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THESIS

**Thermal Performance of Mechanically Fixed Stone and Porcelain Façade
Systems: A Case Study of Hebron, Palestine**

Hala Sameh Salah Nasereddin

Supervisor

Dr. Bader Alatawneh

*Thesis submitted in partial fulfillment of the requirements of the degree
Master of Architecture – Sustainable Design*

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The undersigned hereby certify that they have read, examined, and recommended to the Deanship of Graduate Studies and Scientific Research at Palestine Polytechnic University:

Thermal Performance of Mechanically Fixed Stone and Porcelain Façade Systems: A Case
Study of Hebron, Palestine

Hala Sameh Salah Nasereddin

in partial fulfillment of the requirements for the degree of Master in Architecture – Sustainable Design.

Graduate Advisory Committee:

Prof./Dr.,

(Supervisor), University (typed)

Signature:_____ Date:_____

Prof./ Dr.,

(Co-supervisor), University (typed)

Signature:_____ Date:_____

Prof./Dr.....,

(Internal committee member), University (typed).

Signature:_____ Date:_____

Prof./Dr.,

(External committee member), University (typed).

Signature:_____ Date:_____

Thesis Approved by:

Name:

Dean of Graduate Studies & Scientific Research

Palestine Polytechnic University

Signature:.....

Date:.....

Thermal Performance of Mechanically Fixed Stone and Porcelain Façade Systems: A Case Study of Hebron, Palestine

ABSTRACT

Mechanically fixed cladding systems offer a promising technological solution owing to their thermal performance and their potential to reduce building energy consumption. Recently, dry-stone and mechanically fixed porcelain cladding systems have become increasingly popular in Palestinian residential construction, primarily due to their aesthetic appeal. However, these systems remain insufficiently investigated in the Palestinian climatic context, and context-specific evidence on their effect on façade thermal performance is limited, particularly in Mediterranean climates such as Palestine. Most studies also address either the thermal bridging caused by the fixing system or building-level thermal performance, rather than the combined effect of the system components. This research aims to assess the thermal performance of mechanically fixed stone and porcelain cladding systems under local climatic conditions, examining how cladding material, insulation position, and air cavity depth affect heat transfer and thermal bridging at the component level, and further evaluating the influence on building-level performance. Field surveys, semi-structured interviews, and in situ measurements were employed to document local mechanically fixed façade construction practices in Hebron, followed by numerical simulations using COMSOL Multiphysics for thermal-bridge modeling and DesignBuilder for building-level energy analysis. A parametric framework comprising 18 wall configurations was developed to evaluate the thermal performance of these systems and determine the most thermally efficient configurations. The results show that insulation presence was the dominant variable affecting annual energy demand, reducing it by 9.5 to 16.3% at a fixed 5 cm cavity, whereas insulation position had little influence at the building scale and cavity depth acted as a secondary factor. Relative to the uninsulated reference, the best insulated configurations with a 15 cm cavity reduced annual demand by 13.8 to 23.0% across the four zones. The two cladding systems differed seasonally but balanced over the year. At the component scale, however, insulation position strongly influenced the thermal bridging penalty. The porcelain substructure increased thermal transmittance more than the stone brackets in every configuration, by approximately three times where the fixings did not penetrate the insulation, with the porcelain penalty ranging from 6.8 to 23.0% and peaking at external insulation with the 5 cm cavity.

Keywords: Mechanically fixed façade, Thermal performance, Thermal bridging, Thermal transmittance, Building energy simulation, Palestine.

الأداء الحراري لأنظمة الحجر والبورسلان المثبتة ميكانيكياً في واجهات المباني

حالة دراسية: مدينة الخليل، فلسطين

المستخلص

يلعب غلاف المبنى دوراً أساسياً في التحكم بانتقال الحرارة، ويؤثر بصورة مباشرة في الأداء الحراري وكفاءة استهلاك الطاقة في المباني. تمثل أنظمة التغطية المثبتة ميكانيكياً أحد الحلول التقنية الواعدة لما توفره من أداء حراري وإمكانات للحد من استهلاك الطاقة. لقد شهدت أنظمة تغطية الحجر والبورسلان المثبتة ميكانيكياً انتشاراً متزايداً في المباني السكنية الفلسطينية خلال السنوات الأخيرة، ويرجع ذلك بصورة رئيسية إلى قيمتها الجمالية. بينما الأداء الحراري لهذه الأنظمة ما يزال غير مدروس بصورة كافية ضمن الظروف المناخية الفلسطينية، ولا تزال الأدلة العلمية المحلية محدودة فيما يتعلق بتأثير هذه الأنظمة على الأداء الحراري للواجهات. كما ركزت معظم الدراسات السابقة إما على تأثير الجسور الحرارية الناتجة عن نظام التثبيت أو على الأداء الحراري على مستوى المبنى، دون تقييم الأثر المتكامل لجميع مكونات النظام مجتمعة. بالتالي تهدف هذه الدراسة إلى تقييم الأداء الحراري لأنظمة تغطية الحجر والبورسلان المثبتة ميكانيكياً في ظل الظروف المناخية المحلية، من خلال دراسة تأثير مادة التغطية وموضع العزل الحراري وعمق فجوة الهواء على انتقال الحرارة والجسور الحرارية، ومن ثم تقييم أثر هذه المتغيرات في الأداء الحراري على مستوى المبنى. وبهدف تحقيق ذلك تم إجراء مسوحات ميدانية ومقابلات شبه المنظمة وقياسات موقعية لتوثيق ممارسات تنفيذ أنظمة الواجهات المثبتة ميكانيكياً في مدينة الخليل والتحقق من الظروف الحرارية الفعلية للواجهات، ثم أجريت محاكاة باستخدام برنامج (COMSOL Multiphysics) لنمذجة الجسور الحرارية وبرنامج (DesignBuilder) لتحليل أداء الطاقة على مستوى المبنى، ضمن إطار دراسة بارامترية يضم ثمانية عشر تكويناً مختلفاً للجدران لتحديد أكثرها كفاءة من الناحية الحرارية. وأظهرت النتائج أن نظام تثبيت البورسلان رفع معامل الانتقال الحراري بدرجة أكبر من حوامل التثبيت الحجرية في جميع الحالات، ووصلت الزيادة إلى نحو ثلاثة أضعاف في الحالات التي لا تخترق فيها المثبتات طبقة العزل الحراري، فيما حدد موضع العزل مقدار ما يظهر من أثر هذا الجسر، حيث بلغت الزيادة في معامل الانتقال الحراري المصحح 23.0% في نظام البورسلان عند استخدام العزل الخارجي مع أقل عمق لفجوة الهواء، وانخفضت هذه الزيادة تدريجياً مع ازدياد عمق الفجوة. وعلى مستوى المبنى، اختلف أداء النظامين عن بعضهما في كل من فصلي الصيف والشتاء، إلا أن هذه الفروق الموسمية تعادلت إلى حد كبير عند تقييم الأداء السنوي. وكان وجود العزل الحراري العامل الأكثر تأثيراً في تقليل الطلب السنوي على الطاقة، إذ خفضه بنسبة تراوحت بين 9.5% و 16.3% عند عمق فجوة هواء ثابت مقداره 5 سم، في حين كان تأثير موضعه محدوداً، أما زيادة عمق الفجوة فقد حققت تحسناً إضافياً بعائد متناقص. وحققت أفضل التكوينات، المتمثلة في الجدران المعزولة مع فجوة هواء بعمق 15 سم، انخفاضاً في الطلب السنوي على الطاقة تراوح بين 13.8% و 23.0% في جميع المناطق الحرارية المدروسة مقارنةً بالحالة المرجعية غير المعزولة.

الكلمات المفتاحية: الواجهات ذات التثبيت الميكانيكي، الأداء الحراري، الجسور الحرارية، معامل الانتقال الحراري محاكاة الطاقة في المباني، فلسطين.

DECLARATION

I declare that the Master Thesis entitled “Thermal Performance of Mechanically Fixed Stone and Porcelain Façade Systems: A Case Study of Hebron, Palestine” is my own original work, and I 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.

Student Name.....

Signature:_____

Date:_____

DEDICATION

To my parents, to whom I am most grateful. This is for you, Mum and Dad. I know you are proud. To my beloved siblings, Ilham, Haya, and Mohammed, who never let me carry any of this alone. To my supportive husband, Mohammed Qawasmi, for his patience and for standing beside me through every stage of this work. To my precious daughter Rula, having you is enough to keep me going. And to my tutors and colleagues at Palestine Polytechnic University.

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List of Abbreviations

Abbreviation	Definition
ARIJ	Applied Research Institute – Jerusalem
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
B1-B	Building 1, first-floor bedroom zone
B1-L	Building 1, ground-floor living zone
B2-B	Building 2, first-floor bedroom zone
B2-L	Building 2, ground-floor living zone
CFD	Computational Fluid Dynamics
CV(RMSE)	Coefficient of Variation of the Root Mean Squared Error
FEM	Finite Element Method
GHG	Greenhouse gas
HVAC	Heating, ventilation and air conditioning
IR	Infrared
ISO	International Organization for Standardization
MBE	Mean Bias Error
MoLG	Ministry of Local Government
NMBE	Normalized Mean Bias Error
PCBS	Palestinian Central Bureau of Statistics
PVC	Polyvinyl chloride
RMSE	Root Mean Squared Error
SEAP	Sustainable Energy Action Plan
XPS	Extruded polystyrene

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Chapter 1

Introduction

Chapter 1

Introduction

1.1. Preface

In recent decades, global energy demand has increased significantly, and the residential building construction industry has contributed greatly to this trend. Following the energy crisis of the 1970s, attention shifted to alternative energy sources such as solar and wind (Taileb and Sherzad, 2024), thereby increasing worldwide recognition of the importance of energy efficiency and conservation (Mohajan, 2019). Numerous sectors have implemented new regulations and strategies to minimize energy consumption. (Abdelaziz et al., 2011). The building industry is a major source of total energy consumption and greenhouse gas emissions (Alhawari and Mukhopadhyaya, 2018).

This problem started in the late eighteenth century with the rapid industrial expansion and urbanization (Mohajan, 2019). Population growth in urban areas has led people to seek improved indoor comfort and higher living standards, resulting in increased energy consumption in buildings. (Pérez-Lombard et al., 2008). Buildings consume 30% to 40% of global primary energy and account for about half of total emissions (Taileb and Sherzad, 2024), with heating/ventilation, and air-conditioning (HVAC) systems among the largest energy consumers in the built environment (Trepici and Rodriguez-Ubinas, 2025). Across climates, 60–75% of a building's heat gains/losses occur through the envelope (Elnabawi et al., 2024). Design of façades and thermo-physical properties of its materials (U value, thermal mass, solar absorption, glazing properties) are also important for energy efficiency and comfort (Naeini et al., 2023). Various studies have shown that optimizing the envelope is the most effective passive strategy for building energy reduction (Chai and Fan, 2021; Gupta and Deb, 2023; Elnabawi et al., 2024).

As cities continue to expand, maintaining indoor thermal comfort while reducing energy consumption has become increasingly challenging. The design of a building's envelope, as the interface between the interior and exterior environments, plays a crucial role in its thermal performance by regulating heat transfer across the boundary and directly influencing energy efficiency and occupant comfort. The design of building envelopes can make a reliable change to enhance their energy performance. (Gupta and Deb, 2023)

The term 'building envelope' or 'skin' may be defined as a key element that serves as a protective barrier between the exterior and interior environments (Al-Shatnawi et al., 2024; Mohammed et al., 2024; Benachir et al., 2023), thereby allowing building occupants to inhabit a more comfortable environment. It essentially acts as "a mediator of interaction between in-ness and out-ness conditions" (Timmeren, 2009). With regard to sustainability, the building skin acts as a thermal shield, reducing reliance on mechanical systems and performing several roles that substantially affect building performance (Mohammed et al., 2024). However, façades are the primary elements of the building envelope that play various roles, substantially affecting the building's performance (Deshmukh and Yadav, 2025).

Facade design is now considered a key feature of sustainable construction systems, leading to the development of modern systems such as double-skin, green, and ventilated façades (Pastori et al., 2021). The increasing popularity of contemporary materials for façade applications provides an opportunity to improve the thermal performance of local buildings (Pastori et al., 2021); nevertheless, the lack of local research and design guidelines hinders best practice (Pastori et al., 2021). Ventilated façades should be investigated and designed to fully account for their system-level implications, thereby improving their realization (Pastori et al., 2021; Soudian and Berardi, 2022).

Despite improvements in façade and envelope technologies, some parts of buildings still struggle to maintain good thermal performance. Design flaws and material gaps often create pathways for heat to escape or enter, especially through areas around windows, doors, skylights, and connection points (Alhawari and Mukhopadhyaya, 2018) known as Thermal bridges: sections of the building envelope with very low thermal resistance caused by penetrations or breaks in insulation (Sadauskienė et al., 2020). These bridges lead to higher heating and cooling loads, trouble meeting energy standards, and uncomfortable cold spots inside. Moreover, they may cause condensation on cold surfaces, leading to dampness, mold growth, and health concerns (Alhawari and Mukhopadhyaya, 2018).

1.2. Research problem

Over the past few years, the construction sector in Palestine has shown a growing adoption of modern structural and architectural solutions, among which mechanically fixed cladding systems

have begun to appear in new residential projects. This tendency reflects an effort to develop traditional stone-based construction techniques by integrating them with mechanical fixing systems, which are assumed to enhance the thermal performance of the building envelope. However, the adoption of these systems in local practice is often due to aesthetic appeal.

Mechanically fixed cladding systems consist of several interrelated components: structural wall, thermal insulation, air cavity, fixing system, and external cladding. The thermal performance of such a system is determined by several factors, including the properties of the cladding material, the mechanical fixings and the thermal bridges they cause, the position and continuity of the insulation layer, the air cavity depth, and the surrounding climatic conditions. These factors should be investigated together, as the thermal performance of the façade is affected by the interaction of all components, not only by the properties of individual elements.

However, current construction practices in Palestine indicate that mechanically fixed cladding systems are frequently used without careful consideration of their impact on heat transfer through the building envelope. Design decisions are often made primarily from an architectural or structural perspective, whereas the system's overall thermal performance is not systematically evaluated.

The importance of this issue is highlighted by the recent use of mechanically fixed cladding systems in Palestine. There is still little practical experience regarding how these systems perform thermally. Moreover, there are no specialized local studies or clear guidelines for assessing these systems in Palestinian climate conditions. This has caused designers to depend on general assumptions or solutions from other climates. Consequently, façade systems that are believed to provide better thermal performance may not deliver their expected performance in practice. This situation highlights a clear gap between the increased use of mechanically fixed cladding systems and the limited understanding of their thermal behavior within the building envelope.

The core problem, therefore, is that mechanically fixed cladding systems are currently being used in Palestine as modern façade solutions without a clear analysis of their thermal performance as integrated building envelope systems. The absence of local evidence on how these systems behave thermally leaves designers without a basis for choosing between configurations. This gap makes it difficult to develop design solutions grounded in scientific evidence and prevents these façade systems from being configured for optimal performance.

1.3. Literature review and research gap

The assemblies examined in this study attach cladding to external walls using mechanical anchors across an air cavity. Several terms are applied to them, each naming a different aspect of the assembly. Ventilated façade refers to an airflow condition (Ibañez-Puy et al., 2017), rainscreen to a water management function (Anderson and Gill, 1988), and dry cladding to the change from mortar bedding to mechanical attachment (Camposinhos, 2014). An assembly can therefore be mechanically fixed without being ventilated.

Almost all published evidence on the thermal behavior of these assemblies was generated under ventilated conditions, and the parameters it establishes are related to a moving air cavity. Ibañez-Puy et al. (2017) reported that narrow cavities raise pressure loss and suppress flow, and that widening the gap increases flow only up to about 20 cm. Girma and Tariku (2021) measured progressively lower conductive heat gain as the cavity widened from 19 to 152 mm, the deepest cavity reducing gain by about 40% relative to the shallowest. Roig et al. (2024) concluded that the most effective summer strategy is to block energy in the outermost layers, which favors cladding with low thermal conductivity, and Lin, Song and Chu (2022) found, across twenty configurations, that summer performance was dominated by the features controlling solar radiation at the surface. Each of these parameters is defined by the behavior of moving air, so none of them transfers directly to an assembly whose cavity is closed.

Where the cavity is closed at the top and bottom, these mechanisms do not operate as described. Sanjuan et al. (2011) modeled the sealed and open-joint cases using computational fluid dynamics (CFD) and found that solar heating of the cladding establishes a closed convective loop in a sealed cavity, so that part of the absorbed heat reaches the interior by convection rather than venting outward. The open-joint case reduced summer heat gain on a south façade by about 26%. Levinskytė et al. (2019) reported that a shallower cavity weakens airflow and circulation intensity while raising the thermal resistance of the air layer itself. ISO 6946 (2017) draws the same distinction in its calculation method, assigning a fixed thermal resistance to an unventilated layer and disregarding a well-ventilated layer, along with every layer outside it. Sealed cavities appear in this literature as the reference case against which open-joint performance is measured rather than as a subject of study in their own right.

The mechanical fixing system introduces additional heat flow paths across the insulation layer. Discrete brackets and anchors constitute point thermal bridges under ISO 10211 (2017), whereas continuous rails constitute linear thermal bridges. Point bridges are nevertheless excluded from routine energy assessment, since most European member states account for linear bridges only and treat point bridges as too small and computationally demanding to include (Theodosiou et al., 2017).

The magnitude of these bridges is governed by the properties of the particular wall and fixing tested. Theodosiou et al. (2015) found the thermal resistance of the inner wall to be the dominant variable, reinforced concrete producing point thermal transmittances almost double those of clay brick for every bracket arrangement, and Alghamdi et al. (2021) reported up to 30% greater loss where fasteners were fixed into mortar joints rather than into brick. The conductivity of the subframe metal varies by an order of magnitude, from 160 W/(m·K) for aluminum to 17 W/(m·K) for stainless steel (Grauer, 2019). Fixing density produces the largest single change, with transmission heat loss rising from 54.74 W/K with no anchors to 100.67 W/K at three anchors per square meter in the wall tested by Ingeli, Gašparík and Paulovičová (2021). Šadauskienė, Ramanauskas and Vasylius (2020) found point thermal transmittance rising non-linearly with insulation thickness, adding up to 35% to the overall wall transmittance. These values have been derived primarily for aluminum, steel, and fiberglass fixing systems installed on reinforced concrete, masonry, or light steel-framed walls insulated with mineral wool. Natural stone and porcelain cladding have rarely been examined as systems in their own right, and no study in the reviewed literature has evaluated the wall assemblies and mechanically fixed configurations used in Palestinian residential construction.

The cumulative weight of these bridges is substantial. Theodosiou et al. (2015) found fixings responsible for between 5% and almost 20% of total envelope heat flow in a Thessaloniki office refurbishment, and Theodosiou et al. (2019) reported the point bridges of a cladding substructure accounting for 27% of envelope heat flow at near-zero energy insulation levels, against 7% for the junction linear bridges that conventional procedures already cover. Both figures are shares of steady-state envelope heat flow rather than of annual energy demand.

Work on mechanically fixed façades has therefore developed along two separate lines. Component-level studies quantify the point and linear bridges created by brackets, anchors, and metallic subframes through three-dimensional modeling in accordance with ISO 10211, while building-level studies evaluate annual heating and cooling demand and indoor thermal comfort using a single thermal transmittance that omits the fixing system. The few studies that carry component-scale bridges into annual simulation address office buildings (Grauer, 2019), and residential studies of comparable scope treat conventional junction bridges rather than mechanically fixed cladding (Al-Awadi, Alajmi and Abou-Ziyan, 2022). The effect of fixing-system thermal bridges on the annual energy performance and thermal comfort of residential buildings is unquantified.

Within the Palestinian context, research has addressed the thermal performance of conventional masonry wall construction and the benefits of insulation (Muhaisen, 2015; Lazzeroni et al., 2017; Al Qadi, Sodagar and Elnokaly, 2018; Haj Hussein et al., 2022). It does not extend to mechanically fixed stone or porcelain cladding, to its fixing arrangements, or to the thermal bridges introduced under Palestinian climatic conditions.

Current construction practice has also not been systematically documented, and the cladding materials, fixing systems, insulation placement, cavity depths and installation methods used in Palestine are not described in the available literature. This absence limits the applicability of published findings to locally built assemblies.

This research addresses these gaps by documenting contemporary mechanically fixed stone and porcelain cladding practice in Hebron, Palestine, quantifying the thermal bridge effect of the fixing systems at component level, integrating that effect into whole-building energy simulation, and evaluating its influence on annual energy demand and thermal comfort under local climatic conditions, from which design recommendations for the system are derived.

1.4. Research questions

After defining the research gap, the research adopts the following research question:

How do mechanically fixed stone and porcelain cladding systems perform thermally in residential buildings in Hebron, Palestine, and how is that performance affected by cladding material, insulation position, and air cavity depth?

In addition, several sub-questions were developed to guide the structure of the study:

- What are the construction characteristics of mechanically fixed cladding systems in Hebron residential buildings?
- To what extent do the mechanical fixings affect the thermal transmittance of the wall assembly, and how do the point and linear thermal bridge coefficients vary with different cladding systems, insulation position, and cavity depth?
- Which design variable has the greatest influence on the thermal performance of the mechanically fixed façade assembly: cladding material, insulation position, or air cavity depth?

1.5. Research objectives

This study aims to assess the thermal performance of mechanically fixed cladding systems in residential buildings in Hebron, Palestine, considering the thermal bridging introduced by the fixing system, with a focus on the influence of cladding material, insulation position, and cavity depth.

Accordingly, the research has the following sub-objectives:

1. To document the construction characteristics of mechanically fixed cladding systems in residential buildings in Hebron.
2. To quantify the point and linear thermal bridges introduced by the mechanical fixings, and their effect on the thermal transmittance of the wall.
3. To determine how cladding material, insulation position, and cavity depth influence the system's thermal performance, and which of the three has the greatest influence.
4. To derive design recommendations for mechanically fixed façades in Palestinian residential buildings.

1.6. Research significance

This research bridges the gap between theoretical analysis and real-world use of mechanical cladding systems. Methodologically, the study stands out by combining detailed component-level thermal modeling of mechanically fixed stone and porcelain façades with whole-building energy simulations. By connecting the thermal effects of mechanical fixation systems to the overall energy demand of buildings, this work enhances the reliability of thermal assessments for mechanical cladding façade systems. This integrated approach reduces discrepancies between predicted and actual energy performance, enabling more accurate façade design decisions.

Regionally, the study provides locally relevant knowledge for Palestine, where buildings account for most energy consumption and where climatic conditions, construction practices, and material availability differ from those assumed in many international studies. Mechanical cladding façade systems are increasingly adopted in Palestinian construction, where natural stone remains the predominant façade material; however, their thermal performance under local conditions remains insufficiently studied. By focusing on façade systems commonly used in Palestine, the research yields context-specific results and practical design insights to support more informed design decisions by architects and façade engineers.

The research also carries essential environmental and socio-economic implications. In Palestine, where energy supply is constrained and costly, reducing residential energy consumption enhances energy security and lowers household financial burdens.

Finally, the proposed design recommendations make a practical contribution. By translating analytical and simulation-based findings, the research helps bridge the gap between building physics research and everyday façade design.

1.7. Research limits and limitations

The scope of the study will be limited to the following:

- Firstly, the findings are mostly relevant to the chosen wall assemblies and façade configurations studied in this research. However, both the developed method and the

identified trends regarding thermal bridging and energy performance are generalizable and can guide the implementation of similar designs in comparable contexts.

- Second, the study is limited by the particular climatic conditions, construction techniques, and materials deployed in Palestine. These aspects can constrain the direct applicability of the quantitative results to areas with significantly different climates or construction traditions.
- Third, the research is limited to Mechanical cladding façade systems and does not extend to other façade technologies. In addition, the study focuses on thermal performance and energy consumption; other aspects are not examined and are beyond the scope of this thesis.

1.8. Research structure

This research is organized into five chapters:

Chapter 1 sets out the justification for the research in relation to building energy consumption and mechanically fixed façade systems. It presents the research problem, a brief review of the literature, and the research gap, followed by the research questions, aim and objectives, significance and limitations. The chapter closes with an overview of the research structure.

Chapter 2 establishes the theoretical background of the study. It covers heat transfer through the external walls and the quantities used to describe it, the definition and terminology of mechanically fixed façade systems, and the thermal bridges introduced by their fixings, including the parameters that govern their magnitude and the standardized methods used to quantify them.

Chapter 3 presents the research methodology. It describes the methods in detail, including the research framework chart, and explains the data collection procedure, sample selection, measurement protocol, and the variables examined.

Chapter 4 analyses the output of the simulation models. It covers the thermal performance of the studied façade configurations, the effect of thermal bridging on wall thermal transmittance, alongside the parameters that govern energy performance.

Chapter 5 concludes the research by drawing together the key findings on the performance of mechanically fixed cladding systems. It presents design-oriented recommendations for improving energy efficiency and limiting thermal bridging, and identifies directions for further research on building envelope design.

Chapter 2

Mechanically Fixed Cladding Systems: External Walls and Thermal Bridging

Chapter 2

Mechanically Fixed Cladding Systems: External Walls and Thermal Bridging

2.1 Preface

The building envelope is a primary determinant of both building energy consumption and indoor thermal comfort. While thermal transmittance is important, overall performance is also influenced by construction details. Mechanically fixed façade systems have become common in modern envelope technologies due to their architectural flexibility and associated thermal benefits. However, metallic fixing systems introduce thermal bridges, which can reduce these advantages.

This chapter establishes the theoretical basis of the study. It sets out the role of the external wall in envelope heat transfer, the mechanisms of that transfer and the quantities used to describe them, the criteria applied to energy demand and indoor thermal comfort, the definition and terminology of mechanically fixed façade systems, and thermal bridging, including its types, the parameters that determine its magnitude, and the standardized methods used to quantify it.

2.2 External Walls and Their Role in Energy Efficiency

The building envelope separates the indoor space from the outdoor environment. It consists of the external walls, roof, ground floor, and windows. All heat exchanged between a building and its surroundings crosses this boundary, so improving the envelope reduces heating and cooling loads and improves indoor conditions (Sadineni et al, 2011).

External walls are among the largest exposed surfaces on a building and account for a large share of heat transfer. Among envelope parameters, wall insulation carries the greatest weight. In passive houses across Chinese climate zones, weakening external wall insulation produced the largest increase in energy consumption of the measures tested, which also covered window insulation and airtightness (Duan et al., 2022). In high-rise residential buildings in the hot-summer, cold-winter zone, the wall heat transfer coefficient was the most sensitive of eight envelope parameters at a window-to-wall ratio of 25%, for both heating-season and annual energy use (Yu et al., 2013).

Adding insulation to an uninsulated masonry wall changes performance sharply. A hollow concrete block wall of the type used in Libyan residential construction has a thermal transmittance of $2.33 \text{ W/m}^2\text{K}$, which a single 50 mm external layer of expanded polystyrene reduces by 45% (Alfarawi et al., 2022). The same external thickness produced the largest reduction in annual cooling load among all wall measures tested for a residential typology in the hot desert climate of Al Ain (Elnabawi, Saber and Bande, 2024).

Palestinian residential construction has largely proceeded without applying any building energy code, leaving the typical stone, concrete, and block envelope uninsulated (Haj Hussein et al., 2022). Households in Hebron heat an average of 9.2% of their floor area during winter, spending between 3.5% and 21.6% of monthly income to do so, across a survey of 322 households (Al Qadi et al., 2018). Applying thermal insulation across residential building typologies in Hebron could reduce energy consumption by 29% (Lazzeroni et al., 2017), and in the cooling-dominated climate of the Gaza Strip, reducing wall transmittance to the level recommended by the Palestinian energy code reduced cooling demand by 22% (Muhaisen, 2015).

2.3 Heat Transfer Through External Walls

The thermal performance of a building envelope depends on both the climatic conditions of the site and the physical properties of its construction. Climate determines the thermal energy available at the external surface, while material properties, insulation, air cavities and assembly configuration determine how much of that energy the envelope transmits, stores or releases (Sadineni, Madala and Boehm, 2011).

Wall heat transfer is described under two regimes. Steady-state analysis assumes constant boundary temperatures and yields the thermal transmittance defined in ISO 6946 (2017), the quantity on which envelope requirements are conventionally set, including in the Palestinian code (MoLG, 2004). Periodic analysis imposes a daily temperature cycle and yields the dynamic parameters defined in ISO 13786 (2017), which describe the delay the wall imposes on that cycle. The two regimes characterize different aspects of the same assembly, and walls of equal transmittance can differ substantially in periodic response (Rossi and Rocco, 2014; Mazzeo et al, 2016).

An air layer within an assembly behaves differently according to whether it is connected to the external environment. In an enclosed layer, radiation is suppressed where low-emissivity surfaces are present, and convection is restricted by the narrow width of the cavity, so heat transfer across the layer approximates pure conduction, and the layer acts as an insulating material with a thermal resistance considerably higher than that of the surrounding solid layers (Zhang et al., 2016). In a connected layer, air circulates under buoyancy, wind pressure, or mechanical means, and the layer functions as a ventilation channel rather than as a resistance.

ISO 6946 (2017) formalizes this distinction by classifying an air layer as unventilated, slightly ventilated, or well ventilated according to the area of openings connecting it to the external environment. An unventilated layer is assigned a fixed thermal resistance and enters the resistance summation as an ordinary layer. A well-ventilated layer is disregarded, together with every layer outside it, and the external surface resistance is applied at the outer face of the layer beneath. The classification therefore determines whether the cladding and the cavity contribute to the calculated transmittance at all.

2.3.1 Heat transfer coefficient (U-value)

Thermal transmittance, or U-value, expresses the steady-state rate of heat flow through a unit area of a building element per unit temperature difference between the internal and external environments. It is obtained as the reciprocal of the total thermal resistance of the assembly, which is the sum of the resistances of the individual layers and the internal and external surface resistances (ISO 6946, 2017). Heat crosses the assembly by conduction through the solid layers and by combined convection and radiation at the surfaces and within any enclosed air spaces, all of which are represented in the resistance summation. Lower U-value values indicate lower heat flow (ISO 6946, 2017).

The influence of wall composition on energy demand has been demonstrated in the Palestinian context. Muhaisen (2015) evaluated a range of wall assemblies in the Gaza Strip and found that meeting the U-value of $1.8 \text{ W/m}^2\text{K}$ set by the local energy code, which applies to the external wall, including its windows and opaque elements, reduced combined heating and cooling energy by 22%. That limit is the most permissive among the codes it has been compared against, and

tightening the average envelope requirement to $0.85 \text{ W/m}^2\text{K}$ would cut annual heating energy by a further 44% (Çamur and Abdallah, 2021). Most existing walls do not meet even the current limit. The typical Palestinian wall, composed of stone, reinforced concrete, hollow block, and plaster, transmits approximately $2.3 \text{ W/m}^2\text{K}$ when uninsulated (Monna et al., 2021).

2.3.2 Thermal Mass

Thermal mass is the ability of a material to absorb and retain solar heat during the day, or any amount of thermal energy from a heat source, and release it through the night. The position of the mass relative to the insulation determines its effect, and placing the mass on the internal side of the insulation layer is the more effective arrangement under continuous conditioning (Stazi et al., 2015). In hot climates, optimizing the amount and position of thermal mass in insulated walls reduces annual cooling and heating loads by 17% and 35%, respectively (Al-Sanea, Zedan and Al-Hussain, 2012). The same arrangement holds in Mediterranean climates, where maximizing internal heat capacity behind an external insulation layer improves the winter indoor environment (Baglivo et al., 2014; Stazi et al., 2015).

