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The Control of Thermal Comfort and Energy Saving Through External Walls in Apartment Buildings in Palestine: The Case of Hebron

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A thesis submitted in partial fulfillment of requirements of the degree
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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:

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The Control of Thermal Comfort and Energy Saving Through External Walls in Apartment Buildings in Palestine: The Case of Hebron

Haya Sameh Salah Nasereddin

ABSTRACT

In Palestine, residential buildings, their components, and related enterprises consume a large amount of energy. Moreover, considerable parts of these buildings significantly affect human comfort through their effect on the indoor environment. Apartment buildings are classified as the most dominant housing pattern nowadays in Palestine due to the increasing population rate and the lack of lands. Therefore, these are requested to fulfill occupants' comfort measures and consume substantial quantities of energy. External walls' design and components are one of the most effective strategies for controlling thermal performance and energy consumption. This thesis strives to present an extended evaluation of the common building practice in Hebron in terms of the external walls' components and thermal properties to present a comparative analysis of other less common and proposed patterns' thermal performance and energy consumption. The study further presents multiple interventions for different building patterns and materials installation with different considerations including the insulation material type, thickness, and location for external walls cladded with stone with backfill concrete or stone with concrete hollow block as a second proposed building pattern. The study also rates condensation formation possibilities in external walls. The study aims at controlling the thermal comfort in external walls of middle apartments in residential building in the case of Hebron. The questionnaire, the field visits, and the simulations were the used research tools. Results were carried out using the Design-builder simulation software. Insulators selection guidelines were presented to help the architects in the design and execution phases by enhancing the indoor environment and reducing the consumed energy levels for heating and cooling through the right selection of the building pattern and insulators installed. The presented results encourage using hollow concrete blocks to replace concrete walls, as it has proven a maximum thermal enhancement, and a reasonable percentage of energy saving and payback period, which makes it a feasible solution. The study has also proved an average of 40% energy saving in heating loads for northern and southern orientations, and 30-37% for eastern and western orientations by using Polyurethane foam as the most effective insulator for both building patterns when compared to the base case.

التحكم في الراحة الحرارية واستهلاك الطاقة من خلال الجدران الخارجية لمباني الشقق السكنية في فلسطين، مدينة الخليل كمنطقة الدراسة

هيا سامح صلاح ناصر الدين

المستخلص

تستهلك المباني السكنية بمكوناتها وطريقة انشائها في فلسطين قدراً كبيرا من الطاقة اللازمة للتدفئة والتبريد كما وأن مكونات اغلفة هذه المباني تعتبر ذات تأثير ملموس على البيئة الداخلية وراحة المستخدمين. تعتبر الشقق السكنية الظاهرة الأكثر سيادة للوحدات السكنية في فلسطين اليوم نظراً لارتفاع عدد السكان وقلة الاراضي، لهذا السبب يعتبر تحقيق الراحة الحرارية والاستهلاك المنطقي للطاقة من أهم متطلبات التصميم لهذه المباني. وتشكل الجدران الخارجية النسبة الاعلى المكونة لأغلفة هذه المباني وأكثرها فاعلية في تحقيق هذه المتطلبات، لذلك تقدم هذه الدراسة تقييماً مفصلاً للجدران الخارجية في المباني السكنية وفقاً لنظام البناء الأكثر شيوعاً في مدينة الخليل، كما وتقدم الدراسة تقييماً لجدران الطوب المفرغ المكساة بالحجر كأحد انماط البناء الأقل شيوعا في المباني السكنية لتشجيع استخدامه بما يحقق الأداء الحراري الأفضل وظروف الراحة الحرارية الملائمة للمستخدمين. كما وتقدم الدراسة مقارنات تحليلية للأداء الحراري للجدران الخارجية من خلال عدد من التدخلات في تطبيق عدد من مواد العزل المتوفرة في السوق الفلسطيني باعتبارات متعددة تشمل نوع وسماكة وموقع مواد العزل المستخدمة باستخدام مواد العزل المتاحة في السوق الفلسطيني. كما وتتطرق الدراسة الى تقييم ظاهرة التكاثف المتشكلة في الجدران الخارجية المسببة لتكون العفن والرطوبة للأنماط المقترحة. تهدف هذه الدراسة الى تحسين جودة الجدران الخارجية كونها المكون الأهم لأغلفة المباني استناداً الى الدراسات السابقة لاستنباط وتطوير المعايير الفيزيائية في المناخ المحلي لمدينة الخليل، وتوظف أدوات البحث مثل الاستبانة والزيارات الميدانية والمحاكاة باستخدام برنامج (Design-builder) لتمثيل نموذج معياري لشقة سكنية في الطوابق الوسطية المتكررة للمباني السكنية في المدينة وللتوصل الى مجموعة من التوجيهات للمعماريين لتحسين جودة البيئة الداخلية وتوفير الطاقة المستهلكة للتدفئة والتبريد من خلال اختيار نمط البناء ومواد العزل الأكثر نجاعة. وقد توصلت الدراسة الى كون جدران الطوب المفرغ المكساة بالحجر كتركيب الجدار الخارجي الأعلى توفيراً للطاقة والأكثر تحسيناً لدرجات الحرارة الداخلية صيفاً وشتاءً لمختلف التوجيهات مع حساب فترة الاسترداد للتكلفة التأسيسية. وقد حققت نتائج استخدام البولي يورثان تقليلا بمعدل ما نسبته 40% من الطاقة المستهلكة للتدفئة للواجهتين الشمالية والجنوبية وما نسبته 30-37% للواجهتين الشرقية والغربية لنمطي البناء الذين تناولتهما الدراسة (عند مقارنتها بالحالة الأولى) مما يثبت أفضليته كمادة عزل عن غيره من العوازل الشائعة. أثبتت الدراسة أهمية اختيار مواد العزل الصحيحة للمصممين والمهندسين في كلتي مراحل التصميم والتنفيذ وتساعد هذه الارشادات في تحسين الاداء الحراري للشقق السكنية في المدينة وبالتالي تقليل الطاقة المستهلكة.

DECLARATION

I declare that the Master Thesis entitled” The Control of Thermal Comfort and Energy Saving Through External Walls in Apartment Buildings in Palestine: The Case of Hebron” is my original work, and hereby certify that unless stated, all work contained within this thesis is my independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgment is made in the text.

Student Name:

Haya Sameh Nasereddin

Signature: هيا سامح ناصر الدين Date: 26/09/2023

DEDICATION

To my all-time tutor, my dearest grandfather Salah Nasereddin, may your soul rest in peace.
To the greatest parents to whom I’m most grateful, and my most precious siblings.

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Table of contents

List of figures

List of tables

Chapter 1

Introduction

Chapter 1
Introduction

1.1 Introduction

Modern architecture nowadays tends to use larger windows and a larger ratio of curtain walls in different building types, with no careful consideration to the indoor environment, which has created indoor environment problems and thermal discomfort, leading to increased use of electrical ventilation, heating, and cooling (HVAC). Therefore, excessive energy consumption (Hou, 2016). The HVAC systems in standard buildings are responsible for more than 50% of the global annual energy consumption (Bastide, 2006).

Building in Palestine generally tends to use stone as cladding material. Stone was also used in traditional architecture. However, in different construction methods, traditional architecture involved passive design solutions, which aimed to enhance the levels of thermal sensation for occupants using local, durable, sustainable, and environmentally friendly materials and methods (Salameh, 2012). A study conducted in Jenin confirms the role of the building envelope to reduce the consumed energy for heating and cooling in residential buildings. In a comparative analysis, the study concludes with a 46% in energy saving when comparing traditional buildings with modern un-insulated buildings (Abdel-Hadi, 2013). Traditional architecture and building strategies have depended on the region’s climatic conditions; therefore, designing walls, openings, and shading devices were considered to reduce heat gain in hot summer seasons and increase solar intake in cold winter seasons (Al Tawayha, et al., 2019).

Most residential buildings in Hebron are suffering from poor thermal insulation, which in terms leads to a significant increase in the use of heating and cooling systems and a relative increase the energy consumption. According to (Al Qadi, et al., 2018) Palestinians may spend 3.5%-21.6% of their monthly income on heating less than 10% of their dwellings in winter. This and other minor influencing factors have caused a continuous rise in the levels of consumed energy in residential buildings in Hebron to reach around 43% of the total energy consumption and 38% of the greenhouse gas emissions (GHG) per year (SEAP, 2016). Which requires serious interventions for enhancing the indoor thermal comfort, which is considered directly related to lowering the levels of needed energy.

The study highlights one of the main indoor environment qualities (IEQ) indicators, which is thermal comfort through external walls as the main part of the buildings' envelopes and their contribution to achieving occupants' satisfaction in multi-story residential buildings in Hebron. The study also explores the relationship between the external wall materials, construction, and thermal properties along with thermal comfort and energy consumption. Moreover, the study presents an evaluation of condensation occurring within the layers of the external wall for the proposed solutions to better check their validity. The study performs the most extensive research regarding thermal comfort through external walls combined with energy consumption and condensation evaluation in apartment buildings, using field surveys for a relatively large sample of residential apartments occupants', observations, and simulations of indoor temperatures in Hebron city.

This chapter introduces a background to the subject of thermal comfort to provide a basic background of the topic. In this chapter, the problem of the research is explained along with the research questions. Followed by an explanation of the significance of the research, research aims, and objectives. This chapter further illustrates the thesis structure.

1.2 Background

Buildings are necessary to provide shelter to the occupants, to provide a safe environment, and for carrying out various activities inside a space (Wolfgang, 1995). *"Buildings are also a part of wider socio-economic activities and cultural practices, and as such, part of the transition to a low-carbon economy"* (Shrubsole, et al., 2018). Thus, growth in the building sector is at an all-time because of the increase in population (Asif, 2016). National Statistical Organization reported that buildings stand for consuming approximately 40% of the total electricity and producing over 40% of the total greenhouse gas worldwide (IEA, 2015).

Sustainability is an inevitable part of building practices, and energy-efficient houses are becoming an alternative international need. Passive design strategies are an effective solution for environmentally sustainable houses, which in terms achieve thermal comfort in residential units. For example, in Germany passive house standards, developed in 1990, adopted the concept of energy-efficient and sustainable houses (Asif, 2016). The implementation of innovative design solutions and materials, along with the proper construction techniques and technologies in the building sector aims to enhance occupants' satisfaction, health, and wellbeing. Moreover, responsible building construction will cut off environmental burdens caused by high energy consumption. Buildings are expected to keep up with occupants' modern needs and to provide a safe and comfortable indoor environment with a reasonable level of energy-saving (Shrubsole, et al., 2018).

Improving the indoor environment quality includes thermal comfort achievement. Hence, thermal comfort should always be achieved for occupants under any condition. Thermal comfort is defined as the state of mind for occupants to feel satisfied within their surrounding thermal environment with the ability to fully accomplish their intended activities (Oral & Yilmaz , 2002). Thermal comfort and energy conservation for space are correlated to the space's envelope and its thermo-physical characteristics (Mirrahimi, et al., 2016).

1.3 Research Significance

Apartments buildings have been one of the main building typologies in modern societies (Saglam, et al., 2017). Residential buildings perform as the largest building sector in Palestine (Monna, et al., 2019). Apartment buildings are significantly increasing and are currently the ultimate housing solution in Palestinian cities due to high population rates and lack of land (Harker, 2011). However, these residential buildings are suffering from poor indoor environment quality due to using poor quality materials, poor construction, and site management; therefore, low occupants' satisfaction rate (Mohamid, 2016).

The literature review and previous studies analysis has served the review of the main definitions regarding thermal comfort and external wall’s thermal performance, it has also related these concepts to the levels of consumed energy. The literature review has also performed as a comprehensive summary of previous research serving the same field of study to detect the research gap.

The previous studies which were performed to serve the control of residential buildings' thermal comfort in Palestine, have fallen short to combine the indicators of enhancing thermal comfort and reducing energy consumption through external walls specifically. External walls perform as the most prominent part of the building envelope, which implies additional attention to its design to serve the main goal of achieving more thermally effective and less energy-consuming buildings. This research highlights multiple studies performed to enhance thermal comfort in residential buildings in Palestine, to continue the research cycle of external walls as a building component for enhancing thermal comfort. These studies included:

The levels of energy and electricity consumption needed to provide a better indoor environment's thermal conditions. For example, Al Qadi, has investigated the levels of energy consumption in residential buildings in Hebron and their relation to thermal comfort in her paper "Estimating the heating energy consumption of the residential buildings in Heron" (Al Qadi, et al., 2018).

Other studies have investigated the shape of a building and its contribution to thermal comfort with a shallow consideration of heat insulators in the building envelope; The effect of the building geometry and orientation on the thermal gain, and the heat gain on the effect of heating and cooling loads were analyzed by Qawasmeh in "Thermal performance and comfort in residential buildings: Relationship with building geometry and envelope components" (Qawasmeh, 2017). However, in terms of using heat insulators, the study only mentions whether the heat installation is applied or not with no detailed description of insulators or external wall components.

Thermal assessment of residential buildings in the Jabalia refugees' camp in Gaza was analyzed through the occupants' thermal satisfaction evaluation. 20 residential buildings were analyzed: 10 newly designed and another 10 traditional buildings. Results depending on PMV had shown that in new houses the PMV in summer ranged from (+1.80 to +3.0) and the minimum PMV in winter was (-1.70 to -3.0). On the other hand, traditional houses were colder in summer and warmer in winter. The paper "An investigation into thermal performance and thermal comfort of houses in refugee camps in Palestine using computer simulation” by Saleh, concludes to recommend the installation of thermal insulators to enhance the occupants' satisfaction rate (Saleh, 2016). However, these studies have neglected the application of any heat insulating material.

An evaluating study of thermal comfort for residential buildings in summer and winter in Palestine was Performed from a user-based approach. The paper “Human thermal comfort for residential buildings in hot summer and cold winter region, a user-based approach” by Monna, was based on quantitative measurements for typical multi-story apartment buildings in Palestine. The study further depended on a qualitative survey of inhabitants' satisfaction with their dwellings (Monna, et al., 2019). The paper does not discuss any interventions or construction solutions for enhancing the residents' satisfaction. The study concludes that the perceived comfort level seems more related to the inhabitants' psychological feeling of powerlessness than to real thermal comfort, which confirms that inhabitants tend to adapt to the surrounding indoor environment rather than enhance it.

Another simulation-based study analyzed three different levels of residential building retrofitting interventions for reducing energy consumption using the Design-builder software. The study “Sustainable energy retrofitting for residential buildings in Palestine, a simulation-based approach” by Monna, applies three levels of intervention to one building sample of the local residential buildings. The first level included reducing the infiltration level, the second level included the installation of insulators, shading, and double glazing, and the third level was the active solution of HVAC system installation. The energy use base case was set as the common level of energy consumption. Results have shown potentials of 16.7%, 13.3%, 28.9% for levels 1, 2, and 3 respectively, and a potential of 59% energy saving when applying all three levels of retrofitting plans combined (Monna, et al., 2021). The mentioned study considers applying one type of insulation which is polyurethane foam and focuses mainly on retrofitting strategies allowing energy reduction.

A study for two climatic zones in Palestine investigated the thermal mass and thermal timing to evaluate their effect on energy demand in Jericho and Nablus. The study “Effect of thermal mass of insulated and non-insulated walls on building performance” by Haj

Hussein, analyzed stone concrete walls by applying Polyurethane foam to different locations towards multiple orientations. The results had proven that external walls with an outer layer of insulation had the best performance in both summer and winter in both climate zones, while uninsulated walls have shown the worst performance in winter in moderate climates, but in summer uninsulated walls performed slightly better than walls with inner insulation in both climates. The study however had investigated one building envelope pattern and one insulation material (Haj Hussein, et al., 2021).

In Hebron, less attention has been paid to the installation of thermal insulators in building envelopes and external walls. Additionally, there are no local regulations and guidelines concerning achieving thermal comfort and selecting the accurate building materials and insulators. The Palestinian guidelines for energy efficient building design explain different wall composites with different thicknesses of heat insulators also with no consideration for the location of the insulator between the envelope's layers according to the Ministry of Local Government (MOLG, 2004).

After reviewing the previous studies which were performed in Palestine to achieve thermal comfort and energy saving, they were found to perform as general trials for enhancing thermal comfort through applying one or more insulating materials, and these studies have drawn less attention to external walls as the main component of the building envelop.

This research reviewed the common building practice to develop it using thermal insulation. Trials have included different materials, thicknesses, and placement of the insulation layer. Moreover, the study analyzed a more recent building trend to be considered as one of the applicable solutions, and further applied certain interventions for it. The thermal evaluation included different orientations for external walls in both summer and winter, and the effect of natural ventilation either applied or not. Thermal comfort enhancement is directly related to the levels of consumed energy, which implies an economic analysis for the proposed interventions and payback period. A condensation check was considered when selecting the most proper practice for external walls. All these analyzed factors combined have led to a more comprehensive understanding of thermal comfort through external walls in residential buildings than in other previous studies.

As a result, this research had contributed to enhancing thermal comfort and energy saving from a wider perception than previously analyzed with the combined factors mentioned above, which were not considered in previous studies. The study allows users to consider different insulation strategies for different orientations in the same apartment, which ensures initial cost saving and reduces the potential of required restoration works, which in terms reduces the costs during the building’s life cycle. The results hereby increase the proposed solutions’ feasibility. This study provided extended research regarding thermal comfort through external walls as a part of buildings' envelopes in multi-story apartment buildings in Hebron, which has not been thoroughly investigated. This research relies on thermal comfort standards indices and considers occupants' thermal adaptive methods. This research will also help to expand other future research regarding thermal comfort in residential buildings and further development in the field of thermal insulators. It will also contribute to other studies regarding energy saving, rating of potential condensation, and hereby indoor environment enhancement, directly related to achieving sustainability.

Moreover, this study will significantly contribute to achieving the addressed objectives of the development plan adopted by the municipality of Hebron as a part of “Palestine: Municipality of Hebron Sustainable energy action plan” in 2016 for residential buildings. These objectives included promoting the proper dwelling temperature to avoid excessive heat and extreme cold indoor environments in summer and winter respectively. The sustainable energy action plan also confirms that reasonable heating or cooling temperatures can reduce energy consumption by 20-30%. The plan also included long-term objectives targeting energy-efficient buildings where proper insulation could significantly improve thermal comfort while reducing the levels of consumed energy. Hebron municipality had recommended the construction of high energy performance buildings, which relatively requires more thermally responsible new buildings (SEAP, 2016).

1.4 Scope of the study

The reliability and effectiveness of innovative technologies are the main issues to prove their continuous validity in the long term (Diakiki, et al., 2008). The same concept was adopted by identifying the prior two key points to be considered in such experiments, these were a) The correlated measurements between thermal comfort and energy saving, and b) The rationalistic application of the measures (Georgiou, 2015).

The scope of the study is in line with the notation of the previous two studies. The measures of thermal comfort were accomplished through analyzing occupants' satisfaction in occupied buildings in Hebron city, which aimed at providing a clear evaluation of the common building practice and thermal comfort in a residential apartment in Hebron. While the second is directly related to the set results of recommendations to be valid for as this research results. These recommendations are considered as future rational result since they depend on the simulations of a realistic model that imitate actual cases from Hebron.

1.5 Problem statement

Thermal comfort and occupants' satisfaction is one of the main design requirements in residential buildings. Achieving thermal comfort is becoming an essential need for energy saving in Palestine. The study proposes multiple external wall interventions and construction recommendations for enhancing thermal comfort, reducing condensation, and lowering the energy burdens in multi-story apartment buildings in Hebron. The proposed strategies could be gradually implemented in other cities of Palestine.

1.6 Research questions

After defining the research gap in the field of residential buildings' thermal comfort, the research adopts the question:

- To what extent could the interventions of external walls be applied for controlling thermal performance and saving energy in residential buildings in Palestine?

Among these, other sub-questions were carefully articulated to form the study structure:

- How would changing the type and the thickness of the thermal insulator affect thermal performance and energy saving?
- To what extent could changing the location of the insulating layer affect the external wall thermal performance and energy demand?

- How would the proposed external wall interventions act in terms of the needed payback period?

1.7 Aims and objectives

The study mainly aims to enhance the indoor living quality of residential buildings by enhancing the common practices of external wall construction and materials. The study also aims to introduce general design recommendations for a proper design of buildings' walls in an attempt of lowering cumulative condensation and achieving energy savings in residential buildings toward a better perception of sustainable residential buildings in Palestine.

Objectives: the research has the following objectives:

- To evaluate the physical and thermal characteristics of the proposed pattern of external wall construction depending on the collected data from the field survey accomplished.
- To evaluate the impact of external wall interventions and material selection and select the external wall practice which had best achieved thermal comfort and energy saving.
- To calculate the payback period needed for each intervention to return its costs.

1.8 Methodology

Previous studies were reviewed to assist in the validation of the work's methodology, the study investigates previous studies' methodologies concerning thermal comfort measures and the number of targeted apartment buildings to assist in the determination of the number of residential building samples for this research. For example, in a study regarding the adaptive use of natural ventilation for achieving thermal comfort in apartments in India, the study was conducted in Hyderabad, and it depended on analyzing samples of five small to medium apartment buildings. Other adapting habits information was collected from about 100 subjects through a set of questions (Indraganti, 2010).

Another study aimed at analyzing the main building features for housing projects in Brazil has considered the most common building features through by analyzing five representative building models for assessing the levels of ventilation and lighting in indoor spaces to the space area (Tubelo, et al., 2018).

The effect of buildings' envelope on thermal comfort in residential buildings in Mediterranean climates was investigated by measuring the ambient air temperature and relative humidity in Rome, Italy. Climate data and indoor environment parameters were collected from two apartments in four different neighborhoods, which gives a total number of 8 samples, each apartment had three external walls and all selected buildings were characterized by the same construction material. The climatic data were then used to evaluate the thermal response of a typical Italian residential building to be compared with the simulation results from two different building envelope interventions (Zinzi & Carnielo, 2017).

Another study for evaluating the effect of passive houses in the United Kingdom analyzed 11 passive houses: among these 10 privately owned houses. Samples' characteristics were not identical; however quite similar. Most of the projects were oriented toward the south or within 30° from the south. The U-values of the external walls were all around 0.15 W/m^2k. The U-values of the windows were less than 1 W/m^2k. The study concluded to different levels of adaptations and behavioral residences' differences in passive houses and evaluate their perception of sustainability (Zhao & Carter, 2020).

