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Deanship of Graduate Studies and Scientific Research

Master of Architecture – Sustainable Design

**An Integrated Passive System to Optimize Thermal Comfort and Indoor Air
Quality: A Case Study in Palestine's Hot-Arid Climate**

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Thesis submitted in partial fulfillment of the requirements of the degree

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An Integrated Passive System to Optimize Thermal Comfort and Indoor Air Quality: A Case Study in Palestine's Hot-Arid Climate

Katrina Yousef Hamadneh

ABSTRACT

The reintroduction of earthen architecture in Jericho, in the hot-arid Jordan Valley of Palestine, offers a low-energy alternative to conventional construction, yet the thermal and air-quality performance of Compressed Earth Block (CEB) buildings in this climate remains largely unquantified. This thesis evaluates an integrated passive system in which thermal mass, envelope design, ventilative cooling, and operational control are optimized together to deliver thermal comfort and indoor air quality during a representative summer design week. Combining field monitoring with a calibrated DesignBuilder model, the study follows a seven-phase optimization across three representative spaces, a daycare, an office, and a residence, assessed against the ASHRAE 55 adaptive comfort limit and the EN 16798-1 Category II criteria. The results characterize the earthen mass as a heat modulator rather than a heat rejecter: it damps the outdoor swing, holding the indoor air temperature to a daily range of about 2 °C against 11 to 14 °C outdoors, but underperforms wherever a dominant load, an exposed roof or unshaded glazing, enters continuously. This yields a load-sequencing principle, in which the dominant load is mitigated first and the mass then modulates what remains. A 29.5 cm CEB wall with 5 cm of exterior insulation on all external walls carries most of the available damping, while a reflective roof and reduced glazing address the governing solar and roof loads. A climate-responsive control framework governs operation on three signals, outdoor temperature, occupancy, and indoor operative temperature, deploying cross-ventilation as the primary mode, night flushing where continuous occupancy allows, and direct evaporative cooling through the hot, dry afternoon. Under this framework, the integrated system kept all occupied hours below the 80% comfort limit, with mean operative temperatures of 28.2–29.1 °C and CO₂ concentrations of 693–1207 ppm, within EN 16798-1 limits. Compared with conventional cavity-brick and stone-clad walls, the optimized earthen envelope achieves comfort with fewer interventions. The framework holds comfort and air quality by passive, low-energy means, reducing to a fixed schedule occupants can operate by hand.

Keywords: earthen architecture; Compressed Earth Block (CEB); thermal mass; passive and ventilative cooling; direct evaporative cooling; thermal comfort; indoor air quality; hot-arid climate; Jericho, Jordan Valley.

نظام سلبي متكامل مستجيب للمناخ لتحسين الراحة الحرارية وجودة الهواء الداخلي: دراسة حالة في المناخ الحار والجاف في فلسطين

كاترينا يوسف حمادنة

المستخلص

يمثل إحياء العمارة الطينية في مدينة أريحا، الواقعة في غور الأردن ذي المناخ الحار الجاف في فلسطين، بديلاً منخفض الطاقة عن أساليب البناء التقليدية، إلا أن الأداء الحراري وجودة الهواء الداخلي لمباني الطوب الترابي المضغوط (CEB) في هذا المناخ ما زالا غير مُقيَّمين على نحوٍ كافٍ. تهدف هذه الأطروحة إلى تطوير وتقييم إطارٍ متكاملٍ مستجيبٍ للمناخ تُحسن فيه الكتلة الحرارية وتصميم الغلاف والتبريد بالتهوية والتحكم التشغيلي معاً، بوصفها منظومةً موحدةً تحقق الراحة الحرارية وجودة الهواء الداخلي طوال موسم التبريد مع تقليل الاعتماد على التبريد الميكانيكي. واعتماداً على الرصد الميداني إلى جانب نموذج محاكاة مُعائيرٍ في برنامج DesignBuilder، تتبّع الدراسة منهجية تحسينٍ تتابعيةً من سبع مراحل عبر ثلاثة فضاءاتٍ تمثيلية هي حضنة ومكتبٌ ومسكن، جرى تقييمها وفق حدّ الراحة التكيفية (ASHRAE 55) ومعايير الفئة الثانية من المواصفة EN 16798-1 الخاصة بمعدلات التهوية وتركيز ثاني أكسيد الكربون. تُظهر النتائج أن الكتلة الطينية تعمل كمُعدّلٍ للحرارة لا كطارِدٍ لها؛ إذ تُخمد التذبذب الخارجي فتُبقي درجة حرارة الهواء الداخلي ضمن مدى يوميٍّ يقارب 2°م مقابل 11 إلى 14°م في الخارج، غير أنها تعجز عن تحقيق الراحة حيثما دخل جِملٌ مهيمٌ بشكلٍ مستمر، كالسقف المكشوف أو الزجاج غير المظلل. وينتج عن ذلك مبدأ ترتيب الأحمال، إذ يُطرح الجِمل المهيم أولاً، ثم تتولّى الكتلة تعديل ما تبقى. وقد تبيّن أن جداراً من الطوب الترابي المضغوط بسماكة 29.5 سم مع 5 سم من العزل الخارجي على جميع الجدران الخارجية يحمل معظم قدرة التخمين المتاحة، في حين يعالج السقف العاكس وتقليل نسبة الزجاج الجِملين الشمسي والسقفي المهيمين. ويحكم إطارُ تحكّمٍ مستجيبٍ للمناخ التشغيل اعتماداً على ثلاثة مؤشرات هي درجة الحرارة الخارجية والإشغال ودرجة الحرارة الفعّالة الداخلية، فيوظّف التهوية المتقاطعة نمطاً أساسياً، والتهوية الليلية حيثما سمح الإشغال المستمر، ونظام تبريدٍ تبخيريٍّ مباشرٍ خلال فترة الظهيرة الحارة الجافة. وبمقارنة الغلاف الطيني المُحسن بجدران القرميد المجوّف والحجر السائدة في ممارسات البناء الحالية في أريحا، يبلغ الغلاف الطيني الراحة أبكر وتدخلاتٍ أقل وبهامشٍ أعمق. ويحافظ الإطار على الراحة وجودة الهواء المقبولة بوسائلٍ سلبية ومنخفضة الطاقة، ويُختصر إلى جدولٍ ثابتٍ يستطيع المستخدمون تشغيله يدوياً.

DECLARATION

I declare that the master's thesis entitled "An Integrated Passive System to Optimize Thermal Comfort and Indoor Air Quality: A Case Study in Palestine's Hot-Arid Climate" is my own original work, and hereby certify that, unless stated, all work contained within this thesis is my own independent research

and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

Katrina Yousef Hamadneh

Signature: _____

Date: _____

DEDICATION

I dedicate this work to my beloved mother, whose endless love, prayers, sacrifices, and unwavering faith in me have been my greatest source of strength. Your encouragement has carried me through every challenge, and this achievement would not have been possible without you.

To the memory of my beloved father, your values, guidance, and love continue to inspire me every day. I hope this accomplishment would have made you proud.

To my dear husband, thank you for your patience, constant support, and for standing beside me throughout this journey. Your encouragement gave me the strength to keep going, even during the most demanding times.

To my beloved children, you have been my greatest motivation. Every page of this thesis was written with the hope of making you proud and showing you that perseverance and hard work can turn dreams into reality.

Finally, to my family, thank you for your love, understanding, and continuous encouragement. Your belief in me has meant more than words can express.

This work is dedicated to all of you, with my deepest love and gratitude.

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Chapter 1

Introduction**1.1 Preface**

The building sector is responsible for a significant share of the global energy consumption and greenhouse gas emissions (GHG), with the built environment constituting about 32% of global energy consumption and contributing to 34% of Global CO₂ emissions based on the latest report published by the United Nations Environment Programme (UNEP) and the Global Alliance for Buildings and Construction (UNEP and GlobalABC, 2025). The buildings' substantial energy demand for heating, cooling, and power is largely met by fossil fuels, which are the largest contributors to global warming (United Nations, 2026).

As a result of global warming, rising temperatures, rapid urbanization, and population growth, demand for cooling in the Middle East and North Africa (MENA) region is increasing substantially, potentially increasing by about 50% by 2040 and resulting in even higher GHG emissions (Climate Information Transparency in the MENA Region, 2023). Regions characterized by hot-arid climates, such as parts of the MENA region, face some of the highest climate change risks globally, like increased aridity, decreased rainfall and rising temperatures leading to frequent heat waves and heat stress conditions, which are intensified by poor resource management and inadequate infrastructure (Mohammed Qasem and Scholz, 2025; Khaled Sulaiman, 2025). To cope with these extreme events, people in hot-arid regions tend to rely on mechanical air-conditioning systems for cooling to maintain acceptable thermal comfort, thereby compromising indoor air quality due to insufficient ventilation and fresh air supply (Ahmed et al., 2021). While efficient natural ventilation can dilute indoor contaminants and improve IAQ, in hot arid regions, bringing hot air into the interior space degrades thermal comfort and increases cooling loads (Kakosimos, 2025).

Although the trend in adopting air conditioning systems is increasing due to rising temperatures in developing countries, it remains inaccessible to many households due to economic constraints, unreliable electricity supply, and inadequate energy infrastructure, leaving them vulnerable to heat stress in poorly performing buildings without any sustainable measures (Davis et al., 2021). This challenge is particularly critical in resource-constrained regions, like Palestine, where the energy demand of the building sector accounts for 55% of overall energy demand, and the residential sector accounts for 45%, which mostly relies on electricity, and is expected to increase approximately 70% between 2030 and 2050 (Ersoy et al., 2022). The growing energy demand puts higher pressure on

already limited and heavily constrained energy infrastructure. These challenges are further exacerbated by inefficient energy policies, limited governance mechanisms, and the absence of energy-efficient building standards, making them unable to handle peak energy loads, resulting in increased incidences of power outages and energy insecurity (Hamed and Peric, 2020; Shamroukh and AbuAlZulf, 2023). Therefore, transitioning to sustainable and environmentally friendly solutions to mitigate heat, especially in the hot arid region in Palestine, is essential for both human well-being and environmental sustainability. By reducing exposure to heat, improving indoor air quality and thermal comfort, and reducing buildings' high energy demand, adopting passive cooling strategies can enhance resilience to climate extremes. Effective solutions must moderate indoor temperature and provide sufficient fresh air, thereby achieving both indoor environmental quality (IEQ) and energy efficiency under extreme outdoor conditions.

1.2 Literature Review

1.2.1 Passive Cooling: Principles and Levels of Application

Passive cooling strategies aim to reduce building energy consumption by cooling the building using "ambient cooling sinks," natural or environmental elements that absorb and dissipate heat, such as water, sky, air, and building materials (Guerrero Delgado et al., 2020).

For passive cooling to be effective, it must be applied at three levels. The first is the "heat protection" layer, which shields the building from direct solar radiation through shading and thereby reduces heat gain. The second is the "heat modulation" layer, which moderates heat gain using materials that store heat and release it later through free cooling, such as thermal mass. The third is the "heat dissipation" layer, applied when the first two layers are insufficient to mitigate heat; this approach dissipates the remaining heat to the appropriate environmental heat sink, whether the sky, water, or air (Bhamare et al., 2019).

Adopting and combining appropriate passive cooling strategies to achieve thermal comfort requires an understanding of the local climate, as their effectiveness depends heavily on it (Panchabikesan et al., 2017). Furthermore, selecting cooling strategies that can adapt to variable and severe environmental conditions is vital for maintaining thermal comfort and enhancing resilience to climate extremes (Zhang et al., 2021).

1.2.2 Thermal Comfort and Indoor Air Quality in Naturally Ventilated Buildings

Buildings play a key role in creating comfortable interiors and a healthy indoor environment, particularly as people spend most of their time indoors. Among building elements, the building envelope largely governs energy gains and losses in the interior space and is responsible for 20% to 50% of the energy consumed for cooling and heating (Elnabawi et al., 2024). Ensuring thermal comfort and indoor air quality (IAQ) is therefore a vital concern.

Thermal comfort refers to a state of agreement with the thermal conditions of the environment, shaped by physiological, physical, and psychological factors that govern heat exchange between the body and the environment (Seyit and Umuroğulları, 2018). Several models are available for its assessment. The most widely used is the Predicted Mean Vote (PMV) model, developed by Fanger, which predicts the average thermal sensation from six parameters: air temperature, mean radiant temperature, relative humidity, air velocity, clothing insulation, and metabolic rate (Gilani et al., 2015). A drawback of this model is that it is better suited to mechanically controlled indoor environments (Zhao et al., 2021). The adaptive thermal comfort model is more appropriate for naturally ventilated environments, where occupants tolerate wider temperature ranges through behavioral, physiological, and psychological adaptation (Hoof et al., 2010).

IAQ is closely linked to thermal comfort. Both can be achieved through adequate ventilation, which removes and dilutes airborne pollutants while acting as a heat dissipation layer that provides cooling and humidity control (López Plazas and Sáenz de Tejada, 2024). CO₂ and pollutant concentrations are the indicators most commonly used to characterize IAQ. Organizations including the International Organization for Standardization (ISO), the European Committee for Standardization (EN), the World Health Organization (WHO), and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) have issued guidelines on acceptable maximum concentrations of CO₂ and pollutants, together with recommended ventilation rates for healthy indoor environments (López Plazas and Sáenz de Tejada, 2024).

Ma et al. (2021) identified the variables common to both thermal comfort and IAQ. These comprise outdoor conditions, including air temperature, wind, humidity, and pollutants; the physical and spatial characteristics of the interior space together with the thermal properties of its materials; and, most critically, the "operational variables," which include indoor air temperature,

volume flow rate, air density, contaminant concentration, number of occupants, exposure time, and ventilation rate. In a hot-arid climate, the challenge is to provide optimized natural ventilation while minimizing energy consumption and discomfort, particularly when the outdoor air is hot (Kakosimos, 2025).

1.2.3 Passive Cooling Strategies in Hot-Arid Climates: International Evidence

Recent international studies have investigated the effectiveness of passive cooling strategies in improving energy efficiency and achieving thermal comfort in hot-arid climates. Hu et al. (2023) reviewed empirical studies published between 2000 and 2021 covering thirty passive strategies tailored to hot climates. They developed a framework identifying the six most effective strategies to guide low-cost passive cooling adoption, emphasizing the role of the building envelope, walls, roofs, and windows, alongside optimized cross-ventilation in reducing cooling demand. Ergün and Bekleyen (2024) systematically identified the passive cooling strategies traditionally employed in hot and dry climates and classified them into heat-protection and heat-dissipation methods. They highlight thermal mass as an effective heat-protection strategy, and natural ventilation, particularly when combined with evaporative cooling, as the most widely used and efficient heat-dissipation strategy.

Thermal mass and night ventilation

Benoudjafer (2022) and DeKay and Brown (2013) emphasize the role of high thermal mass and night ventilation in enhancing thermal comfort in hot-arid climates. They note that although thermal mass can reduce daily temperature swings and delay heat transfer during the day, it must be cooled at night through ventilation, which is effective only when outdoor temperatures fall below indoor temperatures. Where outdoor conditions are unfavorable, evaporative cooling can assist night flushing and allow the thermal mass to be effectively discharged.

The converse also holds. Sun et al. (2022) demonstrated the reverse effect of thermal mass in hot-arid climates when effective night cooling is not provided, leading to increased overheating hours, whereas adopting night cooling achieved up to a 30% reduction in overheating hours. Thermal mass, in other words, is only as effective as the ventilation regime that discharges it.

Coupling thermal mass with insulation

To further improve the thermal performance of thermal mass, it must be coupled with thermal insulation, particularly on the exterior face of the wall, in order to minimize the heat reaching the mass. Rodrigues et al. (2025) studied a villa in the hot-arid climate of Saudi Arabia and showed that combining thermal mass with thicker exterior insulation (a lower U-value) achieved the greatest reduction in cooling loads, but produced higher interior temperatures than thinner exterior insulation. Coupling thermal mass with insulation and appropriate ventilation strategies is therefore essential, and the optimum insulation thickness cannot be established independently of the ventilation regime.

Ventilation mode, wind catchers, and evaporative cooling

Ahmed et al. (2021) evaluated the effectiveness of natural ventilation strategies in warm climates, focusing on their capacity to deliver thermal comfort and indoor air quality during heat waves. They found that cross ventilation alone is insufficient to meet these challenges, whereas wind catchers combined with solar chimneys and evaporative coolers achieved promising results by increasing airflow rates and pre-cooling the incoming air. These combined strategies satisfied the recommendations of ASHRAE 55 and ASHRAE 62 when the outdoor temperature remained below 42 °C.

Alwetaishi et al. (2020) investigated thermal comfort in historical buildings in Saudi Arabia, examining the effects of thermal mass, orientation, and ventilative cooling. They found the west and south orientations to be the least favorable. Thermal mass produced only a slight reduction in indoor temperatures and energy loads but improved thermal comfort during summer, while evaporative cooling achieved up to a 4 °C drop in indoor temperature, reinforcing the role of thermal mass.

Taken together, these studies indicate that no single strategy is sufficient in a hot-arid climate. The evidence points consistently toward an integrated combination of high thermal mass, correctly positioned insulation, a ventilation mode capable of delivering adequate airflow, and evaporative pre-cooling when outdoor air is too hot for direct night flushing.

Control strategies for ventilative cooling

The effectiveness of night ventilation for cooling depends on three groups of factors: weather conditions, including relative humidity, wind, and diurnal temperature variation; building parameters that support night cooling, such as thermal mass and thermal inertia; and optimized operation, including appropriate operating hours, ventilation mode, airflow rate,

and control strategy (Darmanis et al., 2020). While the first two groups are well established, the control strategy, whether manual or automated, plays a decisive role in realizing the available performance.

Most buildings, particularly residential ones, rely on manual ventilation control, which is strongly influenced by occupant behavior and can lead to inappropriate operation, such as failing to exploit favorable outdoor conditions. This highlights the limitation of relying on occupants alone to manage passive cooling strategies effectively (Saber et al., 2021).

Recent studies have increasingly demonstrated the advantage of automated control over manual operation. Sarna and Ferdyn-Grygierek (2025) assessed manual and automatic natural ventilation control strategies in which the control logic was based on favorable outdoor conditions. Their results confirmed the superiority of automatic control in achieving thermal comfort and effective ventilation rates, with manual control at times worsening interior thermal conditions. Sorgato et al. (2016) similarly established the importance of a control logic for natural ventilation, particularly when combined with thermal mass; their simulations showed that improper occupant ventilation behavior can increase energy use and discomfort hours, whereas automated ventilation achieved the highest number of comfort hours. These findings underline the need to treat operational control as an integral component of any passive cooling system rather than as an implementation detail.

1.2.4 The Palestinian Context

The challenges outlined above are more acute in resource-constrained developing regions, where inadequate passive adaptation of buildings to local climatic conditions has produced heavy reliance on energy-intensive cooling systems to maintain comfort.

Palestine, with its diverse climatic zones, including the hot-arid climate of the Jordan Valley , generally lacks sustainable practices in the building sector. As a consequence of the political situation, limited awareness, economic pressure, and restricted professional engagement, low-quality buildings are constructed with no architectural identity and poor thermal performance. The same construction prototype is applied across all climates regardless of its suitability, driving higher cooling and heating demand (Sabboubbeh et al., 2019).

The codes intended to address this have proved inadequate. Camur and Abdallah (2021) found that the energy-efficiency code developed in 2004 by the Palestinian Ministry of Local Government specified considerably higher U-values than international codes and was recommended for all seven

Palestinian climate zones irrespective of its effectiveness. Haj Hussein et al. (2022) evaluated a range of Palestinian and international energy-efficiency codes focused primarily on envelope U-values across different Palestinian climate zones. Their study found that adding insulation in accordance with the Palestinian green building guidelines achieved the largest reduction in heating energy demand across all climate zones, reaching 83%. In the hot-arid summer and warm winter zone, a cooling-dominated climate, however, adding insulation according to every code evaluated had a negative effect, slightly raising cooling energy demand. This result underlines that envelope insulation alone is not a solution in the Jordan Valley and that passive cooling strategies are required. In a further attempt to reduce building energy demand, the Palestinian Energy and Natural Resources Authority (PENRA) proposed a sectoral plan to decrease consumption and enhance comfort, but this effort failed to incorporate energy-saving measures or adequate building energy codes (Alsayed and Tayeh, 2019).

Very few studies have evaluated passive cooling strategies for improving indoor environmental quality and reducing cooling loads in Palestine, and fewer still in the hot-arid zone. Samaro et al. (2024) assessed how typical residential buildings across three Palestinian climate zones, including Jericho, respond to current and future climate scenarios. The study found that conventional, low-efficiency buildings are highly susceptible to heat gain, resulting in uncomfortable indoor temperatures, particularly in Jericho, where conditions are further exacerbated under future warming. The authors assessed several mitigation strategies drawn from the Medium Energy Efficiency Buildings (MEET) guidelines, including envelope insulation, external shading, and cool walls and roofs, and found these insufficient to achieve thermal comfort in Jericho compared with the moderate climate zones. This finding points directly to the need for the integrated, ventilation-led strategies identified in the international literature rather than envelope measures alone.

In parallel, recent years have seen a revival of earthen architecture in the Jordan Valley, supported by local and international initiatives. Earthen architecture offers environmental, social, and economic benefits that are especially relevant in hot-arid climates, owing to its high thermal mass and affordability, as well as its role in strengthening architectural heritage and identity (Alatawneh and Germanà, 2016). It therefore provides a construction system in which the thermal mass required by the international evidence is already present, but whose thermal performance in the Jericho climate, and its coupling with ventilation, control, and evaporative cooling, has not been quantified.

1.3 Current Situation and Gap of Knowledge

Despite the growing body of research on passive cooling strategies to improve IAQ and thermal comfort, these two topics are often investigated separately, as many existing studies on passive cooling strategies focus on their effect on thermal performance, thermal comfort, and energy reduction but overlook IAQ metrics or neglect ventilation performance altogether, potentially misleading design recommendations. This and several critical gaps remain, particularly in the context of the hot-arid climate zone in Palestine, where buildings most often lack climate-responsive strategies that operate under energy and infrastructure constraints. These gaps shed light on the need for a more context-specific and performance-based approach that holistically evaluates passive cooling strategies and their combined impact on thermal comfort and indoor air quality.

Existing international studies on passive cooling strategies, such as thermal mass, and ventilative cooling strategies, such as wind catchers with evaporative cooling, have demonstrated promising potential in reducing cooling loads and enhancing thermal comfort; their applicability and performance within the hot arid climate in Palestine remain underexplored.

At the national level, the Ministry of Local Government (2004) published guidelines for energy-efficient building design. The document used Mahoney tables as a key climate analysis tool for all the 7 climates in Palestine to obtain design recommendations. The document ultimately provides general recommendations for all climates, including hot arid climates. Among these recommendations are using high thermal mass, controlled ventilation, shaded courtyards, minimized openings, ventilated double walls and roofs, and others. However, a key limitation of this document is that it's too general, and there is a lack of quantitative evaluation or performance validation. Another critical gap is the lack of post-occupancy evaluation of earthen buildings in Palestine. Although it's known for its good thermal properties, affordability, and cultural significance, most studies in Palestine focus on the theoretical advantages without conducting empirical assessments to validate and refine earthen and passive construction techniques in the local context.

These limitations are of great influence in hot arid regions such as the Jordan Valley in Palestine, which experiences high temperatures, overheating, and limited energy resources, necessitating the development of resilient, low-energy, and climate-adaptive buildings. Therefore, there is a clear need to advance knowledge in context-specific passive cooling and air quality management within the hot arid climate of Palestine, by systematically investigating the adaptability and combined performance of passive cooling strategies. This includes identifying the optimal combined strategies

and operational modes that would enhance thermal comfort and indoor air quality, in addition to reducing cooling loads.

1.4 Research Significance

This research highlights a critical gap in the literature on achieving thermal comfort and IAQ simultaneously through environmentally friendly, energy-efficient, and passive strategies within the hot-arid climate of Palestine. This study explores the combined potential of adopting thermal mass through improved CEB thermal performance and optimized ventilative cooling strategies, and contributes to the knowledge regarding buildings that function as climate-responsive systems. From a scientific perspective, this research contributes to developing a more holistic approach for assessing buildings' performance in hot arid climates, taking into consideration both thermal comfort and indoor air quality.

Locally, the study is highly relevant to Palestine, especially the Jordan Valley, where extreme temperatures, energy insecurity, and inadequate building practices exacerbate indoor discomfort. By providing applicable and adaptable strategies that respond to local climate and socio-economic conditions, this study addresses a pressing local need for context-specific building solutions. Moreover, to the best of the authors' knowledge, this research is considered among the very few studies to comprehensively assess the performance of earthen buildings in the hot-arid climate of Palestine, especially in relation to thermal comfort and indoor air quality.

Ultimately, this research enhances sustainable building practices by addressing thermal comfort and air quality challenges, particularly for constrained developing regions susceptible to overheating and energy shortage, thereby achieving healthier, more resilient indoor environments in hot climates facing climate change and environmental challenges.

1.5 Research Questions & Hypothesis

Earthen building envelopes, incorporating a combination of thermal mass and ventilative cooling strategies, can achieve improved thermal comfort and indoor air quality, along with reduced cooling energy demand, compared to conventional building configurations in the hot-arid climate of the Jordan Valley in Palestine. By optimizing the envelope configuration and operational modes, these passive strategies can provide superior performance compared to adopting each strategy separately, ultimately achieving a holistic, energy-efficient system that can minimize thermal discomfort and provide adequate IAQ. Based on the presented hypothesis, the research question is: How can an integrated passive system combining thermal mass and ventilative cooling be optimally designed

and operated to simultaneously improve thermal comfort and indoor air quality in earthen buildings within the hot-arid climate of the Jordan Valley in Palestine? Thereby, the following sub-questions were raised:

1. What are the thermal performance characteristics of existing earthen buildings using CEB in the Jordan Valley?
2. What is the optimal wall configuration for earthen buildings using compressed earth blocks (CEB), in terms of layer thickness and insulation placement, to maximize thermal performance and effectively enhance the heat-modulation function of the wall?
3. What control logic and operational strategies can be established to define the optimal deployment and switching conditions between ventilative cooling systems, including wind catchers, evaporative cooling, and cross ventilation, under varying outdoor climatic conditions, to simultaneously ensure thermal comfort and acceptable indoor air quality?
4. How does the optimized earthen building envelope perform in comparison with the conventional envelope construction commonly used in Jericho under the same integrated passive cooling and operational control framework, in terms of thermal comfort and indoor air quality?

1.6 Research Objectives

The thesis aims to evaluate and optimize the performance of earthen buildings coupled with ventilative cooling strategies, as a holistic approach for improving thermal comfort and indoor air quality (IAQ) in buildings located in the hot-arid climate of the Jordan Valley in Palestine. Furthermore, the study seeks to build on recent efforts in Jericho to reintroduce earthen architecture as a viable, energy-efficient, and environmentally sustainable alternative to conventional construction methods. It seeks to integrate passive cooling strategies into a comprehensive building system that enhances thermal performance, achieves adequate ventilation, and reduces reliance on energy-intensive mechanical cooling, therefore contributing to enhanced indoor environmental quality and reduced energy demand. From this perspective, the research objectives are as follows:

This thesis aims to develop and evaluate an integrated building system tailored for the hot arid climate, in which thermal mass, envelope design, ventilative cooling strategies, and operational control are all optimized to function as a unified framework that assesses the capability of each strategy to complement the limitations of the others, thereby forming a comprehensive, energy-efficient and climate-responsive solution to achieve thermal comfort, maintain indoor air quality,

and enhance overall building performance. Throughout this thesis, "optimization" and "optimal" denote a systematic, sequential process of parametric evaluation, in which each phase tests a defined set of configurations under the same performance indicators and carries forward the best-performing one to the next phase, rather than a mathematical optimization algorithm searching for a single globally optimal solution. The rationale for this sequential approach, rather than a simultaneous multi-objective method, is set out in Section 4.2.7. The sub-objectives are as follows:

1. To assess the current thermal performance of existing earthen buildings constructed using compressed earth blocks (CEB) in the Jordan Valley.
2. To optimize earthen building envelope configuration by assessing the influence of wall thickness and insulation placement on thermal performance and thermal mass effectiveness.
3. To evaluate multiple ventilative cooling strategies and develop a control framework for their optimal operation and switching under varying climatic conditions to improve thermal comfort, IAQ.
4. To comparatively assess the optimized earthen envelope against the conventional envelope construction prevalent in Jericho, as documented through the field survey of local construction practice, under identical geometry, operational schedules, and passive cooling control conditions, in order to quantify the performance benefit of earthen construction relative to current local building practice.

1.7 Research Limits

The study is conducted in the city of Jericho, located in the Jordan Valley, which represents one of the most extreme hot-arid climate zones in Palestine, characterized by high temperatures and cooling-dominated conditions. It was selected for its severe climate as a representative of hot arid zones with a similar climatic context. It was also selected due to the city's increasing interest in CEB, with existing examples of both older and recent applications available in the city.

The study is limited to small-scale buildings. In this research, the term refers to load-bearing buildings of no more than two storeys and approximately 300 m² of total floor area, with a shallow plan in which every occupied space has direct access to at least one external façade. The case study, the Aqbat Jabr women's centre, falls within this class at 289.5 m² distributed over two levels.

The buildings addressed are community and small institutional facilities of the type delivered by the UNESCO earthen architecture programme in the Jordan Valley, together with the small residential units associated with them. The case study combines three such uses within one

building: a daycare and nursery, a small office, and a residential suite. These uses share modest occupant densities, low equipment loads, and a predominantly daytime occupancy pattern, with the exception of the residential unit, which is also occupied overnight. Building uses characterized by continuous or high-density occupancy, substantial equipment loads, or restricted operation of openings fall outside the scope of this study.

Furthermore, the analysis focuses exclusively on the cooling season, as the research aims to optimize passive cooling performance and indoor environmental conditions during periods of greatest thermal stress.

1.8 Research Limitations

Indoor air quality is assessed primarily based on ventilation rates and carbon dioxide (CO₂) concentration as key indicators. However, the study does not account for the presence of outdoor air pollutants, such as dust, particulate matter, and other contaminants. These factors were excluded as the study focuses on ventilation-based assessment without incorporating filtration or purification methods, which is beyond the scope of this study.

Beyond the exclusion of outdoor pollutants noted above, the CO₂ assessment carries two limitations tied to occupancy. The building stands empty today, so the model was calibrated on measured indoor temperature under free-floating conditions, with no occupants present. Its CO₂ output rests on assumed generation rates and occupancy schedules, and no measured CO₂ exists to validate it; the figures indicate ventilation adequacy rather than a calibrated prediction. The schedules come from former users, who recalled the approximate number of occupants in each zone and the hours each space was used when the building operated. Both headcount and timing are approximate.

In addition, evaporative cooling was evaluated at the performance level using a simplified, well-established, and reliable approach derived from the Givoni model rather than detailed CFD analysis. The study assessed whether cooling the fresh-air supply at the required ventilation rate could maintain thermal comfort during occupied hours. The detailed design and architectural integration of the system, including the evaporative pad housing, duct routing, and installation within the building, were beyond the scope of this research and are left for future work.

1.9 Research Structure

This research is divided into five parts as follows:

First part: the conceptual study of the thesis, covered through Chapter 1. It introduces the research and the conceptual basis on which it is built, namely the justification for reintroducing earthen architecture as an energy-efficient, climate-responsive alternative to conventional construction in the hot-arid Jordan Valley in Palestine, and the need to secure thermal comfort and indoor air quality by passive means. It presents the research background, significance, problem, hypothesis, questions, objectives, limits, and limitations, and ends with a complete overview of the research structure.

Second part: the theoretical study, presented in the second and third chapters and dedicated to the literature review and definitions. Chapter 2 reviews earthen and compressed earth block (CEB) construction, the role of thermal mass, passive and ventilative cooling strategies including cross ventilation, night flushing, wind catchers, and evaporative cooling, and the assessment of indoor air quality, situating the study within existing research and identifying its gap. Chapter 3 establishes the theoretical framework of the dynamic thermal behaviour of the building envelope, defining the thermal-mass indicators, the decrement factor and the time lag.

Third part: the research methodology, presented in Chapter 4. It covers the research type and data-collection methods, the case-study area and its selection criteria, the field measurement instruments, the simulation and validation approach in DesignBuilder, and the integrated seven-phase sequential optimization framework that structures the analysis.

Fourth part: the case study and analytical study, covered in the fifth and sixth chapters. Chapter 5 describes the earthen buildings of Jericho, including the UNESCO-supported projects and the surveyed local construction practice that provides the conventional reference. Chapter 6 reports and discusses the results, from the measured thermal performance and model validation through the seven optimization phases to the comparative assessment of the optimized earthen envelope against the conventional construction of Jericho.

Fifth part: the conclusions, presented in Chapter 7, which answers each research objective and question, draws out the generalizable findings and design principles, and sets out the contributions, practical implications, limitations, and directions for future work.

Passive Cooling & Indoor Environmental Quality Framework

2.1 Preface

Building on the challenges outlined in Chapter 1, the focus moves from problem identification to the exploration of passive strategies tailored for hot arid climates, their control mechanisms, and their roles in achieving indoor environmental quality essential for occupant well-being. Passive cooling covers a range of strategies that utilize natural processes, where some strategies can perform as a heat modulation layer, like thermal mass, and others as a heat dissipation layer, such as natural ventilation, and essentially, how to make them complement each other. From this perspective, this chapter establishes the theoretical foundation needed to evaluate and optimize ventilative cooling strategies in buildings and their contribution to IEQ, with particular focus on how these strategies can be controlled and coordinated under varying environmental conditions. The chapter ultimately leads to a control-oriented understanding of ventilative cooling, which forms the basis for the development of an integrated and optimized cooling approach in hot arid climates.

2.2 Thermal Comfort in Naturally Ventilated Buildings

Among the analytical models for thermal comfort, the two most popular thermal comfort approaches are the steady state and adaptive models (Ma et al., 2021). The steady state model, also known as Fanger's PMV most widely used in building design standards such as ISO 7730 and ASHRAE 55. This model depends on heat exchange between the human body and the environment, and the main outputs are PMV, which represents the predicted mean vote of how cold or hot people feel on a scale from -3 to +3, and PPD, which presents the predicted percentage of dissatisfied people. The key input variables include air temperature, mean radiant temperature, air velocity, humidity, metabolic rate, and clothing insulation. Even though this model is very popular, it's limited in naturally ventilated buildings as it can significantly over- or underestimate comfort, because it was based on lab conditions and assumes steady conditions like mechanically ventilated spaces, unlike naturally ventilated spaces (Cheung et al., 2019).

Fanger and Toftum (2002) addressed the limitation of the PMV model for naturally ventilated buildings and proposed an extended PMV Model suitable for hot climates, also known as (ePMV). The model is a modification of PMV that multiplies it by an expectancy factor (ep), which accounts for occupants' adaptation. The value of ep ranges between 0.5 and 1 and depends on the duration of warm weather, the existence of air conditioning, and occupants' expectations. However, it is

sensitive to the choice of e_p , which can lead to over- or under-prediction (Ma et al., 2021). Yao et al (2009) developed the adaptive predicted mean vote (aPMV), where they added an adaptive coefficient β to the original PMV, which combines psychological, behavioral, and environmental adaptation to better represent naturally ventilated conditions. However, the adaptive coefficient is not universal and is highly climate-dependent and must be modified based on the environment, behavior, and building type (Enescu, 2017).

The adaptive comfort model departs from the heat-balance framework altogether and is based on real field conditions, unlike the PMV model. This model links acceptable indoor operative temperature to outdoor temperature and reflects occupant adaptation behavior like opening windows and changing clothes, and also depends on long-term exposure, as people tend to adapt to their environments. This model has been incorporated into ASHRAE Standard 55 as the adaptive comfort method for free-running buildings in warm climates (Halawa and van Hoof, 2012). The standard sets three conditions for its use: no mechanical cooling in operation, occupant metabolic rates between 1.0 and 1.5 met with freedom to adjust clothing, and a prevailing mean outdoor temperature between 10 °C and 33.5 °C (ASHRAE, 2023), as shown in Figure 2-1. When the operative temperature exceeds 25 °C, air speeds above 0.3 m/s permit the upper acceptability limit to rise by 1.2 °C at 0.6 m/s, 1.8 °C at 0.9 m/s, and 2.2 °C at 1.2 m/s.

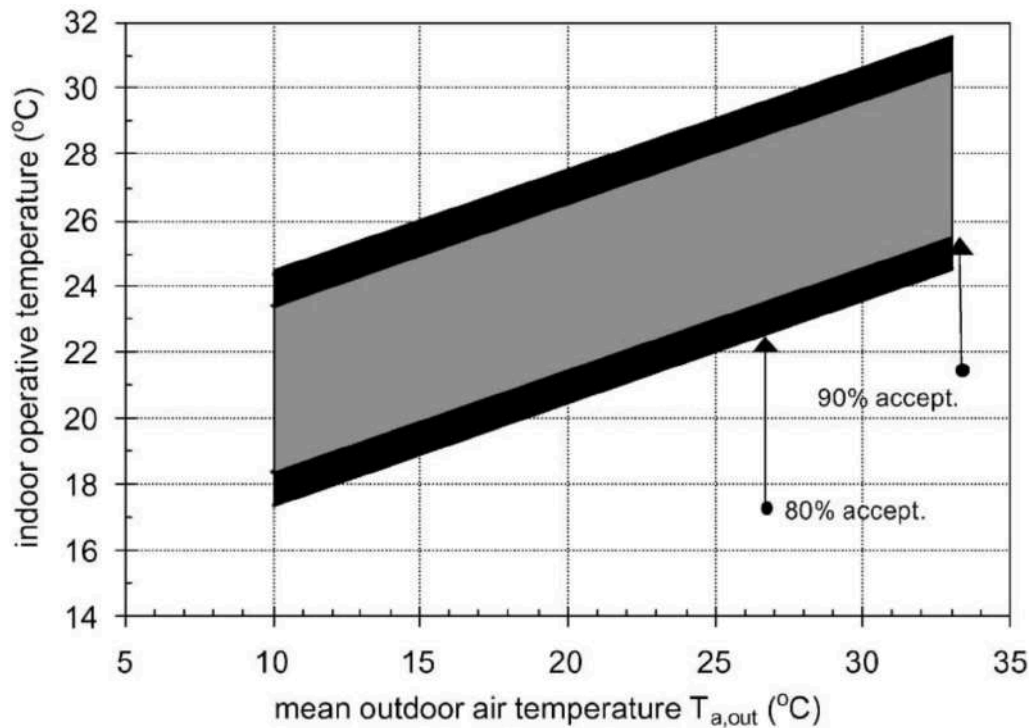


Figure 2-1: Acceptable ranges of indoor operative temperature for naturally ventilated buildings as a function of mean outdoor air temperature, according to the ASHRAE Standard 55 adaptive comfort model (de Dear and Brager, 2002).

The idea of adaptive thermal comfort is that it can have a wider range of comfort temperatures, and this range can be different in different locations and different climates, as it depends on the climate-responsive strategies used, occupant behavior, and outdoor climate. A lot of studies about field thermal comfort assessments have shown that the slope of the adaptive thermal comfort Equation was larger than the standard adaptive thermal comfort in hot-dry climates, as people can adapt to the local climate and stay comfortable at a wider temperature range, highlighting the importance and high potential of passive design in facilitating occupants' adaptation. An example study conducted by Yang et al. (2020), investigated the adaptive thermal comfort of residents in dry hot and dry cold climates in China. The study included field surveys for occupants' thermal sensation votes and filed measurement for indoor and outdoor environmental parameters, and established a linear relationship between indoor operative temperature and outdoor mean temperature to derive comfort limits. Their results showed strong adaptation, particularly for heat, where comfortable temperatures reached 34°C. They also identified the most effective strategies that helped occupants adapt were using semi-basements, thermal mass, night ventilation, and shading. In the hot arid-saharan climate of southern Algeria, the neutral temperature was found to be 31.5 °C and neutral humidity 20% in traditional adobe buildings. The newly developed comfort model was within the range of the ASHRAE model but 4°C higher, with 8% difference from the ASHRAE model regarding the relationship between outdoor and indoor comfort temperatures (Abdelkader et al., 2021). Based on Lamsal et al. (2023), naturally ventilated (NV) office buildings in different climates can have a wide comfort temperature ranging from 17.6°C to 31.2°C, and they concluded that comfort mainly depends on outdoor temperature and the adaptive behavior of the occupants; based on that, they derived an adaptive equation for NV buildings:

$$T_c = 0.43T_o + 14.93 \quad (2-1)$$

where T_c is the indoor comfort temperature (°C), T_o is the running mean outdoor temperature (°C), 0.43 is the regression coefficient, and 14.93 is a constant.

Another adaptive thermal comfort study was conducted by Singh et al. (2023) in the hot- humid climate of India, focusing on naturally ventilated offices. The study relied on a year-long field study, combining questionnaires and indoor measurements. Their investigation found that 80% of occupants were comfortable between 25°C and 30°C, and increasing the air velocity to 0.8 m/s can increase the comfortable limit to 32°C, highlighting the role of ventilation in improving thermal comfort sensation. They also noticed that occupants were less sensitive to the outdoor temperature variations, making the slope of the adaptive thermal comfort lower than the standard adaptive

ASHRAE-55. Kumar et al. (2016) outlined the critical effect of air speed on adaptive thermal comfort. The study developed new adaptive comfort zones on the psychometric chart based on a field study for the composite climate of India, which is characterized by a very hot summer. They found that more than 90% of comfort points lay outside the ASHRAE zone in summer under different air speeds. Based on this study, the comfort range when air velocity was lower than 0.2 m/s is between 18°C and 32°C, and with air velocity higher than 0.2 m/s up to 1.5 m/s, when using a fan, the comfort range was between 34 and 35°C, where the air velocity 1m/s found to be the most efficient. Across these studies, occupants living in hot-arid regions have been shown to tolerate temperatures higher than those permitted by the ASHRAE 55 adaptive model, and the findings are specific to their local climates and cannot be directly applied to Palestine. Since there is no Palestine-specific adaptive comfort model, the ASHRAE 55 adaptive model remains the most appropriate standard for assessing thermal comfort.

2.3 Indoor Air Quality and Ventilation Requirements

2.3.1 Indoor Air Quality Indicators and Standards

Indoor air quality is a key contributor to the quality of the indoor environment and to human health, as good indoor air quality reduces the risk of illness transmission and improves productivity and concentration. Poor IAQ is associated with increased concentrations of indoor pollutants such as carbon dioxide (CO₂), particulate matter, and volatile organic compounds (VOCs), which can lead to long-term health risks (Kakoulli et al., 2022).

Indoor air quality is typically evaluated using parameters such as ventilation airflow rate, air change rate (ACH), CO₂ concentration, air change effectiveness (ACE), and mean age of air (MAA) (Jomehzadeh et al., 2017). Several organizations, including ASHRAE and CIBSE, provide ventilation-related guidelines and threshold values for different building types based on factors such as building size, occupancy level, and building function (López Plazas and Sáenz de Tejada, 2024). Table 2-1 summarizes the criteria of the principal standards.

Table 2-1: ventilation and CO₂ criteria in the principal IAQ standards.

Standard	Scope	CO ₂ criterion	Ventilation rate requirement
ASHRAE 62.1-2022	Non-residential	No limit set; informative guidance suggests ~700 ppm above outdoor for odor acceptability	Breathing-zone rates by space type; offices 2.5 L/s per person + 0.3 L/s·m ²

ASHRAE 62.2-2022	Residential	None	Whole-dwelling: 0.15 L/s per m ² floor area + 3.5 L/s per bedroom + 1
EN 16798-1:2019	All buildings, four IEQ categories	Residential CO ₂ above outdoor (I / II / III): living rooms 550 / 800 / 1350 ppm bedrooms 380 / 550 / 950 ppm Non-residential: no CO ₂ design value; recommended operational setpoints (absolute) 800 ppm (classrooms, meeting rooms), 650 ppm (offices)	Residential Cat II: 2.5 L/s·person + 0.15 L/s·m ² Non-residential Cat II (lowpolluting): 7 L/s·person + 0.7 L/s·m ²

2.3.2 The Interaction between Indoor Air Quality and Thermal Comfort

Thermal comfort and IAQ are strongly connected, as occupants' perceptions of temperature and of air quality are correlated. In a field study of naturally ventilated buildings, Lamberti et al. (2024) found that higher CO₂ levels produced a warmer thermal sensation, lower thermal comfort, and a lower perceived sense of control, as occupants felt less able to adapt. They also observed that changing CO₂ levels affected both the perception of air quality and thermal comfort, and that the gap between the actual and the comfortable temperature widened.

2.3.3 Ventilation and the Comfort–IAQ Trade-off in Hot Climates

Ventilation plays a critical role in maintaining good IAQ by supplying fresh outdoor air and diluting indoor contaminants, and it also reduces energy demand and health risk. During the cooling season, when outdoor conditions are favorable, natural ventilation additionally provides a cooling effect that lowers the energy required to maintain comfort.

Its effectiveness, however, depends on delivering adequate thermal comfort and high indoor air quality at the same time. Research consistently shows that the two are interrelated and that improving one often comes at the expense of the other and of energy use (Escandón et al., 2025; Ahmed et al., 2021). Tognon et al. (2023) further show that the effectiveness of natural ventilation depends on the control strategy and the climate rather than on the ventilation type alone.

This trade-off is most acute in hot climates. Miao et al. (2023) found that admitting hot outdoor air through building openings can effectively improve IAQ and meet the required standards while significantly deteriorating thermal comfort. Strategies are therefore needed that

balance airflow against heat control, limiting ventilation to prevent overheating while maintaining rates sufficient for good IAQ.

2.3.4 Factors Governing the Effectiveness of Natural Ventilation

Achieving this balance requires several context-specific factors to be considered: the local climate, seasonal and diurnal conditions, the building type, its thermal inertia, and user behavior (López Plazas and Sáenz de Tejada, 2024). Technical factors including operating time, airflow rates, and control techniques also exert a significant influence on the efficiency of natural ventilation (Stasi et al., 2024; Darmanis et al., 2020). Ma et al. (2021) grouped the variables governing thermal comfort and IAQ into three sets: outdoor conditions (air temperature, wind, humidity, and pollutants), the physical and material characteristics of the space, and a third set they identify as most critical, the operational variables, comprising indoor air temperature, volume flow rate, air density, contaminant concentration, occupancy, exposure time, and ventilation rate.

2.4 Natural Ventilation: Mechanisms, Strategies, and the Comfort Trade-off

Natural ventilation depends on natural forces such as wind and the buoyancy effect to drive air movement into the interior space. Single-sided and cross ventilation are the most used strategies for natural ventilation induced by the pressure difference created by wind forces or temperature difference between indoor and outdoor, where wind creates positive pressure on the windward facade while negative pressure is created on the leeward facade, causing air to move from the high to lower-pressure zones. While stack ventilation is created by the rising hot air from the interior space, as it becomes less dense and lighter, and cooler, denser air enters through lower openings, producing buoyancy-driven airflow.

The opening configuration governs how much air these forces deliver, as Stasi et al. (2024) assessed the effect of cross ventilation using different window opening configurations, from all open to minimal openings, on the thermal performance of a case study building located in Ahmedabad, India, with a hot arid climate. They found that configurations with higher air change rates (71 ACH) achieved better adaptive thermal comfort, specifically during periods of moderate heat stress of a typical summer day, with a reduction in operative temperature of about 3.9 °C and a reduction of about 77.8% in discomfort hours on a typical cooling-period day, and by 3.1 °C and 31.3% on the hottest day. Another study developed a new indicator called minimum ventilation time (MVT) for achieving healthy IAQ (CO₂ levels) while minimizing the thermal counter effects of

natural ventilation based on the Thom discomfort index dedicated for single-sided, cross, and stack ventilation. Based on their simulations of 10 real homes in Barcelona (Mediterranean climate), they found that cross ventilation performed best, achieving the least required time to replace interior stale air during winter and summer for all opening %, requiring 3 to 7 minutes for 80% openings in spring, summer, and autumn, against 6 to 11 minutes for single-sided ventilation and 12 to 24 minutes for stack ventilation. They set healthy air quality at a 900 ppm annual average under Spanish regulation (CTE HS3) and flagged daily averages above 1000 ppm as poor ventilation. (López Plazas and Sáenz de Tejada, 2024).

Higher airflow improves air quality, but in a hot climate, it carries heat indoors, and the studies that measure both quantities show the tension directly. Ragab et al. (2025) investigated through simulation the effect of different ventilation strategies on CO₂ levels and thermal comfort in a case study classroom in the hot arid climate of Aswan. Their results showed that mixing air conditioning with one-sided ventilation was not sufficient to dilute indoor air, and continuously opening the windows deteriorated thermal comfort, specifically in summer, reducing the AC efficiency. While using cross ventilation only reduced the CO₂ levels significantly and highly increased the periods of thermal discomfort, while using only cross ventilation for 20% during breaks improved thermal comfort periods and reduced CO₂ levels, but was still not enough, and opening the windows for 60-minute intervals in summer, and 20 minutes in winter, held CO₂ within the 1000 ppm limit and added far less discomfort than continuous operation. Heracleous and Michael (2018) reached the same conclusion from the opposite direction, comparing four ventilation strategies: daytime-only, night-only, night with limited daytime (breaks), night with full daytime, and continuous 24-hour ventilation. The study was conducted for a typical classroom in Larnaca, Cyprus, and assessed their role in decreasing overheating hours during the summer period while ensuring adequate IAQ with CO₂ levels below 1000 ppm, in addition to their performance during future climate conditions. In scenarios with periods of no windows open, the door was kept open to ensure fresh air at a minimum rate of 8 l/s per person. Under the current climate, night-only ventilation performed best, cutting overheated occupied hours from 3–4% to 1–2% across orientations, while daytime-only performed worst. Under 2050s and 2090s projections, night ventilation alone could no longer hold comfort, and overheating exceeded the CIBSE limits, which points to the need for additional cooling as the climate warms. Control logic extends the same benefit beyond hot climates; Tognon et al.(2023) found that shifting toward natural ventilation cut sensible cooling demand by 31% in Venice, 24% in Rome, and 11% in Helsinki, while a Wells-Riley analysis showed airborne infection

risk reaching almost 85% in poorly ventilated cases, which well-regulated ventilation reduces. Table 2-2 compares the five studies by climate, method, ventilation strategy, and outcome.

Table 2-2: Ventilation and CO₂ criteria in the principal IAQ standards.

Study	Climate / location	Strategy & opening configuration	Metrics	Key quantitative finding	CO ₂ threshold used
Stasi et al. (2024)	Hot-arid / Ahmedabad, India	Cross ventilation; openings from full to minimal	Operative temperature, discomfort hours	Widest openings: −3.9 °C and −77.8% discomfort hours (typical cooling-period day); −3.1 °C and −31.3% (hottest day)	not assessed
López Plazas & Sáenz de Tejada (2024)	Mediterranean / Barcelona	Single-sided, cross, stack; MVT across opening %	Minimum ventilation time (CO ₂), Thom discomfort index	To clear stale air at ≥80% opening (spring–autumn): cross 3–7 min, single-sided 6–11 min, stack 12–24 min	900 ppm annual average (Spanish CTE HS3); >1000 ppm daily average flagged as poor
Ragab et al. (2025)	Hot-arid / Aswan, Egypt	AC + single-sided; cross; scheduled cross (breaks, 60 min)	CO ₂ , PMV, air temperature	Scheduled cross ventilation, 60 min in summer and 20 min in winter, held CO ₂ within limit with only a slight comfort penalty	1000 ppm (absolute)
Heracleous & Michael (2018)	Mediterranean / Larnaca, Cyprus	Daytime, night, night+breaks, night+full day, 24 h; door ≥8 L/s-person	Overheated occupied hours, CO ₂	Current climate: night-only cuts overheating from 3–4% to 1–2%; daytime-only worst. Future climate: night ventilation alone insufficient, overheating exceeds CIBSE limits	1000 ppm (BS EN 15251 Category II)
Tognon et al. (2023)	Cold and moderate / Venice, Rome, Helsinki	Natural-ventilation-dominant vs mechanical vs hybrid	Sensible/latent cooling demand, airborne infection probability (Wells-Riley)	Shift to natural ventilation cuts sensible cooling demand 31% (Venice), 24% (Rome), 11% (Helsinki); infection risk reaches ~85% in poorly ventilated cases	No CO ₂ limit; Wells-Riley infection probability

These studies show that ventilation effectiveness for thermal comfort and indoor air quality is governed more by duration and control strategy than by ventilation type alone, with scheduled cross ventilation giving the best balance between the two. In a hot-arid climate, though, favorable outdoor conditions do not always arrive when a space needs them, and the following sections turn to the passive strategies that extend natural ventilation past that limit.

2.5 Wind Catchers

2.5.1 Concept, Historical Evolution, and Typologies

Wind catchers are among the oldest passive ventilation strategies that leverage natural resources to provide thermal comfort and better IAQ, particularly in hot climates. It is a tower that is normally roof-mounted or a rooftop projection that captures cleaner outdoor air at a higher elevation and drives it indoors through wind pressure and buoyancy effect (Chohan and Awad, 2022). During the daytime, the wind-induced pressure difference between windward and leeward openings encourages the supply of fresh air and extraction of stale air, while in periods when wind speed is low or at night, the system functions as a thermal chimney where warmer indoor air rises and exits the building (Hughes et al., 2012; Noroozi and Veneris, 2018). Jomehzadeh et al. (2017) place the wind catcher within the passive-cooling framework as a heat dissipation layer, where it delivers outdoor air as a cooling and ventilating agent. Wind catchers vary by the number of openings, internal partitions, cross-section, and height. The one-sided system catches the wind and supplies air inwards, which is popular in regions with a prevailing wind direction, while the multisided system, which can be two, four, six, or eight-sided, can admit air and also exhaust hot air, with the four-sided system usually used in regions that have no specific direction for wind (Chohan and Awad, 2022).

2.5.2 Ventilation and Thermal Performance in Hot-Arid Climates

Jomehzadeh et al. (2017) reviewed traditional and modern wind catchers and examined indoor air quality based on studies mainly conducted in the UK using CFD simulations and experiments. Across these studies, wind catchers delivered ventilation rates ranging from 5 to 27,1 L/s per occupant and can achieve air change rates of 3.2 and as high as 57 ACH, and indoor CO₂ levels were recorded within the acceptable limits. Regarding thermal comfort, their review found that wind catchers can reduce indoor air temperature by about 2-4 °C, depending on the climate and design of the system. The authors further discussed the limitation of night ventilation, which relies on the thermal mass of the building, which achieved reductions between 1-4.2 °C in cold and temperate climates, and found that additional cooling was necessary for hot climates by incorporating strategies such as evaporative cooling and Earth-Air Heat Exchanger (EAHE). A more recent study by Ma et al. (2024) reviewed 96 studies between 2000 and 2024 and found that wind-catcher types in hot-arid areas, taken together, traditional, evaporative, and hybrid catchers, raised indoor air velocity by 10 to 50% and comfortable hours by 25 to 50%,

with the lower end reflecting simple dry towers and the upper end the evaporatively-assisted and hybrid designs. They also found that dry towers held their temperature drop at 2 to 4 °C. In hot-arid climates, dry wind catchers deliver strong ventilation and air movement, with reported indoor air velocities of roughly 0.3 to 3.2 m/s and air change rates reaching over 100 ACH (Ma et al., 2024). Their limitation is thermal rather than aerodynamic, despite this airflow, dry catchers reduced indoor temperature by only about 2 °C at outdoor temperatures above 40 °C, and often failed to meet comfort, because they channel hot outdoor air without cooling it (Ahmed et al., 2021).

2.5.3 Influence of Design Parameters on Ventilation and Cooling Performance

The performance of the wind catcher depends highly on its geometry. Jomehzadeh et al. (2020) reviewed the design parameters that govern ventilation rate and cooling. They identified cross-section, height, roof shape, internal partitions, openings, and control elements as the variables researchers tested most. This section reviews the main design parameters governing wind-catcher performance, drawing on the studies summarised in Table 2-3.

Cross-section:

Maneshi et al. (2012), through their computational fluid dynamics (CFD) model to assess wind catchers' performance, found that a square section outperformed a circular one at the same wind speed because its sharp edges create a wider zone of flow, creating a larger pressure difference that pulls more air through the tower. A square, four-sided catcher worked best when the wind met it at 45° (Maneshi et al., 2012). Farouk (2020) extended the comparison to a 6-sided hexagonal section wind catcher with equal internal area of 0.25 m² in a CFD study for a hot arid climate, and found that it achieved 19% more airflow on average than a square catcher and was not sensitive to wind direction, while the 4-sided louvered square catcher peaked when it met it head on. However, the square section produced higher indoor air velocity and better thermal comfort, whereas the hexagon achieved higher air change rate and air quality. Cross-sectional shape, therefore, trades airflow and directional stability against indoor velocity, rather than yielding a single best form. (Alhraki and Sultan Qurraie, 2024) evaluated square (4x4m) and rectangular (2x8m) four-sided wind catchers of equal area for a mosque in the hot-arid climate of Nizwa, Oman, and found that square geometries outperformed rectangular ones with X or X combined with + internal partitions as the most effective in raising occupied zone air velocity by up to 51.9% (0.33 to 0.69 m/s).

Cross-sectional area interacts with height, where reducing the area while raising the tower slightly improved the windcatcher's ventilation contribution to indoor comfort (McCabe and S., 2013). The cross-sectional area is also sized relative to the room it serves, where it's recommended for the cross-sectional area to equal the inlet opening and to be about 3% of the floor area of the ventilated space (Attia and De Herde, 2009, in Mayhoub et al., 2025). While Benkari et al. (2017) proposed a wind catcher for a room length and width ratio of 1:4. The width of the shaft affects the airflow as reducing a four sided shaft from 2.5 to 2.0m raised indoor velocity by up to 34%, and from 2.0 to 1.5m by up to 50%, though the narrowest width drove high-velocity air into the lower room and caused uneven temperature (Hosseini et al., 2016). However, Mayhoub et al. (2025) note that no standard governs the ratio of cross-section to room size, and previous findings on the optimal outlet-to-inlet ratio remain conflicting.

Height:

Taller towers reach faster, cleaner air and raise the pressure difference that drives flow, so performance fell whenever height was cut in an analytical study in a hot and humid climate (Haghighi Poshtiri et al., 2016). Regarding a traditional windcatcher in the hot arid climate of Yazd, Ghadiri (2011) found that 6 m is the optimum height among the assessed range between 3.5 and 10m for a square four-sided windcatcher with an H-form cross-section. Ayoobi et al. (2024) reached a similar range for the arid climate of Kabul, using DesignBuilder v7 with coupled annual energy simulation and CFD. They compared a single-sided rooftop windcatcher of 1.5m height and an attached windcatcher of 9m, and both had square peaks (2x2m) and were mounted on a south-facing test room. The tower opening was tested in four orientations. Their results showed that the north-facing opening performed best, aligning with the prevailing north wind, and that the 9 m attached tower increased natural ventilation from 3.8 to 8.8 ACH, compared with 5.2 ACH for the 1.5m rooftop tower. They recommend a height to be at least 1.5 times its width, and a height beyond 9m has minimal effect. A comparable optimisation for the temperate climate of Vienna, using the DesignBuilder v6 software, found a lower optimum height of 2.5m for a roof-mounted single-sided wind catcher (Shayegani et al., 2024). Their study modeled natural ventilation that opened automatically when the indoor temperature rose above the outdoor temperature, and tested five variables: tower height, inlet dimensions, and urban exposure. The best configuration had a 2.5m tower, a 90x140cm inlet, and an exposed urban setting (Shayegani et al., 2024). The gap between the

optimum height in this study and the optimum in the hot arid of Yazd and Kabul shows that optimum height is climate-specific.

Roof:

The top surface caps at the top of the wind catchers control how much wind enters the shaft. Mayhoub et al. (2025) trace three forms for the caps: a flat horizontal cap, inclined at 30° to 45° , and, in recent studies, a curved cap shaped as a quarter circle with a radius equal to the shaft width. A curved roof delivered 10% more airflow than a flat roof and 4.5% more than an inclined one at 0° wind, though the inclined top was less sensitive to changes in wind angle. (Dehghan et al., 2013). And a venturi-shaped-roof windcatcher provided sufficient airflow even at a very low outdoor wind speed of 0.1 m/s, producing indoor air velocities of 0.05–0.45 m/s while maintaining adequate IAQ and comfort in a hot, humid climate (Haw et al., 2012).