Thermal mass is quantified by areal heat capacity. A wall with high areal heat capacity damps the amplitude of the external temperature swing before it reaches the internal surface and delays the peak by several hours. ISO 13786 (2017) defines the parameters that describe this behavior under periodic conditions, including periodic thermal transmittance and areal heat capacity.

2.4 Energy consumption and Thermal comfort

Buildings account for between 30 and 40% of world primary energy consumption, with national shares ranging from around a quarter to a half depending on climate, building stock, and construction practice (Zhang et al., 2016). Of the energy consumed within a building for heating and cooling, between 20 and 50% is attributable to the envelope, which forms the interface across which heat is gained and lost. The thermal performance of the external wall therefore governs a substantial part of the energy required to maintain acceptable indoor conditions.

Indoor thermal comfort and energy demand also depend on decisions taken at the design stage. At building scale, these include orientation, built form and the thermal properties of the envelope,

which act together rather than independently, so thermal performance follows from their combined configuration rather than from any single parameter (Oral and Yilmaz, 2002). Among the envelope properties, thermal transmittance determines the steady-state rate of heat flow, thermal mass governs how the assembly stores and releases heat over the daily cycle, and the ratio of external envelope area to enclosed volume sets how much surface is available for that exchange relative to the space being conditioned.

The Palestinian building sector's construction techniques have changed significantly in recent decades; modern techniques, such as reinforced concrete and stone cladding, have become widely used in Palestine. These practices have led to lower thermal comfort in the indoor environment of modern buildings due to certain thermal properties of the building's envelope, resulting in greater heating and cooling burdens and increased energy consumption (Mohaibesh et al., 2021). More than 70% of residential buildings in Palestinian cities use the same external wall, an outer layer of natural stone over reinforced or backfill concrete, backed by hollow block and internal cement plaster (Haj Hussein et al., 2021). Free-running monitoring in Nablus recorded traditional houses 1 to 5°C warmer than modern ones in winter and 1 to 3°C cooler in summer, and simulation of the same pair returned 53% less heating and 76% less cooling energy for the traditional house in the mountain climate zone (Mohaibesh et al., 2021).

2.5 Mechanically Fixed Façade Systems

A mechanically fixed façade attaches the cladding to the external wall through anchor points rather than mortar or adhesive, with a metal sub-frame spanning an air cavity to transfer loads back to the wall (Pizzatto et al., 2025). This section defines the system, sets out the terminology used for it, and describes its thermal behavior.

2.5.1 Definition and Terminology

A mechanically fixed façade is a cladding assembly attached to the external wall through mechanical anchor points rather than mortar or adhesive, using non-adhered industrialized components (Pizzatto et al., 2025). The cladding becomes the weathering skin; the wall behind it carries the load, and an air space separates the two. The build-up runs from the structural wall through the air cavity to the cladding panels, with a metal subframe of brackets and rails crossing

the cavity to carry the panels back to the wall. Most systems include thermal insulation, and the reviewed literature documents it on the outer face of the backing wall, so that it sits inside the cavity through which the subframe passes (Ibañez-Puy et al., 2017). The brackets and rails therefore pass through the insulation and connect the cladding back to the structural wall, interrupting the insulation layer at every fixing point (Theodosiou et al., 2017).

Several names circulate for this family of assemblies, and they do not map cleanly onto one another. Ventilated façade refers to an airflow condition: the rear cavity is opened at the top and bottom so that air rises behind the cladding. Opaque ventilated façade narrows the same idea to non-glazed claddings (Ibañez-Puy et al., 2017). Rainscreen names a water-management function instead. The outer skin is exposed to rain and wind, and the cavity behind it drains water and controls the pressure difference across the panel. Anderson and Gill (1988) distinguish between the drained and back-ventilated rain screen and the pressure-equalized rain screen on this basis. Dry-hung, dry-fixed, and dry cladding are terms used mainly for stone. They refer to the change from mortar bedding to mechanical attachment (Camposinhos, 2014). A dry-hanging stone curtain wall consists of an inner load-bearing wall, an outer stone panel, metal connectors, and an air layer between the two. The stone panels are fixed to metal frames, which are in turn anchored to the load-bearing wall, so that the panels are carried mechanically rather than bedded in mortar (Zhang et al., 2016).

2.5.2 Thermal Performance of Mechanically Fixed Façades

The thermal behavior of a mechanically fixed façade depends first on the condition of its cavity. Where the cavity is opened at top and bottom, buoyancy drives air upward behind the cladding and removes part of the absorbed solar heat before it reaches the wall. Where the cavity is closed, solar heating of the cladding establishes a closed convective loop within it, so part of the absorbed heat reaches the interior by convection rather than venting outward, and an open-joint arrangement reduces summer heat gain on a south façade by about 26% relative to a sealed one (Sanjuan et al., 2011). A closed cavity therefore behaves as a layer of fixed thermal resistance and can be represented within a steady-state calculation, while a ventilated cavity cannot.

Cavity depth governs the airflow within a ventilated cavity and the resistance of the air layer within a closed one. A narrow gap increases pressure loss and suppresses flow, so the cavity runs hotter, while widening it increases flow only up to about 20 cm, beyond which the ventilation rate falls again. The cooling effect begins to appear for cavities wider than 7 cm, peaks between 20 and 30 cm, and stabilizes at 35 cm, values obtained from a mathematical model of a façade in the cooling-dominated climate of Florence (Ibañez-Puy et al., 2017). Conductive heat gain falls progressively as cavity depth increases from 19 mm to 152 mm, the deepest cavity reducing gain by about 40% relative to the shallowest, measured in the moderate marine climate of Burnaby, Canada (Girma and Tariku, 2021).

Cladding material acts through two independent properties, solar absorptance at the external surface and thermal inertia. Absorptance is set by the surface albedo, defined as the ratio of shortwave radiation reflected by a surface to the shortwave radiation incident on it across the full solar spectrum, expressed on a scale from 0 to 1 (Oke et al., 2017). Albedo depends on the colour and finish of the panel rather than its composition, so light stone and light porcelain reflect a larger share of incident radiation and reach lower surface temperatures than dark panels of the same material (Ibañez-Puy et al., 2017). Thermal inertia is the capacity of a construction to absorb, store and release heat over time, which damps the amplitude of an external temperature swing and delays its arrival at the internal surface. It is governed by the density, specific heat capacity and thermal conductivity of each layer and is expressed in dynamic terms through decrement factor and time lag (ISO 13786, 2017; Verbeke and Audenaert, 2018). A large share of the final performance is attributable to the combined thermal resistance and thermal inertia of the cladding and the wall behind it, and the most effective summer strategy is to block energy in the outermost layers, which favours cladding of low thermal conductivity (Roig et al., 2024). Across twenty configurations of an opaque ventilated façade, summer performance was dominated by the features controlling solar radiation at the external surface (Lin, Song and Chu, 2022).

Insulation placement determines where within the assembly heat flow is interrupted rather than the total resistance of the assembly. Two walls with an identical U-value can behave differently under dynamic conditions, because steady-state resistance describes the total transmitted energy while placement controls the timing and amplitude of that transmission (Haj Hussein et al., 2021). Moving the insulation outward increases time lag and reduces the decrement factor, since the

massive layer is then coupled to the indoor environment and stores heat released by the interior rather than heat driven by the external cycle (Ozel, 2014; Zhang et al., 2016). Internal insulation produces the opposite effect. The mass is exposed to the outdoor swing, and the internal surface responds quickly to peak external temperature, which raises the cooling load in hot periods (Al-Sanea, Zedan and Al-Hussain, 2012). The effect is amplified where external surface absorptance is high, as a larger absorbed flux reaches the mass before any resistance is encountered (Mazzeo, Oliveti and Arcuri, 2016; Lin, Song and Chu, 2022). In a ventilated façade, the cavity adds a second control, because the ventilated air layer removes part of the absorbed heat before it reaches the insulation and shields the insulation from direct radiation (Ibañez-Puy et al., 2017).

Under summer conditions, performance is therefore highest when heat flow is reduced in the outer layers, which places the insulation on the exterior face of the backing wall, behind the cavity (Roig et al., 2024). Experimental work supports this arrangement. In a full-scale opaque ventilated façade monitored across a complete cooling season, the ventilated cavity removed a measurable share of the absorbed solar gain and lowered the heat flux relative to an equivalent non-ventilated reference, with the driving variable being the temperature of the outer skin rather than the resistance of the wall as a whole (Salvalai et al., 2026). A comparison of an open-joint ventilated façade with an equivalent sealed cavity façade found lower transmitted energy for the ventilated case under summer conditions, confirming that the cavity acts as a thermal buffer rather than a purely constructive layer (Sanjuan et al., 2011). The benefit is conditional on the cavity being able to sustain buoyancy-driven flow, since restricted openings suppress the extraction of heat and reduce the façade to a conventional insulated wall (Pastori et al., 2021; Karanafti and Theodosiou, 2024).

Placing the insulation immediately behind the cavity keeps this buffered zone continuous. The insulation receives air already partly cooled by the flow, and the backing wall is left on the internal side of the resistance where its mass can damp the residual swing (Stazi et al., 2020). Parametric studies of insulated walls in hot summer and Mediterranean climates report the same ranking, with external placement giving the longest time lag and the lowest decrement factor for a fixed insulation thickness (Ozel, 2014; Stazi et al., 2015).

2.6 Thermal Bridging

The metal sub-frame that carries the cladding penetrates the insulation and reaches the structural wall, forming a thermal bridge as defined in ISO 10211 (2017). This section covers the types of thermal bridge, how they arise in mechanically fixed façades, the parameters that govern their magnitude, and the methods used to evaluate them.

2.6.1 Definition and Types of Thermal Bridges

ISO 10211 (2017) defines a thermal bridge as ‘part of the building envelope where the otherwise uniform thermal resistance is significantly changed by full or partial penetration of the building envelope by materials with a different thermal conductivity, and/or a change in thickness of the fabric, and/or a difference between internal and external areas, such as occur at wall/floor/ceiling junctions.’

ISO 10211 (2017) distinguishes between linear and point thermal bridges based on how their additional heat flow is presented. A linear thermal bridge, such as a junction between wall and slab or wall and roof, has a uniform cross-section along one axis and is quantified by the linear thermal transmittance ψ (W/mK). A point thermal bridge is a localized thermal bridge whose influence can be represented by a point thermal transmittance χ (W/K), such as that of isolated fasteners, brackets, and anchors.

2.6.2 Thermal Bridges in Mechanically Fixed Façades

A mechanically fixed façade transfers the self-weight and wind loading of the cladding back to the structural wall through a metallic substructure. The configuration follows from that requirement: steel wall fasteners anchored into a solid inner wall, distributed on a regular grid vertically and horizontally, carrying an aluminum mullion to which the cladding panels attach (Theodosiou et al., 2015). The same components recur across fastening systems, comprising the brackets that punctuate the wall build-up and the anchors and dowels that hold those brackets in place (Petresevics and Nagy, 2022). Described layer by layer, the assembly consists of a supporting structure, a thermal insulation layer, a supporting grid, an air gap, and a cladding layer, with the grid mechanically anchored back through the insulation (Ingeli, Gašparík and Paulovičová, 2021).

The junction of the metal bracket and the external solid wall is the weakest part of the assembly in thermal terms. Heat flow there separates into two components: direct contact between the bracket footprint and the wall face, and conduction through the anchors that penetrate the wall itself (Theodosiou et al., 2015).

2.6.3 Parameters Affecting Thermal Bridge Magnitude

Substrate wall material. The thermal resistance of the inner wall is the dominant variable, since heat flow bypasses the insulation layer through the bracket and reaches the interior through the wall. Across a range of 0.2 to 2.4 W/(m·K), reinforced concrete produces point transmittances almost double those of clay brick for every bracket arrangement (Theodosiou et al., 2015). Loss increases by up to 30% where fasteners are fixed into mortar joints rather than into brick (Alghamdi et al., 2021), and anchoring elements contribute substantially less to total heat loss in masonry walls of conductivity 0.15 to 0.30 W/(m·K) (Ingeli, Gašparík and Paulovičová, 2021).

Fixing material. The conductivity of the subframe metal varies by an order of magnitude, from 160 W/(m·K) for aluminum to 50 W/(m·K) for steel and 17 W/(m·K) for stainless steel (Grauer, 2019). With 300 mm of expanded polystyrene and 2.78 connectors per square meter, the correction to wall transmittance was 0.111 W/(m²·K) for aluminum alloy connectors, 0.021 W/(m²·K) for stainless steel, and effectively zero for glass-fiber-reinforced plastic at 0.23 W/(m·K), while the intensity of heat flow through an aluminum connector was almost four times that through a stainless steel one (Levinskytė et al., 2019). Aluminum therefore produces substantially greater thermal bridging than stainless steel or fiber-reinforced polymer connectors.

Insulation thickness. The effect of insulation thickness on point thermal bridges is contested, because it depends on the thermal properties of the substrate wall. Point thermal transmittance increases nonlinearly with insulation thickness, adding up to 35% to the overall wall transmittance (Šadauskienė, Ramanauskas and Vasylius, 2020). The direction of the response, however, depends on the supporting wall, since thicker insulation raises point transmittance where the wall itself has some insulating capacity but lowers it over highly conductive substrates (Theodosiou, Tsikaloudaki and Bikas, 2017). Two mechanisms pull against each other. Thicker insulation lengthens the bracket and extends the heat-flow path through the metal, while reducing heat

transfer through the surrounding wall. The net sensitivity is weak, with the point transmittance contribution remaining between 7.5% and 9.8% of the wall U-value across a wide range of insulation thicknesses (Theodosiou et al., 2015).

Bracket geometry and density. Bracket form has a modest effect. At one bracket per square meter and no thermal break, point transmittance reaches 9.4% of the wall U-value for an L-shaped bracket with a single anchor and 9.9% for a T-shaped bracket with two anchors (Theodosiou et al., 2015). Within the fastener itself, length has more influence than diameter (Alghamdi et al., 2021). Fixing density produces the largest change. In a reinforced concrete wall insulated with mineral wool, heat transmission loss rises from 54.74 W/K with no anchors to 70.16 W/K at one anchor per square meter, 87.46 W/K at two, and 100.67 W/K at three, an increase of 83.9% over the unanchored case (Ingeli, Gašparík and Paulovičová, 2021).

Thermal breaks. A 6 mm PVC pad reduces point thermal transmittance from 9.4% to 7.2% of the wall U-value for an L-shaped bracket and from 9.9% to 7.1% for a T-shaped bracket, an influence limited compared with other design parameters (Theodosiou et al., 2015). The limit is structural, since load-bearing requirements restrict insulating pads to a conductivity of about 1 W/(m·K) and a thickness of about 6 mm (Theodosiou, Tsikaloudaki and Bikas, 2017). A thermal break pad interrupts the bracket-to-wall interface, while the anchors themselves remain continuous through it.

Reported reductions range from 2 to 28% across different fastening systems, against differences of up to 70% arising from bracket material and geometry (Petresevics and Nagy, 2022). The difference between conventional and plastic-coated insulating pads is 1.29% (Ingeli, Gašparík and Paulovičová, 2021), and inserting a low-conductivity spacer between the subframe and sheathing leaves the equivalent U-value unchanged at 0.701 W/m²K, since the conductive path through the subframe, fasteners, and structural framing is not interrupted (Grauer, 2019).

2.6.4 Evaluation of Thermal Bridges in Mechanically Fixed Façade Systems and Their Reported Impact

Point thermal bridges are evaluated under ISO 10211 (2017), which specifies the modeling rules, the boundary conditions, and the discretization accuracy required for two-dimensional and three-

dimensional calculation, and obtains the point thermal transmittance by subtracting the one-dimensional and linear contributions from the thermal coupling coefficient of the three-dimensional calculation (Theodosiou et al., 2019). A detailed method is therefore available, but point bridges are still excluded from routine energy assessment, since most European member states account only for linear thermal bridges and treat point bridges as too small and computationally demanding to include (Theodosiou et al., 2017).

Evaluation is carried out as three-dimensional finite element modeling under steady-state conditions, in general-purpose numerical codes rather than in building simulation tools, using Abaqus (Theodosiou et al., 2015), ANSYS Workbench (Theodosiou, Tsikaloudaki and Bikas, 2017), or COMSOL Multiphysics (Theodosiou et al., 2019; Petreševics and Nagy, 2022). The same class of method applies to other heterogeneous assemblies, and has been used with the finite volume code Ansys Fluent, with the geometry built in Gambit, for a heterogeneous roof detail rather than a cladding fixing (Ascione et al., 2012).

The procedure is largely standard. A representative cell containing one fixing is cut from the façade and bounded by adiabatic planes on grounds of thermal symmetry, sized so that heat flow at the boundaries has returned to one dimension. Cell size is settled by testing rather than assumption. A cell of 0.70 by 0.70 m produces no significant change in point transmittance above 0.60 by 0.60 m (Theodosiou et al., 2015), a cell of 1 m² is sufficient where the computed heat flux vectors confirm that the field reverts to one dimension within 25 to 30 cm of the bracket in the vertical direction (Petreševics and Nagy, 2022), and a 4 m² area encloses the entire area affected by the bridge under ISO 10211 (Theodosiou et al., 2019).

Internal and external temperatures of 20 °C and 0 °C are commonly imposed. Under linear steady-state conduction with constant material properties, changing the temperature difference scales the heat flow proportionally and leaves the calculated point thermal transmittance unaltered (Theodosiou et al., 2015). Mesh density is fixed by convergence testing against the ISO 10211 discretization criterion, with refinement concentrated at the bracket and the anchor where geometry is most complex and material contrast greatest. Reported meshes run from 100,000 to 140,000 elements at a discretization error below 1% (Theodosiou et al., 2015) to an average of about 150,000 tetrahedral elements (Theodosiou et al., 2017), with 137,598 and 141,550 tetrahedra for

half-height and full-height brackets at 10 cm insulation thickness (Theodosiou et al., 2019). Element counts are not comparable between these studies because they depend on geometry, element order, and meshing method. The sensitivity is direct: the coarsest automatic mesh departs from the finest by 20%, while a moderately refined mesh of 375,266 elements closes the deviation to 1.33% (Petresevics and Nagy, 2022). A grid is acceptable once the change in computed heat flow falls below 2% (Ascione et al., 2012).

Air cavities are treated as unventilated and entered as a thermal resistance under ISO 6946 instead of resolved as a flow domain, because cavity air velocity is driven by wind, solar gain, temperature variation, stack effect, and geometry, and no general result can be transferred from it into the steady-state framework that the insulation standards and national codes apply (Theodosiou et al., 2015). The steady-state restriction rests on comparability, since transient methods for three-dimensional bridges are less well established, and steady-state results reflect how insulation protection is specified and therefore remain directly comparable to regulatory transmittance requirements (Theodosiou et al., 2019).

The magnitude of these bridges at building scale can exceed that of the linear bridges conventional calculation procedures already include. In the refurbishment of a Thessaloniki office building of 508 m² per story, requiring almost 9,000 brackets at a maximum spacing of 0.70 m, fixings were responsible for between 5% and almost 20% of total envelope heat flow, up to 200% more than the linear bridges (Theodosiou et al., 2015). For an aluminum sub-frame on the same building form, point bridges contributed 22% of envelope heat flow under moderate insulation requirements and 27% under a near-zero energy specification, against 5% and 7% for the linear bridges (Theodosiou et al., 2019). Both figures are shares of steady-state heat flow rather than of annual energy demand.

Building simulation programs solve conduction in one dimension, so detailed results reach them only through a conversion, and that conversion carries its own error. Working without one carries a higher cost. The same roof detail modeled as a simplified equivalent layer, as a series and parallel discretization, and by numerical calculation gave U-values of 2.07, 1.66, and 1.63 W/m²K for one structure and 2.12, 1.78, and 1.70 W/m²K for another, a spread of 24 to 28% that passed directly into simulated energy demand (Ascione et al., 2012).

Two conversions are available, and both have been compared against direct three-dimensional dynamic modelling in WUFI Plus (Ge and Baba, 2015). The equivalent U-value method adjusts a sub-surface until the assembly matches the effective steady-state transmittance taken from the detailed model. The original material arrangement stays in place, so resistance is corrected but the heat capacity added by the bridge is not. The assembly then carries the right total energy with the wrong time lag and decrement factor, which displaces the peak heat flow. It understated annual heating demand by 13% in the cold-climate case and annual cooling demand by 17% in the hot-climate case, the larger cooling error reflecting the dependence of cooling load on peak flux rather than seasonal mean. The equivalent wall method substitutes a one-dimensional, three-layer wall derived from the structure factors and heat capacity of the detail, reproducing its dynamic behavior as well as its resistance. It underestimates the same loads by 9% and 14%. The gap between the conversions and direct modelling narrows as insulation improves and connection details are refined.

The equivalent wall conversion has been applied in a COMSOL to EnergyPlus coupling, replacing each two-dimensional junction bridge with a fictitious three-layer one-dimensional wall matched on thermal resistance, heat capacity, and structure factors, then combining the bridged and clear wall areas into a single equivalent transmittance calculated separately for the ground, intermediate, and top floors (Al-Awadi, Alajmi and Abou-Ziyan, 2022). The bridged transmittance of the external wall exceeded the clear-wall value by 10% to 106%, depending on the wall type.

2.7 Summary

The external wall carries a large share of envelope heat transfer, and sensitivity studies across several climates rank wall transmittance among the most influential envelope parameters. Transmittance and periodic response describe different properties of the same assembly, so two walls of equal U-value can behave differently over the daily cycle. Palestinian residential construction has largely proceeded without the building energy code, which leaves the usual stone, concrete, and block envelope uninsulated. Insulating it cuts energy consumption by 29% across Hebron building typologies.

Terminology for mechanically fixed façade systems is inconsistent. Ventilated façade refers to an airflow condition, rainscreen to water management, and dry cladding to the method of attachment. The three conditions do not necessarily occur together. The condition of the cavity governs the behavior of the assembly, since a ventilated cavity removes part of the absorbed solar heat before it reaches the wall, while a sealed cavity acts as a layer of fixed thermal resistance under ISO 6946. Cavity depth, cladding material, and insulation position each alter performance.

The metallic substructure crosses the insulation, forming point thermal bridges where brackets and anchors are discrete and linear thermal bridges where rails are continuous. Their magnitude depends first on the thermal resistance of the substrate wall, then on fixing material, fixing density, and bracket geometry. Assessment requires three-dimensional finite element modeling in accordance with ISO 10211, and transferring the results to dynamic simulation requires a further conversion that alters the predicted loads. In the reported case study building, the point bridges of the cladding substructure account for 27% of envelope heat flow at near-zero-energy insulation levels, compared with 7% for the junction linear bridges that conventional procedures already cover.

Chapter 3

Methodology

Chapter 3

Methodology

3.1 Research Type

This research employs a quantitative, applied methodology to evaluate the thermal performance of mechanically fixed façade systems in residential buildings under the climatic conditions of Hebron, Palestine. The research assesses the thermal performance of the investigated façade systems using measurable performance indicators, including corrected thermal transmittance, point and linear thermal bridge coefficients, annual heating and cooling loads, operative temperature, and occupied discomfort hours.

To obtain these indicators, the research employs a comparative, simulation-based methodology that combines finite element modeling in COMSOL Multiphysics to evaluate thermal transmittance and thermal bridge effects at the component level, with whole-building energy simulation in DesignBuilder using the EnergyPlus engine to assess annual energy demand and indoor thermal performance. The component-level results feed directly into the building-level model, so that the consequences of thermal bridging are carried through both scales.

3.2 Study Area Selection

Hebron was selected as the study area based on its climatic setting, the presence of the façade construction system investigated in this research, and the feasibility of accessing relevant construction projects.

Hebron is located in the southern highlands of Palestine at an elevation of approximately 943 m above sea level. It has a Mediterranean climate, with cold and wet winters and warm, dry summers. Under the Köppen-Geiger classification, Hebron falls within the Csa climate type, which represents a hot-summer Mediterranean climate. The same climate classification also applies to other Palestinian highland cities, including Ramallah, Bethlehem, Jerusalem and Nablus (Peel, Finlayson and McMahon, 2007). According to the Palestinian Guidelines for Energy Efficient Building Design, Hebron, Ramallah, Bethlehem, Jerusalem and Nablus belong to the fourth climatic zone of the West Bank, which represents the highland climatic conditions (MoLG, 2004).

Accordingly, Hebron can be considered representative of the highland climatic conditions prevailing in these cities. This climatic setting makes Hebron relevant for examining the thermal performance of building envelope systems under highland conditions, particularly where winter heating requirements are an important part of building energy demand.

The second consideration was the presence of the construction system investigated in this research. The system is used in Hebron, while the same method of façade fixing is also applied in other Palestinian highland cities, including Ramallah and Bethlehem. This wider use indicates that the system is not limited to Hebron and forms part of the construction practices used in Palestinian highland areas. Therefore, Hebron was selected as a case study for examining this construction method within its local climatic and construction context.

The third consideration was the feasibility of accessing suitable construction projects. Direct access was important to document the façade assembly, examine the fixing method, and carry out the required field measurements. Hebron provided access to projects during the construction stage. Access to comparable projects in other Palestinian cities was more difficult because of movement restrictions between governorates, limiting repeated visits to construction projects. The availability of suitable projects and practical access to them therefore supported the selection of Hebron as the study area.

Overall, Hebron provides a suitable case study context because it combines highland climatic conditions with the presence of the façade system under investigation and feasible access to relevant construction projects. The selection was therefore based on the compatibility of the location with the research objectives and field requirements.

3.3 Sample Selection

Residential buildings were selected as the building type investigated in this research. The residential sector is the largest energy consumer in Palestine, based on the Sustainable Energy Action Plan (SEAP, 2016) for Hebron, residential buildings account for 43% of total energy use and 38% of annual GHG emissions, underscoring their significance for energy performance research, and most residential buildings in Hebron suffer from poor thermal insulation, increasing reliance on heating and cooling systems, and raising household energy consumption. Palestinians

may spend 3.5%–21.6% of their monthly income on heating less than 10% of their dwelling area in winter (Al Qadi et al., 2018). Investigating the thermal performance of mechanically clad residential buildings, therefore, addresses both the newest application of the technology and the sector where energy savings matter most.

A field survey of engineering offices was conducted from 20 February to 5 May 2026 to determine the number of relevant projects. The official register of licensed engineering offices, obtained from the Engineers Association, Jerusalem Center, Hebron Branch, was used to establish the sampling frame. The register listed 174 engineering offices across Hebron Governorate. Since the study focuses on construction practices within Hebron city, offices outside the city boundary were excluded, resulting in a total of 127 offices. A total of 61 engineering offices were reached, representing 48% of the 127 total registered offices. Of these, 44 offices were engaged through direct telephone inquiry. To extend coverage beyond, site visits were then conducted using a stratified selection approach: the city was divided into main areas, and within each area, a number of the remaining unreached offices were selected. This resulted in 17 offices being visited across eight areas, ensuring even coverage throughout the city. Figure 3-1 illustrates the locations of the visited offices.

The survey identified seven residential projects in Hebron using mechanically fixed cladding systems, and these formed the population from which the case study buildings were selected. The selection sequence is summarized in

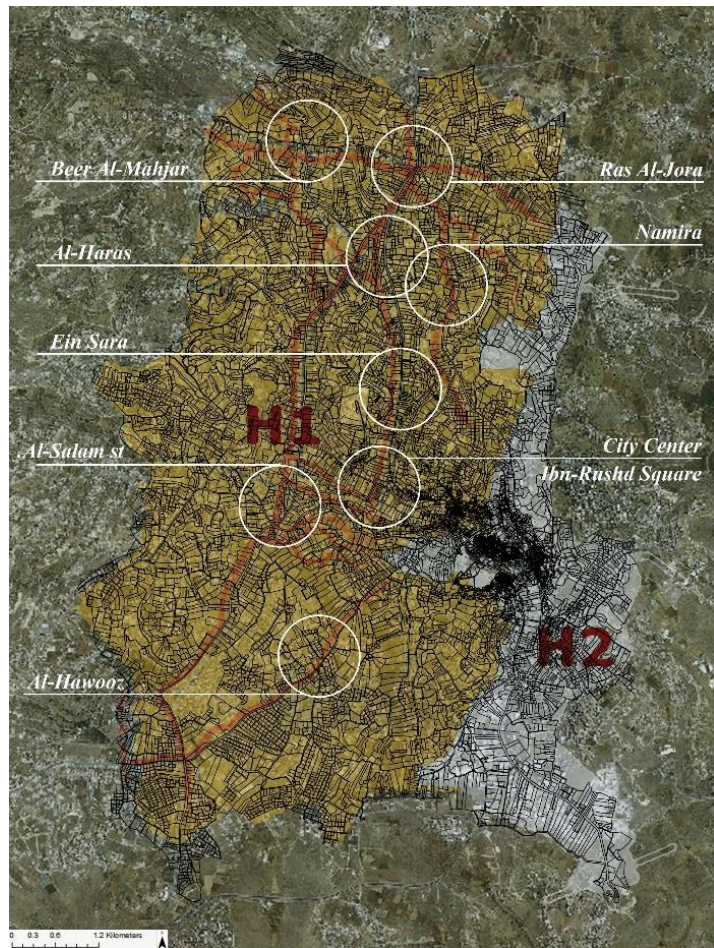


Figure 3-1: Geographical distribution of the engineering offices selected for site visits across the main areas of Hebron city (Google Earth Pro, 2026, with researcher edits)

Figure 3-2. Selection of case study buildings was based on the following criteria:

1. The façade employs a mechanically fixed cladding system.
2. Construction has been completed, ensuring that the façade system is fully operational.
3. The building is occupied under normal operating conditions.
4. The building is accessible for field measurements and instrumentation.