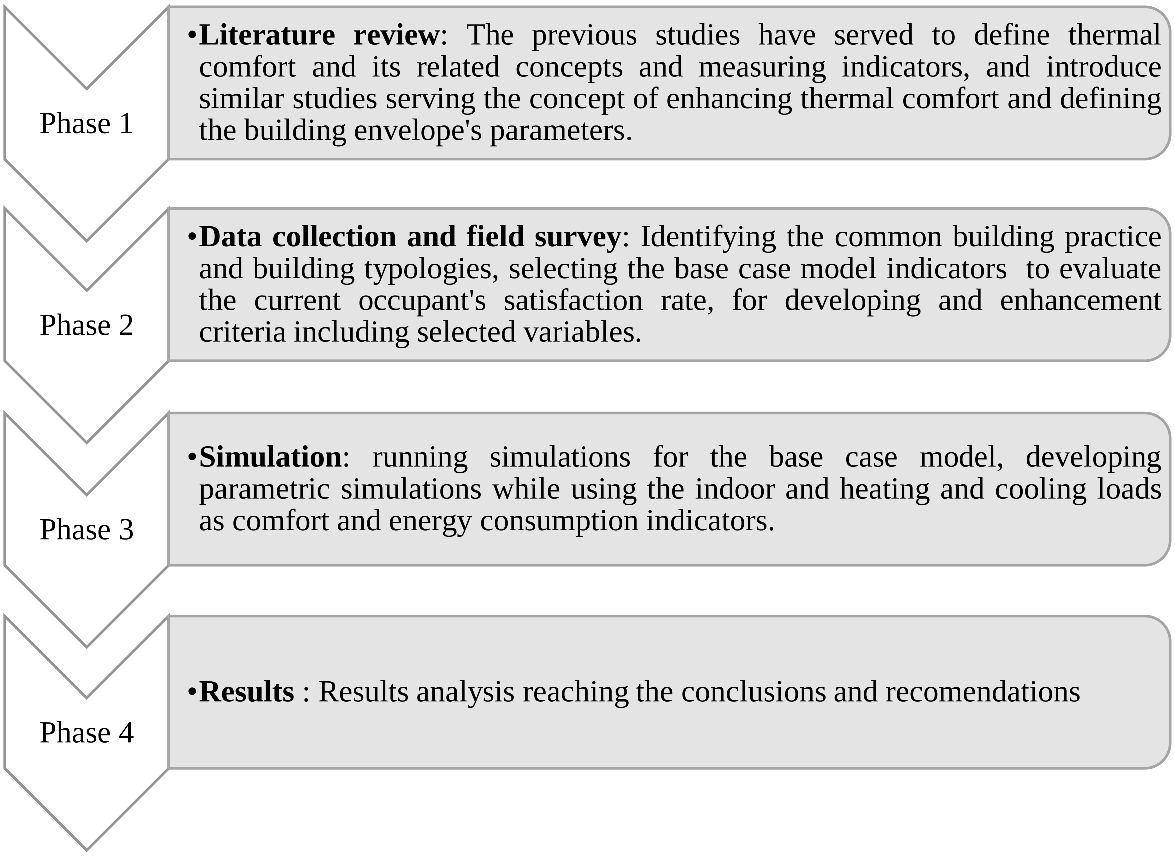
On a larger scale, the levels of thermal comfort in residences in three cities in China were investigated depending on field surveys and measurements. The study obtained 110 responses from the three cities and investigated 26 residential buildings during the summers of 2003 and 2004. The survey and measurements aimed to characterize occupant's thermal perception in the selected housing units the study extended to assess the levels of adaptation according to ASHRAE standard 55 -1992 and depending on the ASHRAE seven-point sensation scale (Han, et al., 2007).

Questionnaires are considered one of the most frequently used investigation methods for the evaluation of occupants' satisfaction and behavior rates, moreover, their most cost-effective. Monitoring the behaviors of users could be achieved at a low-intrusion level using questionnaires, and data could be collected on multiple levels explaining the motivation for certain actions and practices (Hong, et al., 2016), (Wagner, et al., 2018). According to (Balvedi, et al., 2018), questionnaires are the recurrent method used in residential buildings. However, monitoring these self-reported behaviors must be done through direct questions to avoid misinterpretations. Questionnaires were used as analytical tools or studies conducted to evaluate users in their dwellings, for example, (Andersen, et al., 2009) employed a questionnaire to collect users' replies inferring about Danish dwellings' openings, lighting, heating, and other analyzed indoor environment controllers. (Feng, et al., 2015) had also used questionnaires' results to develop the building typical patterns through monitoring the habits of the residents affecting air conditioning consumption in living rooms and bedrooms of residential buildings.

The research mainly involves two stages serving the methodology of the study, these are the field surveys and the simulation. Field surveys included questionnaires and personal interviews serving the needed research data collection. The simulation trials were required for the evaluation of the envelope's interventions evaluation and the justification of the used model. The research methodology flow is explained in Figure 1-1 as follows.

The methodology of the research has depended on the following research tools:

- Field visits and observations have served as a source for the data collection for Identifying the common building practices and external wall construction patterns and composites.
- Questionnaires were used as another source of data collection regarding the evaluation of occupants' satisfaction rates in terms of thermal comfort in the common building practices.
- Simulations have served as the source for the quantitative data collection, values of operative temperatures, levels of needed cooling and heating loads, and amounts of cumulative condensation were obtained.



Phase 1

- **Literature review**: The previous studies have served to define thermal comfort and its related concepts and measuring indicators, and introduce similar studies serving the concept of enhancing thermal comfort and defining the building envelope's parameters.

Phase 2

- **Data collection and field survey**: Identifying the common building practice and building typologies, selecting the base case model indicators to evaluate the current occupant's satisfaction rate, for developing and enhancement criteria including selected variables.

Phase 3

- **Simulation**: running simulations for the base case model, developing parametric simulations while using the indoor and heating and cooling loads as comfort and energy consumption indicators.

Phase 4

- **Results** : Results analysis reaching the conclusions and recomendations

Figure 1-1: The flowchart of the research methodology

1.9 Research structure

This research includes five chapters including the introductory chapter. The first and second chapters describe similar previous studies with a brief introductory historical background regarding thermal comfort and the building's external walls and envelope. Chapters from third to fifth focus on the experimental work starting from the methodology and data collection to the research results and findings, and finally the conclusions and discussions.

- Chapter 1: Introduction, this chapter starts with the justification of this research and the research significance, aims, and objectives, and presents a summary for each chapter.

- Chapter 2: Thermal Comfort and Building Envelope, this chapter is the literature review chapter for thermal comfort and building envelope. The chapter includes definitions of thermal comfort, building envelope, and other related definitions. The chapter also presents related concepts and previous studies regarding external walls, and a brief historical background of thermal comfort in traditional buildings through external walls to enhance thermal sensation and therefore thermal comfort for occupants.

- Chapter 3: Research Methodology, the chapter includes the research methodology. The chapter introduces an extended description and illustrations for the used research methods, it also includes the research structure chart. The chapter explains the framework of data collection, sample selection, and measurements with all related variables.

- Chapter 4: Result and Findings, this chapter includes the analysis of the results, measurements comparisons from the simulation model along with the analysis of occupants' thermal sensations in different studied seasons. Results analysis includes cooling and heating loads analysis, the analysis of condensation probabilities, and finally the payback period calculations for the applied interventions.

- Chapter 5: Conclusions and Recommendations, the last chapter wraps up the research with the main concepts covered by this thesis to finally end up with conclusions and recommendations for future enhancement of the indoor environment quality for future work.

Chapter 2

Thermal Comfort and Building Envelope

Chapter 2

Thermal Comfort and Building Envelope

2.1 Introduction

Thermal comfort is one of the international trends for energy-saving design scope as well as achieving high-quality internal spaces is an architectural and interior design inquiry (Hou, 2016). Indoor environment quality has a great impact on occupants' productivity, health, and well-being since people of modern society are spending most of their time indoors (Tomasi, et al., 2013) (Fanger, 1970). Studies concerning thermal comfort go back to the 19th century; back when Haldane studied design temperatures in England in 1905 (Georgiou, 2015). The definition of thermal comfort continued to gain further attention in the 20th century when comfort was referred to as a 'shelter' protecting users from severe environmental conditions (Shove, 2004). Thermal comfort has started gaining wider eco in the fields of research and had been increasingly highlighted as an international concern since 2006 (de Dear, et al., 2013).

This chapter aims at introducing thermal comfort and its related concepts. The chapter first includes the definition of thermal comfort along with the reflected effects on occupants' health, productivity, and adaptation ways depending on a background from previous studies. It further discusses thermal sensibility and thermal comfort assessment indices in the second section. The third section focuses on thermal comfort indicators in naturally ventilated residential buildings which the study will focus on.

2.2 Definition of thermal comfort

According to ASHRAE standards, thermal comfort is defined as the conditions providing a satisfactory state of mind in response to the surrounding thermal environment (Liu, et al., 2007). Occupants are considered thermally comfortable when they can do and practice their intended activities comfortably within the indoor environment (Akande & Adebamowo, 2010). Which means that occupants' satisfaction rate is higher when occupants' expectations concerning indoor climate best match the existing conditions (Dear, et al., 2013).

Thermal comfort standardization aims to increase the levels of satisfaction by a minimum of 80% among occupants by combining the internal environmental factors and the personal factors (de Dear & Brager, 2002). De Dear summarizes the four main environmental factors as: temperature, thermal radiation, humidity, and airspeed. While the three main personal factors as: personal activity, clothing, and metabolic rate (de Dear & Brager, 2002).

The occupants tend to respond the four main environmental factors mentioned by de Dear differently, for example:

First, occupants respond to indoor air temperatures variably depending on their habitual temperatures; for example, people living in cold climates are expected to be notably more sensible to hot temperatures and just the opposite for people living in hot climates (Iñiguez, et al., 2010). From a wider perception, satisfying and comforting temperatures are directly associated factors with elder people’s mortality (Morabito, et al., 2012). Workers’ safety behaviors are influenced by temperatures higher or lower than they preferred, which lowers their productivity rates by 5-7% (Ramsey, et al., 1983) (Niemela, et al., 2002). Moreover, temperatures around 30°C reduce workers’ productivity by 9% (Seppanen, et al., 2006).

Second, the human body seeks comfort by continuously stabilizing balance between the body and the surrounding environment as long as the body exchanges heat through processes of conduction, convection, evaporation, and radiation is referred to as maintaining thermal comfort (Mohamed, 2011).

Third, humidity is not only correlated to the perception of air quality but also affects humans’ comfort, skin moisture, thermal sensation, and energy balance remarkably. Despite that humidity is a relatively less important factor in cold weather when the body can lose heat by conduction, convection, or radiation, it is a primary factor in hot climates controlling excessive heat loss through evaporation (Stein, et al., 1986). Levels of humidity of 40-60% help sweating and evaporation and thereby skin temperature change leading to thermal comfort (Berglund, 1998). On the other hand, problems of contamination and fungus forming at higher levels of humidity reaching up to 80% cause respiratory infections and skin diseases (Baughman & Arens, 1996); (Toftum & Fanger, 1999).

Fourth, international studies concerning the influence of airspeed on thermal comfort for different categories of people with different activity rates confirm that increased air velocity causes draught sensation in cold weather but could be beneficial in hot climates (Olesen & Parsons, 2002). Draught also causes respiratory system problems and lung diseases (Pantavou, et al., 2011).

Thermal comfort along with the environmental conditions generally affect users' health and wellbeing, which in term contributes to the quantity and quality of productivity (Georgiou, 2015). Generally, the human body and mind both seek to find themal comfort, therefore, occupants' satisfaction is also directly related to their behaviors and the way of adaptation to the previously mentioned environmental factors (de Dear & Brager, 2002). Ways of adaptation are generally divided into four ways. The first is a behavioral adaptation in which a person can adjust to the surroundings by changing some personal parameters such as clothing. Second is the technological adaptation referring to an adjustment in the surrounding, for example turning a fan on, opening a window, or closing a diffuser. The third way of adaptation is physiological acclimatization which is defined as "changes in a person's physiological thermoregulation setpoints (e.g., the onset of sweating) that result from prolonged exposure to climatic conditions outside the traditional comfort zone". The last way of adaptation is psychological which happens when a person's preferred temperatures change according to the change in the indoor environment which is correlated to long-term seasonal outdoor change (Fountain , et al., 1669).

2.3 Thermal comfort assessment indices

Thermal comfort has three definition approaches, these include the rational approach, the adaptive approach, and the social practice approach. The first is based on laboratories and chamber studies like thermostat-based simulations. The second depends on field studies and the third is based on physical reactions to social practices which have proven shortages in consideration of cultural context (Hou, 2016).

Depending on Fanger's experiments subjecting a group of occupants under the same circumstances thermal comfort measuring indices depended on the predicted mean votes (PMV) and the percentage of people dissatisfied (PPD) are two main standard thermal comfort measuring indicators according to the ISO and ASHRAE standards (ISO 7730, 1994) (ASHRAE, 2010). The PMV provide a clear prediction for the levels of discomfort or dissatisfaction within a space through scaling levels from 'cold' to 'hot' on a seven-point scale from -3 to +3, where -3= cold, -2= cool, -1= slightly cool, 0= neutral, +1=slightly warm, +2= warm, and +3= hot. The PPD predicts the dominant percentage of people feeling 'too cold' or 'too hot.' According to Fanger people who responded within ranges of (-3, -2, +2, +3) were considered in discomfort, and responses of (-1, 0, +1) were declared in comfort (Djongyang, et al., 2010). However, controlling, verifying, and considering deviation implies applying indices among people from the same ethnic group and the same geographic region, in good health conditions, and genuinely in the same age group whereby children are not considered (Olesen & Parsons, 2002).

Thermal comfort is gender dependent. Females were proven to be more sensitive to temperature deviation (Fanger, 1970). According to a study conducted in Finland, significant sensitivity differences were found between genders depending on interviews and controlled experiments conducted to simulate the real use of thermostats; females preferred higher temperatures and were more thermal environment critical (Karjalainen, 2007).

2.4 Thermal comfort in residential buildings

Residential buildings are generally not comparable to the previously mentioned scaling approaches, the PMV and PPD models do not subject to the effects of adaptation. The domestic indoor environment requirements are far from the steady state; differences in a smaller timescale may occur such as the activity and metabolic rates, and different rates of required ventilation depending on changing the internal gains and the indoor temperature, as a result, people at home are expected to adapt easily and in a wider range of the previously mentioned adaptation ways if compared to offices or other buildings. For example, changing activity or clothing rate or even drinking cold or warm drinks (Peeters, et al., 2009). Peeters adds, that studies concerning thermal comfort in residential buildings can be based on distinguishing three different thermal zones depending on the thermal requirements of domestic spaces: bathrooms, bedrooms, and other zones including mainly the kitchen, living room, and office. In reference to Morgan and de Dear, the clothing rate is corresponding not only to today's temperature but also to the last few days (Morgan & de Dear, 2003). This supports the Van der Linden model of calculating the adaptive temperature limits involving the summation of the averages of maximum and minimum external temperatures for the day of the study, the day before, 2 and 3 days before the targeted day (van der Linden, et al., 2006).

2.5 Energy consumption and thermal comfort

International urbanization and rapid economic development are causing the world great challenges involving energy shortage. Residential building designs in the last few decades have been suffering from insufficient passive cooling or heating strategies and poor building envelopes' design creating inefficient systems suffering from a lack of energy awareness. Humans' requirements for thermal comfort are improving as well and people are tending to use air conditioners all year long; in extreme and transition seasons (spring and autumn); (Liua & Kojima, 2017). Therefore, maintaining thermal comfort has been high energy consumption in the residential buildings sector (Georgiou, 2015). It was proven that the residential sector is consuming 31% of the global energy consumption. Thus, energy saving is becoming an international concern (Zhang, et al., 2015); (Liang, et al., 2007). Recent studies have also shown high levels of energy consumption reaching up to 68% for mechanical heating and cooling to achieve thermal comfort (Tomasi, et al., 2013).

A building typology directly affects its indoor temperature and the solar gains, the building form acts as one of the most important factors in the above-mentioned comfort indices (Dear, et al., 2013); (Oral & Yilmaz , 2002).

Many studies have investigated the relationship between thermal comfort and energy consumption in a building typology, according to a study conducted in China for three different types of residences; neglecting the effect of the building envelope and the building construction date, has compared the amount of energy demand and thermal comfort for three buildings' types, these were high-rise residential buildings, multi-story residential buildings, and detached houses for 183 family houses as a sample using the predicted mean vote (PMV), field surveys, and a mathematical interpolation method. Results have shown that high-rise residential buildings are the most effective buildings in terms of thermal performance followed with multi-story residential buildings and detached houses being the least thermally effective. However, regarding energy use, multi-story residential buildings had proven to be the lowest energy-consuming building type (Liua & Kojima, 2017).

Indoor thermal comfort and energy consumption of a building are also related to sensible design parameters. On the building scale, these parameters include orientation, building form, and the physically thermal properties of the building's envelope. Interrelated relationships and the optimization of these factors all together will guarantee the best thermal performance for the building (Oral & Yilmaz , 2002). In addition to the building form, the building's envelope’s physical properties notably affect thermal comfort. Physical properties include the heat transfer coefficient (U-value), the envelope's thermal mass, and the ratio of total façade area to the building volume (A/V).

The Palestinian building sector's construction techniques have changed significantly in the last decade; modern techniques, reinforced concrete, and stone cladding have widely spread in Palestine. These practices have led to lowering thermal comfort in the indoor environment of modern buildings due to certain thermal properties of the building’s envelope, which implies larger heating and cooling burdens which increase the energy consumption (Khammash, 2002).

2.6 Building envelope

In sustainable projects, buildings envelopes highly influence the levels of energy required to achieve thermal comfort. The design of the building envelope impacts materials use, indoor air quality, life-cycle performance, and energy efficiency (IMI, 2017). Building envelopes consisting of walls, roof, floor, and windows should be extended beyond structural, architectural, or atheistic to provide comfort and safety. Among these, studies concerning walls’ composition and insulation strategies were intensively investigated. Studies concerning the composition of walls with the placement and thickness of the insulating layer reported the advantages of energy-saving (Al-Sanea, et al., 2012). For example, physical wall properties like heat storage capability contribute to controlling the indoor temperatures without relying on mechanical systems and in terms of reducing required energy (Aliadroos & Krarti, 2014).

A study conducted in Saudi Arabia has proven an average of 35% in energy cost saving in different cities through optimizing the building envelope elements, these included thermal mass considerations, wall, and roof insulation, windows to wall ratio, and glazing type (Aliadroos & Krarti, 2014). Depending on another study for hot climates, analyzing insulators of 5, 7.5, and 10cm thicknesses placed differently within the wall, results have shown that insulating layer of the insulator located within the outside layer of the exterior wall showed the best energy saving results (Saleh, 1990). Another study investigated the application of polyurethane boards in mud bricks and concrete hollow block walls, results showed that walls of mud bricks required a 0.5cm less thickness in insulating boards compared to concrete hollow brick walls. Moreover, the outer placement of the insulator prevents the development of thermal stress (Abdelrahman & Ahmad, 1991).

The influence of the installation for different insulating materials in Mediterranean regions was proven to be directly related to the levels of energy consumed. The results of investigating three typical insulation materials: Polyurethane, Polystyrene, and Mineral wool have shown small, but significant differences between the subjected materials. However, Polyurethane was the lowest energy-consuming (Cabeza, et al., 2010). Moreover, the energy consumption can be reduced by 29% compared to the present energy demand by the implementation of thermal insulation in residential buildings in Hebron (Lazzeroni, et al., 2017).

Building envelopes insulating can involve either insulating materials like polyurethane, wood wool, or similarly any other physical insulators; envelopes also involve internal air layers in external walls, roofs, and windows. Air generally reduces heat gain and losses, it further helps convert solar radiation into thermal energy for passive cooling or spaces heating to enhance thermal comfort using its different types, which can be summarized as the enclosed type, the naturally ventilated type, and the mechanically ventilated type (Zhang, et al., 2015).

2.7 Physical and thermal properties for the building envelope

The thermal performance of buildings is the result of the interaction between the construction features with the climatic conditions of the site. While the climate and weather conditions are responsible for the amount of thermal energy available in the environment, the construction features are directly related to the building envelope's physical and thermal properties of the materials, insulators, air cavities, and construction. Which determines the building's capability of transferring, storing, or emitting heat (Grabarz, et al., 2012). These characteristics include the following (Palestine Building Codes, 2015).

2.7.1 Heat transfer coefficient (U-value)

The heat transfer coefficient is the proportionality constant for the flow of heat. Heat is normally transferred by convection or direct transition between surfaces. The heat transfer coefficient or as referred to as U-value is the reciprocal of thermal resistance (R-value) (Maddox & Mudawar, 1989).

The effect of the thermal properties of different wall combinations on the levels of consumed energy of buildings in the Gaza strip was found to be significant with the recommended U-value of walls (1.8 W/m^2. k) by the local Energy Code saves 22% on the required heating and cooling energy (Muhaisen, 2015).

2.7.2 Thermal mass

Thermal mass is defined as 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 releases it through the night as shown in Figure 2-1 below. According to the International Masonry Institute, researchers have noted that high thermal mass materials are most effective when installed on the internal side of an envelope (IMI, 2017).

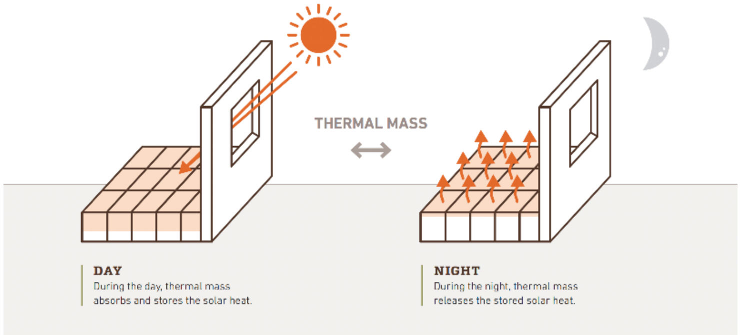


Figure 2-1: Thermal mass day and night
Source: (IMI, 2017)

A study for buildings envelops in hot climates analyzed the effects of amount, location, and thermal mass in the walls of insulated buildings, in consideration of constant nominal resistance and for a given thermal mass, inside insulation was less preferable in terms of the overall thermal performance when compared to outside insulation in continuously air-conditioned spaces. Moreover, the study concludes that optimization of thermal mass saves 17% and 35% of the annual cooling and heating loads respectively (Al-Sanea, et al., 2012).

Analyzing the effect of high thermal insulation and high thermal mass techniques in buildings' dynamic behavior in Mediterranean climates showed that maximizing the internal heat capacity and adding an external insulation layer improves the building's indoor environment in the wintertime (Stazi, et al., 2015).

2.7.3 Airtightness

A building envelope's airtightness, or as referred to as air leakage or infiltration, is defined as the unintentional and uncontrolled flow of the external air into the building through potential leaks in the building envelope. It directly impacts the building's ventilation rates and therefore the indoor environment quality and energy consumption (Persily, 1999). According to ASHRAE standards, it is the penetration of external air into the building through cracks or unintentional openings through normally using a space, which confirms that infiltration happens because of differences in temperatures or driven by the wind (ASHRAE, 2009). Reducing the level of infiltration will enhance the indoor environment and reduce the amount of needed energy for ventilation on the one hand, on the other hand, it will negatively influence the indoor air quality and cause an increase in pollutants concentration like CO, CO_2, moisture, and dust resulting from occupants' activities like cooking and smoking (Georgiou, 2015).

2.7.4 Condensation

Buildings' envelopes are significantly affected by moisture condensation. Buildings' behavior is negatively affected by cumulative condensation in various ways, among these is the deterioration of the materials within the envelope causing the overall weakness of the structure and the growth of mold (Achenbach & Trechsel, 1982).

The condensation occurs due to factors either during construction or operation of the building. The first includes the installation of wet construction materials, infiltration of water, or mechanical problems causing water leakage. The second is mainly caused by differences in the inner and outer surfaces temperatures, and interstitial condensation, which is caused by the cumulation of vapor crossing the external walls due to differences in partial vapor pressure between the internal and external surfaces of the wall (Bellia & Minichiello, 2003), (Yamankaradeniz, 2015).

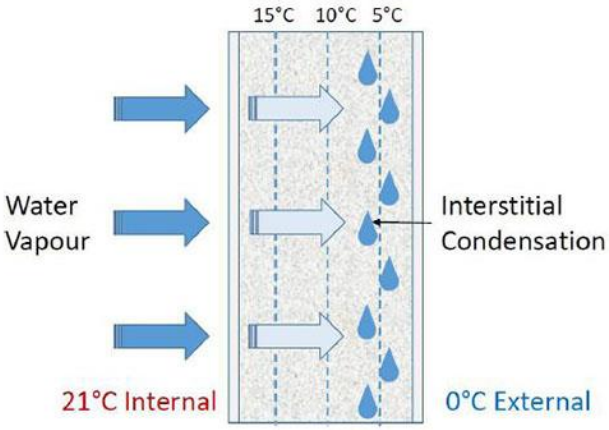


Figure 2-2: Interstitial condensation
Source: (Productpsec, 2015)

The cooling and heating loads reduction is directly related to the insulation in the building envelope. However, the selection of insulating materials should consider the moisture transfer and associated condensation risk along with energy consumption. (Rivas, et al., 2018) Have conducted a quantitative study using the Energy Plus optimization tool. Results have shown that the condensation risk is more likely to occur in higher thickness envelopes.