Openings and internal partitions:

The number, size, and orientation of openings affect both the amount of air that enters the tower and how well the tower tolerates a shifting wind. Opening orientation for a two-sided wind catcher induced about 20% more airflow than when the wind met it at 90° than at 0° (Montazeri et al., 2010). Afshin et al. (2016) traced this behaviour across wind angles through smoke visualisation, showing that the tower captured wind directly at low angles but shifted to a chimney-like suction mode beyond about 55° , with the highest ventilation reached at 90° ; the intermediate transition angles, around 55 – 60° , produced the most disordered internal flow and the greatest risk of short-circuiting (Afshin et al., 2015). The inlet opening is conventionally rectangular and sized to match the shaft cross-section, and increasing the length-to-width ratio of a rectangular opening raises the flow rate (Mayhoub et al., 2025). The internal partition inside the wind catcher splits the shaft into smaller channels, reducing sensitivity to wind direction and strengthening the structure, and increasing the number raised the indoor air velocity (Hosseinnia et al., 2013). And a cross form of the internal partitions has the best indoor comfort among the different forms surveyed in Yazd Jomehzadeh et al. (2020).

Control elements:

Louvers and dampers, which are mostly used in modern wind catchers, regulate the flow the tower admits. Based on the study of Hughes and Ghani (2010), an optimum louver angle of

35° at a wind speed of 4.5 m/s raised ventilation by 45% over a standard 45° louver for a four-sided commercial wind catcher. While adding dampers and diffusers can control the airflow, they can also reduce the airflow by half (Jomehzadeh et al., 2020).

Table 2-3: Summary of studies on wind-catcher design parameters and their effect on ventilation and cooling performance.

Parameter	Study (year)	Climate / location	Method & tool	Windcatcher type	Key finding
Cross-section	Maneshi et al. (2012)	-	CFD	Four-sided, square vs circular	Square outperformed circular (flow separation at sharp edges); square best at 45° wind incidence.
Cross-section	Farouk (2020)	Hot-arid	CFD	Square vs hexagon vs 6-opening circular (equal area 0.25 m ²)	Hexagon +19% airflow vs square and insensitive to wind direction; square gave higher indoor velocity/comfort, hexagon better air change/IAQ.
Cross-section	Alhraki & Qurraie (2024)	Hot-arid / Nizwa, Oman	CFD (Autodesk)	Four-sided; square (4×4 m) vs rectangular (2×8 m), equal area	Square outperformed rectangular; square + X or X+ partitions raised occupied zone velocity up to 51.9% (0.33 to 0.69 m/s).
Cross-section	McCabe & Roaf (2013)	Hot desert / Bastakiya, Dubai	BES (dynamic thermal)	Square four-sided	Reducing cross-sectional area (±50%) while raising height (±33%) slightly improved ventilation contribution to comfort.
Cross-section (sizing)	Attia & De Herde (2009), in Mayhoub et al. (2025)	-	Wind tunnel / review	One-sided (malqaf)	Cross-section = inlet area = 3% of served floor area
Cross-section (sizing)	Benkari et al. (2017)	Hot-arid / Muscat, Oman	CFD (ANSYS Fluent)	Semi closed Courtyard windcatcher	Shaft-to-space linear dimension ratio = 1:4 (= 6% of floor area) for a semienclosed courtyard.
Cross-section (width & height)	Hosseini et al. (2016)	Hot-arid / Yazd, Iran	2D CFD (ANSYS Fluent)	Four-sided, rectangular; width 2.5/2.0/1.5 m, height 9/11 m; 5×2.5 m room	Narrowing width raised mid-room velocity up to 34% (2.5 to 2.0 m) and 50% (2.0 to 1.5 m), but the faster air worsened comfort; the wider 2.5 m tower (9 m) gave the best thermal comfort (7% vs 26% low-comfort area). Raising height to 11 m also caused draft discomfort. Curved top raised inflow; curved bottom sped inflow but gave uneven distribution.
Height	Ghadiri et al. (2011)	Hot-arid / Yazd, Iran	CFD	Square plan 1.5×1.5 m, H blade; room 6×4 m	Heights 3.5–10.5 m tested: below 6 m, the dry tower failed to reduce indoor temperature adequately; 6 m and above gave effective cooling
Height	Jomehzadeh (2020)	-	Review	Various	Jomehzadeh (2020)
Height	Ayoobi et al. (2024)	Hot Arid / Kabul	DesignBuilder v7 (energy + CFD)	Rooftop 1.5 m vs attached 9 m, square 2×2 m	North opening best (prevailing wind); 9 m attached raised NV 3.8 to 8.8 ACH vs 5.2 for 1.5 m rooftop; height ≥ 1.5× width, little gain beyond 9 m.

Height & inlet	Shayegani et al. (2024)	Temperate / Vienna	DesignBuilder v6 (temp-triggered NV)	Roof-mounted one sided; 48 m ² room	Optimum height 2.5 m (of 1.5–3.0 m; energy rose beyond 3 m). Optimum inlet 0.9×1.4 m (of 0.9×0.9, 0.9×1.4, 0.9×1.9 m; 0.9 m width fixed, opening height varied). Vents open when indoor >22 °C. Optima are climate-specific
Roof (top surface)	Dehghan et al. (2013)	-	Wind tunnel + analytical	One-sided; flat/inclined/curved	Curved top +10% airflow vs flat, +4.5% vs inclined (0° wind); inclined top less sensitive to wind angle.
Roof (top surface)	Haw et al. (2012)	Hot-humid / Malaysia	CFD + experiment	Venturi-shaped roof	Sufficient airflow at 0.1 m/s wind; indoor velocities 0.05–0.45 m/s with adequate IAQ and comfort.
Openings (orientation)	Montazeri et al. (2010)	-	Experimental + numerical + analytical	Two-sided	20% more airflow at 90° wind than 0°; pressure coefficients strongly influence performance.
Openings (orientation)	Afshin et al. (2015)	-	Wind tunnel (smoke visualisation)	Two-sided	Direct capture at low angles, chimney mode beyond 55°, max ventilation at 90°; 55–60° transition gave disordered flow and short-circuiting risk.
Internal partitions	Hosseinnia et al. (2013)	Hot-arid / Iran	CFD	Various partitions	More partitions raised indoor air velocity (1.0 to 1.53 m/s) and cut wind-direction sensitivity.
Internal partitions	Mahmoudi (2009), in Jomehzadeh et al. (2020)	Hot-arid / Yazd	CFD	Four-sided; X, I, +, H, K forms	Cross (+) form gave best indoor comfort among the forms tested.
Control (louvre)	Hughes & Ghani (2010)	-	CFD	Square four-sided (commercial)	Optimum louvre angle 35° at 4.5 m/s: +45% ventilation vs standard 45° louvre; -42% trailing-edge stall.
Control (damper)	Elmualim (2006); Hughes & Abdul Ghani (2009)	-	Experimental + CFD	Square four-sided (commercial)	Optimum damper angle 45–55°; adding dampers + diffusers reduced airflow by 50%.

2.5.4 Modelling and Simulation Approaches

Wind catcher performance has been assessed mainly through CFD, which resolves the airflow inside the tower in detail but demands heavy computation and usually covers a single room over a short run (Jomehzadeh et al., 2020). Building energy simulation coupled with an airflow network model offers a more complementary approach by evaluating a whole multizone building across a full cooling season (Jomehzadeh et al., 2020). DesignBuilder is among the most widely used building energy simulation tools, and researchers have applied it to evaluate wind catchers. It combines several methods in one validated platform: dynamic energy simulation on the EnergyPlus engine, natural ventilation through an airflow-network model, and a CFD module for detailed airflow (Shayegani et al., 2024; Ayoobi et al., 2024).

2.5.5 Integration with Evaporative Cooling

Wind catchers can be insufficient by themselves, especially when outdoor conditions are not favorable, as it channels outdoor air without cooling it. As wind catchers deliver the air at ambient temperature, this brings discomfort when the outdoor air is hot. Its output also depends highly on the available wind, and attempts to improve it with guide vans and louvers can raise flow resistance and turn it into a wind blocker (Ahmed et al., 2021). The authors also stated through their review that coupling a wind catcher with evaporative cooling overcomes the towers' inability to cool the air and can achieve substantial reductions in indoor temperature from about 3.5 to 18.6 °C in hot arid climates (Ahmed et al., 2021). Evaporative cooling, therefore, becomes the strategy that carries the wind catcher through the hottest, driest conditions, where ventilation alone falls short. The following section examines how it works and what it achieves in hot-arid climates.

2.6 Evaporative Cooling

2.6.1 Principles of evaporative cooling

Evaporative cooling is "a heat and mass transfer process that uses water evaporation for air cooling, in which a large amount of heat is transferred from air to water, and consequently the air temperature decreases". There are three main types of evaporative cooling. The first one, used mainly in hot-arid climates, is direct evaporative cooling (DEC), the simplest type in which water has direct contact with the air, converting sensible heat into latent heat. This type can be incorporated into a wind tower, a Mashrabiya, or a roof pond (Amer et al., 2015). The second type is indirect evaporative cooling, which is more suitable for hot-humid climates because it reduces sensible heat without increasing humidity. This type relies on a heat exchanger and a fan to provide cooling without direct contact between air and water. The third type combines the first and second types and is suitable for climates that alternate between dry and humid periods (Duan et al., 2012).

Combining ventilative cooling with direct evaporative cooling by utilizing natural airflow and water evaporation can reduce indoor temperatures in hot arid climates and increase air change efficiency, which can achieve a temperature difference between 7.8–18.5 °C under favorable climate conditions (Li et al., 2025). For analysing the DEC, a psychometric chart can be used to present the relationship between air temperature, relative humidity, dew point, and wet bulb temperature, which represent the lowest temperature that can be achieved by evaporation, where

the DEC can shift the air's thermal state along a line of constant enthalpy, allowing it to reach a comfort zone Figure 2-2 (Chiesa and Pearlmutter, 2021).

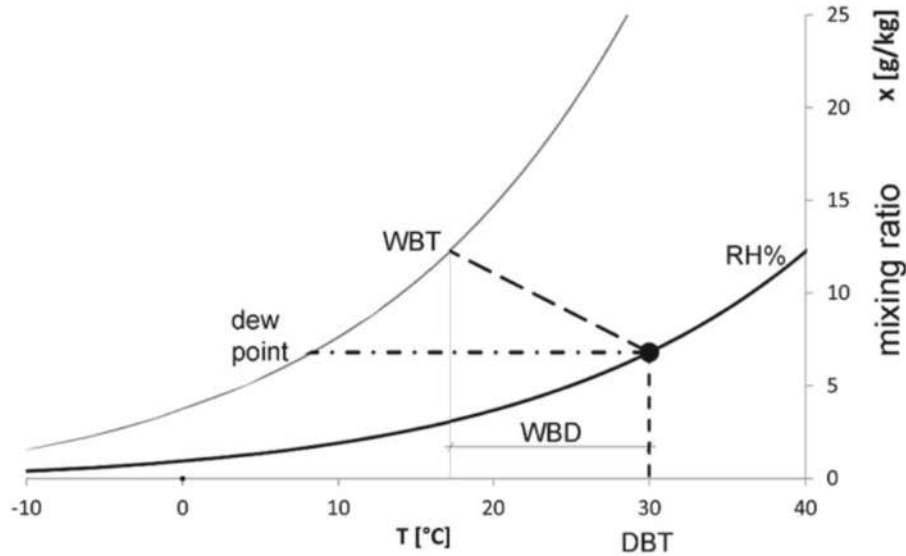


Figure 2-2: Psychrometric chart, source: (Chiesa and Pearlmutter, 2021).

2.6.2 Passive Downdraught Evaporative Cooling (PDEC) systems

PDEC systems are considered among the most effective cooling strategies for hot-arid climates, as they cool outdoor hot, dry air through water evaporation, achieving wet-bulb depressions of more than 80%, thereby reducing cooling energy consumption (Chiesa et al., 2017). PDEC is a modern passive cooling and ventilation strategy, evolved from conventional windcatcher technology that dates back thousands of years, adopted in hot, arid regions like Iran and some Middle Eastern countries (Ma et al., 2024). PDEC systems typically include a wind catcher, evaporative element, and a vertical shaft, and the primary method to naturally move the air through the PDEC tower is either by buoyancy effect where cooled air by evaporation inside the PDEC gets heavier and sinks into the interior space, and by wind-assisted natural ventilation, where positive pressure occurs at the inlet of the tower when it's directed towards the wind, encouraging the airflow to move down the shaft (Ford et al., 2010).

2.6.3 Classification of PDEC systems

PDEC systems can be classified according to how water interacts with airflow: one type involves directly introducing water into the airflow through showers or misting nozzles and

sprayers, and the second type involves getting the air to pass near or through a moist surface, such as wet pads and ceramic. Regarding the first type, the shower system achieves better cooling than the misting system but consumes a lot of water, which must be collected at the bottom of the shaft to prevent water stagnation, whereas the misting tower evaporates its finer droplets more fully and wastes less water, yet reaches a lower effectiveness that does not fully cover the wet-bulb depression, needs higher pump pressure, and clogs more easily (Chiesa and Pearlmutter, 2021). Spray and misting systems also carry a hygiene risk, as non-evaporated water in the bottom of the tower can foster bacteria in the 20–45 °C range; however, the wet pad system sets the air without dispersing droplets, which reduces this exposure (Li et al., 2025). Moreover, the pad system provides steadier cooling, which is easier to define, where a single saturation effectiveness value describes how close the pad brings the air to its wet bulb temperature, while spray systems' performance shifts with nozzle direction, droplet size, and pump pressure (Yu et al., 2025). Also, building energy simulation represents the pad's effectiveness value more readily than spray atomization and pump behavior.

2.6.4 Factors influencing the PDEC performance

The performance of the PDEC tower is highly dependent on the local climate, which determines whether the system is applicable. Its cooling potential is governed by the wet-bulb depression of the ambient air, that is, the difference between the dry-bulb and wet-bulb temperatures, since the wet-bulb temperature represents the theoretical minimum to which air can be cooled by direct evaporation. In practice, this limit is not reached, as the saturation effectiveness of the system determines what proportion of the available depression is realized (Chiesa and Pearlmutter, 2021). Therefore, before refining the PDEC design, an analysis of weather data specifically for the cooling season must be conducted (Chiesa and Pearlmutter, 2021). One of the simplest ways to investigate the applicability of PDEC is by using bioclimatic comfort charts, such as the Givoni-Milne chart, which shows comfortable temperature and humidity ranges for specific climate conditions, and also indicates applicable passive strategies, such as natural ventilation, shading, thermal mass, evaporative cooling, and others (Cortiços and Duarte, 2025). After assessing the suitability of PDEC for a specific climate, the next step is to optimize the PDEC system to achieve the best performance. Physical, morphological, and technological factors influence the performance of the PDEC. The physical factors include wind pressure at the tower inlet, air specific weight, which changes during evaporation, and the momentum transfer between air and water (contact time and speed between air and water

droplets). Morphological and technological factors include tower geometry, such as height, cross-sectional area, water flow rate, and the number and arrangement of sprayers (Chiesa and Pearlmutter, 2021). Al-Hassawi (2020) mentioned that the height of the tower shaft and the design of the outlet and inlet vents were key elements influencing the conditions of the air leaving the system. Kang and Strand (2016) identified five strongly interrelated independent parameters that affect the performance of PDEC with a spray system. These parameters include air mass flow rate, which is driven by inlet air velocity and tower cross section, and tower height, the shape and size of the tower and wind catcher at the top of the tower, in addition to the water droplet size and water flow rate. All these factors influence the dependent variables, which are PDEC outlet air temperature, humidity, and velocity. For pad-based systems, the equivalent parameters are the pad material and thickness, the air velocity through the pad, and the water flow rate, which govern the pad's saturation effectiveness as examined below.

2.6.5 Performance of Wet-pad systems

Morady et al. (2022) tested a corrugated cellulose pad (7090 model, 0.5x0.5m) in a laboratory duct ring, passing heated air across five inlet temperatures from 25 to 42 °C through the pad at a fixed inlet velocity of 3.5 m/s, and proposed its use at the inlet of a wind catcher for passive cooling in hot arid climates. They evaluated pad thicknesses of 10, 15, and 30 cm, which lowered air temperature by 11.3, 12.7, and 13.7 °C, respectively. They found that effectiveness rose with thickness, but with diminishing returns as widening the pad from 15 to 30 added only 8% and decreased the airflow. They also found that the pad cut the velocity from 3.5 m/s to 0.9, 0.7, and 0.6, respectively, for the three thicknesses, and the thicker pad consumed more water and cost more. Khani et al. (2017) conducted an experimental and analytical study to evaluate the performance of a modular wind tower with wetted surfaces of clay conduits and wetted straw curtains for ten days in the hot-arid climate of Keerman. At ambient air from 31 to 25 °C at only 6–12% relative humidity, the tower delivered air at 19–24 °C and 30–59% RH, which decreased the temperature by 9.2 °C on average and up to 13.6 °C. The tower cooled even in calm air with an outlet air velocity of about 1.5 to 2.0 m/s with no measured inlet wind, and worked even better once there was wind. The only power consumed was for the water pump, which was supplied by solar cells, making the system effectively passive. Alshenaifi et al. (2024) monitored two 10 m high pad-based PDEC towers in a single-story library (443 m²) in the hot arid climate of Saudi Arabia, with 1.12m earthen plaster and straw bales walls. Each tower had a four-sided wind catcher with 1.5 m × 2 m openings that supplied cooled air from a 2 m × 1.8 m supply opening at the base. On the hottest day, the towers supplied air at 23.5–24 °C and 61–70%

humidity when outdoor air temperature reached 46 °C at 8% RH. The cooling efficiency held at 66–71% and peaked near 90%, and dropped at night, as the wet bulb depression decreased, and the efficiency also fell at higher wind speeds above 4m/s. At the center of the building, temperature readings were about 23.0–29.5 °C. The saturation effectiveness, which is the fraction of wet-bulb depression the evaporative cooling system achieves, depends on the pad material, thickness, air velocity, and the water flow rate (Tejero-González and Franco-Salas, 2021). Melo Junior et al. (2019) found that air velocity was the dominant factor and that higher face velocities decrease effectiveness, because air spends less time against the wetted surface and exchanges less heat and moisture. Nada et al. (2019) found that a 70 mm cellulose pad reached 84% effectiveness at 1 m/s with a pressure drop of only 8 Pa, running with 40 °C inlet air, 0.167 kg/s water flow, and 25 °C water. Based on the review of Tejero-González and Franco-Salas (2021) studies recommends air velocity at 1 to 1.5 m/s for corrugated cellulose to balance effectiveness against pressure drop. Moreover, the velocity effect weakens as the pad becomes thicker. Martínez et al. (2018) found that saturation effectiveness stabilises above 1 to 1.5 m/s in thicker plastic-mesh pads. Sohani et al. (2017) modeled the smallest cellulose pad that still delivered thermal comfort to hold down pressure drop and cost, and found that a 70 mm thickness pad and 420 m²/m³ were the optimum at air velocities of 2 to 4 m/s. Water flow rate depends on the evaporation rate, where the water evaporated across the pad follows from the air mass flow and the humidity gain, as shown in equation 2 (Tejero-González and Franco-Salas, 2021).

$$\dot{m}_{ew} = \dot{m}_a (w_{out} - w_{in}) \quad (2-2)$$

Where $\dot{m}_{ew}$ is the water evaporation rate (kg/s), $\dot{m}_a$ the air mass flow (kg/s), and w the humidity ratio (kg water per kg dry air), with subscripts out and in denoting the pad outlet and inlet. Yan et al. (2021) recommend supplying 10 to 30 times the evaporation rate, to keep the medium fully wetted.

Occupants of evaporatively cooled buildings in hot-dry climates tend to accept warmer and more humid conditions than the PMV model predicts, as Guo and Wang (2022) observed a neutral operative temperature of 27.3 °C, with 80% of occupants comfortable between 26.4 and 30.3 °C and staying comfortable at elevated relative humidity with a mean of near 63%, with peaks of 86–90% in office buildings that use evaporative cooling in Urumqi. They adjusted the thermal models, ePMV, and aPMV, and found that these models recorded thermal sensation more accurately than the standard PMV.

2.6.6 Modelling and simulation of evaporative cooling

Researchers evaluate evaporative cooling performance at three levels of detail, with dynamic energy tools such as EnergyPlus, TRNSYS, ESP-r, and DOE2 simulating it over a full year but representing it through built-in component models (Chiesa and Grosso, 2015). CFD resolves the airflow and temperature field inside the tower, and CFD spray models that combine air and water droplet behaviour were able to predict the dry-bulb temperature with an error of only about 10% compared with measurements (Montazeri et al., 2015), though it demands high expertise and long run times that is dedicated to a single check, rather than long-period simulation. The third level is the simplified semi-empirical equations, which predict outlet air temperature from inlet conditions and let the designer size a tower early and drive it inside an energy model (Soto et al., 2021; Saif et al., 2021). Givoni's equations remain a widely used simplified approach, which was tested by Chiesa and Grosso (2015) against real towers in Turin, Sde-Boquer, Tucson, and Catania, 7.6 to 10.2 m tall. The towers reached above 90% of the wet bulb depression in most measurements, with effectiveness based on equation 3.

$$\varepsilon = \frac{T_{in,DB} - T_{out,DB}}{T_{in,DB} - T_{in,WB}} \quad (2-3)$$

where ε is the saturation effectiveness, $T_{in,DB}$ and $T_{out,DB}$ are the inlet and outlet dry-bulb temperatures, and $T_{in,WB}$ is the inlet wet-bulb temperature (°C). Givoni's 1994 regression equation proved to be the most reliable, which is the one built into DesignBuilder's Direct CelDekPad routine. The relationship is expressed as follows:

$$T_{out} = T_{in} - k(T_{in} - T_{WB,in}) \quad (2-4)$$

Where k is the slope coefficient, which represents the effectiveness of the evaporative cooling process. Chiesa and Grosso (2015) recommend a fixed slope coefficient of 0.8 for estimating PDEC outlet temperature in early design and in dynamic energy simulation, which corresponds to a saturation effectiveness of 80%.

Saif et al. (2021) use this simulation method, where they modeled a naturally ventilated school classroom in the hot arid climate of Kuwait in DesignBuilder, coupling a wind catcher with a direct evaporative cooler with a saturation effectiveness of 0.7. Their results showed that the evaporative cooling cut summer energy to 52% and raised comfortable hours from 76% to 100% without any supplementary cooling. However, they found that CO₂ stayed high, with time

below the limit rising only from 11% to 24%, and the added moisture pushed relative humidity up by 14%.

2.7 Control Strategies for Ventilative Cooling

Ventilation strategies can improve indoor conditions when the timing is right, specifically in hot climates where the same openings that cool a space at night can pour heat into it at midday, so the control logic that governs when the building is ventilated decides when the strategy enhances or compromises the thermal comfort. Darmanis et al. (2020) list the parameters that determine night ventilation performance, which are operation time, ventilation mode, airflow rate, and control strategy, along with the weather and the building's thermal capacity. The thermal mass is examined in Chapter 3, and this section focuses on the operational logic that decides when and how much the building ventilates.

Khoshbakht et al. (2019) sort building control into fully automated, where a building automation system reads sensors and switches modes on its own, semi-manual, where that system runs, but occupants can override it, and manual, where occupants operate the building. They surveyed occupants across all three and found that automated control deprived occupants of their adaptive opportunities and carried high installation and maintenance costs, while the adaptive comfort model described comfort in the manual and semi-manual buildings better than in the automated ones, as people who could act on their environment stayed adaptive to outdoor conditions. Saber et al. (2021) divide natural ventilation operation into manual, where occupants open and close openings based on their sense of comfort, and automatic, where actuators adjust the openings based on indoor and outdoor readings. They found that occupants often miss favorable outdoor conditions, and open windows at the wrong time or leave them shut when outdoor air could cool the space, leading to raised energy use and discomfort hours. While automated ventilation delivered the most comfortable hours. Sarna and Ferdyn-Grygierek (2025) compared window-control scenarios in a validated simulation where they evaluated an ideal manual case and realistic manual cases where occupants act on it only 25%, 50%, or 75% of the time. Their results proved that the ideal manual case performs close to the automatic actuator system and that the performance deteriorated most when compliance was 25%, proving that the gap isn't between human and machine, but between following the rules less reliably. Zeng et al. (2022) show one way to close the gap between an optimal control rule that performs well in simulation and one that people can do manually. They optimized an hour-by-hour air conditioning set point to pre-cool houses through a heat wave, then simplified that schedule into a handful of steps, which they call improved rule-based control. Their

results proved that the simplified control strategy achieved almost the same thermal comfort performance as the fully optimized approach while still being simple enough to be implemented by the occupants.

The value of the directed control depends on the rule it follows. Peng et al. (2022) sort ventilative cooling and mixed mode controls into rule-based, optimal, and computational-intelligence families, and within rule-based control, they group the rules by climate variables, temporal schedules, occupancy, and thermal comfort standards. Among the climate variables, the temperature differential is the most used trigger for natural ventilation. Darmanis et al. (2020) used this rule for a high mass earth's room, opening a fan between 21:00 and 08:00 only when outdoor air was 2 to 3 °C below the indoor air, which decreased cooling energy up to 27%. Ayala and Ayala (2024) tested the same rule in a hot, arid desert climate on an old, high-mass building in Hermosillo with no air conditioning. They compared Windows closed all day and night, windows open the whole time, and controlled windows that opened only when the indoor temperature rose above the outdoor temperature, with a fan that is turned on when the indoors rose 1 °C above outdoors. The controlled strategy maintained indoor average of about 3.6 °C below the closed windows case and a daytime peak of 4 °C under the outdoor maximum against about 2.9 °C when the windows stayed open continuously, beating both the closed and the always-open arrangements.

Temporal schedules fix ventilation to a defined period, such as occupied hours or night-cooling hours (Peng et al., 2022). Rana (2021) used a schedule-based control based on the building's own behavior rather than an assumed one. She simulated the naturally ventilated buildings on DesignBuilder with windows open all day and based on the results, she developed a zone-specific ventilation schedule by identifying periods when ventilation improved or degraded the door thermal condition. This approach led to approximately 50% reduction in annual discomfort hours.

Thermal comfort standards and conditions use the comfort limit as the trigger. Aguilera et al. (2021) adopted this control logic by simulating five climates, and setting the cooling threshold at the upper edge of the adaptive comfort zone, which they recalculated each day from the mean outdoor temperature. They found that using the adaptive comfort reduced energy consumption up to 20% against a fixed PMV-based setpoint and reduced the number of switches between natural ventilation and air conditioning. They also found that adding night cooling lowered operative temperatures further and saved the most energy in Palermo, the warmest climate of their cases.

Earthen Building Envelope Thermal Performance

3.1 Dynamic Thermal Performance of the Building Envelope

Building envelope materials' density and specific heat capacity determine the material's ability to store heat within a building, while thermal conductivity governs the rate at which heat is transferred. Thermal mass can absorb thermal energy during periods of heat gain and release it with a time delay, therefore reducing indoor temperature fluctuation, while reducing cooling loads by shifting peak energy demand to different times (Song et al., 2021). Therefore, the thermal mass can be applied as a heat modulation layer, reducing heat exchange between the building and the external environment (Song et al., 2021). The effectiveness of thermal mass depends on the relationship between the material properties and the building's daily thermal cycle, where high-density materials with sufficient specific heat capacity make the material able to store more heat while moderate thermal conductivity allows heat to be absorbed and released at a rate that matches indoor temperature fluctuations (Sharaf, 2020). This performance is commonly described based on two indicators: the first is the time lag. (TL), which refers to the delay between the peak outdoor conditions and the time it takes for the outdoor heat to reach inside the building, and the second indicator is the decrement factor (DF), which describes the reduction in the amount of temperature fluctuation as heat passes through the building envelope. Based on Oktay et al. (2020), TL can be calculated as:

$$TL = t_{Ti, \max} - t_{Te, \max} \quad (3-1)$$

Where $t_{Ti, \max}$ is the time at which the maximum indoor surface temperature occurs; $t_{Te, \max}$ is the time at which the maximum Sol-air temperature occurs. And DF can be calculated as:

$$DF = \frac{T_{i, \max} - T_{i, \min}}{T_{e, \max} - T_{e, \min}} \quad (3-2)$$

Where DF is the decrement factor, $T_{i, \max}$ and $T_{i, \min}$ are the maximum and the minimum temperatures on the interior surface; $T_{e, \max}$ and $T_{e, \min}$ are the maximum and the minimum temperatures of the outdoor surface temperature.

Oktay et al. (2020) investigated the effect of materials' thermophysical properties, including density, thermal conductivity, specific heat, and thickness, on thermal mass performance through time lag(TL) and decrement factor (DF). They found that higher density achieves higher TL and

lower DF, higher conductivity has the reverse effect, while higher specific heat leads to higher TL and lower DF, but has a weaker relationship with TL and DF compared with other properties. Additionally, increasing thickness achieves longer TL and greatly reduces DF. However, based on the review conducted by Verbeke and Audenaert (2018), increasing wall thermal mass beyond a certain level can have a reverse effect and increase the cooling demand as the walls become incapable of dissipating the large amount of heat stored during the day. They also highlighted the importance of a ventilation strategy, which can make thermal mass more effective by removing heat stored during the day. They also considered thermal mass as a climate -responsive strategy dependent heavily on the local climate and most beneficial in climates with a large diurnal temperature difference. In hot arid climates, which are characterized by high daytime temperatures, high solar radiation, and large diurnal swings, thermal mass can play a vital role in improving buildings' thermal performance by absorbing daytime heat during the day and releasing it slowly during the night, providing natural cooling during the hottest period of the day (Alayed et al., 2022).

3.2 Thermal Performance of Earthen Buildings in Hot Climates

3.2.1 Field Measurements

Historically, thermal mass has been adopted in traditional architecture in hot arid regions, often employing thick walls made from stone or earth, to create a more comfortable indoor environment naturally (Kharrufa and Noori, 2022). Based on the literature review of (Carrobé et al., 2021), regarding earthen buildings, they found that most of these studies were conducted in arid and temperate climates, indicating their suitability and high performance in these climates, with a decrement factor of about 0.2, indicating strong damping of heat transfer and stable indoor conditions that generally achieve adaptive comfort more than 70% of the monitored time. Additional evidence from a study conducted by Wakil et al. (2024) in a semi-arid Mediterranean climate in two Moroccan cities proves the effectiveness of thick CEB walls in delaying and reducing indoor peak temperature in summer. Their experimental and simulation-based study showed that a 45 cm thick CEB was able to reduce the maximum indoor temperature from 38 °C to 34 °C, with a time lag of about 3 hours contributing to 17% of discomfort hours in summer, based on a set point temperature of about 26 °C with 0.6 ACH infiltration rate and no ventilation. However, winter comfort remained less satisfactory due to low outdoor temperature reaching as low as -2 °C.

3.2.2 Wall thickness and Insulation placement

Although thermal mass is effective in reducing temperature swings, it doesn't replace insulation, which improves R-value and limits heat transfer. Under dynamic conditions, their effects are more complex and interrelated, influenced by their amount and placement in the building (Al-Sanea et al., 2012). Additionally, it is very crucial to integrate thermal mass effective night ventilation to effectively help get rid of the released heat absorbed during the day, and prepare it to absorb more heat the next day (DeKay and Brown, 2013).

Oktay et al. (2020) found that adding an insulation layer to the thermal mass sharply reduces DF and modifies TL based on the insulation layer position. They noticed that TL isn't affected greatly by the location of the added insulation layer but mainly depends on wall thickness and overall conductivity, while the DF is strongly influenced by the insulation layer location, and placing it at the outer side of the wall performed best, as it delayed heat entry more effectively and reduced heat flow intensity. El Fgaier et al. (2016) investigated theoretically and experimentally the required thickness for unfired earth blocks to achieve optimum thermal inertia. Earth blocks with a thermal conductivity of about $0.9 \text{ W/m}\cdot\text{K}$, with a thickness between 30 cm and 40 cm, offered the best heat capacity and thermal lag of 10-12 hours, and a thickness beyond that was considered ineffective as heat doesn't reach the core of the walls within 24 hours. Al-Sanea et al. (2012) examined different locations for thermal insulation within a thermal mass wall in the Riyadh climate under continuous AC conditions, where all configurations had the same nominal thermal resistance. Under dynamic conditions, the thermal performance for each configuration was different, and placing the insulation on the exterior side of the wall is more effective as it reduces heat flow through the building and therefore reduces the amount of heat absorbed by the thermal mass from outdoors and enables it to absorb the heat efficiently from the interior environment. They also recommended a wall thickness between 6 and 30cm to achieve an energy saving of 60-99%. In the hot arid climate of Burkina Faso, Hema et al. (2020) found that replacing conventional hollow block walls with earthen materials can greatly improve the adaptive thermal comfort indoors. They noticed that using a 29 cm thick CEB performed much better than using a 14cm thick CEB, which performed even worse than concrete hollow blocks during daytime when windows were closed (no ventilation). Adding a 5cm insulation layer of expanded polystyrene achieved even higher comfort hours compared to CEB without insulation during the day with no ventilation, and at night with ventilation. Placing

insulation layers internally slightly increased comfort hours at night compared with insulation placed externally.

Hema et al. (2021) experimentally investigated different wall configurations made from compressed earth blocks (CEB) in relation to ventilation scenarios in the hot arid climate of Ouagadougou. They found that the insulation layer position strongly affects indoor thermal performance, where CEB inside and insulation outside performed best in reducing indoor temperature fluctuations and overheating during daytime, while insulation inside was best for nighttime mitigation when night ventilation was applied, but caused more overheating during daytime. Closed windows all day caused the highest overheating, especially during the daytime, because heat became trapped inside. Night ventilation and continuous ventilation greatly mitigated overheating at night, but night ventilation was considered more suitable for reducing overheating both day and night, as ventilation during the day increased overheating.

3.2.3 Ventilation coupling

Darmanis et al. (2020) experimentally investigated the combined effect of thermal mass and night ventilation with two ventilation rates (2.3 and 3.2 ACH) in decreasing air conditioning cooling energy demand during the day in a 45 cm thick earthen building (stabilized adobe) in Istanbul. The building had a thermal conductivity of 0.5 W/m·K and specific heat capacity of 1.2 kJ/kg·K with 1620 kg/m³ density. The most important observation was that the cooling benefit from night ventilation decreased and performed the same as with no night ventilation scenario, when outdoor temperatures remained relatively high, and the diurnal temperature variation was small, and ventilation rates were considered insufficient, and proposed ACH of about 10 based on previous literature. While under a large diurnal temperature difference, energy consumption reduced by about 27%. They also noticed that under free-floating conditions with no night ventilation, the building achieved nearly stable conditions (only 5 °C difference) with a time lag of about 3-4 hours, even though the outside temperature was unstable.

Sun et al. (2022) investigated the role of thermal mass and night ventilation in reducing overheating hours in free-running offices in 5 different climate zones in China under future climate scenarios. In the hot climate zone, the heavy thermal mass performed poorly and even increased overheating hours compared to lightweight walls when there was no night ventilation. When night ventilation was incorporated, the performance of heavy thermal mass greatly improved, decreasing by about 22.5%. Their study emphasized the importance of releasing

stored heat at night, otherwise heavy thermal mass can worsen overheating. Although the number of overheating hours was reduced, it remained relatively high in the hot climate zone, indicating the need for additional passive cooling strategies to enhance heat dissipation.

Results of an experimental and simulation study conducted by Amos-Abanyie et al. (2013) also agree with the previous studies, emphasizing the role of thermal mass in reducing peak indoor air temperature, which was concrete in this study, in the hot and humid tropical climate of Ghana. The peak indoor temperature was delayed up to 5 hours. They also found that night ventilation with 10 ACH decreased overheating hours up to 39% compared to lightweight walls with no ventilation, but ventilation rates higher than 10 ACH had a negligible improvement.

An experimental and simulation study conducted by El-Bichri et al. (2022) in the hot semi-arid climate of Benguerir also showed the negative performance of thermal mass walls, such as rammed earth, without night heat dissipation, although it maintained much more stable temperatures compared to reinforced concrete, fired brick, and cinder blocks, in summer the interior space had higher temperatures, specifically during the night. However, when passive cooling strategies were applied, such as window shading and night ventilation, the rammed earth performed best in respect to thermal comfort hours and cooling energy demand. The study also compared three ventilation scenarios: the first included all-day mechanical ventilation of 4 ACH, the second was smart mechanical ventilation, which is turned on only when the outdoor temperature is lower than inside, and the third was natural night ventilation, which performed best of all, indicating the need for a higher ventilation rate to dissipate heat. Moreover, the rammed performed best in all the ventilation scenarios compared with other wall materials.

The previously reviewed studies highlight that neither thermal mass nor natural ventilation alone can guarantee acceptable thermal comfort in hot arid climates, specifically when IAQ is considered. And their interdependent relationship is governed by the timing, control of heat gain, and the heat dissipation process, which is critical in hot arid climates, indicating the need to balance between heat storage, heat release, and air exchange based on outdoor conditions. And from this point of view, optimized ventilation contributes to air exchange in addition to controlling and regulating the thermal state of the building envelope, especially with thermal mass. Where ventilation timing becomes as important as ventilation rate, creating time-dependent climate-responsive operation strategies.

Research Methodology

4.1 Research Type and Data Collection Method

After the extended literature review and theoretical background presented in chapters 2 and 3, which examined passive cooling strategies focusing on thermal mass, earthen construction, ventilative cooling, and their role in improving thermal comfort, indoor air quality, specifically in hot arid climates, this chapter outlines the research methodology adopted in this study to evaluate and optimize integrated passive cooling strategies in earthen buildings in the hot arid climate of Jericho in Palestine. The methodology combines field measurements, calibration, simulation-based performance analysis, and parametric testing and optimization of integration between thermal mass, ventilative cooling strategies, envelope configuration, and operational control strategies that would achieve thermal comfort, indoor air quality, and reduce cooling energy demand. The previous chapters, relying on research papers, scientific journals, and books, established the theoretical framework by identifying key variables and performance indicators used in the analysis, which can translate climate-responsive strategies into measurable parameters.

The thesis primarily follows a hypothetico-deductive research approach, in which hypotheses were developed from the most recent literature and then tested in a case study, with quantitative evaluations conducted using empirical data and simulation software to identify optimal solutions. Figure 4-1 illustrates the steps of this method, adapted from Tariq (2015).

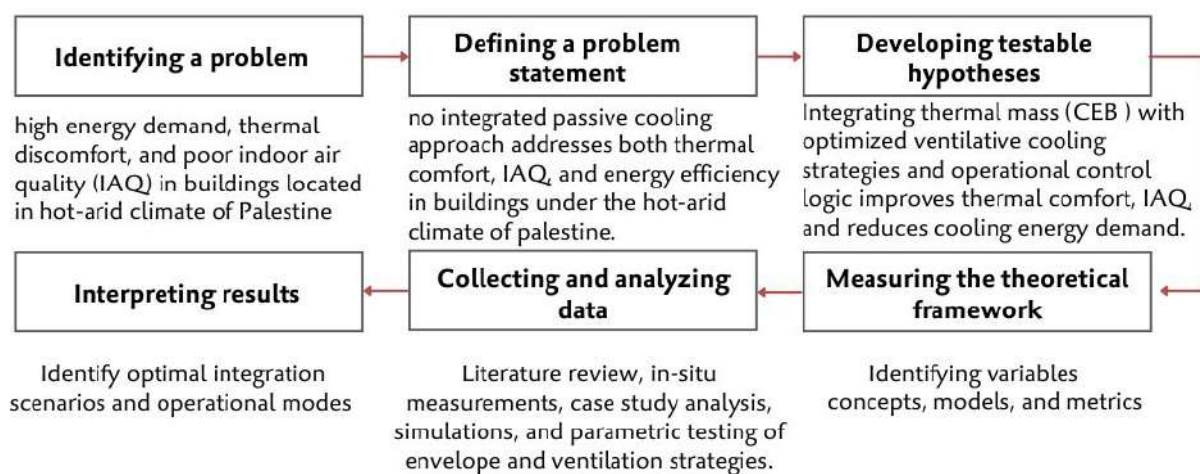


Figure 4-1 Adopted research hypothetical-deductive method

Building on this approach, the study adopts a case study focusing on an existing earthen building in Jericho, Palestine, which will be considered as a base case for further analysis, improvements, and optimization.

4.2. Research Methodological Framework

The methodological framework was structured as a systematic approach to address the objectives of the study. It began with case study selection, followed by a climate analysis, and field assessment involving in situ environmental measurements and an occupant survey. A building simulation model was then developed and calibrated based on the collected field data. Then the calibrated model was employed to evaluate and optimize the building envelope, ventilation strategies, and finally, the results were analyzed and led to the development of an integrated control-oriented passive cooling framework as described in Figure 4-2.

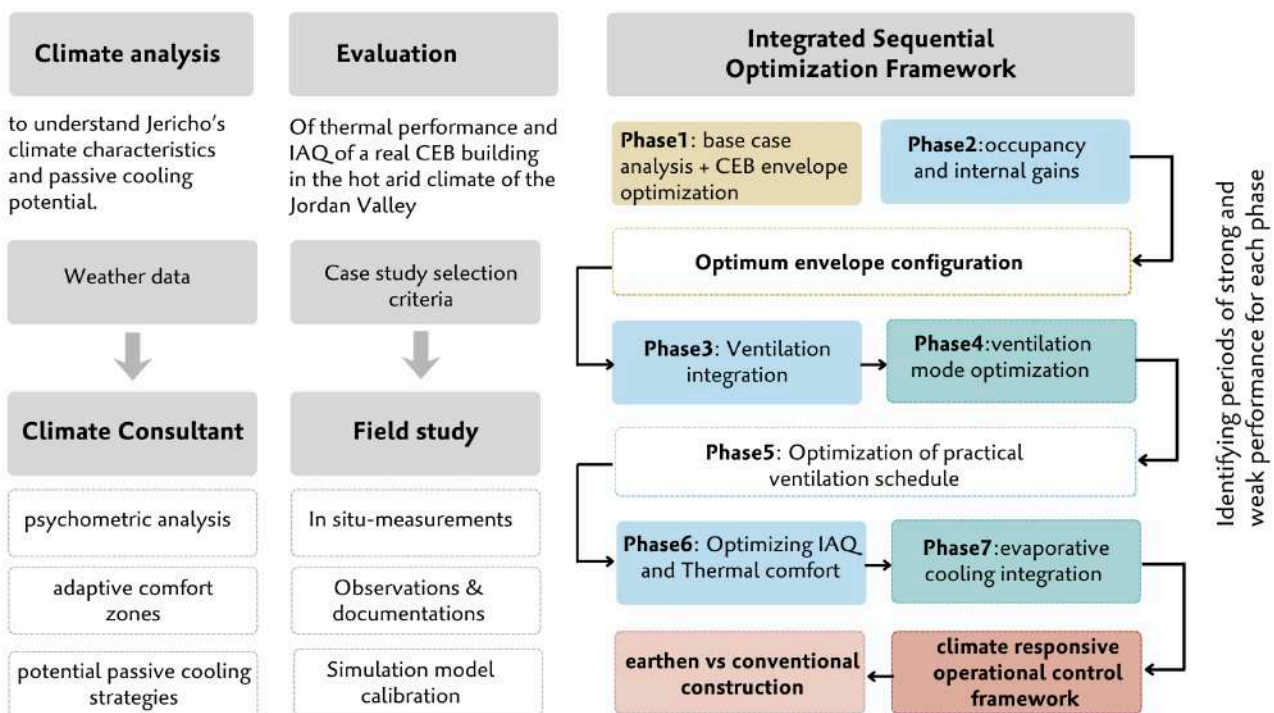


Figure 4-2: Research methodological framework diagram

4.2.1 Case study area and selection criteria

As shown in Figure 4-3, the West Bank and Gaza Strip have 7 climate zones, where the hot arid climate zone, represented by the yellow strip, extends along the Jordan Valley west of the Jordan River and the Dead Sea. Within this zone, Jericho is considered one of the major Urban centers of the Jordan Valley (Applied Research Institute-Jerusalem (ARIJ), 2003). The Jericho governorate includes Jericho city together with several rural communities and refugee camps located in the Jordan Valley lowlands (al-Ghor), including Al-Nuway'ima, Fasayil, Al-Jiftlik, Al-

‘Auja, ‘Ayn al-Duyuk, Deir al-Qilt, Deir Hajla, Nabi Musa, ‘Ayn al-Sultan, and ‘Aqabat Jabr. These settlements share similar climatic conditions characterized by high summer temperatures, low annual rainfall, and arid environmental conditions (Jabara, 2015). Historically, the region had a long tradition of earthen construction spanning around 10,000 years, with Jericho globally recognized as one of the oldest continuously inhabited cities in the world and among the earliest known examples of mud-brick architecture, where the Tel es-Sultan archaeological site, also known as ancient Jericho, was inscribed on the UNESCO World Heritage list in 2023 (UNESCO World Heritage Centre, 2023). In addition to the archaeological remains of early mud structures, the city still has surviving earthen buildings from the late Ottoman and British mandate periods that reflect the city’s rich earthen architectural heritage, which was almost lost after the second half of the twentieth century with the introduction of modern materials. In response, UNESCO, in collaboration with local initiatives, aimed to revive earthen architecture as a sustainable, low-cost, and climate-appropriate alternative to widely used modern construction materials, and initiated several projects in the Jordan valley, constructed from compressed earth blocks (CEB) (Tina and Antonelli, 2013). Accordingly, one of these projects will be selected as the case study for the thesis. The study adopts an embedded single-case study, following Yin (2018), in which the structural and roofing systems used in the UNESCO program form separate units of analysis within one building. Therefore, five selection criteria were fixed for selecting a base case from the candidate buildings as shown in Table 4-1. Two concerns shaped the criteria: the practical demands of the fieldwork and the aim of producing results that are representative of the construction the program actually delivered.

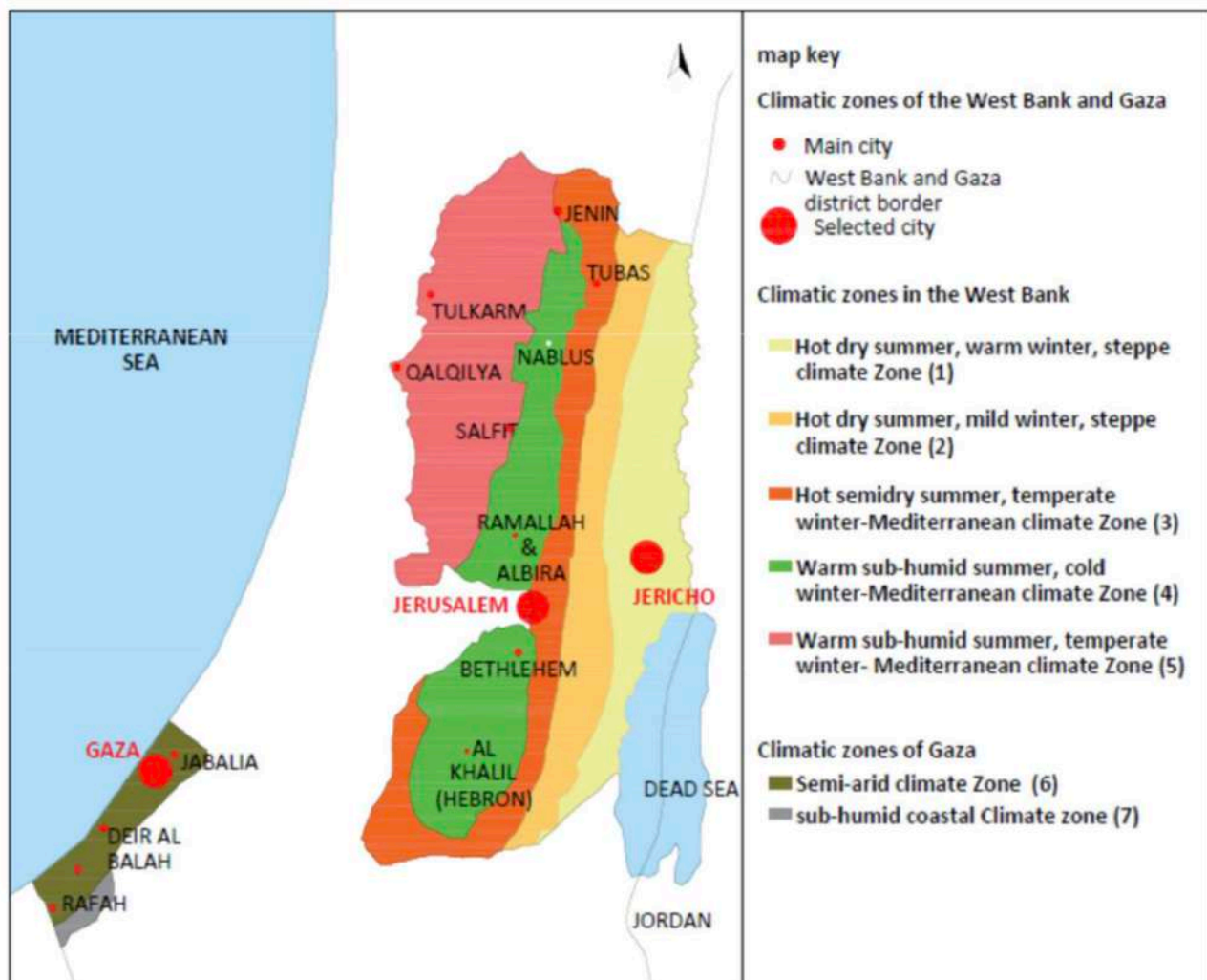


Figure 4-3: West Bank and Gaza Strip climate zones (Mohaibesh et al., 2021).

Table 4-1: Criteria adopted for case-study selection.

Selection criterion	Rationale
C1. Physical accessibility	The researcher must be able to reach the building to survey it, document its geometry, and confirm construction details and boundary conditions on site.
C2. Representative technique	The building must use the stabilised compressed earth block (CEB) method that UNESCO taught the local community, so that the results reflect how the program actually built.
C3. Typological comprehensiveness	The building should hold the full set of structural and roofing systems the program used (barrel vaults, beam-and-vault floors, and domes) rather than one variant.
C4. Diversity of thermal conditions	The building should offer several orientations, spaces, and roof forms to enable the assessment of building performance under different design and environmental conditions.

C5. Significance within the program/scale

A large, representative building was preferred because it better reflects the characteristics of the construction program and enhances the relevance and applicability of the study findings.

The purpose of this phase was to understand Jericho's climate characteristics and passive cooling potential. The weather data used was a typical meteorological year file for Jericho in EnergyPlus Weather (EPW) format, obtained from the Climate.OneBuilding.Org repository (Lawrie and Crawley, 2026). The file belongs to the TMYx dataset, in which each of the twelve calendar months is selected from the most recent fifteen-year record (2011–2025) following the TMY and ISO 15927-4:2005 methodologies. Climate Consultant was used to analyze the weather data using psychrometric analysis and the adaptive comfort model to identify comfort zones, overheating conditions, and determine when passive cooling strategies are needed. Additionally, it was used to analyze wind patterns, diurnal temperature variation, and overheating risk periods.

4.2.3 Field study

The case study building was first selected from the candidate projects by assessing them against the criteria set out in Section 4.2.1, and the outcome of that assessment is reported in Section 5.3. A field study was then conducted on the selected building to collect the data required to develop, calibrate, and validate the simulation model.

Two site visits were made, on 25 May and 4 June 2026, at the start and end of the monitoring period. Building documentation covered the construction system, building materials, envelope characteristics, spatial layout, geometry, orientation, and window and door configurations. Dimensions were taken from available drawings of the building, and the geometry was reconstructed in Revit as the basis for the DesignBuilder model.

The building was closed and unoccupied throughout the study period. Site observations therefore covered the physical condition and configuration of the spaces and the openable area and operation of windows and doors, rather than occupant behavior. These observations, together with the building documentation, informed the selection of the three representative zones reported in Section 5.5.2, chosen for their differing orientation, floor level, roof geometry, and environmental exposure.

Because the building was unoccupied, occupancy patterns could not be observed directly. An interview was conducted with two managers to establish the function of each zone, typical

occupancy levels, and operating hours during the building's period of use. This provided the basis for the occupancy schedules and internal gains applied in the simulation model.

Indoor environmental measurements were recorded over the cooling season of 2026. Data loggers recorded indoor air temperature and relative humidity at 15-minute intervals for 10 days, from 25 May to 4 June 2026, one in each of the three analysis zones, positioned at 1.2 m above floor level, away from direct solar radiation. These data were used for model calibration and validation.

A multi-day duration was chosen for indoor temperature validation as longer periods improve parameter stability and reduce unrealistic boundary convergence compared to single-day calibration periods (Kang et al., 2026). It is also consistent with previous studies that used a multi-day measurement period for validation, such as the study by Khechiba et al. (2023), who adopted a 3-day validation period, and Ouedraogo et al. (2024), who adopted a 7-day validation period. An informal interview was also conducted with two managers to obtain information on the building's operation, including the functions of each zone, typical occupancy levels, and operating hours. As the building was closed during the study period, and direct observation of occupancy patterns was not possible. Therefore, the interview provided the best available basis for defining realistic occupancy schedules and operational conditions for the simulation model. Table 4-2 presents the instrument used in this study and its main technical characteristics.

Table 4-2 Thermophysical Properties of Cement-Stabilized Compressed Earth Blocks (CSEB) Reported in Previous Studies.

Measured Parameter	Instrument	Unit	Accuracy (Condition)	Accuracy	Range
Air temperature (Ta)	UNI-T UT330 USB series data logger	°C	0°C–40°C	±0.5°C	-40 to 80
			-30°~0°C, 40°C	±1°C	
			-40°C~30°C, 70°C	±2°C	



4.2.4 Thermal model development and calibration

Design Builder v6 software was used to simulate the behavior of the case study earthen building. On-site environmental measurements, including indoor temperature and relative humidity, obtained during the monitoring period, were used to validate and calibrate the simulation model. According to the recommendations of ASHRAE 14 (2014), acceptable limits, the model was validated using the normal mean bias error (NMBE), the coefficient of variation

of the root mean squared error (CVRMSE), and the correlation coefficient (R^2) presented in Equations 4-1, 4-2, and 4-3.

$$NMBE = \frac{\sum_1^n (x_s^i - x_m^i)}{(n - 1)\bar{x}_m} \quad (4-1)$$

$$CVRMSE = \sqrt{\frac{\sum_1^n (x_s^i - x_m^i)^2}{(n - 1)}} \frac{1}{\bar{x}_m} \quad (4-2)$$

$$R^2 = \frac{\sum_1^n x_m^i x_s^i - n \bar{x}_m \bar{x}_s}{\sqrt{\left(\sum_1^n (x_m^i)^2 - n \bar{x}_m\right) \left(\sum_1^n (x_s^i)^2 - n \bar{x}_s\right)}} \quad (4-3)$$

where x_m is the measured value at time step i , x_s is the simulated value at time step i , $\bar{x}_m$ is the average measured value, $\bar{x}_s$ is the average simulated value, n is the total number of data points, i is the index of the data point or time step (Ruiz and Bandera, 2017).

4.2.5 Performance evaluation criteria

Every phase reports the same set of measures so the phases stay comparable. Thermal comfort follows the ASHRAE 55 adaptive model on operative temperature, since the building runs free of mechanical cooling and its occupants adapt to the hot-arid climate. Comfort is the share of occupied hours whose operative temperature falls within the 80% adaptive acceptability band, with the upper limit raised for elevated air speed when the indoor air velocity passes 0.3 m/s at operative temperatures above 25 °C (+1.2, 1.8, and 2.2 °C at 0.6, 0.9, and 1.2 m/s). Overheating is measured as the degree-hours by which operative temperature exceeds that upper limit, which weighs how far and how long the space runs hot and the exceedance hours count.

The wall thickness optimization phase additionally includes two thermal-mass indicators: the time lag between the peak indoor surface temperature and the outdoor surface and the decrement factor, the ratio of indoor to outdoor surface temperature swing. Together, they show how well each wall thickness delays and damps the outdoor peak, with an earthen benchmark decrement factor near 0.2.

Indoor air quality is judged by CO₂ concentration against EN 16798-1 Category II, which sets the acceptable concentration as a margin above outdoor, about 420 ppm in Jericho. For the non-residential, this margin is 800 ppm, giving a limit of about 1220 ppm. For the residence, a stricter

margin applies: EN 16798-1 sets the Category II value for dwellings' sleeping spaces at 550 ppm above outdoor, about 970 ppm in Jericho, on the reasoning that occupants sleep there for long, unbroken periods and that air quality through the night warrants the higher standard. The residence is therefore assessed against 970 ppm and the non-residential against 1220 ppm. The companion ventilation rate follows the same standard at Category II. The non-residential zones take the sum of a person component and a building component, 7 L/s per person plus 0.7 L/s·m² of floor, giving 5.51 ac/h for the office and 6.35 ac/h for the daycar. The residence takes the dwelling criterion of 7 L/s per person. Each rate is converted to air changes per hour from the zone volume, using equation 4-4, and it sets the fresh-air target against which the ventilation strategies are judged.

$$n_{ach} = \frac{q_{tot} \times 3.6}{V} \quad (4-4)$$

where n_{ach} is the required air change rate, q_{tot} is the total required outdoor-air rate (L/s), V the zone volume (m³), and 3.6 the conversion from litres per second to cubic metres per hour.

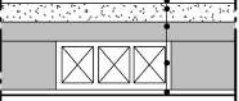
4.2.6 Definition of the conventional reference envelope

To provide a realistic performance benchmark, a conventional reference envelope was defined from a field survey of current construction practice in Jericho, conducted through interviews with local contractors, engineers, and municipality representatives, alongside earlier characterizations of typical Palestinian residential construction (Haj Hussein et al., 2022). The survey identified two common wall types, both already carrying insulation, reflecting present-day practice: a cavity wall of two cement blocks separated by 20 mm of closed-cell sprayed polyurethane foam and a 30 mm air gap, found in recent buildings, and a stone-clad wall of 50 mm natural stone over 150 mm concrete, 30 mm expanded polystyrene and a 70 mm cement-block backing. The cavity wall is the type being built across Jericho Gate, a large residential development of some 1,400 villas at the city's southern entrance close to the case-study building and one of the largest projects of its kind in Palestine, where a site engineer confirmed it as current standard practice. The roof and intermediate floors are ribbed reinforced-concrete slabs with hollow cement-block infill. Current construction practice in Jericho already incorporates insulation. The optimized earthen envelope was therefore benchmarked against an insulated conventional wall rather than an uninsulated one, so that the comparison reflects what is actually built in Jericho today. Comparing against an uninsulated wall would have exaggerated the relative benefit of earthen construction. Material properties (Table 4-3) were taken from the

Palestinian energy-efficient building guidelines (Ministry of Local Government, 2004), with natural stone from Haj Hussein et al. (2022). The two walls were defined in DesignBuilder from their layers, giving $0.67 \text{ W/m}^2\cdot\text{K}$ for the cavity wall and $0.77 \text{ W/m}^2\cdot\text{K}$ for the stone wall.

Table 4-3 Base Case Building Envelope Assemblies.