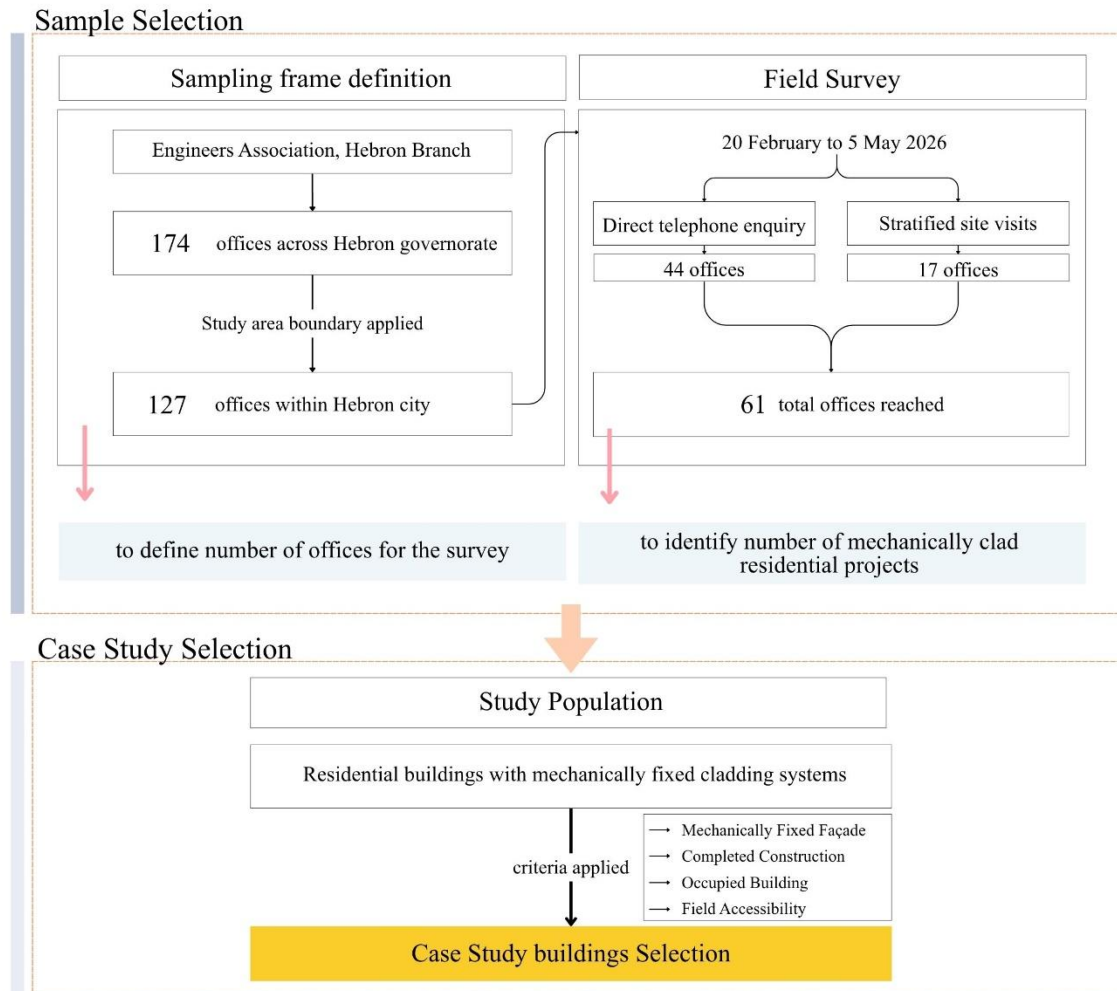


Figure 3-2: Sample and case study selection workflow

3.4 Data collection

Data were collected through three methods: site visits and building documentation, semi-structured interviews, and field measurements. The data collection methods are shown in Figure 3-3.

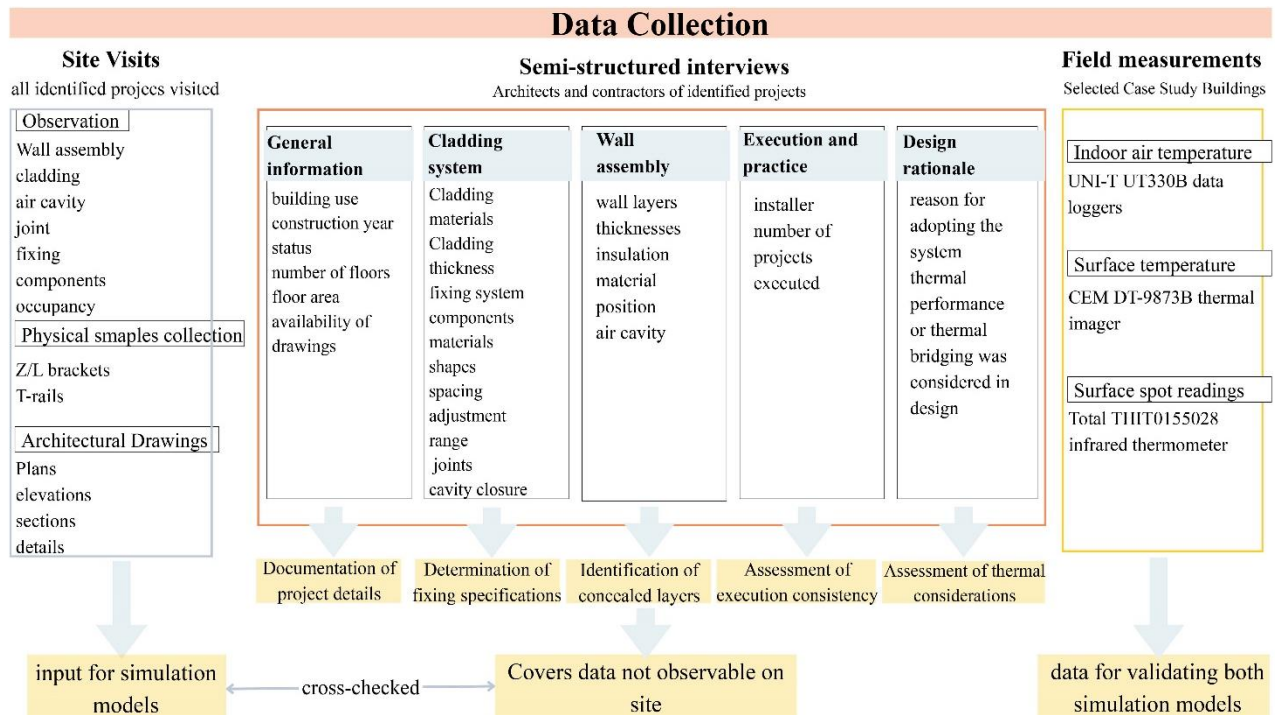


Figure 3-3: Data collection process

Site visits and building documentation covered all identified projects and recorded the construction of the mechanically fixed façade systems in Hebron. For each building, data were collected through direct observation of the wall assembly and its layers, the cladding material and thickness, the air cavity and its closure conditions, the panel joints, and the components of the mechanical fixing system in place. Physical samples of the fixing components, comprising a Z-bracket, an L-bracket, and a T-rail, were obtained, and their dimensions were measured and used as geometric input to the component-level model. During the visits, the complete architectural drawings of the documented buildings, including floor plans, elevations, and construction details, were obtained from the responsible architectural offices, together with records of materials, construction year, and occupancy. These data were collected to define realistic wall configurations for the simulation study, to identify the fixing details that contribute to thermal bridging, and to reproduce the building geometry, thermal zones, construction assemblies, and operational conditions in the building-level simulation model.

Semi-structured interviews were conducted with the architects and contractors responsible for the projects under review. The interviews were structured into five parts:

- The first part collected general information on each building, including its use, construction year, status, number of floors, floor areas, and the availability of drawings.
- The second part addressed the cladding system, covering the cladding materials and thicknesses; the fixing system type, its components, and their materials, shapes, and spacing; the bracket adjustment range; the sourcing of the components; the panel joints; and the cavity closure conditions.
- The third part covered the wall assembly, including the wall layers and their thicknesses; the insulation material, thickness, and position; the air cavity depth and the basis for its selection; and whether waterproofing was applied.
- The fourth part addressed execution and practice, identifying the installer and the number of projects executed with the system in Hebron.
- The fifth part examined the design rationale, namely the reason for adopting the system and whether thermal performance or thermal bridging was considered in the façade design.

The interviews covered, in particular, information not accessible to direct observation, such as the concealed wall layers, the insulation, and the design rationale. Where the same information was available from multiple sources, the interview responses, site observations, and architectural drawings were cross-checked, providing methodological triangulation of the collected data. The full list of interview questions is provided in Appendix A. These data were collected to characterize the construction practice of mechanically fixed façades in Hebron and to inform the definition of the fixed and variable parameters for the simulation study.

Field measurements, including indoor air temperature and surface temperatures, were taken to provide reference data for validating both simulation models. Indoor air temperature was logged using UNI-T UT330B data loggers. Surface temperatures were measured on a stone-clad wall by infrared thermography with a CEM DT-9873B thermal imager and by infrared spot readings with a Total THIT0155028 infrared thermometer. The instruments are shown in Figure 3-4, and their datasheets are provided in Appendix B.

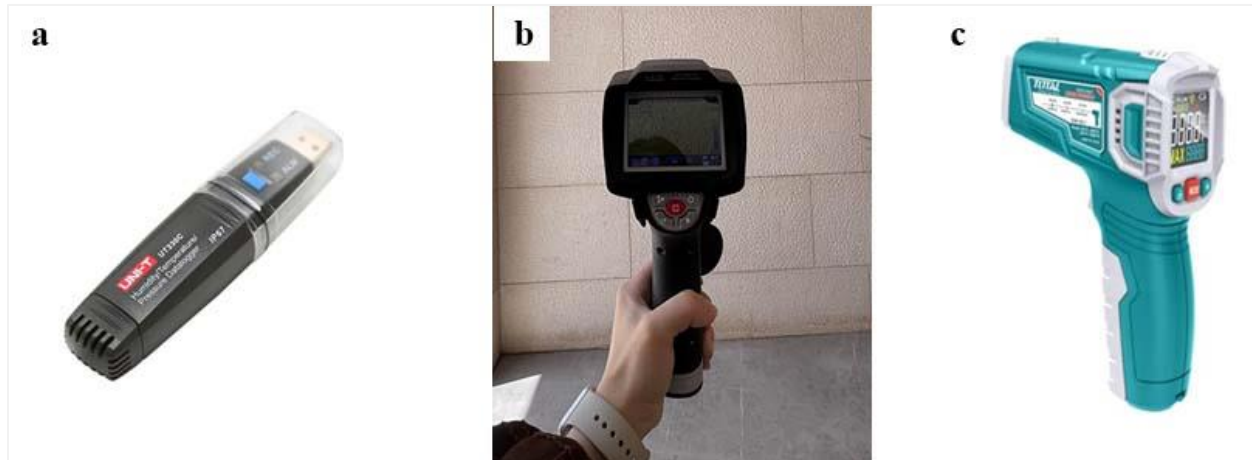


Figure 3-4: Instruments used in the field measurement campaign: (a) UNI-T UT330B USB data logger; (b) CEM DT-9873B thermal imager; (c) Total THIT0155028 infrared thermometer.

3.5 Data Analysis: Cross-Case Comparison of the Surveyed Buildings

The data gathered through site visits, building documentation, and interviews were analyzed through a structured cross-case comparison of the seven identified projects. The comparison was organized in a matrix (Appendix C) in which each project formed a column, and each row recorded a defined attribute under five headings: general information, cladding system, wall assembly, execution and practice, and design rationale. Interview responses were verified against site observations, and drawing dimensions against measurements taken at the buildings, with the site observation taken as authoritative where sources disagreed.

The cross-case comparison distinguished the characteristics that were consistent across the seven projects from those that differed and therefore required further investigation. Several features were common to all projects. The fixing system was identical for each cladding material, with the same bracket type, density, and spacing throughout; the wall assembly behind the cladding followed the same layer sequence; the cavity was closed at both the top and bottom; and a 3 cm XPS insulation layer was used throughout. In addition, interviews confirmed that façade material selection was based solely on architectural appearance, with thermal performance not considered during design.

Four characteristics varied among the projects. The cladding material comprised stone-only systems in three projects and combined stone and porcelain systems in four. The insulation position was external in two projects and internal in five. The cavity depth varied across each façade, following the elevation design projections, and ranged from 5 to 15 cm within the bracket

adjustment range. The joint treatment involved mortar-filled joints in three projects and open joints in four. These varying characteristics formed the design variables investigated in the simulation study, whereas the consistent characteristics were treated as fixed parameters and were incorporated unchanged into all simulated wall configurations.

Each design variable was then assigned a range for the parametric study, anchored in the observed practice. Cladding material takes two values, stone and porcelain, tested separately rather than combined so that the effect of each material can be isolated. Insulation position takes three values: external, internal, and none; the first two are observed in practice, the third is included as a reference floor against which the benefit of insulation can be quantified. Air cavity depth takes three values of 5, 10, and 15 cm, covering the depth range observed across the façades of the surveyed projects. Joint treatment takes two values, with and without joint mortar, both observed in practice; it was examined at the component level on the stone system to establish whether the joint condition alters the thermal transmittance of the assembly.

The first three variables combine into eighteen comparative scenarios: two cladding materials, three insulation positions, and three cavity depths ($2 \times 3 \times 3$). Each scenario defines one complete wall configuration, simulated at both scales of the study, at the component level to quantify its thermal bridging, and at the building level to quantify its annual energy and comfort performance. Joint treatment enters at the component level only, where its effect is isolated within the thermal bridge analysis reported in Chapter 4. Figure 3-5 shows the eighteen simulated wall configurations.

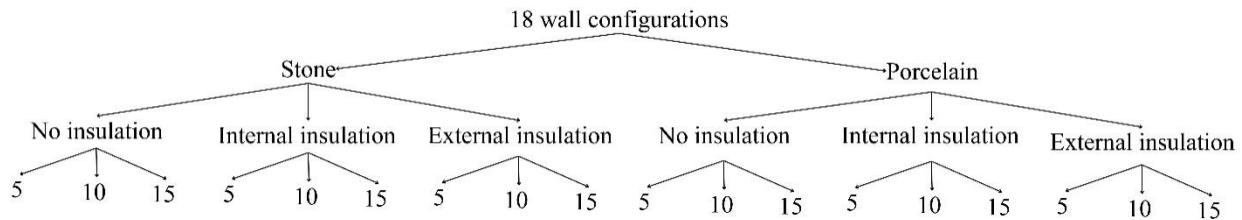


Figure 3-5: The simulated wall configurations

3.6 Simulation Framework

The simulation framework turns the wall configurations defined in Section 3.5 into two linked numerical models, one at component level and one at building level. This section sets out the modeling strategy that connects them, the thermal bridge analysis in COMSOL Multiphysics, the

annual energy and comfort simulation in DesignBuilder, and the validation procedure applied to both models.

3.6.1 Two-Scale Modeling Strategy

The simulation study operates at two scales. Component-level analysis in COMSOL Multiphysics quantifies the thermal bridging of the fixing systems, which building simulation tools cannot resolve because they represent walls as one-dimensional layered constructions. Building-level simulation in DesignBuilder (EnergyPlus) computes the annual heating and cooling loads and thermal comfort of the case study buildings, which component analysis cannot reach. The two scales are linked through the corrected thermal transmittance, U_{corr} , derived at the component level and transferred to the building model as an equivalent wall property. This corresponds to the equivalent U-value method, the standard treatment of thermal bridges in whole-building energy simulation (Ge and Baba, 2015).

The correction is applied by adjusting the thermal resistance of a single low-mass layer within the assembly until the modeled transmittance matches the corrected value. Because resistances in a one-dimensional assembly act in series, the position of the correction does not affect the resulting transmittance, and applying it to a low-mass layer leaves the density and heat capacity of the concrete, block, and cladding layers unchanged, so the thermal mass of the wall and its dynamic response remain physically representative.

3.6.2 Component-Level Thermal Bridge Analysis

Component-level analysis was carried out in COMSOL Multiphysics as steady-state three-dimensional heat transfer through a representative section of each wall configuration, following the principles of ISO 10211 (2017) for the numerical calculation of thermal bridges. For each configuration, the model was solved with and without the fixing components, holding all boundary conditions identical, so that the difference in total heat flow isolates the bridge's contribution alone.

The one-dimensional thermal transmittance of each layered wall was calculated analytically in accordance with ISO 6946 (2017). The total thermal resistance of the assembly is:

$$R_T = R_{si} + \sum_{i=1}^n \left(\frac{d_i}{k_i} \right) + R_{se} \quad (3.1)$$

where d_i is the thickness (m), and k_i is the thermal conductivity (W/m·K) of layer i , n is the number of layers in the assembly, and R_{si} and R_{se} are the internal and external surface resistances (m²K/W), taken from the national guideline values of MoLG (2004). The unbridged transmittance follows as:

$$U_0 = \frac{1}{R_T} \quad (3.2)$$

This analytical value serves two purposes: it verifies the numerical model by comparison with the COMSOL solution for the unbridged assembly, and it provides the baseline to which the thermal bridge correction is applied. The point thermal transmittance χ of a fixing component is obtained from the difference in heat flow between the bridged and unbridged models:

$$\chi = \frac{(Q_{with} - Q_{without})}{\Delta T} \quad (3.3)$$

where Q_{with} and $Q_{without}$ are the total heat flows through the modeled section with and without the point fixing (W), and ΔT is the temperature difference across the assembly (K). The linear thermal transmittance of a continuous bridging element is obtained correspondingly per unit length:

$$\psi = \frac{(Q_{with} - Q_{without})}{\Delta T \cdot l} \quad (3.4)$$

where l is the length of the linear element within the modeled section (m). The combined effect is expressed as an increase in the transmittance of the wall:

$$\Delta U = \chi \cdot n + \psi \cdot L \quad (3.5)$$

where n is the number of point fixings per square meter of façade, and L is the length of linear bridging elements per square meter (m/m²). The corrected thermal transmittance of each configuration is then:

$$U_{corr} = U_0 + \Delta U \quad (3.6)$$

U_{corr} is the value transferred to the building-level model, so that each simulated wall carries the thermal bridging effect of its fixing system. In addition to the eighteen configurations, the stone system was analyzed with and without joint mortar at the component level to determine whether the joint condition alters the thermal transmittance of the assembly.

3.6.3 Building-Level Simulation

Building-level simulation was carried out in DesignBuilder (EnergyPlus) for the two case study buildings. Each of the eighteen wall configurations was applied in turn to the external walls, and all other model settings, geometry, occupancy, internal gains, glazing, and roof and floor constructions were held identical across the cases, so that any difference in the results is attributable to the wall configuration alone. Heating and cooling were supplied by a split system without a mechanical fresh air supply. The heating setpoint was 20 °C and the cooling setpoint 26 °C, corresponding to the limits of the graphic comfort zone method of ASHRAE Standard 55, 20 to 24 °C in winter and 22.2 to 26 °C in summer (ASHRAE, 2017), and matching the setpoints adopted by Haj Hussein et al. (2021) in their simulation study of residential buildings in Nablus.

Simulations were run for a full annual period at six time-steps per hour, driven by the Hebron weather file. A single continuous annual run was used in preference to separate seasonal runs to preserve the shoulder months within a single consistent simulation and to avoid inconsistencies in the EnergyPlus warm-up phase, which is sensitive to the initial conditions of heavyweight assemblies.

Each configuration was simulated twice under identical settings. The first run operated the heating and cooling systems and provided the annual and seasonal heating and cooling loads. The second run switched both systems off, and the resulting free-running operative temperatures provided the thermal comfort indicators.

3.6.4 Model Validation

The simulation models were validated against field measurements at both scales before the parametric study. At the component level, the COMSOL model of the as-built wall was compared with spot surface temperature measurements and infrared thermography, and the unbridged model

was verified against the analytical calculation of Equations (3.1) and (3.2). At the building level, the DesignBuilder model was calibrated and then validated against continuous indoor air temperature records from the four monitored zones.

Validation was assessed using the two statistical indices defined in ASHRAE Guideline 14 for hourly calibration (ASHRAE, 2014). The Normalized Mean Bias Error (NMBE) is computed as:

$$NMBE = \frac{\sum_{i=1}^n (M_i - S_i)}{n * \bar{M}_i} \times 100 \quad (3.7)$$

where M_i and S_i are the measured and simulated values at time step i , n is the number of paired data points, and $\bar{M}_i$ is the mean of the measured values. The Coefficient of Variation of Root Mean Squared Error CV (RMSE) is computed as:

$$CV(RMSE) = \frac{1}{\bar{M}_i} \sqrt{\frac{\sum_{i=1}^n (M_i - S_i)^2}{n}} \times 100 \quad (3.8)$$

ASHRAE Guideline 14 accepts an hourly-calibrated model when NMBE lies within $\pm 10\%$ and CV(RMSE) does not exceed 30%. Both indices were computed separately for each of the four monitored zones.

3.7 Summary

This chapter sets out the study's methodology. A quantitative, applied, simulation-based design was adopted, with Hebron city as the study area and residential buildings as the building type. A survey of the registered engineering offices identified seven residential projects with mechanically fixed cladding, and four criterion-based conditions were used to select the case study buildings. Data were collected through site visits and building documentation, semi-structured interviews, and field measurements, and were analyzed through a cross-case comparison that defined the research variables. The simulation framework operates at two scales: steady-state thermal bridge analysis in COMSOL Multiphysics and annual energy and comfort simulation in DesignBuilder. Figure 3-6 summarizes the research methodology.

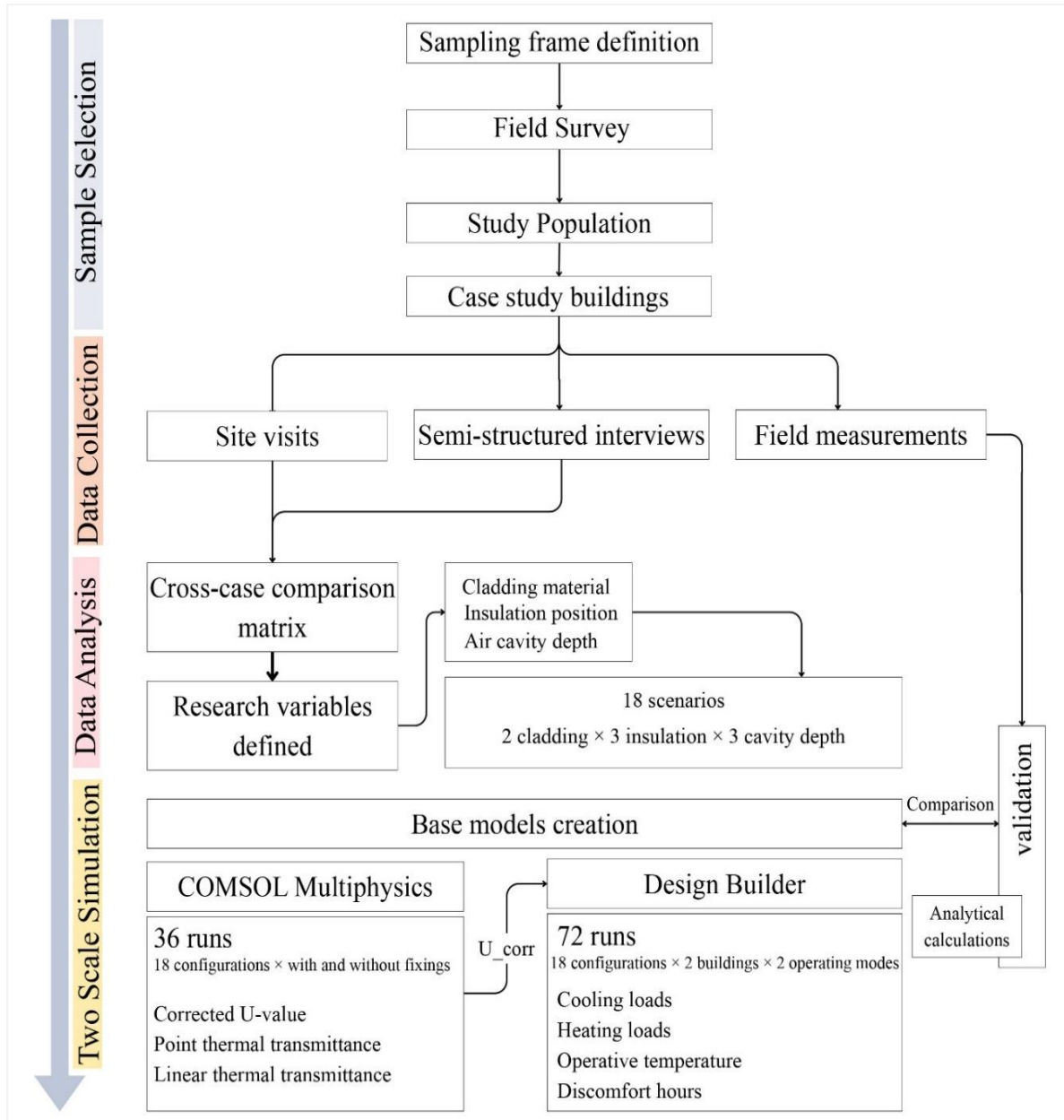


Figure 3-6: Research methodology framework

Chapter 4

Results And Discussion

Chapter 4

Results and Discussion

4.1 Overview

This chapter reports the results of the two-scale simulation study defined in Chapter 3, together with the field data on which it rests. The material is ordered so that each stage supplies the inputs to the next. The survey establishes what is built in practice; the case-study buildings and their as-built assemblies define the geometry and the base case; the two models are described and validated; and the parametric results follow.

Section 4.2 sets out the geographical and climatic context of Hebron. Section 4.3 reports the seven residential buildings with mechanically fixed cladding, designed by two offices and executed by a single specialist subcontractor, and records the fixing components, bracket densities and cavity depths measured on site. Section 4.4 describes the two case-study buildings, the four monitored thermal zones, and the as-built wall assembly that defines the study's base case. Sections 4.5 and 4.6 cover the models and their validation. The component model in COMSOL Multiphysics resolves the three-dimensional heat flow through the fixing system and returns the corrected thermal transmittance of each assembly. The building model in DesignBuilder uses those transmittances as wall inputs to simulate annual energy demand and free-running thermal comfort across the four zones. Validation rests on measured surface temperatures recorded on both faces of an existing wall, an analytical ISO 6946 benchmark of the clear-wall transmittance, and a continuous record of indoor air temperature assessed against ASHRAE Guideline 14.

The parametric results are presented in Sections 4.7 and 4.8. Eighteen wall configurations combine two cladding materials, three insulation positions, and three cavity depths. Each was solved twice in COMSOL, with and without the fixing components, to isolate the additional heat flow attributable to the fixings. Each corrected transmittance was then carried into DesignBuilder and run twice, under conditioned and under free-running operation. Section 4.7 reports the corrected transmittances and the bridging penalties they contain. Section 4.8 reports seasonal and annual sensible loads, mean operative temperatures and discomfort hours across the four zones. Section 4.9 interprets these results in terms of the physical mechanisms that govern them.

4.2 Study Context Description

The study was conducted in Hebron City, in the southern West Bank, Palestine, approximately 30 km south of Jerusalem. The geographical location of Palestine and the administrative boundaries of the Hebron Governorate are presented in Figure 4-1 and Figure 4-2, respectively. Hebron is the largest city in the West Bank and serves as the administrative center of the Hebron Governorate. The city is situated at a latitude of 31.532569° N and a longitude of 35.099826° E, with an average elevation of approximately 943 m above sea level.



Figure 4-1: Palestine Map (WorldAtlas, 2023)
<https://www.worldatlas.com/maps/palestine>

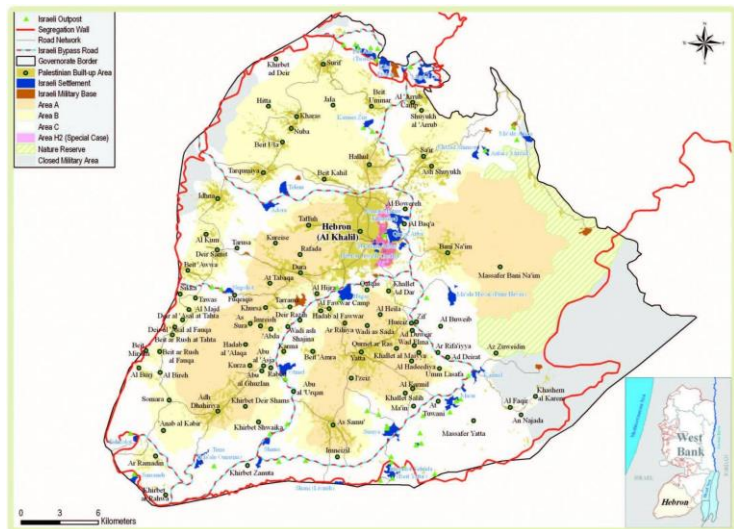


Figure 4-2: Hebron Governorate Map (ARIJ, 2009)
<http://vprofile.arij.org/hebron/pdfs/integrated%20profile%20final%20dd.pdf>

Hebron has a Mediterranean climate, with cold, rainy winters and warm, dry summers. According to the Palestinian Central Bureau of Statistics (PCBS, 2024), the warmest months are June, July, and August, with the highest average maximum temperature of 31.3°C recorded in June, while February has the lowest average maximum temperature, at 12.9°C, and the lowest average minimum temperature (PCBS, 2024) (Figure 4-3). The average annual relative humidity is 74%, with a total annual rainfall of 412.1 mm. January records the highest monthly rainfall, at 204.0 mm (PCBS, 2024) (Figure 4-4).

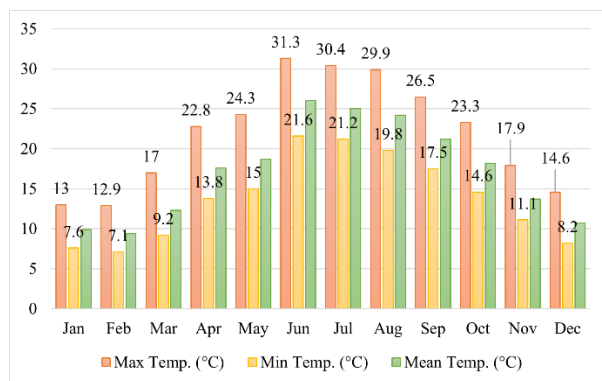


Figure 4-3: Monthly Maximum, minimum, and mean temperatures in Hebron city 2024.
(Researcher, 2026: Based on (PCBS, 2024)).

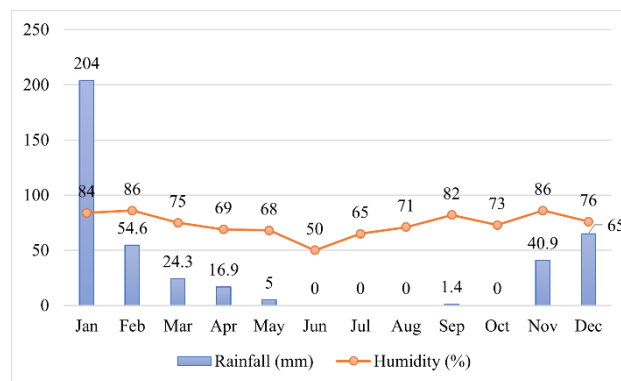


Figure 4-4: Monthly average rainfall and relative humidity in Hebron City 2024.
(Researcher, 2026: based on (PCBS, 2024)).

The mean annual wind speed was 4.8 km/h, with little seasonal variation. Speeds were marginally higher in the transitional and winter months and lowest in June (Figure 4-5). The prevailing wind direction is from the north-west and west. The wind rose for Hebron, shown in Figure 4-6, shows how many hours per year the wind blows from the indicated direction.

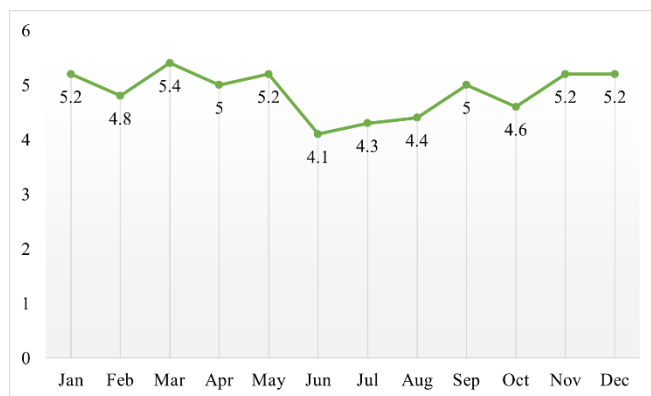


Figure 4-5: Mean Wind Speed (km/hour) 2024.
(Researcher, 2026: Based on (PCBS, 2024)).