2.8 Conclusion

This chapter has introduced a literature review about thermal comfort and its effect on occupants’ health and wellbeing. Related concepts regarding thermal comfort in residential buildings were analyzed, energy-saving patterns related to thermal comfort, the physical parameters including the heat transfer coefficient (U-value), Thermal mass, Airtightness, and condensation potential of a building envelop directly influencing achieving thermal comfort were also reviewed. The literature review has performed as an extended understating of the concept of thermal comfort and assessment methods for evaluating occupants’ satisfaction rates and the application of thermal comfort enhancement for the analyzed building envelopes of common practices and their evaluation in the analyzed study context of Hebron city which will be furthered discussed in the following chapter.

Chapter 3

Research Methodology

Chapter 3

Research Methodology

3.1 Introduction

After the extended literature review and theoretical introduction presented previously in chapter 2 relying on research papers, scientific journals, and books to clarify the concept of thermal comfort by providing an extended introduction about its definition, indices, and measurements. The literature review finally gathers introductory information concerning the building envelopes and their thermal and physical properties.

This chapter describes the adopted methods in the study for the needed data and measures. The chapter explains the used methodology and describes the process of data collection and simulations for evaluating the current building typologies' thermal performance which allows setting a benchmark for this thesis to start the suggested envelop interventions for a space sample in residential buildings within the context.

This chapter extends to provide a clear view of the approaches and motivations for data collection through physical sites survey (site visits and questionnaires distribution), explanation and verification for the selected simulation model, the thermal modeling procedure, and used simulation engines.

The study conducts quantitative research through the enhancement of indoor temperatures. However, the study has also required the adaptation of both the quantitative and qualitative research approaches in the process of data collection. The study has implied research tools including observation, physical site surveys including questionnaires, and building samples collection for the analysis of the local building practices evaluation.

According to the Palestinian Central Bureau of Statistics, the percentage of residential apartment buildings has been increasing in the last two decades. The percentage has nearly doubled from 39.9% in the year 2000, and 53.7% in 2015, to 61.5% in 2017 (PCBS, 2017) as shown in Figure 3-1 below. The percentage has increased to make the residential apartments the most common building typology in Palestine. This percentage equals 46.6% in Hebron (PCBS, 2017).

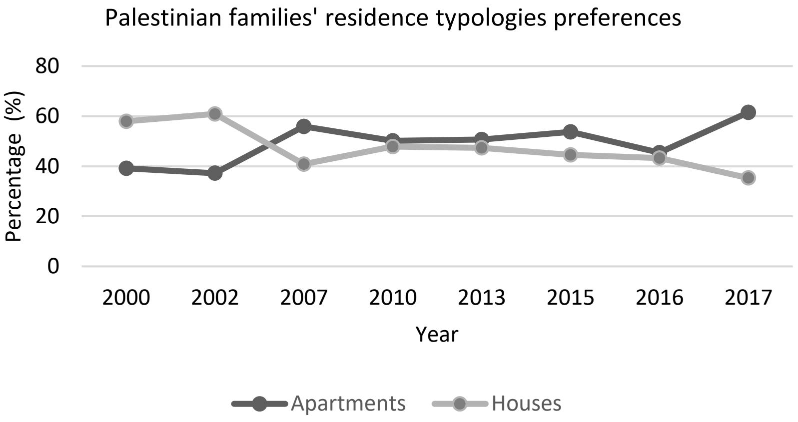


Figure 3-1: Palestinian families' residence typologies preferences.
Source: Researcher depending on (PCBS, 2017)

Regarding the percentage distribution of households in Palestine by the tenure of housing units, around 84.6% of the Palestinian housing units were classified as owned houses according to the statistics of 2017; this percentage equaled 89.3% in Hebron in the same year (PCBS, 2017). Figure 3-2 proves the steady tendency of household ownership in Palestine in the last two decades. Therefore, the study focuses on owned apartments due to the higher possibility of interventions' application in owned houses.

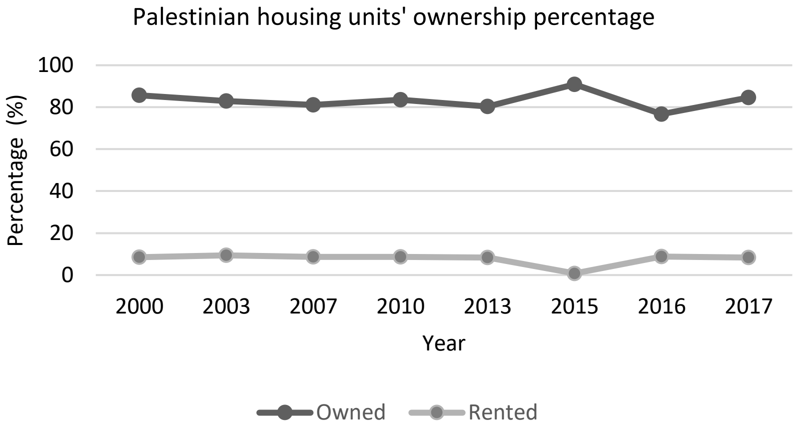


Figure 3-2: Palestinian housing units' ownership percentage
Source: Researcher depending on (PCBS, 2017)

The illustrated measures in the above-shown graphs explain the motives for targeting owned apartment buildings for data collection in the physical field survey using questionnaires due to this reason, the questionnaire included questions regarding the type and household of the housing units. The study has investigated owned residences rather than rented units to be more related to the current social fabric to extend the validity and the feasibility of the study which in terms will better meet the Palestinian community's needs.

3.2 Data collection

The phase of data collection was accomplished after the literature review, where similar previous studies regarding thermal comfort were investigated to indicate the used indices and measurement tools for thermal comfort, the previous phase - the literature review- had focused on the external walls as the main component of a building's envelope, explaining the physical and thermal properties to be considered in the subjected simulation model. Defining the thermal transmittance, the thermal heat transfer coefficient, the thermal mass, and the potential of condensation occurrence were key elements to be solved during the simulation for a more thermally reliable external wall model.

The qualitative data collection extends to include field surveys. This study included a physical field survey depending on observations and questionnaires to serve data collection regarding the occupants' thermal sensations to better understand their perception of thermal comfort, and to better describe the current thermal conditions of residential buildings in Hebron. The survey also aims to explain the increasingly high demand for heating and cooling in residential apartments, which is related to the achievement of thermal comfort nowadays, and therefore excessive energy consumption. Moreover, the survey helps define an essential first step of this research, which is the occupants' need for achieving better thermal comfort.

The field survey included two methods of data collection: a) qualitative data, which was collected through the questionnaires, on-field observations, and interviews with local contractors and manufacturers for validating the selection of un-analyzed external wall components and construction patterns confirmation b) the data collected from a group of selected samples for residential multi-story apartments buildings in Hebron to analyze the common building practices and to conclude to the physical properties for the simulation model which was selected. The data collection methods in reference to the research method were summarized in Figure 3-3 shown below.

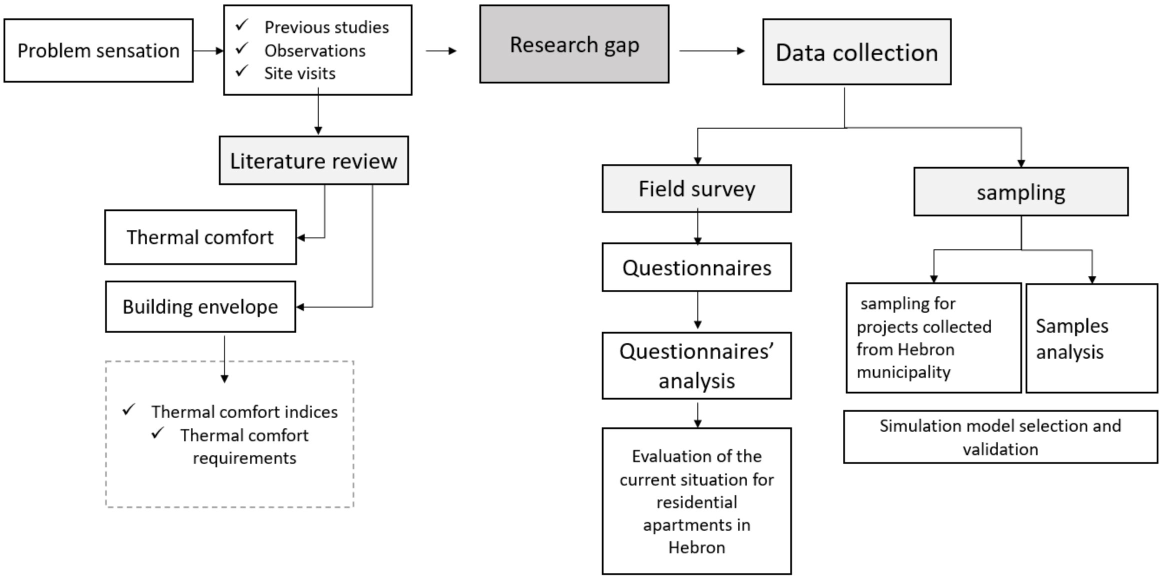


Figure 3-3: Data collection criteria

3.2.1 Questionnaires

The questionnaires and personal interviews aim to provide a better understanding and a wider perception of the thermal conditions in occupied residential apartments in Hebron, occupants' thermal sensation, thermal preference, and thermal adaptation in their homes. The questionnaire included objective and subjective questions. Objective data included the gender and age and other collected information regarding the ownership, the typology, and the area of the housing unit. Subjective variables included the level of satisfaction for occupants and their comfort indices. Along with their sensation and thermal preferences depending on Fanger's thermal sensation scale, thermal comfort was assessed on a scale from -2 (cold) to 2 (hot). Other questions aimed to provide a more detailed description of the building materials and insulators commonly used in external walls in Hebron to help the establishment and the creation of the simulation model. Occupants were asked to determine the type of installed insulation (when applied) depending on the common practice in the city, where apartments are sold with no insulation nor finishing works. Such works are accomplished in the finishing phase by the owners which makes it determinable by them through the questionnaire.

The study applies the small sample technique explained to determine the required questionnaire responses. According to (Krejcie & Morgan, 1970); (NEA, 1960) The National Education Association (NEA) has published a formula for domain and sample size determination. The method, called the 'Small Sample technique', was developed due to the continuously increasing need for surveys, samples, and sample sizing in different research activities.

The Small Sample technique depended on the NEA's formula shown in Equation 3-1 as follows.

$$s = X^2NP(1-P) \,/\, d^2(N-1) + X^2P(1-P) \qquad \textit{(3-1)}$$

- s is the required survey sample size.
- X^2 equals 3.841 from the table value of chi-square for 1 degree of freedom.
- N is the population size.
- P is the population proportion (0.50 provides the maximum sample size).
- d is the degree of accuracy which equals 0.05.

The total population of the Hebron governorate has exceeded 762500 in 2020, and 215500 in Hebron city in 2020 (PCBS, 2020). The total number of people living in apartments in Hebron was selected as the addressed population in relevance to the selected domain of the field survey, which equals 100423 (PCBS, 2019). Depending on Equation 3-1. The equation's inputs were: (N), the number of people living in residential apartments in Hebron, the population proportion (P) was considered 0.50 to give the maximum number of needed responses, and the degree of accuracy tolerance (d) was considered 5% (0.05); The number of maximum questionnaires responses (s) equaled 383.

Based on Geographic sampling, the requested number of questionnaires were distributed to occupants of residential buildings located in different areas of the city. The responses were meant to be collected from different topographic regions affected by different climatic conditions and varying effects of the prevailing wind. Areas subjected were mainly: Ras Al-Jorah in the Northern part of the city, Farsh Al-Hawa in the North-Western district, Habayel Al-Riyah to the East, Wadi Al-Harriyah and Essa in the South-Western region. Other areas in between were also subjected during data collection. The domain of the questionnaire is illustrated on the map of Hebron in Figure 3-4 as shown below. The study had accomplished a maximum response rate around 86.1% of the determined sample size, this was accomplished by setting several targeted residential buildings in each geographic zone, collecting responses in person has assisted as well in retrieving the required number of responses. A total of around 330 responses were collected from 11 apartments from 5 residential buildings in each one of the different 6 geographical zones as shown on the map.

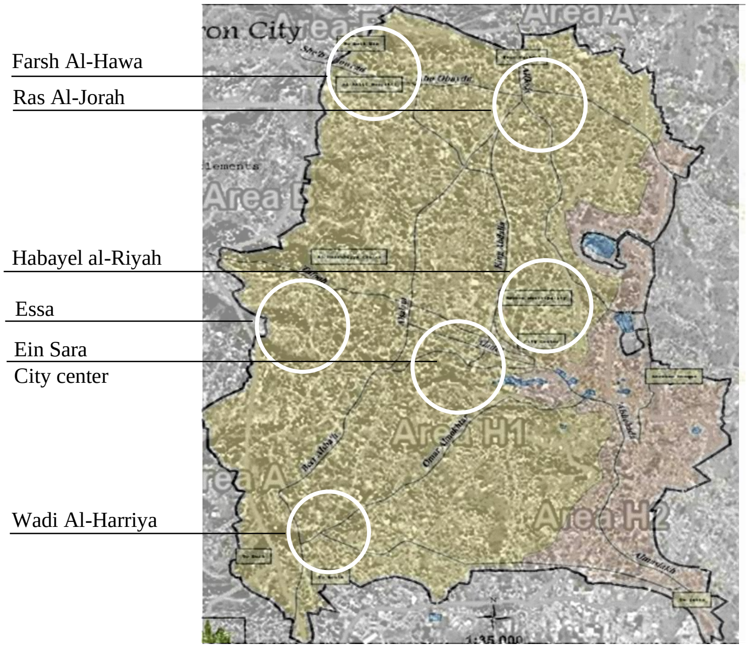
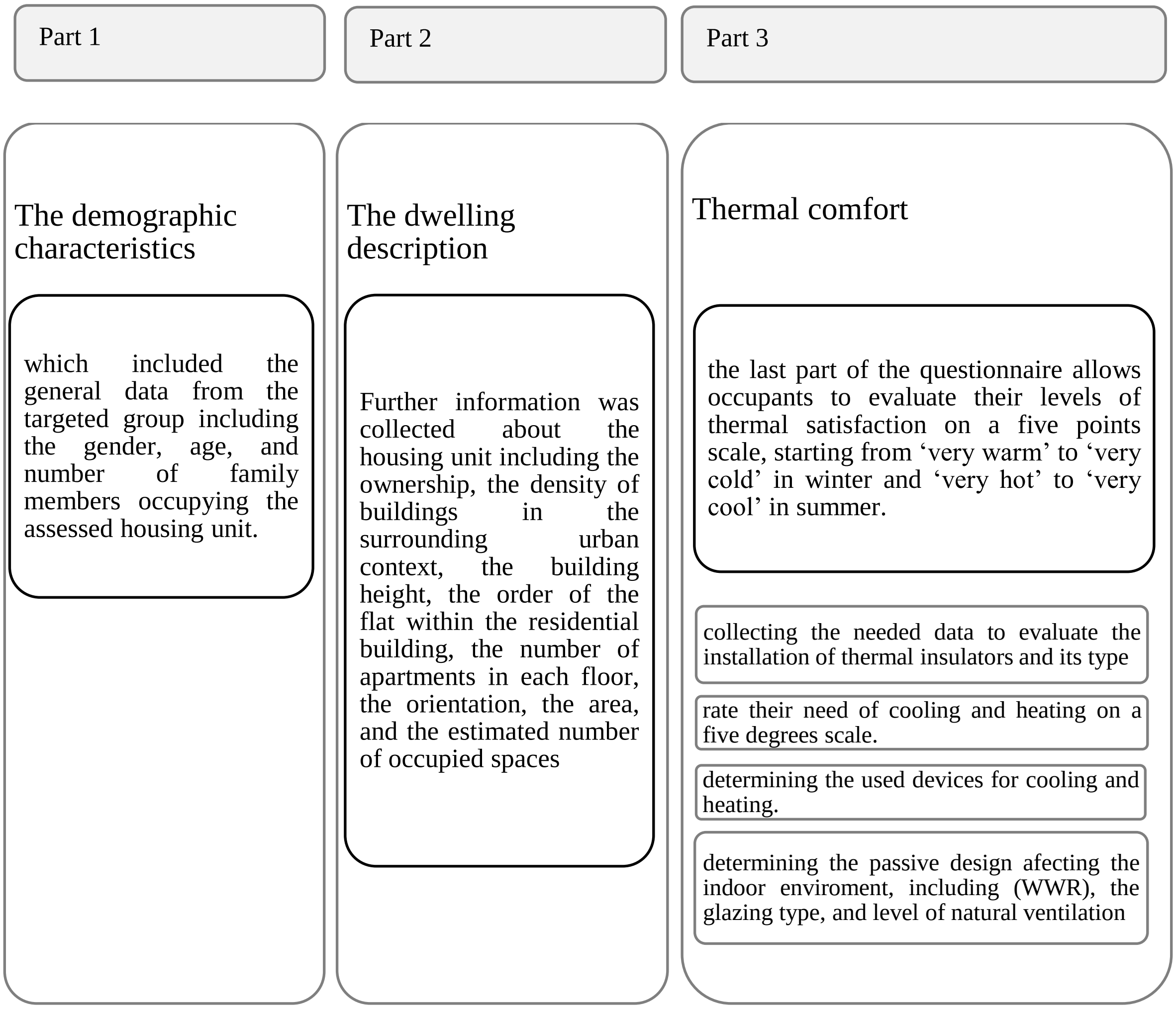


Figure 3-4: Questionnaire distribution domain and regions

Source: (MOLG, 2022) [online: https://geomolg.ps/L5/index.html?viewer=A3.V1]

- The questionnaire’s dimensions

The subjected occupants were asked to rate their homes in terms of the level of comfort they feel both in summer and winter. Demographic data was collected along with further information about the housing units to help determine the common building practices and the occupant’s response toward them. The addressed residential buildings were selected among a group of multistorey residential buildings in different districts in Hebron city. Buildings from the eastern, western, and middle districts were randomly selected as domains. Questionnaires were distributed in person in October 2020 and all responses were collected as hard copies. The questionnaire was designed to include three main sections as summarized in Figure 3-5 below. The questionnaire can be found in Appendix A.



Part 1

The demographic characteristics

which included the general data from the targeted group including the gender, age, and number of family members occupying the assessed housing unit.

Part 2

The dwelling description

Further information was collected about the housing unit including the ownership, the density of buildings in the surrounding urban context, the building height, the order of the flat within the residential building, the number of apartments in each floor, the orientation, the area, and the estimated number of occupied spaces

Part 3

Thermal comfort

the last part of the questionnaire allows occupants to evaluate their levels of thermal satisfaction on a five points scale, starting from ‘very warm’ to ‘very cold’ in winter and ‘very hot’ to ‘very cool’ in summer.

collecting the needed data to evaluate the installation of thermal insulators and its type

rate their need of cooling and heating on a five degrees scale.

determining the used devices for cooling and heating.

determining the passive design afecting the indoor enviroment, including (WWR), the glazing type, and level of natural ventilation

Figure 3-5: The questionnaire’s dimensions

The questionnaire finally gathers answers regarding the occupants’ intentions to install insulators or use any applicable thermal comfort enhancement methods to evaluate the levels of awareness toward the occupants’ comfort.

3.2.2 Physical field survey

Residential building samples were a sensible source for data collection regarding the common building practices. Selected residential buildings perform as a sample for the most common recent practices of building in Hebron to further highlight the characteristics of external walls in residential buildings, the used building materials layers' thicknesses, and order, generally as an overall indication for common envelopes' typologies in Hebron.

In this study, the physical field survey aimed to gather the required information for creating the simulation model base case; targeted buildings were selected from the Municipality of Hebron. Sampling was then followed by a random selection for a representative building for the simulation phase. The study has randomly selected 32 apartment buildings in Hebron since 2010 according to Hebron Municipality. Most of the selected buildings were constructed after 2018; to guarantee the analysis of the most recent building practices.

The 32 buildings' samples were used to collect data regarding building typologies to indicate the construction practices of residential buildings in Hebron; construction norms were investigated depending on these buildings. The samples’ external walls, slabs, and ceilings were analyzed to serve the creation of the simulation model. Among these, one residential multi-story building was randomly selected as a simulations’ base case model (the building plan is explained in chapter 4). Physical components and thermal properties were calculated in the following chapter. to be considered in the base case simulation model as a representative sample. The process of data collection was summarized as shown in Figure 3-6 as follows.

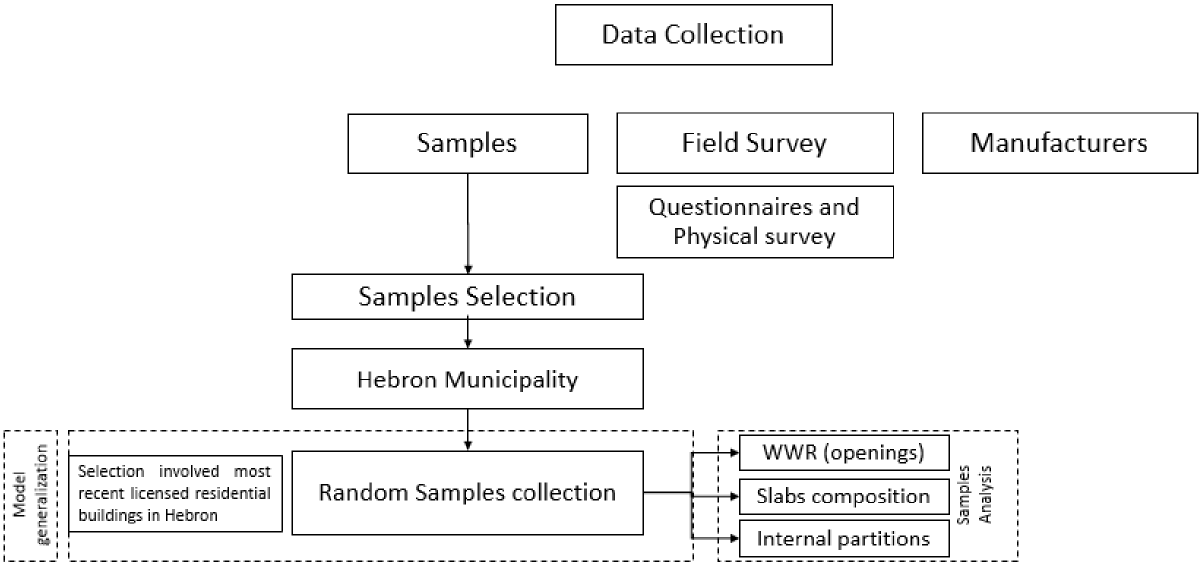


Figure 3-6: Targeted samples and their objectives

3.2.3 Simulations

Design-builder software simulations were carried out to evaluate the thermal enhancement for external walls through the proposed interventions. These interventions aim to reduce the thermal transmittance (U-value) to enhance its thermal performance. The study aims to achieve a notable enhancement in the thermal transmittance (U-value) compared to the calculated base case model's U-value.

Simulations were performed in multiple stages including different insulators, the application of natural ventilation for selected cases, and the change of the position of the insulating layer to evaluate the interventions from a wider perception.

The study proposes simulations in the above-mentioned four phases. Two main common building practices were analyzed, stone-cladded concrete walls and stone cladded hollow block. First, the total of 12 cases were simulated in the four different orientations to analyze the effect of insulators for different facades, results of the 48 simulation trials were summarized presenting the indoor operative temperatures, levels of relative humidity in summer and winter, maximum cooling and heating loads, and total number of dissatisfaction hours. Trials which were best performing in the first phase were reconsidered with the application of natural ventilation to correctly assess the average cooling loads, 3 trials for the four orientations of a total of 12 additional simulations were performed. Moreover, considerations of the location of the insulator continues to the last 8 trials of applying polyurethane foam as an outer insulator. The following chart in Figure 3-7 summarizes the cases of simulations to be performed (the details and the thermal transmittance U-value calculations for the cases shown in Figure 3-7 are further explained in the next chapter).