Element / U-value	Layers (outside to inside)	Density (kg/m ³)	C _p (J/kg.K)	k (W/m.K)	Thickness (m)
Wall A — Cavity brick U = 0.67 W/m².K	Cement plaster	1800	840	0.87	0.020
	Hollow cement block	1400	840	0.90	0.200
	Sprayed polyurethane foam (SPF)	30	1470	0.026	0.020
	Air gap (R = 0.18 m ² K/W)	—	—	—	0.030
	Hollow cement block	1900	840	1.20	0.100
	Cement plaster	1800	840	0.87	0.020
	2 cm plaster				
	20 cm cement block				
Wall B — Stone U = 0.77 W/m².K	Concrete backfill	2300	1000	1.75	0.150
	Expanded polystyrene (EPS)	30	1400	0.033	0.030
	Hollow cement block	1900	840	1.20	0.070
	Cement plaster	1800	840	0.87	0.020
	5 cm Stone				
	15 cm concrete				
	3 cm EPS				
	7 cm cement block				
Roof — Ribbed RC / hollow-block U = 2.17 W/m².K	Moisture barrier	2300	1000	1.10	0.020
	Sloping screed (concrete)	2300	1000	1.75	0.080
	Reinforced concrete	2500	1000	1.75	0.070
	Structural: hollow block (85%)	1620	1000	1.10	0.180
	Structural: concrete rib (15%)	2500	1000	1.75	0.180
	Hollow block + concrete rib	1750	1000	1.20	0.180
	Cement plaster	1800	840	0.87	0.020
	2 cm moisture barrier				
Intermediate floor — Ribbed RC / hollow-block U = 1.87 W/m².K	Terrazzo tile	2450	837	1.60	0.020
	Tile mortar	1900	650	1.20	0.020

	2 cm terrazzo tile					
	2 cm tile mortar	Sand	1500	840	1.40	0.070
	7 cm sand					
	7 cm Reinforced concrete	Reinforced concrete	2500	1000	1.75	0.070
	18 cm hollow block					
	18 cm Reinforced concrete	Hollow block + concrete rib	1750	1000	1.20	0.180
	2 cm plaster					
		Cement plaster	1800	840	0.87	0.020

The roof and intermediate floor are ribbed reinforced-concrete slabs with hollow cement-block infill, so their cross-section is non-uniform. Their transmittance was calculated by the area-weighted parallel method (Ministry of Local Government, 2004), splitting the slab into the hollow-block section (85%) and the concrete-rib section (15%). This gives $2.17 \text{ W/m}^2\cdot\text{K}$ for the non-insulated roof and $1.87 \text{ W/m}^2\cdot\text{K}$ for the intermediate floor. Since a one-dimensional model cannot place ribs and blocks side by side, the composite layer was entered as one equivalent material ($k = 1.20 \text{ W/m}\cdot\text{K}$, density = 1750 kg/m^3 , $cp = 1000 \text{ J/kg}\cdot\text{K}$)¹, preserving both its U-value and its thermal mass.

4.2.7 Integrated Sequential Optimization Framework

The optimization of the earthen building's thermal performance and IAQ was structured into seven simulation-based sequential phases, which together develop an integrated, climate-responsive control framework. Each phase addresses the limitations left by the preceding one, examining the interaction between envelope optimization, passive ventilative cooling, and supplementary cooling together with their operational control logic, so that they function as an integrated system rather than as independent measures.

The sequential structure follows the established hierarchy of passive cooling rather than an arbitrary ordering. Bhamare et al. (2019) define passive cooling as operating at three levels — heat protection, heat modulation, and heat dissipation, with the dissipation layer applied only where the first two prove insufficient, while Ergün and Bekleyen (2024) classify hot-arid strategies into heat-protection and heat-dissipation methods. The seven phases map onto this hierarchy: envelope optimization addresses heat protection and modulation, ventilative cooling addresses dissipation,

¹ The equivalent material is the area-weighted average of the hollow block (85%) and concrete rib (15%), which occupy the same 0.18 m layer: $k = 0.85 \times 1.10 + 0.15 \times 1.75 = 1.20 \text{ W/m}\cdot\text{K}$, $\rho = 0.85 \times 1620 + 0.15 \times 2500 = 1750 \text{ kg/m}^3$, and $cp = 1000 \text{ J/kg}\cdot\text{K}$ (both parts).

and supplementary evaporative cooling is introduced only where dissipation alone cannot maintain comfort.

This ordering also reflects a physical dependency between the strategies. The cooling load that ventilation must remove is determined by the envelope, and the effectiveness of thermal mass depends on the ventilation regime that discharges it; Sun et al. (2022) demonstrated that thermal mass produces the reverse effect where night cooling is absent, while Rodrigues et al. (2025) showed that optimal insulation thickness cannot be established independently of the ventilation strategy. Optimizing ventilation against an envelope that had not yet been fixed would therefore evaluate each strategy against a moving baseline.

A comparable sequence has been adopted in previous optimization research. Harkouss et al. (2018) optimized the envelope of a residential building across twenty-five climates for cooling demand, heating demand, and life-cycle cost, and then assessed thermal comfort in the optimized building separately, finding that overheating persisted for between 43% and 81% of occupied hours in the hot climates studied. Passive cooling strategies were introduced only at that point, and mechanical cooling only where those strategies proved insufficient. The authors state that thermal comfort was deliberately not implemented as a constraint within the optimization problem, so that the effect of the optimal design, the passive cooling strategies, and the air-conditioning system could be observed successively in each room, and they note that attaining minimum thermal loads does not in itself mean the resulting building is comfortable for its occupants. Reviewing integrated passive cooling in hot-arid environments, Benzine et al. (2026) similarly conclude that designs beginning from airflow, shading, thermal mass, and envelope strategy, and layering active assistance only where necessary, use fewer resources, particularly where control logic ensures passive capacity is fully exploited before any active system engages, and identify transferable hierarchical passive-to-active control frameworks as an outstanding need.

A sequential approach was preferred over simultaneous multi-objective optimization, such as the NSGA-II genetic algorithm applied by Chen and Yang (2017) and by Harkouss et al. (2018) to envelope parameters. First, the interdependence described above means the strategies cannot be varied independently without confounding their individual contributions. Second, the aim of this research is to produce transferable design and control guidance rather than a single optimal configuration, which requires the contribution of each layer to be isolated and quantified. The following subsections describe the simulation methodology for each phase, including the

independent variables, operational variables, evaluation framework, and the outputs that informed the subsequent phase.

Base-case analysis

Following the calibration and validation of the simulation model, the thermal performance of the case study building was first evaluated under free-floating conditions during a representative summer design week to establish the base-case scenario for the subsequent envelope optimization. The summer design week was selected because it represents the most demanding cooling conditions of the year, which would provide a more conservative basis for evaluating passive strategies where effective ones under these peak conditions are expected to remain effective throughout the cooling season. The base case analysis focused on identifying hourly indoor operative temperature, including overheating hours above the 80% and 90% comfort limit based on the ASHRAE 55 adaptive comfort, in addition to the dominant heat gains which would guide the optimization towards building components with the greatest influence on thermal performance.

Phase1: Parametric Optimization of Earthen Envelope

After the base-case evaluation, a parametric optimization process improved the earthen envelope by assessing different configurations, computing the same indicators for each under free-floating conditions to rank them by CEB wall composition, thickness, insulation type, and placement. The optimization ran in three stages, each isolating a set of variables, with the full set of configurations in Figure 4-4.

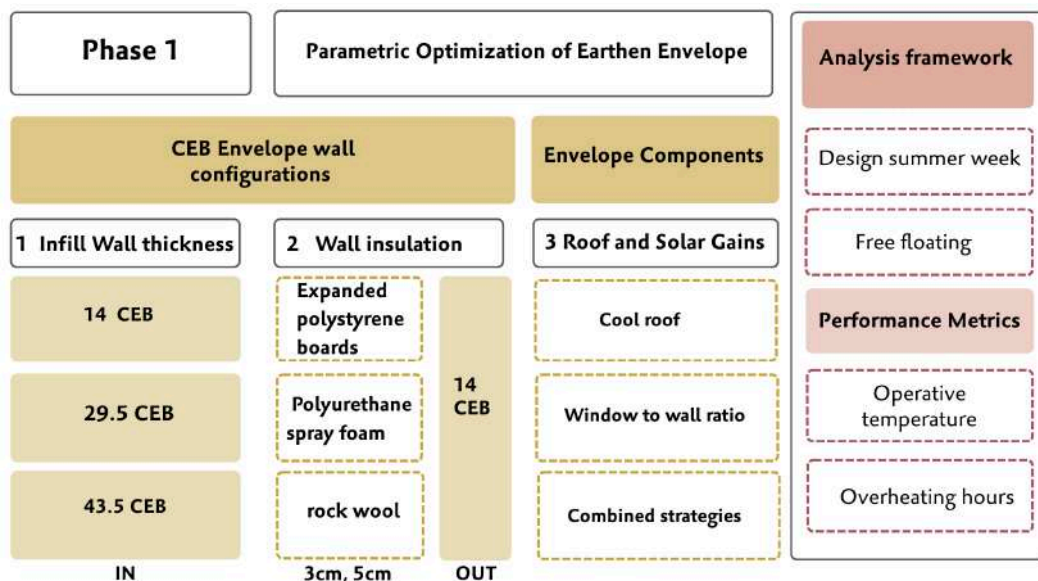


Figure 4-4: Phase 1 optimization framework.

Step 1: compared solid CEB walls of 14, 29.5, and 43.5 cm under free-floating conditions to determine the wall mass required to adequately damp the outdoor temperature swing. These three thicknesses were not selected as arbitrary parametric increments but represent the discrete wall dimensions that can be built from a single standard block. The UNESCO (2013) Compressed Earth Block Construction Manual for the Jordan Valley specifies a standard block of $29.5 \times 14 \times 10$ cm, from which 14 cm corresponds to the block laid as a stretcher, 29.5 cm to the block laid as a header, and 43.5 cm to a header and stretcher combined. Intermediate thicknesses would require cut blocks or non-standard production and were therefore excluded as impractical for local construction.

The manual recommends a CEB mixture comprising 50–60% sand, 20–30% clay, 10–20% gravel, and approximately 15% silt, stabilized with 3–8% cement for sandy soils or 6–12% lime for clay-rich soils. Since Jordan Valley soils are predominantly sandy, this study adopted an 8% cement-stabilized CEB. The thermal properties assigned to the CEB walls in the simulations were adopted from Omar Sore et al. (2018) and are summarized in Table 4-4.

Table 4-4 Thermophysical Properties of Cement-Stabilized Compressed Earth Blocks (CSEB) Reported in Previous Studies.

Reference	thermal conductivity	density	Thermal diffusivity	Specific heat	Location
(Hema et al., 2020)	0.8 -1.2 W/m·K	1700 - 2200 kg/m ³	-	-	-
(Omar Sore et al., 2018)	1.22 W/m·K	1900 kg/m ³	5.75×10^{-7} m ² /s	1106.87 J/kg·K	Ouagadougou, Burkina Faso
(Nshimiyimana et al., 2020)	1.01 W/m·K	1781 kg/m ³	6.8×10^{-7} m ² /s	844 J/kg·K	Serpa, Portugal

The thickness optimization was applied only to the non-load-bearing external infill walls, as the thickness of the structural external walls was fixed by the existing building system. The analysis also examined the relationship between outdoor temperature and indoor operative temperature through two thermal-mass indicators defined in Section 3.2: the time lag between the peak indoor surface temperature, and the decrement factor, the ratio of the indoor to the outdoor temperature swing, which together measure how far the wall delays the outdoor peak and how strongly it damps it, against the decrement factor of about 0.2 reported for earthen buildings by Carrobé et al. (2021). These indicators, read alongside the building's ability to

hold a stable operative temperature under fluctuating outdoor conditions, identified the critical periods when the thermal mass was insufficient and supplementary cooling was needed.

Step 2: fixes the optimum wall thickness identified in Step 1 and selects the best insulation material from EPS, polyurethane, and rock wool. These three are the insulations that Palestinian studies report as common and locally available (Alsayed and Tayeh, 2019; Alsurakji et al., 2021; Haj Hussein et al., 2021), confirmed for the Jericho market through interviews with local suppliers and contractors. Table 4-5 shows the insulation material used and its thermal properties.

Table 4-5 Thermal properties of the insulation materials used in the simulations (Ministry of Local Government, 2004).

Material	Conductivity k (W/m·K)	Specific heat C_p (J/kg·K)	Density ρ (kg/m ³)
Expanded polystyrene (EPS)	0.033	1400	30
Sprayed polyurethane foam (SPF)	0.026	1470	30
Rock wool	0.042	840	92

The insulation was added to the fixed wall thickness placed externally and protected by a 14 cm CEB layer. Each insulation material was evaluated at thicknesses of 3 cm and 5 cm under two application scopes: first insulating the external infill wall only, and second extending the insulation to the exterior face of the structural external walls, and all configurations were simulated under free-floating conditions over the summer design week.

Step 3: This step evaluates passive envelope measures selected in response to the dominant heat gain elements in the envelope identified during the base case analysis. This stage aimed to reduce the influence of the roof and solar heat gains using passive measures recommended by literature for hot-arid climates and compatible with earthen construction, to isolate the effect of the assessed wall configurations in the subsequent phases. A cool roof strategy of reflective white acrylic roof coating and a reduced window-to-wall ratio were selected as passive measures suitable for hot-arid climates and compatible with earthen construction. The interventions were evaluated individually and in combination under free-floating conditions over the summer design week. The cool roof strategy was also assessed together with the minimum insulation configuration (3 cm EPS on the external infill walls) to determine whether the reduced roof and solar heat gains made a thinner insulation layer sufficient.

Phase 2: Occupancy and internal heat gains

Following the free-floating envelope optimization in Phase 1, occupancy and internal heat gains were incorporated to evaluate the optimized envelope's performance under realistic operating conditions as shown in Figure 4-5. The optimum CEB wall thickness and the insulation material identified in Phase 1 were fixed at this phase, and the variables included the insulation thickness (3 and 5 cm), application extent (external infill or all external walls), and roof and solar control measures under occupied conditions. Additionally, insulation placement (exterior or interior of the earthen wall) was also evaluated to assess the interaction between the indoor environment and the earthen thermal mass. The envelope strategies were evaluated according to the dominant heat gain mechanism of each zone.

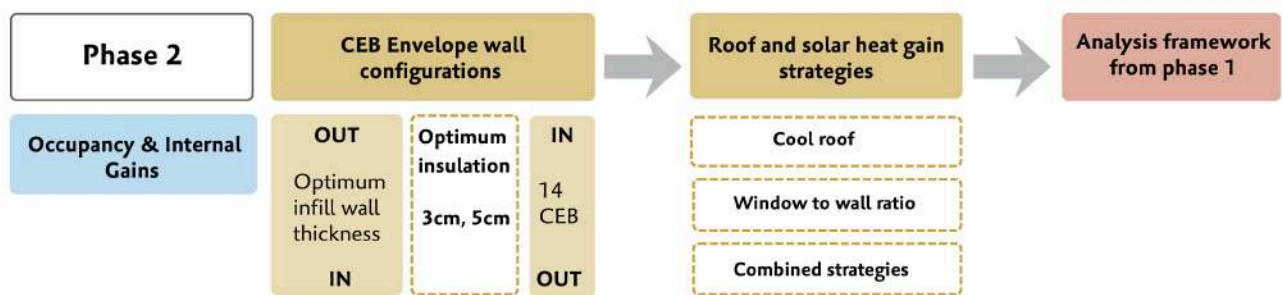


Figure 4-5: Phase 2 optimization framework.

Phase 3: Integrated Ventilation and Thermal Performance Assessment

Phase 2 evaluated the optimized envelope under occupied conditions, with occupancy and internal heat gains incorporated, and identified the best-performing combination of insulation thickness, placement, application extent, and roof and solar control measures for each zone. Building on that outcome, this phase introduced natural ventilation and compared the thermal performance of the occupied free-running case with naturally ventilated cases, as shown in Figure 4-6. The envelope configurations assessed in Phase 2 were re-evaluated under ventilated conditions to determine whether the optimum configuration remained unchanged once ventilation was introduced.

An automated all-day ventilation schedule with temperature control was adopted, allowing windows to open only when the outdoor air temperature was lower than both the indoor air temperature and the upper limit of the 80% adaptive comfort limit. This control served two purposes: first. To quantify the maximum cooling potential of natural ventilation by admitting outdoor air only when it reduced indoor temperature, thereby isolating the cooling effect of

ventilation, and second, to identify the optimum periods for ventilative cooling. By following the approach of Zeng et al. (2022), who derived a practical rule-based strategy from an optimum control schedule, the automated control was used as a benchmark to identify these optimum periods. Therefore, a 24-hour heat map showing the period when the automated control opened the windows for each zone was used, which provided the basis for obtaining practical ventilation schedules that could achieve similar results to the automated control.

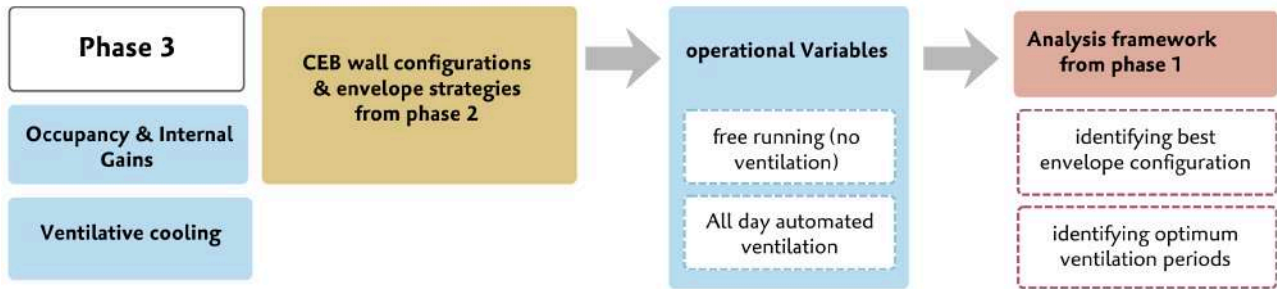


Figure 4-6: Phase 3 optimization framework

Phase 4: Ventilation mode: single-sided, cross ventilation, and windcatcher

Building on the optimized envelope configurations established in the previous phase, Phase 4 evaluates the effectiveness of three natural ventilation strategies: single-sided ventilation, cross ventilation, and windcatcher-assisted ventilation. The objective is to determine whether these strategies can provide adequate ventilation rates according to EN 16798-1 Category II requirements while also improving thermal conditions through increased air movement and heat removal. The performance of each strategy was evaluated based on achieved air change rates (ACH), achieving the required ventilation rates, and the effect on indoor operative temperature.

The same operational conditions established in the previous phase were used, and all ventilation strategies were simulated using an automated all-day ventilation schedule to isolate the influence of the ventilation configuration. Natural ventilation was modeled using DesignBuilder's airflow network model, which considers wind-driven airflow based on wind pressure coefficients derived from outdoor wind speed and direction from the weather file, as well as buoyancy-driven airflow through openings, vents, and cracks.

Among the evaluated strategies, a single-sided windcatcher was investigated because it can enhance natural ventilation by capturing prevailing wind at higher elevations and increasing the pressure difference that drives airflow. A square windcatcher configuration was adopted

based on previous studies showing that square sections can provide higher airflow performance compared with circular and rectangular alternatives (Maneshi et al., 2012; Alhraki and Sultan Qurraie, 2024). The inlet and outlet openings were designed with an aspect ratio of 1:1.5, based on the rectangular opening proportion that showed the best performance among the tested configurations by Shayegani et al. (2024), which achieved the optimum performance. The opening area was maintained equal to the windcatcher shaft cross-sectional area for all tested configurations. However, its performance depends largely on its geometry, particularly the shaft cross-sectional area and height. Therefore, a parametric analysis was conducted to identify the optimal windcatcher configuration, as illustrated in Figure 4-7. The shaft cross-sectional area was evaluated at 3% and 6% of the zone floor area. The 3% ratio was selected based on the recommendation of Attia and De Herde (2009, cited in Mayhoub et al., 2025), while the 6% ratio was included to examine whether a larger shaft improves ventilation performance. Heights of 6 m and 9 m were selected based on previous studies in hot-arid climates, where 6 m was found to be an effective height (Ghadiri, 2011) and 9 m was shown to further improve ventilation performance (Ayoobi et al., 2024).

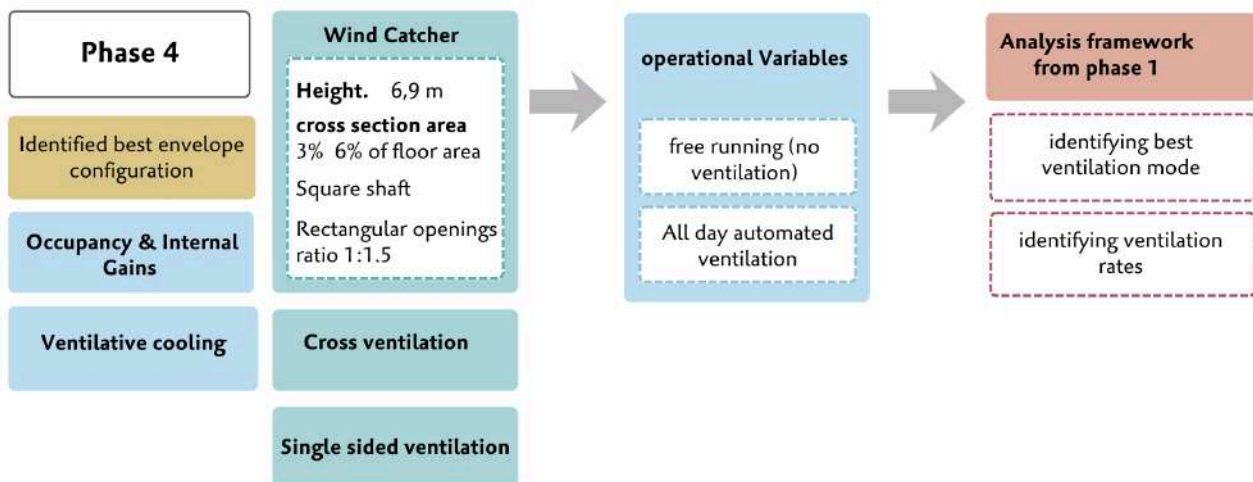


Figure 4-7: Phase 4 optimization framework.

Phase 5: Practical ventilation schedules

The previous phase identified the optimum ventilation mode and performance under an automated control strategy, representing the maximum achievable benefit when ventilation is activated at the most effective periods. However, such control requires continuous monitoring and automatic operation, which may not reflect practical user-operated ventilation. Therefore, this phase evaluates fixed ventilation schedules that can be realistically applied by occupants while maintaining the benefits of natural ventilation as shown in Figure 4-8. The practical

schedules were developed based on the effective ventilation periods identified from the automated ventilation results, considering zone function, occupancy patterns, and operational feasibility. Each zone was assessed separately, and the selected schedules were compared with the automated optimum to determine the performance gap between optimum and manually achievable ventilation control. The evaluation considered ventilation rate (ACH), compliance with EN 16798-1 Category II requirements, and the impact on indoor operative temperature and overheating hours and periods.

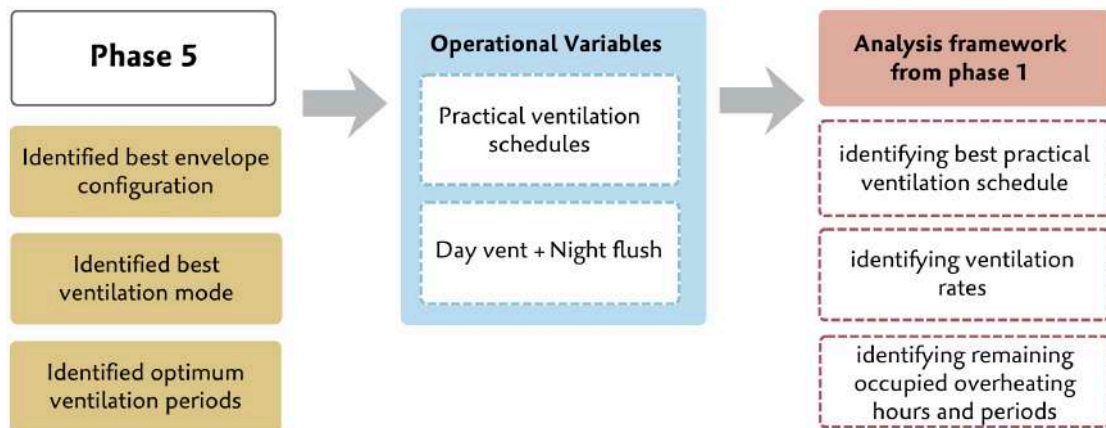


Figure 4-8: Phase 5 optimization framework.

Phase 6: IAQ and thermal comfort assessment under occupied-hours ventilation

Building on the practical ventilation schedules identified in the previous phase, this phase evaluates their ability to maintain both indoor air quality and thermal comfort during occupied hours as shown in Figure 4-9. In addition to the practical schedules, alternative occupied-hour ventilation strategies, including single-sided ventilation and intermittent (decremental) cross ventilation, were evaluated against continuous cross ventilation throughout the occupied period. In this study, indoor air quality is assessed specifically through CO₂ concentration and ventilation rate, which together indicate whether the delivered airflow is adequate to dilute occupant-generated contaminants to the level specified by EN 16798-1 Category II. Thermal performance was evaluated using operative temperature. The objective was to determine whether natural ventilation alone could simultaneously satisfy ventilation and thermal comfort requirements, or whether additional cooling strategies were required.

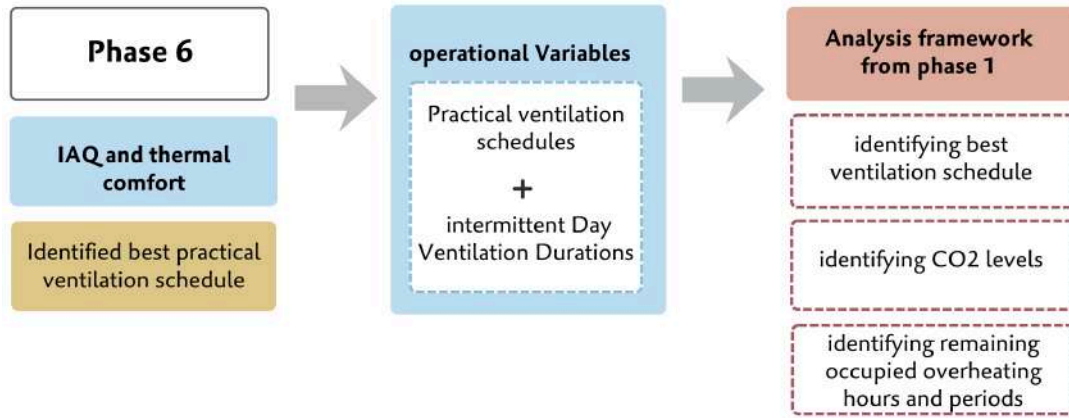


Figure 4-9: Phase 6 optimization framework.

Phase 7: Integration of Direct Evaporative Cooling

This phase investigated the integration of direct evaporative cooling to overcome the thermal limitation that passive ventilation could not close in the hot occupied hours, when the outdoor air is too warm to admit and moving it through the room no longer cools (Figure 4-10). The cooler was modelled as an active direct evaporative cooling system: a constant-volume fan draws 100% outdoor air across a cellulose evaporative pad and supplies it to the zone, so the incoming air is cooled before it enters, following the direct evaporative approach of Saif et al. (2021). It was represented in DesignBuilder by the Direct (Research Special) evaporative cooler in a Detailed HVAC air loop, which predicts the outlet air temperature from the saturation effectiveness of the pad using equation (x):

$$T_{out} = T_{in} - \varepsilon (T_{DB} - T_{WB}) \quad (4-1)$$

Where T_{out} is the outlet air temperature °C, T_{in} is the inlet (outdoor) dry-bulb temperature °C, T_{DB} is the outdoor dry-bulb temperature, T_{WB} is the outdoor dry-bulb temperature, ε is the effectiveness (or slope coefficient). The model is based on the effectiveness of direct evaporative cooling to cool the inlet air toward its wet-bulb temperature, derived from the earlier work of Baruch Givoni on passive downdraught evaporative cooling (PDEC) towers. Chiesa and Grosso (2015) compared several prediction methods against measured outlet temperatures from real evaporative systems, including wet pads and shower cooling towers, and found this simplified model the most accurate; they recommended a slope coefficient of

0.8, which was adopted here and is consistent with the measured effectiveness of corrugated cellulose pads (Nada et al., 2019; Tejero-González and Franco-Salas, 2021).

Within the pad, recirculated water is distributed over the evaporative media and the incoming air passes through the wetted media, allowing the adiabatic saturation of the air: heat is removed from the air by the evaporation of water, producing cooler air at a higher moisture content. The fan runs as an active constant-volume supply rather than on wind-induced airflow, so the delivered rate does not depend on outdoor pressure or wind. The supply flow was set for each zone to its own ventilation requirement, so the system delivers the fresh-air rate and its cooling in one stream of outdoor air. It ran over the hot occupied hours when passive ventilation could not hold comfort, with the cooler morning left to natural cross-ventilation.

This study assessed evaporative cooling at the performance level only, testing whether cooling the fresh-air supply at the required ventilation rate could hold comfort through the occupied hours. The physical integration of the system, the pad housing, the duct routing, and its architectural incorporation into the building, was outside the scope and is left to future work.

Based on the results of all seven phases, a climate-responsive operational control framework was developed. The framework integrates the heat-modulation strategies with the heat-dissipating and ventilation strategies, and defines the periods and the climatic conditions under which each strategy should be activated to complement the others, achieving the optimum thermal comfort conditions and maintaining acceptable indoor air quality while minimizing energy consumption.

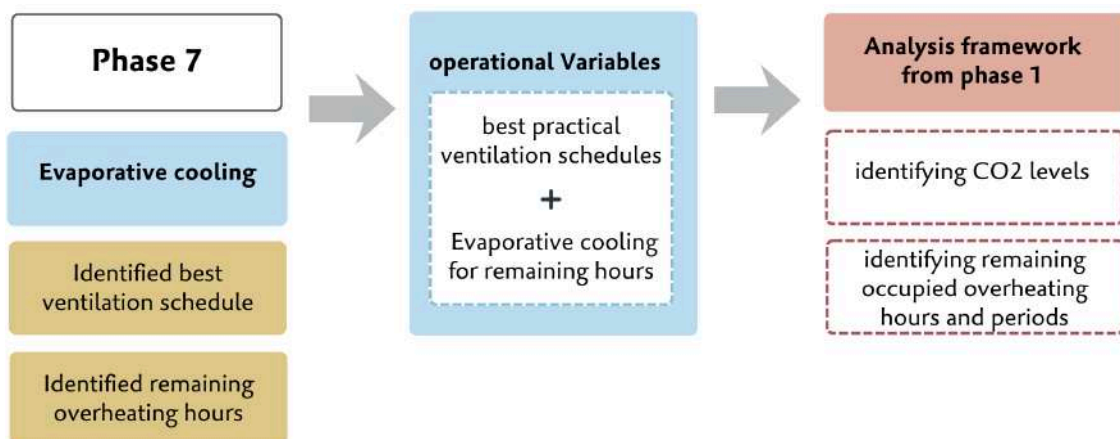


Figure 4-10: Phase 7 optimization framework.

4.2.8 Comparative Assessment of Earthen and Conventional Construction

In this final stage, the optimized earthen envelope resulting from Phases 1–5 was compared against the two conventional reference envelopes defined earlier, which are the insulated cavity brick wall that prevails in current Jericho construction and the insulated stone-clad wall that is also common, each paired with the typical ribbed reinforced-concrete roof. The comparison switches the whole building fabric between the earthen and conventional systems: the external walls, the roof, the intermediate floors, and the internal partitions (replaced with thin 150 mm concrete-brick partitions) were all changed to the conventional construction, while the building geometry, glazing, occupancy, operational schedules, and the climate-responsive control framework developed in Phase 5 were held identical, so that the comparison isolates the effect of the construction alone. And because the earthen and conventional walls differ greatly in thickness, the net internal floor area and volume were held constant across all runs so the comparison reflects the thermal behaviour of the envelope rather than differences in building size. Performance was evaluated based on adaptive thermal comfort, overheating severity, and indoor CO₂ concentration.

Case study**5.1 The UNESCO Projects**

UNESCO initiated a program to revive earthen architecture in the Jordan Valley. The program aimed to encourage community participation and engage the locals in the project implementation through training programs, workshops, and awareness activities that promote the construction technique of earthen structures, which mainly focused on stabilized compressed earth blocks. In addition, the programs provided 4000 work hours for more than 240 workers. The program included a small trial project, three women's centers, a model sustainable building, and a prototype of a low-cost, self-built housing unit dedicated to emergencies (Tina and Antonelli, 2013). All the projects implemented the same construction method with very small variations between them. The blocks were produced from a mixture of soil, gravel, and cement. The mix consisted of 6 buckets of Valley Gravel with 4 buckets of white Soil and 4 buckets of red Soil, plus 0.6 buckets of cement, which produces 18 CEBs (UNESCO, 2013). Soil was first sieved, then all dry materials were mixed and gradually sprayed with water, and then compressed in a hydraulic press to produce the blocks. The blocks were then stored in a dry, shaded area for three days to be cured through condensation, then the blocks were exposed to the sun while regularly sprayed with water until they were ready for use, with the whole process taking nearly eight days. The block dimensions depend on the mould in the manual press, and the standard block produced for the Jordan Valley programme measures $10 \times 29.5 \times 14$ cm (UNESCO, 2013). The foundations were constructed from a reinforced concrete slab on grade, raised approximately 28 cm above ground level. Afterwards, earthen columns were built directly on top of the concrete foundation, which consisted of thick piers made of CEB linked together by arches with a thickness of two brick layers that support the roof. The walls were constructed from one brick layer (30 cm), while in areas with a large span, the facade thickness could reach 120 cm (Jabara, 2015). The completed projects within the program include women's centers in Bardalah, Dyouk, and Aqbat Jabr refugee camp in Jericho city.

5.2 Candidate projects

Three completed projects from the programme were considered as candidates for the case study: the women's centres at Bardalah, Dyouk, and Aqbat Jabr. All three lie within the hot-arid climate zone of the Jordan Valley, shown in yellow in Figure 5-1, which runs the length of the valley's western edge. The following subsections describe each in turn.

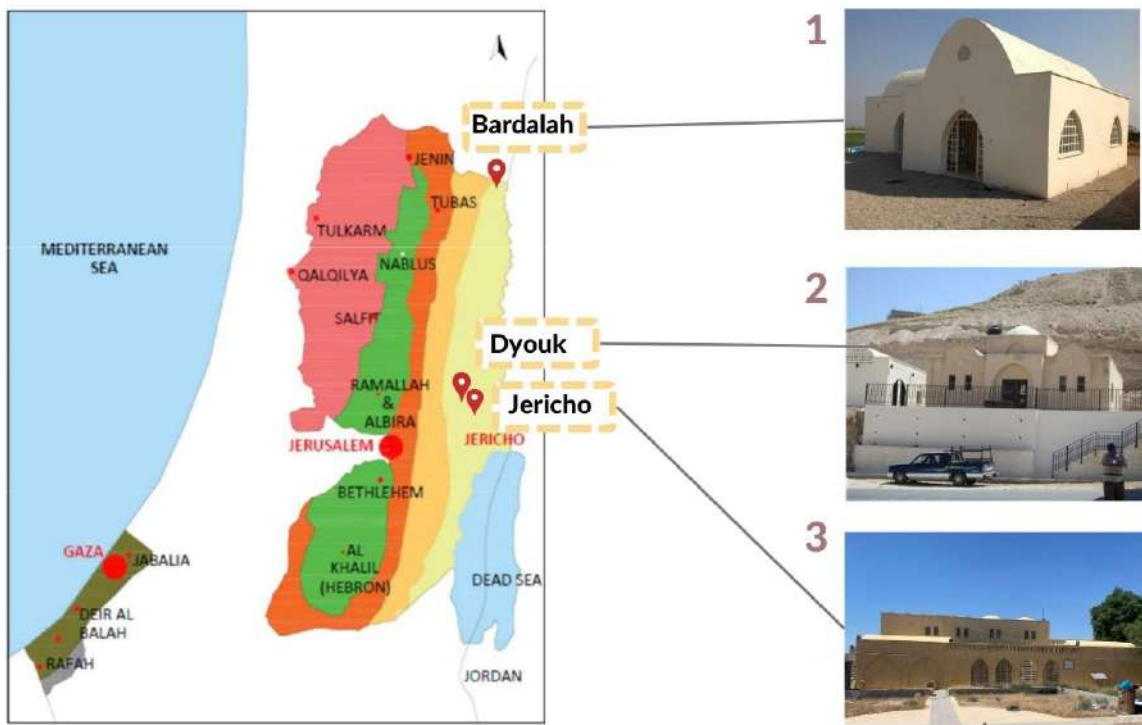


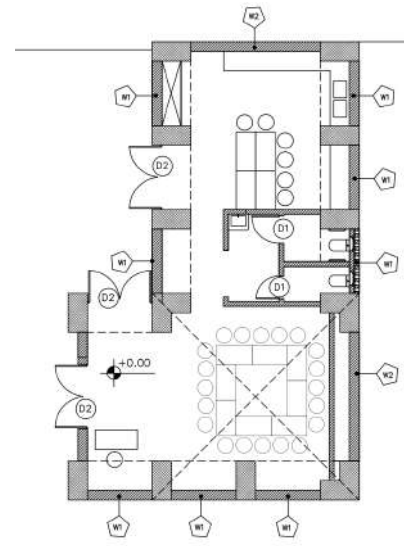
Figure 5-1: The three candidate projects , (1) Bardalah, (2) Dyouk, and (3) Aqbat Jabr, Jericho. Base map after Mohaibesh et al. (2021); photographs (1) and (2) from Germanà and Alatawneh (2016), photograph (3) by the author.

5.2.1 Bardalah women's center

The project was completed in 2013, located in the Northern Jordan Valley in Bardalah village, which falls under Tubas Governorate, north of the West Bank. The building was constructed from CEB, with a total floor area of about 107.5 m², and consists of two rooms and services. The Roof is constructed from two intersecting CEB barrel vaults. The windows are aluminium-framed and 1.50 m high, in two sizes: two-leaf sliding units 2.00 m wide and four-leaf sliding units 4.00 m wide, all fitted with external metal protection; the entrances are single-leaf timber doors and toughened-glass double doors. The design originally included a passive wind catcher integrated into the southeast facade of the building, however it was not constructed and was replaced with a small circular ventilation opening located at the upper part of the facade. Today, the building is used as a kindergarten and a community center.



(a)



(b)

Figure 5-1: (a) Bardalah women's center, (b) floor plan (Germanà and Alatawneh, 2016).

5.2.2 Dyouk women's center and restaurant

The project consisted of two structures, a women's center with a total floor area of about 95 m², completed in 2013, and a restaurant operated by the center, completed in 2014, Figure 5-2. The project is located in Dyouk village, which falls under the Jericho governorate, located northwest of Jericho city. The two structures have CEB barrel vault roofs, which were constructed on a continuous reinforced concrete ring beam cast along the top of all load-bearing walls. The windows are aluminium-framed and 1.80 m high, comprising two-leaf sliding units 0.90 m wide and narrow top-hung units 0.45 m wide, with external metal protection; the openings include single-leaf timber doors, a two-leaf metal door, and toughened-glass hinged and sliding doors. What distinguishes the restaurant's structure from others is that instead of constructing the CEB columns directly above the reinforced concrete foundation, the columns were raised on a continuous stone plinth filled with concrete, which helps to protect the earthen structure from rainwater. This approach followed the traditional way of building earthen structures (Jabara, 2015).

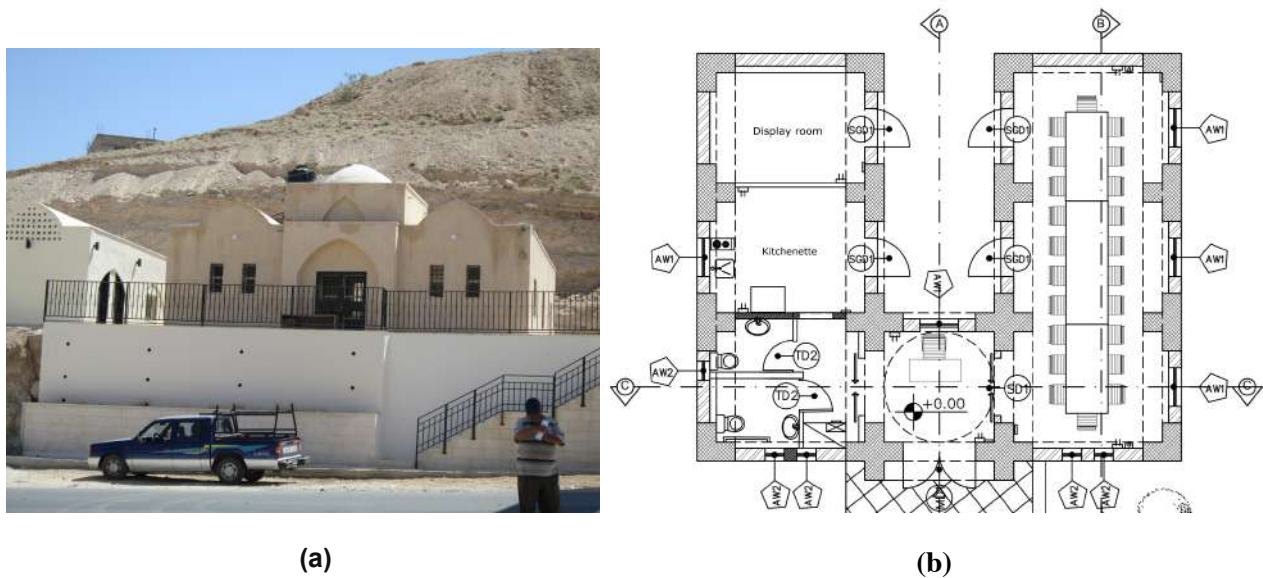


Figure 5-2: (a) Dyouk women's centre and restaurant, exterior view, (b) floor plan (Germanà and Alatawneh, 2016).

5.2.3 Aqbat Jabr women's center

This center was the first project within the program to be completed in the Jordan Valley in 2011. The project has a total floor area of about 289.5 m² distributed over two levels: 208 m² on the ground floor and 81.5 m² on the upper floor. The building was constructed from CEB in a similar way to the previous projects, with a slightly different structural approach adopted for the portion of the building holding the first floor, Figure 5-3. The building has a U-shaped plan composed of several spaces arranged around a courtyard. Most of the ground-floor spaces are covered by CEB barrel vaults connected to the load-bearing walls by a continuous reinforced concrete ring beam. Regarding the spaces that support the upper floor, the roof was constructed from beams and a vaulted structural system. In addition to the reinforced concrete ring beams, transverse beams were also used with smaller CEB barrel vaults filling the spaces between the beams. And the roof of the first floor was constructed from CEB domes. The openings are aluminium-framed and single-glazed, and are strongly differentiated between the two floors. At ground level, the courtyard-facing façades are opened by large arched glazed screens that fill the vaulted bays almost to the springing of the vaults at about 2.40 to 2.70 m, each divided by vertical mullions into a central glazed doorway and flanking glazed panels, giving these spaces a high proportion of glazing. The upper floor, by contrast, is lit only by small top-hung windows, each of two vertical panes approximately 0.40 m wide and 1.00 m high.



Figure 5-3: Aqbat Jabr women's centre, exterior view of the two-storey building (photograph by the author).

5.3 Evaluation of the Candidate Projects

The UNESCO earthen architecture program in the Jordan Valley built three women's centers in Bardalah, Dyouk, and Aqbat Jaber. All three use the same stabilized compressed earth block (CEB) method, yet differ in scale, geometry, and structural complexity. This study takes one of them as the base case for thermal comfort and IAQ optimization work. The three buildings were evaluated against the five selection criteria defined in the methodology chapter, and Table 5-1 presents the results. Bardalah was eliminated as it failed criterion 1, as the location was not easily accessible for measurements and documentation. Dyouk consists of two small structures roofed only with CEB barrel vaults, offering a single typology and so fails C3, and its narrow range of spaces gives little thermal diversity, which weakens C4. Abate Jabr meets all five criteria.

Table 5-1: Evaluation of the candidate projects against the selection criteria.

Criterion	Bardalah	Dyouk	Aqbat Jabr
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C1. Physical accessibility	Not accessible	Accessible	Accessible
C2. Representative technique	Yes	Yes	Yes
C3. Typological comprehensiveness	Vaults only	Vaults only	Vaults, beam-and-vault, domes
C4. Diversity of thermal conditions	Low (one storey, two rooms)	Low (two small structures)	High (two storeys, courtyard, mixed roofs)
C5. Significance within the program	107.5 m ²	95 m ²	289.5 m ² ; first project (2011)

5.3.1 Justification for Selecting Aqbat Jabr

This study selected the Aqate Jabr women's center as its base case. It is accessible, and one building holds the full set of structural and roofing systems that UNESCO taught local builders. CEB barrel vaults on a continuous reinforced concrete ring beam roof the single-storey ground floor, which is the system Bardalah and Dyouk also use. Transverse reinforced concrete beams with smaller CEB barrel vaults between them carry the upper level, and a CEB dome roof the first floor. Each system, therefore, forms a separate unit of analysis in the embedded single-case study, and the U-shaped courtyard plan gives a wider span of thermal conditions than any single-typology building. Figure 5-4 sets out this build-up stage by stage, from the arches on the concrete slab to the completed shell.

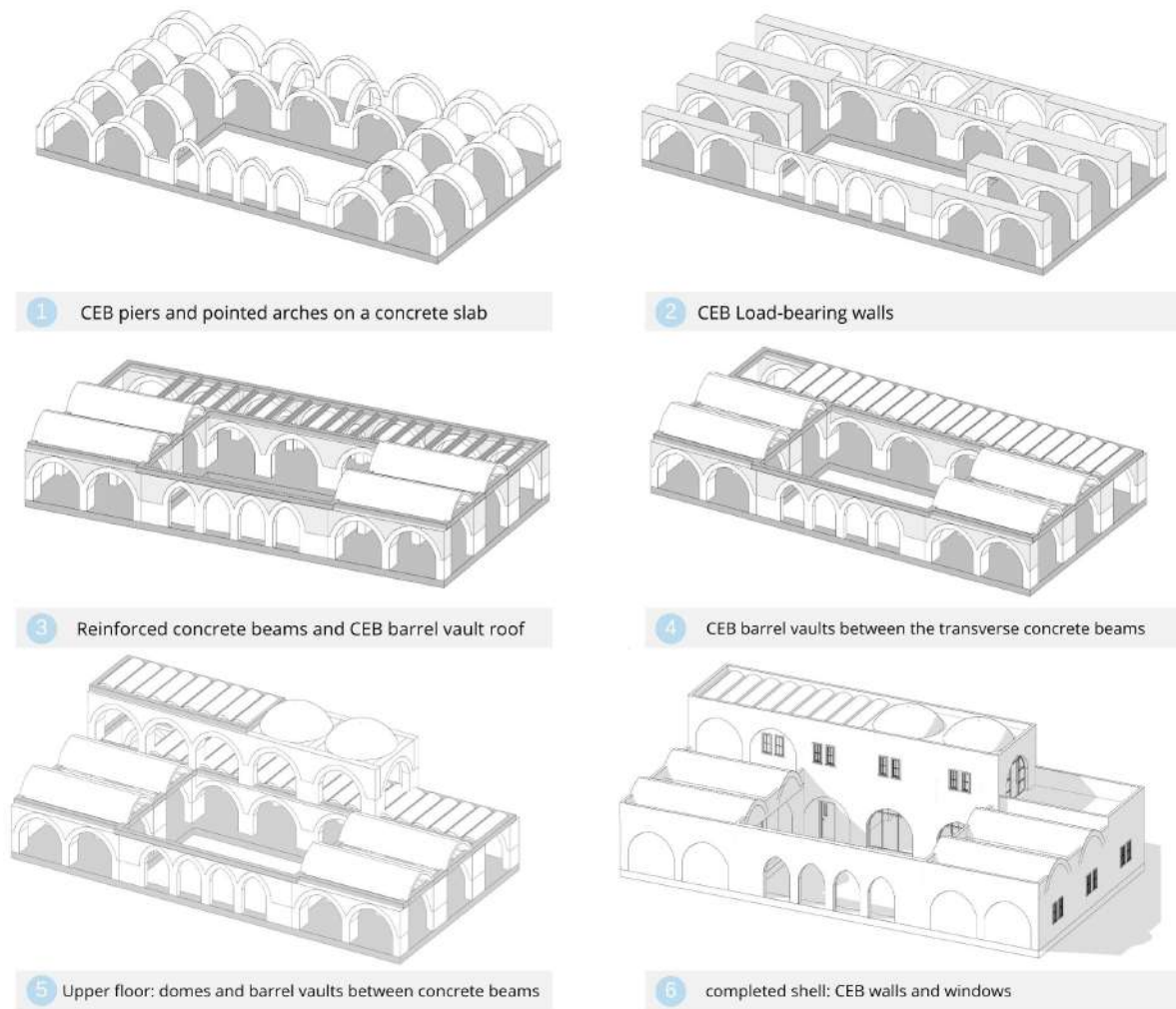


Figure 5-4: Construction build-up of the Aqbat Jabr women's centre, from slab on grade to the completed shell (author's Revit model).

5.4 Jericho climate analysis

The results of this analysis show Jericho's cooling season conditions and set out the passive potential that the phases build on. The weather data was obtained from the Jericho EnergyPlus WeatherFile from (OneBuilding), for a site 275 m below sea level at 31.87° N. Jericho sits among the lowest inhabited places on earth, which leads to its extreme summer heat. Climate Consultant was used to read the weather file through the temperature range, the monthly diurnal averages, the wind wheel, and the psychrometric bioclimatic chart, which were evaluated using the ASHRAE 55 adaptive model. The cooling season in Jericho stretches from May to September, with dry-bulb temperature peaks at 38.6 °C (Figure 5-5). Jericho's mean monthly outdoor temperature ranges from 13.2 °C in January to 30.1 °C in the peak summer month, both within the 10–33.5 °C validity range of the ASHRAE 55 adaptive comfort model, so the model applies to this climate. Within that range, the comfort band runs from 18.4 to 30.6 °C, operative at 80% acceptability and 29.6 °C at 90%

acceptability, as shown in the psychometric chart in Figure 5-6, where 36.2% of the annual hours can be brought into the ASHRAE 55 adaptive comfort zone through adaptive comfort ventilation, which corresponds to approximately 51% of the cooling-season (May–September) hours.

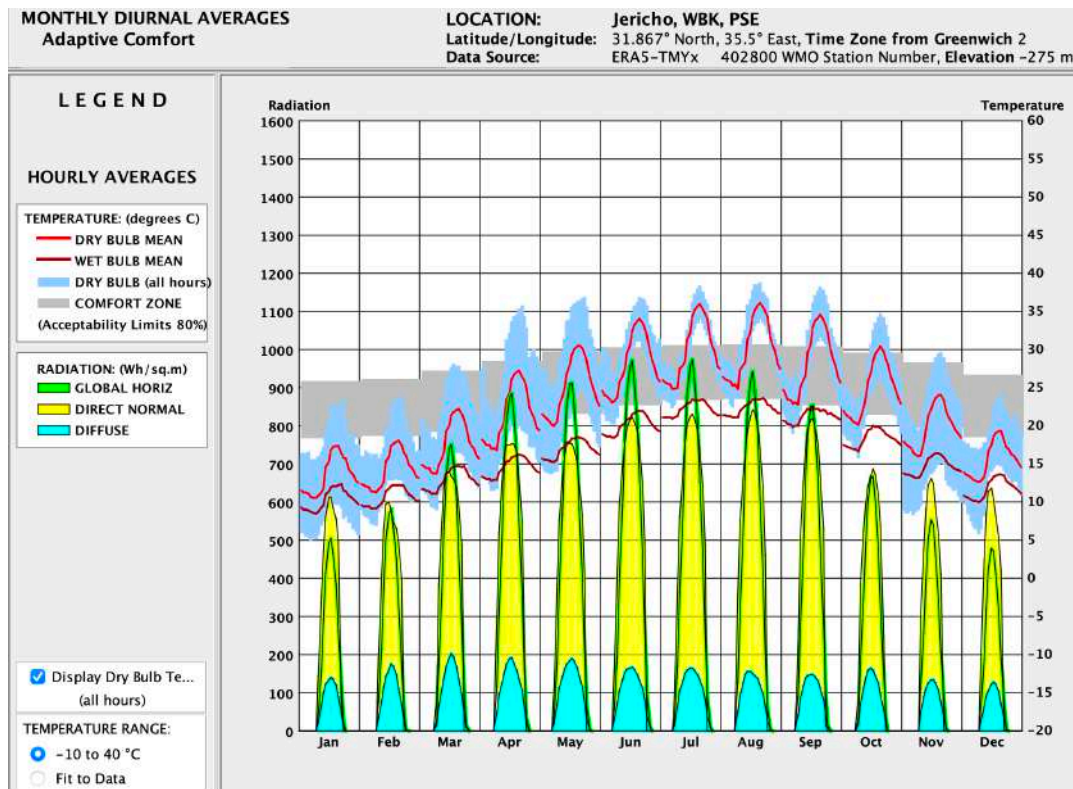


Figure 5-5: Monthly diurnal averages of dry-bulb and wet-bulb temperature, solar radiation, and the adaptive comfort band (80%), Jericho. Source: Climate Consultant, EPW (ERA5-TMYx, 2011–2025).

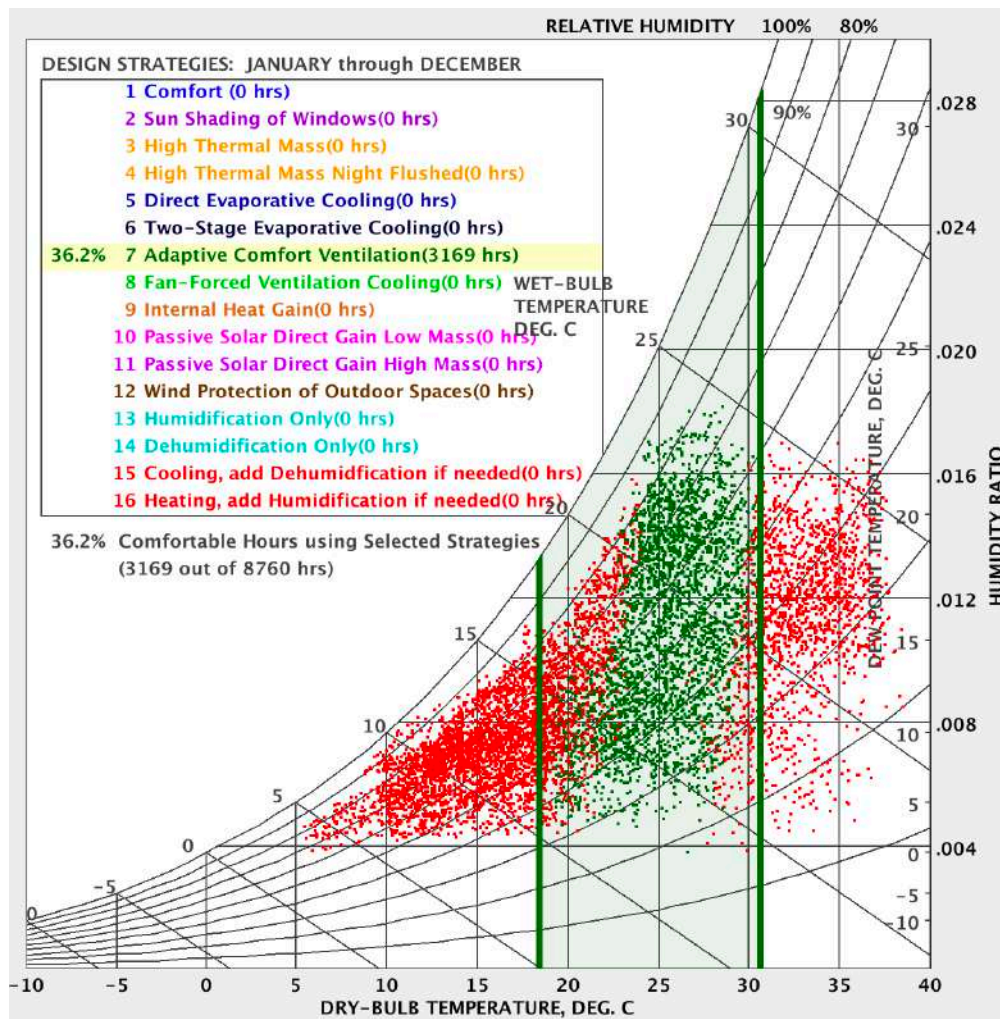


Figure 5-6: Adaptive comfort psychrometric chart for Jericho based on the ASHRAE 55 adaptive comfort model (80% acceptability). Source: Climate Consultant, EPW (ERA5-TMYx, 2011–2025).

Summer days swing an average of 11.4 °C, and the night air mean temperature of about 25.9 °C. The timetable plot maps show this rhythm across the year as shown in Figure 5-7, where the hot 27–38 °C band fills the afternoons from May to October, while the hours above and below, mostly at night and early morning, hold the cooler 20–27 °C and below 20 °C ranges. The summer wind is weak and northerly. From May to September, it blows from the north-northwest (NNW 28%, N 21%, NW 14%) at a mean of about 1.9 m/s, ranging from near-calm to a peak of 7.9 m/s, though the high-summer months rarely pass 5 m/s (Figure 5-8).

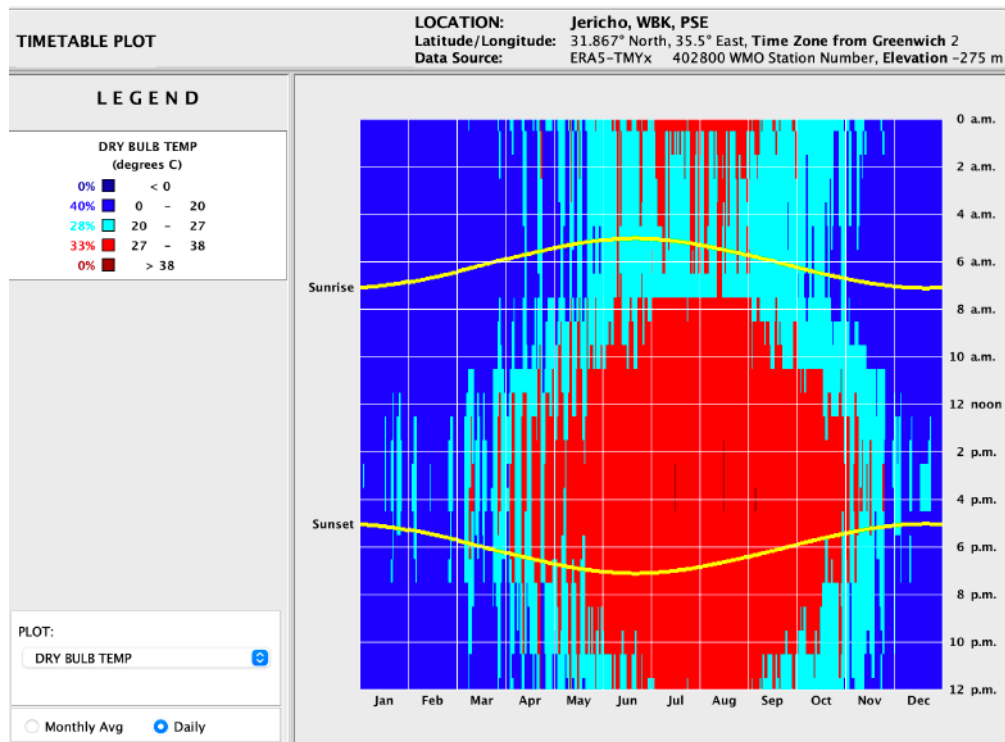


Figure 5-7: Hourly dry-bulb temperature by time of day and month, Jericho. Source: Climate Consultant, EPW (ERA5-TMYx, 2011–2025).