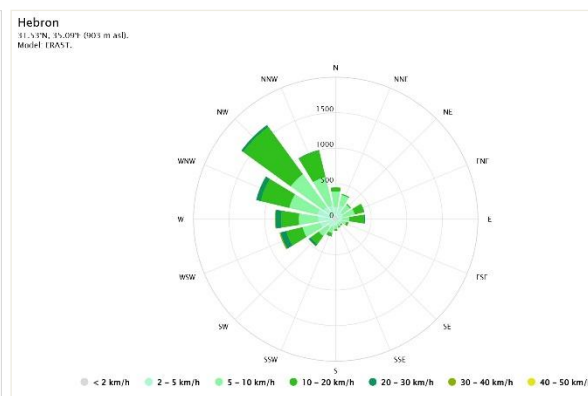


Figure 4-6: Hebron Wind Rose. Meteoblue [online]:
https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/hebron_palestine_285066.

Hebron's average daily solar radiation peaks on June 21st, with a seasonal average of 8.6 kWh/m² and a daily average of 14 hours of daylight in summer. In winter, the average amount of solar radiation drops to 4.2 kWh/m². As shown in Figure 4-7 below.

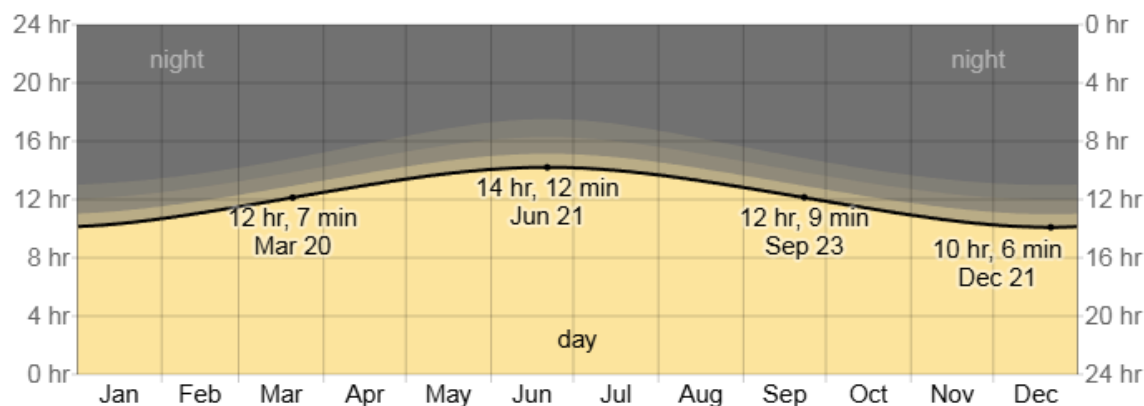


Figure 4-7: Hours of Daylight and Twilight in Hebron. Weather-Spark [online]:
<https://weatherspark.com/y/98840/Average-Weather-in-Hebron-Palestinian-Territories-Year-Round>

Table 4-1 summarizes the seasonal climatic conditions in Hebron City. Summer is characterized by higher temperatures, lower relative humidity, and an average wind speed of 4.3 km/h, while winter has lower temperatures, higher humidity, and a slightly higher average wind speed of 5.1 km/h. Table 4-2 presents the annual climatic averages for Hebron City from 2011 to 2024, including mean air temperature, relative humidity, rainfall, wind speed, and sunshine hours. The study area within the Hebron Governorate is shown in Figure 4-8.

Table 4-1. Hebron city climatic averages (Researcher, based on PCBS (2024)).

Season	Temperature (°C)		Wind speed (km/h)	Wind direction	Humidity (%)
	Average minimum	Average maximum	Average speed		
Summer	20.9	30.5	4.3	North-Western wind	62%
Winter	7.6	13.5	5.1	Western wind	82%

Table 4-2. Annual climatic averages in Hebron City, 2011–2024 (Researcher, based on PCBS (2025)).

Year	Mean Air Temp. (°C)	Mean Max. Temp. (°C)	Mean Min. Temp. (°C)	Relative Humidity (%)	Rainfall (mm)	Wind Speed (km/h)	Sunshine (h/day)
2011	15.8	20.5	12.3	56	375.5	9.7	8.2
2012	16.9	22.8	12.4	61	620.5	10.1	8.2
2013	16.5	21.5	12.6	63	660.5	10.5	8.3

2014	16.8	21.8	12.6	64.7	378.8	8.5	8.4
2015	16.6	21.5	12.7	66	543.9	7.2	8.4
2016	17.2	22.2	12.9	64	605.6	6.7	8.3
2017	17.1	22	12.9	64	355.7	5.5	8.2
2018	17.3	21.9	13.7	69	621	5.7	7.8
2019	16.8	21.5	13.3	67	451.3	5.8	8.2
2020	16.3	20.5	13	63.4	695.7	5.7	7.4
2021	17.8	22.6	13.9	65	338.1	5.9	8.7
2022	—	—	—	—	422.8	—	—
2023	17.4	22.3	14	71	520.7	5	—
2024	17.2	22	13.9	74	412.1	4.8	—

Note: "—" indicates years for which PCBS did not record the corresponding data.

4.3 Mechanically Fixed Cladding in Hebron

Mechanically fixed cladding is a recent addition to residential construction in Hebron, and its use remains limited. Seven residential buildings in the city were executed with the system. All buildings were documented on site and are described here as built, covering their locations and wall assemblies, the cavity depths achieved, and the fixing components that carry the panels.

4.3.1 Documented Buildings

The locations of the seven mechanically clad buildings are shown in Figure 4-9, and photographs of the buildings are presented in Figures 4-10 to 4-20. The projects are distributed across the northern and western districts of the city, in Haska, Farsh Al-Hawa, Wadi Abu-Ektelah, and Sha'abah. All are residential villas of two to three stories. Table 4-3 summarizes the documented projects, including cladding materials, year of construction, cavity depth, insulation position, and wall assembly.



Figure 4-8: The Study Area within Hebron Governorate. (Researcher, 2026)

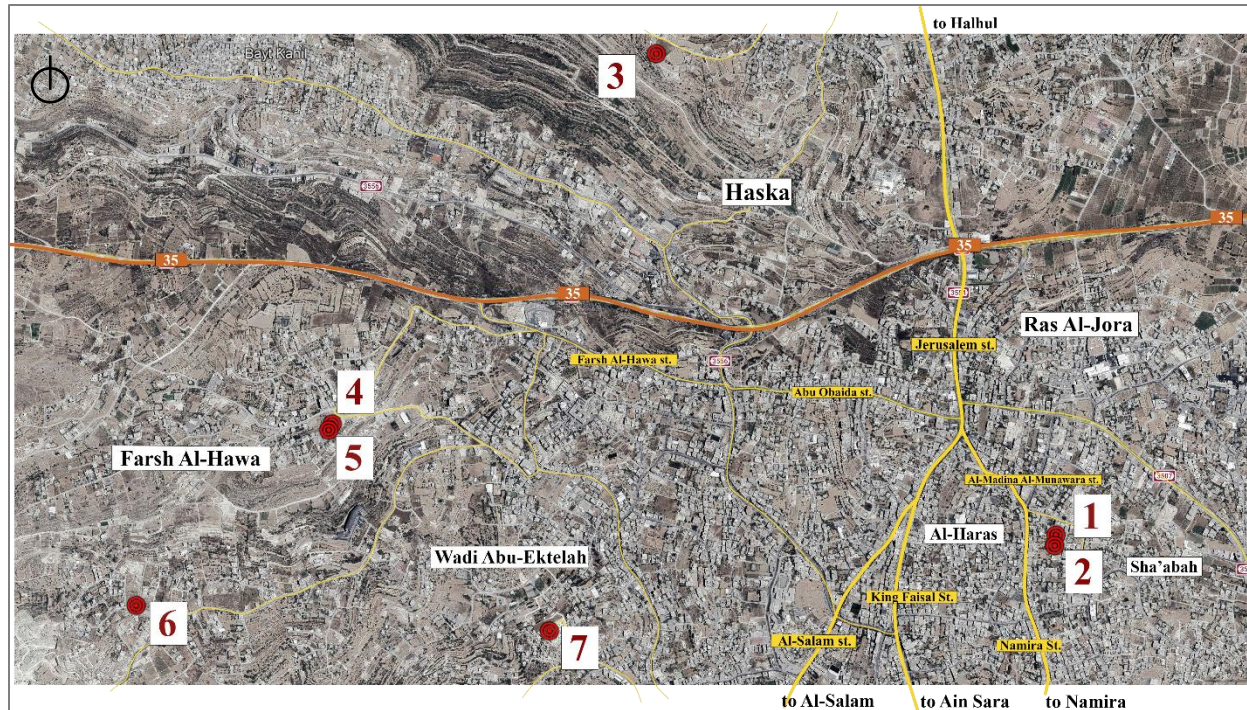


Figure 4-9: Locations of the buildings with mechanically fixed cladding within Hebron City.
(Researcher, 2026) base map: (Google Earth Pro, 2026)



Figure 4-10: Locations of buildings 1 and 2 in Sha'abah
(Researcher, 2026) base map: (Google Earth Pro, 2026)



Figure 4-12 Panoramic view of the two buildings in Sha'abah (Researcher, 2026)



Figure 4-11 Front elevations of buildings 1 and 2, Sha'abah (Researcher, 2026)



Figure 4-13: Location of building 3 in Haska (Researcher, 2026) base map: (Google Earth Pro, 2026)



Figure 4-15: Locations of buildings 4 and 5 in Farsh Al-Hawa (Researcher, 2026), base map: (Google Earth Pro, 2026)



Figure 4-17: Location of building 6 in Farsh Al-Hawa (Researcher, 2026) base map: (Google Earth Pro, 2026)



Figure 4-14: Building 3, Haska



Figure 4-16 The mechanically fixed stone and porcelain-clad buildings 4 and 5, Farsh Al-Hawa, during the cladding phase (Researcher, 2026)



Figure 4-18: Building 6, Farsh Al-Hawa, during cladding installation, showing the bituminous waterproofing membrane on the structural wall and the partially completed mechanically fixed stone cladding (Researcher, 2026)

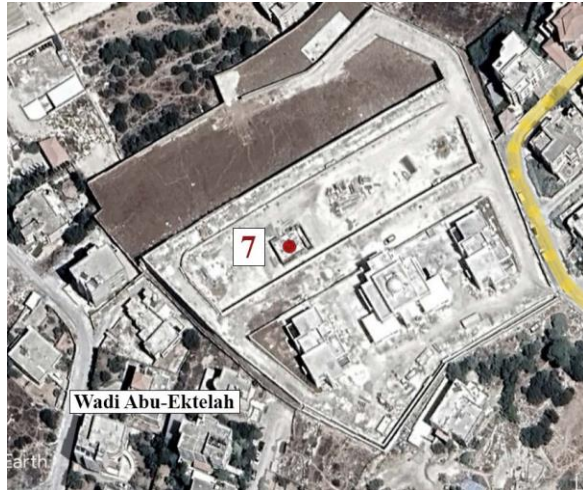


Figure 4-19: Location of building 7 in Wadi Abu-Ektelah (Researcher, 2026) base map: (Google Earth Pro, 2026)



Figure 4-20: Building 7, Wadi Abu-Ektelah, during the cladding phase, showing the mechanically fixed stone cladding in progress (Researcher, 2026)

Table 4-3: Summary of the documented residential buildings with mechanically fixed cladding in Hebron City (Researcher, 2026).

Project	Cladding materials	Year of construction	Air Cavity cm	Insulation position	wall layers	cm
1	Stone Mechanical cladding	2010	8	outer	stone	3
					air cavity	8
					XPS	3
					concrete	20
					air gap	3
					block	10
					Plaster	2
2	Stone Mechanical cladding	2010	8	outer	stone	3
					air cavity	8
					XPS	3
					concrete	20
					air gap	3
					block	10
					Plaster	2
3	Stone Mechanical cladding Traditional stone cladding	2024 Cladding phase finished recently but still under construction	7	inner	stone	3
					air cavity	7
					concrete	20
					XPS	3
					block	10
					plaster	2

4	Stone Mechanical Cladding Porcelain Mechanical Cladding	2024 still in the cladding phase	9	inner	stone	3
					air cavity	9
					concrete	20
					XPS	3
					block	10
					plaster	2
5	Stone Mechanical Cladding Porcelain Mechanical Cladding	2024 still in the cladding phase	9	inner	stone	3
					air cavity	9
					concrete	20
					XPS	3
					block	10
					plaster	2
6	Stone Mechanical cladding	2025 still in the cladding phase	9	inner	stone	3
					air cavity	9
					concrete	20
					XPS	3
					block	10
					plaster	2
7	Stone Mechanical Cladding Porcelain Mechanical Cladding	2024 still in the cladding phase	9	inner	stone	3
					air cavity	9
					concrete	20
					XPS	3
					block	10
					plaster	2

Stone was the primary cladding material in all seven projects, with a panel thickness of 3 cm, which was adopted as a fixed parameter in the simulation matrix. Three recent projects (buildings 4, 5, and 7, started in 2024) combined mechanically fixed stone with mechanically fixed porcelain on the same building, reflecting the recent introduction of porcelain into local cladding practice. Both cladding types were therefore included in the scope of this study.

The documented assemblies showed consistent construction logic, with one structural difference between the projects. Buildings 3 to 7 applied thermal insulation to the inner side of the structural wall, between the concrete and the block layer, while buildings 1 and 2 applied extruded polystyrene to the outer face of the concrete within the cavity, with an additional air gap between

the concrete and the block layer. The coexistence of both insulation positions in local practice supports treating insulation position as a study variable in this research.

Cavity depth varied across and within the façades of each building for two reasons. First, the structural walls were not perfectly plumb, and the cavity absorbs this construction tolerance. Second, the cavity is used as a design tool: architects keep the structural wall at a constant thickness, typically 20 cm of concrete, and form the façade articulation, projections, and decorative relief by varying the cladding offset, which is far cheaper than casting these geometries in concrete. A representative average depth was therefore recorded for each project. The fixing brackets used in local practice accommodate cavity depths from 5 cm (the minimum working distance) to 15 cm (the maximum bracket reach), and all documented cavities fell within this range. Buildings converged on average depths of 7–9 cm. The bracket working range defines the cavity depths examined in the simulation matrix: 5 cm and 15 cm represent the system's mechanical limits. In comparison, 10 cm represents the intermediate depth, close to the averages observed in recent practice. Together, the three depths span the full range the fixing system can produce.

4.3.2 Cladding and Fixing System Details

The documented buildings share a common construction logic regardless of cladding material. The concrete wall is coated with a continuous bituminous waterproofing coat before any fixing work begins. The cladding is then carried on a mechanical fixing system that maintains an air gap of 5 to 15 cm between the wall and the panel. This range defines the working limit of the standard fixing components; when the gap exceeds 15 cm, a structural steel subframe is required to bridge the distance. Within this shared logic, the two cladding materials use different support systems. Stone relies on individual point fixings, while porcelain requires a continuous subframe.

Stone Fixing Details

The stone fixing system relies on individual support components rather than a continuous frame. Its main characteristics are:

- **Support system:** Stainless steel Z- and L-brackets (Grade 304 or 316), fixed to the concrete backing wall with anchor bolts. A threaded flat head bolt connects the bracket to a pin seated in the stone edge, allowing the installer to set the cavity depth within the system's 5 to 15 cm working range. The pin carries a plastic tube that separates the steel from the stone, and a two-component epoxy paste secures the connection (Figure 4-21).
- **Loading points:** Each panel is supported at four points, two at the bottom edge and two at the top. Pinholes are drilled no more than 12-15 cm from the panel edges to preserve the stone's structural integrity (Figure 4-22).
- **Bracket density:** Five brackets per square meter, adopted later in this study as the fastener intensity for the component-level models (Figure 4-23).
- **Joints:** A consistent joint of 5 mm between panels. Practice varies across the documented projects: some leave the joint open, while others fill it with grout mortar. This variation is examined in the component-level simulations, which model each case with and without mortar joints.

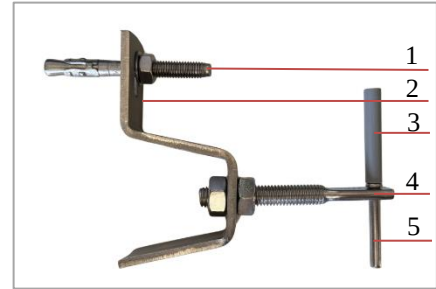


Figure 4-21: Components of the stone fixing system: (1) anchor bolt, (2) Z-bracket, (3) plastic tube, (4) flat head bolt, (5) pin (Researcher, 2026)

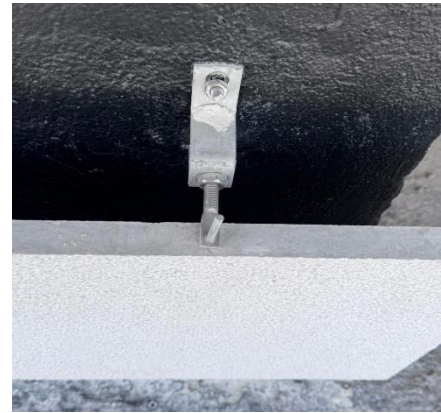


Figure 4-22: Pin connection at the stone panel edge (Researcher, 2026)



Figure 4-23: Installed bracket within the ventilated cavity, showing the waterproofed backing wall (Researcher, 2026)

Porcelain Fixing Details

Porcelain panels are thinner and lighter than stone and cannot accept edge pins. The system therefore uses a continuous rail subframe combined with adhesive panel fixing:

- Support system: Vertical aluminum T-rails installed at 70 cm centers across the facade. Each rail is fixed to the concrete backing wall using stainless steel L-brackets spaced 50 cm apart vertically, anchored with expansion bolts (Figures 4-24 and 4-25).
- Cavity depth: The L-bracket sets the air gap between the backing wall and the panel within the same 5 to 15 cm working range as the stone system, with the bracket length selected to match the required depth.
- Mounting method: The porcelain panels are adhesive-fixed to the T-rails, which distribute the load continuously along the rail rather than concentrating it at discrete points as in the stone system.
- Joints: Panel joints are kept open in all documented projects.



Figure 4-24: Vertical aluminium T-rails fixed to the waterproofed backing wall (Researcher, 2026)

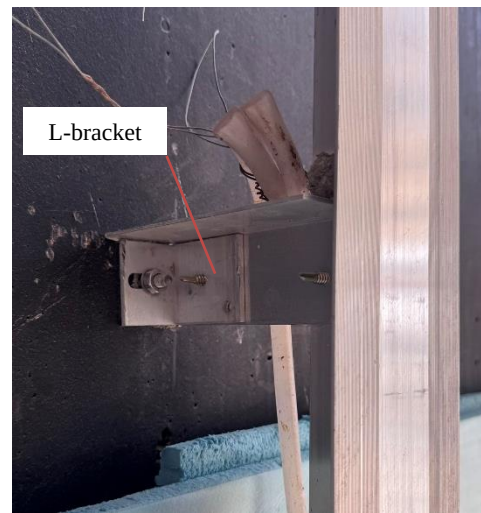


Figure 4-25: L-bracket fixing the T-rail to the concrete backing wall (Researcher, 2026)

4.4 Case Study Buildings

Of the seven documented buildings, Buildings 1 and 2 were the only completed and occupied projects at the time of documentation, so they were selected as the case study buildings. They form a mirrored pair of villas in Sha'abab, clad in mechanically fixed stone over an insulated concrete wall. They provide the geometry for the building-level model, the four monitored thermal zones, and the as-built assembly that defines the base case of the parametric matrix.

4.4.1 Selection and Overview

Buildings 1 and 2, two adjacent villas in Sha'abab (Figures 4-10 to 4-12), were selected as the case study buildings for the field measurement campaign and the simulation study. According to the selection criteria defined in Chapter 3, these were the only completed buildings available for investigation. All other mechanically clad buildings (Buildings 3–7) were still under construction at the time of the survey and were therefore excluded from the study. Buildings 1 and 2 are fully clad with the same mechanically fixed façade system and form a mirrored, near-identical pair located side by side under similar exposure conditions, providing a suitable basis for comparative analysis. Both villas had been occupied for several years before the field measurements, ensuring stable operating conditions and making them suitable for evaluating the thermal performance of mechanically fixed cladding systems.

4.4.2 Architectural Description

The two villas follow a mirrored two-story plan with a ground floor of 174.48 m², a first floor of 163.88 m², and an entrance canopy of 11.34 m², giving a total built-up area of 349.7 m² each (Figure 4-26). The mirrored arrangement places the corresponding spaces of the two houses with reversed north–south exposure, while both houses share the east-facing glazing. All elevations carry the mechanically fixed stone cladding. Villa Architecture and Design Office provided all architectural drawings and building information.

Four thermal zones were selected for measurement and simulation: the ground-floor living zone and a first-floor bedroom zone in each building, denoted B1-L, B1-B, B2-L, and B2-B. The ground-floor living zone was selected over the first-floor living area because it constitutes the primary daytime space of the household, combining living, guest reception, dining, and kitchen

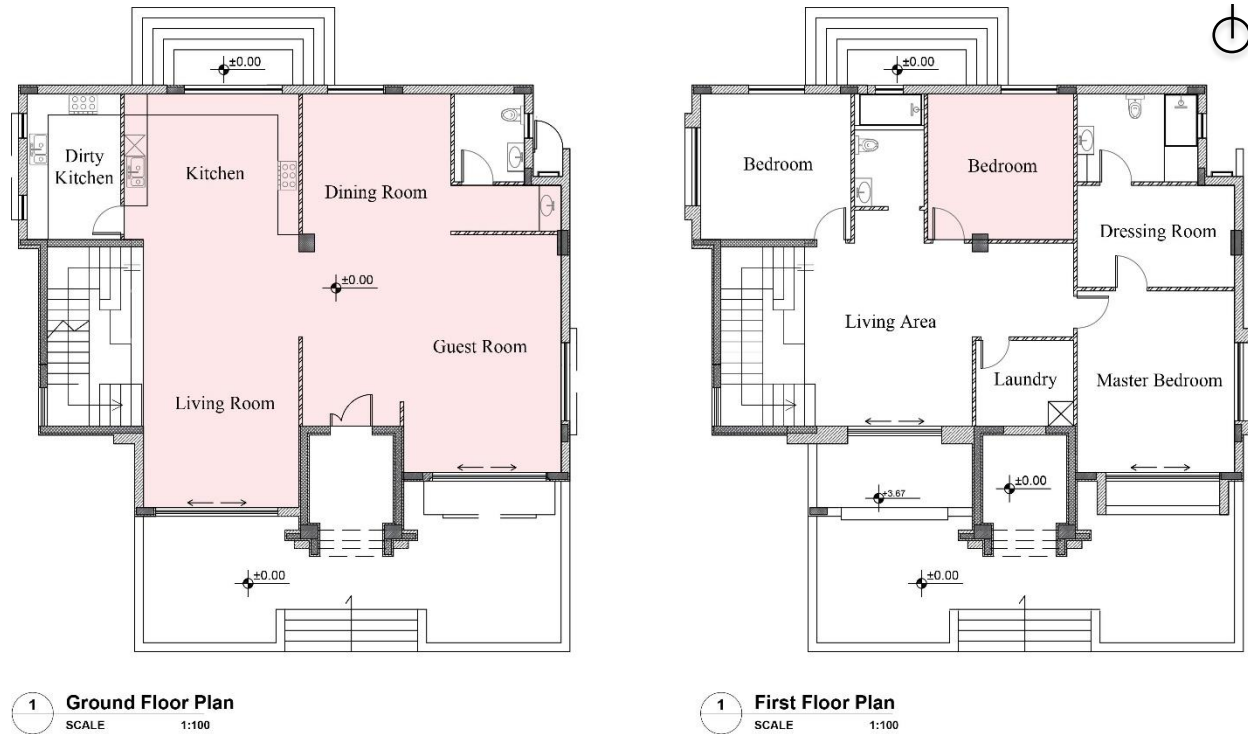


Figure 4-26: Ground and first floor plans of Building 1 with the monitored zones marked; Building 2 follows the same plan, mirrored (Villa Architecture and Design Office, 2026, with researcher edits)

functions in a single continuous zone, and because it presents the largest external wall area and glazing distribution of any zone in the building, making it the most responsive space to the façade assembly under study. The first-floor bedroom complements it by representing the night-time occupancy regime and the upper-floor exposure condition. Together, the two zones cover both floors, both principal occupancy patterns, and the widest range of envelope exposure available within the buildings. The mirrored plan places each zone in one building opposite its counterpart in the other, so the four zones form two matched pairs under reversed orientation.

The ground-floor living zone is an open space with a net floor area of 137.33 m^2 and a clear ceiling height of 3.42 m . In Building 1, its glazing is distributed over three orientations, with the largest share facing north (17.98 m^2), followed by south (10.52 m^2) and east (4.22 m^2), totaling 32.71 m^2 ; in Building 2, the mirrored plan reverses the north and south shares. The bedroom zone is located on the first floor, with a net floor area of 17.4 m^2 , a ceiling height of 3.42 m , and a single window of 3.04 m^2 facing north in Building 1 and south in Building 2. Table 4-4 summarizes the geometry of the four zones, taken from the architectural drawings and used as the geometric basis of the simulation model described in Section 4.5.

Table 4-4: Geometric characteristics of the four monitored zones

Zone	Floor	Net area (m ²)	Ceiling height (m)	Glazing area (m ²)	Glazing orientation
B1-L	Ground	137.33	3.42	32.72	N / S / E
B1-B	First	17.4	3.42	3.04	N
B2-L	Ground	137.33	3.42	32.72	S / N / E
B2-B	First	17.4	3.42	3.04	S

4.4.3 Wall Assembly and Construction

The two buildings share an identical external wall assembly, recorded from the construction drawings provided by the design office and verified against site observations. From the interior outwards, the wall consists of a 2 cm plaster finish, a 10 cm hollow concrete block wall, a 3 cm unventilated air gap, a 20 cm reinforced concrete structural wall, a 3 cm extruded polystyrene (XPS) insulation board fixed to the outer face of the concrete, an air cavity of 5 cm, and a 3 cm mechanically fixed stone cladding panel, giving a total thickness of approximately 46 cm (Figure 4-27). The insulation is therefore placed externally in the as-built condition, within the zone penetrated by the cladding fixings, and this configuration defines the base case of the simulation study. The cladding is fixed with the stainless-steel bracket system, and the joints between the stone panels are grouted with mortar. Construction photographs provided by the executing contractor document the assembly during installation, showing the bituminous waterproofing layer, the externally fixed XPS boards, and the brackets behind the stone panels (Figure 4-28).

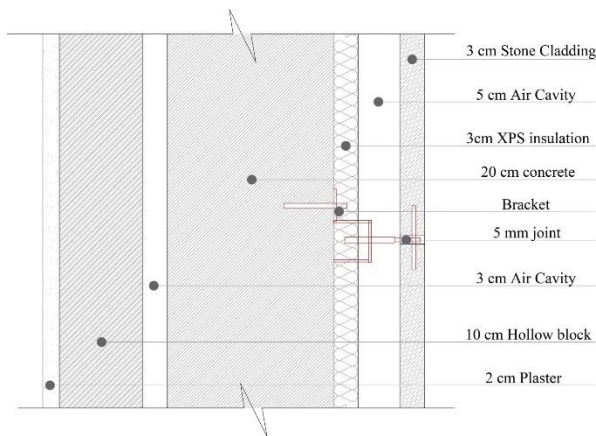


Figure 4-27: Section through the as-built external wall assembly showing the layer sequence and the bracket fixing detail (Researcher, 2026).



Figure 4-28: Construction stage of the external wall assembly in the case study buildings (Source: Mohammed Alamah, cladding contractor, 2010).

4.5 Simulation Models

This section describes the two simulation models used in the study: the component-level model in COMSOL Multiphysics, which quantifies the thermal-bridging effect of the fixing systems, and the building-level model in DesignBuilder, which uses the component-level outputs to simulate annual energy demand and thermal comfort in the two case-study buildings. The component model is presented first because its outputs are inputs to the building model.

4.5.1 Component-Level Model (COMSOL)

The component-level analysis was carried out in COMSOL Multiphysics 6.3, which solves three-dimensional steady-state heat conduction using the finite element method (FEM). Since the fixings are arranged in a regular grid pattern across the façade, the wall was represented by a single repeating unit, referred to here as the representative cell, rather than by the full façade. The cell size equals the fixing spacing in each direction, with the fixing placed at the center (Figure 4-29). For the stone system, the field-observed density of 5 brackets per square meter corresponds to one bracket per 0.45×0.45 m of wall area, which defines the cell. For the porcelain system, the T-rails run at 0.70 m horizontal centers and the L-brackets at 0.50 m vertical spacing, defining a cell of 0.70×0.50 m: the rail passes vertically through the cell center with 0.35 m of clear wall on each side, and the L-bracket sits at mid-height with 0.25 m above and below. The fixing components were modeled with simplified geometry, omitting minor details such as bolt threads and edge rounding, while preserving the material, cross-sectional area, and continuous conduction path of

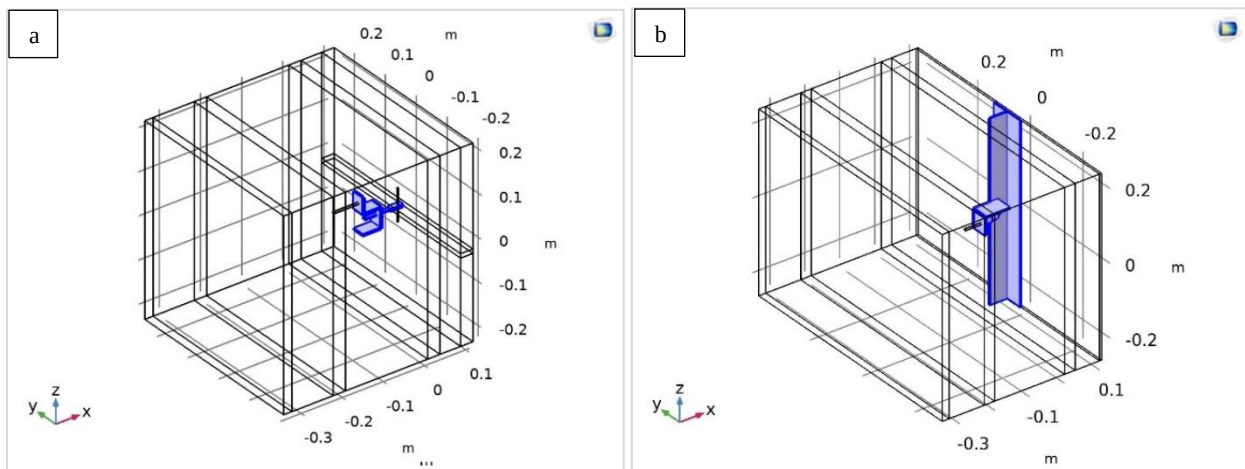


Figure 4-29: Modelled geometry of the representative cells: (a) stone system with the bracket assembly at the cell centre; (b) porcelain system with the vertical T-rail through the cell centre and the L-bracket at mid-height (Researcher, 2026)

each component through the insulation and cavity. Since these three properties govern the heat transfer along the fixing, the simplification does not affect the computed transmittances. Still, it substantially reduces the demand for meshing, consistent with the approach of Petreševics and Nagy (2022). Table 4-5 summarizes both cells.

Table 4-5: Representative cell definition for the two cladding systems

Parameter	Stone system	Porcelain system
Basis	5 brackets/m ² (field survey)	T-rails at 0.70 m centers, L-brackets at 0.50 m (field survey)
Cell dimensions	0.45 × 0.45 m	0.70 × 0.50 m
Cell area	0.2025 m ²	0.35 m ²
Fixing position	Bracket assembly at the cell center	Rail at horizontal center, L-bracket at mid-height

The wall assembly within each cell follows the as-built construction recorded in Section 4.4.3. Table 4-6 lists the layers and their thermophysical properties as entered into the model; the same set of properties is used to feed the building-level model in Section 4.5.2.