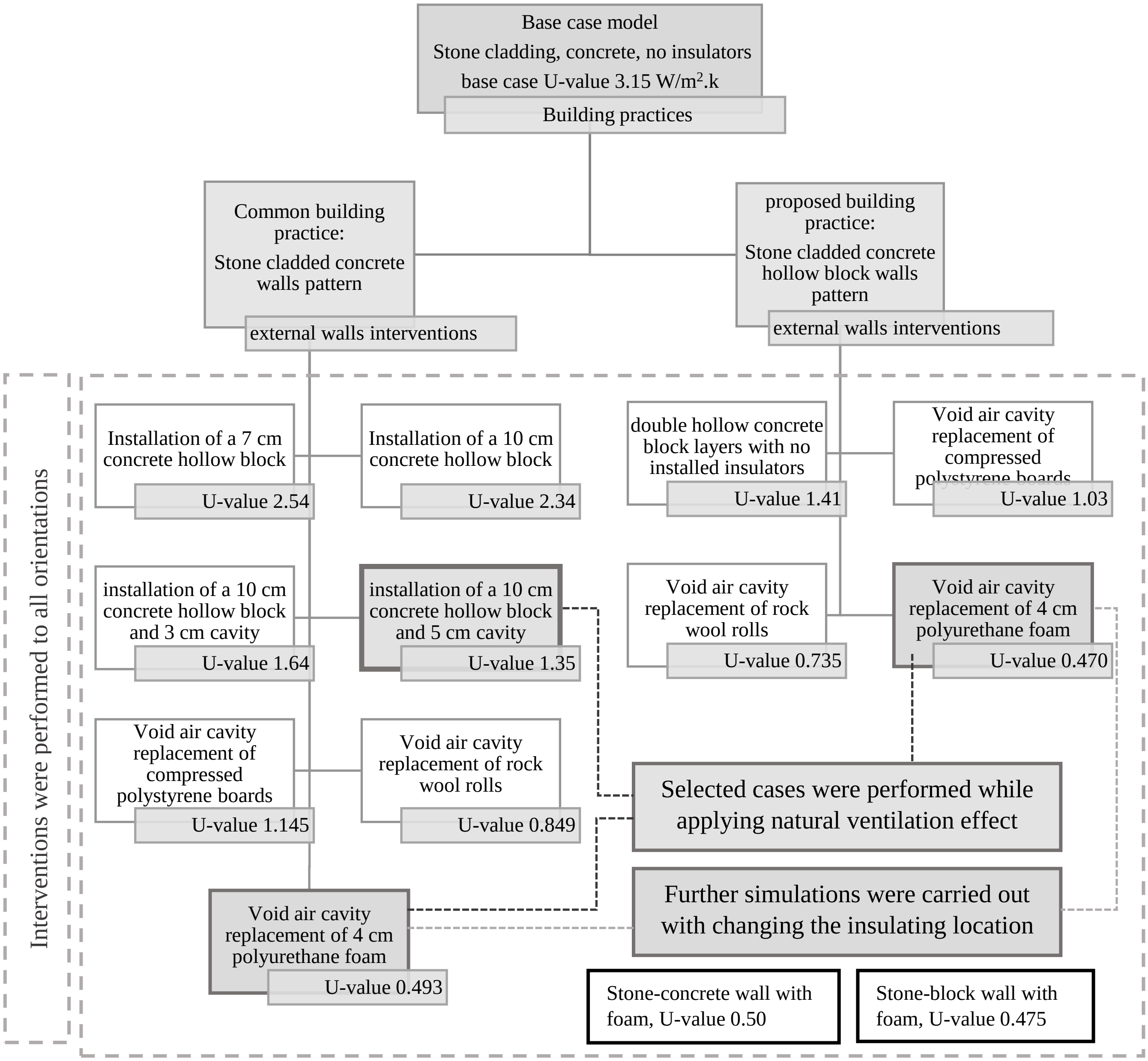


Figure 3-7: Performed simulation trials summary

3.3 Conclusion

This chapter summarizes the used methodology in the phase of data collection using questionnaires and personal interviews. The questionnaires were distributed to the occupants of multistory residential buildings in the city. The data collection has extended to include the selection of multiple residential buildings which were recently constructed in different areas around the city, these buildings plans, and envelops' components were analyzed in the following chapter discussing the analyzed building envelopes to collect the needed measures for the creation of the simulation model which will be analyzed in the following chapter.

Chapter 4

Results and Findings

Chapter 4

Results and Findings

4.1 Introduction

Buildings in Palestine mostly use stone as external cladding and interior decorating material. According to the Palestinian Bureau of statistics and the building license statistics in the first quarter of 2012, more than 743 new residential buildings, 157 new buildings of other functions, 248 residential buildings' extensions, and 43 existing buildings' extensions used the stone as external cladding material (PBS, 2012). Stone is also considered the most durable construction material and highly encourages the Palestinian economy, neglecting the environmental side effects of the stone industry (Abu Hanieh, et al., 2013).

Generally, differences in the climate conditions are notable in different topographical regions of Palestine (Dear, et al., 2013). Therefore, the model could be generalized in the city of Hebron and other Palestinian cities with the same topographical and geographical features.

The simulation process used the design-builder simulation software, with Energy Plus analysis engine, due to the unavailability of Hebron city weather file; Jerusalem weather file data was used in the simulation. According to (Weather-Spark, 2019), 67% of Hebron's climatic data depends on the data obtained from Jerusalem's weather station.

4.2 Study context description

The study takes place in Hebron city, located in the centric area of Palestine, to the south of Jerusalem as shown on the map of Palestine (Figure 4-1) and Hebron governorate (Figure 4-2) as follows. Hebron has a Mediterranean climate with hot summers and wet cold winter with temperatures reaching their peak of around 29°C in summer, temperatures have scored a minimum measure in winter of around 3°C and rarely below 0°C or above 32°C as shown in Table 4-1 below (Meteoblue weather , 2019); (Weather-Spark, 2019). In 2018 the maximum air temperature reached 21.9°C, the minimum air temperature was 13.7°C, and the mean air temperature was 17.3°C. The averages of air temperature in

Hebron from 2010-to 2018 were shown in Figure 4-3 below. The average relative humidity rate in Hebron was around 65% according to the statistics for the years 2010-2018 as shown in Table 4-2 (PCBS, 2018).

Figure 4-1: Palestine Map showing Hebron in the middle. (ARIJ, 2003)

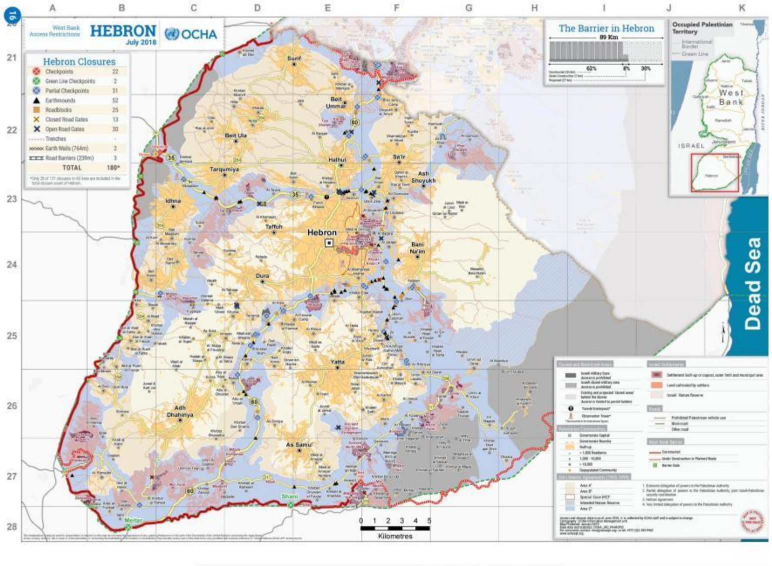


Figure 4-2: Hebron governorate map. (ARIJ, 2003)

[online: https://www.arij.org/maps/#iLightbox[f014da1736e8cc971c1]/0]

Table 4-1: Average annual temperatures in Hebron (2019)

	Summer			**Winter**		
	Avg. daily temperature	Avg. Min. temperature	Avg. Max. temperature	Avg. daily temperature	Avg. Min. temperature	Avg. Max. temperature
Hebron	25°C	18°C	29°C	15°C	3°C	11°C

Table 4-2: Average annual humidity rate in Hebron (2010-2018)

Year	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Average humidity (%)	56	65	61	63	65	66	64	64	69

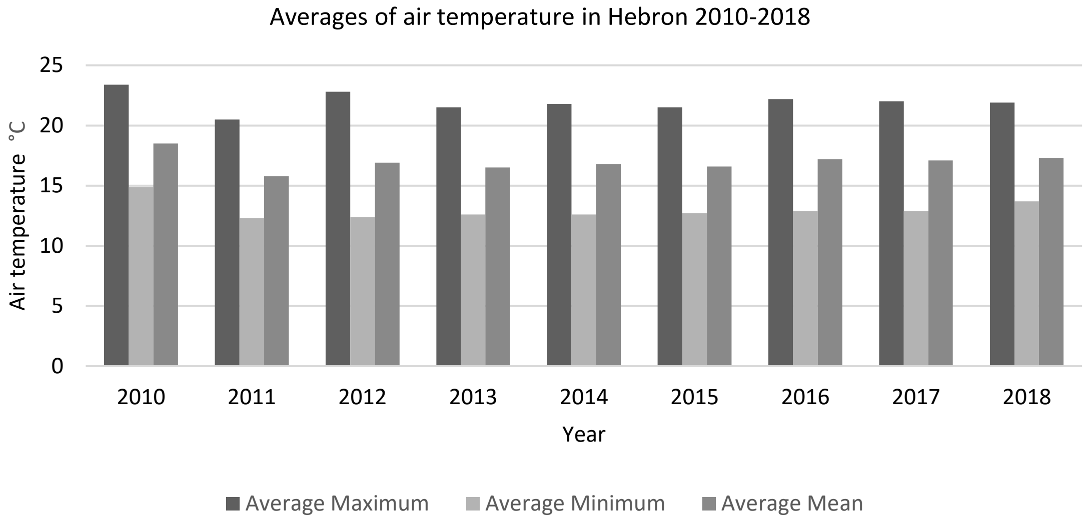


Figure 4-3: Averages of air temperature in Hebron 2010-2018
(Researcher,2020: Based on (PCBS, 2018))

The above shown seasonal temperatures and annual air temperatures explain relatively cold winters and warm summers which are illustrated in the topographic average hourly temperatures in Hebron in Figure 4-4 as follows ranging from cold to comfortable and warm with a narrow range of very cold days (Weather-Spark, 2019).

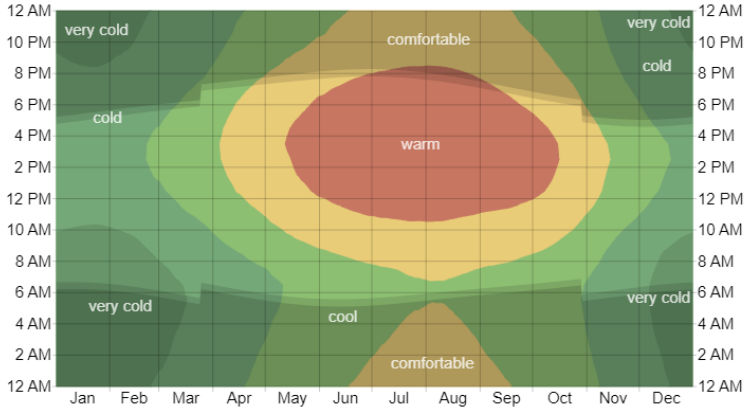


Figure 4-4: Average Hourly Temperature in Hebron (Weather-Spark, 2019)
[Online: https://weatherspark.com/y/98840/Average-Weather-in-Hebron-Palestinian-Territories-Year-Round]

Hebron's average amount of daily solar radiation reaches its peak on June 21st with an average seasonal radian of 8.6 kWh/m^2 and a daily average of 14 hours of daylight in summer. While in winter the average amount of solar radiation drops down to 4.2 kWh/m^2. As shown in the graph below (Weather-Spark, 2019).

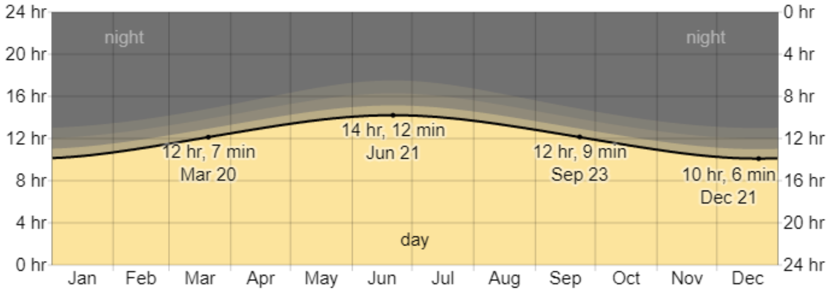


Figure 4-5: Hours of Daylight and Twilight in Hebron (Weather-Spark, 2019).
[Online: https://weatherspark.com/y/98840/Average-Weather-in-Hebron-Palestinian-Territories-Year-Round]

The common wind direction affecting Hebron is the North-western and Western winds about the graph shown in Figure 4-6 with an average speed exceeding 3.2 m/s from May to September, while in July the wind speed reaches its maximum rate of 3.6 m/s. The wind speed however drops to around 3.0 m/s in the period from December to February. The wind speed ranges in between for the rest of the year as illustrated in the graph shown in Figure 4-7 (Weather-Spark, 2019).

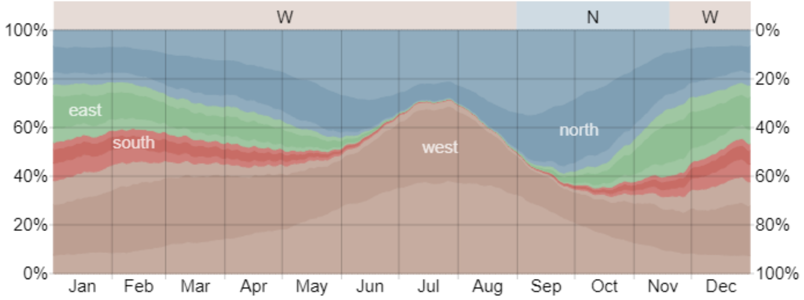


Figure 4-6: Wind direction in Hebron (Weather-Spark, 2019).
[Online: https://weatherspark.com/y/98840/Average-Weather-in-Hebron-Palestinian-Territories-Year-Round]

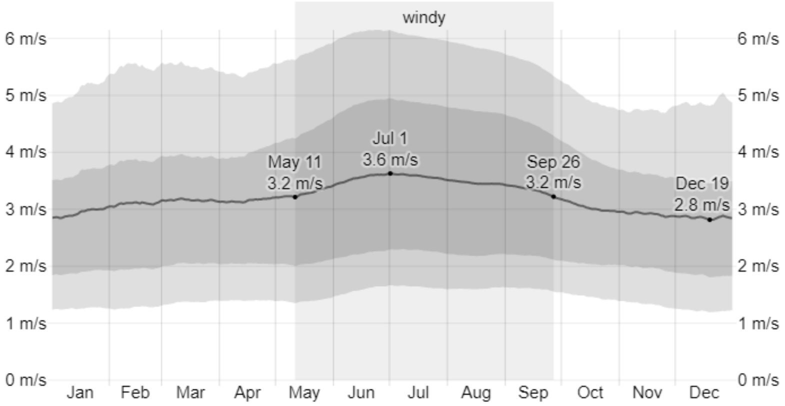


Figure 4-7: Average Wind Speed in Hebron (Weather-Spark, 2019).
[Online: https://weatherspark.com/y/98840/Average-Weather-in-Hebron-Palestinian-Territories-Year-Round]

The previously shown graphs illustrate the weathering profile of Hebron city in terms of temperatures, relative humidity, solar radiation, and wind speed and direction we collected to serve the creation of the simulation model using the Design-Builder software. The obtained data from the graphs were summarized in an average annual weather profile for the city as shown in Table 4-3 as follows.

Table 4-3: Hebron city climatic averages.

	Temperature (°C)		**Wind speed (m/s)**		**Wind direction**	**Humidity (%)**
	Average minimum	Average maximum	Average speed	Maximum speed		
Summer	17	29	3.2	6	225° North-Western wind	45%
Winter	4	12	2.8	5	270° Western wind	65%

4.3 Field Survey Findings

The previous chapter has explained the criteria used for data collection. One of its parts was the field survey allowing collecting the needed occupants' responses and satisfaction rates regarding occupied buildings constructed according to the local building practices. Other quantitative measures were collected from the simulations depending on the analysis of selected existing buildings around the city. The analysis and findings of this field survey were as follows:

4.3.1 Questionnaire results analysis

The questionnaire's first section summarizes the demographic data of the participants, results have shown that a percentage of 51.5% of the responses were recorded by females, which were mostly housewives, and 48.5% were males. In terms of the age categories, 58.7% of the responses were recorded from occupants ranging between 18-40 years and 34.6% were between 18-49 years old when the least percentage represented the elderly. Gender and age percentages and differences explain the variations of thermal sensation due to different metabolism rates and rates of activity (Indraganti & Rao, 2009). The last question in this section is the number of family members who had an average of 6 persons in Hebron in reference to the Palestinian Central Bureau of Statistics (PCBS) for the year 2020, which was recorded maximum in the responses. The rates of the results of the first section of the questionnaire were summarized in Table 4-4 as shown as follows.

Table 4-4: The questionnaire’s answers rates-section 1 (The demographic characteristics)

Gender	**Females**	**Males**	
	51.5%	48.5%	
Age	**18-40 years**	**40-60 years**	**Above 60 years**
	58.7%	34.6%	20.3%
Number of family members	**1-3**	**3-6**	**More than 6**
	22.3%	58.2%	19.5%

The second part of the questionnaire has provided the required details and characteristics for the apartment to be analyzed in the simulation process. Analyzing this part of the questionnaire provides a clearer perception of Hebron's recent typologies of residential buildings. Statistics regarding the building height and the number of apartments on each floor were collected. In addition, the questionnaire lies an eye on the urban density which relatively affects the thermal performance of buildings and is directly related to the rate of natural ventilation allowing a higher level of comfort in the apartments. More details regarding the location of the apartments among floors, area, and orientation were also collected as shown in Table 4-5 as follows.

Table 4-5: The questionnaire’s answers rates-section 2 (The dwelling description)

Building height	**3-5 floors**	**6 floors**	**7 floors and exceeding**	
	56.8%	20.8%	22.4%	
Number of apartments / floor	**1 apartment**	**2 apartments**	**3 apartments**	**4 apartments**
	21.1%	31.1%	20.1%	27.8%
Building’s density in the urban surrounding	**Low-density area**	**Middle dense area**	**High-density area**	
	11.1%	50%	38.9%	
Apartment’s location in reference to the building	**Lower apartment**	**Middle apartment**	**Higher floors**	
	14.2%	61.9%	23.8%	
Apartment’s orientation (In reference to most openings)	**Northern**	**Eastern**	**Southern**	**Western**
	16.8%	29.6%	26.7%	26.9%
Apartment’s area	**Less than 90m^2**	**90m^2 - 120m^2**	**120m^2 - 150m^2**	**More than 150m^2**
	3.1%	33.9%	39.6%	23.4%

From the above-shown Table 4-5 the study concludes that most the residential buildings consist of 3-5 floors with a percentage of 56.8%. Among these, the number of apartments was mostly two apartments on each floor scoring the highest percentage of 31.1%, mostly in a moderate urban context density with a percentage of 50%. The questionnaire’s results have also shown the least percentage of a low urban context density, which confirms the increasing rate of building due to continuously increasing population rates as shown previously in the graphs. However, the urban surrounding density was neglected in the evaluation as it is predefined by local regulations and could hardly be increased due to the lack of lands compared to the economic benefit of each project. Moreover, neglecting surrounding buildings achieves the maximum solar intake through external walls, therefore analyzing the most critical case. Never forgetting that the first-stage simulations have neglected the effect of natural ventilation, which was expected to be affected by surrounding buildings. The researcher's evaluation of residential buildings with setbacks of 3 to 4 meters was classified as middle dense areas.

This study investigates middle apartments in residential buildings. Generally, the number of middle apartments is the largest in each building, and through the field survey these have had a percentage of 61.9% among surveyed apartments. The study has excluded top and lower apartments since it requires additional calculations regarding the roof and slabs insulation which was recommended to be investigated in future research.

Moreover, regarding the orientation, the rates were relatively close which requires the analysis of different orientations in terms of external walls. Apartments areas were ranging between 120 m2 to 150 m2 as a majority, which had an average percentage of 36.75%. The number of spaces in each apartment has served as an estimation indicator of the average area for a certain sample space in the apartments. Based on the statistics in the above-shown Table 4-5, The study has focused on analyzing a selected sample space in middle apartments in multi-story residential buildings, with an estimated area of 16 m2.

The third part of the questionnaire introduces an evaluation of the occupants' satisfaction rate regarding thermal comfort in occupied recently constructed buildings in Hebron. These buildings were constructed according to the common building practice which will be further explained in this chapter. Analyzing the third part of the questionnaire as shown in the attached Table 4-6 explains the occupants' dissatisfaction regarding their dwellings, which confirms the importance of the study.

Table 4-6: The questionnaire's answers rates-section 3 (Thermal comfort)

Occupant's rate for the indoor temperature in winter	**Very warm**	**Warm**	**Comfortable**	**Cold**	**Very cold**
	0.8%	8.2%	18%	51.4%	21.6%
Occupant's rate for the indoor temperature in summer	**Very hot**	**Hot**	**Comfortable**	**Cool**	**Very cool**
	19.1%	46.9%	29.6%	2.92%	1.46%
The installation of insulators	**Installed**	**Not installed**			
	49.7%	50.3%			
Type of insulation, if applied	**Hollow Block**	**Polystyrene boards**	**Polyurethane foam**		
	44.86%	26.46%	30.36%		
Occupant's rating for thermal comfort	**Excellent**	**Good**	**Moderate**	**Bad**	**Very bad**
	2.73%	20.8%	40.5%	30.5%	5.46%
The need for heating in winter	**Not needed**	**Low**	**Moderate**	**High**	**Very high**
	0.8%	2.5%	17.5%	48.6%	30.6%
The need for cooling in summer	**Not needed**	**Low**	**Moderate**	**High**	**Very high**
	10.3%	20.4%	33.8%	24.7%	10.8%
Used heating methods in winter	**Electricity**	**Gas**	**Fireplace**	**All mentioned**	**Other**
	18.5%	47.3%	9.8%	19.8%	4.6%
Used cooling methods in summer	**Windows**	**Fans**	**Air conditioning**	**All mentioned**	**Other**
	20.3%	34.4%	20%	25.4%	---
Opening size in reference to the area of the walls	**Very small**	**Small**	**Moderate**	**Large**	**Very large**
	3.7%	7.5%	63.2%	21.9%	3.7%
Installed type of glazing	**Single glazing**	**Double glazing**	**Triple glazing**		
	48.7%	47.7%	1.3%		
Occupant's rating of the natural ventilation	**Excellent**	**Good**	**Moderate**	**Bad**	**Very bad**
	17.3%	34.4%	38%	9.6%	0.7%
The ability and acceptance of the concept of installing thermal insulators	**Definitely**	**Yes**	**Maybe**	**No**	
	42.9%	42.7%	12.6%	1.8%	

Table 4-6 shown above illustrates the findings of the third part of the questionnaire. Results have shown that occupants were mostly uncomfortable in their dwellings, which was proven by the percentages of 21.6% and 19.1% of occupants rating their homes as very cold and very hot in winter and summer respectively.