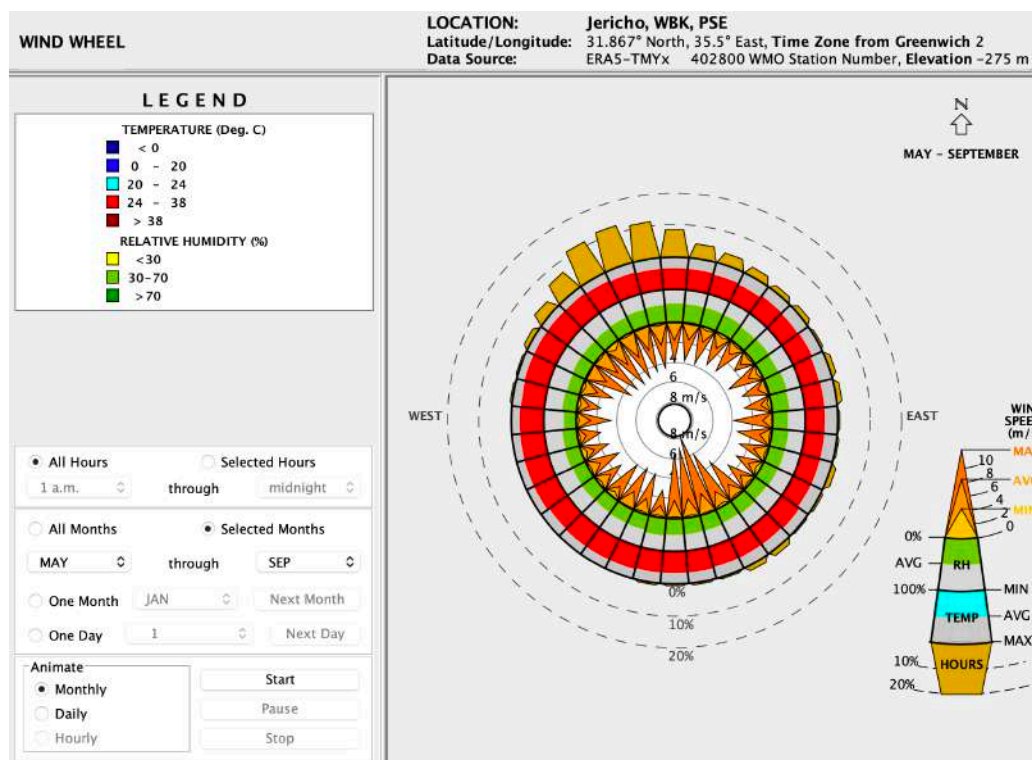


Figure 5-8: Cooling-season wind wheel (May–September), Jericho. Source: Climate Consultant, EPW (ERA5-TMYx, 2011–2025).

5.5 Base Case Model Setup

The Aqbat Jabr women's centre was created as a base-case model in DesignBuilder, shown in Figure 5-9. Its U-shaped plan, geometry, and rotation were derived from a Revit model built from the centre's official drawings. Figure 5- 10 shows the building's location and orientation on site. The orientation was measured from the building's true position on site and applied to the model so that the simulated solar exposure on each façade matches the building as built. Documented construction photographs of the centre, published on the Reviving Earth Architecture in the Jordan Valley – Palestine Facebook page ², guided the Revit documentation of the building and let the plan and geometry be checked against the built structure; the outer dimensions were confirmed against the Jericho Municipality GIS portal³.

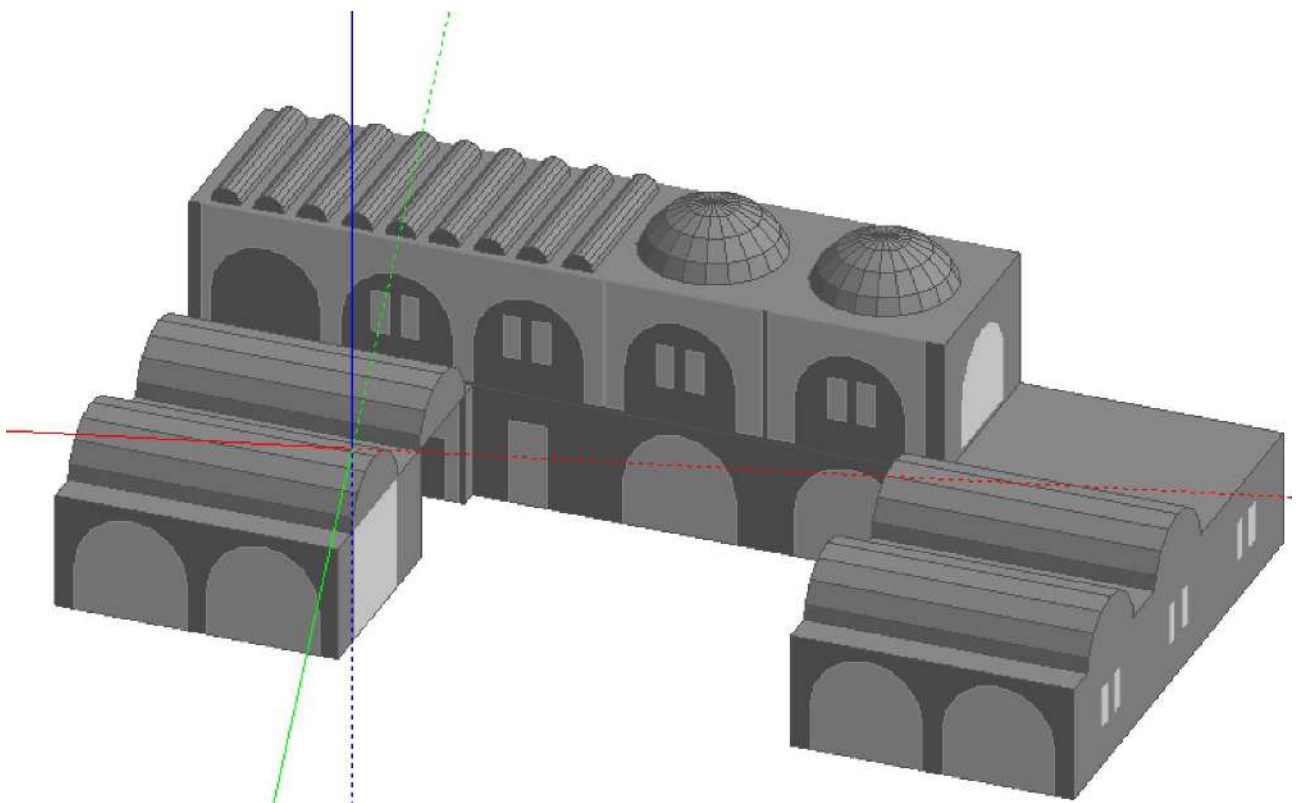


Figure 5-9: DesignBuilder model of the Aqbat Jabr women's centre, showing the barrel-vault and domed roofs (author's model).

² Reviving Earth Architecture in the Jordan Valley – Palestine [Facebook page]. <https://www.facebook.com/people/RevivingEarth-Architecture-in-the-Jordan-Valley-Palestine/100076432087517/> (accessed 2026).

³ Jericho Municipality GIS portal. <https://map.jericho-city.ps/DefaultApp/map> (accessed 2026).

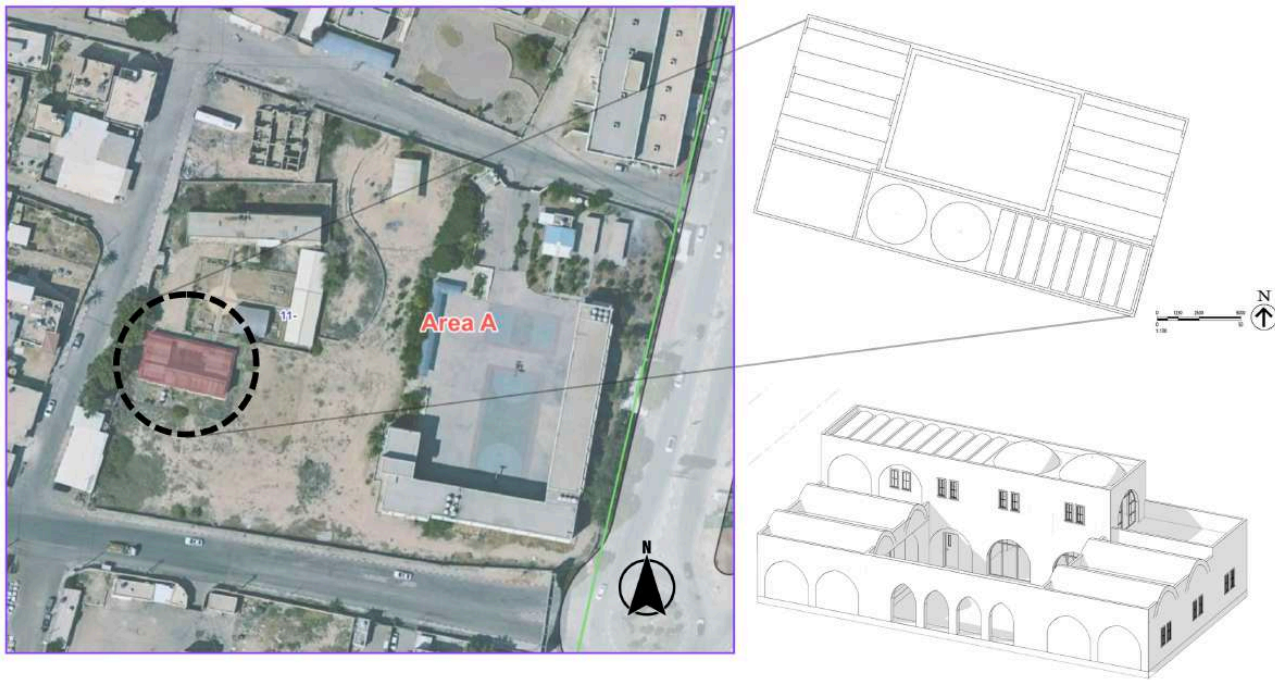


Figure 5-10: Location and orientation of the Aqbat Jabr women's centre on its site in Aqbat Jabr camp, Jericho (aerial imagery: Jericho Municipality GIS portal).

5.5.1 Construction and material properties

Table 5-2, provides the material properties used in the DesignBuilder. The values come from the Palestinian energy guidelines (Ministry of Local Government, 2004), the DesignBuilder libraries (CIBSE Guide A 2006 and ISO 10456), while the stabilized compressed earth block follows Omar

Sore et al. (2018). The CEB is the primary material used for all exterior and interior walls and roofs. Windows use single 6 mm clear glazing ($U = 5.78 \text{ W/m}^2\cdot\text{K}$, $g = 0.82$), fitted with a thin internal shade 3 mm thick, with a conductivity of $0.10 \text{ W/m}\cdot\text{K}$, a solar transmittance of 0.05, a solar reflectance of 0.10, and a long-wave emissivity of 0.90. The internal floor of the earthen building is uniform except for its structural layer, where 0.20 m reinforced-concrete beams alternate with 0.15 m compressed-earth-block (CEB) barrel vaults. The floor is beams and vaults side by side, each with its own thermal resistance, so the two were combined by the share of floor area each covers, following the method for inhomogeneous elements in ISO 6946. Across a representative $7.44 \times 3.509 \text{ m}$ bay (26.107 m^2), seven 0.30 m beams cover 7.369 m^2 (28.2%) and the vaults the remaining 18.738 m^2 (71.8%). With resistances of $0.087 \text{ m}^2\cdot\text{K/W}$ for the concrete (0.20 m, $k = 2.30$) and $0.123 \text{ m}^2\cdot\text{K/W}$ for the CEB (0.15 m, $k = 1.22$), the area-weighted structural resistance is $0.11 \text{ m}^2\cdot\text{K/W}$, which was entered as the resistance of that layer. The continuous layers above and below clay tile,

tile mortar, sand and cement plaster, and the interior surface resistance of 0.12 on both faces then add in series, giving a floor U-value of 2.23 W/m²·K.

Table 5-2: Base-case envelope assemblies and material properties.

Construction / element	Layers (outermost to innermost)	Density (kg/m ³)	C _p (J/kg.K)	k (W/m.K)	thickness(m)	Source
External walls U varies with CEB thickness	Cement plaster	1800	840	0.87	0.020	MoLG 2004
	Compressed earth block (CEB)	1900	1106.87	1.22	variable	Omar Sore 2018
	Cement plaster	1800	840	0.87	0.020	MoLG 2004
Internal walls U varies with CEB thickness	Cement plaster	1800	840	0.87	0.015	MoLG 2004
	Compressed earth block (CEB)	1900	1106.87	1.22	variable	Omar Sore 2018
	Cement plaster	1800	840	0.87	0.015	MoLG 2004
Intermediate floor U = 2.23 W/m ² .K	Clay tile, burnt	2000	840	1.30	0.018	CIBSE 2006
	Tile mortar	1900	650	1.20	0.020	CIBSE 2006
	Sand	1500	840	1.40	0.070	MoLG 2004
	Structural: concrete beams (28.2%)	2300	1000	2.30	0.200	ISO 10456
	Structural: CEB barrel vaults (71.8%)	1900	1106.87	1.22	0.150	Omar Sore 2018
	Structural: equivalent resistance	—	—	R = 0.11 m ² K/W	—	ISO 6946
	Cement plaster	1800	840	0.87	0.015	MoLG 2004
First-floor roof concrete beams U = 2.98 W/m ² .K	Roof screed	2300	1000	1.75	0.080	MoLG 2004
	Reinforced concrete	2300	1000	2.30	0.200	ISO 10456
	Cement plaster	1800	840	0.87	0.020	MoLG 2004
Exposed CEB barrel vaults U = 2.87 W/m ² .K	Cement plaster	1800	840	0.87	0.020	MoLG 2004
	Compressed earth block (CEB)	1900	1106.87	1.22	0.150	Omar Sore 2018
	Cement plaster	1800	840	0.87	0.020	MoLG 2004

	Terrazzo tile	2450	837	1.60	0.020	MoLG 2004
Ground floor (ground-coupled)	Tile mortar	1900	650	1.20	0.020	CIBSE 2006
	Sand	1500	840	1.40	0.070	MoLG 2004
	Concrete slab	2300	1000	2.30	0.400	ISO 10456

5.5.2 Selection of analysis zones

Based on the embedded case study logic from the previous section, three zones were selected for analysis and further optimization. They were chosen so that, between them, they cover the full range of roof and ceiling conditions, floor levels, envelope exposure, and occupancy patterns present in the building, since each of these determines the dominant heat gain mechanism and therefore the envelope and ventilation strategies appropriate to the space. The three zones are shown on the floor plans in Figures 5-11 and 5-12, and their roof geometries and floor-to-ceiling heights in the cross-sections in Figures 5-13 and 5-14.

The first zone sits on the ground floor and is the largest, shown in yellow in Figure 5-11. The zone served as a daycare and nursery with 25 children and 2 adults, has north, east and west walls exposed, and has an exposed CEB barrel vault roof with no floors above. It therefore combines the largest exposed envelope area in the building with a roof-dominated heat gain path and the highest occupant density, which makes it the most demanding zone for both thermal comfort and indoor air quality.

The second zone is also on the ground floor, as shown in Figure 5-11. It served as an office with six occupants and has transverse reinforced concrete beams with CEB barrel vaults between, and has a floor above it. Only its north and south walls are exposed, and its ceiling is buffered by the occupied space above rather than exposed to the sky, so heat gain is dominated by a limited area of wall and openings. It provides the contrasting case to the first zone: the same floor level, but the least exposed envelope in the selection against the most exposed.

The third zone occupies the first floor, above the office, as shown in Figure 5-12. The space served as a residential suite, has north and east walls exposed, and has a CEB dome roof. It combines an upper-floor position, the third roof geometry present in the building, and the only overnight occupancy pattern, which is the condition under which night ventilation strategies must be evaluated against occupant presence rather than an empty building. Its envelope exposure sits

between the other two zones: two exposed walls, as in the office, but with a roof exposed directly to the sky, as in the daycare.

Three zones were considered sufficient because these combinations are exhaustive rather than illustrative. The building contains three distinct roof and ceiling conditions, two floor levels, and three occupancy regimes, and the selected zones span the full range of envelope exposure present in it: three exposed walls with an exposed roof in the daycare, two exposed walls with a buffered ceiling in the office, and two exposed walls with an exposed roof in the residential suite. The three zones therefore represent the highest, lowest, and intermediate exposure conditions in the building without duplication, whereas additional zones would repeat combinations already represented while multiplying the number of simulations required across the seven sequential phases. The vertical relationship between the second and third zones has the further advantage of allowing the thermal interaction between stacked spaces to be observed directly.

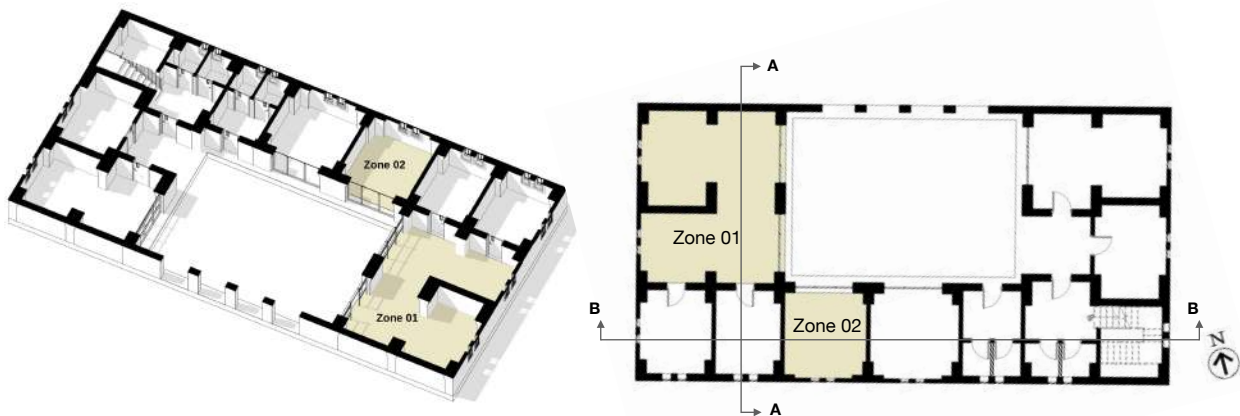


Figure 5-11: Ground floor of the base case model; the zones selected for analysis are shown in yellow (author's model).

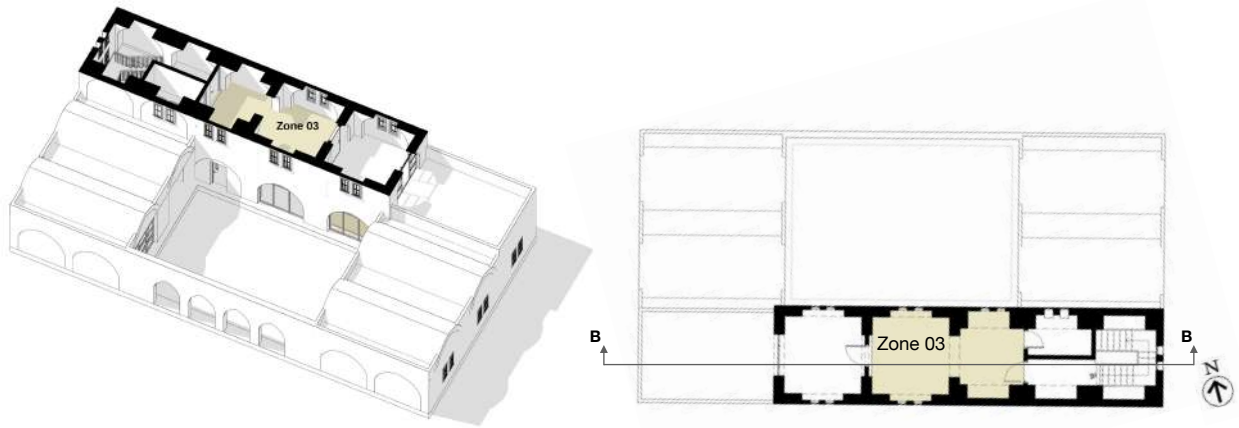


Figure 5-12: First floor of the base case model; the zones selected for analysis are shown in yellow (author's model).

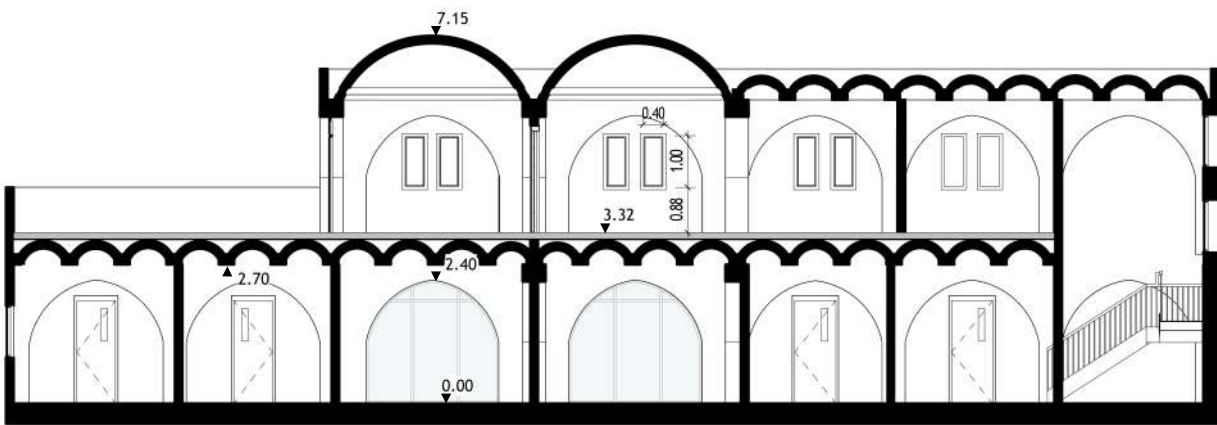


Figure 5-13: Section A–A through the single-storey wing, showing the barrel-vault geometry and floor-to-ceiling heights (author's drawing).

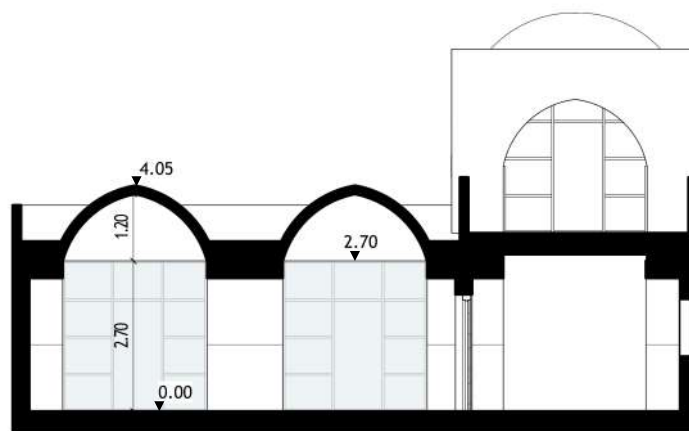


Figure 5-14: Section B–B through the two-storey portion, showing the ground-floor vaults, the first-floor dome, and the stacked relationship of Zones 2 and 3 (author's drawing).

Results and Discussion

6.1 Measured Thermal Performance of the Selected Earthen Building

6.1.2 Monitoring conditions

Data loggers recorded indoor temperature and relative humidity at 15-minute intervals across three zones of the earthen building from 25 May to 4 June 2026. Hourly outdoor dry-bulb temperature and relative humidity came from Open-Meteo historical records for the same period (31.81°N, 35.44°E, -230 m elevation). Outdoor peak temperatures rose from 32.8°C on 25 May to 38.2°C on 4 June, placing the monitoring period at the onset of summer in Jericho.

Three adjustments apply across all zones. The loggers ran for partial days on 25 May (starting mid-morning) and 4 June (ending early evening), so their diurnal swings and decrement factors are excluded from the zone means, although their recorded minima and maxima are retained in the overall ranges. On 28 May, a split-unit AC unit ran briefly in Zone 1, producing an irregular indoor temperature response. That day is excluded from the Zone 1 decrement factor and thermal lag calculations, while Zones 2 and 3 recorded no AC activity.

6.1.3 Outdoor Climate

Over the monitoring period, outdoor temperature ranged from 20.2°C to 38.2°C, with a mean of 27.94°C peaking daily between 15:00 and 16:00. Outdoor RH ranged from 9% to 79% and held a mean of 47%-49% through the night and early morning (22:00-07:00), occasionally reaching 62-79% on the more humid late May days. From 9:00, RH fell as the temperature rose, reaching its daily minimum between 14:00 and 16:00, with a mean of 24%-25%. A progressive drying trend developed across the monitoring period, tracking the seasonal rise in temperature as June approached. From 26–30 May, daily means ranged from 36% to 46%, and no hourly reading fell below 20%. By 1 June, 15 hours dropped below 30%, with a minimum of 15%. On 3 June, 8 hours fell below 20% and on 4 June, all 20 recorded hours were below 30%, reaching a minimum of 9%.

6.1.4 Zone 1 — Daycare

Indoor Temperature

The data logger in Zone 1 was positioned at 1.2 m above floor level, as shown in Figure 6-1. Over the monitoring period, indoor air temperature ranged from 29.5 °C to 33.9 °C under free-running conditions, with a mean of 31.6 °C, as shown in Figure 6-1. The first hour of readings was excluded while the data logger equilibrated to the indoor environment, and Figure 6-1 therefore begins at 10:57 on 25 May.

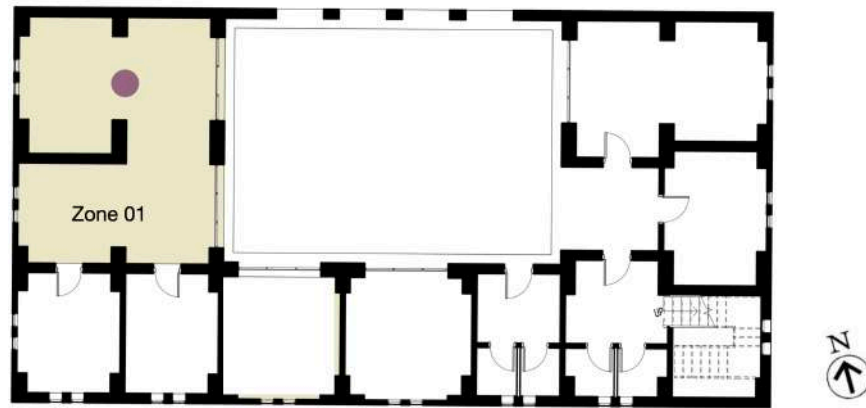


Figure 6-1: Location of the data logger in Zone 1 (marked by the circle), positioned at 1.2 m above floor level, on the ground-floor plan (author's drawing).

On 28 May, a split-unit air conditioner was operated briefly in Zone 1 to maintain suitable conditions while donated meat was being distributed ahead of Eid al-Adha. During this period, the external doors were also opened, resulting in an irregular indoor temperature response due to the combined effects of mechanical cooling and increased air exchange ; this interval is marked by the grey band in Figure 6-2. Indoor air temperature fell from 32.2 °C at 12:42 to 26.3 °C at 13:12, a drop of 5.9 °C in thirty minutes, before recovering to 31.0 °C over the following four hours. This absolute minimum of 26.3 °C does not represent passive performance and is excluded from the free-running range reported above. At all other times, no occupants were present, and no equipment other than the data loggers was in operation, so internal heat gains were negligible. Windows and external doors remained closed, and internal doors were also closed, so air exchange was limited to infiltration through the building fabric and around closed openings. Apart from the excluded period, the measured data therefore represent the free-floating thermal response of the envelope alone, without ventilation, occupancy, or internal gains.

During the hottest part of the day (12:00–16:00), the mean indoor temperature was held at 31.90 °C while the outdoor temperature averaged 33.27 °C, a gap of 1.37 °C. At night (00:00–06:00), the pattern reversed, with the interior averaging 30.88 °C against an outdoor mean of 23.39 °C, a difference of 7.49 °C. Of the 250 hourly readings, indoor temperature exceeded outdoor

temperature in 193 cases (77%). The remaining 57 cases (23%), where the interior was cooler, clustered in the afternoon peak between 13:00 and 18:00.

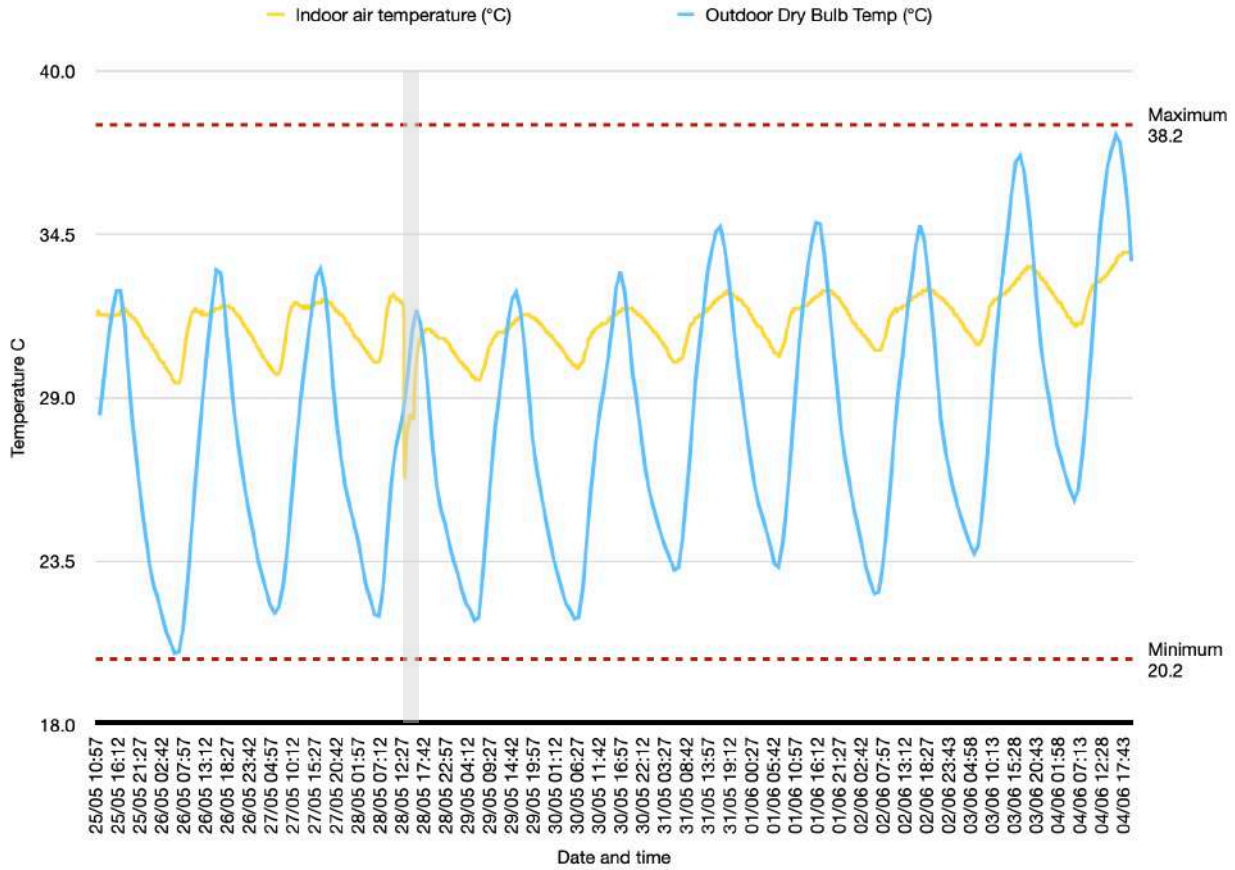


Figure 6-2: Zone 1, measured Indoor air temperature (yellow) and outdoor dry-bulb temperature (blue), 25 May–4 June 2026. The grey band marks the brief air-conditioning event on 28 May.

Diurnal Temperature Swing and Decrement Factor

Table 6-1 lists the daily minimum, maximum, and diurnal swing for both indoor and outdoor temperature, along with the decrement factor, calculated as the ratio of indoor amplitude to outdoor amplitude as described by Murtyas et al. (2020) and Rathore et al. (2020), as shown in Equation 6-1. 25 May and 4 June were excluded from the calculations as they didn't cover 24 hours record, and 26 May was also excluded for confirmed AC operation.

$$f = \frac{T_{i, \max} - T_{i, \min}}{T_{o, \max} - T_{o, \min}} \quad (6-1)$$

where f is the decrement factor, $T_{i, \max}$ is the maximum indoor air temperature ($^{\circ}\text{C}$), $T_{i, \min}$ is the minimum indoor air temperature ($^{\circ}\text{C}$), $T_{o, \max}$ is the maximum outdoor air temperature ($^{\circ}\text{C}$), and $T_{o, \min}$ is the minimum outdoor air temperature ($^{\circ}\text{C}$).

Table 6-1: Daily temperature statistics, decrement factor, and thermal lag for zone 1.

Date	T-in min ($^{\circ}\text{C}$)	T-in max ($^{\circ}\text{C}$)	Indoor swing ($^{\circ}\text{C}$)	T-out min ($^{\circ}\text{C}$)	T-out max ($^{\circ}\text{C}$)	Outdoor swing ($^{\circ}\text{C}$)	Decrement factor	T-out peak time	T-in peak time	Lag (h)
26 May	29.5	32.1	2.6	20.2	33.7	13.5	0.19	15:57	17:12	+1.25
27 May	29.8	32.3	2.5	21.7	33.6	11.9	0.21	15:57	17:27	+1.50
29 May	29.6	31.8	2.2	21.2	32.6	11.4	0.19	14:57	17:12	+2.25
30 May	30.0	32.0	2.0	21.3	33.4	12.1	0.17	15:57	17:27	+1.50
31 May	30.2	32.6	2.4	23.0	35.0	12.0	0.20	15:57	18:27	+2.50
1 June	30.4	32.6	2.2	23.0	35.2	12.2	0.18	15:57	17:27	+1.50
2 June	30.6	32.7	2.1	22.2	34.9	12.7	0.17	15:57	18:42	+2.75
3 June	30.8	33.4	2.6	23.6	37.2	13.6	0.19	15:58	18:43	+2.75

On the eight complete passive days, the outdoor diurnal swing ranged from 11.4 to 13.6 $^{\circ}\text{C}$ while the indoor swing held between 2.0 and 2.6 $^{\circ}\text{C}$. The building envelope reduced the outdoor amplitude by 81%, giving a mean decrement factor of 0.19. Outdoor temperature peaked daily at around 16:00; the indoor peak arrived between 17:12 and 18:43, a mean lag of 2.0 hours. This lag was calculated across all ten non-AC days, including the two partial days, both of which captured the afternoon peaks in full.

Relative humidity

Indoor relative humidity ranged from 34.0% to 52.8%, as shown in Figure 6-3. Across the nine complete monitoring days (26 May–3 June), the indoor RH swing ranged from 2.8% on 26 May to 10.7% on 3 June, with a mean of 6.3%. Outdoor swings reached 15–50% over the same days. The daily indoor RH means held between 44% and 48% from 25 May to 2 June, and fell to 41.6% on 3 June, and dropped to 36% on 4 June, corresponding to the most acute outdoor aridity recorded during the study. Indoor RH fell within the ASHRAE 55 comfort band of 40%-60% for 88.5% of the monitoring period.

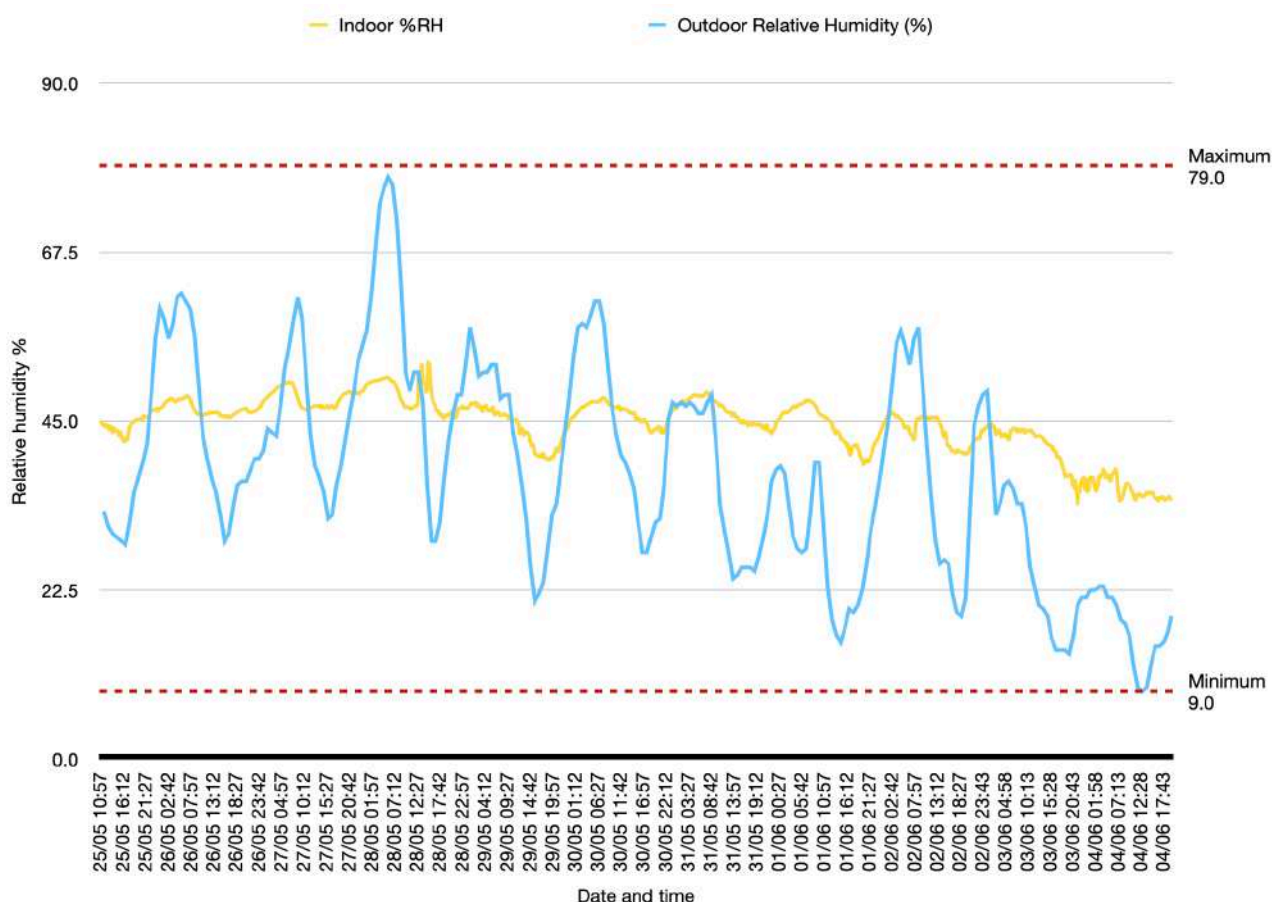


Figure 6-3: Zone 1, Indoor relative humidity (yellow) and outdoor relative humidity (blue), 25 May–4 June 2026.

The drying trend across the monitoring period is clear, as shown in Figure 3.2. Before 30 May, all the recorded RH fell above 20%. By 1 June, 15 hours fell below 30%, reaching 15%. On 3 June, 8 hours dropped below 20%. On 4 June, all 20 recorded hours were below 30%, with a minimum of 9% RH.

6.1.5 Zone 2—Office

Indoor Temperature

Zone 2 was monitored under the same conditions as Zone 1, unoccupied and with windows and external doors closed, as described in Section 6.1. The data logger in Zone 2 was positioned at 1.2 m above floor level, as shown in Figure 6-4. Over the monitoring period, indoor air temperature ranged from 29.1 °C to 32.5°C, with a mean of 30.74°C, as shown in Figure 6-5. During peak hours between 12:00 and 16:00, the indoor mean temperature of 31.44°C was 1.82°C below the outdoor mean of 33.27°C, a greater attenuation than observed in Zone 1. Between 00:00 and 06:00, the indoor mean of 29.92°C exceeded the outdoor mean

of 23.39°C by 6.53°C , reflecting nocturnal heat retention by the thermal mass. Of the 250 hourly comparison points, 64 (25.6%) recorded indoor temperatures below the corresponding outdoor value.

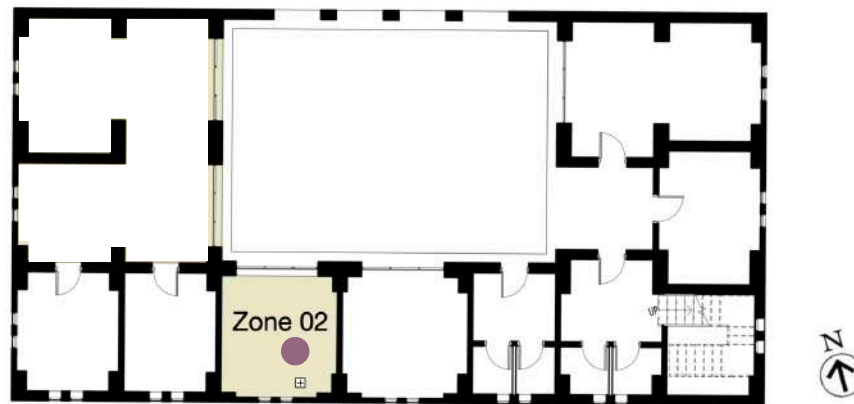


Figure 6-4: Location of the data logger in Zone 2 (marked by the circle), positioned at 1.2 m above floor level, on the ground-floor plan (author's drawing).

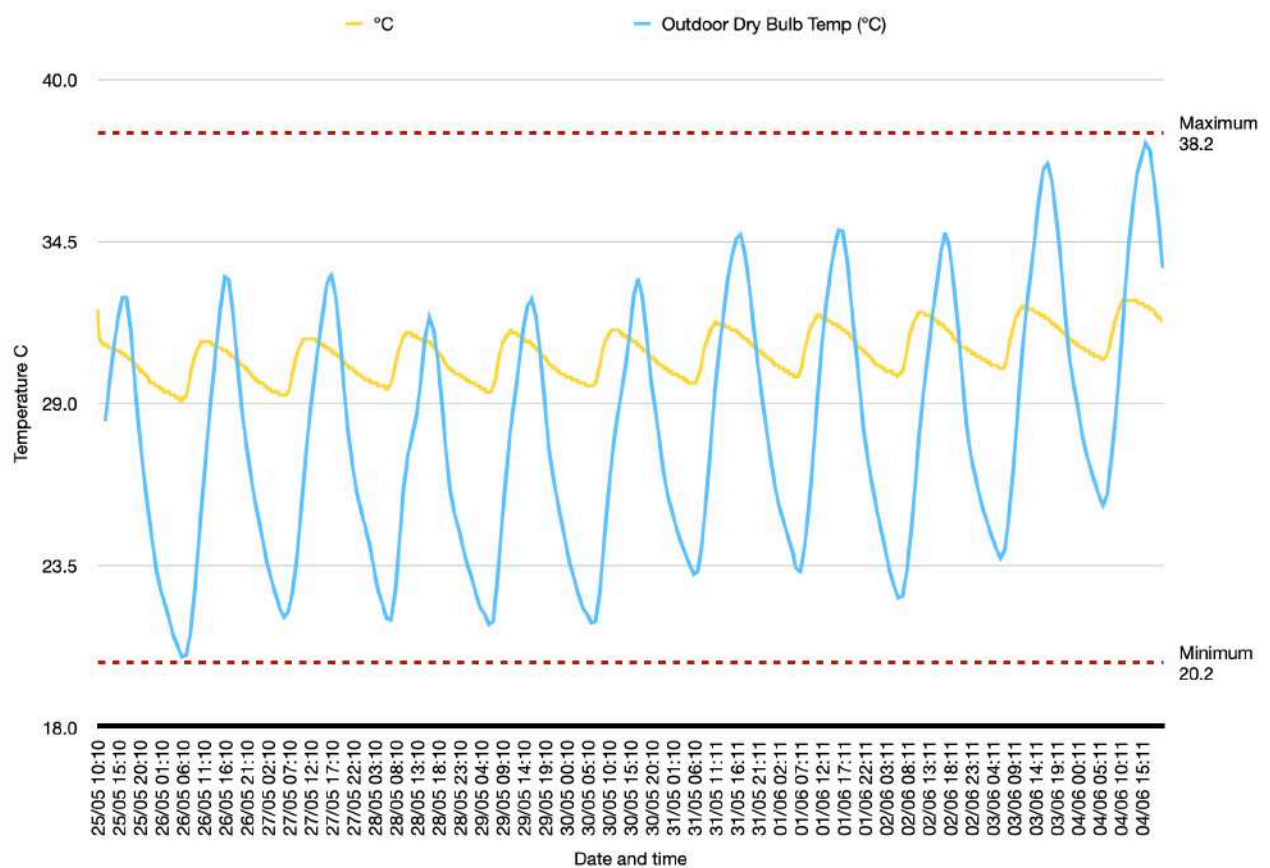


Figure 6-5: Zone 2, measured Indoor air temperature (yellow) and outdoor dry-bulb temperature (blue), 25 May–4 June 2026.

Diurnal Temperature Swing and Decrement Factor

Table 6-2 presents the same daily temperature characteristics for Zone 2, calculated using the same approach. The two partial days (25 May, 4 June) are again excluded from the decrement factor and swing means, and all nine complete days contribute to the calculations.

Table 6-2: Daily temperature statistics, decrement factor, and thermal lag for zone 2.

Date	T-in min (°C)	T-in max (°C)	Indoor swing (°C)	T-out min (°C)	T-out max (°C)	Outdoor swing (°C)	Decrement factor	T-out peak time	T-in peak time	Lag (h)
26 May	29.1	31.1	2.0	20.2	33.7	13.5	0.15	15:55	10:25	−5.50
27 May	29.3	31.2	1.9	21.7	33.6	11.9	0.16	15:55	10:25	−5.50
28 May	29.5	31.4	1.9	21.4	32.0	10.6	0.18	14:55	10:25	−4.50
29 May	29.4	31.5	2.1	21.2	32.6	11.4	0.18	14:55	10:55	−4.00
30 May	29.6	31.5	1.9	21.3	33.4	12.1	0.16	15:55	10:40	−5.25
31 May	29.7	31.8	2.1	23.0	35.0	12.0	0.18	15:56	11:11	−4.75
1 June	29.9	32.0	2.1	23.0	35.2	12.2	0.17	15:56	10:56	−5.00
2 June	29.9	32.1	2.2	22.2	34.9	12.7	0.17	15:56	10:41	−5.25
3 June	30.2	32.3	2.1	23.6	37.2	13.6	0.15	15:56	10:56	−5.00

Across the nine complete monitoring days, the indoor temperature swing ranged from 1.9 to 2.2°C. The mean decrement factor of 0.167 indicates that the building envelope attenuated 83% of the outdoor temperature amplitude, marginally exceeding the attenuation recorded in Zone 1. Zone 2 exhibits a thermal lag pattern distinct from Zone 1. The indoor temperature peaked between 10:10 and 11:11 each day, approximately five hours before the outdoor peak at around 16:00 (mean lag −4.97 hours).

Relative humidity

Indoor relative humidity ranged from 36.9% to 54.8%, as shown in Figure 6-6. Across the nine complete days, the indoor RH swing ranged from 1.9% to 5.5%, with a mean of 3.87%. Indoor RH stayed within the 40– 60% comfort band for 95.1% of the monitoring period. The 4.9% of RH below 40% readings occurred exclusively on 4 June (the driest recorded day), with a minimum of 36.9%.

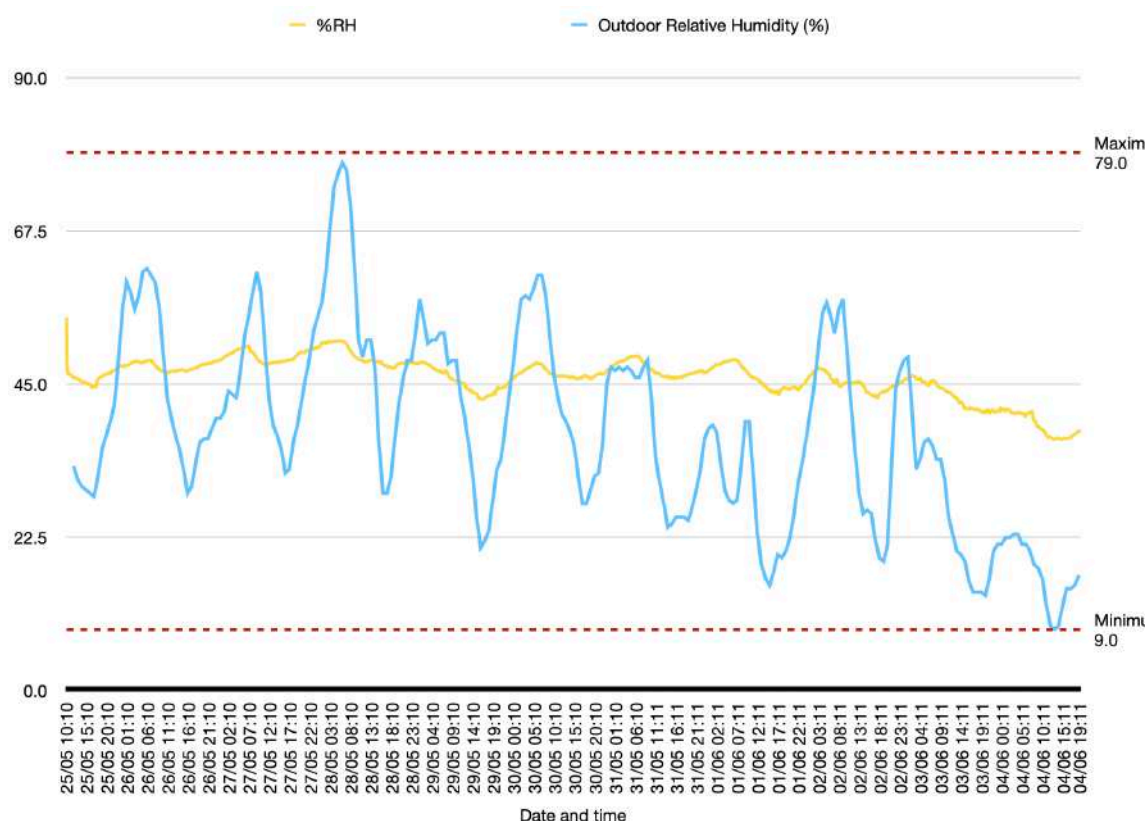


Figure 6-6: Zone 2, Indoor relative humidity (yellow) and outdoor relative humidity (blue), 25 May–4 June 2026.

6.1.6 Zone 3— Residential suite

Indoor Temperature

Zone 3 was monitored with its windows open and its internal door closed, in contrast to Zones 1 and 2, which were monitored sealed as described in Section 6.1. The zone was therefore naturally ventilated throughout the monitoring period, and its measurements represent the combined effect of the envelope and uncontrolled ventilation rather than the free-floating envelope response recorded in the other two zones.

The data logger in Zone 2 was positioned at 1.2 m above floor level, as shown in Figure 6-7. Over the monitoring period, indoor air temperature ranged from 27.7 °C to 35.3 °C, with a mean of 30.71 °C, as shown in Figure 6-8. The range of 7.6 °C is substantially wider than that recorded in Zone 1 (4.4 °C) or Zone 2 (3.4 °C), consistent with a ventilated zone tracking outdoor conditions more closely. During peak hours (12:00–16:00), the indoor mean of 31.28 °C was 1.99 °C below the outdoor mean of 33.27 °C, a margin between those recorded in Zone 1 (1.37 °C) and Zone 2 (1.82 °C). At night (00:00–06:00) the pattern reversed, with the interior averaging 29.81 °C against an outdoor mean of 23.39 °C, a difference of 6.42 °C. Of the 250 hourly readings, indoor

temperature exceeded outdoor temperature in 186 cases (74%). The remaining 64 cases (26%), where the interior was cooler, clustered in the afternoon and early evening between 12:00 and 19:00.



Figure 6-7: Location of the data logger in Zone 3 (marked by the circle), positioned at 1.2 m above floor level, on the first-floor plan (author's drawing).

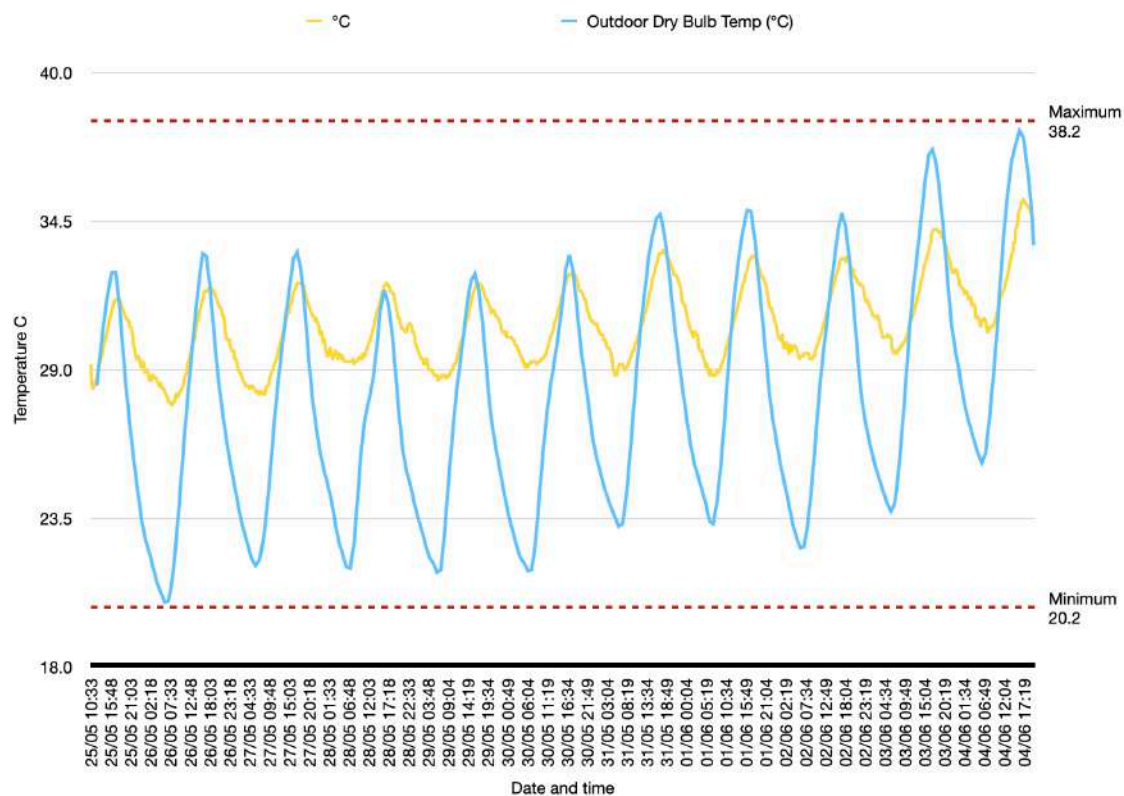


Figure 6-8: Zone 3, measured Indoor air temperature (yellow) and outdoor dry-bulb temperature (blue), 25 May–4 June 2026.

Diurnal Temperature Swing and Decrement Factor

Table 6-3 shows the daily temperature characteristics for Zone 3. The partial days (25 May and 4 June) are excluded from the decrement factor and swing averages. It should be noted that windows in Zone 3 stayed open throughout the monitoring period, so the decrement factor captures both the envelope and ventilation together, not envelope behaviour in isolation.

Table 6-3: Daily temperature statistics, decrement factor, and thermal lag for zone 3.

Date	T-in min (°C)	T-in max (°C)	Indoor swing (°C)	T-out min (°C)	T-out max (°C)	Outdoor swing (°C)	Decrement factor	T-out peak time	T-in peak time	Lag (h)
26 May	27.7	32.0	4.3	20.2	33.7	13.5	0.32	16:00	17:33	+1.56
27 May	28.1	32.2	4.1	21.7	33.6	11.9	0.35	16:00	17:03	+1.06
28 May	29.2	32.2	3.0	21.4	32.0	10.6	0.28	15:00	16:33	+1.57
29 May	28.6	32.2	3.6	21.2	32.6	11.4	0.32	15:00	16:34	+1.57
30 May	29.1	32.6	3.5	21.3	33.4	12.1	0.29	16:00	17:49	+1.82
31 May	28.8	33.4	4.6	23.0	35.0	12.0	0.38	16:00	17:49	+1.82
1 June	28.8	33.2	4.4	23.0	35.2	12.2	0.36	16:00	17:19	+1.32
2 June	29.4	33.2	3.8	22.2	34.9	12.7	0.30	16:00	18:34	+2.58
3 June	29.6	34.2	4.6	23.6	37.2	13.6	0.34	16:00	17:19	+1.33

Across the nine complete monitoring days (26 May–3 June), the indoor temperature swing ranged from 3.0 to 4.6°C, with a mean decrement factor of 0.326, approximately double that of Zone 1 (0.160) and Zone 2 (0.167). This reflects the continuous ventilation through open windows throughout the monitoring period, which increased thermal coupling between the interior and the outdoor environment. The ventilation through the windows drove the daily minimum below 29°C on several mornings, reaching 27.7°C on 26 May, the lowest passive indoor reading across all three zones, as outdoor air between 20 and 23°C moved freely through the space at night. The indoor temperature peaked consistently between 16:33 and 18:34 each day, after the outdoor peak at approximately 15:00–16:00, yielding a mean positive thermal lag of +1.63 hours. The outdoor air cools after 16:00 while the thermal mass

continues to release stored heat into the interior, sustaining the indoor maximum into the early evening.

Relative humidity

Indoor RH in Zone 3 ranged from 22.7% to 55.6% across the full monitoring period, with a mean of 42.85% as shown in Figure 6-9. Indoor RH stayed within the ASHRAE 55 comfort band of 40–60% for 77.2% of readings on complete days. A further 19.6% fell in the 30–40% range, and only 3.2% (28 readings) dropped below 30%, predominantly on the drier evenings of late May and early June, and indoor RH never exceeded 60%.

Across the nine complete monitoring days (26 May–3 June), the indoor RH swing ranged from 9.2% to 20.8%, with a mean of 14.0%, substantially wider than Zone 1 (mean 6.3%) and Zone 2 (mean 3.87%). Continuous window ventilation throughout the monitoring period allowed outdoor air, itself subject to diurnal RH swings of 26–50%, to directly influence indoor humidity, reducing the buffering the earthen mass provides in more enclosed conditions. On most days, the RH peak fell between 07:00 and 09:30, and the daily minimum fell consistently in the afternoon or evening, between 15:30 and 21:30. The daily minimum fell in the afternoon and evening (15:30–21:30), following the outdoor RH pattern as indoor humidity dropped in response to the rising afternoon temperatures.

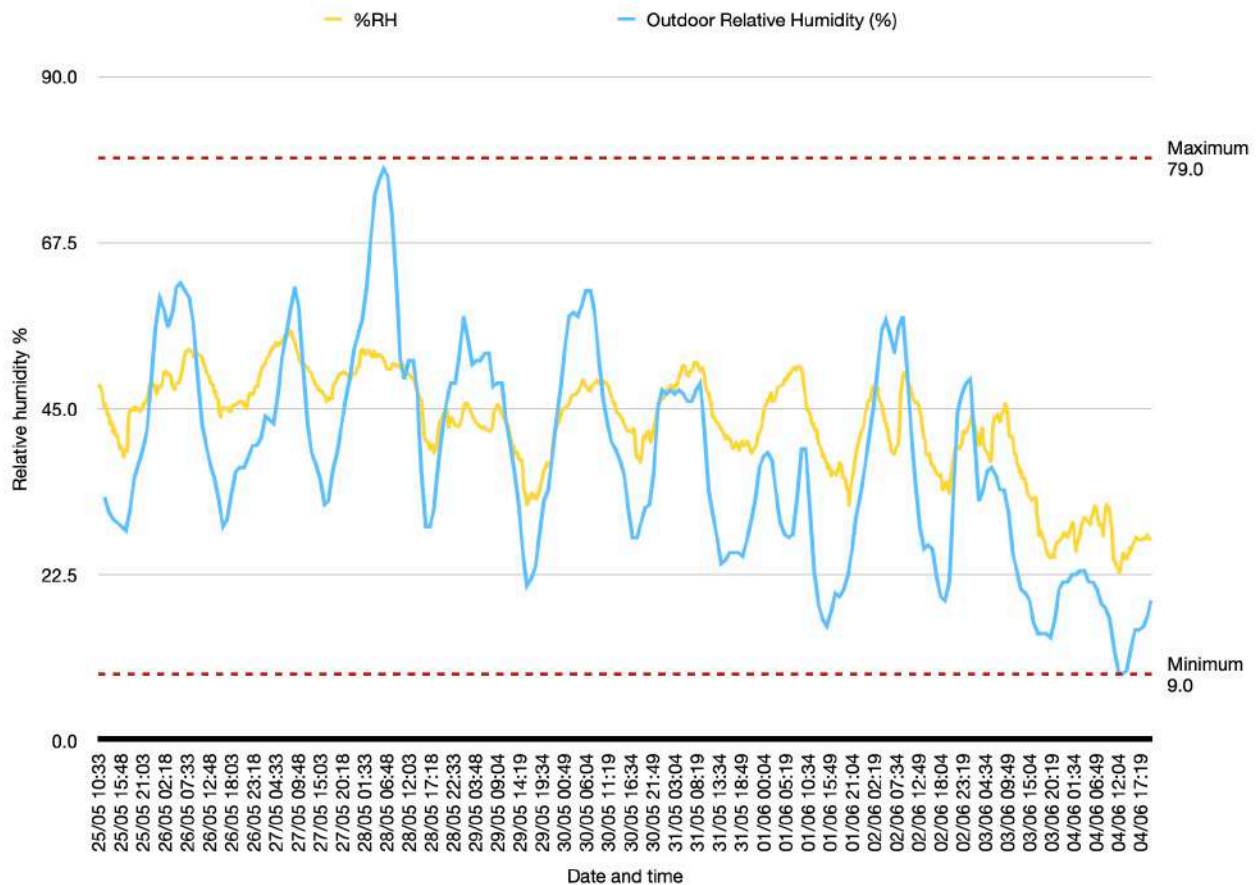


Figure 6-9: Zone 3, Indoor relative humidity (yellow) and outdoor relative humidity (blue), 25 May–4 June 2026.