Boundary conditions apply the national guideline values for surface resistances and a fixed temperature difference across the assembly (Table 4-7). The boundary temperatures of 20 °C internal and 0 °C external follow those used in the ISO 10211 (2017, Annex A) reference cases. The lateral cell boundaries are assigned a zero-heat-flux (adiabatic) condition.

Table 4-6: Materials' thermal properties (interior to exterior)

#	Layer	d (m)	k (W/m·K)	ρ (kg/m ³)	Cp (J/kg·K)	R (m ² K/W)	Source
1	Internal plaster	0.02	1.2	2000	1000	0.017	MoLG (2004)
2	Hollow block	0.1	0.9	1400	1000	0.111	MoLG (2004)
3	Air gap	0.03	0.28	1.25	1000	0.107	MoLG (2004)
4	Reinforced concrete	0.2	1.75	2300	1000	0.114	MoLG (2004)
5	XPS insulation	0.03	0.041	34	1450	0.732	COMSOL AB (2024)
6	air cavity	0.05	0.28	1.25	1000	0.18	MoLG (2004)
7a	Stone cladding	0.03	1.7	2250	1000	0.018	MoLG (2004)
7b	Porcelain cladding	0.006	1.3	2400	900	0.005	COMSOL AB (2024)
8	Stone joint mortar	0.005	1.4	2200	1000	0.004	MoLG (2004)

Table 4-7: Boundary conditions of the simulation models

Parameter	Value	Source
Internal air temperature T_i	20 °C	ISO 10211 (2017)
External air temperature T_e	0 °C	ISO 10211 (2017)
Temperature difference ΔT	20 °C	—
Internal surface resistance R_{si}	0.12 m ² K/W ($h = 8.33$ W/m ² K)	MoLG (2004)
External surface resistance R_{se}	0.06 m ² K/W ($h = 16.67$ W/m ² K)	MoLG (2004)
Lateral cell boundaries	Adiabatic (symmetry planes)	ISO 10211 (2017)

The mesh was generated using the physics-controlled sequence at the Extra-fine setting, which automatically concentrates refinement on the fixing components where temperature gradients are

steepest (Figure 4-30). Table 4-8 reports the mesh statistics. The porcelain model requires roughly twice as many elements as the stone model because the thin rail and panel geometry impose smaller local element sizes.

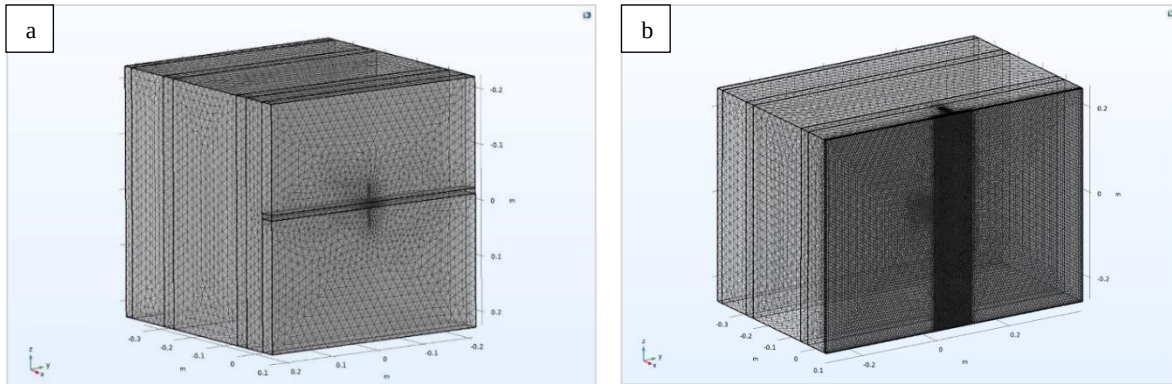


Figure 4-30: Finite element mesh of the representative cells at the Extra fine setting, refined around the fixing components: (a) stone system; (b) porcelain system (Researcher, 2026)

Table 4-8: Mesh statistics for both component models

Model	Domain elements	Boundary elements	Edge elements
Stone cell	578,302	42,362	2,995
Porcelain cell	1,313,122	150,706	5,042

The corrected transmittances quantify the bridging penalty for each cladding system, insulation position, and cavity depth and serve as the wall-construction inputs to the building-level model described in Section 4.5.2.

4.5.2 Building-Level Model (DesignBuilder)

The building-level simulations were carried out in DesignBuilder v7.0, which uses EnergyPlus as its calculation engine. The model geometry was constructed from the architectural drawings (Villa Architecture and Design Office, 2026), with both buildings placed in a single site model at their documented orientations. Each room was treated as a separate thermal zone, and the four monitored zones defined in Section 4.4.2 serve as the study's reporting zones. Fixed architectural projections, including the roof parapets, window surrounds, and the entrance canopy, were modeled as component blocks. Figure 4-31 shows the model of the two buildings.

Each façade wall configuration was defined layer by layer according to the assemblies described in Section 4.4.3. The equivalent U-value correction was applied to the layer between the hollow block and the concrete wall, whose thermal resistance was adjusted until the assembly transmittance matched the corrected value obtained from the component model (Section 4.5.1).

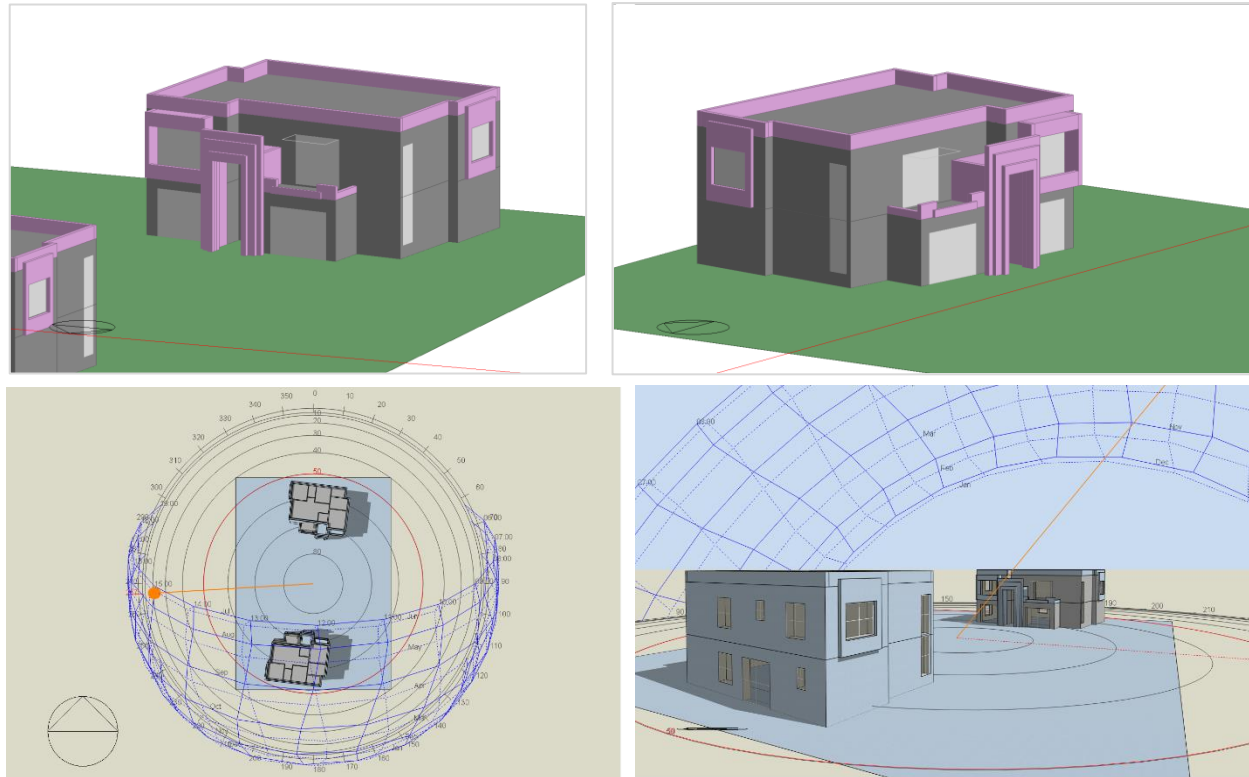


Figure 4-31: DesignBuilder model of the two case study buildings and sun path visualisation of the site model
(Source: researcher)

4.6 Field Measurements and Model Validation

A field campaign was carried out in May 2026 to generate measured data against which the two simulation models could be tested. Two sets of measurements were taken. The first was a spot measurement of wall surface temperatures, recorded on 9 May 2026 at approximately 12:00 on both faces of an existing stone-clad wall corresponding to the base case of this study. Surface temperatures were recorded with an infrared thermometer at 9 points per face, and each face was also infrared thermographed. The measurement cell was located by selecting two cladding stones with a joint at their center. Because the joints are grouted, the fixing system is not visible on the finished façade, and the bracket position was supposed to be 10 cm from the stone edge. The inside

points were co-located with the outside points by referencing the distance to the nearest window opening and the height above floor level, so both grids sample the same wall area. The air temperatures at the time of measurement were 20.5°C indoors and 25.0°C outdoors, giving a temperature difference of 4.5 K across the wall.

The second set was a continuous record of indoor air temperature and relative humidity, logged at 10-second intervals over 72 hours from 9 to 12 May 2026 in the living room and bedroom of each case-study building, resulting in four monitored zones. The loggers were positioned away from direct solar radiation. Both buildings were occupied and in normal residential use throughout the campaign, with the heating and cooling systems switched off, so the monitored zones operated in free-running mode. Outdoor conditions were taken from the weather file described in Section 4.5.2. The measuring tools used are described in Chapter 3.

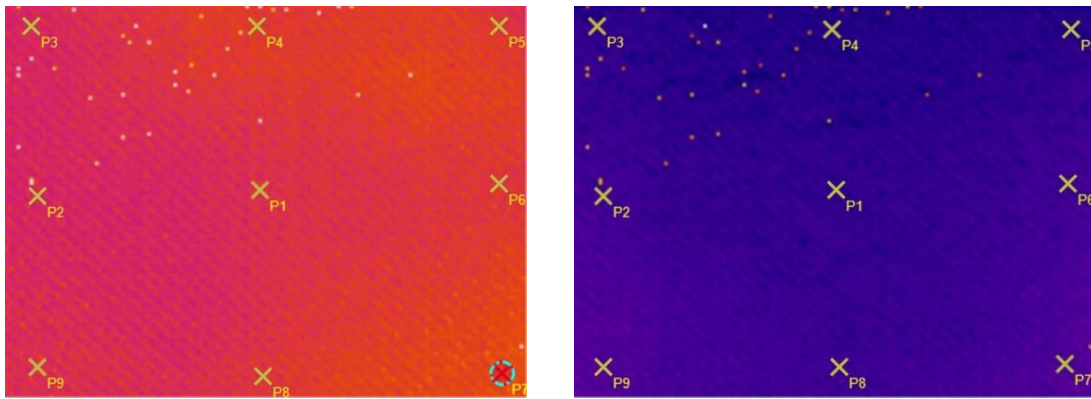


Figure 4-32: Infrared thermography of the outside (left) and inside (right) wall surfaces at the measurement time.

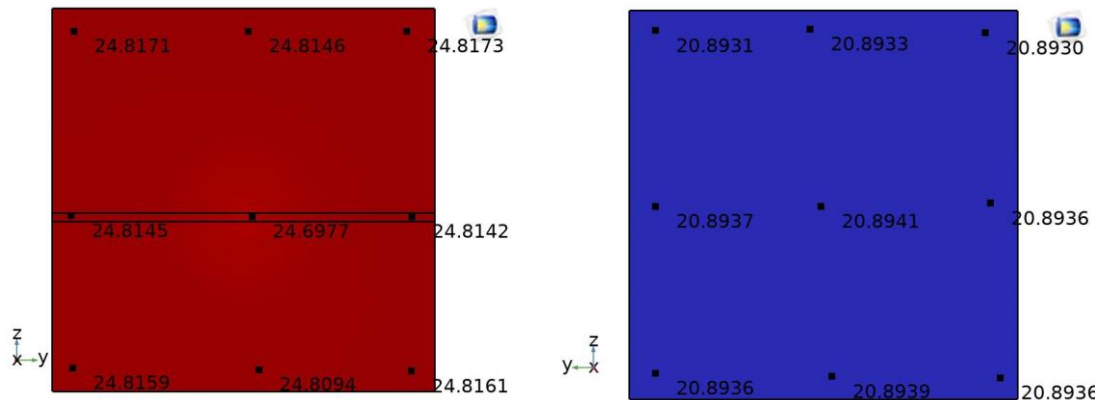


Figure 4-33: COMSOL simulated surface temperature fields

The COMSOL model was validated first against the measured surface temperatures. The model of the existing wall was run under the measured boundary conditions, and the simulated surface temperatures were extracted at nine probe points matching the measurement grid on each face. Figure 4-32 shows the thermograms of both faces, and Figure 4-33 shows the simulated temperature fields. Table 4-9 reports the infrared spot readings, the infrared readings, and the simulated values.

Table 4-9: Measured and simulated surface temperatures at nine points per face

Point	infrared spot readings (°C)		IR (°C)		COMSOL (°C)		Difference, infrared spot readings–COMSOL (°C)	
	outside	inside	outside	inside	outside	inside	outside	inside
P1	24.8	20.7	23.5	20.5	24.7	20.89	0.1	−0.19
P2	24.6	20.5	23.4	20.7	24.81	20.89	−0.21	−0.39
P3	24.9	20.7	23.7	20.4	24.82	20.89	0.08	−0.19
P4	24.5	20.8	24	20.1	24.81	20.89	−0.31	−0.09
P5	24.7	20.7	24	20	24.82	20.89	−0.12	−0.19
P6	24.9	20.6	24.1	20.6	24.81	20.89	0.09	−0.29
P7	25	20.7	24.8	21	24.82	20.89	0.18	−0.19
P8	24.2	20.8	23.5	20.4	24.81	20.89	−0.61	−0.09
P9	24.5	20.8	23.4	20.8	24.82	20.89	−0.32	−0.19
Mean	24.7	20.7	23.8	20.5	24.8	20.89	−0.12	−0.19

The infrared spot measurements agree with the simulated values to within 0.2°C at the mean on both faces, and individual points fall within $\pm 0.6^\circ\text{C}$. The largest single-point deviation, -0.61°C at P8 on the outside face, is attributable to the combined effects of instrument accuracy and the natural surface variation of the stone cladding. The simulated values are nearly uniform across each face because the model represents an idealized homogeneous assembly, whereas the measured readings scatter around them as expected for a real wall.

The infrared readings sit below the infrared spot measurements on both faces, by 0.9°C on average on the outside face and 0.2°C on the inside face. This offset follows from the camera's radiometric settings. Infrared surface temperatures depend on the assumed emissivity (here, 0.95) and the reflected ambient temperature; errors in either parameter translate directly into the reading (Fokaides and Kalogirou, 2011). On the exterior face, the cold sky lowers the effective reflected

temperature, pulling the apparent reading down. In contrast, the interior face, surrounded by room surfaces at near-air temperature, shows a smaller offset. The infrared spot measurements are therefore used as the reference for quantitative comparison.

The field check was complemented by an analytical benchmark of the clear-wall thermal transmittance, calculated using the one-dimensional method of ISO 6946 (ISO, 2017). The reference wall is the external-insulation, 5-cm-cavity, stone-clad assembly without any fixing elements. The clear-wall field is the correct basis for this check because the transmittance of the undisturbed wall is independent of the fixing system. The total thermal resistance was obtained by summing the surface resistances and the resistance of each material layer, as shown in Table 4-10.

Table 4-10: Analytical thermal resistance of the reference clear wall (exterior to interior) versus simulated clear-wall transmittance

Layer	d (m)		R = d/k (m ² K/W)
External surface resistance (R _{se})	–	–	0.06
Stone cladding	0.03	1.7	0.018
Air cavity	0.05	0.28	0.179
XPS insulation	0.03	0.041	0.732
Concrete	0.2	1.75	0.114
Internal air gap	0.03	0.28	0.107
Hollow block	0.1	0.9	0.111
Plaster	0.02	1.2	0.017
Internal surface resistance (R _{si})	–	–	0.12
Total ΣR			1.457
U = 1/ ΣR			0.686 W/m ² K
COMSOL Simulation U-value			0.685 W/m ² K
Deviation			0.14%

The same assembly was then modeled in COMSOL under steady-state conditions, and the transmittance was extracted from the total heat flow across the cell. Because steady-state conduction is a linear problem, the transmittance is a property of the assembly. It does not depend on the applied temperature difference, so the two values are directly comparable, and the

agreement observed under the mild May conditions carries over to the design conditions used in the component analysis. Table 4-10 compares the analytical and simulated values. The deviation is 0.14%, an order of magnitude below the differences typically reported between analytical and numerical transmittance calculations for wall assemblies (Santos et al., 2019; Gaši et al., 2023). This indicates that the model geometry, material properties, and boundary conditions were implemented correctly and that the model can be trusted for the three-dimensional cases that include the fixing system.

The DesignBuilder model was then validated against the 72-hour logger records from the four monitored zones. The measured series was compared point-by-point with the simulated series for the same zones under matching weather conditions. Agreement was assessed using the NMBE and CV(RMSE) indices of ASHRAE Guideline 14. Each zone used 4,465 paired data points. The results are shown in Table 4-11.

Table 4-11: ASHRAE Guideline 14 validation of indoor air temperature, four zones

Metric	B01 Living	B01 Bedroom	B02 Living	B02 Bedroom
Data points (n)	4465	4465	4465	4465
MBE (°C)	−0.708	−0.597	−0.611	−0.795
NMBE (%)	−3.60	−3.02	−3.03	−4.12
RMSE (°C)	1.373	0.981	1.322	1.071
CV(RMSE) (%)	6.98	4.96	6.55	5.55

Both metrics passed the ASHRAE Guideline 14 hourly calibration criteria in every zone. The absolute NMBE stayed well below the 10% limit, and CV(RMSE) stayed well below the 30% limit. The slight negative bias across all four zones indicates that the model marginally **under**predicts indoor temperature, which is consistent with uncontrolled occupant behavior that the fixed schedules do not fully capture. These results indicate that the DesignBuilder model is a reliable representation of the buildings' thermal behavior and is suitable for the energy and comfort analysis that follows.

In summary, the three checks validate the credibility of the numerical framework. The COMSOL model accurately replicates the surface thermal behavior of the actual wall and the analytical transmittance of the clear assembly. In contrast, the DesignBuilder model reproduces indoor temperature measurements within the accepted calibration criteria. The subsequent results in this chapter are based on this validated foundation.

4.7 Component-Level Thermal Bridging Results

The component model returns two transmittances for each wall configuration: that of the clear layered assembly, and that of the same assembly with its fixing system in place. The difference between them is the thermal bridging penalty carried by the fixings, and it is this penalty that the building-level model receives as a corrected wall property. Before the eighteen configurations were solved, the treatment of the panel joints was tested to establish whether it had to be carried through the matrix as a variable.

4.7.1 Effect of Joint Mortar

Table 4-12 reports the transmittances of the four stone configurations run with both grouted and open joints.

Table 4-12: Effect of joint mortar on simulated U-values of the stone system

Configuration	Cavity	U with mortar (W/m ² K)	U without mortar (W/m ² K)	Difference
No insulation	10 cm	1.112	1.111	0.09%
Internal insulation	10 cm	0.6563	0.6559	0.05%
External insulation	10 cm	0.6914	0.6907	0.10%
External insulation	15 cm	0.6157	0.6154	0.06%

The results indicate that the difference between grouted and open joints was minimal across all four configurations, with a maximum U-value variation of just 0.10%. This is expected because joints make up only a small part of the total façade area. The main factors influencing overall thermal performance are the continuous insulation layer, the air cavity, and the stainless-steel mechanical fixings. Changing the joint condition affects only a small section of the heat-transfer pathway, while the primary thermal bridge caused by the mechanical fixings remains unaffected.

Based on these findings, the joint condition was excluded as a variable from the subsequent parametric analysis. The largest difference noted was 0.10%, which is considered negligible. Therefore, all subsequent simulations assume mortar-filled joints, which match the actual condition of the case study buildings.

4.7.2 Thermal Transmittance of the Wall Configurations

Simulation trials were carried out in COMSOL Multiphysics for the eighteen wall configurations, using the wall assemblies, fixing systems and dimensions documented in Sections 4.3 and 4.4. Boundary conditions were 20°C internal and 0°C external. The modeled panel area was 0.2025 m² for the stone cell and 0.35 m² for the porcelain cell.

The difference between the two heat flows of each pair is the additional heat passing through the fixings. In the stone system, it was expressed as a point transmittance for the modeled bracket, applied at five brackets per square meter. The porcelain system required different treatment depending on cavity depth, because the behavior of its T-rail changes with depth. At 5 cm, the rail penetrates the externally placed insulation and bears directly on the concrete wall, forming a continuous bridge along its full length, so the correction combines a point transmittance for the L-brackets with a linear transmittance for the rail, referred to the 70 × 50 cm panel module recorded in Section 4.3. At 10 and 15 cm, the rail stands clear of the wall within the cavity and connects to the structure only through discrete brackets, so no continuous bridge exists, and the fixing system was modeled as a unit. The final column of Table 4-13 expresses the correction as a percentage of the clear-wall value, showing by how much the fixing system raises the transmittance of each wall above its nominal design value. The extended simulation results are given in Appendix D.

The internal and external configurations yielded the same clear-wall transmittance across all cavity depths. This equality follows directly from the theory of one-dimensional heat transfer: the two configurations contain the same layers, and the total resistance of a wall is the sum of the resistances of its layers, regardless of their order. Its appearance in the simulation results also serves as an internal check, since the paired configurations were built as separate models, and any difference between them would have indicated an error in geometry or material inputs. The clear-wall values further show that cavity depth matters most when insulation is absent: deepening the cavity from 5 to 15 cm reduced the transmittance of the uninsulated stone wall by 33%, compared

with 21% for the insulated walls, because the air space provides a larger share of the total resistance when no insulation layer is present.

Table 4-13: Simulated thermal transmittance of the eighteen wall configurations.

Case	Cladding	Insulation position	Cavity depth (cm)	U _{clear} (W/m ² K)	χ (W/K)	ψ (W/m ² ·K)	ΔU (W/m ² K)	U _{corr} (W/m ² K)	Increase in U due to fixings (%)
Stone System									
1	Stone	None	5	1.375	0.0020	–	0.01	1.385	0.74%
2	Stone	None	10	1.104	0.0016	–	0.008	1.112	0.71%
3	Stone	None	15	0.922	0.0015	–	0.007	0.93	0.80%
4	Stone	Internal	5	0.74	0.0006	–	0.003	0.743	0.40%
5	Stone	Internal	10	0.654	0.0006	–	0.003	0.656	0.43%
6	Stone	Internal	15	0.585	0.0006	–	0.003	0.588	0.50%
7	Stone	External	5	0.74	0.0112	–	0.056	0.796	7.54%
8	Stone	External	10	0.654	0.0077	–	0.038	0.692	5.86%
9	Stone	External	15	0.585	0.0062	–	0.031	0.616	5.26%
Porcelain System									
1	Porcelain	None	5	1.404	0.0015	0.0229	0.036	1.44	2.56%
2	Porcelain	None	10	1.122	0.0096	–	0.028	1.15	2.46%
3	Porcelain	None	15	0.935	0.0082	–	0.024	0.958	2.51%
4	Porcelain	Internal	5	0.748	0.0004	0.0064	0.01	0.758	1.35%
5	Porcelain	Internal	10	0.66	0.0033	–	0.01	0.67	1.46%
6	Porcelain	Internal	15	0.59	0.0032	–	0.009	0.6	1.56%
7	Porcelain	External	5	0.748	0.0100	0.1092	0.172	0.92	22.96%
8	Porcelain	External	10	0.66	0.0180	–	0.052	0.712	7.83%
9	Porcelain	External	15	0.59	0.0141	–	0.04	0.631	6.83%

The corrected values change this picture entirely (Figure 4-34). The fixing system is identical across the nine cases for each cladding, yet its effect ranges from below 1% to 23%, depending on where the insulation is located. Fixings cause heat loss proportional to the amount of wall resistance they penetrate. In the uninsulated walls, the fixings cross only the air cavity, and the increase stays below 1% for stone and near 2.5% for porcelain. With internal insulation, the fixings remain on the outer side of the XPS and again cross only the cavity, resulting in increases of 0.4 to 1.6%, slightly below those for the uninsulated wall in both systems. But with external insulation, the same fixings pass through the layer that carries about half of the wall's resistance, and the increase ranges from 5.3 to 7.5% for stone and from 6.8 to 23.0% for porcelain. The position of the insulation, therefore, does not determine the wall's performance; it determines how much of that performance the fixing system takes back.

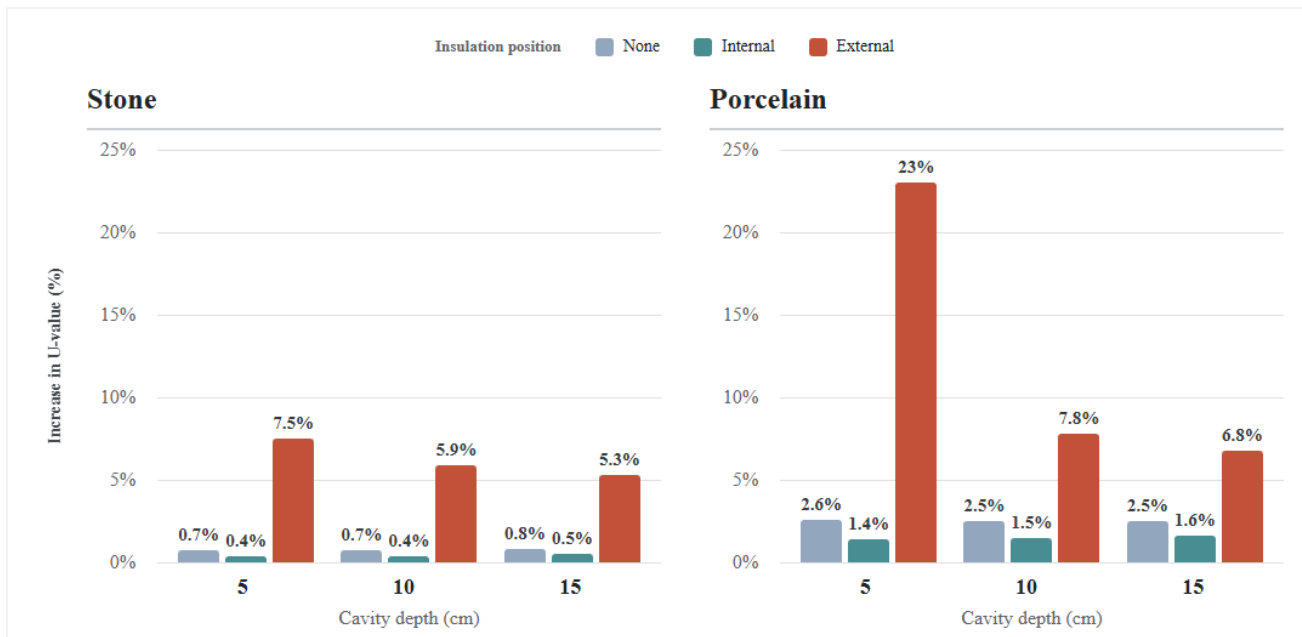


Figure 4-34: Percentage increase in wall thermal transmittance attributable to the fixing system, by cladding material, insulation position and cavity depth.

The increase becomes smaller as the cavity deepens. For the stone system, χ fell from 0.0112 W/K at 5 cm depth to 0.0062 W/K at 15 cm depth because a longer bracket provides a longer path for heat to travel between the concrete and the cladding. The porcelain system shows a far stronger version of the same trend, and its cause lies in the rail geometry. At a depth of 5 cm, the rail passes through the insulation and rests on the concrete. This continuous contact is responsible for most

of the heat loss. Taken separately, the rail alone raises the transmittance by 20.9% ($\psi = 0.109 \text{ W/m}\cdot\text{K}$), and the brackets alone by 3.8%, compared with 23.0% for the two acting together. At a depth of 10 cm, the rail no longer reaches the wall, the continuous bridge disappears, and the increase falls sharply to 7.8%. The internal cases show the opposite and much weaker trend, with the increase in the stone case growing slightly with depth from 0.4 to 0.5%, because ΔU remains effectively constant while the clear-wall value it is compared against decreases.

The difference between the two cladding systems comes from the substructure material. The stone system hangs on stainless-steel brackets. The porcelain system incorporates a continuous aluminum rail, which has higher thermal conductivity than stainless steel. The effect is visible even in the uninsulated walls, where the porcelain fixing system produces about three times the relative increase of the stone brackets.

4.8 Building-Level Thermal Performance

The eighteen wall configurations were simulated at the building level in Design Builder over a full year, using the corrected transmittances of Table 4-13 as the façade wall input. All other settings were held identical across the eighteen runs, so that the wall assembly is the only variable separating one case from another. Each case was run twice, conditioned and free-running, the first giving the zone sensible loads and the second the mean operative indoor temperature and the discomfort hours. Results are reported for the four thermal zones defined in Section 4.4.2: the living and bedroom zones of Building 1 (B1-L, B1-B) and of Building 2 (B2-L, B2-B). the extended simulation results are given in Appendix E.

4.8.1 Summer Thermal Performance of Stone Cladding

Table 4-14 presents the summer thermal performance of the nine stone-clad wall configurations in the four analyzed zones. Cooling demand ranks consistently across all cases, with the uninsulated wall in the 5 cm cavity (Case 1) recording the highest cooling load and the externally insulated wall with the 15 cm cavity (Case 9) consistently providing the lowest. The results indicate that insulation is the primary parameter governing summer cooling demand, while cavity depth provides an additional improvement.

Table 4-14: Summer results for the nine stone-clad configurations across the four zones

Season				Summer											
Cladding				Stone											
Zone				B1 - L			B1 – B (northern)			B2 - L			B2 – B (southern)		
case	insulation position	Cavity (cm)	U-value (W/m ² K)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Cooling Loads (kWh)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Cooling Loads (kWh)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Cooling Loads (kWh)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Cooling Loads (kWh)
1	None	5	1.385	27.15	918	1943.20	29.00	930	495.50	27.21	926	1961.50	29.18	925	593.60
2	None	10	1.112	27.02	894	1796.20	28.95	928	472.60	27.08	902	1810.70	29.11	925	557.40
3	None	15	0.93	26.93	872	1689.10	28.91	928	457.70	26.99	882	1700.80	29.06	926	534.10
4	Internal	5	0.743	26.98	894	1685.30	29.00	932	454.30	27.04	906	1694.80	29.15	929	523.40
5	Internal	10	0.656	26.9	870	1633.30	28.95	932	449.10	26.97	884	1640.30	29.09	928	514.10
6	Internal	15	0.588	26.84	852	1565.60	28.92	930	440.20	26.91	866	1571.70	29.05	928	501.70
7	External	5	0.796	26.93	875	1670.94	28.94	931	448.38	26.98	885	1680.30	29.08	928	517.81
8	External	10	0.692	26.88	858	1626.28	28.91	931	446.19	26.93	872	1633.96	29.05	928	511.87
9	External	15	0.616	26.82	839	1563.10	28.89	931	438.60	26.89	856	1569.80	29.02	928	501.00

The results show that adding insulation provides the greatest reduction in cooling demand. At the same cavity depth, both internal and external insulation substantially reduce cooling loads compared with the uninsulated wall. Relative to the uninsulated Case 1 at a fixed 5 cm cavity, external insulation (Case 7) reduces the cooling load by 14.0%, 9.5%, 14.3%, and 12.8% in B1-L, B1-B, B2-L, and B2-B, respectively, while internal insulation (Case 4) cuts load by 13.3%, 8.3%, 13.6%, and 11.8% in the same zones. The external position therefore yields a slightly larger reduction than the internal position in all four zones (Figure 4-35). Still, the margin between the two is small: no more than 1.2% at 5 cm and narrowing to below 0.4% at 15 cm. The southern bedroom (B2-B) shows a consistently higher cooling load than the northern bedroom (B1-B), reflecting its orientation.