Moderate was the most common evaluation from occupants for the rate of thermal comfort in their homes. While percentages of 2.73%, 20.8%, 30.5%, and 5.46% rated their homes as excellent, good, bad, and very bad respectively. Generally, the questionnaire had proven an ultimate need for both cooling and heating in summer and winter, where more than 75% of responses have rated the need for heating as high and very high, while around 35% rated their need for cooling as high and very high, which in terms enlarges the burdens of energy consumed as proven through the types of used cooling and heating methods since mostly relying on electricity, or else, gas in winter, which directly affects occupants' health.

The collected responses regarding the building openings size and the natural ventilation rates' evaluations helped the determination of the WWR in the simulation model creation which will be further explained in this chapter.

The questionnaire had proven the high level of awareness among inhabitances and had shown a relatively high response to the acceptance of the concept of enhancing buildings' envelopes and installing insulators which were proven depending on the open questions asked in this regard. Despite this, more than 50% of the targeted dwellers did not apply thermal insulation in their apartments, probably due to the high cost of insulation.

On the other hand, among others who have, a majority of around 45% have installed concrete hollow blocks on the external walls. This could be due to the relatively lower cost of hollow blocks compared to other insulators. Occupants were able to determine the type of insulation due to the common typology of installing the insulator by owners during the finishing phase as previously mentioned. The following Figures 4-8 and 4-9 illustrate a sample of external walls before installing the external wall's insulation in an apartment sample in Hebron.

Figure 4-8: External walls before starting the finishing phase in apartments sample in Hebron.
Figure 4-9: An external wall section before the insulation installation.

The questionnaire's analysis concludes with the relevance of thermal comfort to the indoor environment quality and occupants' comfort, health, and wellbeing. Results of the questionnaire show that the levels of cooling and heating loads in summer and winter are relatively high, which causes higher energy consumption in residential buildings. Therefore, intensive studies are required in the field of enhancing residential building envelopes. The questionnaire's detailed charts, numbers, and percentages are illustrated in Appendix B.

4.3.2 Samples analysis

The study includes a sample collection of existing buildings from the building department in Hebron Municipality. These buildings were selected in different locations in the city. Moreover, the date of construction was also a factor in the sample's selection. The study focuses on recently constructed buildings to evaluate the recent building typologies. Therefore, the samples selected were constructed between the years 2018 to 2020. These buildings were described in Appendix C. The table in Appendix C includes an analytical description of the selected samples of residential buildings in Hebron considering the number of apartments on each floor, the components of the slabs, external cladding, internal partitions, and the year of construction.

Depending on the collected data of a total number of 32 buildings, the following Table 4-7 summarizes the characteristics of the common building depending on the averages from the previously mentioned samples.

Table 4-7: The selected samples summary

No. of Apartment	**WWR%**	**Slabs components**	**Internal Partition components**	**Exterior Cladding and wall components**	**Year of construction**
2	19.2	25cm ribbed RC slab, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	Stone, fixed on concrete walls of 12 to 13 cm	2018-2020

From Table 4-7 shown above the most common number of apartments on each floor was 2 apartments. While the WWR was calculated as average for the cases analyzed and equaled 19.2%. The composites of the slabs were all ribbed slabs which are considered the most common construction solution and most affordable when applicable according to the building's scale. Floors were finished with porcelain tiles with thicknesses ranging from 6 to 8mm. As for the internal partitions, both sides plastered hollow concrete block is the most used practice. The most common external cladding for all buildings - including residential buildings - in Hebron uses stone as an external cladding material with thicknesses from 3 to 5cm. The analysis of the selected samples was considered a reference for the thermal properties of the base case simulation model. A detailed calculation for the thermal resistance (U-value) was explained in this chapter.

Buildings were analyzed in terms of the physical layers used for external cladding, internal partitions, windows glazing type, and the glazing area (WWR). Therefore, the field survey has also included a minor study of the local market, through multiple personal interviews which were conducted with local manufacturers and contractors regarding the external wall composites, construction, and the most common glazing and insulation types. Generally, the preference of certain practices may be related to the construction's timeframe or corresponding to the economic needs of users. A. Haimouni, A. Qawasmi, and R. Joulani are contractors from Hebron, all three contractors were asked to explain the building practice most used, and their answers were relatively similar. Accordingly, stone is the outer cladding layer followed by concrete of 12-13 cm in most buildings with the same scale. They have also confirmed the building process could affect the thickness of the concrete layer. Poured walls before the stone cladding are usually executed in larger thicknesses than in buildings where concrete is used as a backfill layer behind the stone. I. Quneibi, H. Shammas, and T. Hriez are local aluminum manufacturers in Hebron, they have confirmed that aluminum windows with single glazing were mostly installed in residential apartments due to its lower costs. However, in smaller-scale projects and private residential units, double glazing is mostly preferred. These interviews have served the data collections for the base case model creation and for fixing the unanalyzed parameters.

As previously mentioned, the analyzed apartments were all concrete structures externally cladded with stone, with no heat insulation. Apartments internally have partitions of both sides plastered concrete hollow blocks. Slabs and floors were all reinforced concrete ribbed slabs finished with 6-8mm ceramic tiles on the upper side and plaster on the inner lower surface. The average calculated WWR depending on the architectural drawings has equaled 19%. Windows' height has ranged from 1.25-1.50m with single reflective glazing. All selected buildings were multi-story residential buildings with one or more apartments in each floor. This study was specialized in external walls of middle floors and has excluded roofs and ground floors, due to the extended required research for thermal transmittance through roofs and floors.

The study refers to the Guidelines for Energy Efficient Building Design in Palestine, the study extends the previously analyzed cases with the installation of different insulators. This research also presents cases based on merging the common practices discussed in previous studies. The previously collected data was combined to create the simulation model starting with its physical components, followed by the thermal properties, leading to the detailed calculations of the basic thermal transmittance.

4.4 Simulation Model Creation

The research depended on selecting a simple model serving as a prototype for spaces in an apartment in Hebron. The model was created depending on the data collected from the questionnaires and field survey as explained previously. The process of selecting the external walls' base case model has started with the analysis of the common construction practice and local manufacturers in Hebron; this served validating the selection of the simulation model used as a benchmark to apply the interventions for controlling thermal comfort.

Generally, differences in the climate conditions are notable in different topographical regions of Palestine (Dear, et al., 2013). Therefore, the model could be generalized in the city of Hebron and other Palestinian cities with the same topographical and geographical features. The simulation process used the design-builder simulation software, with Energy Plus analysis engine. Jerusalem weather file data was used in the simulation due to the unavailability of Hebron city weather file. According to (Weather-Spark, 2019), 67% of Hebron's climatic data depends on the data obtained from Jerusalem's weather station. The hierarchy of selecting the simulation model is illustrated in Figures 4-10 Below.

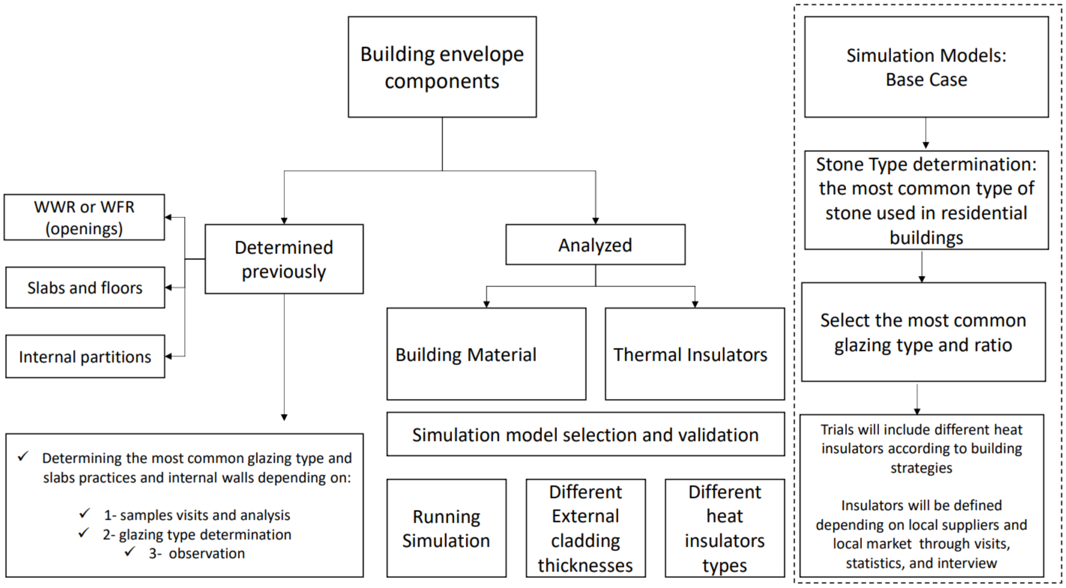


Figure 4-10 The simulation model creation criteria

Depending on the collected information from the field, the simulation model is a 16 square meter space, square-shaped with a length and width of 4 meters, the ceiling height is 2.75m, and the window to wall ratio (WWR) equaled 19%. For the selected WWR the window dimensions have equaled 1.70m in width and 1.25m in height which is the average of windows' dimensions commonly used in residential buildings in Hebron.

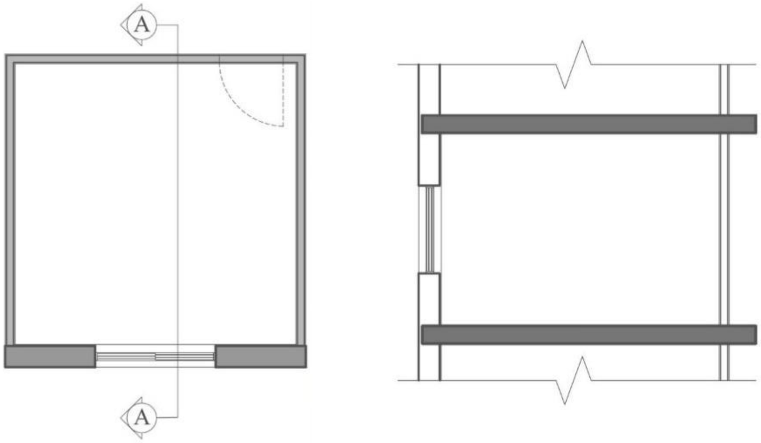


Figure 4-11: Simulation model's plan and section (A-A) for the simulation model

Physical properties of the simulation model, as described earlier, were investigated in reference to the Palestinian Guidelines for Energy Efficient Building Design. The following section of this chapter explains the model's physical layers and thermal properties of external walls, internal partitions, slabs, and floors (MOLG, 2004).

4.5 Simulation Model Thermal Transmittance Calculations

Buildings' components like external walls, internal partitions, slabs, and floors consist of multiple layers with different thermal properties, these properties significantly affect calculating the thermal transmittance of a building component. The values of thermal transmittance differ in reference to the materials and their thicknesses forming each component and whether this component is homogeneous or heterogeneous. The thermal transmittance values (U value) must be calculated when thermally analyzing a building (MOLG, 2004).

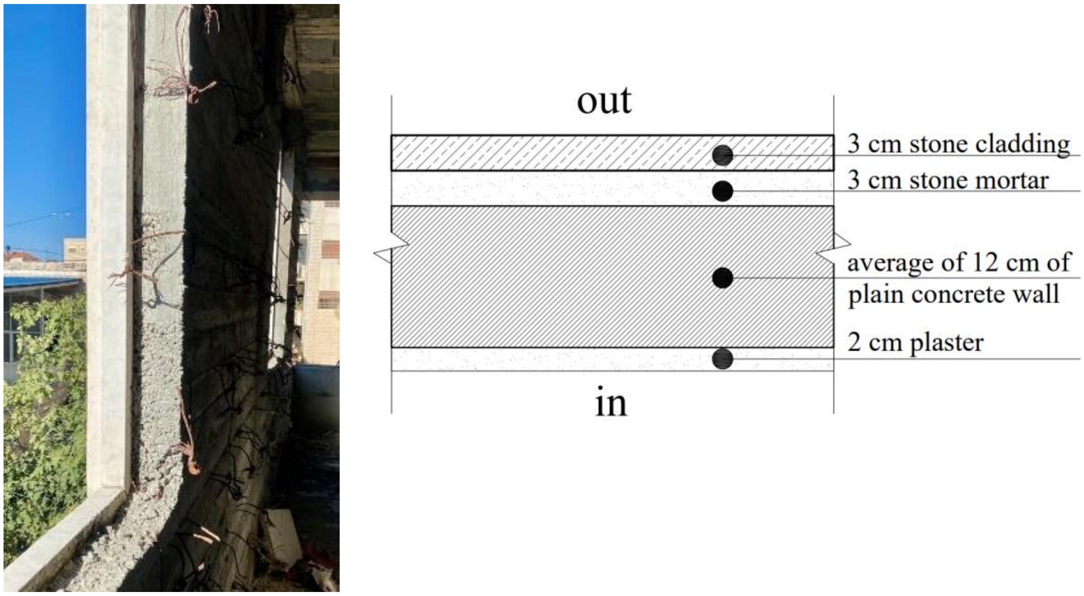
4.5.1 External walls

Depending on this research observations and previous studies. The available building materials were mainly stone, concrete, and heat insulators if applied. Amongst all the advantages of stone as a building material, the stone is one of the most popular cladding materials in the sector of buildings in Palestine (PCBS, 2017). Adding to the fact that stone is a sustainable material, it is naturally available in Palestine and exclusively in Hebron. Stone in Palestine is usually named after the extraction district found. The simulation model applied Hebron stone as an external wall covering. Hebron's stone's density ranges around 2200 kg /m^2 with an average thermal conductivity of 1.70 W/m. k (MOLG, 2004).

Besides stone, concrete is another main component of walls, either as a main construction material or as a bonding material behind the stone cladding (Muallem, 2020). The thermal properties of a ready mixture of concrete depend on its density. Ready concrete mixtures usually range around 2300 to 2500 kg/m^2 with an average thermal conductivity of 1.75 W/m. k (MOLG, 2004).

The installation of thermal insulation had been recently increasing due to increasing awareness regarding its importance. However, the local market provides limited choices of thermal insulators; polystyrene boards, rock wool, and polyurethane foam are their most common (Muallem, 2020).

Depending on the analyzed buildings from the field survey, the simulation model's external wall was designed according to the common building practice in the city. That consisted of stone as an external layer, stone mortar, and a layer of 11 to 13 cm of plain concrete as shown in the detail illustrated in Figure 4-12. These layers were summarized in Table 4-8 below, this cross section had a thermal transmittance of 3.15 W/m^2. k.



Figures 4-12, a, and b: External walls common practice and simulation model's composites

Table 4-8: The simulation model's external walls' base-case thermal properties

External walls					
Layer's order (Out-to-in)	Material	Thickness (d) m	Apparent mass density ($\dot{\rho}$) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) m^2.k/W
1	External air	-	-	-	0.060
2	Stone cladding	0.03	2200	1.70	0.017
3	Stone mortar	0.03	1440	1.20	0.025
4	Concrete	0.12	2300	1.75	0.068
5	Plaster	0.02	1850	0.72	0.027
6	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					0.317
Thermal transmittance (U-value) = 1/R_a					3.15 W/m^2. k

4.5.2 Internal partitions

Internal partitions in the common building practice usually consist of 10cm hollow concrete block covered with cement plaster on both its surfaces, as previously mentioned and shown in the detail in Figure 4-13. Hollow concrete block wall acts as a good sound insulator between internal spaces. Internal partitions' thermal transmittance equaled 2.65 W/m². k as shown in Table 4-9 as follows.

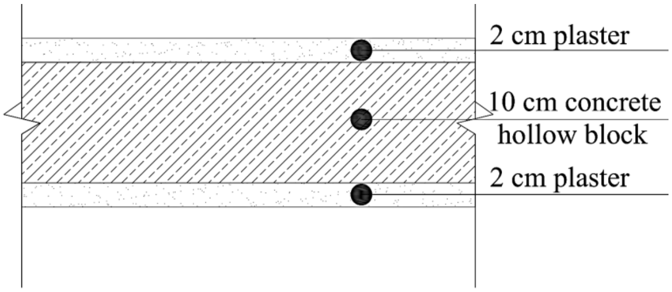


Figure 4-13: The simulation model's internal partitions detail

Table 4-9: The simulation model's internal partitions thermal properties

Internal partitions					
Layer's order (Out-to-in)	Material	Thickness (d) m	Apparent mass density (ṗ) Kg/m³	Thermal conductivity (k) W/m. k	Thermal resistance (R) m².k/W
1	Internal air	-	-	-	0.120
2	plaster	0.02	1850	0.72	0.027
3	Concrete hollow block	0.10	1900	1.20	0.083
4	plaster	0.02	1850	0.72	0.027
5	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					0.377
Thermal transmittance (U-value) = 1/R_a					2.65 W/m². k

4.5.3 Slabs

The study investigated middle floors. Figure 4-14 explains repeated floors' slab detail in common building practices. The slabs are usually hollow concrete block ribbed slabs, covered with tile mortar and porcelain tiles with a total average thickness of 36 cm. The thermal properties of the slabs are explained in tables 4-10 and 4-11 as follows.

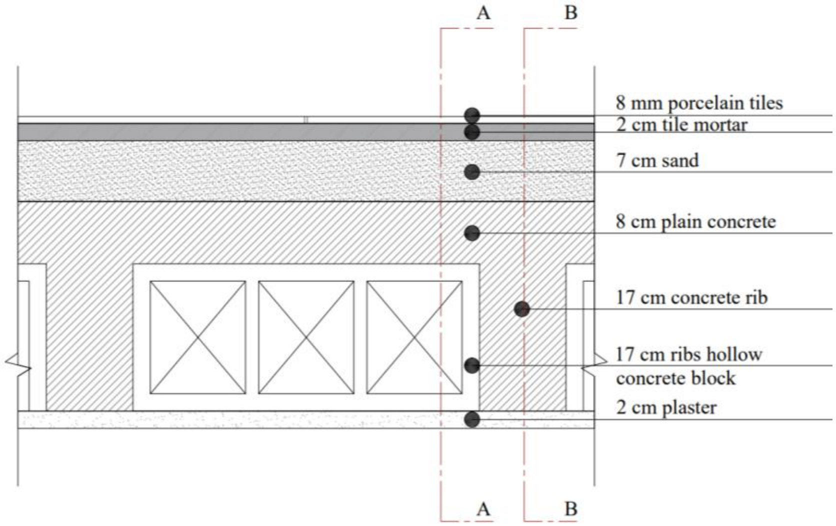


Figure 4-14: The simulation model's slabs detail

Heterogeneous surfaces are surfaces consisting of different component for a certain amount of surface area (MOLG, 2004). Heterogeneous surfaces' thermal transmittance calculation requires calculating the detailed thermal resistance for all their composites depending on each surface area according to the following equation 4-1. Ribbed slabs are considered an example of such surfaces, their composites are illustrated in sections (A-A) and (B-B) on Figure 4-12 shown above.

$$U = \sum_{k=1}^{n} \left(\frac{Ui\ Ai}{A}\right) \qquad (4\text{-}1)$$

- U is the total thermal transmittance of a heterogeneous surface.
- A is the total area
- Ui is the thermal transmittance for each part.
- Ai is the area of each part.

The slab of an average space in a residential building with an area of 16 square meters (4.00m by 4.00m). The concrete block ribs area covers 10.24 m^2 of the total slab area while the ribs and beams area equal 5.76 m^2. Accordingly, equation 4-1 was applied to find the total thermal transmittance as shown below depending on tables 4-10 and 4-11 as follows for each part's U-value calculation. The total U-value of the slab has equaled 1.54 W/m^2k.

$$Us = \left(\frac{10.24X1.47}{16}\right) + \left(\frac{5.76X1.69}{16}\right) = 1.54\ \mathrm{W/m2.k}$$

Table 4-10: The simulation model's slabs’ thermal properties (A-A crossing a concrete block)

Slabs and floors (concrete block surface area)					
Layer's order (Higher-to-lower)	Material	Thickness (d) m	Apparent mass density (ῥ) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) $m^2.k/W$
1	Internal air	-	-	-	0.120
2	Ceramic tiles	0.08	1900	1.05	0.076
3	Tile mortar	0.02	1900	1.20	0.016
4	Sand	0.07	1500	0.72	0.097
5	Concrete	0.08	2400	1.85	0.043
6	concrete hollow block	0.17	1400	0.95	0.178
7	Ceiling plaster	0.02	1850	0.72	0.027
8	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					0.677
Thermal transmittance (U-value) = $1/R_a$					1.47 W/m^2. k

Table 4-11: The simulation model's slabs and floors thermal properties (B-B crossing a slab rib)

Slabs and floors (ribs and beams surface area)					
Layer's order (Higher-to-lower)	Material	Thickness (d) m	Apparent mass density (ῥ) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) $m^2.k/W$
1	Internal air	-	-	-	0.120
2	Ceramic tiles	0.08	1900	1.05	0.076
3	Tile mortar	0.02	1900	1.20	0.016
4	Sand	0.07	1500	0.72	0.097
5	Concrete	0.25	2400	1.85	0.135
7	Ceiling plaster	0.02	1850	0.72	0.027
8	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					0.591
Thermal transmittance (U-value) = $1/R_a$					1.69 W/m^2. k

4.5.4 Openings

Depending on the previously explained data for the building components, and the determination of the WWR of the studied space. The U value of the external wall depends also on the windows area and glazing type. Therefore, the external wall thermal transmittance was calculated according to equation 4-1 and Figure 4-15 as shown below.

The U value of the external wall equaled 3.15 W/m^{2}k as calculated previously, and of a single reflective glazing aluminum window is 3.50 W/m^{2}k (MOLG, 2004).

The selected window in the model has an area of 2.125 m^2 and a WWR of 19% from a total wall area of 11m^2 as shown in Figure 4-15. The equation below explains the calculation of the model's external wall U value calculation which equals 3.217 W/m^{2}k.

$$Uw = \left(\frac{2.125X3.50}{11}\right) + \left(\frac{8.875X3.15}{11}\right) = 3.217\ \mathrm{W/m2.k}$$

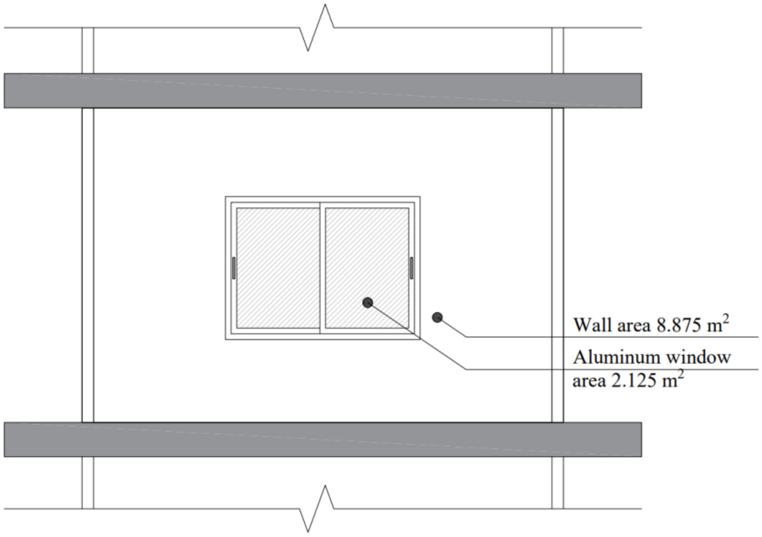
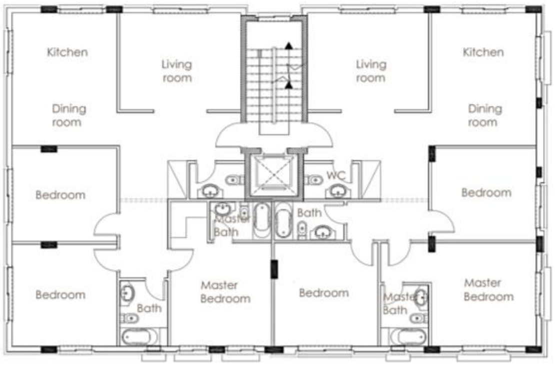


Figure 4-15: The simulation model's external wall areas (a view from inside the space)

After the determination of the simulation model form, geometry, and thermal properties, the study continues with the base-case modeling using the Design-builder software. The initial simulation was run to evaluate the thermal performance of the common practice in Hebron. The study then applied multiple interventions for controlling the building envelope's thermal transmittance to reduce thermal gains and losses in summer and winter respectively. The study further evaluates these interventions' effects in reducing the heating and cooling loads for the analyzed space within the climatic condition of Hebron.