All three zones buffered indoor temperatures against outdoor peaks without mechanical cooling, but each revealed a different constraint. Zone 1 attenuated 84% of the outdoor swing, but the 2-hour thermal lag left the indoor peak in the late afternoon when outdoor temperatures were still high. Zone 2 was the most stable, with the tightest temperature range and 95% of readings within the ASHRAE humidity comfort band. Zone 3 shows what night ventilation can do when outdoor conditions cooperate, where open windows pulled the daily minimum to 27.7°C, the lowest passive reading across all three zones. The same windows let afternoon heat in freely, pushing the indoor maximum to 35.3°C, higher than either of the other zones reached. This shows the importance of controlled ventilation, timed to the outdoor temperature cycle rather than left open continuously, which would capture the night-cooling benefit while limiting afternoon heat ingress. Across all three zones, the indoor temperature peak still occurred during the hottest hours of the day, pointing to thermal lag as the primary limitation and indicating that the earthen envelope requires further optimisations of wall thickness or composition to fully decouple the interior from the outdoor cycle.

6.2 Model validation results

After case and zone selection, a base model was developed in DesignBuilder to simulate and validate the indoor air temperature against the data loggers across the monitoring period, following ASHRAE Guideline 14 (2014). This section reports the comparison of the three monitored zones. The simulation was based on a modified typical-year weather file, where the base file was a TMYx typical meteorological year for Jericho, compiled from 2011 to 2025, downloaded from the OneBuilding climate database (OneBuilding, n.d). To reproduce the conditions of the monitoring period, the period from 7 April to 4 June in the original EPW file was replaced with hourly meteorological data obtained from Open-Meteo for the site coordinates (31.81° N, 35.44° E, -230 m, time zone Asia/Hebron, GMT+3) and the matching local times (Open-Meteo, n.d.). The replacement covered dry-bulb temperature, relative humidity, atmospheric pressure, wind speed and direction, and the global, direct, and diffuse solar radiation, referenced to local time (GMT+3). Replacing the weeks ahead of the monitored period, let the modeled outdoor temperature align with the site data, and let the earthen mass settle under real conditions before the comparison period of 25 May to 4 June.

6.2.1 Validation against measured indoor temperature

The base model created on DesignBuilder was calibrated against the indoor air temperature measured in the case study earthen building between 25 May and 4 June. The Data loggers monitored three thermal zones, and each measured data point was compared with the corresponding simulated air temperature obtained from DesignBuilder at hourly resolution. Following ASHRAE Guideline 14 (2014), the agreement was quantified with the three indices defined in Equations 3 to 5, which are the normalized mean bias error (NMBE), the coefficient of variation of the root mean square error (CV(RMSE)), and the coefficient of determination R^2 was also checked as most building simulation studies adopt these indices to validate their models (Ruiz and Bandera, 2017). The Guideline 14 sets the hourly acceptance limits at $\pm 10\%$ for NMBE and 30% for CV(RMSE) and recommends $R^2 \geq 0.75$.

The loggers' sampled temperatures were reduced to hourly values by taking the reading nearest the top of each hour, and the comparison ran for 250 paired hours per zone for the period from 11:00 am on 25 May and ended on 7:00 pm on 4 June. The building had no occupants during the monitoring period and ran in free-floating mode with no internal gains from people or equipment. And the 4 hours of AC operation in zone 1, as mentioned before, were excluded from

the validation, which leaves 246 paired hours for that zone. Table 6-4 reports the three indices for each zone where every zone falls within the Guideline 14 limits, and all three zones pass.

Table 6-4: ASHRAE Guideline 14 (2014) hourly validation indices for the simulated indoor air temperature of the three monitored zones, against the on-site data loggers over 25 May to 4 June.

Zone	Data points	NMBE %	CV(RMSE) %	R ²	Status
01	250	-4.36	5.00	0.8	Pass
02	246	-8.64	8.86	0.75	Pass
03	250	+0.52	1.84	0.88	Pass
ASHRAE 14 limit	-	≤ ±10	≤ 30	≥ 0.75	-

Zone 03 shows the closest agreement, and its simulated mean of 30.9 °C is well within 0.2 °C of the measured mean, and the model follows the daily cycle, including the late afternoon peak as shown in Figure 6-12. Zone 01 also passes with a wide margin, and the negative bias shows that the model runs cooler than the measured as shown in Figure 6-10. Zone 2 follows the measured daily cycle in phase and shape but sits consistently below it, the two curves remaining roughly parallel throughout. The deviation is therefore systematic rather than a failure to reproduce the zone's dynamic behaviour. This is consistent with Zone 2 being an internal zone: it has the smallest exposed envelope of the three and is the only one with an occupied space above, so much of its heat exchange occurs through the floor and internal partitions rather than the external walls, making it more sensitive to the assumed ground and adjacent-zone conditions. As the error is a near-constant offset, it enters the validation indices as bias while the coefficient of variation stays low, and the zone passes the Guideline 14 criteria, as shown in Figure 6-11. All three zones' results pass and stay below the AHRAE 14 limits.

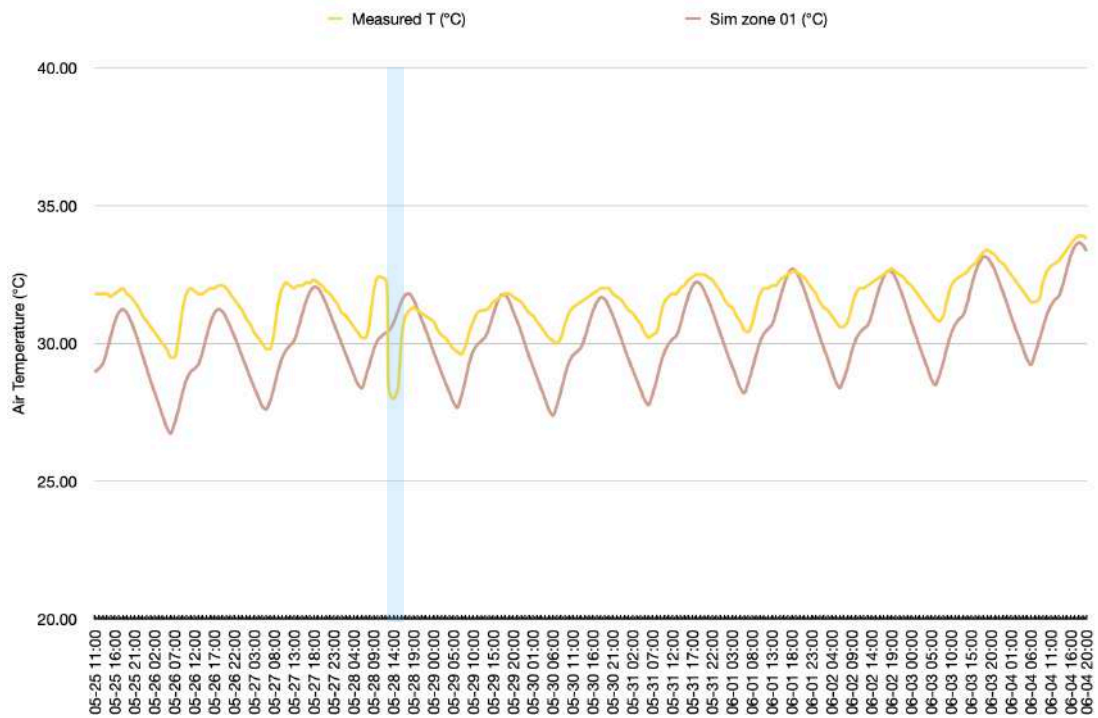


Figure 6-10: Measured and simulated indoor air temperature, Zone 01 (the shaded band is the excluded air conditioning period on 28 May).



Figure 6-11: Measured and simulated indoor air temperature, Zone 02, 25 May to 4 June.

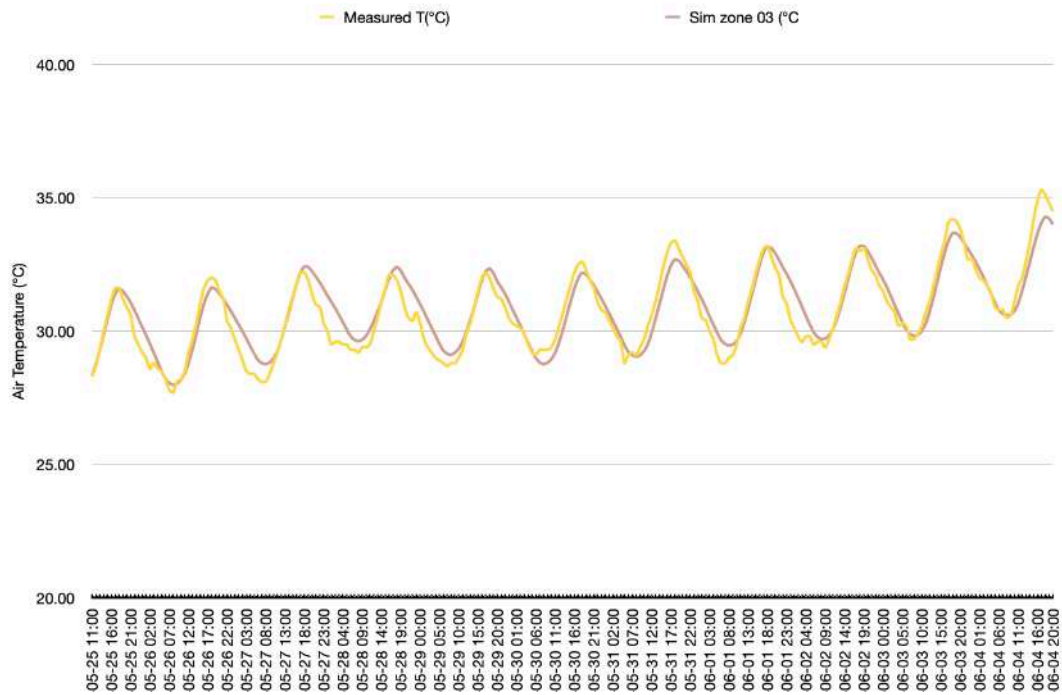


Figure 6-12: Measured and simulated indoor air temperature, Zone 03, 25 May to 4 June.

6.3 Phase 1 simulation results

6.3.1 Base case simulation results

Phase 1 begins with the building as-built simulation results, in free-floating mode and no ventilation or cooling; the results set the base case as a reference for later intervention work. Table 6-5 gives the simulation results of the base case for the three zones across a summer design week, and these runs use the original Jericho TMYx weather file reporting the operative temperature range, the hours above the adaptive 80% and 90% comfort limits, and the dominant heat gain in each zone.

Table 6-5: Base-case simulation results by zone, summer design week.

Zone	Op T min/mean/ max (°C)	Hours over 30.6 (80%)	Hours over 29.6 (90%)	Dominant gain (peak)
1	29.6 / 32.1 / 34.4	139/168 (83%)	167/168 (99%)	solar 6.8 kW (roof 2.1, walls 1.1)
02	28.8 / 30.1 / 31.2	44/168 (26%)	129/168 (77%)	solar 0.32 kW, walls 0.20 kW
03	31.8 / 33.8 / 35.9	168/168 (100%)	168/168 (100%)	roof 1.14 kW

All zones sit above the adaptive comfort limit for most of the week. In Zone 1 (33.51 m²) which its place in the U-shape puts its long walls on the east and west, the orientations that take

the heaviest sun causes the solar gain to pour through its north east large glazing with a mean value of 1.49 kW(peak 6.8), its exposed barrel-vault roof adds a second load with a mean value of 0.74 kW (Peak 2.1), and at last comes the wall with a mean heat gain at about 0.35 k (peak 1.1), making the solar gain the dominant factor and the operative temperature reached 34.4 °C, and for 139 hours of the 168 hours, it was above the 80% acceptability limit.

Zone 2 (12.23 m²) is the mildest, peaking at 31.2 °C and over the 80% limit 26% of the time. It's oriented north and south with no exposed walls from the east and west, and although it has a large glazed façade too, the glazing faces north, so it admits little direct sun, and as a ground-floor space with an internal ceiling, it takes no roof load. The wall conduction and solar gain through the windows are similar, with the walls' mean gain 0.10 kW (0.20) kW and solar gains 0.12 kW (0.32).

Zone 3 (24.01 m²) performs the worst, as the roof drives a peak heat gain of 1.14 kW and a mean value of 0.32 kW into the space while solar gains are negligible, and the results are 100% of the time above the 80% limit, with a peak of 35.9 °C. Its walls do almost nothing, with a mean heat gain of −0.08 kW (0.08 peak), because it's oriented north and south with no exposed east and west facades and has a mean solar heat gain of 0.09 kW (0.26 peak). Figure 6-13 shows that the outdoor dry-bulb temperature varies by about 12 °C per day, while the operative temperature in the three zones varies by 2-4 °C.

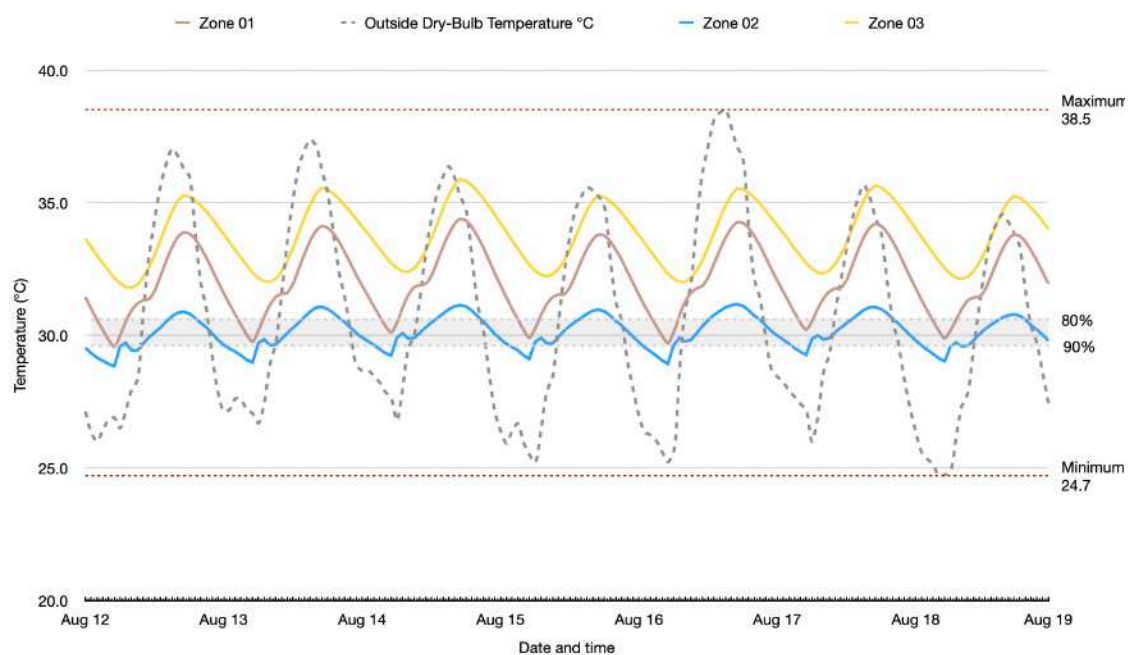


Figure 6-13: Zone case operative temperatures vs outdoor dry-bulb, summer design week. Shaded zone: adaptive 80% and 90% limit (30.6, 29.6°C).

6.3.2 Step 1: Wall thickness optimization results

In Step 1, the thickness of the CEB external walls was evaluated at three values: 14, 29.5, and 43.5 cm, with the rest of the model held at its base-case values. As set out in Section 4.2.7, these correspond to the standard block laid as a stretcher, as a header, and as a header and stretcher combined, and are the only wall thicknesses buildable from the standard block without cutting. Table 6-6 shows the simulation results. In zone 1, its peak operative temperature drops from 34.6 to 34.0 °C between 14 and 29.5 cm, then loses another 0.2 °C at 43.5 cm, and the hours above the 80% stay near 80% since the solar gain peaks at around 6.8 kW, keeping the operative temperature high. Wall mean conduction drops as the thickness increases, with a 0.06 kW decrease in mean heat gain from 14 to 29.5 cm, and 0.04 kW decrease for the 43.5 cm. Zone 1 follows a similar trend, and because the operative temperatures run near the comfort line, the added mass makes a real effect where its overheating hours decreased from 27% to 13% when the thickness increased from 14 to 29.5, and only another 3% hours decreased when the thickness was 43.5. The wall mean heat gain decreased 0.011 kW from 14 to 43.5 and 0.008 kW from 29.5 to 43.5. Zone 3, which is located on the first floor, stays the hottest because it has no way to lose the accumulated heat compared with the cool ground of zones 1 and 2. The roof adds about 0.3 kW, peaking at around 1 kW, so adding mass to the walls barely has any effect. At this stage, the 29.5 cm was considered as the optimum as it provides most of the thermal damping while avoiding the diminishing returns related to increasing the thickness further. By 29.5 cm, the operative swing has already done most of its narrowing, from 4.5 to 3.7 °C in Zone 1, 1.95 to 1.6 °C in Zone 2, and 3.7 to 3.05 °C in Zone 3, and it holds there. Beyond 29.5 cm, the swing stops tightening because the core of a thicker wall sits past the depth the daily heat wave reaches, so the step to 43.5 cm adds mass without adding damping.

Table 6-6: Parametric Analysis of External Wall Thickness for the Three Zones

Zone	Wall Thickness	Op T min/ mean/max (°C)	Hours over 30.6 (80%)	Hours over 29.6 (90%)	Wall peak (kW)	Mean wall gain (kW)	Op T swing (°C)
1	14 cm	29.4 / 32.1 / 34.6	136/168 (81%)	165/168 (98%)	1.24	0.363	4.54
	29.5 cm	29.6 / 31.9 / 34.0	141/168 (84%)	168/168 (100%)	0.99	0.302	3.73
	43.5 cm	29.4 / 31.8 / 33.8	131/168 (78%)	165/168 (98%)	0.92	0.257	3.84

2	14 cm	28.9 / 30.2 / 31.2	46/168 (27%)	132/168 (79%)	0.201	0.103	1.95
	29.5 cm	28.8 / 30.0 / 30.9	21/168 (13%)	127/168 (76%)	0.184	0.092	1.64
	43.5 cm	28.6 / 29.9 / 30.8	16/168 (10%)	110/168 (65%)	0.165	0.084	1.72
3	14 cm	31.7 / 33.8 / 36.1	168/168 (100%)	168/168 (100%)	0.05	-0.092	3.65
	29.5 cm	31.9 / 33.8 / 35.7	168/168 (100%)	168/168 (100%)	0.16	-0.077	3.05
	43.5 cm	31.8 / 33.7 / 35.6	168/168 (100%)	168/168 (100%)	0.18	-0.071	3.05

Time lag and decrement factor

The inside and outside surface temperature of a specific external wall for each zone and wall thickness was exported from the DesignBuilder simulation results and was used to calculate the time lag based on equation 3 and the decrement factor based on equation 4 as stated in chapter 3. All three walls share the same CEB construction, so they damp the outdoor swing the same way, and the results follow one trend as shown in Figure 6-14. Across the three walls, the outer surface swings by 18 to 25 °C over the day, widest on Zone 1's more sun-exposed wall, and climbs past 45 °C at midday. At 14 cm, the inner surface swings about 6 °C a day, which is 30% of the outside surface swing, and lags 3 to 4 hours, with a decrement factor near 0.3. At 29.5 cm, the interior surface swings drop to about 2 °C, with a time lag of about 8 hours and a decrement factor of around 0.1. At 43.5 cm, the inner swing falls to about 1 °C, showing that increasing the wall thickness beyond 30cm provides little additional benefit. The diminishing benefit of increasing wall thickness can be explained by how the daily outdoor temperature wave becomes weaker as it moves through the wall. For the CEB used in this study, the diurnal thermal penetration depth was calculated using the following equation (Szokolay, 2014):

$$d = \sqrt{\frac{\alpha P}{\pi}} \quad (6-1)$$

Where α is the thermal diffusivity of the material, and P is the period of the cycle (86,400 s). For the CEB adopted here, with $\alpha = 5.75 \times 10^{-7} \text{ m}^2/\text{s}$ (Omar Sore et al., 2018), $d = 12.6 \text{ cm}$. Therefore, a 29.5 cm wall corresponds to approximately 2.3 diurnal penetration depths, indicating that the daily temperature fluctuation is already strongly attenuated before reaching

the inner surface. Therefore, adding more material beyond this point gives only a small improvement. These results are consistent with the 30- 40 cm optimum reported by El Fgaier et al (2016), and the 8–12 hour time lag reported by Toure et al (2019).

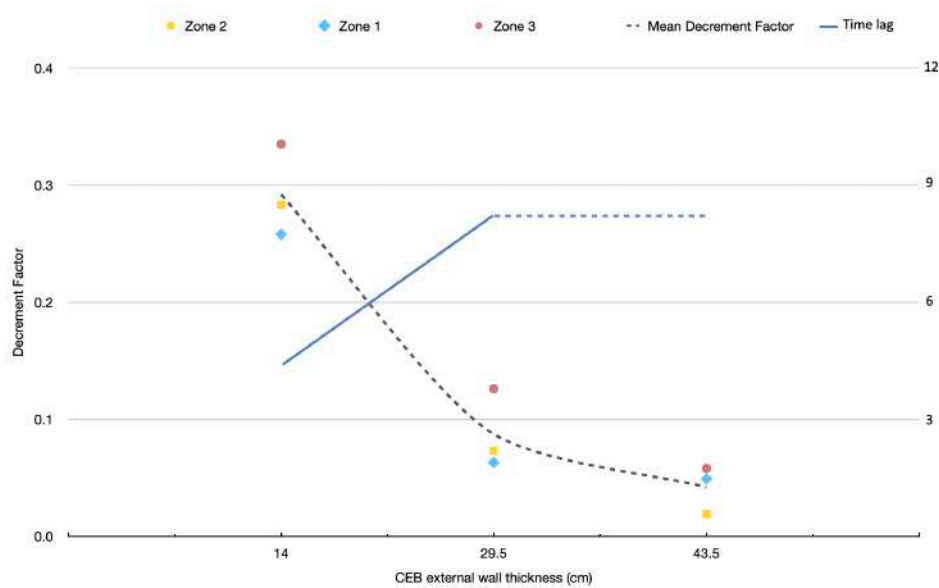


Figure 6-14: Decrement factor and time lag of the external CEB wall against thickness, mean of the three zones.

6.3.3 Stage 2: Wall insulation optimization results

Stage 2 evaluates the thermal performance of the wall insulation configurations described in the methodology to determine the optimum insulation material, thickness, and application extent. All configurations were simulated under free-floating conditions over the summer design week. The full results for all runs, giving the operative temperature (minimum, mean, maximum), the hours over the adaptive 80% and 90% comfort limits, and the wall peak heat gain for each material, thickness, and wall scope, are provided in Tables 6-7 to 6-9, one per zone. All runs were simulated in free-floating mode across the summer design week.

As shown in Figure 6-15, the insulation reduces the mean operative temperature in every zone, but only zone 2 reaches a comfortable level. The mean falls from 30.0 °C with 30 cm bare walls to 29.0 °C with 5 cm of polyurethane on all external walls, crossing below the 30.6 °C limit. Zone 1 drops from 31.9 with 30 cm bare walls to 31.18 °C with 5 cm of polyurethane on all walls, and stays above the line, because the solar heat gain associated with the large east-facing glazed façade is the dominant source of heat, and the insulation reduces only a small portion of the heat entering the space. This highlights the unsuitability of large glazed facades in hot arid climates unless effective solar shading is employed. Zone 3 moves from 33.78 to 33.35 °C and holds far above comfort, since the roof is the dominant heat source.

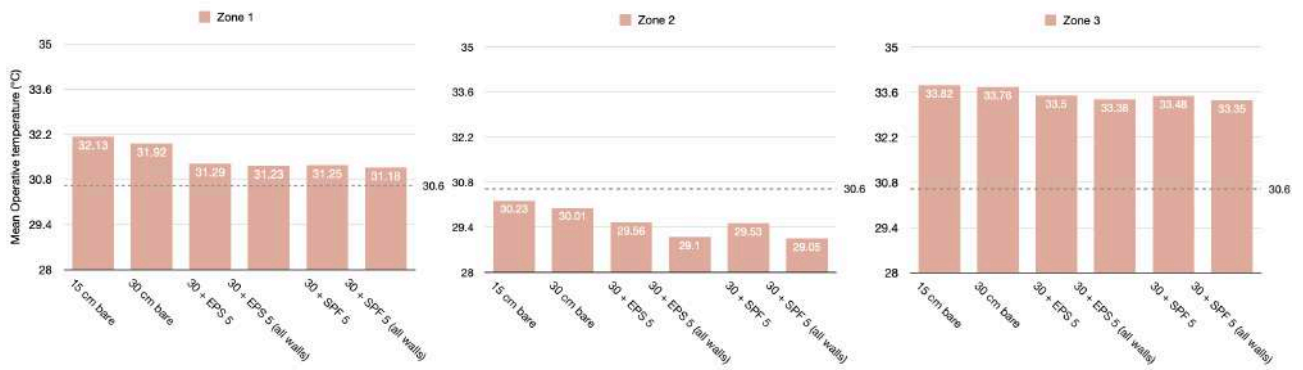


Figure 6-15: Mean operative temperature by zone for the evaluated CEB wall configurations. The dashed line represents the ASHRAE 55 adaptive comfort limit (30.6 °C, 80% acceptability).

Against the 80% adaptive comfort limit, adding insulation, whatever thickness or scope meets comfort in zone 2. Zone 1 achieves 109 to 117 hours over the limit, whatever the built-up, since solar gain dominates as shown in Figure 6-16. Zone 3 achieved all hours above the comfort limit. At this limit, it makes little difference whether the load-bearing walls are insulated too. Insulating only the infill walls —the non-load-bearing CEB walls located between the structural CEB piers that support the vaults, rather than the load-bearing walls themselves— lands within four hours of insulating every wall, so the infill walls carry nearly the whole effect. To separate the effect of each insulation material, the comparison is tightened to the 90% limit.

Against the 90% adaptive comfort limit, in zone 2 at 5 cm on all walls, Polyurethane achieves 38 hours above the 90% limit against EPS at 42 hours and rock wool at 49 hours, as shown in Figure 6-17, The same ranking appears in Zone 1, though all three stay high at 145 to 150 hours because solar keeps it overheated, while Zone 3 holds at 168 hours regardless of material, driven by its roof.

Between the two thicknesses, 5 cm outperforms 3cm for the EPS and SPF by a limited margin. Moving EPS and SPF from 3 to 5cm on all walls cuts about 11 to 14 hours in zone 2, and 6 to 7 hours reduction in zone 1; zone 3 holds at 168 hours above the 90% comfort limit, whatever the thickness.

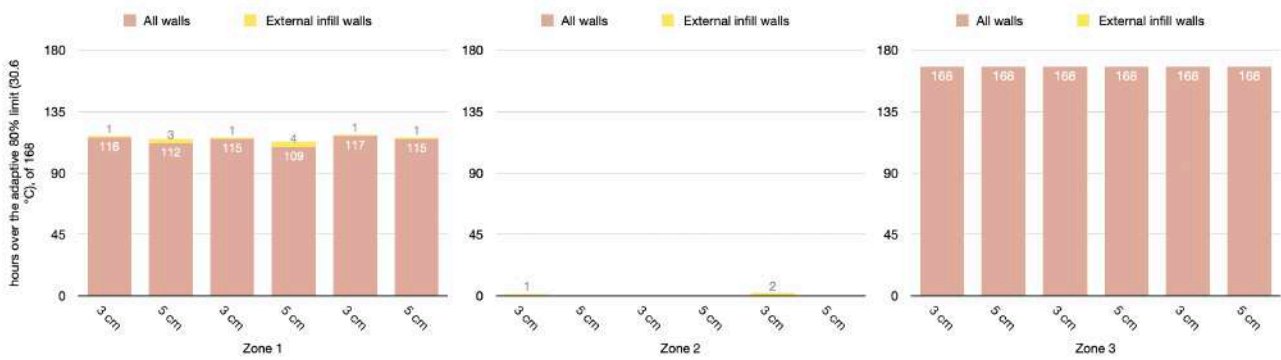


Figure 6-16: Hours above the ASHRAE 55 adaptive comfort limit (30.6 °C, 80% acceptability) for the evaluated CEB wall configurations in each zone. Bars compare insulation applied to all external walls and to infill walls only.

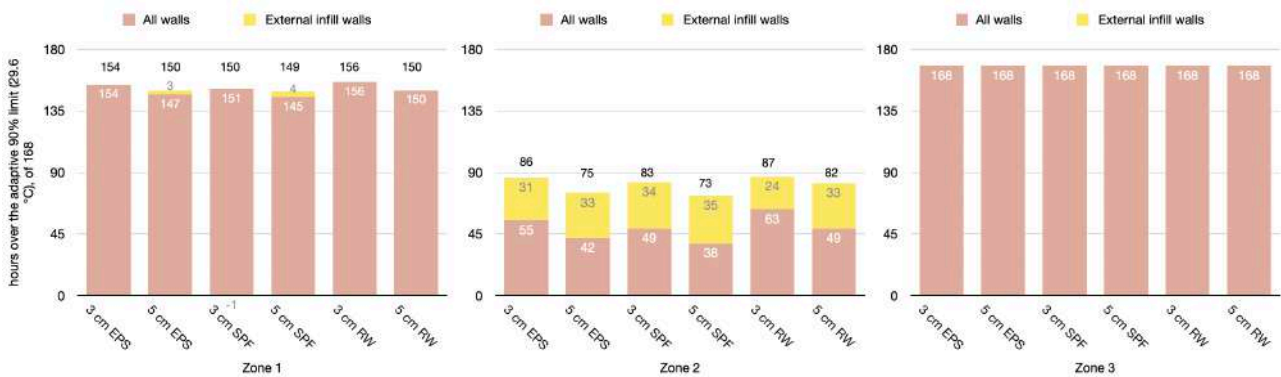


Figure 6-17: Hours above the ASHRAE 55 adaptive comfort limit (29.6 °C, 90% acceptability) for the evaluated CEB wall configurations in each zone. Bars compare insulation applied to all external walls and to infill walls only.

EPS appears to offer a favourable cost–performance balance among the insulation options tested. Alsurakji et al. (2021) reported that EPS was approximately one-third the price of polyurethane in Palestine; however, this earlier cost comparison is used only as an indicative reference. This observation was also consistent with informal discussions with local site engineers and suppliers, who indicated that polyurethane spray foam is generally more expensive than EPS in the local market. Nevertheless, a dedicated cost analysis based on current material, installation, and labour prices would be required to determine the most cost-effective option. From a thermal-performance perspective, polyurethane provided the highest performance, but its additional benefit over EPS was limited to approximately 2–3 fewer overheating hours. Therefore, EPS may provide a more practical cost–performance balance, although this conclusion should be confirmed through a detailed economic analysis.

Moreover, Figures 6-16 and 6-17 show the benefit of adding insulation to all external walls compared to only infill external walls. In Zone 2, adding insulation to all walls removes another 0.32 to 0.48 °C from the mean operative temperature and reduces the overheating hours over the 90% limit by about 24 to 35 hours. Zone 1 shows almost no change, with a reduction of up to 4 h

and a 0.1 °C reduction in operative temperature or less. Zone 3, adding insulation to all walls, reduced the mean operative temperature by 0.06 to 0.13 °C, yet it stays 100% over the 90% limit.

Based on the comfort achieved and the cost-tradeoff, 3 cm EPS on the infill external walls meets the 80% adaptive comfort acceptability limit in zone 2. The extra 2 cm of wall insulation buys only a tighter 90% margin, and the night ventilation phase is expected to address the remaining overheating that wall insulation alone could not eliminate.

Table 6-7: Comparison of the thermal performance of the evaluated wall insulation configurations in Zone 1.

Configuration	Scope	Op T min/mean/ max (°C)	Mean reduction vs bare 30 cm (°C)	Hours over 30.6 (80%)	Hours over 29.6 (90%)
Base case (30 cm CEB infill walls)	External infill walls	29.6 / 31.92 / 34.0	-	141/168 (84%)	168/168 (100%)
EPS 3 cm	External infill walls	29.0 / 31.40 / 33.5	-0.52	116/168 (69%)	154/168 (92%)
EPS 3 cm	all walls	29.0 / 31.36 / 33.5	-0.56	116/168 (69%)	154/168 (92%)
EPS 5 cm	External infill walls	28.8 / 31.29 / 33.4	-0.63	115/168 (68%)	150/168 (89%)
EPS 5 cm	all walls	28.9 / 31.23 / 33.3	-0.69	112/168 (67%)	147/168 (88%)
SPF 3 cm	External infill walls	28.9 / 31.35 / 33.5	-0.57	116/168 (69%)	150/168 (89%)
SPF 3 cm	all walls	28.9 / 31.30 / 33.4	-0.62	115/168 (68%)	151/168 (90%)
SPF 5 cm	free walls	28.8 / 31.25 / 33.4	-0.67	113/168 (67%)	149/168 (89%)
SPF 5 cm	all walls	28.8 / 31.18 / 33.3	-0.74	109/168 (65%)	145/168 (86%)
Rock wool 3 cm	External infill walls	29.0 / 31.45 / 33.6	-0.47	118/168 (70%)	156/168 (93%)
Rock wool 3 cm	all walls	29.1 / 31.42 / 33.5	-0.50	117/168 (70%)	156/168 (93%)
Rock wool 5 cm	free walls	28.9 / 31.34 / 33.5	-0.58	116/168 (69%)	150/168 (89%)
Rock wool 5 cm	all walls	28.9 / 31.28 / 33.4	-0.64	115/168 (68%)	150/168 (89%)

Table 6-8: Comparison of the thermal performance of the evaluated wall insulation configurations in Zone 2.

Configuration	Scope	Op T min/mean/ max (°C)	Mean reduction vs bare 30 cm (°C)	Hours over 30.6 (80%)	Hours over 29.6 (90%)
Base case (30 cm CEB infill walls)	Baseline	28.8 / 30.01 / 30.9	—	21/168 (12%)	127/168 (76%)
EPS 3 cm	External infill walls	28.4 / 29.63 / 30.6	-0.37	1/168 (1%)	86/168 (51%)
EPS 3 cm	all walls	27.9 / 29.27 / 30.4	-0.74	0/168 (0%)	55/168 (33%)

EPS 5 cm	External infill walls	28.3 / 29.56 / 30.6	-0.45	0/168 (0%)	75/168 (45%)
EPS 5 cm	all walls	27.7 / 29.10 / 30.2	-0.91	0/168 (0%)	42/168 (25%)
SPF 3 cm	External infill walls	28.3 / 29.60 / 30.6	-0.41	0/168 (0%)	83/168 (49%)
SPF 3 cm	all walls	27.8 / 29.17 / 30.3	-0.84	0/168 (0%)	49/168 (29%)
SPF 5 cm	External infill walls	28.2 / 29.53 / 30.5	-0.48	0/168 (0%)	73/168 (43%)
SPF 5 cm	all walls	27.6 / 29.05 / 30.2	-0.96	0/168 (0%)	38/168 (23%)
Rock wool 3 cm	External infill walls	28.4 / 29.67 / 30.7	-0.34	2/168 (1%)	87/168 (52%)
Rock wool 3 cm	all walls	28.0 / 29.35 / 30.4	-0.66	0/168 (0%)	63/168 (38%)
Rock wool 5 cm	External infill walls	28.3 / 29.59 / 30.6	-0.41	0/168 (0%)	82/168 (49%)
Rock wool 5 cm	all walls	27.8 / 29.18 / 30.3	-0.83	0/168 (0%)	49/168 (29%)

Table 6-9: Comparison of the thermal performance of the evaluated wall insulation configurations in Zone 3.

Configuration	Scope	Op T min/mean/ max (°C)	Mean reduction vs bare 30 cm (°C)	Hours over 30.6 (80%)	Hours over 29.6 (90%)
Base case (30 cm CEB infill walls)	baseline	31.9 / 33.76 / 35.7	—	168/168 (100%)	168/168 (100%)
EPS 3 cm	External infill walls	31.6 / 33.57 / 35.5	-0.19	168/168 (100%)	168/168 (100%)
EPS 3 cm	all walls	31.5 / 33.49 / 35.4	-0.26	168/168 (100%)	168/168 (100%)
EPS 5 cm	External infill walls	31.5 / 33.50 / 35.4	-0.26	168/168 (100%)	168/168 (100%)
EPS 5 cm	all walls	31.3 / 33.38 / 35.3	-0.38	168/168 (100%)	168/168 (100%)
SPF 3 cm	External infill walls	31.6 / 33.54 / 35.5	-0.22	168/168 (100%)	168/168 (100%)
SPF 3 cm	all walls	31.4 / 33.43 / 35.4	-0.33	168/168 (100%)	168/168 (100%)
SPF 5 cm	External infill walls	31.5 / 33.48 / 35.4	-0.28	168/168 (100%)	168/168 (100%)
SPF 5 cm	all walls	31.3 / 33.35 / 35.3	-0.41	168/168 (100%)	168/168 (100%)
Rock wool 3 cm	External infill walls	31.7 / 33.60 / 35.5	-0.16	168/168 (100%)	168/168 (100%)
Rock wool 3 cm	all walls	31.6 / 33.54 / 35.5	-0.22	168/168 (100%)	168/168 (100%)
Rock wool 5 cm	External infill walls	31.6 / 33.53 / 35.5	-0.22	168/168 (100%)	168/168 (100%)
Rock wool 5 cm	all walls	31.4 / 33.43 / 35.4	-0.32	168/168 (100%)	168/168 (100%)

6.3.4 Stage 3: Results of Roof and solar heat gain control

To overcome the limitations of the walls in mitigating the overheating hours in zones 1 and 3, this stage addresses the two loads that the base case identified as dominant, which are the heat gain through the exposed roof in zones 1 and 3, and the heat gain from the large glazed facade in zone 1 (WWR 63%). For zones 1 and 3, a cool roof strategy was evaluated in addition to cutting the glazing window-to-wall ratio to 20% in zone 1, the low end of the range reported as optimum for hot-arid climates and sun-exposed east facades (Alwetaishi and Benjeddou, 2021; Alwetaishi and Taki, 2020). A reflective white acrylic coating was evaluated as the cool roof strategy because of its proven effectiveness in substantially reducing roof heat gain. This coating was also chosen as it is applied as a thin layer over the existing roof, so the barrel vault and dome keep their form and take no added load and need no structural change, which is critical in earthen buildings. The coating has a thermal emissivity of 0.85, solar absorptance of 0.25, and visible absorptance of 0.2 (Synnefa et al., 2007). These strategies were evaluated across the summer design week under free-running conditions, with all windows and external doors closed and air exchange limited to infiltration, so that ventilation was excluded at this stage and introduced only in Phase 3. They were assessed as single strategies and in combination according to the zone, against the base case of 30 cm CEB infill external walls with no insulation.. In addition, it was evaluated in combination with the minimum insulation configuration (3 cm EPS applied to the external infill walls) to determine whether these strategies affected the amount of insulation needed and whether a thinner insulation layer became sufficient to achieve the desired thermal performance.

Zone 1

The simulation results show that the cool roof removes 100 of the 139 hours over the 80% limit. The WWR reduction removes 76 hours of overheating on its own, and the wall insulation removes 22 hours, as shown in Figure 6-15. None of the three strategies reaches comfort on its own. The cool roof and the reduced glazing together reduce the overheating hours to zero for both adaptive comfort limits, at a mean of 28.1 °C and a peak of 29.2 °C (Table 6-18). Adding the insulation leaves the hours count above the comfort limit at zero, but reduces the mean operative temperature to 26.7 °C and the peak to 28.0. And combining the cool roof with Insulation also reduces the overheating hours to only 2 at 80% limit and 57

hours at the 90% limit. While insulation combined with the reduced glazing doesn't achieve 100% comfort hours for both limits.

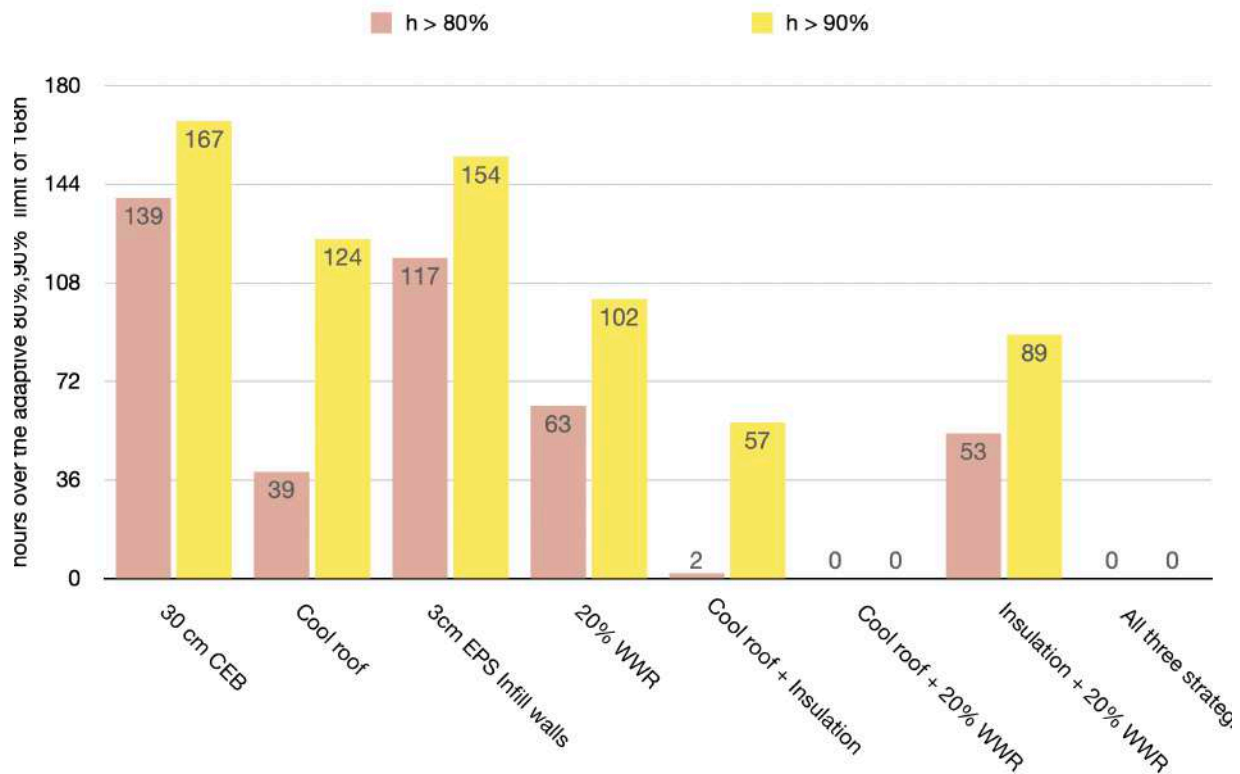


Figure 6-18: Overheating hours above the ASHRAE 55 adaptive comfort limits (80% and 90% acceptability) for the eight evaluated envelope configurations in Zone 1.

Table 6-10: Operative temperature (mean, peak, and minimum) and hours over the 80% and 90% adaptive comfort limits for the eight strategy combinations in Zone 1.

Strategy combination	Mean Op T °C	Peak Op T °C	Min Op T °C	h>80%	h>90%
Base case (30 cm CEB infill walls)	32.07	34.39	29.57	139	167
Reflective roof only	30.08	31.33	28.37	39	124
3 cm EPS infill insulation only	31.40	33.52	28.97	117	154
20% glazing only	30.13	32.08	28.41	63	102
Reflective roof + insulation	29.21	30.69	27.32	2	57
Reflective roof + 20% glazing	28.07	29.20	26.96	0	0
Insulation + 20% glazing	29.92	31.90	28.08	53	89
All three strategies	26.66	27.99	25.46	0	0

Zone 3

As shown in Figure 6-19, The Insulation on its own doesn't decrease the number of hours above the 90% and 80% comfort limit, so it holds 168 hours, and the mean operative temperature is reduced by about 0.19 °C only, as shown in Table 6-11. The cool roof alone reduced the overheating hours from 168 to 69 hours and when combined with the insulation it removes another 53 down to 16 hours above the 80% limit. This is because without the cool roof, the heat gain from the roof dominates, so wall insulation has little effect, and when the roof heat gain is reduced, the indoor temperature also decreases, which makes the wall insulation more effective.

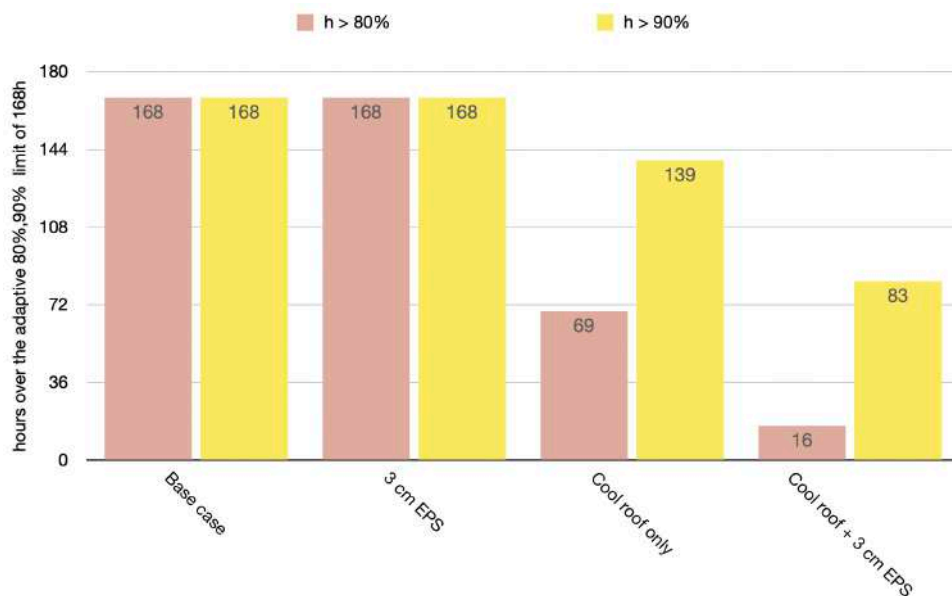


Figure 6-19: Overheating hours above the ASHRAE 55 adaptive comfort limits (80% and 90% acceptability) for the eight evaluated envelope configurations in Zone 3.

Table 6-11: Operative temperature (mean, peak, and minimum) and hours over the 80% and 90% adaptive comfort limits for the eight strategy combinations in Zone 3.

Strategy combination	Mean Op T °C	Peak Op T °C	Min Op T °C	h>80%	h>90%
Base case (30 cm CEB infill walls)	33.76	35.89	31.80	168	168
3 cm EPS	33.57	35.51	31.61	168	168
Cool roof only	30.39	31.63	28.97	69	139
Cool roof + 3 cm EPS	29.64	31.01	28.21	16	83

6.4 Phase 2 simulation results

This stage incorporated occupancy into the simulation and re-evaluated the envelope strategies settled in the previous phase. Each zone carries its own occupants and schedule, and comfort is assessed over both the whole week and the occupied hours, since the operative temperature matters to the users only while the space is in use. The measures examined follow each zone's dominant load: the wall configuration in Zone 2, which the base case tied to wall conduction, with the cool roof and reduced WWR assessed in Zone 1, and the cool roof assessed in Zone 3, which are governed by roof and solar gain. Any envelope variable left open from the previous phase is resolved here under occupancy, and all runs are free-running with no ventilation.

6.4.1 Zone 1

This phase analysed the strategies established in the previous section, which are the cool roof and window-to-wall ratio reduction to 20%, under occupancy. Zone 1 is a daycare occupied by 25 people, mostly children, with 2 adults, from 8:00 to 14:00, Sunday to Thursday. The best-performing strategies from the cool roof and glazing study were tested with occupancy and no ventilation, combined with the optimum wall configuration (5 cm EPS on all exterior walls exterior to the mass) and the least required wall configuration (3 cm EPS on infill exterior walls). Table 6-12 shows the operative temperature and the hours over 80% and 90% comfort limit for the whole week and the occupied hours.

Under occupancy, the optimum envelope configuration is the cool roof combined with the reduced 20% window-to-wall ratio for the east facade. This combination achieved zero hours above the 80% and 90% comfort limit. The Insulation further improves thermal performance by deepening the occupied mean from 28.9 °C with the roof and glazing alone to 27.8 °C with 3 cm infill and 27.3 at 5 cm on all walls, but it's not necessary to achieve comfort. Roof only and glazing alone with insulation are the only strategies that didn't achieve full comfort, with 13 hours above the 80% limit for the occupied hours for the cool roof only and 7 and 3 hours for the reduced window-to-wall ratio with 3cm infill insulation and 5 cm all-walls insulation, respectively. The difference between the 3 cm infill and the 5 cm on-walls insulation is only apparent under full glazing on the cool roof, where the 5cm insulation cuts the overheating hours from 24 to 8 hours above the 90% comfort limit. Still, both achieve zero hours above the 80% limit. And once the 20% glazing is incorporated, the difference is only 0.45 °C.

Table 6-12: Zone 1 (daycare) thermal performance by envelope configuration over a full week (168 hours) and over the occupied hours (08:00–14:00 Sunday to Thursday, 30 hours) in free-floating mode.

Strategy	Full week (of 168 h)					Occupied hours (of 30 h)		
	Mean Op T °C	Max Op T °C	Min Op T °C	h>80%	h>90%	Mean Op T °C	h>80%	h>90%
With cool roof								
Roof only	29.70	30.98	27.68	23	97	30.57	13	30
Roof + 3 cm infill insulation	28.86	30.47	26.68	0	51	29.91	0	24
Roof + 5 cm all-walls insulation	28.40	29.93	26.21	0	14	29.37	0	8
Roof + 20% glazing	28.54	29.59	27.09	0	0	28.88	0	0
Roof + 3 cm infill insulation + 20% glazing	27.21	28.51	25.61	0	0	27.79	0	0
Roof + 5 cm all-walls insulation + 20% glazing	26.82	28.07	25.25	0	0	27.34	0	0
Without cool roof								
3 cm infill insulation + 20% glazing	30.24	32.06	28.16	67	115	30.23	7	26
5 cm all-walls insulation + 20% glazing	30.06	31.97	27.96	59	104	29.93	3	20

6.4.2 Zone 2

Wall Assembly Optimization with Occupancy results

This stage evaluated the effects of insulation material, thickness (3cm and 5 cm EPS), application extent (infill walls or all external walls), and insulation placement (internal or external to the earthen wall) plus occupancy. The wall configuration assessment with occupancy was run only in Zone 2, which is the only zone governed by wall conduction. The results of this stage, being the properties of the wall assembly, can be carried on in the other zones.

Occupancy in Zone 2, an office with 6 people occupied from 8:00 am to 2:00 pm Sunday to Thursday, raised the overheating hours from 0 to 65 over the 80% comfort limit for the whole week, with 5 cm insulation on all external walls, which was found to be the optimum in the previous phase. Among the externally insulated configurations, the 3 cm insulation applied to the infill external walls performed worst, with 82 hours above the 80% comfort limit.

Exterior insulation beats interior insulation in every single pair, by 4 to 9 hours for the whole week. Reversing the layers, mass outside and insulation inside cuts the earthen mass off from the room, making it unable to absorb the heat from inside. This agrees with the literature on insulation placement. Oktay et al. (2020) and Al-Sanea et al. (2012) both found that placing the insulation on the outer face reduces heat flow into the wall and lets the mass absorb heat from the interior more effectively, and Hema et al. (2021) reported that a CEB layer inside with the insulation outside performed best against daytime overheating. Table 6-13 reports the mean, maximum, and minimum operative temperature and the hours over the 80% and 90% limits for the eight wall configurations for the whole week and the occupied hours.

Table 6-13: Zone 2 (office, six people) thermal performance by wall configuration, over a full week (168 hours) and over the occupied hours (08:00–14:00 Sunday to Thursday, 30 hours) in free-floating mode.

Wall scope	Insulation	Position	Full week (of 168 h)					Occupied hours (of 30 h)		
			Mean Op T °C	Max Op T °C	Min Op T °C	h>80 %	h>90 %	Mean Op T °C	h>80 %	h>90 %
All external walls	5 cm	exterior	30.14	31.88	28.11	65	110	31.20	28	30
All external walls	5 cm	interior	30.35	32.05	28.40	74	122	31.40	30	30
All external walls	3 cm	exterior	30.29	32.02	28.30	73	120	31.35	30	30
All external walls	3 cm	interior	30.43	32.12	28.50	77	124	31.48	30	30
Infill walls only	5 cm	exterior	30.54	32.18	28.61	81	131	31.58	30	30
Infill walls only	5 cm	interior	30.64	32.25	28.79	84	135	31.68	30	30
Infill walls only	3 cm	exterior	30.61	32.25	28.70	82	134	31.65	30	30
Infill walls only	3 cm	interior	30.68	32.29	28.84	86	137	31.72	30	30

For the occupied period between 8:00 am and 2:00 pm, the results are different, where every configuration was over the 80% limit for at least 28 of the 30 occupied hours, which was achieved in the 5cm insulation on all walls, while the rest of the configurations had all the occupied hours above the 80% comfort limit. The operative temperature rises from about 30.6 °C at 08:00 at the beginning of the week and reaches 31.9 at 13:00 on the last day of the week, with only 2 hours below the 80% limit. The overheating hours span from 8:00 to 19:00, and the coolest period is between 01:00 and 06:00, reaching 28 to 29 °C.

Influence of Upper-Floor Roof Cooling

Although Zone 2 does not have an exposed roof, it is located beneath Zone 3 with an exposed roof, where the two are joined by a floor slab. Therefore, the indirect effect of the cool roof on the thermal performance of Zone 2 was evaluated, which would decrease the heat transfer through the intermediate floor into Zone 2, Table 6-14.

With the cool roof above accounted for, the optimum envelope (5cm insulation on all walls) reduced the overheating hours above the 80% limit from 28 to 2 hours during the occupied hours, with a mean operative temperature of about 30.02 °C, which is a drop of about 1.18 °C. And the heat conducted down through the slab into Zone 2 fell from a weekly mean of 21.5 W/m² to 14.2, a cut of about 7.4 W/m², and its peak fell from 0.48 to 0.38 kW. The only two occupied hours that cross the limit both fall at 13:00 at 30.77 and 30.72 °C.

The wall assembly comparison gave the same results, with insulating the outer side of the mass beating the interior side, and insulating all external walls gave better results than insulating only the infill walls, and 5cm EPS insulation as the optimum. Moreover, the influence of insulation placement will be further evaluated in the subsequent phase with ventilation to determine the most effective configuration.

Table 6-14: Zone 2 (office, six people) thermal performance by wall configuration, over a full week (168 hours) and over the occupied hours (08:00–14:00 Sunday to Thursday, 30 hours) in free-floating mode.

Wall scope	Insulation	Position	Full week (of 168 h)				Occupied hours (of 30 h)			
			Mean Op T °C	Max Op T °C	Min Op T °C	h>80 %	h>90 %	Mean Op T °C	h>80 %	h>90 %
All external walls	5 cm	exterior	28.85	30.77	26.76	2	56	30.02	2	25
All external walls	5 cm	interior	29.05	30.93	26.99	6	60	30.21	6	28
All external walls	3 cm	exterior	29.07	30.97	27.00	6	63	30.23	6	28
All external walls	3 cm	interior	29.20	31.08	27.16	7	70	30.36	6	30
Infill walls only	5 cm	exterior	29.45	31.26	27.44	20	76	30.59	11	30
Infill walls only	5 cm	interior	29.55	31.34	27.60	29	79	30.69	16	30
Infill walls only	3 cm	exterior	29.55	31.36	27.55	29	80	30.69	16	30
Infill walls only	3 cm	interior	29.63	31.41	27.68	37	82	30.76	17	30

6.4.3 Zone 3

This phase assessed the most effective strategies from the previous section, which are the cool roof alone, and the combination of cool roof and wall insulation of 3 cm EPS on infill walls, and also the 5 cm EPS insulation on all exterior walls spanning the least and the most insulated build-ups. Zone 3 is a residential suite, so the assessment was for the whole week instead of a certain occupancy period. Table 6-15 shows the operative temperature and the hours over the 80% and 90% comfort limits across the week.

The occupancy raised the hours over the 80% limit from 69 to 125 for the cool roof and from 16 to 24 for the cool roof combined with 3cm infill insulation, and when combined with the 5 cm insulation on all external walls, the hours reached 8 over the 80% limit with a mean operative temperature of about 29.4 °C and max 30.8 °C, achieving the least overheating hours with a difference of about 0.7 °C indicating the importance of insulating all walls.

Table 6-15: Zone 3 (residential suite) thermal performance by envelope configuration over a full week (168 hours) occupied, no ventilation.

Strategy	Mean Op T °C	Max Op T °C	Min Op T °C	h>80%	h>90%
Roof only	30.9	31.6	30.0	125	168
Roof + 3 cm infill insulation	30.1	31.0	29.1	24	145
Roof + 5 cm all-walls insulation	29.4	30.8	27.9	8	66

6.5 Phase 3 simulation results

Ventilative cooling is assessed for each zone's settled envelope under an automated optimum: all-day ventilation with temperature control, where the windows may open at any hour but open only when the outdoor air is cooler than the indoor air and lower than the 80% comfort operative temperature limit, so ventilation is admitted whenever it cools and never when opening would draw in warmer air. Because it takes every cooling opportunity, day or night, this is the most that ventilation can achieve. It serves two purposes: it isolates the cooling that ventilation alone contributes, so the envelope and strategy comparisons rest on that benefit and are never charged with heat the openings would not have let in, and it reveals the timing of when each zone benefits from ventilation, from the hours the control actually opens the windows.

6.5.1 Zone 1

The automated optimum, all-day ventilation with temperature control, was assessed on the same eight envelope strategies as the free-floating occupancy analysis, against the no-ventilation case (Table 6-16). The ventilation draws through the zone's four west-facing windows, each 1×0.4 m, bottom-hung and set to open fully at a discharge coefficient (C_d) of 0.65. Every strategy holds zero occupied hours over the 80% limit except the cool roof alone and the two glazing cases that drop the roof, matching the free-floating counts almost exactly. With all-day ventilation, the operative temperature is reduced at most by about 0.13°C among all envelope configurations against the sealed case and lowers the overheating counts by 1 to 2 at most within the envelopes that didn't reach zero overheating hours during the occupied hours and at most 3 hours reduced within the stricter 90% comfort limit within the occupied hours.