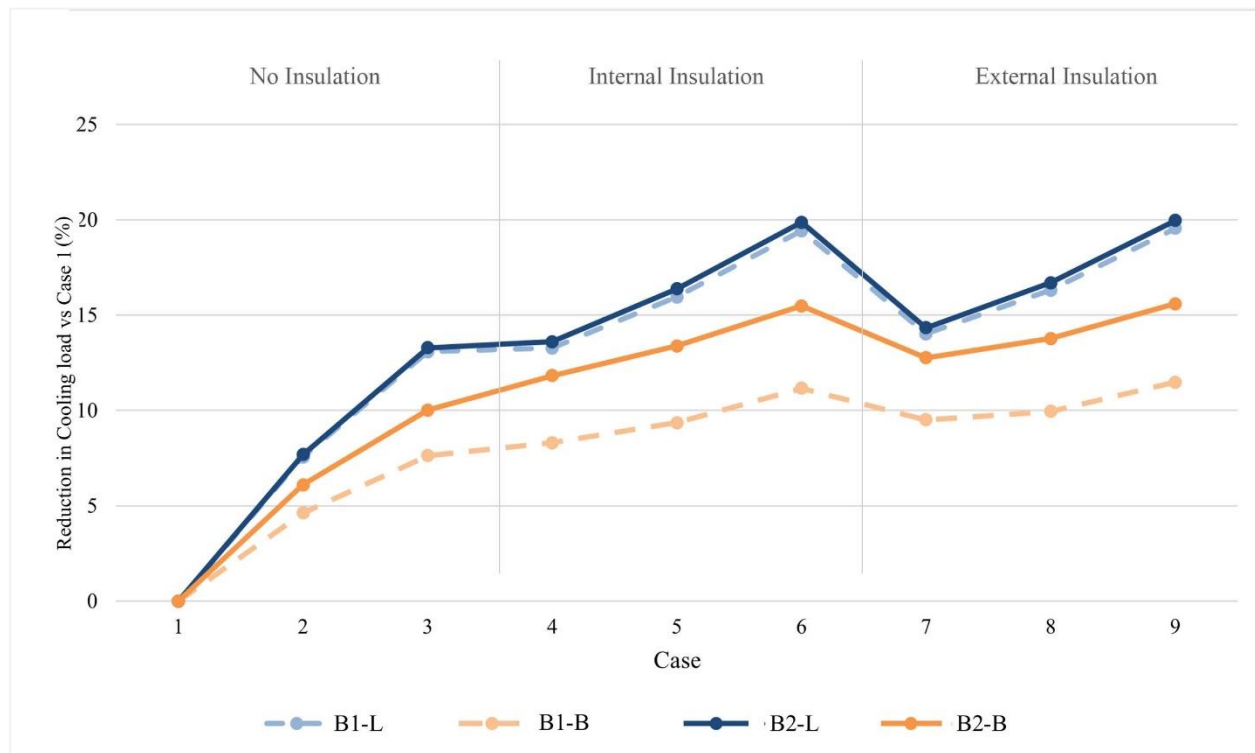


Figure 4-35: Summer cooling load reduction relative to Case 1, stone cladding, four zones

Cavity depth further improves summer performance. In the uninsulated wall, increasing the cavity from 5 cm to 10 cm reduces the B1-L cooling load by 7.6%, and increasing it further to 15 cm reduces it by an additional 6.0%. The equivalent steps are smaller once insulation is present: 3.1% and 4.2% for internal insulation, and 2.7% and 3.9% for external insulation, in the same zone. The bedrooms follow the same direction. The results also show that the uninsulated 15 cm cavity (Case

3) performs almost the same as the insulated 5 cm cavity (Case 4), despite its much higher corrected U-value (0.930 vs. 0.743 W/m²K).

The best performance is achieved by the 15 cm cavity combined with external insulation (Case 9), which reduces cooling demand by 19.6%, 11.5%, 20.0%, and 15.6% in B1-L, B1-B, B2-L, and B2-B, respectively, compared with the reference case.

The comfort indicators confirm the thermal benefits of increasing cavity depth and adding insulation. Mean operative temperature decreases by around 0.3 °C across the nine cases in the living zones, with the lowest values consistently observed in Case 9; in the bedrooms, it varies by no more than 0.16 °C (Figure 4-36). Discomfort hours follow the same trend, particularly in the living rooms, where they decrease from 918 to 839 h in B1-L and from 926 to 856 h in B2-L between Cases 1 and 9, while in the bedrooms they remain almost constant (Figure 4-37). The influence of orientation is evident in the operative temperature, with the south-facing bedroom (B2-B) running 0.13 to 0.18 °C warmer than the north-facing bedroom (B1-B) across all wall configurations. The two indicators are not directly comparable. Mean operative temperature locates the center of the seasonal temperature distribution. In contrast, discomfort hours count as occupied hours that fall outside a fixed range, so a zone can record a higher mean while returning a similar or lower number of discomfort hours. Consequently, cooling load remains the most sensitive indicator for distinguishing the performance of the stone wall configurations.

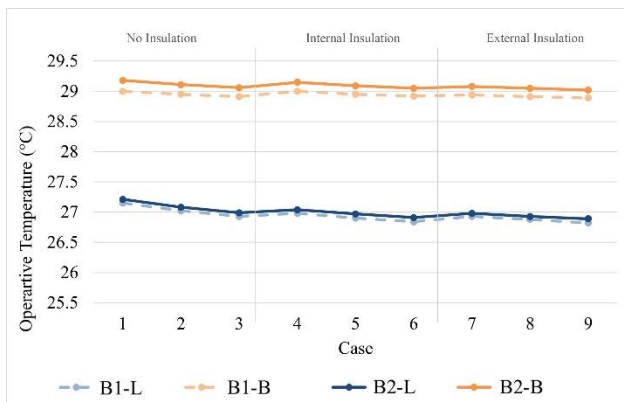


Figure 4-36: Mean summer operative temperature, stone cladding, four zones

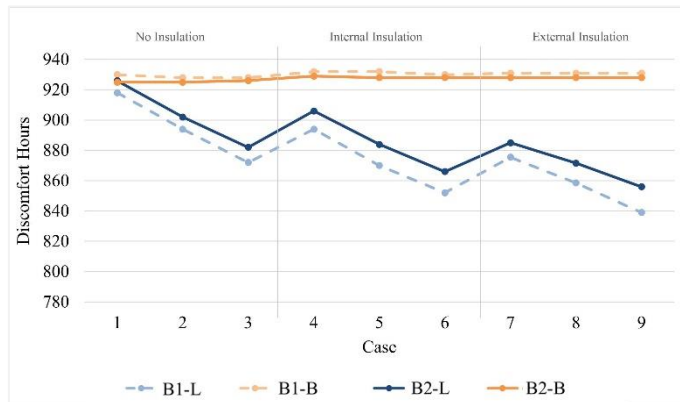


Figure 4-37: Summer discomfort hours, stone cladding, four zones

4.8.2 Summer Thermal Performance of Porcelain Cladding

Table 4-15 presents the summer results for the nine porcelain-clad configurations. The cooling-load ranking is identical to that observed for the stone system. Case 1 remains the poorest performer, whereas Case 9 delivers the best performance. Insulation remains the dominant design variable, while cavity depth provides a secondary improvement.

Table 4-15: Summer results for the nine porcelain-clad configurations across the four zones

Season				Summer											
Cladding				Porcelain											
Zone				B1 - L			B1 - B			B2 - L			B2 - B		
case	insulation	Cavity (cm)	U-value (W/m ² K)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Cooling Loads (kWh)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Cooling Loads (kWh)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Cooling Loads (kWh)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Cooling Loads (kWh)
1	None	5	1.44	26.72	828	1646.10	28.58	901	431.60	26.77	838	1660.90	28.73	898	503.60
2	None	10	1.15	26.66	806	1555.80	28.59	904	420.10	26.71	818	1568.40	28.73	901	484.70
3	None	15	0.958	26.61	790	1487.30	28.6	904	412.90	26.67	804	1497.70	28.73	900	472.80
4	Internal	5	0.758	26.71	832	1544.50	28.73	916	423.90	26.77	845	1551.90	28.86	913	480.20
5	Internal	10	0.67	26.66	810	1485.40	28.71	915	416.10	26.72	826	1491.60	28.84	913	469.60
6	Internal	15	0.6	26.62	796	1434.90	28.7	914	410.60	26.69	810	1440.60	28.82	913	462.00
7	External	5	0.92	26.66	804	1520.40	28.62	908	414.00	26.7	811	1530.10	28.75	902	472.40
8	External	10	0.712	26.6	788	1452.90	28.65	908	408.20	26.67	800	1460.30	28.77	906	461.60
9	External	15	0.631	26.58	774	1407.30	28.64	908	404.10	26.64	790	1413.80	28.77	906	455.60

The position of the insulation again has only a minor influence on summer performance, and the porcelain system tests this under a far more severe thermal bridge. At the 5 cm cavity, the T-profile contacts the structural wall, raising the corrected U-value of the externally insulated configuration to 0.920 against 0.758 W/m²K for the internally insulated one, a penalty of 21%. It still achieves a lower cooling load, at 1520.40 kWh versus 1544.50 kWh in B1-L, and the external configuration remains lower across all twelve zone-depth comparisons. Insulation and cavity depth act in the same direction as in the stone system, but return smaller savings. In B1-L, internal insulation with a 5 cm cavity reduces the cooling load by 6.2% relative to the uninsulated reference, compared with 13.3% for the equivalent stone configuration. Deepening the cavity from 5 cm to 15 cm without insulation reduces the cooling load by 9.6%, compared with 13.1% for stone. The best case, Case 9, saves 14.5% against the reference, compared with 19.6% for stone. Similar trends are observed in the remaining three zones, although the magnitude of the savings varies with orientation and room type (Figure 4-38).

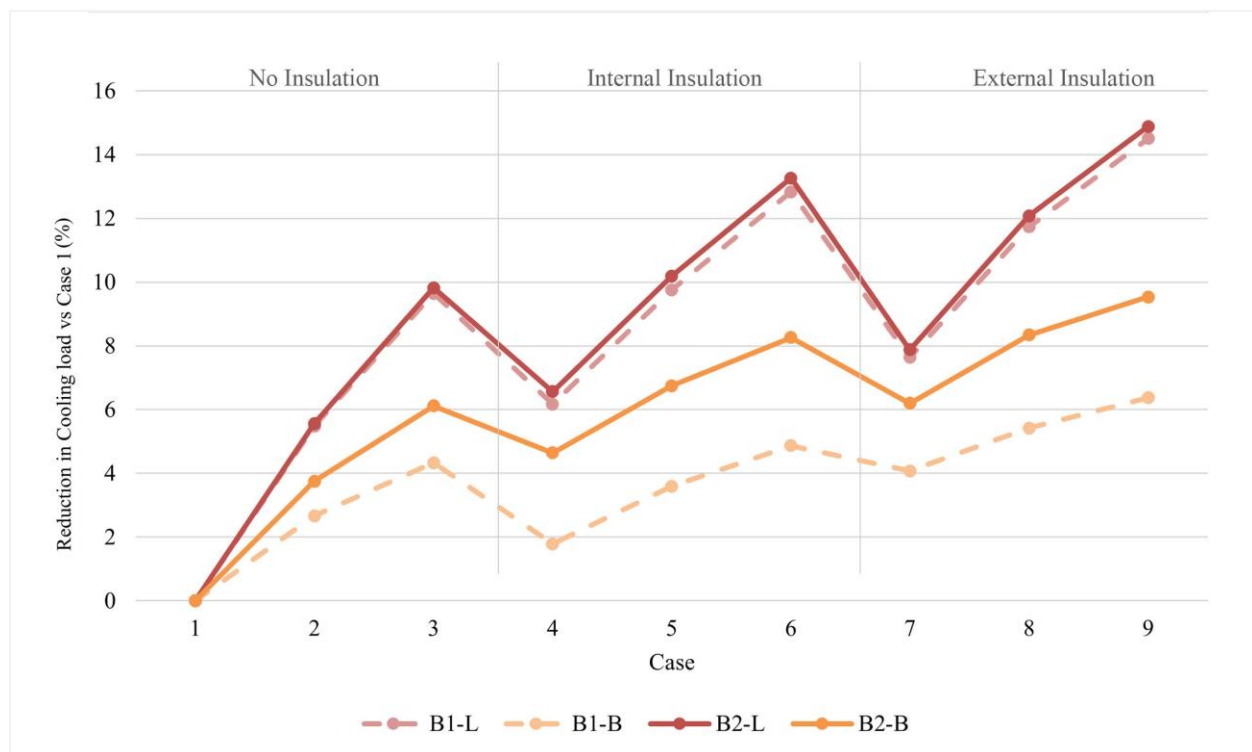


Figure 4-38: Summer cooling load reduction relative to Case 1, porcelain cladding, four zones

The comfort indicators distinguish the wall configurations more clearly than the cooling loads and reveal a different response in the bedrooms. At the same cavity depth, external insulation

consistently records fewer discomfort hours and lower mean operative temperatures than internal insulation in all four zones (Figure 4-40). Increasing the cavity depth also improves comfort in the living rooms, where Case 9 achieves the best performance, reducing discomfort hours from 828 to 774 h in B1-L and from 838 to 790 h in B2-L. In contrast, the bedrooms exhibit a different trend. The uninsulated wall records the fewest discomfort hours, with 901 and 898 h in B1-B and B2-B, respectively. In contrast, internal insulation increases these values to 916 and 913 h despite reducing the seasonal cooling load by approximately 2–4%.

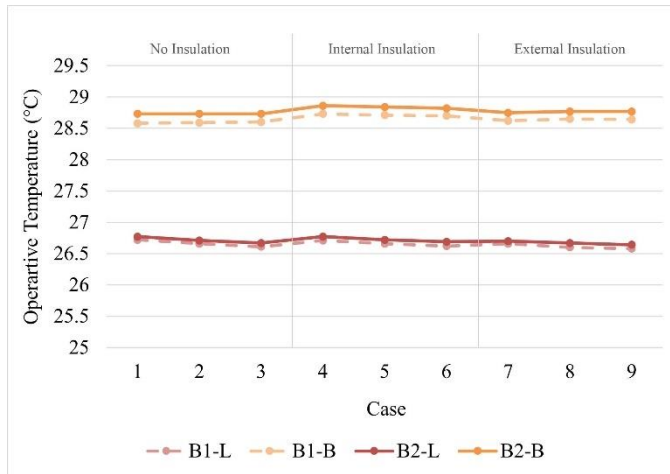


Figure 4-39: Mean summer operative temperature, porcelain cladding, four zones

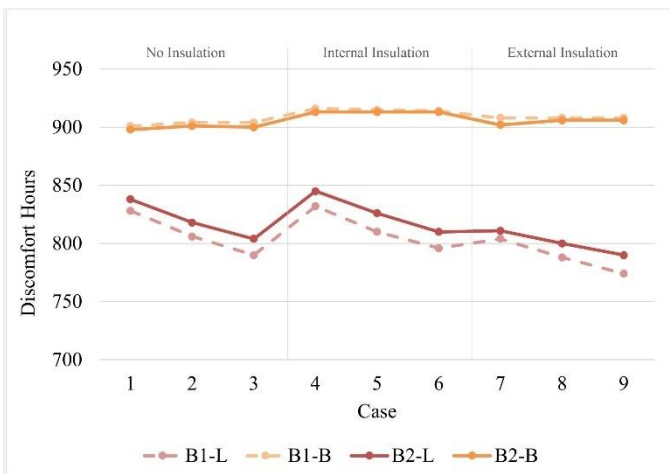


Figure 4-40: Summer discomfort hours, porcelain cladding, four zones

Mean operative temperatures follow the same trend (Figures 4-39). At the 5 cm cavity, for example, B1-B records 28.58 °C for the uninsulated wall, 28.62 °C for external insulation, and 28.73 °C for internal insulation, while B2-B records 28.73, 28.75, and 28.86 °C, respectively.

4.8.3 Winter Thermal Performance of Stone Cladding

Table 4-16 presents the winter thermal performance of the nine stone-clad wall configurations across the four analyzed zones. In contrast to the summer results, the internally insulated configurations consistently record the lowest heating loads, while the uninsulated walls remain the poorest performers. Insulation remains the dominant design variable, whereas cavity depth provides an additional, albeit smaller, reduction in heating demand.

Table 4-16: Winter results for the nine stone-clad configurations across the four zones

Season				Winter											
Cladding				Stone											
Zone				B1 - L			B1 - B			B2 - L			B2 - B		
case	insulation	Cavity (cm)	U-value (W/m ² K)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Heating Loads (kWh)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Heating Loads (kWh)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Heating Loads (kWh)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Heating Loads (kWh)
1	None	5	1.385	17.3	1096	2213.70	15.09	990	354.70	16.93	1156	2502.30	16.36	990	210.10
2	None	10	1.112	17.46	1088	2036.50	15.25	990	323.70	17.05	1160	2339.50	16.39	990	200.50
3	None	15	0.93	17.59	1079	1905.50	15.39	990	300.90	17.14	1159	2217.40	16.42	990	192.20
4	Internal	5	0.743	17.74	1046	1801.60	15.54	990	283.60	17.26	1144	2119.90	16.49	990	188.60
5	Internal	10	0.656	17.8	1044	1717.50	15.61	990	269.40	17.3	1146	2040.30	16.49	990	182.10
6	Internal	15	0.588	17.87	1042	1658.90	15.67	990	259.10	17.35	1146	1987.40	16.51	990	177.60
7	External	5	0.796	17.7	1069	1834.14	15.51	990	288.14	17.22	1155	2154.43	16.47	990	190.22
8	External	10	0.692	17.79	1062	1735.54	15.6	990	271.50	17.3	1155	2059.39	16.5	990	182.26
9	External	15	0.616	17.87	1054	1672.50	15.68	990	260.70	17.35	1154	2001.20	16.53	990	177.70

At a constant cavity depth, both insulation positions substantially reduce the seasonal heating load compared with the uninsulated reference wall. In the 5 cm cavity, internal insulation (Case 4) reduces the heating load by 412.10 kWh in B1-L, 71.10 kWh in B1-B, 382.40 kWh in B2-L, and 21.50 kWh in B2-B. The corresponding externally insulated configuration (Case 7) records slightly higher heating loads. Although the differences between the two insulation positions remain relatively small, internal insulation consistently yields the lowest heating demand across all 12 zone-depth comparisons.

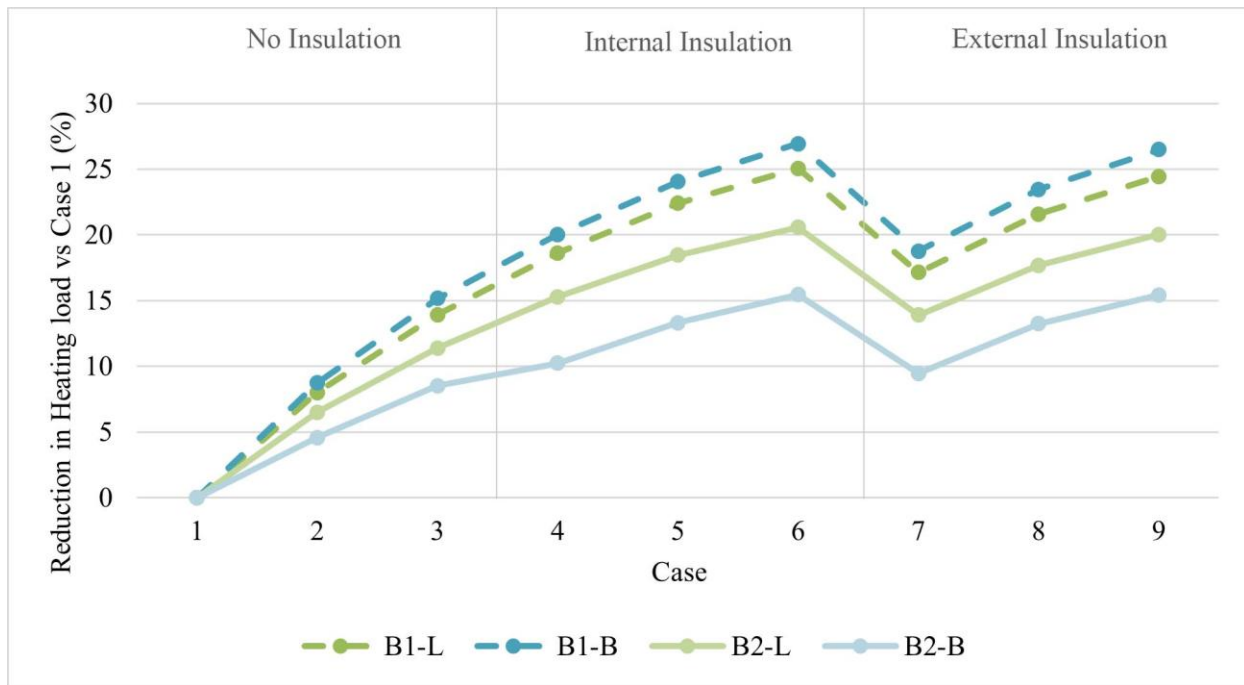


Figure 4-41: Winter heating load reduction relative to Case 1, stone cladding, four zones

Increasing cavity depth further improves winter performance for all wall configurations. For the uninsulated wall, increasing the cavity depth from 5 cm to 15 cm reduces the heating load by 13.9% in B1-L, 15.2% in B1-B, 11.4% in B2-L, and 8.5% in B2-B (Figure 4-41). Similar reductions are observed for the insulated configurations, although the incremental improvement decreases with increasing cavity depth.

The combined influence of insulation and cavity depth is reflected in the overall performance of the wall configurations. Case 1 records the highest heating load in every analyzed zone, whereas Case 6, comprising internal insulation with a 15 cm cavity, consistently achieves the lowest values.

Relative to the reference configuration, Case 6 reduces the seasonal heating demand by 25.1% in B1-L, 27.0% in B1-B, 20.6% in B2-L, and 15.5% in B2-B.

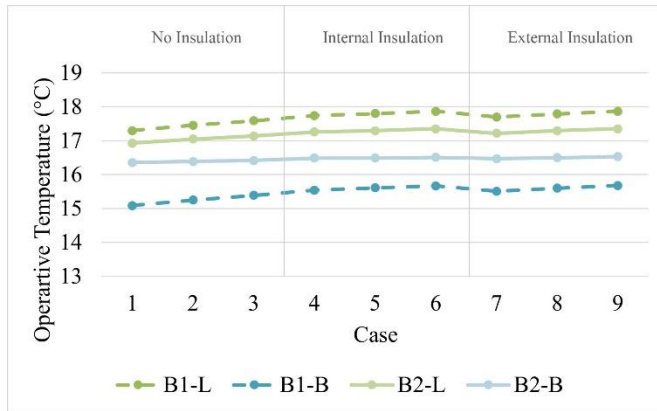


Figure 4-42: Mean winter operative temperature, stone cladding, four zones

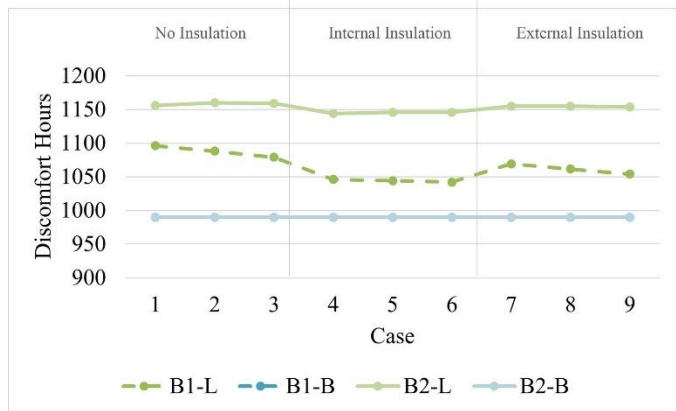


Figure 4-43: Winter discomfort hours, stone cladding, four zones

Under free-running conditions, the mean operative temperature in B1-L increases from 17.30 °C in Case 1 to 17.87 °C in Case 6, a gain of 0.57 °C, while B2-L increases from 16.93 °C to 17.35 °C. In the bedrooms, the variation is even smaller, ranging from 15.09 to 15.68 °C in B1-B and from 16.36 to 16.53 °C in B2-B (Figure 4-42). Every zone remains well below the lower comfort limit throughout the heating season. Accordingly, discomfort hours remain unchanged in both bedrooms across all nine configurations, while the living rooms show a reduction from 1096 to 1042 h in B1-L and from 1160 h to 1144 h in B2-L (Figure 4-43). Overall, heating load provides the clearest distinction between the wall configurations during winter, whereas the thermal comfort indicators show only minor differences.

4.8.4 Winter Thermal Performance of Porcelain Cladding

Table 4-17 presents the winter thermal performance of the nine porcelain-clad wall configurations across the four analyzed zones. Similar to the stone system, the uninsulated wall with a 5 cm cavity (Case 1) records the highest heating load in every zone, whereas the internally insulated wall with a 15 cm cavity (Case 6) consistently achieves the lowest heating load. Internal insulation remains the best-performing insulation position throughout the winter season, while cavity depth provides an additional reduction in heating demand.

Table 4-17: Winter results for the nine porcelain-clad configurations across the four zones

Season				Winter											
Cladding				Porcelain											
Zone				B1 - L			B1 - B			B2 - L			B2 - B		
case	insulation	Cavity (cm)	U-value (W/m ² K)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Heating Loads (kWh)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Heating Loads (kWh)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Heating Loads (kWh)	Mean Operative Indoor Temp (°C)	Discomfort hours	Zone Sensible Heating Loads (kWh)
1	None	5	1.44	16.93	1138	2531.90	14.76	990	397.50	16.51	1168	2874.90	15.8	990	267.20
2	None	10	1.15	17.14	1122	2293.30	14.97	990	357.90	16.69	1167	2645.90	15.91	990	246.70
3	None	15	0.958	17.31	1112	2124.80	15.12	990	329.80	16.83	1167	2481.70	16	990	231.30
4	Internal	5	0.758	17.51	1084	1952.90	15.33	990	303.30	16.99	1164	2311.40	16.13	990	217.70
5	Internal	10	0.67	17.59	1080	1866.20	15.42	990	288.80	17.06	1166	2227.30	16.18	990	209.50
6	Internal	15	0.6	17.68	1074	1793.00	15.49	990	276.60	17.13	1166	2155.80	16.22	990	202.20
7	External	5	0.92	17.38	1105	2093.60	15.18	990	324.90	16.87	1166	2450.20	16.04	990	229.10
8	External	10	0.712	17.57	1093	1893.00	15.39	990	292.10	17.04	1166	2253.90	16.17	990	210.60
9	External	15	0.631	17.67	1084	1811.30	15.48	990	278.80	17.12	1166	2173.50	16.22	990	202.80

At a constant cavity depth, both insulation positions substantially reduce the seasonal heating load relative to the uninsulated reference wall. At the 5 cm cavity, internal insulation (Case 4) reduces the heating load by 22.9%, 23.7%, 19.6%, and 18.5% in B1-L, B1-B, B2-L, and B2-B, respectively (Figure 4-44). The corresponding externally insulated wall (Case 7) achieves slightly smaller reductions of 17.3%, 18.3%, 14.8%, and 14.3% in the same zones, respectively. Internal

insulation, therefore, records the lowest heating demand in all twelve zone-depth comparisons, although the difference between the two insulation positions decreases as the cavity depth increases.

Increasing the cavity depth further improves winter performance for all wall configurations. For the uninsulated wall, increasing the cavity depth from 5 cm to 15 cm reduces the heating load by 16.1%, 17.0%, 13.7%, and 13.4% in B1-L, B1-B, B2-L, and B2-B, respectively (Figure 4-44). Similar trends are observed in the insulated configurations, although the incremental improvement becomes smaller as the cavity depth increases.

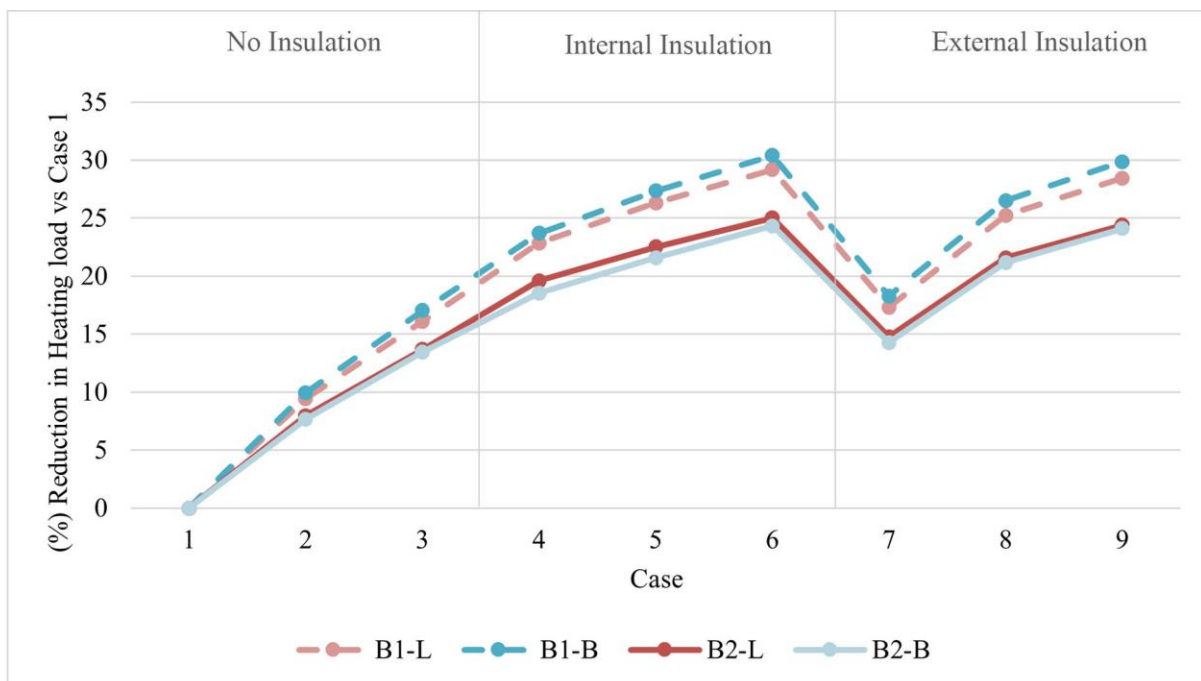


Figure 4-44: Winter heating load reduction relative to Case 1, porcelain cladding, four zones

The combined effect of insulation and cavity depth is reflected in the overall ranking of the wall configurations. Case 6, combining internal insulation with a 15 cm cavity, consistently achieves the lowest heating load, reducing seasonal heating demand by 29.2%, 30.4%, 25.0%, and 24.3% in B1-L, B1-B, B2-L, and B2-B, respectively, relative to the reference Case 1.