The selected building performs as design module for the analysis. A multistory residential building of five floors, each floor has two apartments and a staircase with a total floor area of around 290 m^2 as shown in the illustrated plan in Figure 4-16 as follows. Underground parking floors were neglected in the study.



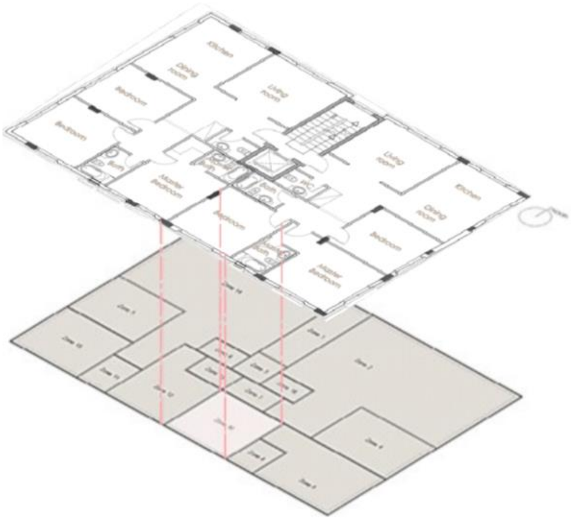


Figure 4-16: The simulation model of a representative space in a residential building

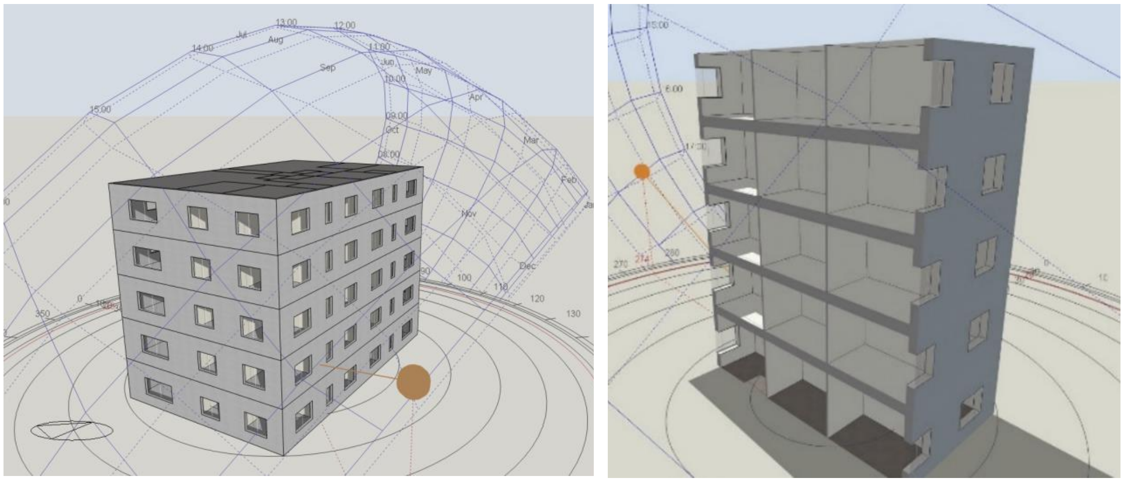


Figure 4-17: The simulation model of the residential building

Modular spaces in the residential apartment were selected for simulation, four spaces were selected toward different orientations for the simulation trials and external wall interventions, as shown in Figure 4-18 as follows. The average area of the analyzed spaces was 16 m^2 with dimensions around 4.00m by 4.00m. Each space's simulation trials included multiple external wall interventions to best evaluate the envelope's composites.

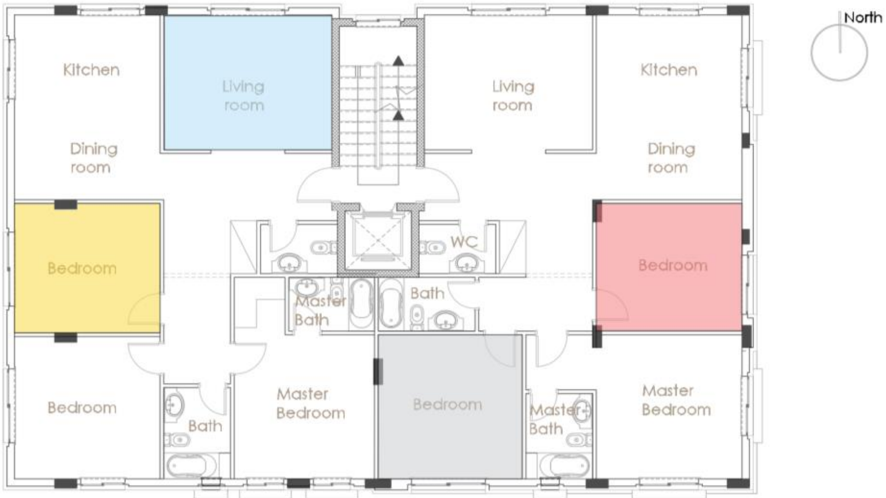


Figure 4-18: The building plan showing the analyzed spaces toward different orientations

According to ASHRAE standards, the preferred ranges of controlled air temperature for occupants are 22.2°C to 26°C in summer and 20°C to 24°C in winter (ASHRAE, 2017). Moreover, (Haj Hussein, et al., 2021) conducted a study analyzing the thermal performance of residential buildings in Nablus by considering setpoints of 20 °C in winter and 26 °C in summer. In this research, the indoor air temperature setpoints are equal to 26 °C in summer and 20°C in winter. The initial simulation for the base-case model was run with no addition of thermal insulators depending on the envelope's physical properties as calculated previously. The initial simulation was carried out to evaluate the annual performance in terms of indoor operative temperatures, levels of relative humidity, and the initial levels of sensible cooling and heating loads. The simulation parameters using the design builder software were summarized in Table 4-11b as follows.

Table 4-11b: design builder software used simulation parameters.

Parameters		**Value**
Activity	Occupancy density (people/m^2)	0.0384
Construction	Envelope U- Values (W/m^{2}k)	According to the case
Openings	WWR % Window height (m) Window width (m) Natural ventilation	19% 1.25 1.70 According to the case
Environmental control	Mechanical ventilation Heating system Heating set point (°C) Cooling system Cooling set point (°C) Air infiltration (ac/h)	Active Natural gas 20 Electricity from the grid 26 0.25

Simulation results in reference to the base case external wall have shown that the applied methods and building practices fall short to achieve the requirements of thermal comfort; as shown in the simplified results in reference to the air temperatures in Figures 4-19, 4-20 below, the temperature falls to under 15°C on most of the days in winter, and rises around 25°C on most of the days in summer. Moreover, the temperature rises near to 30°C on some days of summer. The levels of relative humidity average range from 40% to 60% on most of the days all year long. However, it reaches around 70% on extreme days and falls to around 20% on dry summer days. Buildings also suffer from excessive seasonal cooling and heating loads. For example, such buildings consume an average daily cooling load of around 6 KW/h in summer and an average of 3 or 4 KW/h in winter, which implies high burdens of seasonal heating and cooling loads.

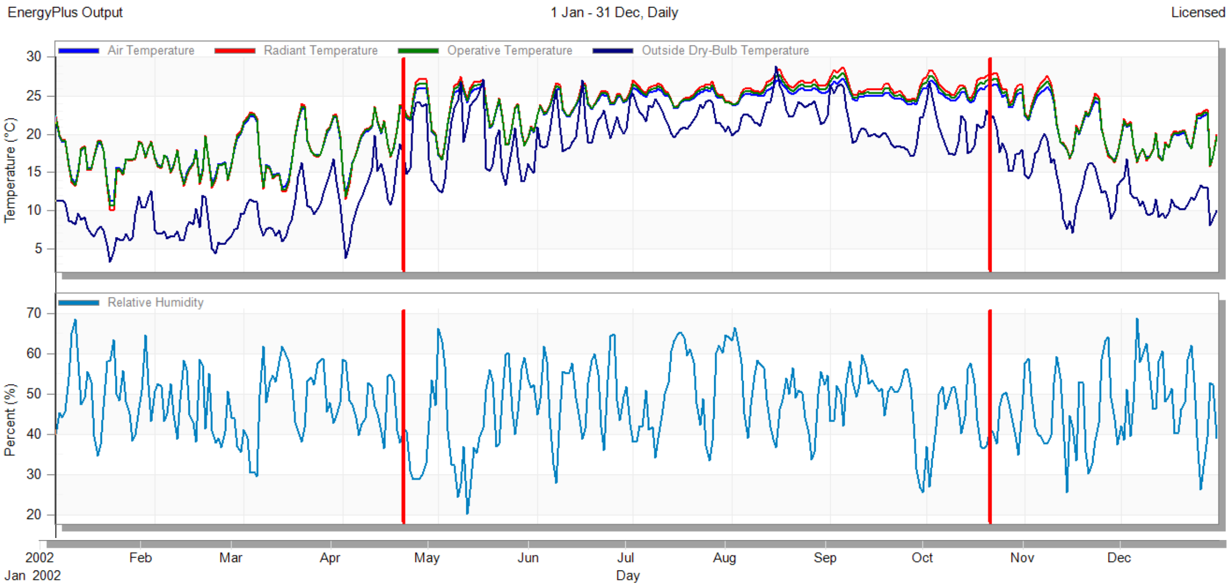


Figure 4-19: The initial base case model’s simulation results for temperatures and relative humidity

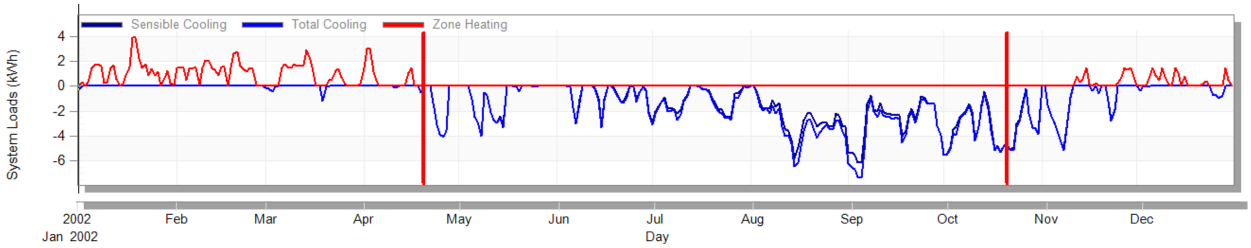


Figure 4-20: The initial base case model’s simulation for cooling and heating loads

Results have also shown no initial potential of condensation accumulation due to the evaporation effect in summer caused by higher temperatures. However, mold growth is probable. The total initial evaluation of thermal performance for the common building pattern was evaluated as poor. The study had further evaluated the formation of condensation and mold growth in the external wall interventions as will be explained in this chapter.

4.6 Envelope’s interventions

The study proposes multiple interventions for the residential buildings’ common envelope, these refer to an addition or modification of the layers of the analyzed base-case model. These interventions were explained in two main categories depending on the building pattern as follows:

4.6.1 Interventions to a stone-concrete wall

a- Hollow concrete block installation with air cavity

One of the main insulators is the installation of hollow concrete blocks with an air cavity. Depending on the field survey, this was the most applicable and most affordable type of insulation for occupants in Hebron. Local manufacturers also produce 7cm hollow concrete blocks. However, it is considered impractical for electrical works and probably causes thermal bridging due to less thicknesses, findings regarding the installation of 7cm hollow block are summarized in Table 4-13 as follows. The 10 cm blocks better serve the electrical requirements and the integration of work as shown in Figure 4-21 and Table 4-12.

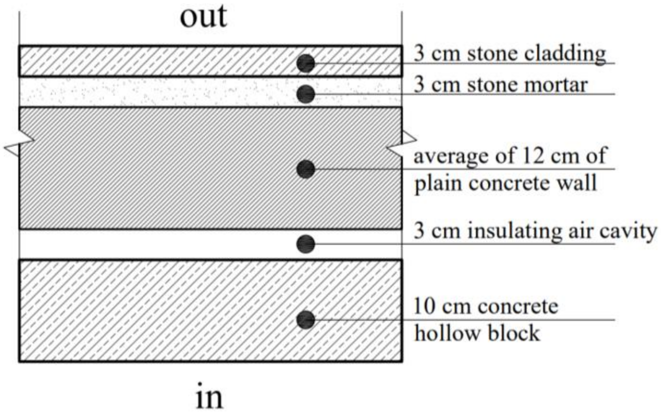


Figure 4-21 Trial 1, The installation of a 10 cm concrete hollow block and 3 cm cavity

Table 4-12: Envelope interventions – Trial 1: The installation of a 10 cm concrete hollow block

External walls					
Layer's order (Out-to-in)	Material	Thick-ness (d) m	Apparent mass density (ῤ) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) m^2.k/W
1	External air	-	-	-	0.060
2	Stone cladding	0.03	2200	1.70	0.017
3	Stone mortar	0.03	1440	1.20	0.025
4	Concrete	0.12	2300	1.75	0.068
5	Insulating air cavity	0.03	-	0.16	0.18
6	Hollow concrete block	0.10	1400	0.90	0.111
7	Plaster	0.02	1850	0.72	0.027
8	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					0.608
Thermal transmittance (U-value) = 1/R_a					1.64 W/m^2. k

Further trials were carried out during the study, among these, was the increase of the insulating air cavity for higher heat insulation efficiency. With total thermal resistance of 0.74 m^{2}k/W, and thermal transmittance of 1.35 W/m^{2}k. This trial had shown that increasing thermal insulation is directly related to the enhancement thermal performance as shown in the comparative analysis for the first five trials in the following Table 4-13.

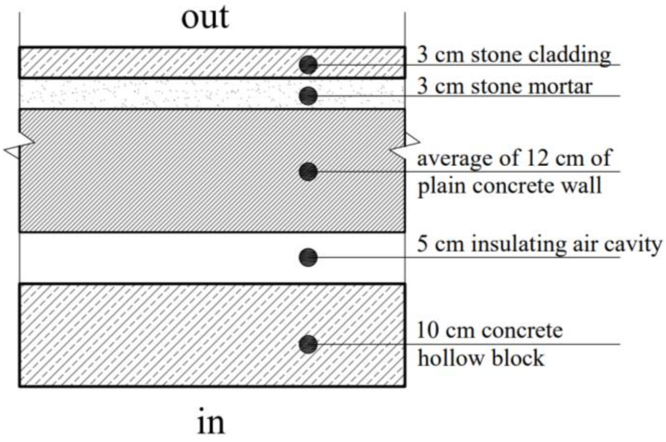


Figure 4-22: Trial 2, The installation of a 10 cm concrete hollow block and 5 cm cavity

Table 4-13: Envelope interventions – comparative analysis of trials 1,2,3,4, and 5.

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
	Stone cladding, concrete, no insulators	Installation of a 7 cm concrete hollow block	Installation of a 10 cm concrete hollow block	10 cm concrete hollow block and a 3 cm air cavity	10 cm concrete hollow block and a 5 cm air cavity
Wall section thickness (m)	0.20	0.26	0.28	0.33	0.35
Thermal resistance (m^2.k/W)	0.317	0.394	0.428	0.608	0.74
Thermal transmittance (U-value) (W/m^2. k)	3.15	2.54	2.34	1.64	1.35
Efficiency in terms of insulation (Darker color assembles better evaluation)	░	▒	▒	▓	█

From the previous table, the study has confirmed that the installation of hollow concrete block has increased thermal resistance. Moreover, combined hollow block with an air cavity is notably more effective in terms of thermal performance.

Table 4-13 had shown an increase in the thermal resistance when installing concrete hollow block with larger thicknesses, and hereby a reduction in the thermal transmittance (U-value). For example, the maximum enhancement using hollow block was when installing 10 cm hollow block with 5 cm air cavity, this has decreased the thermal transmittance from 3.15W/m^2k (base case U-value) to 1.35W/m^2k.

Findings confirm that the optimum air cavity thickness is 5 cm. While increasing the void layer to more than 5 cm may become ineffective in terms of insulation when bonded by either ordinary or reflective materials, due to the possibility of the formation of the convection currents allowing an internal dynamic pattern for the air parcels causing an increase of heat transmittance and heat exchange between the inner surfaces of the layers. (Bekkouche, et al., 2013)

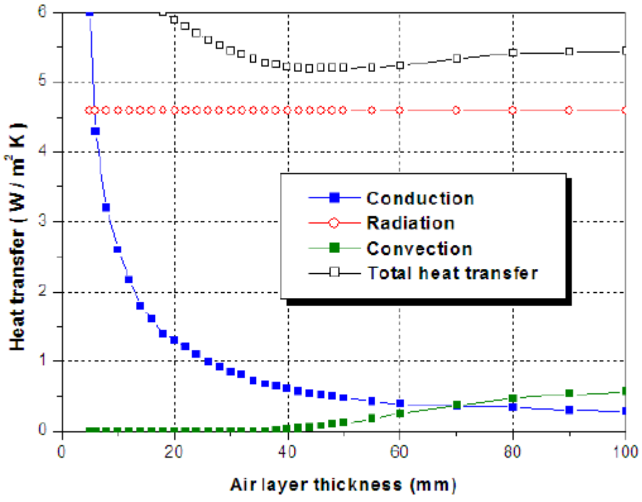


Figure 4-23: Estimated heat transfer in a closed air cavity bounded by ordinary materials

Source: (Bekkouche, et al., 2013)

b- Hollow concrete block installation with solid insulators

The air cavity replacement by solid insulators were further developments for Trial 1. The insulators were selected depending on the field survey of the local market analysis as previously mentioned. The simulation trials included the application of expanded polystyrene boards, rock wool rolls, and spray polyurethane foam in thicknesses of 2, 3, and 4cm respectively. The trials' results were as follows:

- Polystyrene boards

Expanded and extruded polystyrene boards are locally manufactured insulators, produced with different densities and thicknesses ranging from 2 to 10 cm. however, 2cm were their most used and most affordable with relatively similar thermal properties (Muallem, 2020).

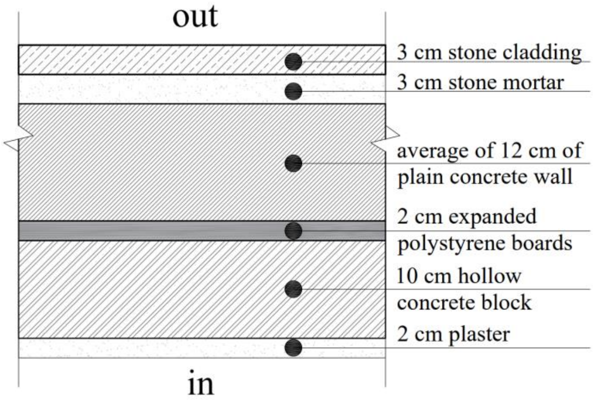


Figure 4-24: Trial 6, Void air cavity replacement with compressed polystyrene boards

Table 4-14: Envelope interventions – Trial 6: 2 cm expanded polystyrene boards

External walls					
Layer's order (Out-to-in)	Material	Thick-ness (d) m	Apparent mass density (ῥ) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) m^2.k/W
1	External air	-	-	-	0.060
2	Stone cladding	0.03	2200	1.70	0.017
3	Stone mortar	0.03	1440	1.20	0.025
4	Concrete	0.12	2300	1.75	0.068
5	Expanded polystyrene boards	0.02	160	0.045	0.445
6	Hollow concrete block	0.10	1400	0.90	0.111
7	Plaster	0.02	1850	0.72	0.027
8	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					0.873
Thermal transmittance (U-value) = 1/R_a					1.145 W/m^2. k

- Rock wool rolls

Rock wool is produced either as high-density rigid panels for roof and floor insulation or as semi-rigid panels or rolls wrapped with reflective surfaces for walls insulation. Rock wool were proven to be an efficient thermal insulator due to its resistance to corrosion, rust, and solar rays, and it is shape-conserving as it does not expand or shrink due to thermal changes (Salameh, 2012). The wall interventions included adding 3cm rock wool insulator as shown in Figure 4-25, and the U-value calculation were as shown in Table 4-15.

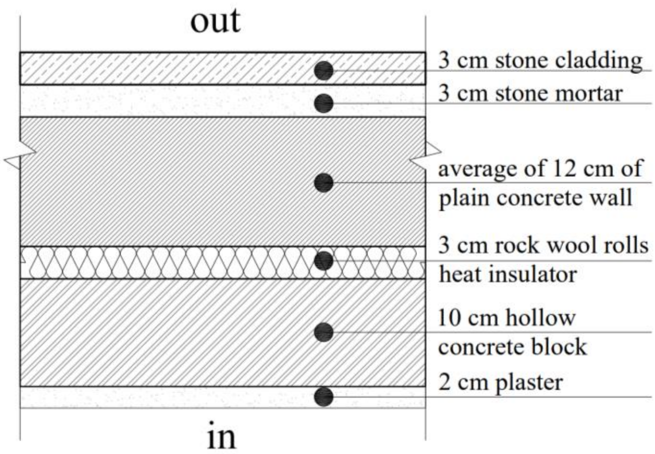


Figure 4-25: Trial 7, Void air cavity replacement with rock wool rolls

Table 4-15: Envelope interventions – Trial 7: 3 cm rock wool rolls

External walls					
Layer's order (Out-to-in)	Material	Thickness (d) m	Apparent mass density (ῤ) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) m^2.k/W
1	External air	-	-	-	0.060
2	Stone cladding	0.03	2200	1.70	0.017
3	Stone mortar	0.03	1440	1.20	0.025
4	Concrete	0.12	2300	1.75	0.068
5	rock wool rolls	0.03	70	0.036	0.834
6	Hollow concrete block	0.10	1400	0.90	0.111
7	Plaster	0.02	1850	0.72	0.027
8	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					1.262
Thermal transmittance (U-value) = 1/R_a					0.792 W/m^2. k

- Polyurethane (PU) spray foam

PU foam’s both types, open and close cell PU foam, are considered efficient thermal insulators, which are affective in most climates. The density of PU foam depends on the amount of water as a blowing agent. Increasing the amount of water increases the cell size and reduces density (Khazami, et al., 2020). Therefore, PU Foam with higher density-closed cell provides condensation control and lower density-open cell PU foam performs as a breathing layer that could control condensation when installed with an interior vapor retarder paint (Lstiburek, 2020). While medium-density PU foam is mainly used for wall thermal insulation with density of 42 kg/m^3 (Bomberg & Kumaran, 1999).

Regarding the thickness of the PU foam layer, increasing the insulation thickness decreases the moisture transport rate, therefore, thin layers of PU foam (less than 1.5cm) are not recommended and thicker layers (around 4cm) generally perform better. However, increasing the insulation to more than 4 cm slightly increases the thermal resistivity for higher prices which is considered economic inefficient, for example, 4 and 5 cm gives values of 39.5 m. k/W and 39.9 m. k/W respectively as shown in Table 4-16 (Bomberg & Kumaran, 1999). Moreover, the thickness was also selected to minimize the seasonal accumulation of moisture in the foam, which is caused by the pressure differential causing the “vapor drive” due to inner and out temperature differences driving the vapor drops through the envelope from higher to lower temperatures to achieve balance.

Table 4-16: Thermal resistivity values by the thickness of foam

Thickness (mm)	**Thermal resistivity (m. k/W)**
4.00	39.5
5.00	39.9
7.50	42.4

The following Figure 4-26 and Table 4-17 illustrate the construction detail and the thermal properties of installing 4cm PU foam in external walls.