The reason is the flow and the temperature difference, which are both small. The openings exchange very little heat with the room because the air change is low, and across the eight envelopes, over the hours the control opens the windows, they deliver a mean of about 1.5 to 2.4 ACH and peak between 2.7 and 3.2 ACH under all-day ventilation; the cooler envelopes open for fewer hours and move less air, far below what would cool the zone. And when the windows do open, the room and the outside sit at almost the same temperature, where on the settled design the indoor air leads the outdoor by only about 0.5°C on average and at most 1.6°C . Ventilative cooling depends on air change and the temperature difference, so with both this small, the openings exchange almost no heat. The warmer envelopes open at a wider gap, leading the outside by about 1.4 to 1.6°C and up to 3.4°C , but their air change is still only about 2 ACH, so the cooling stays negligible there too; across every envelope, either the difference is too small to act on or the flow too weak to act on it. Ventilation is not what carries this zone; the roof and the glazing are, and with 3 cm EPS infill walls about 1°C is reduced while the heavier 5 cm all-walls build-up runs about half a degree cooler than the 3 cm design, 27.3 against 27.8°C occupied and 26.8 against 27.2 over the week, yet both already hold zero hours over either limit, so the extra insulation buys margin rather than compliance.

The control opens the windows overnight and through the morning, from about midnight to 10:00, with the highest airflow between 08:00 and 10:00, when the outdoor air has cooled below the room, and shuts them from 11:00 through the evening once the outside runs hotter than the room and above the 80% comfort limit; see Figure 6-20. The pattern follows the office's, open at night and in the morning and shut through the hot afternoon, but on fewer hours and at a lower flow as the cooler envelope holds the interior below the outdoor air for most of the week, so the control

finds fewer moments when opening would cool and the flow is slight throughout, peaking at 2.7 ACH.

Table 6-16: Zone 1 (daycare) performance by wall configuration and ventilation schedule, reported over the full week (168 hours) and over the occupied hours (08:00–14:00 Sunday to Thursday, 30 hours).

Envelope	Occupied hours over 80% / 90% limit (of 30)		Full-week hours over 80% / 90% limit (of 168)	
	No vent	All-day	No vent	All-day
Roof only	13 / 30	12 / 28	23 / 97	21 / 93
Roof + 3 cm infill	0 / 24	0 / 23	0 / 51	0 / 50
Roof + 5 cm all walls	0 / 8	0 / 6	0 / 14	0 / 11
Roof + 20% glazing	0 / 0	0 / 0	0 / 0	0 / 0
Roof + 3 cm infill + 20%	0 / 0	0 / 0	0 / 0	0 / 0
Roof + 5 cm all walls + 20%	0 / 0	0 / 0	0 / 0	0 / 0
3 cm infill + 20%	7 / 26	7 / 23	67 / 115	66 / 107
5 cm all walls + 20% glazing	3 / 20	3 / 18	59 / 104	57 / 99
	Mean operative temperature, occupied (°C)		Mean operative temperature, full week (°C)	
	No vent	All-day	No vent	All-day
Roof only	30.6	30.4	29.7	29.6
Roof + 3 cm infill	29.9	29.8	28.9	28.8
Roof + 5 cm all walls	29.4	29.3	28.4	28.4
Roof + 20% glazing	28.9	28.8	28.5	28.5
Roof + 3 cm infill + 20%	27.8	27.8	27.2	27.2
Roof + 5 cm all walls + 20%	27.3	27.3	26.8	26.8
3 cm infill + 20%, no roof	30.2	30.1	30.2	30.2
5 cm all walls + 20%, no roof	29.9	29.8	30.1	30.0

Hour	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
01:00	26.4 / 27.1	26.5 / 27.1	26.8 / 28.7	26.9 / 26.4	26.9 / 27.0	27.3 / 28.4	27.2 / 26.4
02:00	26.2 / 26.3	26.3 / 27.2	26.7 / 28.7	26.7 / 25.9	26.8 / 26.3	27.1 / 28.2	27.0 / 25.6
03:00	26.1 / 26.0	26.2 / 27.6	26.5 / 28.5	26.5 / 26.4	26.6 / 26.2	27.0 / 27.9	26.8 / 25.3
04:00	25.9 / 26.4	26.0 / 27.6	26.4 / 28.2	26.4 / 26.7	26.4 / 26.0	26.8 / 27.7	26.6 / 25.1
05:00	25.7 / 26.8	25.9 / 27.2	26.2 / 27.9	26.2 / 26.0	26.3 / 25.6	26.6 / 27.4	26.5 / 24.7
06:00	25.6 / 26.9	25.7 / 27.1	26.1 / 27.6	26.0 / 25.5	26.1 / 25.2	26.5 / 27.2	26.3 / 24.7
07:00	25.6 / 26.5	25.8 / 26.7	26.1 / 26.8	26.0 / 25.2	26.2 / 25.6	26.4 / 26.0	26.3 / 24.9
08:00	25.7 / 27.1	27.0 / 27.4	27.3 / 27.9	27.1 / 26.4	27.4 / 28.6	27.5 / 26.9	26.4 / 26.2
09:00	25.8 / 27.9	27.3 / 28.9	27.6 / 29.5	27.5 / 27.9	27.7 / 30.9	27.8 / 28.6	26.5 / 27.3
10:00	25.9 / 28.3	27.4 / 29.7	27.7 / 30.0	27.6 / 28.4	27.9 / 31.9	27.9 / 29.3	26.6 / 27.8
11:00	26.0 / 30.8	27.6 / 31.5	27.9 / 31.4	27.8 / 30.4	28.1 / 34.3	28.1 / 30.8	26.7 / 29.5
12:00	26.1 / 32.9	27.7 / 33.5	28.0 / 33.1	27.9 / 32.3	28.3 / 36.1	28.2 / 32.1	26.8 / 31.1
13:00	26.3 / 34.4	27.9 / 35.1	28.2 / 34.4	28.2 / 33.7	28.5 / 37.2	28.4 / 33.2	26.9 / 32.5
14:00	26.6 / 35.6	27.3 / 36.3	27.6 / 35.4	27.5 / 34.8	27.9 / 38.1	27.8 / 34.4	27.2 / 33.7
15:00	27.0 / 36.5	27.4 / 37.0	27.7 / 36.0	27.6 / 35.2	28.0 / 38.4	27.9 / 35.2	27.5 / 34.2
16:00	27.2 / 37.0	27.6 / 37.4	27.9 / 36.4	27.8 / 35.6	28.2 / 38.5	28.1 / 35.7	27.8 / 34.6
17:00	27.4 / 36.8	27.8 / 37.1	28.1 / 36.0	28.0 / 35.5	28.4 / 37.8	28.3 / 35.2	28.0 / 34.3
18:00	27.5 / 36.3	27.9 / 36.3	28.1 / 35.2	28.0 / 35.2	28.4 / 37.1	28.4 / 34.5	28.0 / 33.9
19:00	27.4 / 36.0	27.8 / 35.4	28.0 / 34.8	27.9 / 34.9	28.3 / 36.7	28.2 / 33.9	27.9 / 33.4
20:00	27.3 / 34.0	27.6 / 33.9	27.8 / 33.0	27.8 / 32.9	28.2 / 34.2	28.1 / 32.1	27.8 / 31.8
21:00	27.2 / 32.0	27.5 / 32.4	27.7 / 31.2	27.6 / 31.2	28.0 / 32.1	27.9 / 30.5	27.6 / 30.3
22:00	27.0 / 31.0	27.3 / 31.4	27.5 / 30.2	27.4 / 30.6	27.9 / 31.4	27.7 / 29.7	27.5 / 29.7
23:00	26.8 / 29.2	27.1 / 30.1	27.3 / 28.6	27.3 / 29.1	27.7 / 29.9	27.5 / 28.4	27.3 / 28.6
24:00	26.7 / 27.9	27.0 / 28.9	27.1 / 27.1	27.1 / 28.0	27.5 / 28.7	27.3 / 27.3	27.1 / 27.4

Figure 6-20: Zone 1 window-opening across the design week (12–18 August) for the settled envelope (3cm insulation infill walls+ cool roof +20% glazing) under all-day ventilation. Cells are shaded by air-change rate (darker blue = higher ACH) and labelled with the indoor operative and outdoor dry-bulb temperature

6.5.2 Zone 2

The office ventilates through its two south-facing windows (8.5% WWR), each 1×0.4 m, bottom-hung and set to open fully at a discharge coefficient (C_d) of 0.65, under the optimum control that opens them only while the outdoor air is cooler than the indoor. Table 6-16 reports each wall configuration with the windows shut and under this ventilation, over the full week and the occupied hours.

The office already sits near comfort on the envelope, so the optimum ventilation has little left to add. On the settled 5 cm all-walls exterior wall, it removes one occupied hour over the 80% limit, from 2 to 1, and trims the stricter 90% band from 25 occupied hours to 17, at an occupied mean of 29.76°C , a drop of about 0.26°C from the non-ventilated schedule. The wall ranking holds under ventilation as it did without it: insulating all external walls beats the infill walls alone, exterior placement beats interior, and 5 cm beats 3 cm, so the office keeps 5 cm of EPS on all external walls, outboard of the mass. The reversed build-up, with the insulation interior to the mass, stayed about 0.2 to 0.3°C warmer than the exterior placement at every hour and held more hours over both limits, which diverges from Hema et al. (2021), who found interior insulation

more effective for nighttime mitigation once night ventilation was applied; here the exterior placement was cooler throughout, night included. Even at its optimum, the flush is modest. While the windows are open, around 3.0 ACH overnight, strengthening to about 4.6 through the occupied morning with a peak of 6.8 ACH when the occupants' own heat widens the indoor–outdoor gap that drives the buoyancy flow. Both stay well below the roughly 10 ACH that Darmanis et al. (2020) and Amos-Abanyie et al. (2013) report as necessary for night ventilation to be effective, so the cool air the openings admit does only a little for a zone the envelope has already carried within reach of comfort.

The control opens the windows overnight and through the morning, from about midnight to 11:00, and highest airflow between 07:00 and 11:00, when the outdoor air has cooled below it, and shuts them from noon through the evening when the outside runs hotter than the room and above the 80% comfort limit; see Figure 6-21.

Table 6-17: Zone 2 (office) thermal performance by wall configuration and ventilation schedule, reported over the full week (168 hours) and over the occupied hours (08:00–14:00 Sunday to Thursday, 30 hours).

Wall scope	Insulation	Position	ventilation schedule	Full week (of 168 h)			Occupied hours (of 30 h)		
				Mean Op T °C	h>80%	h>90 %	Mean Op T °C	h>80 %	h>90 %
All external walls	5 cm	exterior	No vent	28.85	2	56	30.02	2	25
			All-day	28.67	1	42	29.76	1	17
All external walls	5 cm	interior	No vent	29.05	6	60	30.21	6	28
			All-day	28.97	3	53	30.03	3	21
All external walls	3 cm	exterior	No vent	29.07	6	63	30.23	6	28
			All-day	28.99	4	55	30.05	4	22
All external walls	3 cm	interior	No vent	29.20	7	70	30.36	6	30
			All-day	29.11	6	62	30.16	6	24
Infill walls only	5 cm	exterior	No vent	29.45	20	76	30.59	11	30
			All-day	29.36	18	74	30.38	11	28
Infill walls only	5 cm	interior	No vent	29.55	29	79	30.69	16	30
			All-day	29.45	22	77	30.46	13	29
Infill walls only	3 cm	exterior	No vent	29.55	29	80	30.69	16	30
			All-day	29.45	23	78	30.47	13	29
Infill walls only	3 cm	interior	No vent	29.63	37	82	30.76	17	30

All-day 29.52 27 80 30.53 14 29

Hour	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
01:00	27.00 / 27.13	27.20 / 27.13	27.63 / 28.68	27.57 / 26.39	27.76 / 26.98	28.07 / 28.44	27.98 / 26.36
02:00	26.84 / 26.33	27.10 / 27.21	27.52 / 28.68	27.37 / 25.93	27.53 / 26.34	27.93 / 28.23	27.81 / 25.61
03:00	26.70 / 26.00	27.01 / 27.62	27.40 / 28.48	27.34 / 26.38	27.41 / 26.24	27.80 / 27.93	27.68 / 25.34
04:00	26.64 / 26.41	26.92 / 27.58	27.29 / 28.23	27.30 / 26.68	27.28 / 26.02	27.69 / 27.68	27.57 / 25.12
05:00	26.56 / 26.82	26.81 / 27.21	27.18 / 27.87	27.11 / 25.96	27.11 / 25.61	27.59 / 27.43	27.45 / 24.71
06:00	26.54 / 26.90	26.76 / 27.06	27.14 / 27.64	26.97 / 25.50	26.98 / 25.23	27.52 / 27.18	27.40 / 24.73
07:00	27.79 / 26.49	27.99 / 26.69	28.08 / 26.78	27.75 / 25.21	27.94 / 25.62	28.22 / 25.99	28.46 / 24.90
08:00	28.08 / 27.13	28.86 / 27.45	29.17 / 27.95	28.91 / 26.40	29.39 / 28.57	29.29 / 26.89	28.80 / 26.18
09:00	27.94 / 27.92	29.05 / 28.90	29.39 / 29.49	29.14 / 27.87	29.73 / 30.93	29.56 / 28.62	28.75 / 27.33
10:00	28.01 / 28.29	29.27 / 29.69	29.57 / 29.99	29.32 / 28.43	29.90 / 31.88	29.78 / 29.29	28.86 / 27.79
11:00	28.28 / 30.77	29.6 / 31.5	29.9 / 31.4	29.8 / 30.4	30.2 / 34.3	30.1 / 30.8	29.09 / 29.46
12:00	28.51 / 32.92	29.83 / 33.52	30.10 / 33.08	30.12 / 32.28	30.43 / 36.11	30.42 / 32.09	29.32 / 31.08
13:00	28.69 / 34.35	30.03 / 35.09	30.29 / 34.40	30.31 / 33.69	30.63 / 37.16	30.59 / 33.23	29.50 / 32.55
14:00	28.89 / 35.62	29.49 / 36.33	29.73 / 35.37	29.75 / 34.75	30.14 / 38.11	30.02 / 34.37	29.63 / 33.71
15:00	29.05 / 36.47	29.53 / 36.99	29.72 / 35.99	29.76 / 35.23	30.15 / 38.40	30.03 / 35.17	29.72 / 34.23
16:00	29.18 / 37.03	29.63 / 37.38	29.77 / 36.38	29.82 / 35.58	30.18 / 38.52	30.10 / 35.67	29.77 / 34.58
17:00	29.20 / 36.79	29.65 / 37.15	29.75 / 35.98	29.82 / 35.47	30.15 / 37.84	30.07 / 35.22	29.76 / 34.29
18:00	29.15 / 36.33	29.57 / 36.26	29.68 / 35.25	29.77 / 35.24	30.07 / 37.12	29.97 / 34.45	29.71 / 33.88
19:00	28.60 / 36.02	29.00 / 35.39	29.13 / 34.77	29.20 / 34.85	29.52 / 36.71	29.36 / 33.85	29.15 / 33.39
20:00	28.28 / 34.03	28.67 / 33.88	28.80 / 33.02	28.88 / 32.91	29.16 / 34.23	29.06 / 32.08	28.87 / 31.76
21:00	28.00 / 32.00	28.40 / 32.36	28.53 / 31.20	28.60 / 31.23	28.86 / 32.13	28.80 / 30.53	28.62 / 30.33
22:00	27.82 / 30.98	28.21 / 31.43	28.32 / 30.23	28.43 / 30.55	28.68 / 31.39	28.60 / 29.68	28.44 / 29.71
23:00	27.59 / 29.20	28.00 / 30.11	28.07 / 28.56	28.22 / 29.07	28.44 / 29.88	28.37 / 28.37	28.23 / 28.57
24:00	27.36 / 27.85	27.78 / 28.88	27.80 / 27.13	28.01 / 27.97	28.22 / 28.71	28.12 / 27.29	28.02 / 27.43

Figure 6-21: Zone 2 window-opening across the design week (12–18 August) for the settled envelope (5 cm EPS on all external walls) under all-day ventilation. Cells are shaded by air-change rate (darker blue = higher ac/h) and labelled with the indoor operative and outdoor dry-bulb temperature

6.5.3 Zone 3

The three envelopes assessed under occupancy were also evaluated with all-day ventilation under temperature control, each compared with the sealed case, as shown in Table 6-18. The residence ventilates through six windows, four on the north facade (8.5% WWR) and two on the south facade (4.25% WWR), each 1×0.4 m, bottom-hung and set to open fully at a discharge coefficient (Cd) of 0.65, and the results are analyzed over the full design week.

Airflow distinguishes Zone 3 from the other two zones, as its openings sit on opposite facades, north and south, achieving cross-ventilation and a higher air change, where the other two zones manage only single-sided ventilation. Averaged over the open hours the flow runs about 9 ACH and peaks near 21. This higher air change is what lets ventilation contribute at all here, unlike the daycare where it did almost nothing: it lowers the hours over the 80% limit sharply on the weaker envelopes, from 125 to 55 on the cool roof alone and from 24 to 9 with 3 cm of infill insulation. On the settled 5 cm all-walls envelope, however, which the walls have already carried close to comfort, its effect is modest, trimming the hours over the stricter 90%

limit only from 66 to 55 and over the 80% from 8 to 4, at a mean 0.25 °C cooler than sealed (Table 6-18).

The cooling is delivered as a night flush (Figure 6-22). The windows open on all seven nights from about 23:00 to 08:00, extending on some mornings to 09:00–11:00 while the outdoor air is still below the interior, and shut through the hot afternoon from noon to 20:00, reopening in the late evening around 21:00–22:00; the overnight flush runs about 10 to 13 ac/h around midnight. Occupied around the clock, sealed, it is hottest in the early evening, from 17:00 to 20:00, where all its hours over the limit fall, and coolest in the late morning. Because it stays warm into the night while the outdoor air cools to 26 to 28 °C, it keeps a real temperature difference to flush against, where the office and daycare, cooler and closed at night, do not. The control opens the windows across exactly those hours, drawing some of the accumulated heat from the mass so the following day runs cooler. The gain, however, is small, even at its most effective; in the small hours when the outdoor air has dropped near 25 °C, some 4 °C below the room, the flush lowers the operative temperature by only about 1.0 °C against the sealed case, and by 0.25 °C on the weekly mean. The residence is the zone ventilation that helps most of the three, but the envelope carries the comfort, and the night flush only refines it.

Table 6-18: Zone 3 (residential suite) performance by wall configuration and automated ventilation schedule, reported over the full week (168 hours)

Envelope	Ventilation	Mean Op T °C	Max Op T °C	h>80%	h>90%
Roof only	No ventilation	30.92	31.64	125	168
	All day	30.31	31.42	55	138
Roof + 3 cm infill	No ventilation	30.13	31.00	24	145
	All day	29.74	30.85	9	97
Roof + 5 cm all walls	No ventilation	29.41	30.84	8	66
	All day	29.16	30.75	4	55

Hour	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
01:00	28.4 / 27.1	28.4 / 27.1	29.2 / 28.7	28.7 / 26.4	29.0 / 27.0	29.5 / 28.4	28.9 / 26.4
02:00	28.0 / 26.3	28.3 / 27.2	29.1 / 28.7	28.6 / 25.9	28.8 / 26.3	29.4 / 28.2	28.7 / 25.6
03:00	27.8 / 26.0	28.4 / 27.6	29.0 / 28.5	28.6 / 26.4	28.5 / 26.2	29.3 / 27.9	28.5 / 25.3
04:00	27.8 / 26.4	28.3 / 27.6	28.8 / 28.2	28.5 / 26.7	28.4 / 26.0	29.1 / 27.7	28.4 / 25.1
05:00	27.9 / 26.8	28.2 / 27.2	28.6 / 27.9	28.2 / 26.0	28.2 / 25.6	28.9 / 27.4	28.3 / 24.7
06:00	27.8 / 26.9	28.1 / 27.1	28.4 / 27.6	27.9 / 25.5	28.1 / 25.2	28.7 / 27.2	28.2 / 24.7
07:00	27.7 / 26.5	28.0 / 26.7	28.3 / 26.8	27.7 / 25.2	28.1 / 25.6	28.5 / 26.0	28.1 / 24.9
08:00	27.8 / 27.1	28.0 / 27.4	28.4 / 27.9	27.8 / 26.4	28.4 / 28.6	28.5 / 26.9	28.2 / 26.2
09:00	27.8 / 27.9	28.1 / 28.9	28.5 / 29.5	28.1 / 27.9	28.5 / 30.9	28.7 / 28.6	28.3 / 27.3
10:00	27.9 / 28.3	28.2 / 29.7	28.5 / 30.0	28.3 / 28.4	28.7 / 31.9	28.9 / 29.3	28.4 / 27.8
11:00	28.1 / 30.8	28.3 / 31.5	28.7 / 31.4	28.6 / 30.4	28.9 / 34.3	29.0 / 30.8	28.8 / 29.5
12:00	28.3 / 32.9	28.6 / 33.5	28.9 / 33.1	28.8 / 32.3	29.2 / 36.1	29.3 / 32.1	29.1 / 31.1
13:00	28.5 / 34.4	28.9 / 35.1	29.2 / 34.4	29.1 / 33.7	29.5 / 37.2	29.5 / 33.2	29.3 / 32.5
14:00	28.9 / 35.6	29.2 / 36.3	29.5 / 35.4	29.4 / 34.8	29.8 / 38.1	29.8 / 34.4	29.7 / 33.7
15:00	29.3 / 36.5	29.5 / 37.0	29.9 / 36.0	29.7 / 35.2	30.1 / 38.4	30.2 / 35.2	30.0 / 34.2
16:00	29.6 / 37.0	29.8 / 37.4	30.1 / 36.4	30.0 / 35.6	30.4 / 38.5	30.4 / 35.7	30.3 / 34.6
17:00	29.8 / 36.8	30.0 / 37.1	30.3 / 36.0	30.2 / 35.5	30.6 / 37.8	30.6 / 35.2	30.4 / 34.3
18:00	29.9 / 36.3	30.1 / 36.3	30.4 / 35.2	30.3 / 35.2	30.8 / 37.1	30.7 / 34.5	30.5 / 33.9
19:00	29.8 / 36.0	30.0 / 35.4	30.3 / 34.8	30.2 / 34.9	30.6 / 36.7	30.6 / 33.9	30.4 / 33.4
20:00	29.7 / 34.0	29.9 / 33.9	30.2 / 33.0	30.1 / 32.9	30.5 / 34.2	30.5 / 32.1	30.3 / 31.8
21:00	29.6 / 32.0	29.8 / 32.4	30.1 / 31.2	30.0 / 31.2	30.4 / 32.1	30.3 / 30.5	30.2 / 30.3
22:00	29.5 / 31.0	29.7 / 31.4	29.9 / 30.2	29.9 / 30.6	30.3 / 31.4	30.1 / 29.7	30.0 / 29.7
23:00	29.2 / 29.2	29.6 / 30.1	29.4 / 28.6	29.6 / 29.1	30.0 / 29.9	29.6 / 28.4	29.6 / 28.6
24:00	28.8 / 27.9	29.3 / 28.9	28.9 / 27.1	29.3 / 28.0	29.6 / 28.7	29.2 / 27.3	29.2 / 27.4

Figure 6-22: Zone 3 window-opening across the design week (12–18 August) for the settled envelope (5cm insulation on all external walls+ cool roof) under all-day automated ventilation. Cells are shaded by air-change rate (darker blue = higher ACH) and labelled with the indoor operative and outdoor dry-bulb temperature.

6.6 Phase 4 Results

After settling each zone envelope and its schedule, this stage evaluates three ventilation modes: single-sided against cross ventilation and a windcatcher tested across shaft cross section (3% and 6% of Zone floor area) and heights (6 and 9m). All the strategies were assessed under an all-day ventilation automated schedule so the comparison isolates the effect of the ventilation mode. The results show which mode gives higher ACH and whether it lifts the ventilation rate to the required standard based on EN 16798-1 Category II ventilation rates, which were calculated to be 6.35 ACH for zone 1, 5.51 ACH for zone 2, and 1.76 ACH for zone 3, in addition to the cooling effect of the ventilation mode.

6.6.1 Zone 1

The three ventilation strategies were evaluated using the optimized envelope under the same all-day automated operating schedule. Single-sided ventilation was provided through the four west-facing windows, while cross-ventilation was achieved by opening the two north doors and the west-facing windows. For the windcatcher configuration, it was placed on the north facade of

the zone with a north-facing inlet as shown in Figure 6-23, which was evaluated using two shaft cross-sections and two tower heights.

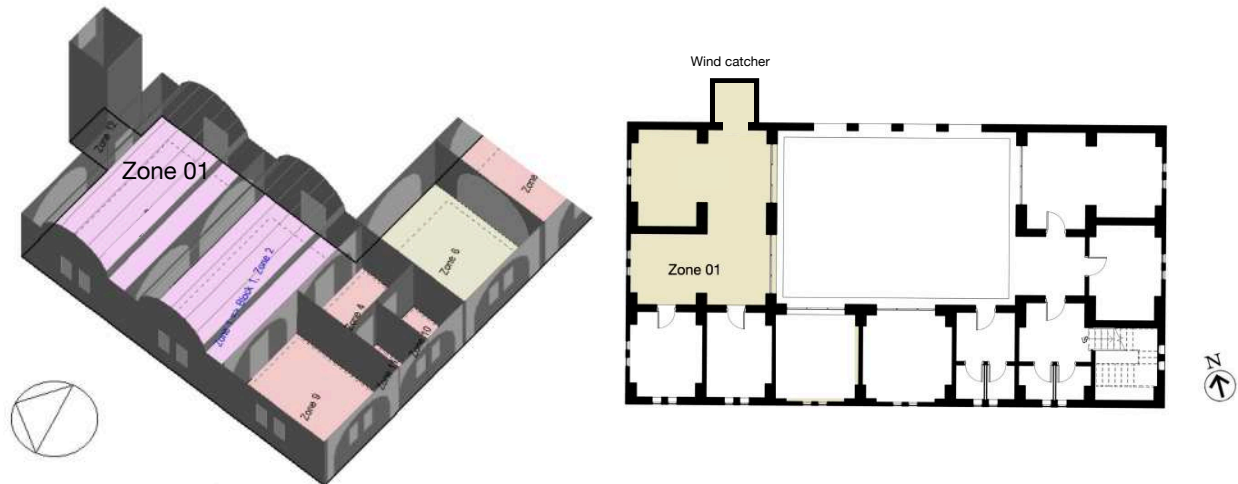


Figure 6-23: The wind catcher serving Zone 1 of the Aqbat Jabr women's centre: (left) the DesignBuilder model, and (right) the wind catcher's position on the ground-floor plan (author's model and drawing).

Every strategy achieves zero hours above the 80% and 90% comfort limits (Table 6-19). However, the ACH distinguishes between them, as the single-sided ventilation moves only a mean of 2.0 ACH over the occupied hours, well below the required 6.35 ACH. Cross ventilation lifts that to 11.7 ACH, and wind catchers to between 9 and 23 ACH.

For cooling, neither strategy was effective, and the windcatcher even worked counterproductively. The occupied mean operative temperature falls about 0.06 °C under cross-ventilation, but rises about 0.2 °C to 0.35 °C under every windcatcher configuration.

Cross-ventilation is therefore the mode carried forward for the daycare. It delivers the required ventilation rate while the windows are open, matches the windcatcher on air without its slight thermal penalty, and needs only a through-path across the space rather than a built shaft, so it is the simplest and least costly of the three. Single-sided is retained only as the fallback where a through-path cannot be opened, since it alone falls short of the rate.

Table 6-19: Zone 1 (office) occupied-hours performance under single-sided, cross, hybrid, and windcatcher ventilation, on the settled 5 cm all-walls envelope, all-day automated schedule with temperature control.

Strategy	Occ hrs >80%	Occ hrs >90%	Occ Op T °C	Occ open- hrs ACH	open-hrs ACH	Peak ACH
No ventilation	0	0	27.79	-	-	-
Single-sided	0	0	27.78	2.0	1.7	2.7

Cross-ventilation	0	0	27.73	11.7	11.9	23.1
Windcatcher 1 m ² / 6 m	0	0	28.00	17.0	17.8	35.7
Windcatcher 1 m ² / 9 m	0	0	28.09	17.3	18.2	37.4
Windcatcher 2 m ² / 6 m	0	0	28.08	9.4	9.9	16.7
Windcatcher 2 m ² / 9 m	0	0	28.15	22.6	22.9	48.4

6.6.2 Zone 2

The three ventilation strategies were evaluated using the optimized envelope under the same all-day automated operating schedule. Single-sided ventilation was provided through the two south-facing windows, while cross-ventilation was achieved by opening the north door and the south-facing windows. For the windcatcher configuration, the two south-facing windows were replaced with a windcatcher as shown in Figure 6-24, which was evaluated using two shaft cross-sections and two tower heights.

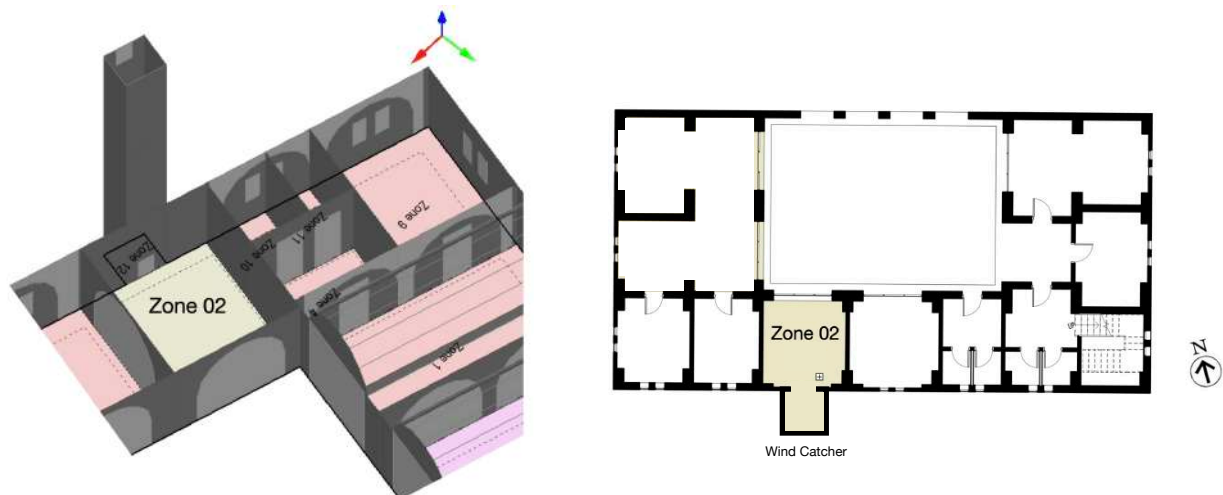


Figure 6-24: The wind catcher serving Zone 2 of the Aqbat Jabr women's centre: (left) the DesignBuilder model, and (right) the wind catcher's position on the ground-floor plan (author's model and drawing).

As shown in Table 6-20, the comfort limit barely moves across the ventilation modes. The envelope already carries the office to the edge of the comfort limit, holding 2 occupied hours over the 80% limit, under the free floating mode, and 25 hours above the 90% comfort limit. The occupied mean operative temperature nearly stays the same, falling from 30.02 °C under no ventilation to between 29.76 and 29.37 across all the modes, with under 0.5 °C difference. And even the stricter 90% comfort band moves little, from 25 hours with no ventilation to 17 under single-sided and 14 under the largest wind catcher.

The ventilation rate clearly distinguishes the three strategies. The single-sided moves 4.6 ACH over the open occupied hours, below the 5.51 the standard requires; cross ventilation reaches 21.3 ACH, and the wind catchers 18 to 26 ACH, with a peak of 43.9 for the cross ventilation. Even though all the modes exceed the 10 ACH the literature recommends, the operative temperature didn't follow the air change, with a very slight decrease compared to the single-sided mode, showing that higher airflow buys no further cooling. The reason is that the temperature difference is never higher than 2.5 °C and mostly below 2 °C. The results also show that cross ventilation is more than enough, as it clears the required ventilation rate and matches the wind catchers on both airflow rate and comfort, without the added structure and cost of the tower. Cross-ventilation is therefore the mode carried forward.

Table 6-20: Zone 2 (office) occupied-hours performance under single-sided, cross, hybrid, and windcatcher ventilation, on the settled 5 cm all-walls envelope, all-day automated schedule with temperature control.

Strategy	Occ hrs >80%	Occ hrs >90%	Occ mean Operative	Open-hrs mean ACH	Occ open- hrs ACH	Peak ACH
No vent	2	25	30.02	-	-	-
Single-sided	1	17	29.76	3.8	4.6	6.8
Cross-ventilation	0	16	29.54	20.1	21.3	43.9
Windcatcher 0.33 m ² / 6 m	0	17	29.65	14.8	18.0	26.3
Windcatcher 0.33 m ² / 9 m	0	15	29.50	13.5	18.0	30.9
Windcatcher 0.66 m ² / 6 m	0	14	29.39	21.6	23.0	32.0
Windcatcher 0.66 m ² / 9 m	0	14	29.37	21.2	25.9	36.1

6.6.3 Zone 3

Ventilation modes were not assessed in this zone, as the windows sit on opposite facades, so it easily ventilates by cross flow, delivering about 9 ACH over open hours, which is well above the required 1.76 ACH. So the cross ventilation is already its settled mode, and the wind catcher only delivers higher airflows with no cooling, as proved in the other zones.

6.7 Phase 5 results

This section assessed how closely a fixed, manually operated schedule can deliver. Ventilation schedules are determined for each zone based on the periods identified as feasible for ventilation and based on practicality.

6.7.1 Zone 1

As shown in the previous section, ventilative cooling has a negligible benefit to this zone as on the optimum envelope the cross ventilation lowered the occupied mean operative temperature by at most 0.06 °C with zero overheating hours on both limits. Zone 2 also showed that the only practical schedule to take advantage of the cooling effect of ventilation is during the occupied early morning hours. Therefore, the ventilation purpose in Zone 1 is not to flush heat but to provide adequate ventilation while also maintaining thermal comfort, which will be assessed in the next section.

6.7.2 Zone 2

For the office, two periods can be operated by hand: the occupied morning, when the windows are open on arrival, and the unoccupied afternoon and night, when windows can be left open after the office closes at 14:00. Therefore, 5 practical schedules were evaluated and compared with the automated optimum as shown in Table 6-21. The morning opening achieved the best results where cross ventilation from 8:00 to 11:00, with no flush at all holds 1 occupied hour over the 80% comfort limit and 17 over the 90%, with a peak operative temperature of 30.72 °C, nearly matching the automated optimum, with a mean airflow rate of about 11.7 ACH well above the required 5.51 ACH. The night flush adds nothing, as a fixed schedule that starts at 14:00 imports heat during the day's hottest period, thereby increasing the peak operative temperature and carrying heat into the mass and pushing the next occupied morning from 2 to 4 hours over the comfort limit.

Table 6-21: Zone 2 (office) manual fixed ventilation schedules versus the automated optimum, settled 5 cm all-walls envelope, over the occupied hours.

Schedule	Occ hrs >80%	Occ hrs >90%	Occ mean Operative	Occ mean ACH	Peak Operative	Overheating period
Optimum single-sided (all-day + control)	1	17	29.76	4.6	30.63	13:00
Optimum cross (all-day + control)	0	16	29.54	21.3	30.61	-
Single-sided 08-11	2	20	29.89	2.7	30.75	13:00
Cross 08-11	1	17	29.62	11.7	30.72	13:00
Single-sided 08-11 + 14-08 flush	2	20	29.95	2.7	31.48	13:00
Cross 08-11 + cross 14-08 flush	4	19	29.79	12.8	33.04	12:00–13:00
Cross 08-11 + single-sided 14-08 flush	2	17	29.69	12.7	31.46	13:00

6.7.3 Zone 3

For the residence, night flush is possible due to occupancy, and based on the automated ventilation, the windows opened through the night and morning and closed across the hot afternoon. Therefore, three night flush schedules were tested, opening at 21:00, 22:00, and 23:00 and each closing at 11:00, against the automated optimum as shown in Table 6-22.

The 23:00 to 11:00 schedule achieved the same results as the automated, with 4 hours above the 80% limit and 55 above the 90% limit and a mean of 29.13 °C. While shifting the start earlier to 22:00 raised the hours above the 90% limit to 65 against 55, and at 21:00 raised the overheating hours above the 80% to 9 against 4 hours and widened the overheating period from 17:00-19:00 to 22:00. Therefore, the 23:00-11:00 schedule was considered the optimum, delivering the same comfort as the automated ventilation with a mean ACH of about 9.2 well above the required 1.76 ACH.

Table 6-22: Table X. Zone 3 (residence) manual fixed ventilation schedules versus the automated optimum, settled 5 cm all-walls envelope, over the occupied hours.

Schedule	Occ hrs >80%	Occ hrs >90%	Occ mean Operative	Occ mean ACH	Peak Operative	Overheating period
Optimum cross (all-day + control)	4	55	29.16	8.9	30.75	17:00-19:00
Cross 23:00-11:00	4	55	29.13	9.2	30.76	17:00-19:00
Cross 22:00-11:00	4	57	29.16	9.6	30.77	17:00-19:00
Cross 21:00-11:00	9	65	29.30	10.0	30.94	17:00-22:00

6.8 Phase 6 results

The cooling stages judged ventilation by the heat it removes. This section evaluates the same openings by the fresh air they deliver to the occupants, and weighs the two against each other, since ventilating for fresh air can work against ventilating for cooling. Each zone is read on both counts at once: whether it holds the operative temperature within the comfort limit, so the fresh air is not accompanied by overheating, and whether it brings the carbon dioxide under the standard. Air quality is assessed through CO₂ against the EN 16798-1 Category II limits defined in the methodology: 1220 ppm for the office and daycare, and 970 ppm for the residence, together with the corresponding ventilation rate for each space.

6.8.1 Zone 1

When the daycare is sealed through the occupied hours, the CO₂ levels reach above the limit in all 30 occupied hours at a mean of 4580 ppm, while the cross ventilation schedule from 8:00-11:00 achieved the lowest operative temperature with a mean of 27.83 and brought the CO₂ levels below the limit with an adequate ventilation rate but fails once the windows were shut after 11:00 where the CO₂ levels reached above the limit for the rest of the occupied hours at a peak of 4053 as shown in Figure 6-24.

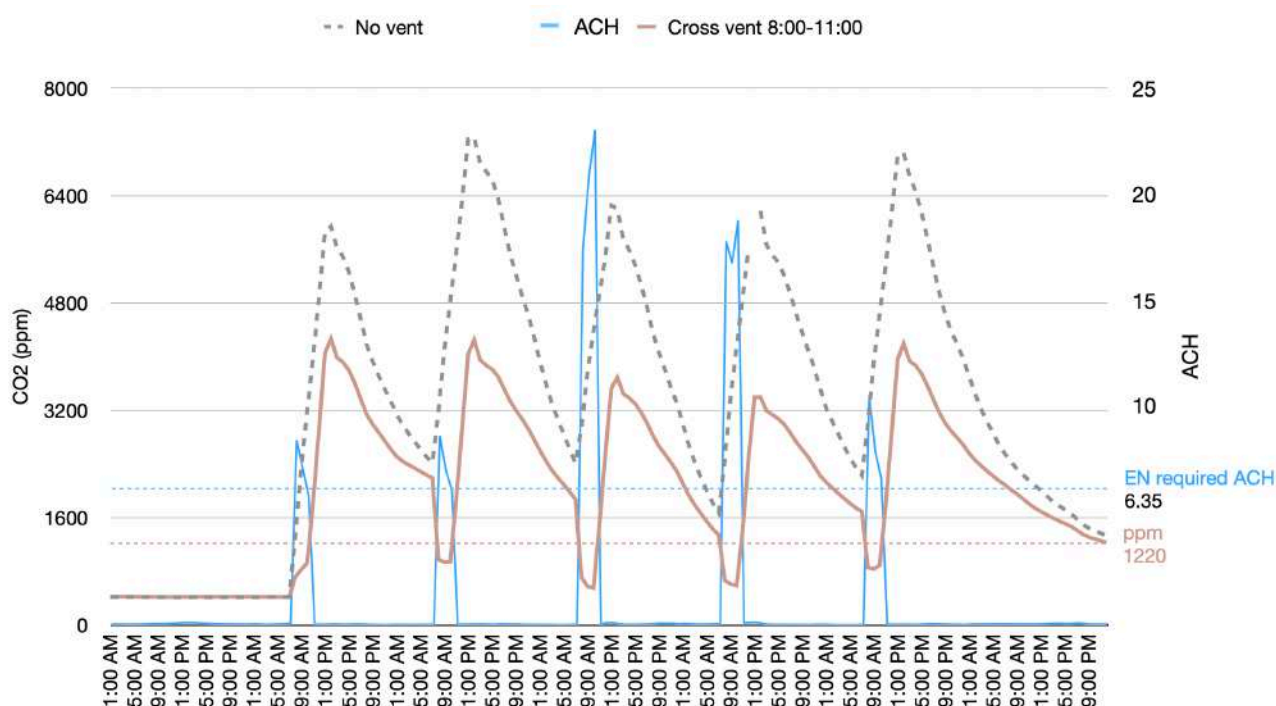


Figure 6-24: Zone 1 (daycare), CO₂ concentration and delivered air-change rate through the design week under occupancy. Horizontal lines mark the Category II CO₂ limit (1220 ppm) and the required rate (6.35 ACH).

Table 6-23 summarises the thermal comfort, ventilation rate, and indoor air quality performance of the evaluated ventilation schedules during the occupied hours in Zone 2. The single-sided ventilation schedule maintained comfort over both limits but failed to sufficiently decrease the CO₂ concentration below the limit, leading to 29 hours above the limit due to an inadequate ventilation rate of about 1.9 ACH. The cross-ventilation combined with single-sided and intermittent ventilation for 30 min every 30 min also fails but slightly decreases the hours where the CO₂ concentration is above the limit to 29 and 14, respectively, and the intermittent ventilation increased the comfort hours to 2 above the 90% limit. Cross ventilation during the occupied hours and cross ventilation combined with intermittent ventilation for 45 mins every 30 min are the only schedules that maintained CO₂ levels below the limit, as shown in Figure 6-25,

reaching mean CO₂ levels of about 717 and 824 with a max of about 968 and 1207, respectively. However, the cross with the intermittent 30/45 raised the max operative temperature to 1.71 °C compared to the free-floating mode, while the cross ventilation raised it to 2.46 °C and added one hour above the 80% limit, and both added 2 hours above the 90% limit. This pattern aligns with Ragab et al. (2025), who reported for a hot-arid classroom in Aswan that scheduled cross-ventilation at 60-minute intervals in summer held indoor carbon dioxide within the limit while adding far less discomfort than continuous operation, whereas single-sided and shorter, partial schemes were insufficient. The same applies to this zone; the longer 45-minute interval cleared the carbon dioxide where the 30-minute one could not, and at a lower operative-temperature rise than continuous cross-ventilation.

Table 6-23: Comparison of the thermal comfort, ventilation rate (ACH), and indoor air quality performance of the evaluated ventilation schedules in Zone 1 during occupied hours.

Ventilation	Occ hrs >80%	Occ hrs >90%	Occ mean Operative	Occ open ACH	Peak operative	CO ₂ mean ppm	CO ₂ hrs >1220	CO ₂ peak ppm
Base: No ventilation	0	0	27.79	-	28.50	4580	30	7241
Base: cross 08-11	0	0	27.83	12.3	28.70	1757	15	4053
Cross 08-11 + single-sided 11-14	0	0	27.92	7.1	29.12	1322	14	2808
Cross 08-11 + door 30/30	0	2	28.17	10.1	30.19	888	5	1331
Cross 08-11 + door 30/45	0	2	28.22	10.8	30.21	824	0	1207
Cross 08-14 continuous	1	2	28.36	13.4	30.96	717	0	968
Single-sided 08-14	0	0	27.88	1.9	28.82	1919	29	2822

Unlike the office, ventilating during occupied hours doesn't greatly compromise the indoor thermal comfort, even though the openings admit the full afternoon heat. With cross ventilation at 13:00, the openings draw in 35 °C outdoor air at 16 ACH, and the air temperature rises to 31.8 °C indoors, but the operative temperature reaches only 29.6 °C, five degrees below the outside. The reason is that the thermal mass could keep the surface temperature near 28 °C, maintaining indoor comfort.

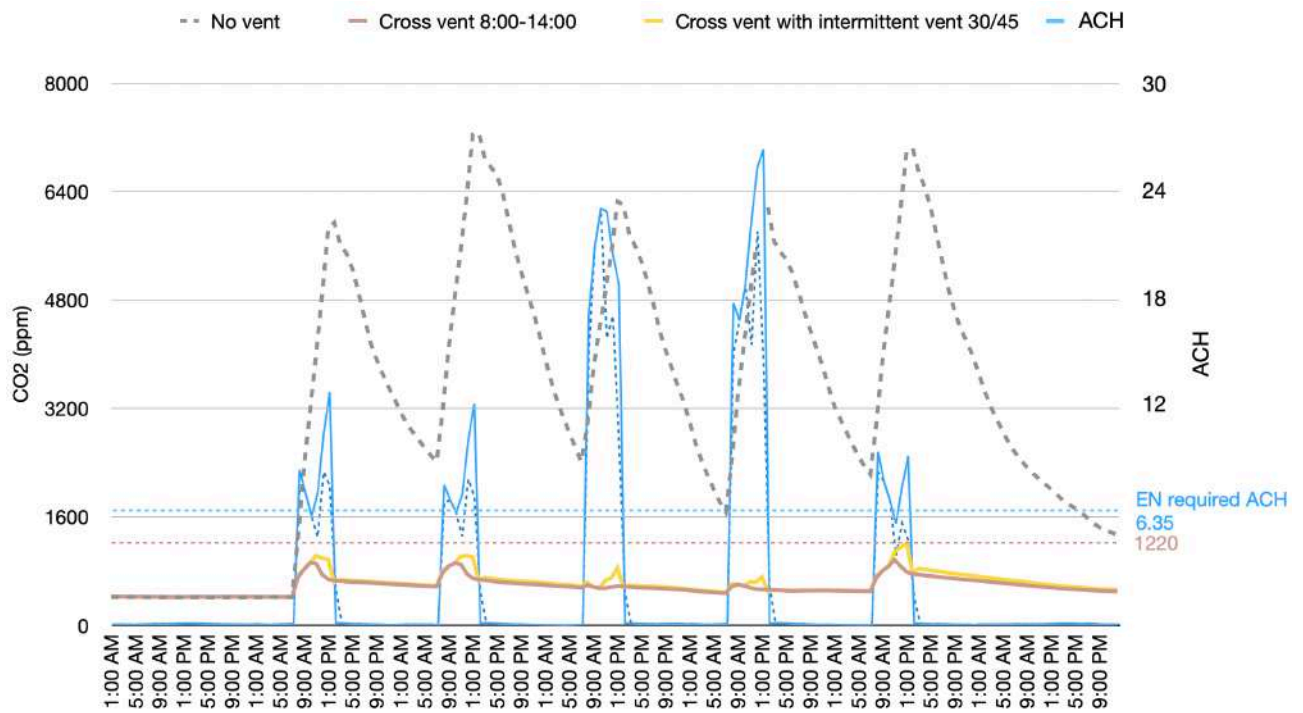


Figure 6-25: Zone 1 (daycare), CO₂ concentration and delivered air-change rate under the optimum ventilation schedule.

6.8.2 Zone 2

When the office is sealed through the occupied hours, the CO₂ levels reach above the limit in all 30 occupied hours at a mean of 3174 ppm, and the ventilation mode of cross ventilation from 8:00-11:00 achieved the best comfort and brought the CO₂ levels below the limit with an adequate ventilation rate but fails once the windows were shut after 11:00 were the CO₂ levels reached at a peak of 4162 for the rest of the occupied hours as shown in Figure 6-26.

Adding a single-sided ventilation from 11:00-14:00 holds the CO₂ close to the limit but still fails, peaking at 1595 ppm at a modest cost of 3 comfort hours, while opening windows for cross-ventilation through the occupied hours, whether it was continuous or intermittent, as shown in Table 6-24, maintain CO₂ levels below the limit but add up to 6 to 7 discomfort hours, and the operative temperature peaks about 32 to 32.5 °C. The office therefore cannot hold both comfort IAQ using the outdoor air alone, as every strategy that clears the afternoon CO₂ imports enough heat to break the comfort envelope secured, and the gender compromise that protects comfort also leaves the air marginally over the limit. The overheating always ends at 13:00 (the last occupied hour), but it spreads earlier as more daytime ventilation is added. The sealed and morning-only cases overheat only at 13:00, while the schedules that keep opening through the afternoon (intermittent and continuous) admit hot outdoor air and push the overheating back to

11:00. So the extra ventilation that clears the CO₂ is the same air movement that widens the overheating window.

Table 6-24: Thermal comfort and indoor air quality performance of the ventilation schedules in Zone 2 during occupied hours.

Ventilation	Occ hrs >80%	Occ hrs >90%	Occ mean Operative	Occ open ACH	Peak operative	CO ₂ mean ppm	CO ₂ hrs >1220	CO ₂ peak ppm	
Base: no ventilation	2	25	30.02	0.1	30.77	3174	30	4479	13:00
Base: cross 08-11	1	17	29.62	23.2	30.72	1819	15	4162	13:00
Cross 08-11 + single-sided 11-14	3	17	29.69	14.3	31.12	882	9	1595	12:00–13:00
Cross 08-11 + intermittent (30/30)	6	18	29.80	17.8	31.92	685	0	924	11:00–13:00
Cross 08-11 + intermittent (30/45)	7	19	29.83	16.5	31.95	736	0	1172	11:00–13:00
Cross 08-14 continuous	7	16	29.87	23.7	32.53	561	0	862	11:00–13:00

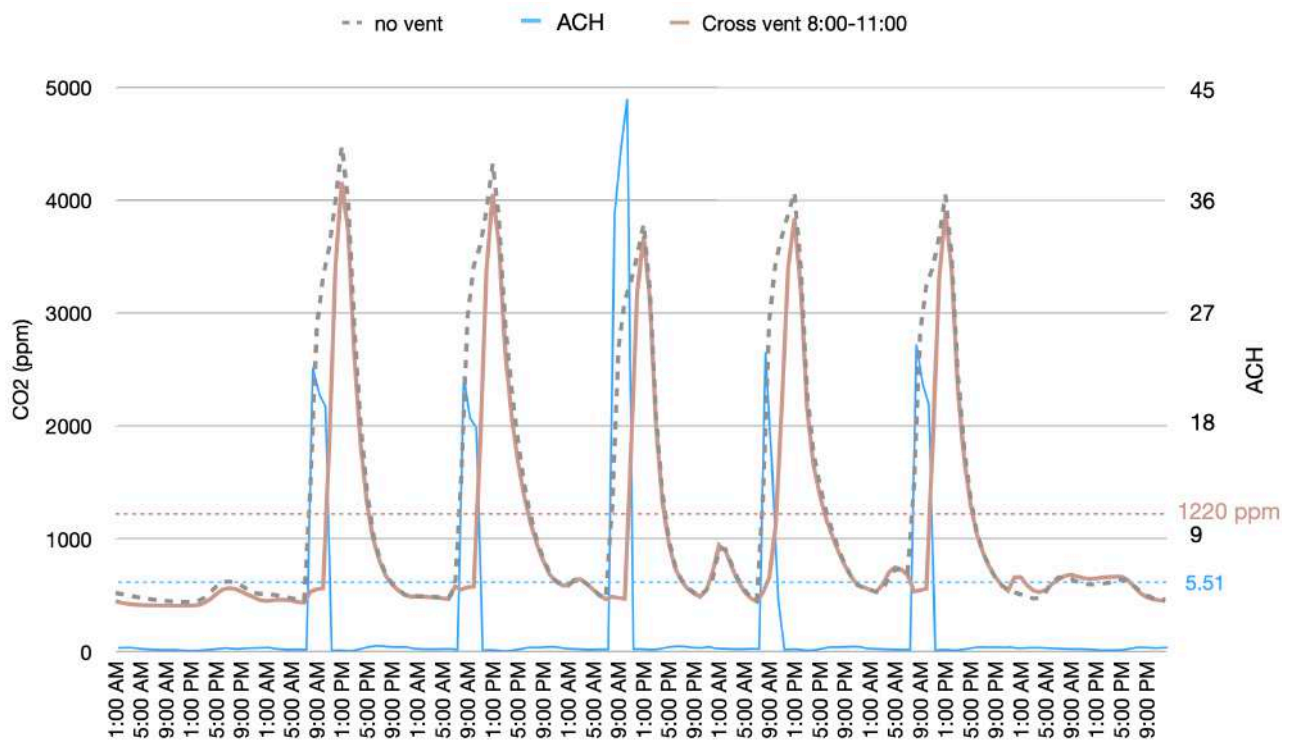


Figure 6-26: Zone 2 (office) CO₂ concentration and delivered air-change rate through the design week under occupancy.

Horizontal lines mark the Category II CO₂ limit (1220 ppm) and the required rate (5.51 ACH).

6.8.3 Zone 3

When the residence is sealed through the day, the CO₂ levels reach above the limit in all 168 occupied hours at a mean of 2701 ppm, while the cross ventilation schedule from 23:00-11:00 achieved the lowest operative temperature with a mean of 29.13 and brought the CO₂ levels below the limit with an adequate ventilation rate but fails once the windows were shut after 11:00 where the CO₂ levels reached above the limit for the rest of the occupied hours till 23:00 at a peak of 3571 as shown in Figure 6-27.

Table 6-25 summarises the thermal comfort, ventilation rate, and indoor air quality performance of the evaluated ventilation schedules during the occupied hours in Zone 3. The south single-sided ventilation and the cross ventilation from 23:00-11 with south single-sided ventilation failed to maintain CO₂ levels below 970 and raised the overheating hours to 28 and 23 above the 80% comfort limit, respectively. Only the cross ventilation from 23:00-11:00 plus north single-sided ventilation maintained CO₂ levels below 970 ppm with an adequate ventilation rate, with a mean of 6.7 ACH, but raised the overheating hours above the 80% limit to 42, which is the lowest against the all-day cross ventilation, which also maintained the required CO₂ levels with 57 hours above the 80% comfort limit and north single sided ventilation which left 44 hours above the comfort limit with one hour above the required CO₂ limit.

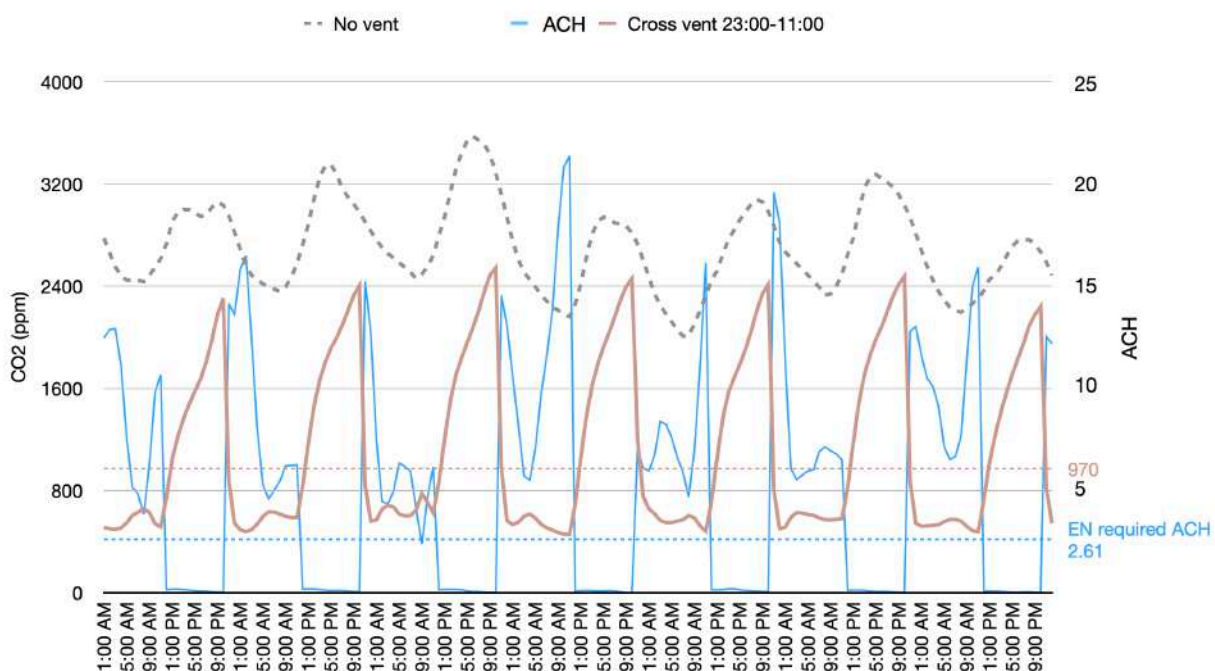


Figure 6-27: Zone 3 (residence), CO₂ concentration and delivered air-change rate through the design week under occupancy. Horizontal lines mark the Category II CO₂ limit (970 ppm) and the required rate (2.61 ACH).

Table 6-25: Comparison of the thermal comfort, ventilation rate (ACH), and indoor air quality performance of the evaluated ventilation schedules in Zone 3 during occupied hours.

Ventilation	Occ hrs >80%	Occ hrs >90%	Occ mean Operative	Occ mean ACH	Peak operative	CO2 mean ppm	CO2 hrs >970	CO2 peak ppm	Overheating period
Base: No ventilation	8	66	29.41	-	30.84	2701	168	3571	17:00-20:00
Base: cross 23-11	4	55	29.13	9.2	30.76	1129	72	2543	17:00-19:00
Cross 23:00-11:00+. South single sided	23	74	29.48	5.7	31.42	728	26	1200	14:00-21:00
South single-sided all day	28	83	29.65	2.0	31.47	935	58	1256	14:00-22:00
Cross 23:00-11:00+ north single sided	42	81	29.68	6.7	31.87	624	0	924	14:00-22:00
North single sided	44	88	29.80	3.9	31.90	714	1	981	13:00-22:00
All day cross ventilation	57	94	30.06	11.7	32.86	526	0	713	12:00-22:00

Figure 6-28 maps the operative temperature under the cross-ventilation 23-11 plus north single-sided ventilation across the assessed week. The zone stays within the comfort limit through the night and morning, and reaches the overheating hours between about 14:00 and 23:00, peaking at 17:00 to 18:00. So the additional single-sided north ventilation buys another 3 hours from 11:00 to 14:00 before the ventilation fails thermally. Similar to the office, this zone needs a supply that cools the incoming air rather than only moving it, taken up next with evaporative cooling.

Hour	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
01:00	28.67	28.74	29.49	28.97	29.28	29.76	29.13
02:00	28.33	28.60	29.44	28.82	28.99	29.72	28.88
03:00	28.10	28.66	29.28	28.86	28.76	29.55	28.69
04:00	28.11	28.62	29.09	28.78	28.59	29.36	28.56
05:00	28.16	28.50	28.87	28.47	28.42	29.17	28.46
06:00	28.13	28.37	28.72	28.14	28.29	29.00	28.38
07:00	28.02	28.25	28.54	27.94	28.32	28.71	28.33
08:00	28.05	28.27	28.65	28.04	28.69	28.73	28.41
09:00	28.10	28.46	28.83	28.33	29.11	28.99	28.50
10:00	28.19	28.65	28.98	28.52	29.49	29.15	28.58
11:00	28.56	28.91	29.20	28.86	29.71	29.41	29.05
12:00	29.04	29.38	29.61	29.31	30.20	29.73	29.33
13:00	29.49	29.85	30.04	29.73	30.62	30.10	29.72
14:00	29.97	30.31	30.44	30.16	31.05	30.51	30.18
15:00	30.40	30.72	30.81	30.53	31.42	30.90	30.53
16:00	30.76	31.06	31.11	30.86	31.71	31.22	30.82
17:00	30.94	31.26	31.24	31.04	31.83	31.36	30.96
18:00	31.00	31.26	31.25	31.13	31.87	31.35	31.02
19:00	30.93	31.10	31.11	31.03	31.78	31.17	30.89
20:00	30.60	30.82	30.82	30.68	31.38	30.93	30.70
21:00	30.23	30.50	30.57	30.42	31.00	30.70	30.50
22:00	30.05	30.32	30.36	30.27	30.85	30.49	30.32
23:00	29.60	30.03	29.70	29.91	30.34	29.85	29.78
24:00	29.10	29.59	29.20	29.57	29.85	29.43	29.37

Figure 6-28: Zone 3 operative temperature during the design week (12–18 August) under the optimized ventilation schedule and envelope. Orange shading indicates hours above the 80% comfort limit ($>30.63^{\circ}\text{C}$).