Case 7 departs from the pattern. Although it has the same 3 cm of insulation as Cases 4 to 6, its reductions range from 4.3 to 5.6 percentage points below those of the internally insulated wall at the same cavity depth. In contrast, the equivalent gap in the stone system does not exceed 1.5

percentage points. The cause lies in the corrected transmittance of $0.920 \text{ W/m}^2\text{K}$, since the supporting T-rail makes direct contact with the structural wall at the 5 cm cavity and forms a combined point and linear bridge, raising the fixing penalty to 23.0% against 7.8% and 6.8% at the 10 cm and 15 cm cavities (Section 4.7.2).

Compared with the corresponding stone-clad configurations, the porcelain system records higher heating loads throughout the winter season. In B1-L, the heating load increases from 2213.70 kWh in the stone system to 2531.90 kWh in the porcelain system in Case 1, representing a 14.4% increase. For the best-performing configuration (Case 6), the heating load increases from 1658.90 to 1793.00 kWh, representing an 8.1% increase. Similar differences are observed in the remaining three zones across all wall configurations. The difference is largest in Case 7, where the porcelain load exceeds the stone value by 14.2% in B1-L, compared with 8.1%-9.1% in the remaining insulated configurations.

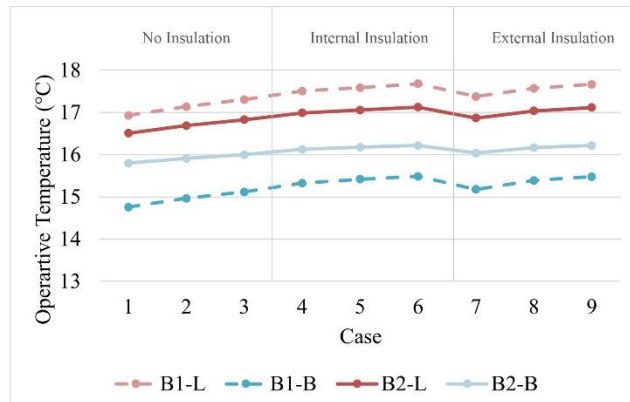


Figure 4-45: Mean winter operative temperature, porcelain cladding, four zones

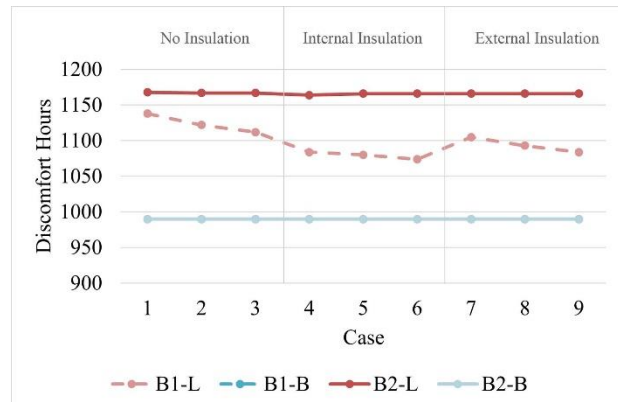


Figure 4-46: Winter discomfort hours, porcelain cladding, four zones

The thermal comfort results show only a limited response to changes in the wall configuration. Mean operative temperature in B1-L increases from $16.93 \text{ }^{\circ}\text{C}$ in Case 1 to $17.68 \text{ }^{\circ}\text{C}$ in Case 6, while B2-L increases from $16.51 \text{ }^{\circ}\text{C}$ to $17.13 \text{ }^{\circ}\text{C}$. In the bedrooms, the variation is smaller, ranging from 14.76 to $15.49 \text{ }^{\circ}\text{C}$ in B1-B and from 15.80 to $16.22 \text{ }^{\circ}\text{C}$ in B2-B (Figure 4-45). All zones remain below the lower comfort limit throughout the heating season. Case 7 is the exception. Its mean operative temperature falls below Case 6 in all four zones, recording $17.38 \text{ }^{\circ}\text{C}$ against $17.68 \text{ }^{\circ}\text{C}$ in B1-L, $15.18 \text{ }^{\circ}\text{C}$ against $15.49 \text{ }^{\circ}\text{C}$ in B1-B, $16.87 \text{ }^{\circ}\text{C}$ against $17.13 \text{ }^{\circ}\text{C}$ in B2-L, and $16.04 \text{ }^{\circ}\text{C}$ against $16.22 \text{ }^{\circ}\text{C}$ in B2-B.

Discomfort hours exhibit only minor variation. In the living rooms, discomfort hours decrease from 1138 to 1074 h in B1-L and from 1168 to 1166 h in B2-L between Cases 1 and 6 (Figure 4-46). In both bedrooms, the number of discomfort hours remains unchanged across all nine wall configurations despite the reduced heating load and the slight increase in operative temperature. Overall, the heating-load results clearly distinguish the performance of the wall configurations, whereas the thermal comfort indicators show only minor differences between cases during the winter season, with Case 7 the only exception.

4.8.5 Annual Performance

Table 4-18 presents the annual sensible loads of the four analyzed zones. Unlike the seasonal analyses, the annual results reflect the net effect of each design parameter. Some parameters retain their influence at the annual scale, whereas others offset one another between the two seasons. The results can therefore be summarized into four principal findings.

The first finding is that the presence of insulation remains the dominant design parameter. Adding 3 cm of insulation at an unchanged 5 cm cavity reduces the annual load in B1-L from 4156.90 kWh in Case 1 to 3486.90 kWh in Case 4, a reduction of 16.1%. The other zones follow the same step: 13.2% in B1-B, 14.5% in B2-L, and 11.4% in B2-B. The porcelain system responds similarly, and Case 4 reduces the annual load in B1-L by 16.3% relative to the uninsulated reference. No other single parameter in the matrix produces reductions of this size.

The second finding is that increasing cavity depth adds a further reduction, though with diminishing returns. In an uninsulated stone wall, increasing the cavity depth from 5 cm to 15 cm reduces the B1-L load by 13.5%. The same change in the insulated wall yields 7.5%. The remaining zones and the porcelain system show the same trend. The insulated configurations with a 15 cm cavity give the lowest annual loads throughout. In the stone system, Cases 6 and 9 reduce the B1-L load by 22.4% and 22.2%, respectively, relative to Case 1, with reductions of 17.7% in B1-B, 20.3% and 20.0% in B2-L, and 15.5% in B2-B. The porcelain system reaches comparable values, and Case 9 achieves a 23.0% reduction in B1-L (Figure 4-47).

Table 4-18: Annual results for both stone-clad and porcelain-clad configurations across the four zones

Annual zone sensible loads												
Cladding			Stone					Porcelain				
Zone			U-value (W/m ² K)	B1 - L	B1 - B	B2 - L	B2 - B	U-value (W/m ² K)	B1 - L	B1 - B	B2 - L	B2 - B
case	Insulation	Cavity (cm)										
1	None	5	1.385	4156.9	850.20	4463.8	803.7	1.44	4178	829.10	4535.8	770.8
2	None	10	1.112	3832.7	796.30	4150.2	757.9	1.15	3849.1	778.00	4214.3	731.4
3	None	15	0.93	3594.6	758.60	3918.2	726.3	0.958	3612.1	742.70	3979.4	704.1
4	Internal	5	0.743	3486.9	737.90	3814.7	712	0.758	3497.4	727.20	3863.3	697.9
5	Internal	10	0.656	3350.8	718.50	3680.6	696.2	0.67	3351.6	704.90	3718.9	679.1
6	Internal	15	0.588	3224.5	699.30	3559.1	679.3	0.6	3227.9	687.20	3596.4	664.2
7	External	5	0.796	3505.08	736.52	3834.73	708.03	0.92	3614	738.90	3980.3	701.5
8	External	10	0.692	3361.82	717.69	3693.35	694.13	0.712	3345.9	700.30	3714.2	672.2
9	External	15	0.616	3235.6	699.30	3571	678.7	0.631	3218.6	682.90	3587.3	658.4

The third finding concerns the externally insulated porcelain configuration at the 5 cm cavity depth. Case 7 reduces the annual load by only 13.5%, compared with 16.3% for the internally insulated Case 4 in B1-L (Figure 4-47), and the gap between the two positions ranges from 3.0% to 3.3% in the living zones. At cavity depths of 10 cm and 15 cm, the annual gap is approximately 1% or less across all analyzed zones. The behavior follows from the fixing penalty quantified in Section 4.7.2.

The penalty is large enough to cancel the insulation completely. Case 7 records an annual load of 3614.00 kWh in B1-L, compared with 3612.10 kWh for the uninsulated Case 3, and 3980.30 kWh in B2-L, compared with 3979.40 kWh. Their corrected transmittances converge on 0.920 and 0.958 W/m²K, so the two assemblies transmit heat at nearly the same rate, although only one carries a 3-cm insulation layer. The equivalent stone configuration retains a 2.1% to 2.9%

advantage over its uninsulated 15 cm counterpart across all zones, confirming that the cancellation is specific to the continuous rail of the porcelain system.

The fourth finding concerns the comparison between the two cladding materials. In Case 1, the uninsulated wall with a 5 cm cavity, the porcelain annual loads are 0.5% and 1.6% higher than the

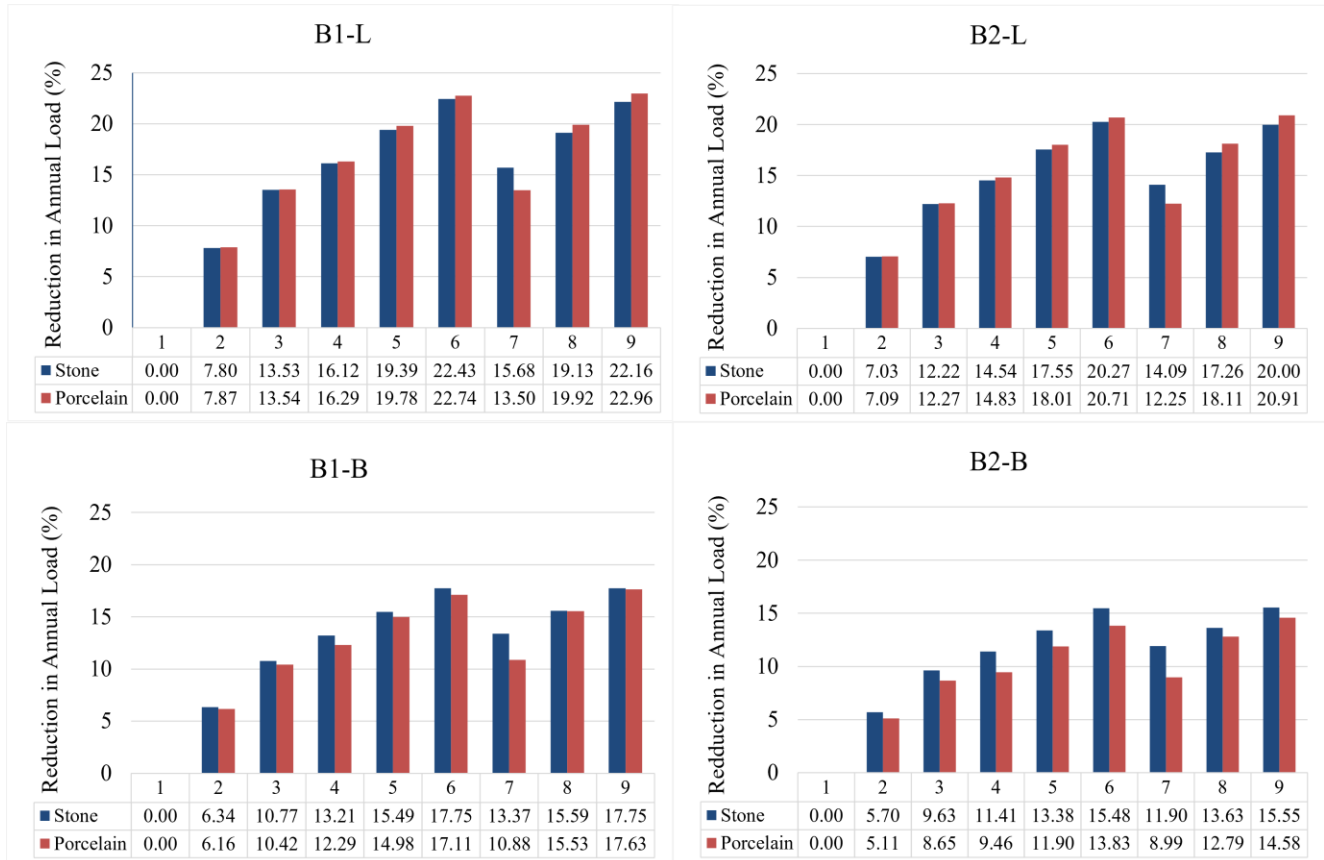


Figure 4-47: Annual sensible load reduction relative to the uninsulated 5 cm cavity case, by zone and cladding material. Each cladding system is referenced to its own Case 1.

stone loads in B1-L and B2-L, and 2.5% and 4.1% lower in B1-B and B2-B. The divergence follows from the seasonal balance of each zone rather than from the cladding itself. Porcelain shows higher heating loads and lower cooling loads across all four zones, so the annual outcome depends on which season contributes the larger share of annual demand. In the stone system, the heating share of the annual load decreases from 56% in B2-L and 53% in B1-L to 42% in B1-B and 26% in B2-B. The porcelain penalty, therefore, appears in the heating-dominated living zones, and the porcelain advantage in the cooling-dominated bedrooms. The same pattern persists throughout the simulation matrix. The living-zone difference remains between -0.5% and $+1.6\%$ in every configuration except Case 7, where the porcelain penalty increases to 3.11% in B1-L and

3.80% in B2-L. The bedroom advantage remains between 1.5% and 4.1% except in Case 7, where it falls to 0.9% in B2-B and reverses to a 0.3% penalty in B1-B.

4.9 Discussion

The results of Sections 4.7 and 4.8 are interpreted in this section against the physical mechanisms that produce them and against the published evidence on mechanically fixed and ventilated cladding. Four properties govern the outcomes: the presence of insulation, the depth of the cavity, the position of the insulation relative to the fixings, and the areal heat capacity of the cladding panel.

4.9.1 Effect of Insulation and Cavity Depth

Insulation is the dominant design parameter across both seasons and all four zones, consistent with Palestinian evidence. Al Qadi et al. (2018) identified the wall insulation level as a significant predictor of household heating consumption in Hebron, and Haj Hussein et al. (2022) reported that introducing wall insulation reduced simulated heating demand by 43-83% across Palestinian building types and climate zones. The equivalent step in the present study, adding 3 cm of XPS at an unchanged 5 cm cavity, reduces seasonal heating demand by 10.2 to 20.1% in the stone system, rising to 15.5 to 27.0% when internal insulation is combined with a 15 cm cavity. The lower magnitude reflects the single 3 cm layer tested here, compared with the thicker assemblies modeled by Haj Hussein et al. (2022).

The diminishing returns of cavity depth agree with the ventilated façade literature. Balocco (2002) found that the summer cooling benefit stabilizes once cavity width exceeds approximately 7 cm, and Roig et al. (2024) reported lower average heat flux as the cavity widens towards 10 cm. The agreement is in the trend rather than the mechanism, since the present cavities are treated as unventilated in accordance with ISO 6946 and the benefit accrues through added thermal resistance rather than convective heat removal.

The relative weight of the two parameters shifts with the wall's thermal state. Deepening the uninsulated stone cavity from 5 to 15 cm reduces the clear-wall transmittance by 33%, against 21% for the insulated walls, because the air space carries a larger share of the total resistance when

no insulation layer is present. The same asymmetry appears at the building scale, where deepening the cavity lowers the annual load in B1-L by 13.5% for the uninsulated stone wall and by 7.5% for the insulated one. Cavity depth is therefore a substitute for insulation only in the uninsulated wall, and a secondary refinement once insulation is present.

4.9.2 Effect of Cladding Material

The summer advantage of the porcelain system, 6.7 to 15.3% across all 36 paired comparisons, originates in the cladding layer rather than in the wall behind it. The governing property is the areal heat capacity of the outermost layer, the product of thickness, density, and specific heat capacity (ISO 13786, 2017). The stone panel is 30 mm thick at 2250 kg/m³ and 1000 J/kgK, giving 67.5 kJ/m²K, whereas the 6 mm porcelain panel at 2400 kg/m³ and 900 J/kgK gives 13.0 kJ/m²K, one-fifth of the stone value (Table 4-6). The stone cladding absorbs and stores solar radiation through the day and releases it into the cavity for several hours after sunset, sustaining inward heat flow into the evening. The porcelain panel stores almost no heat, heating rapidly under peak irradiation and shedding it as soon as the solar load drops, so the heat delivered to the structural wall over the full daily cycle is smaller.

This reverses the ranking reported for ventilated systems. Stazi et al. (2020) analyzed narrow-cavity façades with heavy external cladding against identical lightweight enclosures. They found that the heavy cladding reduced external and internal surface temperatures by 2 °C and 1 °C in summer, acting as a buffer between outdoor conditions and the ventilation chamber while also increasing air velocity in the gap. Their cavities were open, so the buffering depends on the cavity removing heat before it reaches the structural wall. In the closed cavities modeled here, the stored heat has no escape route, and the mass that buffers in a ventilated façade instead acts as a reservoir, releasing heat inward after sunset. The reversal follows from the cavity condition rather than from the cladding properties, which is why findings from ventilated façades cannot be transferred directly to sealed assemblies.

The winter penalty of the porcelain system, 6.8 to 27.2% across the same 36 comparisons, is the same mechanism in the opposite season. Solar heat stored in the stone panel raises the mean cavity temperature during and after the day, offsetting part of the conductive loss. In contrast, the low-capacity porcelain panel offers no such buffer, and the higher corrected transmittances of the

porcelain configurations widen the gap further. The penalty stays within a narrow band in the living zones, 8.1 to 14.4% in B1-L and 8.5 to 14.9% in B2-L, and spreads in the bedrooms, 6.8 to 12.8% in the northern bedroom and 13.9 to 27.2% in the southern.

The two seasonal effects largely cancel over the year. For externally insulated configurations in the 10- and 15-cm cavities, the annual loads in the living zones differ by 0.6%, while the porcelain bedrooms retain an advantage of 2.4- 3.2%. Cladding material therefore shifts the seasonal composition of heat transfer more than the annual total, and the choice between the two systems depends on which season and which metric the design prioritizes.

4.9.3 Effect of Insulation Position

The two insulation positions divide the seasons between them. Internal insulation records the lowest heating load, and external insulation the lowest cooling load, in every zone-depth comparison for both cladding systems. The division reflects two distinct heat-transfer regimes.

The winter ranking follows from the corrected transmittances reported in Section 4.7.2. A sustained indoor-outdoor temperature difference governs heating loss, so corrected transmittance is the controlling property, with transient effects secondary (Al-Sanea et al., 2012; Rossi and Rocco, 2014). Internal insulation results in a lower corrected transmittance in all cases because the anchors and rails are outside the insulation layer and do not contribute to the principal resistance. In contrast, externally insulated assemblies are crossed by fixings that create point bridges and, in the porcelain system, an additional linear bridge at the 5 cm cavity (Theodosiou et al., 2015; Petresevics and Nagy, 2022). In the stone system, the heating load difference between the two positions in B1-L falls from 1.8% at the 5 cm cavity to 0.8% at 15 cm as the bridging penalty falls. The effect is larger in the porcelain system, where the T-rail contacts the structural wall at the 5 cm cavity, raising the corrected transmittance by 21% above the internally insulated equivalent, and diminishes as deeper cavities separate the rail from the wall.

The summer ranking cannot be read from the corrected transmittance. Summer performance depends more on the transient response of the envelope, through storage and periodic heat transfer, while winter performance depends on the steady loss expressed by the effective transmittance (Al-Sanea et al., 2012; Rossi and Rocco, 2014; Mazzeo, Oliveti and Arcuri, 2016). The present results

follow that pattern. Externally insulated configurations achieve higher corrected transmittance yet record slightly lower cooling loads than their internally insulated counterparts, including the 5 cm porcelain case, where the transmittance penalty reaches 21%. The small summer differences arise from the combined action of storage and transient conduction in a heavyweight assembly rather than from any single steady-state property.

At annual scale, the two seasonal benefits offset each other. The position gap falls below 0.6% in the stone system and to about 1% in the porcelain system for the 10- and 15-cm cavities. This near-neutral outcome agrees with Ozel (2014), whose transmission-load analysis found that annual loads and the optimum insulation thickness were independent of insulation position. It extends that finding from the continuous insulation layer Ozel modeled to mechanically fixed assemblies in which the layer is penetrated at discrete points. External insulation in the porcelain system at the 5 cm cavity is the only configuration in the matrix that deviates from position neutrality.

4.9.4 Thermal Bridge Effects

The thermal bridges introduced by the fixing system are where the two scales of this study meet, and the component-level magnitudes are consistent with the published evidence on metal fixings. Šadauskienė et al. (2015), modeling aluminum brackets at 2.78 fasteners per square meter, obtained point transmittances of 0.008 to 0.039 W/K and a whole-wall transmittance increase of 13 to 35%, growing with the conductivity of the bearing layer and the thickness of the insulation. The stone results here, between 0.0062 and 0.0112 W/K, sit at and below the lower end of that range, consistent with stainless steel fixings of far lower conductivity and an insulation layer of only 3 cm. The porcelain result at the shallowest cavity, 23.0, reflects the continuous aluminum rail. The trends match as well. Point transmittance decreases as the conduction path through the assembly lengthens (Šadauskienė et al., 2015), which is reflected in the reduction observed here with deeper cavities, and Petreševics and Nagy (2022) identified reinforced concrete, the anchor substrate in both systems studied here, as the bearing material producing the highest point transmittances. Theodosiou et al. (2015) estimated that ignoring substructure point bridges understates envelope heat flows by 5 to 20%, and Ge and Baba (2015) found that the percentage effect on heating load increases with insulation level, which is the pattern shown in Table 4-13.

Case 7 of the porcelain system most clearly shows the coupling between the scales. At the 5 cm cavity, the T-rail contacts the structural wall, converting the fixing system from a set of point bridges to a combined point and linear bridge, thereby raising the corrected transmittance by 21% above the internally insulated equivalent at the same depth (Section 4.7.2). The increase propagates to building scale in attenuated form, raising seasonal heating demand by 7.20% in B1-L, 7.12% in B1-B, 6.00% in B2-L, and 5.24% in B2-B, since it applies only to the wall. At the same time, heat transfer through the roof, floor, and glazing, as well as the ventilation and infiltration rates, remain unchanged. The building model received the corrected transmittance as its only input from the component scale and returns the consequence in the correct season at a magnitude set by the wall share of each zone heat balance: approximately 140.7 kWh of additional heating in B1-L and an annual position gap of 3.0 to 3.3% in the living zones.

The penalty appears almost entirely in the heating season, which follows from the two regimes identified in Section 4.9.3. Winter exposes the bridge because the load is quasi-steady and each increment of corrected transmittance acts on a large sustained gradient throughout the season. Summer masks it because cooling demand is governed by the envelope's periodic thermal response, to which the additional bridge contributes only marginally. Case 7 accordingly records a lower seasonal cooling load than the internally insulated Case 4, 1520.40 kWh against 1544.50 kWh in B1-L, despite its 21% higher corrected transmittance. The bridge is present in the summer result, but it is small enough to be outweighed by storage and attenuation, and the seasonal loads alone do not isolate it.

The design consequence is that the insulation layer in this configuration returns almost nothing. Case 7 records an annual load of 3614.00 kWh in B1-L against 3612.10 kWh for Case 3, which carries no insulation and reaches its transmittance through cavity depth alone, the two converging on 0.920 and 0.958 W/m²K. The equivalent stone configuration retains a 2.1 to 2.9% advantage over its uninsulated 15 cm counterpart in every zone, so the cancellation belongs to the continuous aluminum rail rather than to external insulation in general.

Two points follow for calculation practice. The simplified layered method of ISO 6946, applied without a fastener correction, returns identical transmittances for Cases 4 and 7 in either cladding system. In contrast, the corrected values show the external porcelain case losing approximately

one-fifth of its effective thermal resistance to the fixings, falling from 1.34 m²K/W in the clear wall to 1.09 m²K/W once rail and brackets are included. This confirms the concern of Petreševics and Nagy (2022) that point thermal bridges are routinely neglected in simplified energy calculations, and it qualifies the finding of Nowak et al. (2018) that a sufficiently thick insulation layer renders the anchorage effect negligible, since the layer tested here is thin and the effect correspondingly large. Specifying external insulation and fixing the cladding through it at a 5 cm cavity delivers an annual load within 0.6% of the uninsulated wall at a 15 cm cavity in all four zones, marginally higher in the living zones and marginally lower in the bedrooms.

4.10 Summary

This chapter opened with the field documentation that established the object of study. A survey of practicing offices in Hebron and site inspection of seven executed projects established that mechanically fixed stone and porcelain façades are an emerging rather than an established practice, confined to a small number of offices and executed through a single specialist subcontractor. That subcontractor applies the same details in other Palestinian cities, which extends the relevance of the findings beyond the study area. The documentation established the two substructure types that define the parametric matrix, stainless steel point-fixed brackets for the 30 mm stone panel and a continuous aluminium T-rail for the 6 mm porcelain panel, together with the anchorage spacing, cavity depths and insulation thicknesses used in practice.

The case study followed from that documentation. Two mirrored villas of identical geometry and construction provided four monitored zones, a living zone and a bedroom on each of the northern and southern exposures, with orientation held as a control variable so that the wall configuration remained the only variable under test. Field monitoring over a continuous 72-hour period supplied indoor air and surface temperature records, and infrared thermography confirmed the position of the fixings in the executed wall.

Two models were then built and verified. A steady-state finite element model in COMSOL Multiphysics quantified the point and linear transmittances of the fixing system and returned a corrected transmittance for each of the eighteen wall configurations, formed from two cladding systems, three insulation positions and three cavity depths. A whole-building model in

DesignBuilder and EnergyPlus, driven by the Hebron TMYx weather file, converted those transmittances into annual and seasonal demand and free-running comfort. The building model was validated against the monitored records for all four zones using the NMBE and CV(RMSE) criteria of ASHRAE Guideline 14, and the results fell within the acceptance limits in every zone.

This chapter also reported the component-scale and building-scale results for eighteen wall configurations across two cladding systems and four monitored zones, and interpreted them against the published evidence. Three findings carry the chapter, and each stands in a different relation to the literature.

The first relation is confirmation. Insulation presence dominates every other parameter tested, which agrees with the Palestinian evidence directly. Al Qadi et al. (2018) identified wall insulation level as a significant predictor of heating consumption in Hebron, and Haj Hussein et al. (2022) reported heating reductions of 43 to 83% on introducing wall insulation. The equivalent step here, 3 cm of XPS at an unchanged 5 cm cavity, reduced seasonal heating demand by 10.2 to 20.1% and annual demand by 9.5 to 16.3%, a smaller magnitude that reflects the single thin layer tested rather than any disagreement in mechanism. Cavity depth ranked second and substituted for insulation only in the uninsulated wall, with returns diminishing beyond 10 cm. That trend reproduces Balocco (2002) and Roig et al. (2024), although those studies attribute the effect to convective removal in open cavities while the sealed cavities modeled here gain only added thermal resistance under ISO 6946. The agreement is in the trend and not in the mechanism, and the distinction matters for any attempt to apply ventilated façade guidance to the sealed systems built in Palestine.

The second relation is contradiction. Stazi et al. (2020) found heavy external cladding buffering the structural wall in summer and lowering surface temperatures, whereas the low-capacity porcelain panel held the summer advantage here, 6.7 to 15.3% across all 36 paired comparisons, against a winter penalty of 6.8 to 27.2%. The reversal follows from the cavity condition. In an open cavity the stored heat leaves the assembly before reaching the wall, while in a sealed cavity the same mass releases it inward after sunset and acts as a reservoir rather than a buffer. The two seasonal effects largely cancel at annual scale, so cladding material shifts the seasonal composition of heat transfer more than the annual total.

The third relation is qualification. Insulation position proved close to neutral over the year, with the gap staying below 0.6% in the stone system and near 1% in the porcelain system at the 10 and 15 cm cavities. This reproduces the conclusion of Ozel (2014) for a continuous insulation layer and extends it to assemblies penetrated at discrete points. External insulation in the porcelain system at the 5 cm cavity is the only configuration in the matrix that departs from that pattern. There the T-rail meets the structural wall, raising the corrected transmittance by 21% above the internally insulated equivalent at the same depth and bringing the annual load within 0.6% of an uninsulated wall at a 15 cm cavity. The same case qualifies Nowak et al. (2018), whose finding that a sufficiently thick insulation layer renders the anchorage effect negligible does not hold at the 3 cm thickness common in Palestinian practice, where the fixings remove approximately one-fifth of the effective thermal resistance.

The component-scale magnitudes themselves fall within established ranges. Point transmittances of 0.0062 to 0.0112 W/K in the stone system sit at and below the lower bound reported by Šadauskienė et al. (2015) for aluminum brackets, consistent with stainless steel fixings and a thin insulation layer. The dependence on substrate matches Petreševics and Nagy (2022), and the growth of the percentage heating effect with insulation level matches Ge and Baba (2015). Theodosiou et al. (2015) estimated that ignoring substructure point bridges understates envelope heat flows by 5 to 20%, which is the order of the effect observed here.

Taken together, the results locate the practical problem in the calculation method rather than in the materials. The simplified layered method of ISO 6946 returns identical transmittances for the internally and externally insulated cases in either cladding system, so a design assessed without a fastener correction cannot distinguish an assembly that performs from one that returns almost nothing for its insulation layer. The two scales of the study meet at that point. The component model supplies a corrected transmittance, the building model converts it into seasonal demand at a magnitude set by the wall share of each zone heat balance, and the consequence becomes visible only when the fixings are represented explicitly. These outcomes form the basis of the conclusions and design recommendations that follow.

Chapter 5

Conclusion and Recommendations

Chapter 5

Conclusion and Recommendations

5.1 Preface

Mechanically fixed stone and porcelain cladding became part of Palestinian residential construction based on architectural considerations, but their thermal performance under local conditions has not been determined. The fixing components pass through the insulation layer and air cavity, so the transmittance assumed during design does not accurately reflect the actual constructed wall.

This research addressed that gap with a two-scale simulation study based on field data from Hebron. Seven residential buildings with mechanically fixed cladding were surveyed and documented; two were instrumented and monitored over 72 hours. Eighteen wall configurations combining two cladding materials, three insulation positions, and three cavity depths were modeled in COMSOL Multiphysics to determine corrected thermal transmittances that incorporate the fixing system. These values were carried into DesignBuilder to simulate annual energy demand and free-running thermal comfort across four zones with northern and southern exposures in both buildings. The conclusions below are based on component and building models that were both validated against measured data before conducting the parametric analyses.

This chapter summarizes the main findings of the study, outlines its scientific and practical contributions, offers design recommendations based on the results, and identifies priorities for future research.

5.2 Conclusions

The conclusions are set out below against the objectives of the research.

5.2.1 Construction characteristics

Mechanically fixed cladding remains an emerging practice in Hebron, confined to a small number of design offices and a single execution chain. All seven documented buildings were clad for

architectural and aesthetic reasons, and thermal performance was absent from the design considerations in every project surveyed.