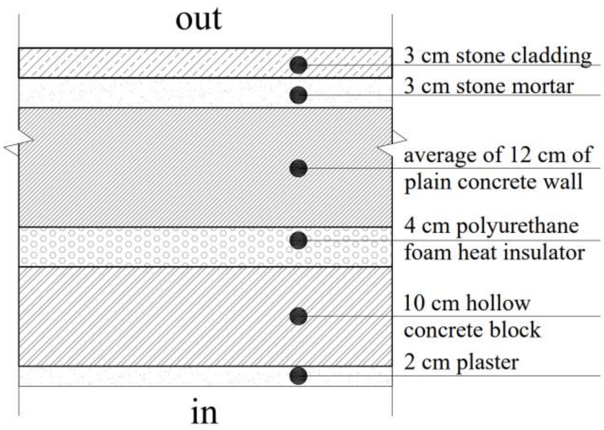


Figure 4-26: Trial 8, Void air cavity replacement with polyurethane foam

Table 4-17: Envelope interventions – Trial 8, Void air cavity replacement of polyurethane foam

External walls					
Layer's order (Out-to-in)	Material	Thickness (d) m	Apparent mass density ($\dot{\rho}$) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) m^2.k/W
1	External air	-	-	-	0.060
2	Stone cladding	0.03	2200	1.70	0.017
3	Stone mortar	0.03	1440	1.20	0.025
4	Concrete	0.12	2300	1.75	0.068
5	Polyurethane spray foam	0.04	42	0.025	1.60
6	Hollow concrete block	0.10	1400	0.90	0.111
7	Plaster	0.02	1850	0.72	0.027
8	Internal air	-	-	-	0.120
Total thermal resistance (R$_a$)					2.028
Thermal transmittance (U-value) = 1/R$_a$					0.493 W/m^2. k

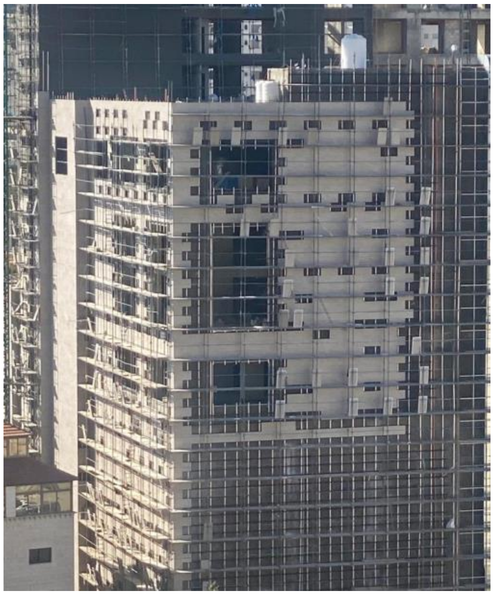
Table 4-18: Comparative analysis for the trials 6,7, and 8 insulators’ thermal properties

	2 cm expanded polystyrene boards	**3 cm rock wool rolls**	**4 cm spray polyurethane foam**
Wall section thickness (m)	0.32	0.33	0.34
Thermal resistance (m^2.k/W)	0.873	1.178	1.732
Thermal transmittance (U-value) (W/m^2. k)	1.145	0.849	0.493
Efficiency in terms of insulation (Darker color assembles better evaluation)	░	▒	▓

The previous Table 4-18, summarizes the trials of adding solid insulators to stone concrete walls. The trials had major thermal differences, despite the sections' thickness were relatively close. Calculations have shown a significant difference in the levels of thermal resistance and hereby in the thermal transmittance, which is directly related to the efficiency of controlling thermal comfort. For example, PU foam was more effective insulator than polystyrene boards since its thermal transmittance was proven to be less than half the transmittance when applying polystyrene boards. In table 4-18 darker color meant better thermal insulation evaluation regarding the numbers shown. For example, all three trials have performed better than the air cavity trials explained earlier. And among these three PU foam acts as most efficient.

4.6.2 Interventions to a stone-concrete hollow block wall

A less common building practice in Hebron is stone cladded external walls using hollow concrete block instead of backfill concrete. In this pattern, walls are considered non-structural elements. External walls consist of a stone outer layer fixed with galvanized steel clappers or stainless-steel angels holding the stone from its lower edge to a galvanized steel structure of horizontal and vertical profiles grid, walls are finished with an internal layer of a 2cm cement plaster as shown in Figure 4-27 as follows.



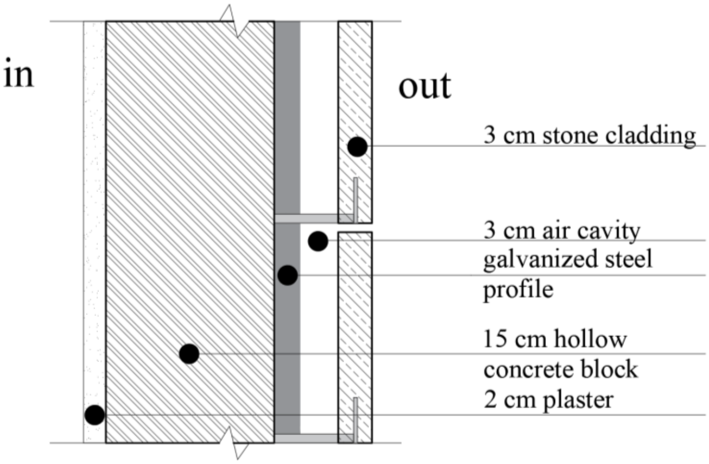


Figure 4-27: The detail and application of mechanical stone cladding in Hebron

Figure 4-27 (b): Additional pictures for mechanical stone cladding on hollow concrete block walls in Hebron

This building pattern could be executed using galvanized wires to connect the stone to a galvanized steel mesh from four angles, while the steel mesh is directly fixed to the hollow block wall, backfill stone mortar consisting of white cement, sand, and fine aggregate is added for additional bond. This wall composite is illustrated in Figure 4-28 as follows, Figure 4-29 show using this building pattern in recent projects in Hebron.

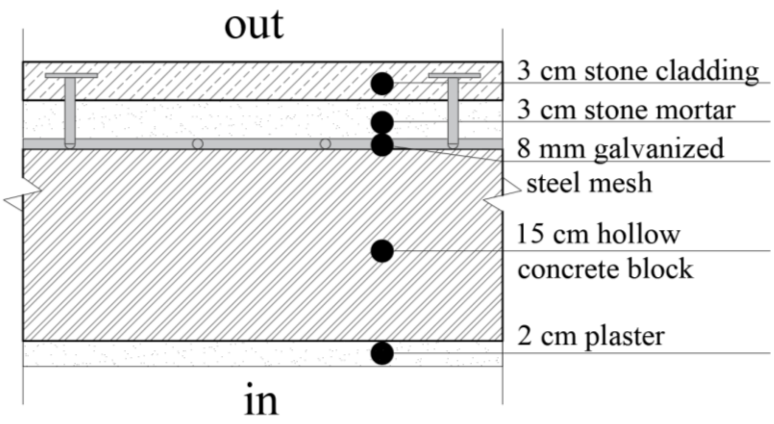


Figure 4-28: Stone cladded- hollow concrete block wall detail

Figure 4-29: Images showing using hollow concrete block building pattern

Until today, this pattern was mostly used in commercial buildings. The study aims to prove its efficiency to encourage using it in apartments buildings as it had shown a great amount of timesaving, still, it is not very dominant.

This building pattern could be thermally enhanced using an inner layer of 10 cm hollow concrete block. Furthermore, an insulating layer of an air cavity or a solid insulator could be applied between the hollow block layers as shown in the following Figure 4-30 and Table 4-19 as follows.

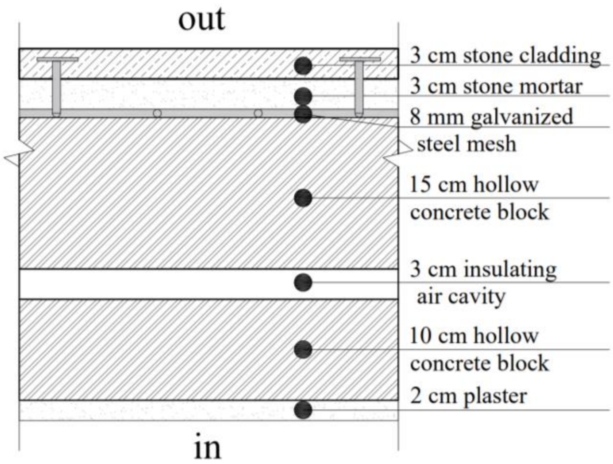


Figure 4-30: Trial 9, double hollow concrete block layers with insulating air cavity

Table 4-19: Envelope interventions – Trial 9, double hollow concrete block layers with no installed insulators

External walls					
Layer's order (Out-to-in)	Material	Thickness (d) m	Apparent mass density (ṗ) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) m^2.k/W
1	External air	-	-	-	0.060
2	Stone cladding	0.03	2200	1.70	0.017
3	Stone mortar	0.03	1440	1.20	0.025
4	Hollow concrete block	0.15	1400	0.90	0.167
5	Insulating air cavity	0.03	-	0.16	0.18
6	Hollow concrete block	0.10	1400	0.90	0.111
7	Plaster	0.02	1850	0.72	0.027
8	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					0.707
Thermal transmittance (U-value) = 1/R_a					1.41 W/m^2. k

For the same wall composite, a 3cm air cavity was applied to give a total thermal transmittance of 1.41 W/m^2. K which implies an enhancement of the insulation properties. The study proposes further enhancement for this second type of common building practice by multiple proposals for the insulating layer in the middle. The same common heat insulators previously analyzed were applied to this pattern to evaluate another 3 cases of the external wall composites as shown in detail in the following figures and tables.

- Polystyrene boards

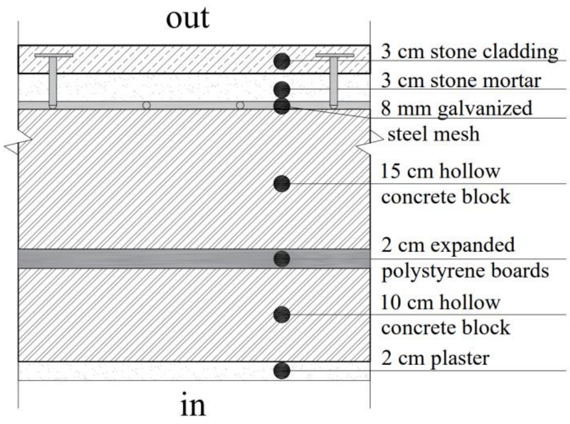


Figure 4-31: Trial 10, Void air cavity replacement of compressed polystyrene boards

Table 4-20: Envelope interventions – Trial 10: 2 cm expanded polystyrene boards

External walls					
Layer's order (Out-to-in)	Material	Thickness (d) m	Apparent mass density (ρ̇) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) m^2.k/W
1	External air	-	-	-	0.060
2	Stone cladding	0.03	2200	1.70	0.017
3	Stone mortar	0.03	1440	1.20	0.025
4	Hollow concrete block	0.15	1400	0.90	0.167
5	Expanded polystyrene boards	0.02	160	0.045	0.445
6	Hollow concrete block	0.10	1400	0.90	0.111
7	Plaster	0.02	1850	0.72	0.027
8	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					0.972
Thermal transmittance (U-value) = 1/R_a					1.03 W/m^2. k

- Rock wool rolls

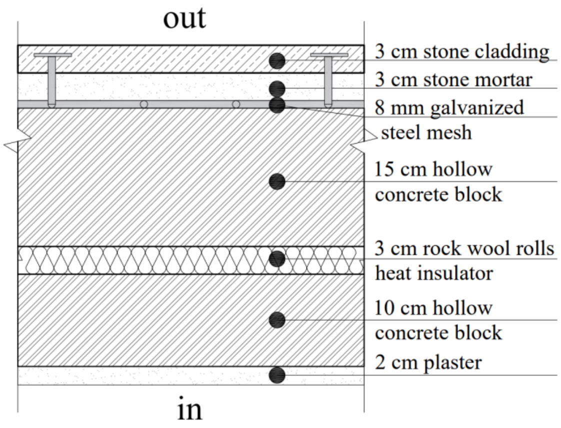


Figure 4-32: Trial 11, Void air cavity replacement of rock wool rolls

Table 4-21: Envelope interventions – Trial 11: 3 cm rock wool rolls

External walls					
Layer's order (Out-to-in)	Material	Thickness (d) m	Apparent mass density (ρ̇) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) m^2.k/W
1	External air	-	-	-	0.060
2	Stone cladding	0.03	2200	1.70	0.017
3	Stone mortar	0.03	1440	1.20	0.025
4	Hollow concrete block	0.15	1400	0.90	0.167
5	Rock wool rolls	0.03	70	0.036	0.834
6	Hollow concrete block	0.10	1400	0.90	0.111
7	Plaster	0.02	1850	0.72	0.027
8	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					1.361
Thermal transmittance (U-value) = 1/R_a					0.735 W/m^2. k

- Polyurethane (PU) spray foam

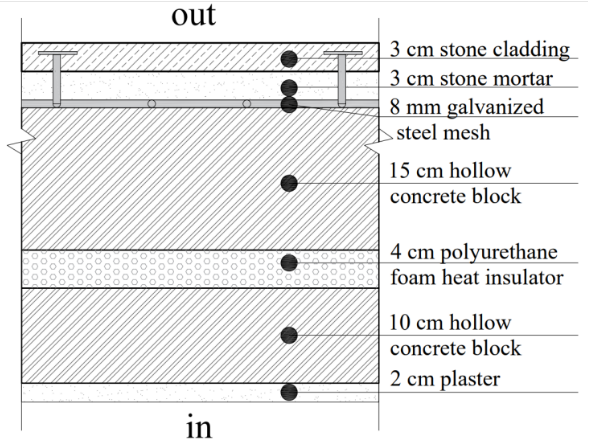


Figure 4-33: Trial 12, Void air cavity replacement of polyurethane foam.

Figure 4-34: Applying spray polyurethane foam to hollow block walls.

Table 4-22: Envelope interventions – Trial 12: 4 cm Polyurethane spray foam.

External walls					
Layer's order (Out-to-in)	Material	Thickness (d) m	Apparent mass density ($\dot{\rho}$) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) m^2.k/W
1	External air	-	-	-	0.060
2	Stone cladding	0.03	2200	1.70	0.017
3	Stone mortar	0.03	1440	1.20	0.025
4	Polyurethane spray foam	0.04	42	0.025	1.60
5	Rock wool rolls	0.03	70	0.036	0.834
6	Hollow concrete block	0.10	1400	0.90	0.111
7	Plaster	0.02	1850	0.72	0.027
8	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					2.127
Thermal transmittance (U-value) = 1/R_a					0.470 W/m^2. k

4.6.3 Outer application of the thermal insulator

After the previously explained thermal transmittance calculations, results have shown that 4cm of PU foam has given the lowest U-vale among other insulators. Moreover, polyurethane foam can be installed as an outside layer behind the stone cladding as shown in Figure 4-23 and Table 4-24 as follows. Therefore, this was tested for the two analyzed external wall patterns.

- Outer polyurethane (PU) spray foam on concrete wall composite

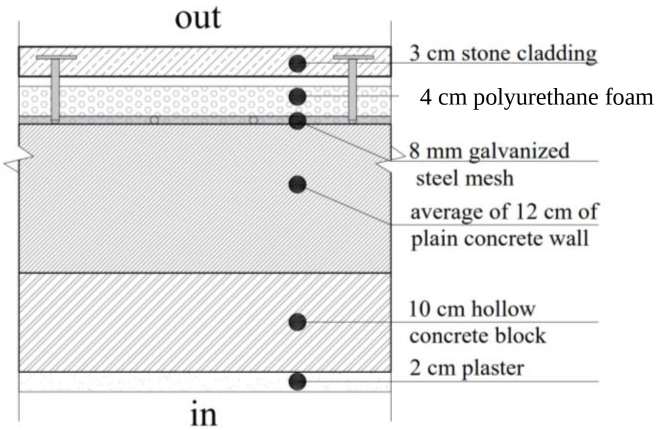


Figure 4-35: Trial 13, outer installation of PU foam on concrete wall composite

Table 4-23: Envelope interventions – Trial 13, outer installation of PU foam on concrete wall composite

External walls					
Layer's order (Out-to-in)	Material	Thickness (d) m	Apparent mass density (ṗ) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) m^2.k/W
1	External air	-	-	-	0.060
2	Stone cladding	0.03	2200	1.70	0.017
5	Polyurethane spray foam	0.04	42	0.025	1.60
4	Concrete	0.12	2300	1.75	0.068
6	Hollow concrete block	0.10	1400	0.90	0.111
7	Plaster	0.02	1850	0.72	0.027
8	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					2.00
Thermal transmittance (U-value) = 1/R_a					0.50 W/m^{2}k

- Outer polyurethane (PU) spray foam on hollow block wall composite

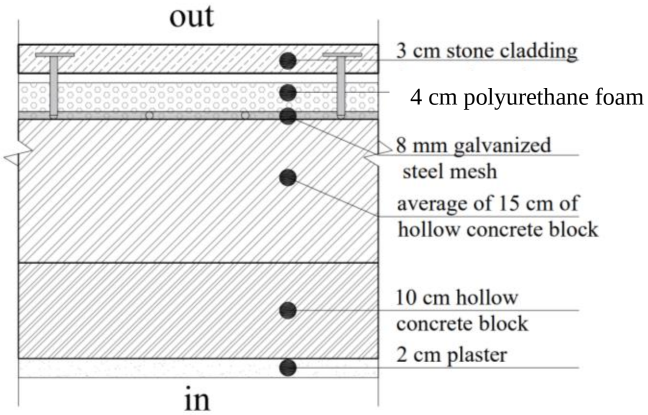


Figure 4-36: Trial 14, outer installation of PU foam on hollow block wall composite

Table 4-24: Envelope interventions – Trial 14, outer installation of PU foam on hollow block wall

External walls					
Layer's order (Out-to-in)	Material	Thickness (d) m	Apparent mass density (ṗ) Kg/m^3	Thermal conductivity (k) W/m. k	Thermal resistance (R) m^2.k/W
1	External air	-	-	-	0.060
2	Stone cladding	0.03	2200	1.70	0.017
5	Polyurethane spray foam	0.04	42	0.025	1.60
4	Hollow concrete block	0.15	1400	0.90	0.167
6	Hollow concrete block	0.10	1400	0.90	0.111
7	Plaster	0.02	1850	0.72	0.027
8	Internal air	-	-	-	0.120
Total thermal resistance (R_a)					2.10
Thermal transmittance (U-value) = 1/R_a					0.475 W/m^{2}k

4.7 Simulation results

The previous calculations of thermal transmittance for the interventions of external walls illustrate the potential of enhancing the thermal performance and the reduction of the heat gains in Summer and losses in winter to contribute to enhancing the occupants' satisfaction rate. The previous calculations were developed into simulation trials using the Design-builder software with the Energy Plus analysis engine. Simulations were carried out depending on the Jerusalem weather data due to the unavailability of the Hebron city weather file. According to (Weather-Spark, 2019), 67% of Hebron's climatic data depends on the data obtained from Jerusalem's weather station. The factor of infiltration was considered constant, and metabolic rates data and clothing for occupants were neglected.

The simulation for the previously explained cases was carried out in summer and winter to assess the thermal losses and gains for all four orientations. Simulations extended results were shown in Appendix D. The summarized results for each orientation were explained in Tables 4-25, 4-26, 4-27, and 4-28 as follows. The tables compared the U-values, the indoor and outdoor air temperatures, the humidity levels, the discomfort hours, and the heating and cooling loads in summer and winter.

4.7.1 North-oriented spaces

The study analyzes a modular space oriented toward the north as the first case of the simulations carried out as shown in Figure 4-37.

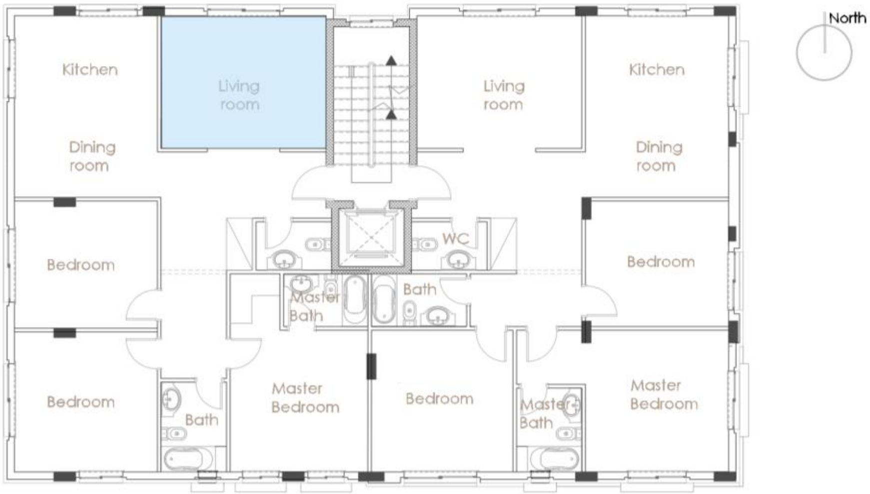


Figure 4-37: Modular plan showing the north-oriented analyzed space

Comparing the envelops interventions starts with comparing the U-value for the composites. External walls with lower thermal transmittance factors are expected to act as more efficient external wall solutions for thicknesses ranging around 35 cm.

Table 4-25 as follows illustrates the findings of the simulations for the Northern façade of the modular residential building analyzed. The trials include changing the type and thickness of the insulator as explained previously.

Table 4-25: Simulation trials results' analysis of Northern facade

Orientation: Northern façade											
				Summer **Average outdoor air temperature in Summer (22.12°C)**				**Winter** **Average outdoor air temperature in winter (7.91°C)**			
Case number	**Case description and construction detail**		**U-value** (W/m^2. k)	**Average operative indoor air temperature in Summer** (°C)	**Relative Humidity in Summer** (%)	**Sensible cooling loads in summer** (kW/h)	**Discomfort hours (all clothing) in Summer** (hrs.)	**Average operative indoor air temperature in Winter** (°C)	**Relative Humidity in Winter** (%)	**Total zone heating load in winter** (kW/h)	**Discomfort hours (all clothing) in Winter** (hrs.)
1	**Interventions to a stone-concrete wall**	Stone cladding, concrete, no insulators	3.15	25.40	50.48	49.05	472.50	13.33	55.53	104.36	780.50
2		Installation of a 7 cm concrete hollow block	2.54	25.63	49.59	56.78	464.00	13.60	54.79	91.38	784.50
3		Installation of a 10 cm concrete hollow block	2.34	25.71	49.29	59.74	458.50	13.70	54.49	87.13	772.00
4		installation of a 10 cm concrete hollow block and 3 cm cavity	1.64	25.71	49.29	59.74	458.50	13.70	54.49	87.13	772.50
5		installation of a 10 cm concrete hollow block and 5 cm cavity	1.35	25.90	48.48	68.90	439.50	14.22	53.06	71.52	760.00
6		Void air cavity replacement of compressed polystyrene boards	1.145	26.02	47.84	81.67	422.50	14.02	53.61	76.35	771.50
7		Void air cavity replacement of rock wool rolls	0.849	26.09	47.47	87.26	407.50	14.37	52.62	68.21	734.00
8		Void air cavity replacement of 4 cm polyurethane foam	0.493	25.39	50.59	46.19	445.50	14.78	51.51	61.04	710.50
9	**Interventions to a stone-concrete hollow block wall**	double hollow concrete block layers with no installed insulators	1.41	25.38	50.18	55.18	456.50	13.67	45.57	85.70	779.00
10		Void air cavity replacement of compressed polystyrene boards	1.03	25.29	49.83	58.65	453.50	13.94	53.81	76.78	720.50
11		Void air cavity replacement of rock wool rolls	0.735	25.65	49.67	51.99	452.50	14.72	51.57	46.04	764.50
12		Void air cavity replacement of 4 cm polyurethane foam	0.470	25.62	49.21	64.90	442.50	14.72	51.66	61.72	732.00

External wall interventions have shown an enhancement in the thermal resistance, hereby a reduction in the thermal transmittance factor (U-value) which is expected to enhance the wall's thermal properties in general. The base case simulation model had a U-value of 3.15 W/m^2. k, while the interventions have reduced it gradually to reach its most optimum values when applying PU foam, it was cut short to 0.493 W/m^2. k and 0.470 W/m^2. k for concrete walls and hollow block walls respectively.