6.9 Phase 7 results

The passive ventilation strategies carried each zone close to comfort, but failed to maintain it specifically through the afternoon occupied period while also maintaining acceptable CO₂ levels and an adequate ventilation rate specifically for the office and the residence. Therefore, evaporative cooling is tested as the air supply that could resolve this tradeoff. It cools the incoming air before it enters, so a single strategy can both meet the ventilation requirement and the comfort limit together. This strategy was found suitable for Jericho's cooling season, which is mostly hot and dry. Direct evaporative cooling draws its capacity from the gap between the dry-bulb and the wet-bulb temperature, and the drier the incoming air, the further it cools as it takes up water. The climate analysis for Jericho showed this gap is widest in the hot afternoon: through the cooling-season hours when the evaporative cooler runs and the passive openings fail, the relative humidity falls to a mean near 40% and as low as about 20%, while the dry-bulb holds above 33°C . The afternoon is at once the hottest part of the day and the driest, so the moment the room most needs cooling is the moment evaporation works best. This section sets out the model and its inputs as described in the

methodology section, shown in Figure 6-29, then applies it to the office (Zone 2) and the residence (Zone 3), each at its own required ventilation rate and occupied schedule.

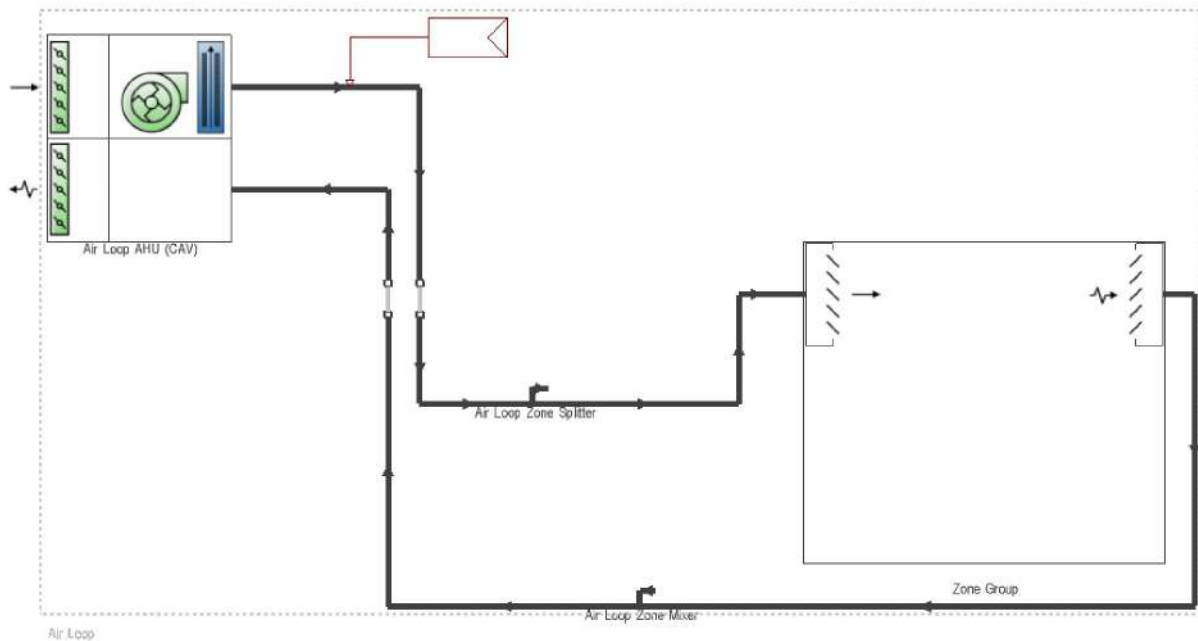


Figure 6-29: Air-loop model of the direct evaporative supply built in DesignBuilder.

6.9.1 Zone 2

The office was cooled in two stages across the occupied hours, where natural cross-ventilation ran from 8:00 to 11:00, then the evaporative cooling took over the remaining occupied hours from 11:00 to 14:00. The airflow rate of the evaporative cooling was set to the office requirement of about 0.0505 m³/s based on the 5.51 ACH the standard requires for 6 occupants in the 33m³ room, at the fixed 0.8 effectiveness.

The two-stage supply maintained both comfort and IAQ through the occupied hours. The operative temperature stays under the 80% comfort limit in every occupied hour and crosses the 90% limit in only two hours, with a mean of 29.07 and a peak of 30.08 °C, against the sealed room's 30.02 °C mean and its 25 hours above the 90% limit. The CO₂ levels had a mean of 693 ppm. Peak of 862, well below the 1220 limit, as shown in Table 6-26 and Figure 6-30. Table 6-26 sets the evaporative cooling system against the passive strategies, each of which held one standard but broke the other.

The relative humidity rises to a mean of 53.9% and a peak of 69.8%, compared with the 44.5% the cross-plus-intermittent opening held over the same hours. This sits within the comfortable range and well below saturation, and it matches the field evidence for a pad-based

direct evaporative system in hot-dry climates where Alshenaifi et al. (2024) measured 61–70% RH.

Table 6-26: Thermal comfort and indoor air quality performance of the ventilation schedules in Zone 2 during occupied hours.

Ventilation	Occ hrs >80%	Occ hrs >90%	Occ mean Operative	Occ open ACH	Peak operative	CO2 hrs >1220	CO2 peak ppm
Base: no ventilation	2	25	30.02	-	30.77	30	4479
Base: cross 08-11	1	17	29.62	23.2	30.72	15	4162
Cross 08-11 + intermittent (30/30) 11:00-14:00	6	18	29.80	17.8	31.92	0	924
Cross vent 8:00-11:00 + Evaporative cooling 11:00-14:00	0	2	29.07	13.1	30.08	0	841

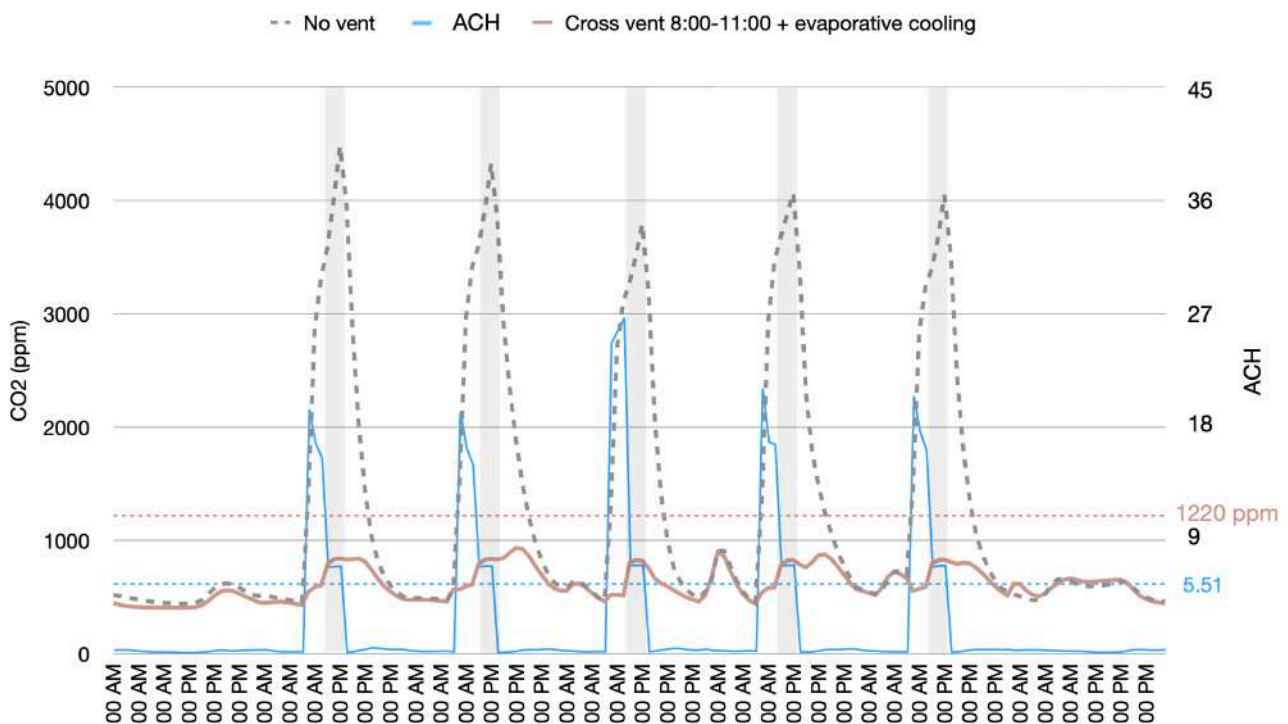


Figure 6-30: Zone 2 (office): CO₂ concentration and air-change rate for the sealed case and the two-stage ventilation strategy. Horizontal lines indicate the CO₂ limit (1220 ppm) and required ventilation rate (5.51 ACH).

6.9.2 Zone 3

The residence was cooled in three stages across the day, since it's occupied around the clock, where cross ventilation ran from 23:00 to 11:00, and a single sided north windows then carried the late morning from 11:00 to 14:00, then the evaporative cooling system took over from 14:00

to 23:00. The evaporative cooling supply air flow rate was set to the residence requirement, of about 0.035 m³/s, which achieved the 1.76 ACH the standard requires for sleeping spaces, at the fixed 0.8 effectiveness.

The three-stage ventilation schedule achieved both comfort and IAQ across the whole week. The operative temperature stayed under the 80% limit in every one of the 168 hours and below the 90% comfort limit in 39 hours at a mean of 29.00 °C and a peak of 30.38 °C, against the non-ventilated base with 8 hours above the 80% comfort limit and 66 hours above the 90% limit. The CO₂ levels remained below the 970 ppm limit in every hour, as shown in Table 6-27 and Figure 6-26. Table 6-27 sets the evaporative cooling system against the passive strategies, each of which held one standard but broke the other. The north single-sided ventilation bought 3 hours before the evaporative system became necessary, but a stricter schedule would run the evaporative system from 11:00 to 23:00.

The relative humidity rises to a mean of 54.4% and a peak of 68.8% against the 48.4% mean the same schedule held without the cooler, moving only dry outdoor air, yet it stays within the comfortable range and below saturation.

Table 6-27: Thermal comfort and indoor air quality performance of the ventilation schedules in Zone 3 during occupied hours.

Ventilation	Occ hrs >80%	Occ hrs >90%	Occ mean Operative	Occ open ACH	Peak operative	CO ₂ hrs >1220	CO ₂ peak ppm
Base: no ventilation	8	66	30.41	-	30.84	168	3571
Base: cross 23:00-11:00	4	55	29.13	9.2	30.76	72	2543
Cross 23:00-11:00+ north single sided 11:00-23:00	42	81	29.68	6.7	31.87	0	924
Cross 23:00-11:00+ north single sided+ evaporative 14:00-23:00	0	39	29.00	6.7	30.38	0	826

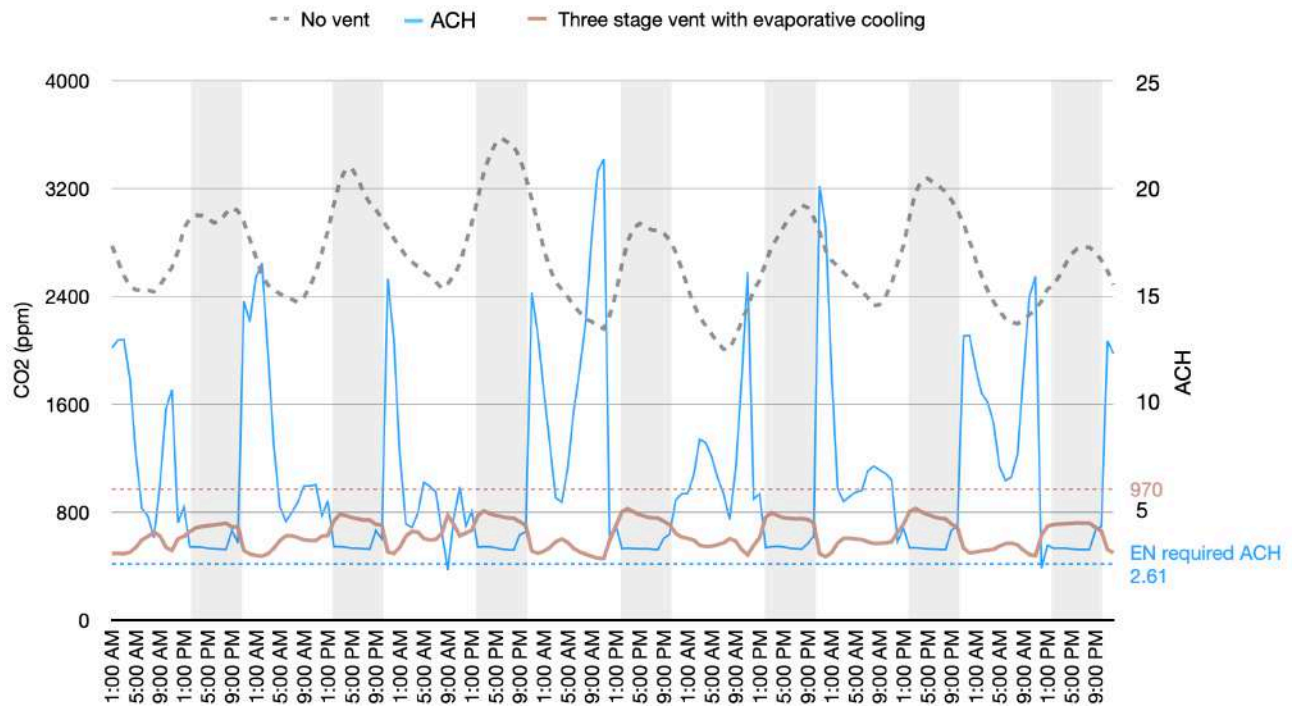


Figure 6-26: Zone 3 (residence): CO₂ concentration and air-change rate for the sealed case and the three-stage ventilation.

6. 10 Comparative analysis

The comparison between the three envelopes was assessed only on zone 2, the office, chosen for reasons of both geometry and thermal representativeness. Exchanging the earthen construction for the conventional ones changes the wall thickness substantially, and in zones 1 and 3, this changes the floor area and volume, as these remaining spaces are not single zones but pairs of adjacent rooms joined by openings separated by very thick internal walls that are also structural. So zone 2 is the one space whose geometry keeps the correct floor area and volume after the wall swap, and the results remain comparable for the three constructions. The comparison therefore offers an indicative glimpse of how the optimized earthen envelope performs against current conventional construction, not as a full whole building or per zone assessment, which is left to future work. Based on that, Table 6-28 reports the three constructions across four operating strategies, from sealed building to cross ventilation, evaporative cooling and a reflective roof, and Figure 6-27 shows their overheating hours side by side.

When sealed, the three are compared by their mass alone, where the earthen envelope holds a mean operative temperature of 31.20 °C and crosses the 80% limit in 28 of the 30 occupied hours, where the brick and stone walls reach 32.38 and 32.62 °C and fail in all thirty. The 1.2 °C difference in the mean operative temperature reflects the earthen build heat capacity, where it stores the heat

during occupancy and release its later after occupancy hours, reducing the peak operative temperature. The addition of a cool roof separates sharply between the constructions as it lowers the mean operative temperature by about 1.2 °C in all of them, but the effect on comfort was not even. The earthen envelope falls from 28 hours over the limit to 2, while the brick and stone walls barely move, from 30 to 28 and 29, and that is because the earthen envelope already sits just above the 80% comfort limit. Under the optimum ventilation schedule, which is cross-ventilation from 8:00 to 11:00, the evaporative cooling till 14:00 reaches 7 hours over the 80% limit without the cool roof, against 19 and 20 for the brick and stone envelopes at a mean of about 0.6 °C cooler. And when combined with the cool roof, the three reach comfort at 0 for the earthen envelope and 1 hour over the 80% limit for the conventional envelopes. However, the earthen envelope holds a mean of 29.07 °C, which is about 0.8 °C lower than the other envelopes and reaches only 2 hours above the stricter 90% limit compared to 20 and 23 hours for the brick and stone envelopes. Even though the difference in the operative temperature is relatively low, the earthen envelope is comfortably below the 80% limit while the conventional envelope lies near the threshold. However, both envelopes achieve thermal comfort under the optimum ventilation schedule, demonstrating that it's effective for both construction types.

Table 6-28: Thermal comfort and indoor air quality performance of the earthen, brick cavity, and stone envelopes under the evaluated passive strategies.

Construction	Strategy	h>80%	h>90%	Mean operative C	Peak operative C	CO2 mean/peak
Earthen (CEB)	Sealed	28	30	31.20	31.88	
	+ cool roof	2	25	30.02	30.77	
	Vent + evaporative	7	23	30.11	30.94	
	+ cool roof + vent + evap	0	2	29.07	30.08	693 / 862
Brick (cavity)	Sealed	30	30	32.38	33.04	
	+ cool roof	28	30	31.17	31.81	
	Vent + evaporative	19	29	30.69	31.62	659 / 822
	+ cool roof + vent + evap	1	20	29.79	30.78	
Stone	Sealed	30	30	32.62	33.27	
	+ cool roof	29	30	31.39	32.03	
	Vent + evaporative	20	29	30.85	31.76	

+ cool + vent +
evap

1

23

29.94

30.93

661 / 816

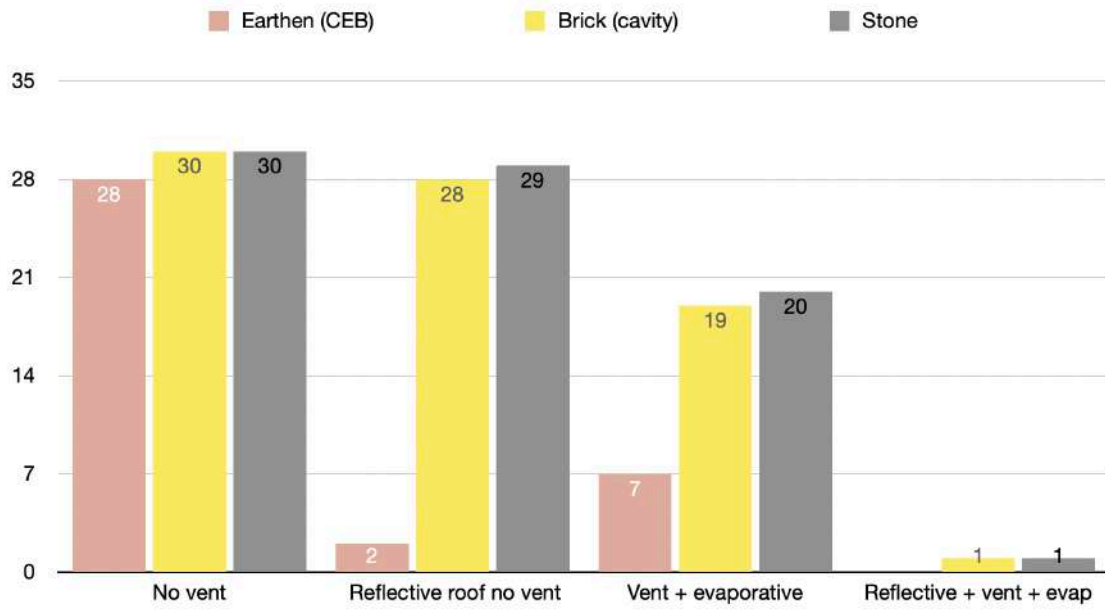


Figure 6-27: Comparison of overheating hours (>80% adaptive comfort limit) for the earthen, brick cavity, and stone envelopes under successive passive strategies.

Conclusion and Recommendations

This thesis set out to evaluate and optimize the performance of earth buildings coupled with ventilative cooling in the hot-arid climate of the Jordan Valley, and to develop an integrated climate-responsive control framework in which thermal mass, envelope configuration, natural ventilation, and an evaporative cooling system operate as one system to achieve thermal comfort and IAQ. This chapter summarizes the methodology, states how each research objective was met and each research question answered, sets out the major scientific findings and the contributions they make, and ends with practical implications, design recommendations, limitations, and directions for future work that follow the research.

The study was built on a calibrated simulation model of a real compressed earth block building in Jericho, the Aqbat Jabr women's centre. A field study documented the building's construction and operation and monitored indoor temperature and humidity over ten days of the cooling season, which was used to calibrate and validate a DesignBuilder model within the ASHRAE 14 recommendations. The validated model was then used to perform seven sequential optimization phases, each addressing the limitation of the previous one exposed, and these phases include base case analysis, parametric optimization of the CEB envelope, integrated natural ventilation, and ventilation mode selection, practical ventilation schedules, and indoor air quality assessment and evaporative cooling. Three zones with different thermal characteristics and occupancy were selected and were carried through the phases and judged on adaptive thermal comfort (ASHRAE 55) and indoor air quality (CO₂ ppm against EN 16798-1 Category II). Lastly, a Final phase compared the optimized earthen envelope against the two insulated wall types now built in Jericho, documented through a field survey of local practice.

7.1 Findings in Relation to the Research Objectives and Questions

The field monitoring and the simulated base case both showed that the earthen envelope is a strong heat modulator, but that damping the daily swing is not the same as achieving thermal comfort. The heavy CEB fabric held the interior steady against a large outdoor swing: in the field measurements the indoor air temperature varied by only about 2.0 to 2.6 °C over the day against an outdoor swing of 11 to 14 °C, a reduction of about 80%, and the simulated design summer week gave a similar result, with operative temperature swinging 2 to 4 °C against a 12 °C outdoor swing. This stability, however, was achieved around a mean that stayed above the comfort range: the

indoor temperature exceeded the outdoor temperature for most of the monitored period and remained warm through the night. The mass delays and stores heat but does not remove it, so wherever a dominant load enters the space continuously it is overwhelmed. As built, with 14 cm CEB infill walls in most zones, exposed barrel-vault and dome roofs of the same 14 cm earthen thickness, and a large glazed façade, the envelope could not shed the heat it accumulated, and the simulated design week confirmed that the earthen mass underperforms wherever other envelope elements dominate the heat gain.

A 29.5 cm CEB was found to be the most practical thickness that can carry most of the available damping, lowering the decrement factor from about 0.3 at 14 cm to about 0.1 and lengthening the time lag between the outdoor and indoor surface from 3 or 4 hours to about eight, with no further gain beyond it since the core then lies past the depth the daily heat wave reaches. Insulation is most effectively placed on the exterior face of the wall, keeping the earthen mass on the room side where it can absorb the indoor heat, and applied to all external walls. The choice of insulation material makes little difference; the three tested materials fall within 0.1 °C in mean operative temperature and have narrow and nearly the same overheating hours, so expanded polystyrene, at about a third of the price of polyurethane in Palestine, is the value choice, while polyurethane gives the peak. 5 cm EPS on all external walls produces a reduction of about 1 to 1.5 °C in mean operative temperature wherever the wall is the governing heat source. While when other heat sources are not considered, the impact of insulation becomes less significant, resulting in only a minor reduction in operative temperature of a few tenths of a degree. Between the least insulation of 3 cm on infill walls and the full treatment, 5cm on all walls, the operative temperature differs by less than 1 °C, but the effect on overheating hours is far larger, especially when the zone sits near the comfort limit. Crucially, the wall configuration reaches comfort only where wall conduction is the dominant load; therefore, a balanced envelope strategy that addresses the major heat gain transfer pathways, including the roof and solar heat gain, is required.

The study developed a climate-responsive control framework for the case study building and identified the conditions that determine when each operational control mode should operate, as shown in Figure 7-1. The framework, and the schedules derived from it, apply to the summer design week (12–18 August), the period of greatest thermal stress on which the analysis was based. The framework opens the building only when the outdoor air is cooler than both the interior and the 80% adaptive comfort limit, so that ventilation is admitted only when it cools the space rather than

importing heat. Two conditions then decide what each opening can achieve: the airflow it allows, and the temperature gap between the room and the outdoor air at the moment the control opens.

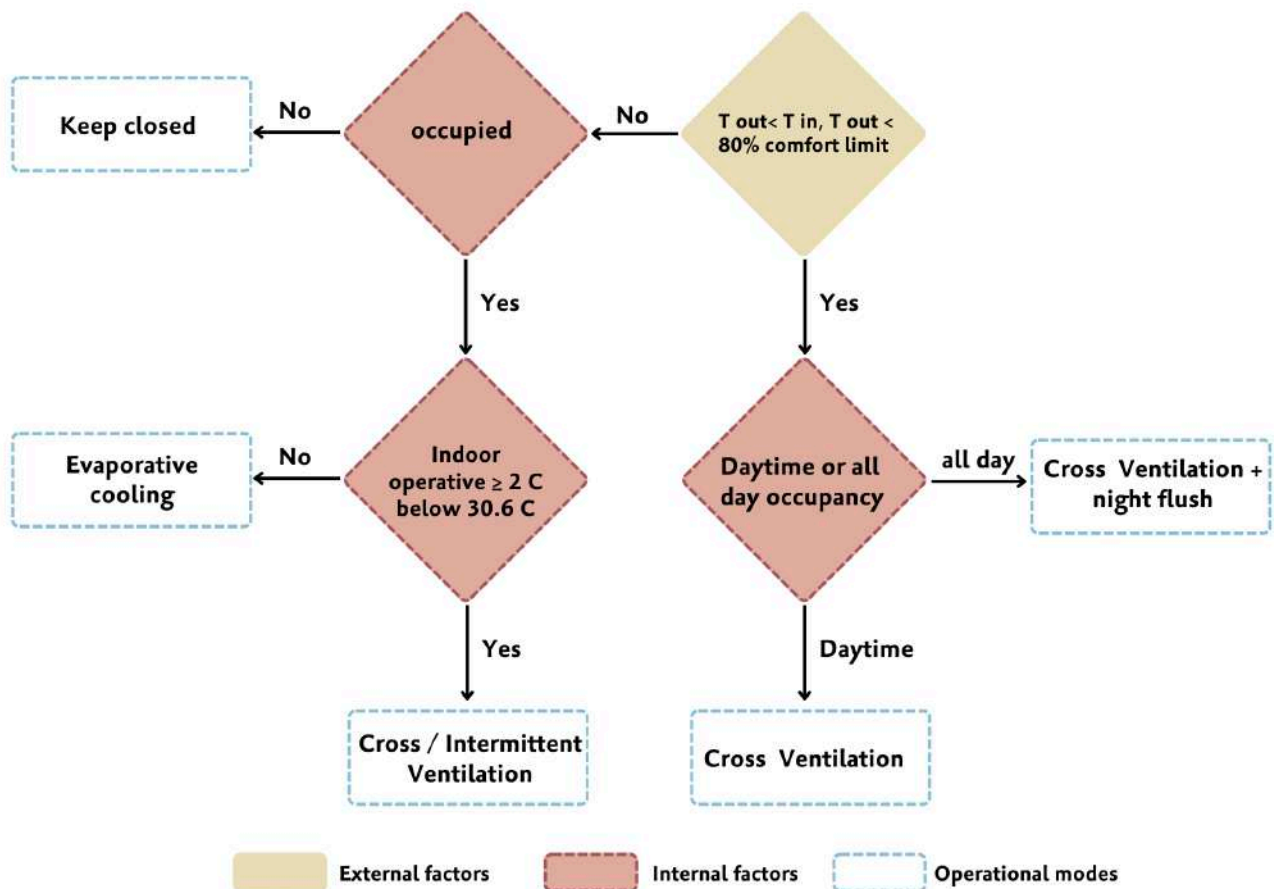


Figure 7-1: Climate responsive control logic for the earthen building in the Jordan valley.

Cross ventilation was identified as the primary mode, delivering ventilation rates of about 9 to 21 mean ACH, peaking near 44 ACH, in the occupied zones, whereas single-sided ventilation held to a mean of 2 to 5 ACH and generally stayed below the required rate. The exception was the low-demand residence, where single-sided ventilation at a window-to-wall ratio of about 8.5% was adequate, though lower ratios could not reach the required rate. The wind catcher raised the air change rate further but delivered no additional cooling. Cross ventilation therefore already captures the available cooling potential, and the additional airflow from the wind catcher offers no meaningful thermal benefit; it was not considered further.

Ventilation cools only where a real temperature gap exists for it to act on, and once the envelope holds the interior near comfort, that remaining gap decides whether night flushing is worth operating. In the cooler hours the indoor–outdoor gap is generally small, about 0.5 to 2.5 °C, because the outdoor air remains relatively warm even overnight, so ventilation lowers the occupied

operative temperature by at most 0.06 to 0.26 °C, rising to about 1 °C only in the residence where all-day occupancy widens the gap to about 4 °C. Night flushing is therefore most useful where a space stays warm into the night while the outdoor air cools, opening a usable gap between indoor and outdoor. This tends to arise under continuous occupancy, whose internal gains, together with the heat still held in the mass, keep the interior warm after sunset so that a gap opens as the outdoor air cools. The simulations confirmed this: in the daycare and office, occupied only until 14:00, the space has largely cooled and closed by nightfall, so there is little gradient to flush, and opening the windows after occupancy hours imports the day's stored heat rather than removing it, leaving the operative temperature higher at the start of the next occupancy than if the space had been kept closed. Beyond this negligible benefit, leaving the windows open through the night in an unoccupied building is neither secure nor realistic in normal use. Night flushing was therefore applied only to the continuously occupied residence, while the daytime zones rely instead on morning cross ventilation and, through the hot afternoon, on pre-cooled fresh air.

A further finding concerns the operative-temperature margin that decides whether a space can ventilate through the hot hours at all: this requires the operative temperature to sit at least 2.5 °C below the comfort limit. The earthen mass makes this possible by keeping the surrounding surfaces cool and decoupling the operative temperature from the incoming air. Within that margin, pulsing the openings rather than holding them open clears the CO₂ at a smaller thermal cost. In the daycare, an intermittent schedule of about 45 minutes open and 30 minutes closed met the air-quality limit while raising the peak operative temperature by about 1.7 °C, against about 2.5 °C under continuous cross ventilation; a shorter 30-minute interval did not clear the CO₂.

Where the openings could no longer maintain thermal comfort in the space and dilute the stale air at the same time. Pre-cooling the fresh air becomes necessary; otherwise, ventilation would raise the discomfort hours. So evaporative cooling proved to be effective through the hot, dry occupied hours. Particularly during the afternoon, when the hottest and driest part of the day with relative humidity near 40% while the outdoor temperature is above 33 °C, which is the time the evaporation works best. Sized to each zone's required ventilation rate at 0.8 effectiveness, the evaporative system supplied cooled air that was able to maintain comfort and healthy CO₂ levels.

The control framework is therefore governed by three factors: outdoor temperature, occupancy, and the indoor operative temperature relative to the comfort limit. Together these determine which strategy operates at each hour, each taking over precisely where the previous one could no longer maintain comfort and air quality. The outdoor gap decides whether an opening cools or merely

refreshes: the control admits air whenever it is cooler than the room and below the comfort limit, but the flush removes meaningful heat only once that gap approaches about 4 °C. The operative-temperature margin covers the hot hours: while the space sits about 2.5 °C below the limit it can be ventilated for fresh air, and only as that margin closes does it hand over to pre-cooled air; within that margin, pulsing the openings rather than holding them open meets the air-quality requirement at a lower thermal cost. This ordering, cross ventilation as the primary mode, night flushing added where continuous occupancy makes it useful, and evaporative cooling as the fallback for the hot, dry afternoon, is the study's principal operational contribution: comfort in this climate is reached not by any single strategy but by handing the space from one measure to the next as outdoor conditions and occupancy demand. Translated into practice, this logic reduces to a fixed daily schedule for each zone (Figure 7-2) that an operator can follow hour by hour to reproduce the same climate-responsive behaviour without automated controls.

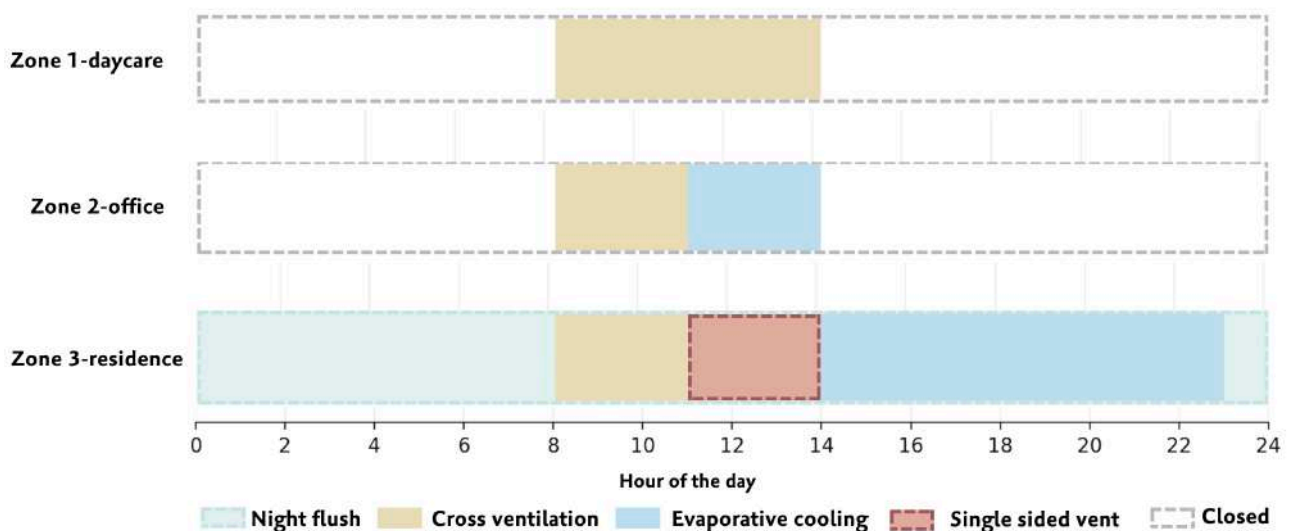


Figure 7-2: Daily practical control schedule for each zone.

This framework integrates two categories of determinants: the properties of the building itself, and the way it is used. The building-related factors describe what the fabric can do. The first is the envelope's damping, the extent to which the heavy earthen mass flattens the outdoor temperature swing before it reaches the interior. The second is the operative-temperature margin: how far below the comfort limit the treated envelope holds the space, which determines how much imported heat it can absorb before comfort is lost. Together, these set what each zone is physically capable of at a given hour, whether it can be cooled by outdoor air, whether it can tolerate the heat that ventilation brings in, and whether it has enough stored coolness to be ventilated for fresh air without

overheating. The occupancy and behaviour-related factors describe what the space needs, and when. These are the hours a zone is occupied, which fix when fresh air and CO₂ control are required; the occupancy pattern, which determines whether the space stays warm into the night and so whether night flushing can work; and the operation the occupants can realistically carry out, such as opening and closing windows at set times or leaving a building secure overnight. Comfort is reached where these two sets meet: a strategy is deployed only where the fabric's capability and the occupants' demand coincide. This is why night flushing suits the continuously occupied residence, which stays warm at night and is occupied to make use of the cooler morning, but not the daytime zones, which are empty and already cool by night; and why intermittent window operation suits a zone whose thermal margin is wide enough to absorb the interruption while still clearing the stale air.

The framework was developed and tested on the Aqbat Jabr women's centre, and its specific thresholds, the airflow rates, the 2.5 °C margin, the evaporative sizing, reflect that building's geometry, zoning, and occupancy. The underlying logic, which matches each strategy to outdoor conditions and occupancy, is expected to transfer to the other UNESCO earthen projects in the Jordan Valley, which share the same construction system, climate, and building types. Confirming this would require the framework to be applied and re-tested on those buildings, since their differing plan forms, orientations, and occupancy patterns would shift the specific thresholds even if the ordering of strategies held. This transferability is identified as a direction for future work rather than a claim of the present study.

The final stage set the optimized earthen envelope against the two conventional constructions of current Jericho practice, the insulated cavity brick wall and the stone-clad wall, on the representative office zone. The earthen envelope led at every operating stage. Sealed, its mass alone held it about 1.2 °C cooler than the two conventional walls. The reflective roof rewarded only the earthen envelope, carrying it under the comfort limit because it already sat close, while the conventional walls stayed too warm for the same roof to reach comfort and needed the full addition of ventilation and evaporative cooling before they approached it. Under that full control logic the three converge near comfort, so the integrated strategy proves effective for either construction. The earthen envelope's edge is that it reaches comfort sooner and with fewer interventions, and holds a deeper margin, sitting comfortably below the limit where the conventional walls sit on it.

7.2 Major scientific findings

The study points to one common principle, load sequencing. Because the earthen mass stores heat and releases it later rather than dissipating it, it delays and reduces the heat reaching the interior

but cannot carry heat out of the building. It is therefore overwhelmed wherever a dominant load enters continuously, such as an unshaded façade or an exposed roof, and no wall thickness, insulation, or placement reaches comfort until that load is cut. Optimizing the envelope by working on the thermal mass alone is therefore not sufficient: thickening the wall or improving the insulation refines how the mass handles the heat that reaches it, but does nothing about the dominant gains entering through the roof and the glazing. Those gains must be mitigated first. Only once the roof gain is rejected does insulation begin to matter, and the two then work well in combination, the reflective roof cutting the incoming load and the insulation holding the treated mass at the level it reaches, so that together they carry the zone below the comfort limit where neither does so alone.

This establishes a clear order of priority: the dominant load must be cut before the mass can dampen what remains. Figure 7-3 shows this directly. Counted over the hours the zones are occupied, adding insulation removes almost none of the overheating in the roof- and solar-governed zones, none at all in the daycare and only a small fraction in the office, whereas rejecting the roof heat gain collapses it. The combination of insulation and a reflective roof clears the occupied period where insulation alone leaves it almost unchanged. This matches hot-arid studies that identify the roof as the dominant heat-gain path, on the order of half the total gain in single-storey buildings (Sharma and Sengar, 2019; Shohan et al., 2021).

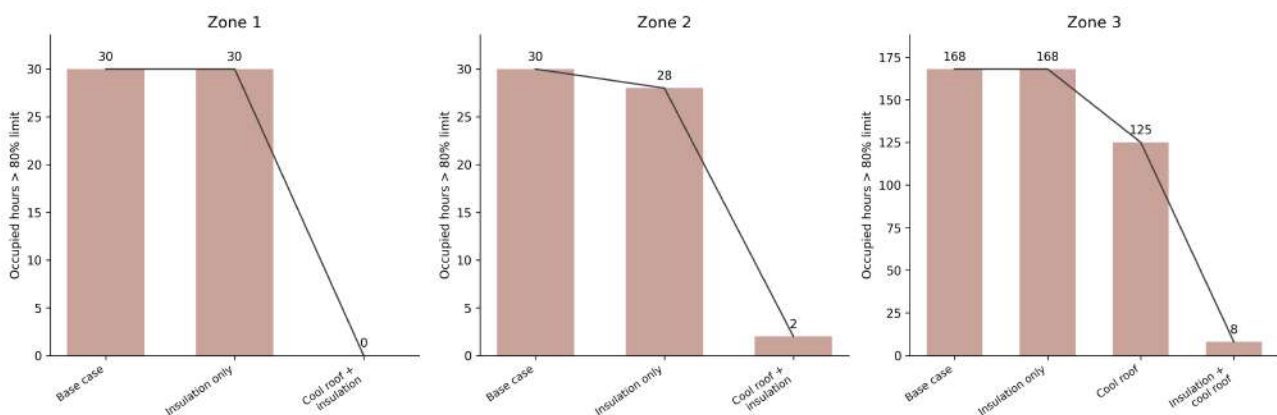


Figure 7-3: Overheating hours above the 80% adaptive comfort limit over the design week during occupancy hours for each zone.

A second finding is that the three analysis zones represent three thermal archetypes, each with a generalizable path to comfort and air quality. The first, a single-storey space with an exposed roof and large glazing, is the common configuration in the UNESCO buildings, represented here by the daycare. It is solved by cutting its two dominant loads, the solar gain through the exposed vault or dome roof and the direct solar gain through the large glazed façade, and then ventilating for fresh

air; because its treated mass then sits deep below the comfort limit, it absorbs the warm air the ventilation during the day admits and meets both the comfort and the air-quality standard on ventilation alone. The second, an internal space with no exposed roof, represented by the office, is carried to the edge of comfort by mass and insulation but not past it, so it needs an evaporative supply to cool the fresh air through the occupied afternoon. The third, a top-floor space under an exposed roof and occupied around the clock, represented by the residence, must first have the heat gain through its roof cut, can then night-flush while the outdoor air is cool, and still needs an evaporative supply through the hot evening. Across all three the sequence is the same: cut the dominant load, let the mass dampen what remains, ventilate for fresh air, and add evaporative cooling only where the envelope's margin is too thin for ventilation to cool the air it admits.

The fourth, which unifies the archetypes, is that the envelope's comfort margin decides whether ventilation alone suffices: where the treated envelope holds the space well below the limit, the mass absorbs ventilation's imported heat and ventilation serves both comfort and air; where it holds the space at the limit, imported heat breaks comfort and evaporative cooling becomes necessary.

7.3 Research contributions

To the author's knowledge, this study provides the first comprehensive assessment of earthen (CEB) building performance in the hot-arid climate of Palestine, evaluated on thermal comfort and indoor air quality together rather than either alone. It establishes a load-sequencing principle for earthen design, expressed through three transferable thermal archetypes and their routes to comfort. The study provides a clear framework for how ventilative cooling should be operated and reproduces practical, operable occupant schedules based on an automated optimum by fixed occupant schedules. And it delivers an integrated, climate-responsive control framework that switches between mass, ventilation, and evaporative cooling by outdoor condition, and quantifies the comfort advantage of earthen construction over current local practice.

7.4 Practical implications

For the reintroduction of earthen architecture in Jericho, the study carries three practical implications. It shows that a heavy earthen envelope alone is not a guarantee of comfort, so the revival of earthen construction should not rely solely on thermal mass but should integrate a treated roof and carefully controlled glazing through effective shading and an appropriate window-to-wall ratio (WWR), without which the mass underperforms, and the case for earthen construction is weakened. It shows that comfort and acceptable air quality can be achieved across the cooling

season on passive and low-energy means, a cross-path opening, a night flush, and an evaporative cooling system, without mechanical refrigeration, which matters directly in a region facing energy insecurity. And it shows that the operation these strategies require is simple enough for occupants to run by hand, so the framework can be delivered as guidance to users rather than as an automated control system that a low-cost building could not sustain. Moreover, the same logic could serve as an intermediate step between hand operation and full automation through a simple sensor tracking the indoor and outdoor conditions would let occupants follow the control logic more precisely, signalling when to open, close, or switch to the cooler while keeping control in their hands.

7.5 Limitations

The findings hold within the study's bounds. The analysis addresses the cooling season only, on small-scale buildings in the hot-arid climate of Palestine, so the strategies may not transfer to other climates or to larger building types and larger occupancy. Indoor air quality was assessed on CO₂ and ventilation rate alone; outdoor pollutants, dust, lay outside its scope. Because the case-study building stands empty, the model was calibrated on measured indoor temperature under free-floating conditions, and the CO₂ results, resting on assumed generation and occupancy recalled by former users, indicate ventilation adequacy rather than a validated prediction of occupant CO₂. The evaporative cooling was assessed at the performance level only; its physical and architectural integration, and its water consumption, a real consideration in a water-scarce valley, were not examined. The earthen-versus-conventional comparison was drawn on a single, geometrically stable zone and is offered as an indicative glimpse rather than a whole-building account.

7.6 Future work

Future work should extend the framework to the winter season for a year-round assessment. In winter, the goal reverses, from rejecting heat to retaining it, so the control logic must be reworked to hold warmth while still meeting the fresh-air requirement. Compressed earth should also be evaluated as infill within a conventional structural frame rather than as the load-bearing structure, a more likely route to adoption. Future work should also validate the CO₂ predictions against measurement in an occupied earthen building, quantify the water use of the evaporative supply, and pursue the architectural integration and airflow (CFD) study that were beyond the scope of this thesis. Testing the control framework under projected future climate would complete the case for earthen construction as a resilient response to the hot-arid climates most exposed to a warming world.

REFERENCES

- Abdelkader, B., Khelafi, H., Mokhtari, A. and Abdelmalek, B. (2021) 'Evaluation of summer thermal comfort in arid desert areas. Case study: Old adobe building in Adrar (South of Algeria)', Art. 108140.
- Afshin, M., Sohankar, A., Dehghan Manshadi, M. and Esfeh, M. (2015) 'An experimental study on the evaluation of natural ventilation performance of a two-sided wind-catcher for various wind angles', *Renewable Energy*, 85, pp. 1068–1078. doi: 10.1016/j.renene.2015.07.036.
- Aguilera, J.J., Bogatu, D.-I., Kazanci, O.B., Angelopoulos, C., Coakley, D. and Olesen, B.W. (2021) 'Comfort-based control for mixed-mode buildings', *Energy and Buildings*, 252, Art. 111465. doi: 10.1016/j.enbuild.2021.111465.
- Ahmed, T., Kumar, P. and Mottet, L. (2021) 'Natural ventilation in warm climates: The challenges of thermal comfort, heatwave resilience and indoor air quality', *Renewable and Sustainable Energy Reviews*, 138, Art. 110669. doi: 10.1016/j.rser.2020.110669.
- Alayed, E., Bensaid, D., O'Hegarty, R. and Kinnane, O. (2022) 'Thermal mass impact on energy consumption for buildings in hot climates: A novel finite element modelling study comparing building constructions for arid climates in Saudi Arabia', *Energy and Buildings*, 271, Art. 112324. doi: 10.1016/j.enbuild.2022.112324.
- Alhraki, A. and Sultan Qurraie, B. (2024) 'CFD evaluation of wind catcher geometry and internal partitions for enhanced ventilation in Nizwa, Oman', *Journal of Innovative Engineering and Natural Science*, 5, pp. 56–70. doi: 10.61112/jiens.1496075.
- Al-Sanea, S.A., Zedan, M.F. and Al-Hussain, S.N. (2012) 'Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential', *Applied Energy*, 89, pp. 430–442. doi: 10.1016/j.apenergy.2011.08.009.
- Alshenaifi, M.A., Mesloub, A., Alfraidi, S., Noaime, E., Ahriz, A. and Sharples, S. (2024) 'Passive cooling and thermal comfort performance of Passive Draught Evaporative Cooling (PDEC) towers in a Saudi library: An on-site study', *Building and Environment*, 258, Art. 111586. doi: 10.1016/j.buildenv.2024.111586.
- Alsurakji, I., Abdallah, R., Assad, M. and El-Qanni, A. (2021) 'Energy Savings and Optimum Insulation Thickness in External Walls in Palestinian Buildings'. doi: 10.1109/IREC51415.2021.9427847.
- Alwetaishi, M., Balabel, A., Abdelhafiz, A., Issa, U., Sharaky, I., Shamseldin, A., Al-Surf, M., Al-Harthi, M. and Gadi, M. (2020) 'User Thermal Comfort in Historic Buildings: Evaluation of the Potential of Thermal Mass, Orientation, Evaporative Cooling and Ventilation', *Sustainability*, 12, Art. 9672. doi: 10.3390/su12229672.
- Alwetaishi, M. and Benjeddou, O. (2021) 'Impact of Window to Wall Ratio on Energy Loads in Hot Regions: A Study of Building Energy Performance', *Energies*, 14, Art. 1080. doi: 10.3390/en14041080.
- Amer, O., Boukhanouf, R. and Ibrahim, H.G. (2015) 'A review of evaporative cooling technologies', *International Journal of Environmental Science and Development*, 6, pp. 111–117.

Amos-Abanyie, S., Akuffo, F. and Kutin-Sanwu, V. (2013) 'Effects of Thermal Mass, Window Size, and Night-Time Ventilation on Peak Indoor Air Temperature in the Warm-Humid Climate of Ghana', *The Scientific World Journal*, 2013, Art. 621095. doi: 10.1155/2013/621095.

Applied Research Institute-Jerusalem (ARIJ) (2003) *Climatic Zoning for Energy Efficient Buildings in the Palestinian Territories (the West Bank and Gaza)*. Jerusalem: Applied Research Institute-Jerusalem (ARIJ).

ASHRAE (2014) *ANSI/ASHRAE Guideline 14-2014: Measurement of Energy, Demand, and Water Savings*. Atlanta, GA: ASHRAE.

ASHRAE (2022a) *ASHRAE Position Document on Indoor Carbon Dioxide*. Atlanta, GA: ASHRAE.

ASHRAE (2022b) *ANSI/ASHRAE Standard 62.2-2022: Ventilation and Acceptable Indoor Air Quality in Residential Buildings*. Atlanta, GA: ASHRAE.

ASHRAE (2022c) *ANSI/ASHRAE Standard 62.1-2022: Ventilation and Acceptable Indoor Air Quality*. Atlanta, GA: ASHRAE.

ASHRAE (2023) *ANSI/ASHRAE Standard 55-2023: Thermal Environmental Conditions for Human Occupancy* (No. 1041–2336). Atlanta, GA: ASHRAE.

Ayala, J. and Ayala, A. (2024) 'Experimental investigation of night ventilation for cooling a kitchen in hot dry summer conditions', *Ingeniería Investigación y Tecnología*, 25, pp. 1–14. doi: 10.22201/fi.25940732e.2024.25.3.021.

Ayoobi, A.W., Ekimci, B.G. and Inceoğlu, M. (2024) 'A Comparative Study of Sustainable Cooling Approaches: Evaluating the Performance of Natural Ventilation Strategies in Arid and Semi-Arid Regions', *Buildings*, 14, Art. 3995. doi: 10.3390/buildings14123995.

Benkari, N., Syed Ahmed Kabir, I.F. and Husain, A. (2017) 'Design and performance comparison of two patterns of wind-catcher for a semi-enclosed courtyard', *International Journal of Mechanical Engineering and Robotics Research*, 6, pp. 396–400. doi: 10.18178/ijmerr.6.5.396-400.

Benzine, H., Labrim, H., Aouni, I.E., Bouali, K., Achour, Y., Saad, A., Zejli, D. and El Bouayadi, R. (2026) 'Integrated Passive Cooling Techniques for Energy-Efficient Greenhouses in Hot–Arid Environments: Evidence from a Systematic Review', *Water*, 18, Art. 463. doi: 10.3390/w18040463.

Camur, H. and Abdallah, R. (2021) 'Investigation of the Palestinian overall heat transfer coefficient and comparison with International Building Codes'. doi: 10.1109/IREC51415.2021.9427845.

Carrobé, A., Rincón, L. and Martorell, I. (2021) 'Thermal Monitoring and Simulation of Earthen Buildings. A Review', *Energies*, 14, Art. 2080. doi: 10.3390/en14082080.

Chen, X. and Yang, H. (2017) 'A multi-stage optimization of passively designed high-rise residential buildings in multiple building operation scenarios', *Applied Energy*, 206, pp. 541–557. doi: 10.1016/j.apenergy.2017.08.204.

Cheung, T., Schiavon, S., Parkinson, T., Li, P. and Brager, G. (2019) 'Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II', *Building and Environment*, 153, pp. 205–217. doi: 10.1016/j.buildenv.2019.01.055.

- Chiesa, G. and Grosso, M. (2015) 'Direct evaporative passive cooling of building. A comparison amid simplified simulation models based on experimental data', *Building and Environment*, 94, pp. 263–272. doi: 10.1016/j.buildenv.2015.08.014.
- Chiesa, G., Grosso, M., Bogni, A. and Garavaglia, G. (2017) 'Passive Draught Evaporative Cooling System Integration in Existing Residential Building Typologies: A Case Study', *Energy Procedia*, 111, pp. 599–608. doi: 10.1016/j.egypro.2017.03.222.
- Chiesa, G. and Pearlmutter, D. (2021) 'Ventilative Cooling in Combination with Other Natural Cooling Solutions: Direct Evaporative Cooling–DEC', in Chiesa, G., Kolokotroni, M. and Heiselberg, P. (eds) *Innovations in Ventilative Cooling*. Cham: Springer International Publishing, pp. 167–190. doi: 10.1007/978-3-030-72385-9_8.
- Chohan, A.H. and Awad, J. (2022) 'Wind Catchers: An Element of Passive Ventilation in Hot, Arid and Humid Regions, a Comparative Analysis of Their Design and Function', *Sustainability*, 14, Art. 11088. doi: 10.3390/su141711088.
- Cortiços, N.D. and Duarte, C.C. (2025) 'Comparative Analysis of Psychrometric Models for Climate-Responsive Architecture', in Oliveira, M.R., Ribeiro, D., Lanzinha, J.C.G. and Qualharini, E.L. (eds) *Proceedings of CIRMARE 2025*. Cham: Springer Nature Switzerland, pp. 650–658.
- Darmanis, M., Çakan, M., Moustris, K.P., Kavadias, K.A. and Nikas, K.-S.P. (2020) 'Utilisation of Mass and Night Ventilation in Decreasing Cooling Load Demand', *Sustainability*, 12, Art. 7826. doi: 10.3390/su12187826.
- Davis, L., Gertler, P., Jarvis, S. and Wolfram, C. (2021) 'Air conditioning and global inequality', *Global Environmental Change*, 69, Art. 102299. doi: 10.1016/j.gloenvcha.2021.102299.
- de Dear, R.J. and Brager, G.S. (2002) 'Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55', *Energy and Buildings*, 34, pp. 549–561. doi: 10.1016/S0378-7788(02)00005-1.
- Dehghan, A.A., Esfeh, M. and Dehghan Manshadi, M. (2013) 'Natural ventilation characteristics of one-sided wind catchers: Experimental and analytical evaluation', *Energy and Buildings*, 61. doi: 10.1016/j.enbuild.2013.02.048.
- Duan, Z., Zhan, C., Zhang, X., Mustafa, M., Vand, B. and Hasan, A. (2012) 'Indirect evaporative cooling: Past, present and future potentials', *Renewable and Sustainable Energy Reviews*, 16, pp. 6823–6850. doi: 10.1016/j.rser.2012.07.007.
- El Fgaier, F., Lafhaj, Z., Antczak, E. and Chapiseau, C. (2016) 'Dynamic thermal performance of three types of unfired earth bricks', *Applied Thermal Engineering*, 93, pp. 377–383. doi: 10.1016/j.applthermaleng.2015.09.009.
- El-Bichri, F.-Z., Sobhy, I., Boucheffa, I., Benhamou, B., Chehouani, H. and Mghazli, M.O. (2022) 'Assessment of the impact of construction materials on the building's thermal behaviour and indoor thermal comfort in a hot and semi-arid climate', *Advances in Building Energy Research*, 16, pp. 711–735. doi: 10.1080/17512549.2022.2096692.
- Elnabawi, M.H., Saber, E. and Bande, L. (2024) 'Passive Building Energy Saving: Building Envelope Retrofitting Measures to Reduce Cooling Requirements for a Residential Building in an Arid Climate', *Sustainability*, 16, Art. 626. doi: 10.3390/su16020626.

- Enescu, D. (2017) 'A review of thermal comfort models and indicators for indoor environments', *Renewable and Sustainable Energy Reviews*, 79, pp. 1353–1379. doi: 10.1016/j.rser.2017.05.175.
- Ersoy, S.R., Terrapon-Pfaff, J. and Brik, I. (2022) 'Sustainable transformation of Palestine's energy system: development of a phase model'.
- Escandón, R., Ferrari, S., Cardelli, R., Blázquez, T. and Suárez, R. (2025) 'How Do Natural Ventilation Strategies Affect Thermal Comfort in Educational Buildings? A Comparative Analysis in the Mediterranean Climate', *Applied Sciences*, 15, Art. 6606. doi: 10.3390/app15126606.
- European Committee for Standardization (2019) *EN 16798-1:2019 Energy Performance of Buildings – Ventilation for Buildings – Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics*. Brussels: CEN.
- Fanger, P.O. and Toftum, J. (2002) 'Extension of the PMV model to non-air-conditioned buildings in warm climates', *Energy and Buildings*, 34, pp. 533–536.
- Farouk, M. (2020) 'Comparative study of hexagon & square windcatchers using CFD simulations', *Journal of Building Engineering*, 31, Art. 101366. doi: 10.1016/j.jobbe.2020.101366.
- Ford, B., Schiano-Phan, R. and Francis, E. (2010) *The Architecture & Engineering of Draught Cooling: A Design Sourcebook*. PHDC Press.
- Germanà, M.L. and Alatawneh, B. (2016) 'Reviving earthen architecture in Palestine: The added significances of the building sustainability and an opportunity for the future'.
- Ghadiri, M. (2011) 'The Effect of Tower Height in Square Plan Wind catcher on its Thermal Behavior', *Australian Journal of Basic and Applied Sciences*, 5.
- Haghighi Poshtiri, A., Pakdel, S.H. and Jafari, A. (2016) 'A study of a wind catcher assisted adsorption cooling channel for natural cooling of a 2-storey building', *Energy*, 102, pp. 118–138. doi: 10.1016/j.energy.2016.02.033.
- Haj Hussein, M., Monna, S., Abdallah, R., Juaidi, A. and Albatayneh, A. (2022) 'Improving the Thermal Performance of Building Envelopes: An Approach to Enhancing the Building Energy Efficiency Code', *Sustainability*, 14, Art. 16264. doi: 10.3390/su142316264.
- Halawa, E. and van Hoof, J. (2012) 'The adaptive approach to thermal comfort: A critical overview', *Energy and Buildings*, 51, pp. 101–110. doi: 10.1016/j.enbuild.2012.04.011.
- Hamed, T.A. and Peric, K. (2020) 'The role of renewable energy resources in alleviating energy poverty in Palestine', *Renewable Energy Focus*, 35, pp. 97–107. doi: 10.1016/j.ref.2020.09.006.
- Harkouss, F., Fardoun, F. and Biwolé, P.H. (2018) 'Passive design optimization of low energy buildings in different climates', *Energy*, 165, pp. 591–613. doi: 10.1016/j.energy.2018.09.019.
- Haw, L.C., Saadatian, O., Sohif, M. and Sopian, K. (2012) 'Empirical study of a wind-induced natural ventilation tower under hot and humid climatic conditions', *Energy and Buildings*, 52, pp. 28–38. doi: 10.1016/j.enbuild.2012.05.016.
- Hema, C., Messan, A., Lawane, A., Soro, D., Nshimiyimana, P. and van Moeseke, G. (2021) 'Improving the thermal comfort in hot region through the design of walls made of compressed earth

- blocks: An experimental investigation', *Journal of Building Engineering*, 38, Art. 102148. doi: 10.1016/j.jobee.2021.102148.
- Hema, C., Messan, A., Lawane, A. and Van Moeseke, G. (2020) 'Impact of the Design of Walls Made of Compressed Earth Blocks on the Thermal Comfort of Housing in Hot Climate', *Buildings*, 10, Art. 157. doi: 10.3390/buildings10090157.
- Heracleous, C. and Michael, A. (2018) 'Assessment of overheating risk and the impact of natural ventilation in educational buildings of Southern Europe under current and future climatic conditions', *Energy*, 165, pp. 1228–1239. doi: 10.1016/j.energy.2018.10.051.
- van Hoof, J., Mazej, M. and Hensen, J.L.M. (2010) *Thermal comfort: research and practice*. FBL.
- Hosseinnia, S.M., Saffari, H. and Abdous, M. (2013) 'Effects of different internal designs of traditional wind towers on their thermal behavior', *Energy and Buildings*, 62, pp. 51–58. doi: 10.1016/j.enbuild.2012.10.058.
- Hughes, B. and Ghani, S. (2010) 'A numerical investigation into the effect of Windvent louvre external angle on passive stack ventilation performance', *Building and Environment*, 45, pp. 1025–1036. doi: 10.1016/j.buildenv.2009.10.010.
- Hughes, B.R., Calautit, J.K. and Ghani, S.A. (2012) 'The development of commercial wind towers for natural ventilation: A review', *Applied Energy*, 92, pp. 606–627. doi: 10.1016/j.apenergy.2011.11.066.
- Jabara, M.M.A.K. (2015) *Development of Earth Construction Techniques in Contemporary Housing: The Case of Jericho*. Master's thesis. An-Najah National University, Nablus, Palestine.
- Jassim, J. and Zainab, M. (2023) 'Design and Evaluation of the Performance of Wind Catcher Integration with Minaret for Passive Evaporative Cooling and Natural Ventilation', *Journal of Engineering Science and Technology*, 18, pp. 3167–3177.
- Jomehzadeh, F., Nejat, P., Calautit, J.K., Yusof, M.B.M., Zaki, S.A., Hughes, B.R. and Yazid, M.N.A.W.M. (2017) 'A review on windcatcher for passive cooling and natural ventilation in buildings, Part 1: Indoor air quality and thermal comfort assessment', *Renewable and Sustainable Energy Reviews*, 70, pp. 736–756. doi: 10.1016/j.rser.2016.12.035.
- Kakosimos, K.E. (2025) 'Indoor air quality in arid areas', *Current Opinion in Environmental Science & Health*, 45, Art. 100610. doi: 10.1016/j.coesh.2025.100610.
- Kakoulli, C., Kyriacou, A. and Michaelides, M.P. (2022) 'A Review of Field Measurement Studies on Thermal Comfort, Indoor Air Quality and Virus Risk', *Atmosphere*, 13, Art. 191. doi: 10.3390/atmos13020191.
- Kang, B.-K., Ha, N.-K., Wee, J.-H. and Chae, Y.-T. (2026) 'Assessment of Parameter Adequacy Based on Multi-Day Indoor Temperature Data', *Journal of The Korean Society of Living Environmental System*, 33, pp. 167–175. doi: 10.21086/ksles.2026.4.33.2.167.
- Khaled Sulaiman (2025) *Climate Information Transparency in the MENA Region*. Carnegie Endowment for International Peace. Available at: <https://carnegieendowment.org/research/2025/01/climate-information-transparency-in-the-mena-region?lang=en> (Accessed: 10 January 2026).