The assemblies share a common construction logic. Waterproofing is applied to the concrete backing wall before any fixing work begins, insulation is 3 cm of extruded polystyrene throughout, and the cavity is closed at top and bottom in every project, which is why the assemblies in this thesis cannot be described as ventilated. Stone panels hang on stainless steel brackets, while porcelain panels are fixed to a continuous aluminum rail carried on steel brackets. Cavity depth varies within a single façade between 5 and 15 cm, set by the working range of the bracket and used to form design projections while the structural wall stays at a constant thickness.

Cladding material, insulation position, and cavity depth varied between projects and became the design variables of the study. The semi-structured interviews showed that this construction practice is used in other Palestinian cities, which verifies that the demonstrated assemblies reflect common practice in Palestine, not a practice which is specific to Hebron.

5.2.2 Thermal bridge behavior

The fixing system raises the thermal transmittance of every configuration tested, and the size of the increase is governed by the resistance the fixings penetrate rather than by the fixings themselves. Where the insulation is positioned on the interior side of the structure, the components cross only the air cavity and the penalty stays below 1.6%. Where the insulation is positioned outside, the same components pass through the insulation, the layer carrying roughly half the resistance of the wall, and the penalty rises to between 5.26 and 23%. Insulation position does not determine the performance of the wall. It determines how much of that performance the fixing system removes.

The substructure material explains the difference between the two systems. The continuous aluminum rail in the porcelain assembly results in roughly three times the relative increase compared to the stainless-steel brackets at the same cavity depth.

The porcelain case with external insulation at the 5 cm cavity is where the thermal bridge influence appears the most. At this depth, the rail penetrates the insulation and makes direct contact with the

concrete, changing from separate point bridges to a combined point and linear bridge, which results in a 23% penalty. When the cavity reaches 10 cm, the rail is away from the wall, the continuous bridge no longer exists, and the penalty decreases to 7.83%.

5.2.3 Building-level performance

The presence of insulation is the dominant parameter governing annual sensible demand, followed by cavity depth, while insulation position and cladding material have comparatively small annual effects. Adding 3 cm of extruded polystyrene reduces annual demand by 9.5 to 16.3% at the 5 cm cavity of the reference case, and by 5.7 to 16.3% across all three cavity depths when insulation is isolated as a variable, the lower figure reflecting the smaller marginal gain once a 15 cm cavity is already present.

Cavity depth acts as a secondary parameter. Deepening the cavity from 5 to 15 cm in both systems returns 8.7 to 13.5% when the wall is uninsulated, 4.6 to 7.7% with internal insulation, and 4.1 to 10.9% with external insulation. In the uninsulated wall, deepening it from 5 to 10 cm increases returns by 5.1 to 7.9%, whereas from 10 to 15cm returns 3.7 to 6.2%, demonstrating diminishing returns.

Insulation position remains nearly neutral throughout the year, with each position winning in one season. Internal insulation yields the lowest heating load across all zone-depth comparisons in both systems, due to its lower corrected transmittance. External insulation offers the lowest cooling load in similar comparisons because summer performance depends more on the assembly's transient response. These two effects balance out over the year. The difference between positions stays under 0.56% in the stone system for all cavity depths, and under 1.02% in the porcelain system at 10 and 15 cm cavities.

Cladding material affects the seasonal pattern of heat transfer rather than the total annual amount. Porcelain consistently results in lower cooling demands and higher heating requirements across all 36 comparisons, due to the outer layer's areal heat capacity, 67.5 kJ/m²K for stone versus 13.0 kJ/m²K for porcelain. Stone absorbs solar heat during the day and releases it inward at night in a cavity with no outlet, whereas porcelain stores almost no heat. Over the year the two effects largely cancel, and the maximum annual difference observed between the two systems was 4.1%.

The comfort indicators respond less than the loads. Under free-running operation, the living zones improve consistently with insulation and cavity depth, while winter discomfort hours in both bedrooms hold at the schedule maximum across all eighteen configurations, because every configuration leaves the zone below the lower comfort limit for the whole occupied period. In summer, the uninsulated bedrooms record the fewest discomfort hours, since roof gains hold the free-running zone above outdoor air for much of the day and insulation restricts the outward rejection path. Under conditioned operation, the same configurations reduce bedroom cooling load by 1.8% to 15.6%. The inversion therefore limits what the free-running comfort metric can show, and does not weaken the case for insulating.

5.2.4 Integration of the two scales

These two analyses focus on different questions: component-scale analysis examines the heat-transfer mechanisms within the wall assembly, whereas whole-building simulation demonstrates how these mechanisms impact annual demand once climate, thermal mass, and building operation are taken into account.

Insulation position illustrates why both analyses are necessary. Although its annual effect is no more than 1% at the 10 and 15 cm cavities, the same change alters the corrected transmittance by 4.7% to 6.3% at those depths, because it determines how the fixing system interacts with the insulation layer and therefore governs the magnitude of the thermal bridge. Judged from annual results alone, it is the least influential of the four design decisions. At component scale, however, it becomes one of the most influential.

The externally insulated porcelain system with a 5 cm cavity represents the exceptional case. Direct rail-to-wall contact creates a severe linear thermal bridge that raises the corrected transmittance by 21.3% above the internally insulated wall of identical composition. At building scale, its annual demand differs by only 0.05% from that of the best-performing uninsulated configuration, the wall with a 15 cm cavity. The annual result captures that outcome, but not its physical cause. A conventional one-dimensional calculation would not reveal this behavior either, because it assigns identical transmittances to internally and externally insulated walls without representing the fixing system. The same design parameter therefore appears fundamentally different depending on the level of analysis.

No single level of analysis describes the façade completely on its own. Component-scale analysis explains the physical mechanism, while whole-building simulation reveals its consequences for annual building performance. Together, they provide a complete understanding of how fixing configuration influences the thermal performance of mechanically fixed façades.

5.3 Research Contributions

The contribution of this work lies in describing and quantifying a construction system that had entered Palestinian housing without a local thermal account, and in showing why such systems cannot be assessed at a single scale. Four contributions are scientific, and one is practical.

Scientific contributions

- The study provides thermal characterization of mechanically fixed residential cladding as built in Palestine, covering the assembly sequence, fixing components, cavity treatment and insulation practice of an execution chain that operates nationally.
- It quantifies the thermal bridge penalties of the stone and porcelain fixing systems actually used in Palestinian construction.
- It indicates that the closed cavity alters, and may reverse, the cladding material ranking reported for ventilated façades, which suggests that findings from ventilated systems cannot be transferred to sealed assemblies of the same geometry.
- It demonstrates why component-level thermal bridge analysis and whole-building simulation must be analyzed and read together for assemblies where fixings penetrate the insulation, since the same design parameter is judged differently at each scale.

Practical contribution

- It provides practical recommendations based on the configurations examined, particularly regarding the selection of cavity depth and insulation position in mechanically fixed façade systems.

5.4 Recommendations

The recommendations below derive from the simulated performance of the eighteen configurations against the uninsulated wall with a 5 cm cavity. The first group applies to both cladding systems and to the design and execution process, and the two that follow address the decisions specific to each system.

5.4.1 General recommendations for mechanically fixed façades

- Insulation is essential in all cases, as no non-insulated case matches the performance of an insulated one at the same cavity depth.
- The cavity should be at least 10 cm, and 15 cm when the design allows, because the 15 cm insulated configurations consistently result in the lowest annual load across all zones and both systems.
- The clear-wall transmittance should not be used for energy modeling of a mechanically fixed façade. Where the fixings cross the insulation layer, modeling on the uncorrected value understates demand.
- Substructure material should be taken into account when selecting between a continuous aluminum rail versus separate stainless steel brackets, which can increase the penalty by about three times under similar conditions.

5.4.2 Recommendations specific to stone cladding

- Insulation position can be decided on constructability, cost, and detailing. Where the design prioritizes winter performance, internal placement is preferable, and where summer performance governs, external placement is preferable.

5.4.3 Recommendations specific to porcelain cladding

- External insulation should not be combined with a 5 cm cavity because the T-rail rests directly on the structural wall at that depth and could compromise the insulation's effectiveness, making the insulated assembly's annual load almost the same as that of an uninsulated wall.

- Where external insulation is specified, the cavity should be held at 10 cm or more so that the rail stands clear of the structural wall.
- Where cavity depth cannot be controlled reliably during execution, internal insulation should be specified. Its bridging penalty is an order of magnitude smaller and stays constant across all cavity depths, so the assembly performs to its design intent irrespective of how the cavity is set on site.

5.5 Future Work

Further research is recommended in the following:

- Extending the parametric matrix to a multi-objective optimization covering insulation type, thickness and position, fixing configuration and cavity depth, and optimizing energy demand, thermal comfort, cost and payback together would identify the optimum solutions for such systems in a given context.
- Extending the study to cover design and environmental parameters, including orientation, window-to-wall ratio, shading, solar exposure and wind conditions, would show how façade design and site exposure interact with the bridging penalty.
- Examining the cavity as a ventilated element. Comparing sealed against ventilated operation under Palestinian conditions would establish how far opening the cavity alters the performance of the system.
- Testing alternative fixing materials and thermal-break components. Substituting the bracket and rail materials, or introducing isolators at the anchor, would establish how far the penalty reported here can be reduced without changing the cavity or the insulation position.
- Assessing the accuracy of the two-scale method. Bridging effects enter the building model through a single corrected transmittance calculated under steady-state conditions. Three-dimensional transient analysis of the same assemblies would describe how the fixings behave under the daily temperature swing that governs summer performance, and would establish the size of the deviation in annual demand and whether it changes the relative performance of the configurations.

- Extending the assessment to other Palestinian cities with different climatic and construction contexts would help determine whether the observed thermal performance patterns remain consistent beyond Hebron and assess the applicability of the findings under other local conditions.

5.6 Closing Remarks

Mechanical fixing of stone and porcelain cladding spread through Palestinian residential buildings before any local guidance existed on how to detail it. This study shows that the fixing method is not a minor construction detail but a determinant of how the wall performs, and that its effect is decided at the design stage by choices currently made on appearance alone. The two-scale method applied here can be transferred to other fixing types and climates. For the configurations studied, the work provides the first validated thermal assessment of mechanically fixed residential cladding under Palestinian conditions, and the findings provide a valuable starting point for design until more local data is available.

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APPENDICES

APPENDIX A

Semi-Structured Interview Questions

The following questions guided the interviews conducted with the architects and contractors of the visited and documented projects. The interviews were structured into five parts.

GENERAL INFORMATION

1. What is the use of the building, and what is its current construction status?
2. In which year was the building constructed (or when did construction begin)?
3. How many floors does the building comprise, and what is the area per floor?
4. Are the architectural and construction drawings of the building available?

CLADDING SYSTEM

5. What cladding material or materials are used on the façades?
 6. What determined the choice between stone and porcelain on different parts of the façade?
 7. What is the thickness of the stone (or porcelain) panels?
 8. What type of mechanical fixing system is used, and what are its components?
 9. What material are the fixing components made of?
 10. What is the shape of each fixing component?
 11. What is the spacing or density of the fixing brackets?
 12. What are the minimum and maximum adjustment ranges of the brackets?
 13. Where are the fixing components sourced from — locally manufactured or imported?
 14. Are the joints between the cladding panels sealed or open?
 15. What is the height of the joints between panels?
 16. Is the air cavity open or closed at the top and bottom of the façade?
-

WALL ASSEMBLY

17. What are the layers of the external wall, from outside to inside, and what is the thickness of each layer?
18. What insulation material is used?
19. What is the thickness of the insulation?
20. Where is the insulation positioned within the assembly?
21. What is the depth of the air cavity between the cladding and the wall?
22. On what basis was the air cavity depth chosen?
23. Was the cavity depth uniform across the façade, or did it vary to absorb structural tolerance?
24. Is any waterproofing membrane or coating applied?

EXECUTION AND PRACTICE

25. Who installs the system — a specialized subcontractor or the general contractor?
26. How many projects has the office or contractor executed with this system in Hebron?

DESIGN RATIONALE

27. Why was the mechanically fixed system adopted for this project?
 28. Were thermal performance or thermal bridging considered in the design of the façade?
-

APPENDIX B

Instruments' Datasheets

B.1. UNI-T UT330B USB data logger

SPECIFICATIONS					
		Range	UT330A	UT330B	UT330C
Temperature	Range	-40°C~80°C (-40°F~176°F)	√	√	√
	Accuracy	0°C~40°C	±0.5°C	±0.5°C	±0.5°C
		-30°C~0°C, 40°C~70°C	±1°C	±1°C	±1°C
		-40°C~-30°C, 70°C~80°C	±2°C	±2°C	±2°C
	Resolution	0.1°C/0.1°F	√	√	√
Relative humidity	Range	0%RH~100%RH		√	√
	Accuracy	20%RH~80%RH		±3%RH	±3%RH
		<20%RH or >80%RH		±5%RH	±5%RH
	Resolution	0.1%RH		√	√
Atmospheric pressure	Range	750hPa~1100hPa			√
	Accuracy				±3hPa
	Resolution	0.1hPa			√
Features					
IP67			√	√	√
°C/°F selection			√	√	√
Temperature offset settings			√	√	√
Humidity offset settings				√	√
Pressure offset settings					√
Data storage			60000	60000	60000
Data recall			√	√	√
USB interface			√	√	√
Auto record time setup			√	√	√
User name settings			√	√	√
Alarm threshold			√	√	√
Start mode setup			√	√	√



● UT330C

Figure A-1: Data logger datasheet

[online]: <https://meters.uni-trend.com/product/ut330-usb-series/>

B.2 Total THIT0155028 infrared thermometer

Technical Specifications	
Display	Black and white LCD display
D:S	12: 1
Emissivity	0.10~1.00
Response spectrum	8~14um
Laser	<1mW /630-670nm Level 2
Response time	<0.5S
Auto power off	30 seconds
Work temperature	0~40°C
Storage temperature	-10~60°C
Power supply	2 x 1.5VAAA batteries
Measurement range	-50°C~+450°C(-58°F~+842°F)
Accuracy	-50°C~0°C (-58°F~32°F): ±3°C
	0°C~450°C (32°F~842°F) : ±2.0% or ±2°C



Figure A-2: Infrared thermometer datasheet

[online]: <https://totaltools.si/wp-content/uploads/2025/02/THIT0155028.pdf>

B.3 CEM DT-9873B thermal imager

SPECIFICATIONS	
Imaging And Optical Data	
Field of view (FOV) / Minimum focus distance	29.8° x 22.6° / 0.2m
Spatial resolution (IFOV)	3.33mrad
Thermal sensitivity/NETD	< 0.08°C @ +30°C (+86°F) / 80 mK
Image frequency	50Hz
Focus mode	Manual
Focal length	7.5mm
Focal Plane Array (FPA) / Spectral range	Uncooled microbolometer / 8-14 μ m
IR resolution	160 x 120 pixels
Image Presentation	
Display	Capacitive Touch screen, 3.5 in. LCD, 320 x 240 pixels
Image modes	IR image only
Color palettes	IRON, Rainbow, Grey, GreyInverted, Sepia, Blue_Red, Hot Cold, Humidity
Measurement	
Object temperature range	-20°C to +150°C (-4°F to +302°F) 0°C to +400°C (+32°F to +752°F)
Accuracy	$\pm 2^\circ\text{C}$ ($\pm 3.6^\circ\text{F}$) or $\pm 2\%$ of reading
Measurement Analysis	
Spot	Center Spot
Automatic hot/cold detection	Auto hot or cold markers
Isotherm	Detect high/low temperature/interval
Emissivity correction	Variable from 0.01 to 1.0
Measurement corrections	Emissivity, ambient temperature, distance, relative humidity, offset temperature
Storage Of Videos	
Storage media	4Gbytes Micro SD card
Video storage format	Standard MPEG-4, 640x480@30fps, on memory card > 60 minutes
Video storage mode	IR images with audio
Storage Of Images	
Image storage format	Standard JPEG, including measurement data, on memory card > 1000 pictures
Image storage mode	IR images with annotation (audio or text)
Set-Up	
Set-up commands	Local adaptation of units, language, date and time formats, information of camera
Languages	Multinational



Figure A-3: Thermal camera datasheet
[online]: <https://www.cem-instruments.in/pdf/DT-9873B.pdf>

Cross-Case Comparison of the Documented Projects

Attribute		Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7	
General information	Use	Residential							
	Status at survey	Completed		Cladding phase					
	Year	2010		2024			2025		2024
	Floors	2 (G, 1)		3 (B, G, 1)					
	Area per floor (m²)	174.48, 163.88		330, 523, 172	471, 332, 327	387, 290, 310	108, 108, 95		274, 206, 230
	Drawings available	Yes							
Cladding system	Cladding material	Stone (mech.)		Stone (mech. + trad.)	Stone + porcelain (mech.)		Stone (mech.)		Stone + porcelain (mech.)
	Basis for material choice	-			Aesthetic		-		Aesthetic
	Cladding thickness (cm)	3							
	Fixing system	Brackets			Brackets (S); T-rails (P)		Brackets		Brackets (S); T-rails (P)
	Fixing material	SS 304/316			SS 304/316 + Al T-rail		SS 304/316		SS 304/316 + Al T-rail
	Fixing shape	Z bracket			Z (S); T-rail + L (P)		Z bracket		Z (S); T-rail + L (P)
	Bracket spacing	~5/m²			~5/m² (S); T-rail 70, L 50 cm (P)		~5/m²		~5/m² (S); T-rail 70, L 50 cm (P)
	Bracket adjustment (cm)	5-15							
	Fixing source	Israeli supplier							
	Panel joints (stone)	Grouted			Grouted				
	Panel joints (porcelain)	–			Open		–		Open
Joint height (mm)	5								

	Attribute	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7
Wall assembly	Cavity closure	Closed						
	Wall layers, out to in (cm)	Concrete 20 + gap 3 + block 10		Concrete 20 + XPS 3 + block 10				
	Internal finish	Plaster 2						
	Insulation material	XPS						
	Insulation thickness (cm)	3						
	Insulation position	External		Internal				
	Cavity depth (avg) (cm)	8		7	9			
	Basis for cavity depth	Projections, aesthetics						
	Cavity depth uniformity	Varying						
	Waterproofing	Yes						
Execution and practice	Installer	Same specialized contractor						
	Projects with this system	7 (all surveyed)						
Design rationale	Reason for adoption	Aesthetic						
	Thermal bridging considered	No						

Extended Component-Level Simulation Results

Table D-1: COMSOL model runs for the mechanically fixed stone system

[illegible]

8	External	10	With fixings	Grouted	20.0	0.0	20.0	2.80010	0.2025	0.691383
8	External	10	Without fixings	Grouted	20.0	0.0	20.0	2.64690	0.2025	0.653556
8	External	10	With fixings	Open	20.0	0.0	20.0	2.79720	0.2025	0.690667
9	External	15	With fixings	Grouted	20.0	0.0	20.0	2.49370	0.2025	0.615728
9	External	15	Without fixings	Grouted	20.0	0.0	20.0	2.37050	0.2025	0.585309
9	External	15	With fixings	Open	20.0	0.0	20.0	2.49230	0.2025	0.615383

Table D-2: COMSOL model runs for the mechanically fixed porcelain system

Case	Insulation position	Cavity (cm)	Model	θ_i (°C)	θ_e (°C)	$\Delta\theta$ (K)	Q (W)	A (m ²)	U_value (W/m ² K)
1	None	5	Q-total	20.0	0.0	20.0	10.0770	0.35	1.439571
1	None	5	Q ₀	20.0	0.0	20.0	9.8251	0.35	1.403586
1	None	5	Q-linear	20.0	0.0	20.0	10.0540	0.35	1.436286
1	None	5	Q-point	20.0	0.0	20.0	9.8552	0.35	1.407886
2	None	10	Q-total	20.0	0.0	20.0	8.0487	0.35	1.149814
2	None	10	Q ₀	20.0	0.0	20.0	7.8556	0.35	1.122229
3	None	15	Q-total	20.0	0.0	20.0	6.7090	0.35	0.958429
3	None	15	Q ₀	20.0	0.0	20.0	6.5445	0.35	0.934929
4	Internal	5	Q-total	20.0	0.0	20.0	5.3062	0.35	0.758029
4	Internal	5	Q ₀	20.0	0.0	20.0	5.2355	0.35	0.747929
4	Internal	5	Q-linear	20.0	0.0	20.0	5.2995	0.35	0.757071
4	Internal	5	Q-point	20.0	0.0	20.0	5.2442	0.35	0.749171
5	Internal	10	Q-total	20.0	0.0	20.0	4.6862	0.35	0.669457
5	Internal	10	Q ₀	20.0	0.0	20.0	4.6186	0.35	0.659800
6	Internal	15	Q-total	20.0	0.0	20.0	4.1966	0.35	0.599514
6	Internal	15	Q ₀	20.0	0.0	20.0	4.1323	0.35	0.590329
7	External	5	Q-total	20.0	0.0	20.0	6.4379	0.35	0.919700
7	External	5	Q ₀	20.0	0.0	20.0	5.2359	0.35	0.747986
7	External	5	Q-linear	20.0	0.0	20.0	6.3280	0.35	0.904000

7	External	5	Q-point	20.0	0.0	20.0	5.4361	0.35	0.776586
8	External	10	Q-total	20.0	0.0	20.0	4.9804	0.35	0.711486
8	External	10	Q _o	20.0	0.0	20.0	4.6186	0.35	0.659800
9	External	15	Q-total	20.0	0.0	20.0	4.4145	0.35	0.630643
9	External	15	Q _o	20.0	0.0	20.0	4.1323	0.35	0.590329

Table D-3: Simulated thermal transmittance of the eighteen wall configurations

Case	Cladding	Insulation position	Cavity (cm)	U _{clear} (W/m ² K)	χ (W/K)	ψ (W/m·K)	ΔU (W/m ² K)	U _{corr} (W/m ² K)	Increase (%)
1	Stone	None	5	1.3752	0.00204	—	0.0102	1.3854	0.74%
2	Stone	None	10	1.1043	0.001565	—	0.0078	1.1121	0.71%
3	Stone	None	15	0.9224	0.00145	—	0.0072	0.9297	0.79%
4	Stone	Internal	5	0.7398	0.00058	—	0.0029	0.7427	0.39%
5	Stone	Internal	10	0.6535	0.00056	—	0.0028	0.6563	0.43%
6	Stone	Internal	15	0.5853	0.00058	—	0.0029	0.5882	0.50%
7	Stone	External	5	0.7400	0.01116	—	0.0558	0.7958	7.54%
8	Stone	External	10	0.6536	0.00766	—	0.0383	0.6919	5.86%
9	Stone	External	15	0.5853	0.00616	—	0.0308	0.6161	5.26%
1	Porcelain	None	5	1.4036	0.00151	0.02289	0.0360	1.4396	2.56%
2	Porcelain	None	10	1.1222	0.00965	—	0.0276	1.1498	2.46%
3	Porcelain	None	15	0.9349	0.00822	—	0.0235	0.9584	2.51%
4	Porcelain	Internal	5	0.7479	0.00044	0.00640	0.0101	0.7580	1.35%
5	Porcelain	Internal	10	0.6598	0.00338	—	0.0097	0.6695	1.46%
6	Porcelain	Internal	15	0.5903	0.003215	—	0.0092	0.5995	1.56%
7	Porcelain	External	5	0.7480	0.01001	0.10921	0.1717	0.9197	22.96%
8	Porcelain	External	10	0.6598	0.01809	—	0.0517	0.7115	7.83%
9	Porcelain	External	15	0.5903	0.01411	—	0.0403	0.6306	6.83%

APPENDIX E

Extended Building-Level Simulation Results

This appendix reports the annual and seasonal zone sensible loads for the eighteen wall configurations for the four monitored zones for both cladding systems. Table E-1 covers the summer cooling loads, Table E-2 the winter heating loads, and Table E-3 the annual loads.

Table E-1: Summer zone sensible cooling loads and change relative to Case 1

Summer											
Case	Insulation position	Cavity (cm)	U_corr (W/m²K)	B1 - L		B1 - B (northern)		B2 - L		B2 - B (southern)	
				kWh	reduction	kWh	reduction	kWh	reduction	kWh	reduction
STONE CLADDING											
1	None	5	1.385	1,943.2	reference	495.5	reference	1,961.5	reference	593.6	reference
2	None	10	1.112	1,796.2	7.6%	472.6	4.6%	1,810.7	7.7%	557.4	6.1%
3	None	15	0.930	1,689.1	13.1%	457.7	7.6%	1,700.8	13.3%	534.1	10.0%
4	Internal	5	0.743	1,685.3	13.3%	454.3	8.3%	1,694.8	13.6%	523.4	11.8%
5	Internal	10	0.656	1,633.3	15.9%	449.1	9.4%	1,640.3	16.4%	514.1	13.4%
6	Internal	15	0.588	1,565.6	19.4%	440.2	11.2%	1,571.7	19.9%	501.7	15.5%
7	External	5	0.796	1,670.9	14.0%	448.4	9.5%	1,680.3	14.3%	517.8	12.8%
8	External	10	0.692	1,626.3	16.3%	446.2	10.0%	1,634.0	16.7%	511.9	13.8%
9	External	15	0.616	1,563.1	19.6%	438.6	11.5%	1,569.8	20.0%	501.0	15.6%
PORCELAIN CLADDING											
1	None	5	1.440	1,646.1	reference	431.6	reference	1,660.9	reference	503.6	reference
2	None	10	1.150	1,555.8	5.5%	420.1	2.7%	1,568.4	5.6%	484.7	3.8%
3	None	15	0.958	1,487.3	9.6%	412.9	4.3%	1,497.7	9.8%	472.8	6.1%
4	Internal	5	0.758	1,544.5	6.2%	423.9	1.8%	1,551.9	6.6%	480.2	4.6%
5	Internal	10	0.670	1,485.4	9.8%	416.1	3.6%	1,491.6	10.2%	469.6	6.8%
6	Internal	15	0.600	1,434.9	12.8%	410.6	4.9%	1,440.6	13.3%	462.0	8.3%
7	External	5	0.920	1,520.4	7.6%	414.0	4.1%	1,530.1	7.9%	472.4	6.2%
8	External	10	0.712	1,452.9	11.7%	408.2	5.4%	1,460.3	12.1%	461.6	8.3%
9	External	15	0.631	1,407.3	14.5%	404.1	6.4%	1,413.8	14.9%	455.6	9.5%

Table E-2: Winter zone sensible heating loads and change relative to Case 1

Winter											
Case	Insulation position	Cavity (cm)	U_corr (W/m²K)	B1 - L		B1 - B (northern)		B2 - L		B2 - B (southern)	
				kWh	reduction	kWh	reduction	kWh	reduction	kWh	reduction
STONE CLADDING											
1	None	5	1.385	2,213.7	reference	354.7	reference	2,502.3	reference	210.1	reference
2	None	10	1.112	2,036.5	8.0%	323.7	8.7%	2,339.5	6.5%	200.5	4.6%
3	None	15	0.930	1,905.5	13.9%	300.9	15.2%	2,217.4	11.4%	192.2	8.5%
4	Internal	5	0.743	1,801.6	18.6%	283.6	20.0%	2,119.9	15.3%	188.6	10.2%
5	Internal	10	0.656	1,717.5	22.4%	269.4	24.0%	2,040.3	18.5%	182.1	13.3%
6	Internal	15	0.588	1,658.9	25.1%	259.1	27.0%	1,987.4	20.6%	177.6	15.5%
7	External	5	0.796	1,834.1	17.1%	288.1	18.8%	2,154.4	13.9%	190.2	9.5%
8	External	10	0.692	1,735.5	21.6%	271.5	23.5%	2,059.4	17.7%	182.3	13.3%
9	External	15	0.616	1,672.5	24.4%	260.7	26.5%	2,001.2	20.0%	177.7	15.4%
PORCELAIN CLADDING											
1	None	5	1.440	2,531.9	reference	397.5	reference	2,874.9	reference	267.2	reference
2	None	10	1.150	2,293.3	9.4%	357.9	10.0%	2,645.9	8.0%	246.7	7.7%
3	None	15	0.958	2,124.8	16.1%	329.8	17.0%	2,481.7	13.7%	231.3	13.4%
4	Internal	5	0.758	1,952.9	22.9%	303.3	23.7%	2,311.4	19.6%	217.7	18.5%
5	Internal	10	0.670	1,866.2	26.3%	288.8	27.3%	2,227.3	22.5%	209.5	21.6%
6	Internal	15	0.600	1,793.0	29.2%	276.6	30.4%	2,155.8	25.0%	202.2	24.3%
7	External	5	0.920	2,093.6	17.3%	324.9	18.3%	2,450.2	14.8%	229.1	14.3%
8	External	10	0.712	1,893.0	25.2%	292.1	26.5%	2,253.9	21.6%	210.6	21.2%
9	External	15	0.631	1,811.3	28.5%	278.8	29.9%	2,173.5	24.4%	202.8	24.1%

Table E-3: Annual zone sensible loads and change relative to Case 1

Annual											
Case	Insulation position	Cavity (cm)	U_corr (W/m²K)	B1 - L		B1 - B (northern)		B2 - L		B2 - B (southern)	
				kWh	reduction	kWh	reduction	kWh	reduction	kWh	reduction
STONE CLADDING											
1	None	5	1.385	4,156.9	reference	850.2	reference	4,463.8	reference	803.7	reference
2	None	10	1.112	3,832.7	7.8%	796.3	6.3%	4,150.2	7.0%	757.9	5.7%
3	None	15	0.930	3,594.6	13.5%	758.6	10.8%	3,918.2	12.2%	726.3	9.6%
4	Internal	5	0.743	3,486.9	16.1%	737.9	13.2%	3,814.7	14.5%	712.0	11.4%
5	Internal	10	0.656	3,350.8	19.4%	718.5	15.5%	3,680.6	17.5%	696.2	13.4%
6	Internal	15	0.588	3,224.5	22.4%	699.3	17.7%	3,559.1	20.3%	679.3	15.5%
7	External	5	0.796	3,505.1	15.7%	736.5	13.4%	3,834.7	14.1%	708.0	11.9%
8	External	10	0.692	3,361.8	19.1%	717.7	15.6%	3,693.4	17.3%	694.1	13.6%
9	External	15	0.616	3,235.6	22.2%	699.3	17.7%	3,571.0	20.0%	678.7	15.6%
PORCELAIN CLADDING											
1	None	5	1.440	4,178.0	reference	829.1	reference	4,535.8	reference	770.8	reference
2	None	10	1.150	3,849.1	7.9%	778.0	6.2%	4,214.3	7.1%	731.4	5.1%
3	None	15	0.958	3,612.1	13.5%	742.7	10.4%	3,979.4	12.3%	704.1	8.7%
4	Internal	5	0.758	3,497.4	16.3%	727.2	12.3%	3,863.3	14.8%	697.9	9.5%
5	Internal	10	0.670	3,351.6	19.8%	704.9	15.0%	3,718.9	18.0%	679.1	11.9%
6	Internal	15	0.600	3,227.9	22.7%	687.2	17.1%	3,596.4	20.7%	664.2	13.8%
7	External	5	0.920	3,614.0	13.5%	738.9	10.9%	3,980.3	12.2%	701.5	9.0%
8	External	10	0.712	3,345.9	19.9%	700.3	15.5%	3,714.2	18.1%	672.2	12.8%
9	External	15	0.631	3,218.6	23.0%	682.9	17.6%	3,587.3	20.9%	658.4	14.6%