detailed investigations. A starting point would be to conduct hourly calculations over an annual dataset, enabling a deeper understanding of the intricacies and variations in hourly data across different months. Additionally, while Chicago offers a temperate climate perspective, expanding the study to other climates, specifically one that's notably hot and another that's distinctively cold, would provide a broader understanding of building performances.

There's also a need to incorporate a greater number of occupants, which would allow us to simulate and analyse the effects of varied human interaction and occupancy rates on energy consumption and indoor comfort. Exploring different building types and materials would be essential to understand the diverse behaviours associated with thermal mass more comprehensively. Lastly, evaluating various ventilation systems would help shed light on the unique characteristics and benefits each might present in terms of energy efficiency and indoor air quality.

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APPENDICES

Appendix 1 – Gantt Chart