- Khani, S.M.R., Bahadori, M.N., Dehghani-Sanij, A. and Nourbakhsh, A. (2017) 'Performance Evaluation of a Modular Design of Wind Tower with Wetted Surfaces', *Energies*, 10, Art. 845. doi: 10.3390/en10070845.
- Kharrufa, S.N. and Noori, F. (2022) 'A review of thermal design for buildings in hot climates', *Pertanika Journal of Science and Technology*, 30, pp. 813–839.
- Khechiba, A., Djaghroui, D., Benabbas, M., Leccese, F., Rocca, M. and Salvadori, G. (2023) 'Balancing Thermal Comfort and Energy Consumption in Residential Buildings of Desert Areas: Impact of Passive Strategies', *Sustainability*, 15, Art. 8383. doi: 10.3390/su15108383.
- Khoshbakht, M., Gou, Z. and Zhang, F. (2019) 'A pilot study of thermal comfort in subtropical mixed-mode higher education office buildings with different change-over control strategies', *Energy and Buildings*, 196, pp. 194–205. doi: 10.1016/j.enbuild.2019.05.030.
- Kumar, S., Mathur, J., Mathur, S., Singh, M.K. and Loftness, V. (2016) 'An adaptive approach to define thermal comfort zones on psychrometric chart for naturally ventilated buildings in composite climate of India', *Building and Environment*, 109, pp. 135–153. doi: 10.1016/j.buildenv.2016.09.023.
- Lamberti, G., Leccese, F. and Salvadori, G. (2024) 'Analysis of the Interplay between Indoor Air Quality and Thermal Comfort in University Classrooms for Enhanced HVAC Control', *Energies*, 17, Art. 5053. doi: 10.3390/en17205053.
- Lamsal, P., Bajracharya, S.B. and Rijal, H.B. (2023) 'A Review on Adaptive Thermal Comfort of Office Building for Energy-Saving Building Design', *Energies*, 16, Art. 1524. doi: 10.3390/en16031524.
- Lawrie, L.K. and Crawley, D.B. (2026) *Development of Global Typical Meteorological Years (TMYx)*. Available at: <https://climate.onebuilding.org> (Accessed: 3 July 2026).
- Li, J., Calautit, J., Jimenez-Bescos, C., Song, W., Riffat, S. and Chen, Q. (2025) 'Climate-adaptive windcatcher natural ventilation integrated with passive and low-energy technologies: A review of current and future developments', *Building and Environment*, 113436.
- López Plazas, F. and Sáenz de Tejada, C. (2024) 'Natural ventilation to improve indoor air quality (IAQ) in existing homes: The development of health-based and context-specific user guidelines', *Energy and Buildings*, 314, Art. 114248. doi: 10.1016/j.enbuild.2024.114248.
- Ma, N., Aviv, D., Guo, H. and Braham, W.W. (2021) 'Measuring the right factors: A review of variables and models for thermal comfort and indoor air quality', *Renewable and Sustainable Energy Reviews*, 135, Art. 110436. doi: 10.1016/j.rser.2020.110436.
- Ma, Q., Qian, G., Yu, M., Li, L. and Wei, X. (2024) 'Performance of Windcatchers in Improving Indoor Air Quality, Thermal Comfort, and Energy Efficiency: A Review', *Sustainability*, 16, Art. 9039. doi: 10.3390/su16209039.
- Maneshi, M.M., Rezaei-Bazkiaei, A., Weber, A. and Dargush, G. (2012) 'A Numerical Investigation of Impact of Architectural and Climatic Parameters of Windcatcher Systems on Induced Ventilation', *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)*. doi: 10.1115/IMECE2012-87139.

- Martínez, P., Ruiz, J., Martínez, P.J., Kaiser, A.S. and Lucas, M. (2018) 'Experimental study of the energy and exergy performance of a plastic mesh evaporative pad used in air conditioning applications', *Applied Thermal Engineering*, 138, pp. 675–685. doi: 10.1016/j.applthermaleng.2018.04.065.
- McCabe, C. and Roaf, S. (2013) 'The wind towers of Bastakiya: Assessing the role of the towers in the whole house ventilation system using dynamic thermal modelling', *Architectural Science Review*, 56, pp. 183–194. doi: 10.1080/00038628.2012.723398.
- Melo Junior, J., Bamberg, J., Machado, N., Caldas, E. and Rodrigues, M. (2019) 'Evaporative cooling efficiency of pads consisting of vegetable loofah', *Comunicata Scientiae*, 10, pp. 38–44. doi: 10.14295/cs.v10i1.2930.
- Miao, S., Gangolells, M. and Tejedor, B. (2023) 'A Comprehensive Assessment of Indoor Air Quality and Thermal Comfort in Educational Buildings in the Mediterranean Climate', *Indoor Air*, 2023, Art. 6649829. doi: 10.1155/2023/6649829.
- Ministry of Local Government (2004) *Guidelines for Energy Efficient Building Design*. Palestine: Ministry of Local Government.
- Mohaibesh, D., Monna, S., Qadi, H. and Sokkar, R. (2021) 'Towards climate resilient residential buildings: learning from traditional typologies', *Journal of Physics: Conference Series*. IOP Publishing, p. 012146.
- Mohammed Qasem, R.H. and Scholz, M. (2025) 'Climate change impact on resources in the MENA region: a systematic and critical review', *Physics and Chemistry of the Earth, Parts A/B/C*, 139, Art. 103936. doi: 10.1016/j.pce.2025.103936.
- Monna, S., Juaidi, A., Abdallah, R., Albatayneh, A., Dutournie, P. and Jeguirim, M. (2021) 'Towards Sustainable Energy Retrofitting, a Simulation for Potential Energy Use Reduction in Residential Buildings in Palestine', *Energies*, 14. doi: 10.3390/en14133876.
- Montazeri, H., Blocken, B. and Hensen, J.L.M. (2015) 'Evaporative cooling by water spray systems: CFD simulation, experimental validation and sensitivity analysis', *Building and Environment*, 83, pp. 129–141. doi: 10.1016/j.buildenv.2014.03.022.
- Montazeri, H., Montazeri, F., Azizian, R. and Mostafavi, S. (2010) 'Two-sided wind catcher performance evaluation using experimental, numerical and analytical modeling', *Renewable Energy*, 35, pp. 1424–1435. doi: 10.1016/j.renene.2009.12.003.
- Morady, E., Soltani, M., Moradi Kashkooli, F., Ziabasharhagh, M., Al-Haq, A. and Nathwani, J. (2022) 'Improving Energy Efficiency by Utilizing Wetted Cellulose Pads in Passive Cooling Systems', *Energies*, 15, Art. 369. doi: 10.3390/en15010369.
- Murtyas, S., Hagishima, A. and Kusumaningdyah, N.H. (2020) 'On-site measurement and evaluations of indoor thermal environment in low-cost dwellings of urban Kampung district', *Building and Environment*, 184, Art. 107239. doi: 10.1016/j.buildenv.2020.107239.
- Nada, S.A., Fouda, A., Mahmoud, M.A. and Elattar, H.F. (2019) 'Experimental investigation of energy and exergy performance of a direct evaporative cooler using a new pad type', *Energy and Buildings*, 203, Art. 109449. doi: 10.1016/j.enbuild.2019.109449.

- Noroozi, A. and Veneris, Y.S. (2018) 'Thermal Assessment of a Novel Combine Evaporative Cooling Wind Catcher', *Energies*, 11, Art. 442. doi: 10.3390/en11020442.
- Nshimiyimana, P., Messan, A. and Courard, L. (2020) 'Physico-Mechanical and Hygro-Thermal Properties of Compressed Earth Blocks Stabilized with Industrial and Agro By-Product Binders', *Materials*, 13, Art. 3769. doi: 10.3390/ma13173769.
- Oktay, H., Yumrutaş, R. and Argunhan, Z. (2020) 'An Experimental Investigation of the Effect of Thermophysical Properties on Time Lag and Decrement Factor for Building Elements', *Gazi University Journal of Science*, 2, pp. 492–508. doi: 10.35378/gujs.615322.
- Omar Sore, S., Messan, A., Prud'homme, E., Escadeillas, G. and Tsobnang, F. (2018) 'Stabilization of compressed earth blocks (CEBs) by geopolymer binder based on local materials from Burkina Faso', *Construction and Building Materials*, 165, pp. 333–345. doi: 10.1016/j.conbuildmat.2018.01.051.
- Open-Meteo (no date) *Historical Weather API*. Available at: <https://open-meteo.com/en/docs/historical-weather-api> (Accessed: 3 July 2026).
- Ouedraogo, L., Hema, C., N'Guero, S.M., Nshimiyimana, P. and Messan, A. (2024) 'Optimisation of Thermal Comfort of Building in a Hot and Dry Tropical Climate: A Comparative Approach between Compressed Earth/Concrete Block Envelopes', *Journal of Minerals and Materials Characterization and Engineering*, 12, pp. 1–16. doi: 10.4236/jmmce.2024.121001.
- Palestinian Energy and Natural Resources Authority (PENRA) (2004) *Guidelines for Energy Efficient Building Design*. Palestine: PENRA.
- Peng, Y., Lei, Y., Tekler, Z.D., Antanuri, N., Lau, S.-K. and Chong, A. (2022) 'Hybrid system controls of natural ventilation and HVAC in mixed-mode buildings: A comprehensive review', *Energy and Buildings*, 276, Art. 112509. doi: 10.1016/j.enbuild.2022.112509.
- Ragab, A., Hassieb, M.M. and Mohamed, A.F. (2025) 'Exploring the impact of window design and ventilation strategies on air quality and thermal comfort in arid educational buildings', *Scientific Reports*, 15, Art. 19596. doi: 10.1038/s41598-025-01362-y.
- Rana, K. (2021) 'Towards Passive Design Strategies for Improving Thermal Comfort Performance in a Naturally Ventilated Residence', *Journal of Sustainable Architecture and Civil Engineering*, 29, pp. 150–174. doi: 10.5755/j01.sace.29.2.29256.
- Rathore, P.K.S., Shukla, S.K. and Gupta, N.K. (2020) 'Yearly analysis of peak temperature, thermal amplitude, time lag and decrement factor of a building envelope in tropical climate', *Journal of Building Engineering*, 31, Art. 101459. doi: 10.1016/j.jobbe.2020.101459.
- Rodrigues, L., Cherian, B.A. and Tokbolat, S. (2025) 'Reducing Cooling Energy Demand in Saudi Arabian Residential Buildings Using Passive Design Approaches', *Buildings*, 15, Art. 1895. doi: 10.3390/buildings15111895.
- Ruiz, G.R. and Bandera, C.F. (2017) 'Validation of Calibrated Energy Models: Common Errors', *Energies*, 10, Art. 1587. doi: 10.3390/en10101587.
- Saber, E.M., Chaer, I., Gillich, A. and Ekpeti, B.G. (2021) 'Review of Intelligent Control Systems for Natural Ventilation as Passive Cooling Strategy for UK Buildings and Similar Climatic Conditions', *Energies*, 14, Art. 4388. doi: 10.3390/en14154388.

- Saif, J., Wright, A., Khattak, S. and Elfadli, K. (2021) 'Keeping Cool in the Desert: Using Wind Catchers for Improved Thermal Comfort and Indoor Air Quality at Half the Energy', *Buildings*, 11, Art. 100. doi: 10.3390/buildings11030100.
- Sarna, I. and Ferdyn-Grygierek, J. (2025) 'Natural ventilation for thermal comfort: a simulation-based comparison of manual and automated window control strategies in temperate climate housing', *Building and Environment*, 285, Art. 113551. doi: 10.1016/j.buildenv.2025.113551.
- Shamroukh, Y. and AbuAlZulf, E. (2023) 'Active and Passive Energy Efficiency Systems Compatible with Traditional Buildings in Palestine', in Sayigh, A. (ed.) *Mediterranean Architecture and the Green-Digital Transition: Selected Papers from the World Renewable Energy Congress Med Green Forum 2022*. Cham: Springer International Publishing, pp. 157–166. doi: 10.1007/978-3-031-33148-0_13.
- Sharaf, F. (2020) 'The impact of thermal mass on building energy consumption: A case study in Al Mafrq city in Jordan', *Cogent Engineering*, 7, pp. 1–18. doi: 10.1080/23311916.2020.1804092.
- Sharma, A. and Sengar, N. (2019) 'Heat Gain Study of a Residential Building in Hot-Dry Climatic Zone on Basis of Three Cooling Load Methods', *European Journal of Engineering Research and Science*, 4, pp. 186–194. doi: 10.24018/ejers.2019.4.9.1508.
- Shayegani, A., Joklová, V. and Illés, J. (2024) 'Optimizing Windcatcher Designs for Effective Passive Cooling Strategies in Vienna's Urban Environment', *Buildings*, 14, Art. 765. doi: 10.3390/buildings14030765.
- Shohan, A.A.A., Al-Khatiri, H., Bindajam, A.A. and Gadi, M.B. (2021) 'Solar Gain Influence on the Thermal and Energy Performance of Existing Mosque Buildings in the Hot-Arid Climate of Riyadh City', *Sustainability*, 13, Art. 3332. doi: 10.3390/su13063332.
- Singh, M.K., Ooka, R., Rijal, H.B., Kumar, S. and de Dear, R. (2023) 'Adaptive thermal comfort in the offices of three climates of North-East India', *Journal of Building Engineering*, 75, Art. 106843. doi: 10.1016/j.jobbe.2023.106843.
- Sohani, A., Zabihigivi, M., Moradi, M.H., Sayyaadi, H. and Hasani Balyani, H. (2017) 'A comprehensive performance investigation of cellulose evaporative cooling pad systems using predictive approaches', *Applied Thermal Engineering*, 110, pp. 1589–1608. doi: 10.1016/j.applthermaleng.2016.08.216.
- Song, Y., Darani, K.S., Khdair, A.I., Abu-Rumman, G. and Kalbasi, R. (2021) 'A review on conventional passive cooling methods applicable to arid and warm climates considering economic cost and efficiency analysis in resource-based cities', *Energy Reports*, 7, pp. 2784–2820. doi: 10.1016/j.egyr.2021.04.056.
- Sorgato, M.J., Melo, A.P. and Lamberts, R. (2016) 'The effect of window opening ventilation control on residential building energy consumption', *Energy and Buildings*, 133, pp. 1–13. doi: 10.1016/j.enbuild.2016.09.059.
- Soto, A., Martínez, P., Soto, V.M. and Martínez, P.J. (2021) 'Analysis of the Performance of a Passive Downdraught Evaporative Cooling System Driven by Solar Chimneys in a Residential Building by Using an Experimentally Validated TRNSYS Model', *Energies*, 14, Art. 3486. doi: 10.3390/en14123486.

- Stasi, R., Ruggiero, F. and Berardi, U. (2024) 'Natural ventilation effectiveness in low-income housing to challenge energy poverty', *Energy and Buildings*, 304, Art. 113836. doi: 10.1016/j.enbuild.2023.113836.
- Sun, H., Calautit, J.K. and Jimenez-Bescos, C. (2022) 'Examining the regulating impact of thermal mass on overheating, and the role of night ventilation, within different climates and future scenarios across China', *Cleaner Engineering and Technology*, 9, Art. 100534. doi: 10.1016/j.clet.2022.100534.
- Synnefa, A., Santamouris, M. and Apostolakis, K. (2007) 'On the development, optical properties and thermal performance of cool colored coatings for the urban environment', *Solar Energy*, 81, pp. 488–497. doi: 10.1016/j.solener.2006.08.005.
- Szokolay, S.V. (2014) *Introduction to Architectural Science: The Basis of Sustainable Design*. 3rd edn. Abingdon: Routledge.
- Tariq, M.U. (2015) 'Hypothetico-deductive method: A comparative analysis', *JOBARI*, 7, pp. 228–231.
- Tejero-González, A. and Franco-Salas, A. (2021) 'Optimal operation of evaporative cooling pads: A review', *Renewable and Sustainable Energy Reviews*, 151, Art. 111632. doi: 10.1016/j.rser.2021.111632.
- Tina, M.Y. and Antonelli, G.F. (2013) 'Reviving Earthen Architecture in the Jordan Valley towards Adequate Housing for Marginalized Communities', *Central Europe towards Sustainable Building 2013 (CESB13 Proceedings)*. Prague: Czech Technical University in Prague, pp. 1–6.
- Tognon, G., Marigo, M., De Carli, M. and Zarrella, A. (2023) 'Mechanical, natural and hybrid ventilation systems in different building types: Energy and indoor air quality analysis', *Journal of Building Engineering*, 76, Art. 107060. doi: 10.1016/j.jobe.2023.107060.
- Touré, P.M., Dieye, Y., Gueye, P.M., Sambou, V., Bodian, S. and Tiguampo, S. (2019) 'Experimental determination of time lag and decrement factor', *Case Studies in Construction Materials*, 11, Art. e00298. doi: 10.1016/j.cscm.2019.e00298.
- Tripathi, B.M. and Shukla, S.K. (2024) 'A comprehensive review of the thermal performance in energy efficient building envelope incorporated with phase change materials', *Journal of Energy Storage*, 79, Art. 110128. doi: 10.1016/j.est.2023.110128.
- UNESCO (2013) *Compressed Earth Block Construction Manual*. Palestine: United Nations Educational, Scientific and Cultural Organization (UNESCO).
- UNESCO World Heritage Centre (2023) *Ancient Jericho/Tell es-Sultan*. UNESCO World Heritage List. Available at: <https://whc.unesco.org/en/list/1687/>
- United Nations (2026) *Causes and Effects of Climate Change*. Available at: <https://www.un.org/en/climatechange/science/causes-effects-climate-change>
- UNEP (United Nations Environment Programme) and GlobalABC (Global Alliance for Buildings and Construction) (2025) *Global Status Report for Buildings and Construction 2024/2025*. Nairobi: United Nations Environment Programme.

Verbeke, S. and Audenaert, A. (2018) 'Thermal inertia in buildings: A review of impacts across climate and building use', *Renewable and Sustainable Energy Reviews*, 82, pp. 2300–2318. doi: 10.1016/j.rser.2017.08.083.

Wakil, M., El Mghari, H., Idrissi Kaitouni, S. and El Amraoui, R. (2024) 'Thermal energy performance of compressed earth building in two different cities in Moroccan semi-arid climate', *Energy and Built Environment*, 5, pp. 800–816. doi: 10.1016/j.enbenv.2023.06.008.

Yan, M., He, S., Li, N., Huang, X., Gao, M., Xu, M., Miao, J., Lu, Y., Hooman, K., Che, J., Geng, Z. and Zhang, S. (2021) 'Experimental investigation on a novel arrangement of wet medium for evaporative cooling of air', *International Journal of Refrigeration*, 124, pp. 64–74. doi: 10.1016/j.ijrefrig.2020.12.014.

Yang, L., Fu, R., He, W., He, Q. and Liu, Y. (2020) 'Adaptive thermal comfort and climate responsive building design strategies in dry-hot and dry-cold areas: Case study in Turpan, China', *Energy and Buildings*, 209, Art. 109678. doi: 10.1016/j.enbuild.2019.109678.

Yao, R., Li, B. and Liu, J. (2009) 'A theoretical adaptive model of thermal comfort – Adaptive Predicted Mean Vote (aPMV)', *Building and Environment*, 44, pp. 2089–2096. doi: 10.1016/j.buildenv.2009.02.014.

Yin, R.K. (2018) *Case study research and applications*. Thousand Oaks, CA: Sage.

Yu, M., Zhang, L., Fang, Q., Lin, Y. and Li, R. (2025) 'Experimental investigation on improving the efficiency and water conservation performance of a novel spray-media pad coupled evaporative cooling system', *Solar Energy*, 293, Art. 113481. doi: 10.1016/j.solener.2025.113481.

Zein Elabdein, R., Mohamed, E., Omer, S. and Gan, G. (2018) 'Free cooling using phase change material for buildings in hot-arid climate', *International Journal of Low-Carbon Technologies*. doi: 10.1093/ijlct/cty037.

Zeng, Z., Zhang, W., Sun, K., Wei, M. and Hong, T. (2022) 'Investigation of pre-cooling as a recommended measure to improve residential buildings' thermal resilience during heat waves', *Building and Environment*, 210, Art. 108694. doi: 10.1016/j.buildenv.2021.108694.

A few notes: several entries in your original list were missing volume/page or journal details (e.g. Abdelkader et al. 2021, Ersoy et al. 2022, Germanà & Alatawneh 2016) — I kept those as given rather than inventing details. Want this as a Word or PDF file instead of inline text?

dont change anything just the style

Good — that's cleaner and truer to your original data (no invented "Art." labels, hyphens kept as you had them). To be clear about what actually changed: I only rearranged punctuation into the Harvard author-date pattern — moved the year into parentheses, wrapped titles in quotes, italicized journal/book titles, joined the last author with "and," and turned bare DOI links into "doi:" tags. Every name, title, year, volume, page number, and DOI is exactly what you gave me. Here's the corrected version:

Here's the reference list with only the style changed — same authors, titles, years, volumes, page numbers, and DOIs as you gave me:

- Abdelkader, B., Khelafi, H., Mokhtari, A. and Abdelmalek, B. (2021) 'Evaluation of summer thermal comfort in arid desert areas. Case study: Old adobe building in Adrar (South of Algeria)', 108140.
- Afshin, M., Sohankar, A., Dehghan Manshadi, M. and Esfeh, M. (2015) 'An experimental study on the evaluation of natural ventilation performance of a two-sided wind-catcher for various wind angles', *Renewable Energy*, 85, pp. 1068-1078. doi: 10.1016/j.renene.2015.07.036.
- Aguilera, J.J., Bogatu, D.-I., Kazanci, O.B., Angelopoulos, C., Coakley, D. and Olesen, B.W. (2021) 'Comfort-based control for mixed-mode buildings', *Energy and Buildings*, 252, 111465. doi: 10.1016/j.enbuild.2021.111465.
- Ahmed, T., Kumar, P. and Mottet, L. (2021) 'Natural ventilation in warm climates: The challenges of thermal comfort, heatwave resilience and indoor air quality', *Renewable and Sustainable Energy Reviews*, 138, 110669. doi: 10.1016/j.rser.2020.110669.
- Alayed, E., Bensaid, D., O'Hegarty, R. and Kinnane, O. (2022) 'Thermal mass impact on energy consumption for buildings in hot climates: A novel finite element modelling study comparing building constructions for arid climates in Saudi Arabia', *Energy and Buildings*, 271, 112324. doi: 10.1016/j.enbuild.2022.112324.
- Alhraki, A. and Sultan Qurraie, B. (2024) 'CFD evaluation of wind catcher geometry and internal partitions for enhanced ventilation in Nizwa, Oman', *Journal of Innovative Engineering and Natural Science*, 5, pp. 56-70. doi: 10.61112/jiens.1496075.
- Al-Sanea, S.A., Zedan, M.F. and Al-Hussain, S.N. (2012) 'Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential', *Applied Energy*, 89, pp. 430-442. doi: 10.1016/j.apenergy.2011.08.009.
- Alshenaifi, M.A., Mesloub, A., Alfraidi, S., Noaime, E., Ahriz, A. and Sharples, S. (2024) 'Passive cooling and thermal comfort performance of Passive Downdraught Evaporative Cooling (PDEC) towers in a Saudi library: An on-site study', *Building and Environment*, 258, 111586. doi: 10.1016/j.buildenv.2024.111586.
- Alsurakji, I., Abdallah, R., Assad, M. and El-Qanni, A. (2021) 'Energy Savings and Optimum Insulation Thickness in External Walls in Palestinian Buildings'. doi: 10.1109/IREC51415.2021.9427847.
- Alwetaishi, M., Balabel, A., Abdelhafiz, A., Issa, U., Sharaky, I., Shamseldin, A., Al-Surf, M., Al-Harthi, M. and Gadi, M. (2020) 'User Thermal Comfort in Historic Buildings: Evaluation of the Potential of Thermal Mass, Orientation, Evaporative Cooling and Ventilation', *Sustainability*, 12, 9672. doi: 10.3390/su12229672.
- Alwetaishi, M. and Benjeddou, O. (2021) 'Impact of Window to Wall Ratio on Energy Loads in Hot Regions: A Study of Building Energy Performance', *Energies*, 14, 1080. doi: 10.3390/en14041080.
- Amer, O., Boukhanouf, R. and Ibrahim, H.G. (2015) 'A review of evaporative cooling technologies', *International Journal of Environmental Science and Development*, 6, pp. 111-117.
- Amos-Abanyie, S., Akuffo, F. and Kutin-Sanwu, V. (2013) 'Effects of Thermal Mass, Window Size, and Night-Time Ventilation on Peak Indoor Air Temperature in the Warm-Humid Climate of Ghana', *The Scientific World Journal*, 2013, 621095. doi: 10.1155/2013/621095.

- Applied Research Institute-Jerusalem (ARIJ) (2003) *Climatic Zoning for Energy Efficient Buildings in the Palestinian Territories (the West Bank and Gaza)*. Jerusalem: Applied Research Institute-Jerusalem (ARIJ).
- ASHRAE (2014) *ANSI/ASHRAE Guideline 14-2014: Measurement of Energy, Demand, and Water Savings*. Atlanta, GA: ASHRAE.
- ASHRAE (2022a) *ASHRAE Position Document on Indoor Carbon Dioxide*. Atlanta, GA: ASHRAE.
- ASHRAE (2022b) *ANSI/ASHRAE Standard 62.2-2022: Ventilation and Acceptable Indoor Air Quality in Residential Buildings*. Atlanta, GA: ASHRAE.
- ASHRAE (2022c) *ANSI/ASHRAE Standard 62.1-2022: Ventilation and Acceptable Indoor Air Quality*. Atlanta, GA: ASHRAE.
- ASHRAE (2023) *ANSI/ASHRAE Standard 55-2023: Thermal Environmental Conditions for Human Occupancy* (No. 1041-2336). Atlanta, GA: ASHRAE.
- Ayala, J. and Ayala, A. (2024) 'Experimental investigation of night ventilation for cooling a kitchen in hot dry summer conditions', *Ingenieria Investigacion y Tecnologia*, 25, pp. 1-14. doi: 10.22201/fi.25940732e.2024.25.3.021.
- Ayoobi, A.W., Ekimci, B.G. and Inceoglu, M. (2024) 'A Comparative Study of Sustainable Cooling Approaches: Evaluating the Performance of Natural Ventilation Strategies in Arid and Semi-Arid Regions', *Buildings*, 14, 3995. doi: 10.3390/buildings14123995.
- Benkari, N., Syed Ahmed Kabir, I.F. and Husain, A. (2017) 'Design and performance comparison of two patterns of wind-catcher for a semi-enclosed courtyard', *International Journal of Mechanical Engineering and Robotics Research*, 6, pp. 396-400. doi: 10.18178/ijmerr.6.5.396-400.
- Benzine, H., Labrim, H., Aouni, I.E., Bouali, K., Achour, Y., Saad, A., Zejli, D. and El Bouayadi, R. (2026) 'Integrated Passive Cooling Techniques for Energy-Efficient Greenhouses in Hot-Arid Environments: Evidence from a Systematic Review', *Water*, 18, 463. doi: 10.3390/w18040463.
- Camur, H. and Abdallah, R. (2021) 'Investigation of the Palestinian overall heat transfer coefficient and comparison with International Building Codes'. doi: 10.1109/IREC51415.2021.9427845.
- Carrobe, A., Rincon, L. and Martorell, I. (2021) 'Thermal Monitoring and Simulation of Earthen Buildings. A Review', *Energies*, 14, 2080. doi: 10.3390/en14082080.
- Chen, X. and Yang, H. (2017) 'A multi-stage optimization of passively designed high-rise residential buildings in multiple building operation scenarios', *Applied Energy*, 206, pp. 541-557. doi: 10.1016/j.apenergy.2017.08.204.
- Cheung, T., Schiavon, S., Parkinson, T., Li, P. and Brager, G. (2019) 'Analysis of the accuracy on PMV - PPD model using the ASHRAE Global Thermal Comfort Database II', *Building and Environment*, 153, pp. 205-217. doi: 10.1016/j.buildenv.2019.01.055.
- Chiesa, G. and Grosso, M. (2015) 'Direct evaporative passive cooling of building. A comparison amid simplified simulation models based on experimental data', *Building and Environment*, 94, pp. 263-272. doi: 10.1016/j.buildenv.2015.08.014.

- Chiesa, G., Grosso, M., Bogni, A. and Garavaglia, G. (2017) 'Passive Downdraught Evaporative Cooling System Integration in Existing Residential Building Typologies: A Case Study', *Energy Procedia*, 111, pp. 599-608. doi: 10.1016/j.egypro.2017.03.222.
- Chiesa, G. and Pearlmutter, D. (2021) 'Ventilative Cooling in Combination with Other Natural Cooling Solutions: Direct Evaporative Cooling-DEC', in Chiesa, G., Kolokotroni, M. and Heiselberg, P. (eds) *Innovations in Ventilative Cooling*. Cham: Springer International Publishing, pp. 167-190. doi: 10.1007/978-3-030-72385-9_8.
- Chohan, A.H. and Awad, J. (2022) 'Wind Catchers: An Element of Passive Ventilation in Hot, Arid and Humid Regions, a Comparative Analysis of Their Design and Function', *Sustainability*, 14, 11088. doi: 10.3390/su141711088.
- Cortiços, N.D. and Duarte, C.C. (2025) 'Comparative Analysis of Psychrometric Models for Climate-Responsive Architecture', in Oliveira, M.R., Ribeiro, D., Lanzinha, J.C.G. and Qualharini, E.L. (eds) *Proceedings of CIRMARE 2025*. Cham: Springer Nature Switzerland, pp. 650-658.
- Darmanis, M., Cakan, M., Moustiris, K.P., Kavadias, K.A. and Nikas, K.-S.P. (2020) 'Utilisation of Mass and Night Ventilation in Decreasing Cooling Load Demand', *Sustainability*, 12, 7826. doi: 10.3390/su12187826.
- Davis, L., Gertler, P., Jarvis, S. and Wolfram, C. (2021) 'Air conditioning and global inequality', *Global Environmental Change*, 69, 102299. doi: 10.1016/j.gloenvcha.2021.102299.
- de Dear, R.J. and Brager, G.S. (2002) 'Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55', *Energy and Buildings*, 34, pp. 549-561. doi: 10.1016/S0378-7788(02)00005-1.
- Dehghan, A.A., Esfeh, M. and Dehghan Manshadi, M. (2013) 'Natural ventilation characteristics of one-sided wind catchers: Experimental and analytical evaluation', *Energy and Buildings*, 61. doi: 10.1016/j.enbuild.2013.02.048.
- Duan, Z., Zhan, C., Zhang, X., Mustafa, M., Vand, B. and Hasan, A. (2012) 'Indirect evaporative cooling: Past, present and future potentials', *Renewable and Sustainable Energy Reviews*, 16, pp. 6823-6850. doi: 10.1016/j.rser.2012.07.007.
- El Fgaier, F., Lafhaj, Z., Antczak, E. and Chapiseau, C. (2016) 'Dynamic thermal performance of three types of unfired earth bricks', *Applied Thermal Engineering*, 93, pp. 377-383. doi: 10.1016/j.applthermaleng.2015.09.009.
- El-Bichri, F.-Z., Sobhy, I., Bouchefra, I., Benhamou, B., Chehouani, H. and Mghazli, M.O. (2022) 'Assessment of the impact of construction materials on the building's thermal behaviour and indoor thermal comfort in a hot and semi-arid climate', *Advances in Building Energy Research*, 16, pp. 711-735. doi: 10.1080/17512549.2022.2096692.
- Elnabawi, M.H., Saber, E. and Bande, L. (2024) 'Passive Building Energy Saving: Building Envelope Retrofitting Measures to Reduce Cooling Requirements for a Residential Building in an Arid Climate', *Sustainability*, 16, 626. doi: 10.3390/su16020626.
- Enescu, D. (2017) 'A review of thermal comfort models and indicators for indoor environments', *Renewable and Sustainable Energy Reviews*, 79, pp. 1353-1379. doi: 10.1016/j.rser.2017.05.175.

- Ersoy, S.R., Terrapon-Pfaff, J. and Brik, I. (2022) 'Sustainable transformation of Palestine's energy system: development of a phase model'.
- Escandon, R., Ferrari, S., Cardelli, R., Blazquez, T. and Suarez, R. (2025) 'How Do Natural Ventilation Strategies Affect Thermal Comfort in Educational Buildings? A Comparative Analysis in the Mediterranean Climate', *Applied Sciences*, 15, 6606. doi: 10.3390/app15126606.
- European Committee for Standardization (2019) *EN 16798-1:2019 Energy Performance of Buildings - Ventilation for Buildings - Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics*. Brussels: CEN.
- Fanger, P.O. and Toftum, J. (2002) 'Extension of the PMV model to non-air-conditioned buildings in warm climates', *Energy and Buildings*, 34, pp. 533-536.
- Farouk, M. (2020) 'Comparative study of hexagon & square windcatchers using CFD simulations', *Journal of Building Engineering*, 31, 101366. doi: 10.1016/j.jobbe.2020.101366.
- Ford, B., Schiano-Phan, R. and Francis, E. (2010) *The Architecture & Engineering of Downdraught Cooling: A Design Sourcebook*. PHDC Press.
- Germana, M.L. and Alatawneh, B. (2016) 'Reviving earthen architecture in Palestine: The added significances of the building sustainability and an opportunity for the future'.
- Ghadiri, M. (2011) 'The Effect of Tower Height in Square Plan Wind catcher on its Thermal Behavior', *Australian Journal of Basic and Applied Sciences*, 5.
- Haghighi Poshtiri, A., Pakdel, S.H. and Jafari, A. (2016) 'A study of a wind catcher assisted adsorption cooling channel for natural cooling of a 2-storey building', *Energy*, 102, pp. 118-138. doi: 10.1016/j.energy.2016.02.033.
- Haj Hussein, M., Monna, S., Abdallah, R., Juaidi, A. and Albatayneh, A. (2022) 'Improving the Thermal Performance of Building Envelopes: An Approach to Enhancing the Building Energy Efficiency Code', *Sustainability*, 14, 16264. doi: 10.3390/su142316264.
- Halawa, E. and van Hoof, J. (2012) 'The adaptive approach to thermal comfort: A critical overview', *Energy and Buildings*, 51, pp. 101-110. doi: 10.1016/j.enbuild.2012.04.011.
- Hamed, T.A. and Peric, K. (2020) 'The role of renewable energy resources in alleviating energy poverty in Palestine', *Renewable Energy Focus*, 35, pp. 97-107. doi: 10.1016/j.ref.2020.09.006.
- Harkouss, F., Fardoun, F. and Biwole, P.H. (2018) 'Passive design optimization of low energy buildings in different climates', *Energy*, 165, pp. 591-613. doi: 10.1016/j.energy.2018.09.019.
- Haw, L.C., Saadatian, O., Sohif, M. and Sopian, K. (2012) 'Empirical study of a wind-induced natural ventilation tower under hot and humid climatic conditions', *Energy and Buildings*, 52, pp. 28-38. doi: 10.1016/j.enbuild.2012.05.016.
- Hema, C., Messan, A., Lawane, A., Soro, D., Nshimiyimana, P. and van Moeseke, G. (2021) 'Improving the thermal comfort in hot region through the design of walls made of compressed earth blocks: An experimental investigation', *Journal of Building Engineering*, 38, 102148. doi: 10.1016/j.jobbe.2021.102148.

- Hema, C., Messan, A., Lawane, A. and Van Moeseke, G. (2020) 'Impact of the Design of Walls Made of Compressed Earth Blocks on the Thermal Comfort of Housing in Hot Climate', *Buildings*, 10, 157. doi: 10.3390/buildings10090157.
- Heracleous, C. and Michael, A. (2018) 'Assessment of overheating risk and the impact of natural ventilation in educational buildings of Southern Europe under current and future climatic conditions', *Energy*, 165, pp. 1228-1239. doi: 10.1016/j.energy.2018.10.051.
- van Hoof, J., Mazej, M. and Hensen, J.L.M. (2010) *Thermal comfort: research and practice*. FBL.
- Hosseinnia, S.M., Saffari, H. and Abdous, M. (2013) 'Effects of different internal designs of traditional wind towers on their thermal behavior', *Energy and Buildings*, 62, pp. 51-58. doi: 10.1016/j.enbuild.2012.10.058.
- Hughes, B. and Ghani, S. (2010) 'A numerical investigation into the effect of Windvent louvre external angle on passive stack ventilation performance', *Building and Environment*, 45, pp. 1025-1036. doi: 10.1016/j.buildenv.2009.10.010.
- Hughes, B.R., Calautit, J.K. and Ghani, S.A. (2012) 'The development of commercial wind towers for natural ventilation: A review', *Applied Energy*, 92, pp. 606-627. doi: 10.1016/j.apenergy.2011.11.066.
- Jabara, M.M.A.K. (2015) *Development of Earth Construction Techniques in Contemporary Housing: The Case of Jericho* (Master's Thesis). An-Najah National University, Faculty of Graduate Studies, Nablus, Palestine.
- Jassim, J. and Zainab, M. (2023) 'Design and Evaluation of the Performance of Wind Catcher Integration with Minaret for Passive Evaporative Cooling and Natural Ventilation', *Journal of Engineering Science and Technology*, 18, pp. 3167-3177.
- Jomehzadeh, F., Nejat, P., Calautit, J.K., Yusof, M.B.M., Zaki, S.A., Hughes, B.R. and Yazid, M.N.A.W.M. (2017) 'A review on windcatcher for passive cooling and natural ventilation in buildings, Part 1: Indoor air quality and thermal comfort assessment', *Renewable and Sustainable Energy Reviews*, 70, pp. 736-756. doi: 10.1016/j.rser.2016.12.035.
- Kakosimos, K.E. (2025) 'Indoor air quality in arid areas', *Current Opinion in Environmental Science & Health*, 45, 100610. doi: 10.1016/j.coesh.2025.100610.
- Kakoulli, C., Kyriacou, A. and Michaelides, M.P. (2022) 'A Review of Field Measurement Studies on Thermal Comfort, Indoor Air Quality and Virus Risk', *Atmosphere*, 13, 191. doi: 10.3390/atmos13020191.
- Kang, B.-K., Ha, N.-K., Wee, J.-H. and Chae, Y.-T. (2026) 'Assessment of Parameter Adequacy Based on Multi-Day Indoor Temperature Data', *Journal of The Korean Society of Living Environmental System*, 33, pp. 167-175. doi: 10.21086/ksles.2026.4.33.2.167.
- Khaled Sulaiman (2025) *Climate Information Transparency in the MENA Region* [WWW Document]. Carnegie Endowment for International Peace. Available at: <https://carnegieendowment.org/research/2025/01/climate-information-transparency-in-the-mena-region?lang=en> (accessed 1.10.26).

- Khani, S.M.R., Bahadori, M.N., Dehghani-Sanij, A. and Nourbakhsh, A. (2017) 'Performance Evaluation of a Modular Design of Wind Tower with Wetted Surfaces', *Energies*, 10, 845. doi: 10.3390/en10070845.
- Kharrufa, S.N. and Noori, F. (2022) 'A review of thermal design for buildings in hot climates', *Pertanika Journal of Science and Technology*, 30, pp. 813-839.
- Khechiba, A., Djaghroui, D., Benabbas, M., Leccese, F., Rocca, M. and Salvadori, G. (2023) 'Balancing Thermal Comfort and Energy Consumption in Residential Buildings of Desert Areas: Impact of Passive Strategies', *Sustainability*, 15, 8383. doi: 10.3390/su15108383.
- Khoshbakht, M., Gou, Z. and Zhang, F. (2019) 'A pilot study of thermal comfort in subtropical mixed-mode higher education office buildings with different change-over control strategies', *Energy and Buildings*, 196, pp. 194-205. doi: 10.1016/j.enbuild.2019.05.030.
- Kumar, S., Mathur, J., Mathur, S., Singh, M.K. and Loftness, V. (2016) 'An adaptive approach to define thermal comfort zones on psychrometric chart for naturally ventilated buildings in composite climate of India', *Building and Environment*, 109, pp. 135-153. doi: 10.1016/j.buildenv.2016.09.023.
- Lamberti, G., Leccese, F. and Salvadori, G. (2024) 'Analysis of the Interplay between Indoor Air Quality and Thermal Comfort in University Classrooms for Enhanced HVAC Control', *Energies*, 17, 5053. doi: 10.3390/en17205053.
- Lamsal, P., Bajracharya, S.B. and Rijal, H.B. (2023) 'A Review on Adaptive Thermal Comfort of Office Building for Energy-Saving Building Design', *Energies*, 16, 1524. doi: 10.3390/en16031524.
- Lawrie, L.K. and Crawley, D.B. (2026) *Development of Global Typical Meteorological Years (TMYx)* [WWW Document]. Available at: <https://climate.onebuilding.org> (Palestine EPW files: https://climate.onebuilding.org/WMO_Region_6_Europe/PSE_Palestine/index.html) (accessed 7.3.26).
- Li, J., Calautit, J., Jimenez-Bescos, C., Song, W., Riffat, S. and Chen, Q. (2025) 'Climate-adaptive windcatcher natural ventilation integrated with passive and low-energy technologies: A review of current and future developments', *Building and Environment*, 113436.
- Lopez Plazas, F. and Saenz de Tejada, C. (2024) 'Natural ventilation to improve indoor air quality (IAQ) in existing homes: The development of health-based and context-specific user guidelines', *Energy and Buildings*, 314, 114248. doi: 10.1016/j.enbuild.2024.114248.
- Ma, N., Aviv, D., Guo, H. and Braham, W.W. (2021) 'Measuring the right factors: A review of variables and models for thermal comfort and indoor air quality', *Renewable and Sustainable Energy Reviews*, 135, 110436. doi: 10.1016/j.rser.2020.110436.
- Ma, Q., Qian, G., Yu, M., Li, L. and Wei, X. (2024) 'Performance of Windcatchers in Improving Indoor Air Quality, Thermal Comfort, and Energy Efficiency: A Review', *Sustainability*, 16, 9039. doi: 10.3390/su16209039.
- Maneshi, M.M., Rezaei-Bazkiaei, A., Weber, A. and Dargush, G. (2012) 'A Numerical Investigation of Impact of Architectural and Climatic Parameters of Windcatcher Systems on Induced Ventilation', ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE). doi: 10.1115/IMECE2012-87139.

- Martinez, P., Ruiz, J., Martinez, P.J., Kaiser, A.S. and Lucas, M. (2018) 'Experimental study of the energy and exergy performance of a plastic mesh evaporative pad used in air conditioning applications', *Applied Thermal Engineering*, 138, pp. 675-685. doi: 10.1016/j.applthermaleng.2018.04.065.
- McCabe, C. and Roaf, S. (2013) 'The wind towers of Bastakiya: Assessing the role of the towers in the whole house ventilation system using dynamic thermal modelling', *Architectural Science Review*, 56, pp. 183-194. doi: 10.1080/00038628.2012.723398.
- Melo Junior, J., Bamberg, J., Machado, N., Caldas, E. and Rodrigues, M. (2019) 'Evaporative cooling efficiency of pads consisting of vegetable loofah', *Comunicata Scientiae*, 10, pp. 38-44. doi: 10.14295/cs.v10i1.2930.
- Miao, S., Gangolells, M. and Tejedor, B. (2023) 'A Comprehensive Assessment of Indoor Air Quality and Thermal Comfort in Educational Buildings in the Mediterranean Climate', *Indoor Air*, 2023, 6649829. doi: 10.1155/2023/6649829.
- Ministry of Local Government (2004) *Guidelines for Energy Efficient Building Design*. Ministry of Local Government, Palestine.
- Mohaibesh, D., Monna, S., Qadi, H. and Sokkar, R. (2021) 'Towards climate resilient residential buildings: learning from traditional typologies', in *Journal of Physics: Conference Series*. IOP Publishing, p. 012146.
- Mohammed Qasem, R.H. and Scholz, M. (2025) 'Climate change impact on resources in the MENA region: a systematic and critical review', *Physics and Chemistry of the Earth, Parts A/B/C*, 139, 103936. doi: 10.1016/j.pce.2025.103936.
- Monna, S., Juaidi, A., Abdallah, R., Albatayneh, A., Dutournie, P. and Jeguirim, M. (2021) 'Towards Sustainable Energy Retrofitting, a Simulation for Potential Energy Use Reduction in Residential Buildings in Palestine', *Energies*, 14. doi: 10.3390/en14133876.
- Montazeri, H., Blocken, B. and Hensen, J.L.M. (2015) 'Evaporative cooling by water spray systems: CFD simulation, experimental validation and sensitivity analysis', *Building and Environment*, 83, pp. 129-141. doi: 10.1016/j.buildenv.2014.03.022.
- Montazeri, H., Montazeri, F., Azizian, R. and Mostafavi, S. (2010) 'Two-sided wind catcher performance evaluation using experimental, numerical and analytical modeling', *Renewable Energy*, 35, pp. 1424-1435. doi: 10.1016/j.renene.2009.12.003.
- Morady, E., Soltani, M., Moradi Kashkooli, F., Ziabasharhagh, M., Al-Haq, A. and Nathwani, J. (2022) 'Improving Energy Efficiency by Utilizing Wetted Cellulose Pads in Passive Cooling Systems', *Energies*, 15, 369. doi: 10.3390/en15010369.
- Murtyas, S., Hagishima, A. and Kusumaningdyah, N.H. (2020) 'On-site measurement and evaluations of indoor thermal environment in low-cost dwellings of urban Kampung district', *Building and Environment*, 184, 107239. doi: 10.1016/j.buildenv.2020.107239.
- Nada, S.A., Fouda, A., Mahmoud, M.A. and Elattar, H.F. (2019) 'Experimental investigation of energy and exergy performance of a direct evaporative cooler using a new pad type', *Energy and Buildings*, 203, 109449. doi: 10.1016/j.enbuild.2019.109449.

- Noroozi, A. and Veneris, Y.S. (2018) 'Thermal Assessment of a Novel Combine Evaporative Cooling Wind Catcher', *Energies*, 11, 442. doi: 10.3390/en11020442.
- Nshimiyimana, P., Messan, A. and Courard, L. (2020) 'Physico-Mechanical and Hygro-Thermal Properties of Compressed Earth Blocks Stabilized with Industrial and Agro By-Product Binders', *Materials*, 13, 3769. doi: 10.3390/ma13173769.
- Oktay, H., Yumrutas, R. and Argunhan, Z. (2020) 'An Experimental Investigation of the Effect of Thermophysical Properties on Time Lag and Decrement Factor for Building Elements', *Gazi University Journal of Science*, 2, pp. 492-508. doi: 10.35378/gujs.615322.
- Omar Sore, S., Messan, A., Prud'homme, E., Escadeillas, G. and Tsobnang, F. (2018) 'Stabilization of compressed earth blocks (CEBs) by geopolymer binder based on local materials from Burkina Faso', *Construction and Building Materials*, 165, pp. 333-345. doi: 10.1016/j.conbuildmat.2018.01.051.
- Open-Meteo (no date) *Historical Weather API* [WWW Document]. Available at: <https://open-meteo.com/en/docs/historical-weather-api> (accessed 7.3.26).
- Ouedraogo, L., Hema, C., N'Guero, S.M., Nshimiyimana, P. and Messan, A. (2024) 'Optimisation of Thermal Comfort of Building in a Hot and Dry Tropical Climate: A Comparative Approach between Compressed Earth/Concrete Block Envelopes', *Journal of Minerals and Materials Characterization and Engineering*, 12, pp. 1-16. doi: 10.4236/jmmce.2024.121001.
- Palestinian Energy and Natural Resources Authority (PENRA) (2004) *Guidelines for Energy Efficient Building Design*. Palestinian Energy and Natural Resources Authority (PENRA), Palestine.
- Peng, Y., Lei, Y., Tekler, Z.D., Antanuri, N., Lau, S.-K. and Chong, A. (2022) 'Hybrid system controls of natural ventilation and HVAC in mixed-mode buildings: A comprehensive review', *Energy and Buildings*, 276, 112509. doi: 10.1016/j.enbuild.2022.112509.
- Ragab, A., Hassieb, M.M. and Mohamed, A.F. (2025) 'Exploring the impact of window design and ventilation strategies on air quality and thermal comfort in arid educational buildings', *Scientific Reports*, 15, 19596. doi: 10.1038/s41598-025-01362-y.
- Rana, K. (2021) 'Towards Passive Design Strategies for Improving Thermal Comfort Performance in a Naturally Ventilated Residence', *Journal of Sustainable Architecture and Civil Engineering*, 29, pp. 150-174. doi: 10.5755/j01.sace.29.2.29256.
- Rathore, P.K.S., Shukla, S.K. and Gupta, N.K. (2020) 'Yearly analysis of peak temperature, thermal amplitude, time lag and decrement factor of a building envelope in tropical climate', *Journal of Building Engineering*, 31, 101459. doi: 10.1016/j.jobbe.2020.101459.
- Rodrigues, L., Cherian, B.A. and Tokbolat, S. (2025) 'Reducing Cooling Energy Demand in Saudi Arabian Residential Buildings Using Passive Design Approaches', *Buildings*, 15, 1895. doi: 10.3390/buildings15111895.
- Ruiz, G.R. and Bandera, C.F. (2017) 'Validation of Calibrated Energy Models: Common Errors', *Energies*, 10, 1587. doi: 10.3390/en10101587.
- Saber, E.M., Chaer, I., Gillich, A. and Ekpeti, B.G. (2021) 'Review of Intelligent Control Systems for Natural Ventilation as Passive Cooling Strategy for UK Buildings and Similar Climatic Conditions', *Energies*, 14, 4388. doi: 10.3390/en14154388.

- Saif, J., Wright, A., Khattak, S. and Elfadli, K. (2021) 'Keeping Cool in the Desert: Using Wind Catchers for Improved Thermal Comfort and Indoor Air Quality at Half the Energy', *Buildings*, 11, 100. doi: 10.3390/buildings11030100.
- Sarna, I. and Ferdyn-Grygierek, J. (2025) 'Natural ventilation for thermal comfort: a simulation-based comparison of manual and automated window control strategies in temperate climate housing', *Building and Environment*, 285, 113551. doi: 10.1016/j.buildenv.2025.113551.
- Shamroukh, Y. and AbuAlZulf, E. (2023) 'Active and Passive Energy Efficiency Systems Compatible with Traditional Buildings in Palestine', in Sayigh, A. (ed.) *Mediterranean Architecture and the Green-Digital Transition: Selected Papers from the World Renewable Energy Congress Med Green Forum 2022*. Cham: Springer International Publishing, pp. 157-166. doi: 10.1007/978-3-031-33148-0_13.
- Sharaf, F. (2020) 'The impact of thermal mass on building energy consumption: A case study in Al Mafrqa city in Jordan', *Cogent Engineering*, 7, pp. 1-18. doi: 10.1080/23311916.2020.1804092.
- Sharma, A. and Sengar, N. (2019) 'Heat Gain Study of a Residential Building in Hot-Dry Climatic Zone on Basis of Three Cooling Load Methods', *European Journal of Engineering Research and Science*, 4, pp. 186-194. doi: 10.24018/ejers.2019.4.9.1508.
- Shayegani, A., Joklova, V. and Illes, J. (2024) 'Optimizing Windcatcher Designs for Effective Passive Cooling Strategies in Vienna's Urban Environment', *Buildings*, 14, 765. doi: 10.3390/buildings14030765.
- Shohan, A.A.A., Al-Khatiri, H., Bindajam, A.A. and Gadi, M.B. (2021) 'Solar Gain Influence on the Thermal and Energy Performance of Existing Mosque Buildings in the Hot-Arid Climate of Riyadh City', *Sustainability*, 13, 3332. doi: 10.3390/su13063332.
- Singh, M.K., Ooka, R., Rijal, H.B., Kumar, S. and de Dear, R. (2023) 'Adaptive thermal comfort in the offices of three climates of North-East India', *Journal of Building Engineering*, 75, 106843. doi: 10.1016/j.jobbe.2023.106843.
- Sohani, A., Zabihigivi, M., Moradi, M.H., Sayyaadi, H. and Hasani Balyani, H. (2017) 'A comprehensive performance investigation of cellulose evaporative cooling pad systems using predictive approaches', *Applied Thermal Engineering*, 110, pp. 1589-1608. doi: 10.1016/j.applthermaleng.2016.08.216.
- Song, Y., Darani, K.S., Khdair, A.I., Abu-Rumman, G. and Kalbasi, R. (2021) 'A review on conventional passive cooling methods applicable to arid and warm climates considering economic cost and efficiency analysis in resource-based cities', *Energy Reports*, 7, pp. 2784-2820. doi: 10.1016/j.egyr.2021.04.056.
- Sorgato, M.J., Melo, A.P. and Lamberts, R. (2016) 'The effect of window opening ventilation control on residential building energy consumption', *Energy and Buildings*, 133, pp. 1-13. doi: 10.1016/j.enbuild.2016.09.059.
- Soto, A., Martinez, P., Soto, V.M. and Martinez, P.J. (2021) 'Analysis of the Performance of a Passive Downdraught Evaporative Cooling System Driven by Solar Chimneys in a Residential Building by Using an Experimentally Validated TRNSYS Model', *Energies*, 14, 3486. doi: 10.3390/en14123486.

- Stasi, R., Ruggiero, F. and Berardi, U. (2024) 'Natural ventilation effectiveness in low-income housing to challenge energy poverty', *Energy and Buildings*, 304, 113836. doi: 10.1016/j.enbuild.2023.113836.
- Sun, H., Calautit, J.K. and Jimenez-Bescos, C. (2022) 'Examining the regulating impact of thermal mass on overheating, and the role of night ventilation, within different climates and future scenarios across China', *Cleaner Engineering and Technology*, 9, 100534. doi: 10.1016/j.clet.2022.100534.
- Synnefa, A., Santamouris, M. and Apostolakis, K. (2007) 'On the development, optical properties and thermal performance of cool colored coatings for the urban environment', *Solar Energy*, 81, pp. 488-497. doi: 10.1016/j.solener.2006.08.005.
- Szokolay, S.V. (2014) *Introduction to Architectural Science: The Basis of Sustainable Design*, 3rd ed. Routledge, Abingdon.
- Tariq, M.U. (2015) 'Hypothetico-deductive method: A comparative analysis', *JOBARI*, 7, pp. 228-31.
- Tejero-Gonzalez, A. and Franco-Salas, A. (2021) 'Optimal operation of evaporative cooling pads: A review', *Renewable and Sustainable Energy Reviews*, 151, 111632. doi: 10.1016/j.rser.2021.111632.
- Tina, M.Y. and Antonelli, G.F. (2013) 'Reviving Earthen Architecture in the Jordan Valley towards Adequate Housing for Marginalized Communities'. Presented at the Central Europe towards Sustainable Building 2013 (CESB13 Proceedings), Czech Technical University in Prague, Prague, pp. 1-6.
- Tognon, G., Marigo, M., De Carli, M. and Zarrella, A. (2023) 'Mechanical, natural and hybrid ventilation systems in different building types: Energy and indoor air quality analysis', *Journal of Building Engineering*, 76, 107060. doi: 10.1016/j.jobe.2023.107060.
- Toure, P.M., Dieye, Y., Gueye, P.M., Sambou, V., Bodian, S. and Tiguampo, S. (2019) 'Experimental determination of time lag and decrement factor', *Case Studies in Construction Materials*, 11, e00298. doi: 10.1016/j.cscm.2019.e00298.
- Tripathi, B.M. and Shukla, S.K. (2024) 'A comprehensive review of the thermal performance in energy efficient building envelope incorporated with phase change materials', *Journal of Energy Storage*, 79, 110128. doi: 10.1016/j.est.2023.110128.
- UNESCO (2013) *Compressed Earth Block Construction Manual*. United Nations Educational, Scientific and Cultural Organization (UNESCO), Palestine.
- UNESCO World Heritage Centre (2023) *Ancient Jericho/Tell es-Sultan* [WWW Document]. UNESCO World Heritage List. Available at: <https://whc.unesco.org/en/list/1687/>
- United Nations (2026) *Causes and Effects of Climate Change* [WWW Document]. Available at: <https://www.un.org/en/climatechange/science/causes-effects-climate-change>
- UNEP (United Nations Environment Programme), GlobalABC (Global Alliance for Buildings and Construction) (2025) *Global Status Report for Buildings and Construction 2024/2025*. United Nations Environment Programme, Nairobi.
- Verbeke, S. and Audenaert, A. (2018) 'Thermal inertia in buildings: A review of impacts across climate and building use', *Renewable and Sustainable Energy Reviews*, 82, pp. 2300-2318. doi: 10.1016/j.rser.2017.08.083.

Wakil, M., El Mghari, H., Idrissi Kaitouni, S. and El Amraoui, R. (2024) 'Thermal energy performance of compressed earth building in two different cities in Moroccan semi-arid climate', *Energy and Built Environment*, 5, pp. 800-816. doi: 10.1016/j.enbenv.2023.06.008.

Yan, M., He, S., Li, N., Huang, X., Gao, M., Xu, M., Miao, J., Lu, Y., Hooman, K., Che, J., Geng, Z. and Zhang, S. (2021) 'Experimental investigation on a novel arrangement of wet medium for evaporative cooling of air', *International Journal of Refrigeration*, 124, pp. 64-74. doi: 10.1016/j.ijrefrig.2020.12.014.

Yang, L., Fu, R., He, W., He, Q. and Liu, Y. (2020) 'Adaptive thermal comfort and climate responsive building design strategies in dry-hot and dry-cold areas: Case study in Turpan, China', *Energy and Buildings*, 209, 109678. doi: 10.1016/j.enbuild.2019.109678.

Yao, R., Li, B. and Liu, J. (2009) 'A theoretical adaptive model of thermal comfort - Adaptive Predicted Mean Vote (aPMV)', *Building and Environment*, 44, pp. 2089-2096. doi: 10.1016/j.buildenv.2009.02.014.

Yin, R.K. (2018) *Case study research and applications*. Sage, Thousand Oaks, CA.

Yu, M., Zhang, L., Fang, Q., Lin, Y. and Li, R. (2025) 'Experimental investigation on improving the efficiency and water conservation performance of a novel spray-media pad coupled evaporative cooling system', *Solar Energy*, 293, 113481. doi: 10.1016/j.solener.2025.113481.

Zein Elabdein, R., Mohamed, E., Omer, S. and Gan, G. (2018) 'Free cooling using phase change material for buildings in hot-arid climate', *International Journal of Low-Carbon Technologies*. doi: 10.1093/ijlct/cty037.

Zeng, Z., Zhang, W., Sun, K., Wei, M. and Hong, T. (2022) 'Investigation of pre-cooling as a recommended measure to improve residential buildings' thermal resilience during heat waves', *Building and Environment*, 210, 108694. doi: 10.1016/j.buildenv.2021.108694.