The indoor operative temperature genuinely rises when applying insulators, this effect is considered most effective in winter, while in summer it increases the internal temperature. In summer, a gradual increase of operative temperature has resulted when increasing the thermal insulator’s thickness or efficiency. For example, the base case model had caused 25.40 °C, but reached its peak around 26 °C when applying polystyrene boards and rock wool rolls for both walls patterns, this could probably be a result for these being a high-density nonporous insulator. Moreover, wrapped rock wool is considered a radiant material that helps retain heat. On the other hand, in winter these two insulators for both practices have performed well and helped to increase the indoor temperature by around 6.5 degrees.

The comfortable indoor relative humidity rates in Mediterranean climates are expected to be most satisfying when it is in the range of 40% to 60% according to (Ghrab, 2005); (ANSI/ASHRAE 2013b). Simulation trials have proven that the humidity ranges were kept within the comfort range as its lowest level around 47% in summer and its maximum level around 54%,

Generally, north oriented spaces are the coldest with the highest heating loads compared to other orientations. These spaces have also had the lowest cooling loads in summer among all analyzed orientations due to lower solar exposure, this makes winter assessment the key role for the evaluation for insulators’ efficiency. Interventions achieving the lowest heating loads in winter along with heating load remaining within the original range were considered optimum. For stone-concrete walls the PU-foam had performed best in terms of retaining the indoor temperature and reducing cooling load by 6% and increasing the indoor temperature along with reducing heat load in winter by 41.5%. As for stone-hollow block walls pattern the rockwool panels had perform best in terms of retaining the indoor temperature despite the minor increase in cooling load by 6% and increasing the indoor temperature along with reducing heat load in winter by 40%.

4.7.2 South-oriented spaces

The study analyzes a modular space oriented toward the south as the second case of the simulations carried out as shown in Figure 4-38.

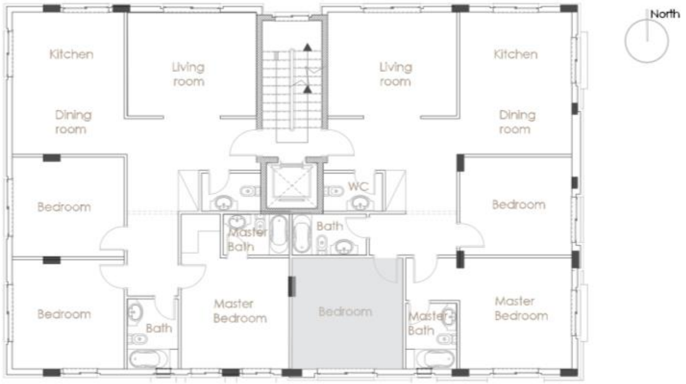


Figure 4-38: Modular plan showing the south-oriented analyzed space

In south oriented spaces, external walls with lower U-value have performed better in terms of indoor operative temperatures for both common and proposed building patterns. For example, in summer in trials 8, 12 –applying PU foam to both patterns – the temperature was slightly lowered compared to the base case. While in winter the temperature was increased by around 1.2 degrees compared to the base case. On the other hand, other insulators applied in other trials have less increased the temperature in winter and increased internal temperature in summer, despite maintaining humidity rates in all cases.

The sensible cooling load in summer was noted to be relatively larger in concrete walls. The cooling loads have increased when applying hollow block with air cavity (107.08 kW/h) which equals 21% (84.40 kW/h), and 26% when applying polystyrene boards (115 kW/h), and 30% when applying rockwool (120 kW/h) when compared to the base case. Haj Hussein et. al. has mentioned that buildings with inside insulation consume higher energy for cooling compared with buildings with outside insulation. This is probably related to the effect of the thermal mass, while concrete as a high thermal mass envelope component is more effective when applied internally with outside insulation. Since materials with higher heat capacity tend to absorb and store heat from the exterior (Haj Hussein, et al., 2021). Therefore, this research further discusses cases with outside layer of insulation.

This however was met by enhancement of winter performance by reducing the heating loads in the two cases from (60.09 kW/h) to reach (46.35 kW/h) using polystyrene boards with a 23.8% enhancement percentage, and (41.50 kW/h) using rockwool with a 32% enhancement percentage. It is also worth mentioning that installing hollow block of 10 cm with an air cavity of 3 cm to concrete walls had performed well, and had not significantly increased heating loads nor reduced cooling loads, but reduced the hours of discomfort for occupants, which define these solutions as thermally good, however not very effective.

In hollow block external wall building pattern, the cooling loads in summer were noted to be either equal or slightly larger than the base case, which concludes that hollow block walls do not cause internal overheating in summer. However, a maximum reduction of the heating load was achieved by applying Polyurethane spray foam (PU-foam). It reduced 23.73 kW/h which equals 40%, and 12.60 kW/h which equals 15% saving in cooling loads compared to the base case. Results were as shown in Table 4-26 below.

Table 4-26: Simulation trials results' analysis of Southern façade

Orientation: Southern façade											
				Summer **Average outdoor air temperature in Summer (22.12 °C)**				**Winter** **Average outdoor air temperature in winter (7.91°C)**			
Case number	**Case description and construction detail**		**U-value** (W/m². k)	**Average operative indoor air temperature in Summer** (°C)	**Relative Humidity in Summer** (%)	**Sensible cooling loads in summer** (kW/h)	**Discomfort hours (all clothing) in Summer** (hrs.)	**Average operative indoor air temperature in Winter** (°C)	**Relative Humidity in Winter** (%)	**Total zone heating load in winter** (kW/h)	**Discomfort hours (all clothing) in Winter** (hrs.)
1	**Interventions to a stone-concrete wall**	Stone cladding, concrete, no insulators	3.15	25.54	49.28	84.40	468.00	16.79	46.41	61.09	710.50
2		Installation of a 7 cm concrete hollow block	2.54	25.66	49.07	61.51	444.00	17.51	44.50	47.50	714.50
3		Installation of a 10 cm concrete hollow block	2.34	25.81	48.38	93.26	468.00	17.17	45.44	52.42	702.00
4		installation of a 10 cm concrete hollow block and 3 cm cavity	1.64	25.81	48.38	93.26	468.00	17.18	45.44	52.43	702.00
5		installation of a 10 cm concrete hollow block and 5 cm cavity	1.35	26.05	47.41	107.08	476.00	17.18	45.44	52.43	702.00
6		Void air cavity replacement of compressed polystyrene boards	1.145	26.10	47.17	115.63	470.00	17.32	45.12	46.35	691.50
7		Void air cavity replacement of rock wool rolls	0.849	26.17	46.89	120.76	461.00	17.63	44.39	41.50	676.50
8		Void air cavity replacement of 4 cm polyurethane foam	0.493	25.44	50.25	71.86	491.50	17.93	43.66	36.88	649.50
9	**Interventions to a stone-concrete hollow block wall**	double hollow concrete block layers with no installed insulators	1.41	25.47	49.31	87.00	464.50	16.92	46.06	51.41	709.50
10		Void air cavity replacement of compressed polystyrene boards	1.03	25.54	49.06	89.50	434.50	17.17	45.47	46.65	689.50
11		Void air cavity replacement of rock wool rolls	0.735	26.61	48.84	91.91	462.00	17.46	44.76	42.06	684.00
12		Void air cavity replacement of 4 cm polyurethane foam	0.470	25.67	48.63	94.39	464.50	17.84	43.85	37.36	655.50

As noted from Table 4 -26, the optimum solution for south-oriented external walls was the intervention which had achieved balancing the given parameters. That was the 4 cm PU-foam for both building patterns. In summary, First, in concrete walls, PU-foam has increased the indoor temperature in winter by 1.2 degrees and maintained the base case summer temperature. PU- foam had also reduced the cooling load in summer by 15% and the heating load in winter by 40% which reduces the energy consumption significantly. It had reduced the hours of discomfort by 61 hours for the winter season despite the slight increase in summer. Secondly, in hollow block walls, PU-foam had not increased the indoor temperature and maintained the base case summer and winter temperatures. PU-foam had also reduced the heating load in winter by 39% which reduces the energy consumption significantly but had slightly increased the cooling load in summer by 10%. It moreover had reduced the hours of discomfort by 55 hours for the analyzed winter season despite the slight increase in summer.

4.7.3 East-oriented spaces

The study analyzes a modular space oriented toward the east as the third case of the simulations carried out as shown in Figure 4-39.

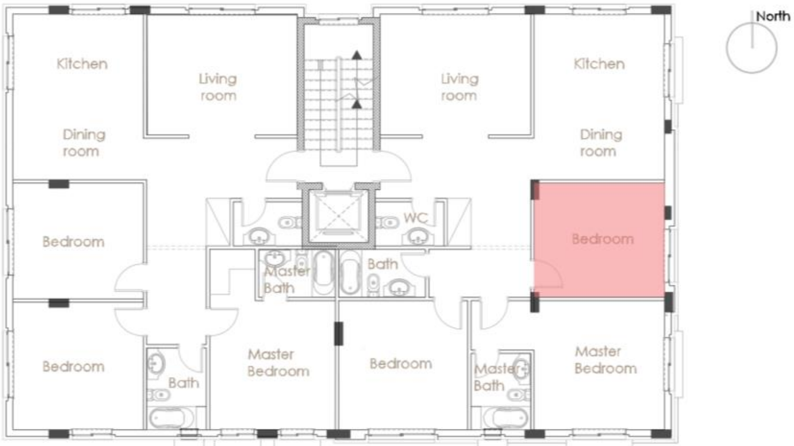


Figure 4-39: Modular plan showing the east-oriented analyzed space

Simulation analysis had shown that east-oriented spaces' external walls with lower U-value have also performed better in terms of indoor operative temperatures for both building patterns with the same previously analyzed levels of estimated temperature changes for the southern façade analysis.

Eastern façades simulation had shown quite a large amount of cooling load compared to the northern and southern façades; the base case model had an initial cooling load of around 220 kW/h. The simulation results were as shown in Table 4-27 as follows.

Table 4-27: Simulation trials results' analysis of Eastern facade

Orientation: Eastern façade											
				Summer **Average outdoor air temperature in Summer (22.12 °C)**				**Winter** **Average outdoor air temperature in winter (7.91°C)**			
Case number	**Case description and construction detail**		**U-value** (W/m^2. k)	**Average operative indoor air temperature in Summer** (°C)	**Relative Humidity in Summer** (%)	**Sensible cooling loads in summer** (kW/h)	**Discomfort hours (all clothing) in Summer** (hrs.)	**Average operative indoor air temperature in Winter** (°C)	**Relative Humidity in Winter** (%)	**Total zone heating load in winter** (kW/h)	**Discomfort hours (all clothing) in Winter** (hrs.)
1	**Interventions to a stone-concrete wall**	Stone cladding, concrete, no insulators	3.15	26.90	44.53	218.89	819.00	14.04	53.57	91.98	698.50
2		Installation of a 7 cm concrete hollow block	2.54	27.03	44.04	224.7	832.50	14.27	52.97	82.43	695.50
3		Installation of a 10 cm concrete hollow block	2.34	27.06	43.88	228.06	841.00	14.36	52.69	79.43	695.00
4		installation of a 10 cm concrete hollow block and 3 cm cavity	1.64	27.07	43.88	228.07	841.00	14.36	52.69	79.43	695.00
5		installation of a 10 cm concrete hollow block and 5 cm cavity	1.35	27.15	43.57	237.15	859.50	14.82	51.47	68.70	687.00
6		Void air cavity replacement of compressed polystyrene boards	1.145	27.17	43.41	250.14	887.50	14.57	52.12	71.93	687.00
7		Void air cavity replacement of rock wool rolls	0.849	27.22	43.25	245.74	903.00	14.88	51.28	66.12	686.50
8		Void air cavity replacement of 4 cm polyurethane foam	0.493	26.57	47.02	155.05	827.00	15.26	50.22	60.62	685.00
9	**Interventions to a stone-concrete hollow block wall**	double hollow concrete block layers with no installed insulators	1.41	26.73	45.07	203.94	795.00	14.29	52.89	78.24	696.00
10		Void air cavity replacement of compressed polystyrene boards	1.03	26.77	44.90	206.24	793.50	14.53	52.20	72.06	704.50
11		Void air cavity replacement of rock wool rolls	0.735	26.81	44.72	208.72	797.50	14.82	51.43	66.53	684.50
12		Void air cavity replacement of 4 cm polyurethane foam	0.470	26.85	44.59	211.37	800.00	15.21	50.35	61.15	684.50

Generally, all interventions applied to the stone-concrete walls except for the PU-foam had caused an increase in the cooling loads in summer and had slightly lowered the heating loads in winter. Simulations had proven the efficiency of polyurethane foam insulation for spaces with eastern external walls. Compared to the base case model, PU-foam had reduced the cooling loads in summer by 30% and reduced the heating loads by 34%in winter.

However, in summer for eastern orientations PU-foam did not perform as efficiently in concrete hollow block walls. The cooling load had nearly remained equal with an enhancement of 3.5% compared to the base case despite a reduction in the heating load of 33.5%. Generally hollow block external walls may not require the addition of solid insulators in the originally existing air cavity for eastern façades as the building pattern saves nearly 7% in cooling loads and 15% in heating loads with no additional insulators as shown in the simulation results in Table 4-27.

4.7.4 West-oriented spaces

The study finally analyzes a modular space oriented toward the west as the fourth case of the simulations carried out as shown in Figure 4-40.

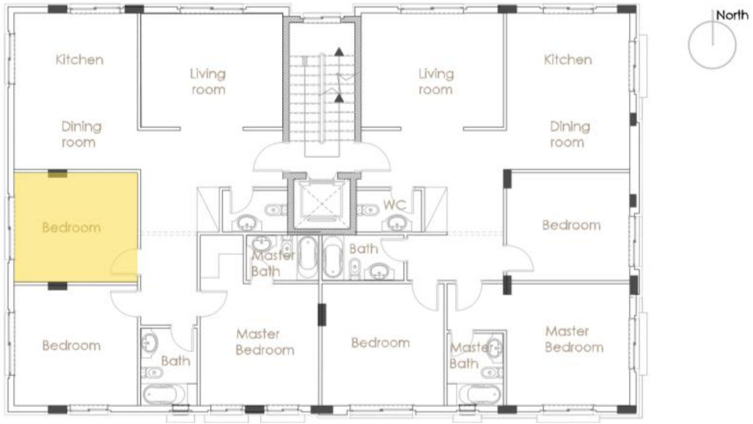


Figure 4-40: Modular plan showing the west-oriented analyzed space

Simulation analysis had shown that west-oriented external walls are subjected to a maximum solar intake, which causes a large burden of energy consumed by cooling loads in summer of (313.95 kW/h), with a relatively high heating load in winter of (81.47 kW/h) for the base case as shown in the simulation results in Table 4-28 as follows.

Optimum external wall intervention for western façades is expected to lower the cooling and heating loads while maintaining a reasonable average of indoor operative temperatures. Applying PU-foam had resulted indoor temperature retaining of 27°C in summer, and an increase from 15°C to 16.39°C in winter. This was achieved along with a reduction of heating loads by 37% and an increase of cooling load by 15% in stone concrete walls. While in stone hollow block walls cooling loads were increased by 2.5% and heating loads were reduced by 36%. Despite those other interventions had less-increased the cooling loads, they had not lowered the heating loads effectively. For example, 7 cm hollow concrete block had increased the cooling loads by only 5.7%, but it had lowered the heating load by 10%, which is considered cost consuming. Therefore, the study performs additional simulations with the application of natural ventilation effect for the interventions that have performed best in winter, however, fell short to keep up in summer performance. These simulations were explained in the following section of the study as enhancements for summer season, which mainly include a dependence on natural ventilation.

Table 4-28: Simulation trials results' analysis of Western facade

Orientation: Western façade											
				Summer **Average outdoor air temperature in Summer (22.12 °C)**				**Winter** **Average outdoor air temperature in winter (7.91°C)**			
Case number	**Case description and construction detail**		**U-value (W/m^2. k)**	**Average operative indoor air temperature in Summer (°C)**	**Relative Humidity in Summer (%)**	**Sensible cooling loads in summer (kW/h)**	**Discomfort hours (all clothing) in Summer (hrs.)**	**Average operative indoor air temperature in Winter (°C)**	**Relative Humidity in Winter (%)**	**Total zone heating load in winter (kW/h)**	**Discomfort hours (all clothing) in Winter (hrs.)**
1	**Interventions to a stone-concrete wall**	Stone cladding, concrete, no insulators	3.15	26.99	43.57	313.95	860.00	15.03	50.75	81.47	780.00
2		Installation of a 7 cm concrete hollow block	2.54	27.15	43.15	333.20	927.00	15.32	49.94	72.84	777.50
3		Installation of a 10 cm concrete hollow block	2.34	27.19	43.04	339.95	947.00	15.43	49.67	70.01	777.00
4		installation of a 10 cm concrete hollow block and 3 cm cavity	1.64	27.19	43.04	339.96	947.00	15.43	49.67	70.01	777.00
5		installation of a 10 cm concrete hollow block and 5 cm cavity	1.35	27.24	42.84	353.17	974.50	15.94	48.38	59.58	770.00
6		Void air cavity replacement of compressed polystyrene boards	1.145	27.24	42.85	362.23	963.00	15.67	49.05	62.31	770.00
7		Void air cavity replacement of rock wool rolls	0.849	27.26	42.78	367.35	985.00	16.00	48.25	56.54	769.50
8		Void air cavity replacement of 4 cm polyurethane foam	0.493	27.00	43.48	372.47	896.00	16.39	47.24	51.30	768.00
9	**Interventions to a stone-concrete hollow block wall**	double hollow concrete block layers with no installed insulators	1.41	26.85	43.92	305.42	836.00	15.30	50.03	68.87	778.00
10		Void air cavity replacement of compressed polystyrene boards	1.03	26.90	43.78	311.63	855.00	15.58	49.30	63.08	786.50
11		Void air cavity replacement of rock wool rolls	0.735	26.93	53.67	316.84	870.00	15.89	48.51	57.84	766.50
12		Void air cavity replacement of 4 cm polyurethane foam	0.470	26.97	43.57	321.87	880.50	16.30	47.47	51.97	766.50

4.7.5 Summer season external envelope enhancement trials

From the previously analyzed cases, three of the most effective cases were further simulated with applying the effect of natural ventilation in summer. These attempts aim at evaluating the levels of energy saving when natural ventilation was active. 50% of the glazing area was considered open. The following Table 4-29 illustrates the results of these trials.

Table 4-29: Simulation results for selected cases when applying natural ventilation toward different orientations.

Case number	Case description and construction detail		U-value (W/m^2. k)	Orientation	Summer					Winter
					Average operative indoor air temperature in Summer (°C)	**Average outdoor air temperature in Summer (°C)**	**Relative Humidity in Summer (%)**	**Maximum sensible cooling loads in summer (kW/h)**	**Discomfort hours (all clothing) in Summer (hrs.)**	
5	**Interventions to a stone-concrete wall**	Naturally ventilated- Installation of a 10 cm concrete hollow block and 5 cm cavity	1.35	N	25.68	22.12	49.70	52.59	452.00	Windows are more likely to be closed during winter Simulations were not performed
				E	26.88	22.12	46.11	175.18	893.00	
				S	25.78	22.12	49.15	82.07	509.00	
				W	27.08	22.12	44.86	295.66	880.50	
8		Naturally ventilated- Void air cavity replacement of 4 cm polyurethane foam	0.493	N	25.39	22.12	50.59	46.19	445.50	
				E	26.58	22.12	47.05	155.05	827.00	
				S	25.44	22.12	50.25	71.86	491.50	
				W	26.85	22.12	45.60	236.88	822.00	
12	**Interventions to a stone-concrete hollow block wall**	Naturally ventilated- Void air cavity replacement of 4 cm polyurethane foam	0.470	N	25.62	22.12	49.21	64.90	442.50	
				E	26.85	22.12	44.59	211.37	800.00	
				S	25.67	22.12	48.63	94.39	464.50	
				W	27.09	22.12	44.81	262.00	882.50	

Results have shown an enhancement of the indoor environment parameters in terms of the indoor temperature and the levels of relative humidity due to the availability of natural ventilation through the analyzed space's window. The effect of natural ventilation was probably most noted on the western façade as a result of the local wind's direction and less effective in cases of other orientations. The indoor operative temperature values were not highly improved by natural ventilation for other orientations, due to lower wind effect. In west-oriented spaces the natural ventilation effect had contributed to lowering the burdens of mechanical cooling loads in summer. The selected three envelope intervention 5, 8, and

12 had shown a decrease of cooling levels of 16.3%, 36.4%, and 18.6% relatively. Moreover, the effect of natural ventilation has slightly lowered the indoor operative temperatures in the three cases.

4.7.6 Changing the location of the insulator

For the analyzed cases after applying the effect of natural ventilation, the effect of changing the location of the insulator aimed to enhance the balance of indoor environment, reduce the cooling loads in summer, and solve the potentials of condensation accumulation within the envelope’s layers. Winter simulation trials were accomplished after changing the insulation layer location but with inactive natural ventilation effect.

Table 4-30: Simulation results for both construction patterns with outer polyurethane layer with applying natural ventilation in summer.

Case number	**Case description and construction detail**		**U-value** (W/m^2. k)	**Orientation**	**Summer Average outdoor air temperature in Summer (22.12 °C)**				**Winter Average outdoor air temperature in winter (7.91°C)**			
					Average operative indoor air temperature in Summer (°C)	**Relative Humidity in Summer** (%)	**Maximum sensible cooling loads in summer** (kW/h)	**Discomfort hours (all clothing) in Summer** (hrs.)	**Average operative indoor air temperature in Winter** (°C)	**Relative Humidity in Winter** (%)	**Total zone heating load in winter** (kW/h)	**Discomfort hours (all clothing) in Winter** (hrs.)
13	Stone-concrete wall	Stone cladding, with outer 3 cm polyurethane foam concrete wall with 10 cm hollow block	0.50	N	25.35	50.75	44.51	440.00	14.82	51.39	59.96	760.50
				E	26.55	47.11	154.87	824.00	15.28	50.21	59.75	682.00
				S	25.41	50.39	70.74	486.50	17.95	43.53	36.90	625.50
				W	26.80	45.80	232.75	805.00	16.41	47.20	50.81	766.50
14	Stone-block wall	Double hollow concrete block layers with outer 4 cm polyurethane foam	0.470	N	25.30	44.73	58.40	444.00	14.73	51.60	62.56	710.00
				E	26.50	47.29	156.04	829.50	15.21	50.35	61.43	687.00
				S	25.41	50.28	69.84	486.50	17.82	43.85	36.95	643.50
				W	26.84	45.64	234.15	814.50	16.30	47.44	51.69	766.50

From the results shown in Table 4-30, for the two trials performed for the outer insulating layer installation, an overall enhancement of the measurements of the indoor environment and occupants’ comfort was detected.

In trial 13 - stone cladded concrete wall with outer polyurethane foam layer and internal installation of 10 cm hollow concrete block- had proven a slight enhancement of the indoor temperatures for all orientations. The humidity levels were within the comfort range according to the ASHRAE standards (ASHRAE, 2017). It had also contributed to lowering the sensible cooling loads by an average of 4% for all orientations. The hours of discomfort were also decreased by an equivalent percentage when compared with the same envelope composition with inner insulating layer with the same estimated cost.

In trial 14 - stone cladded hollow concrete block wall with external polyurethane foam insulation- had proven a sensible enhancement for the analyzed parameters when compared to the base case model. For example, summer simulations for stone cladded concrete wall showed a reduction of sensible cooling loads of 30%, 16%, and 26% for south, east, and west orientations. While for the hollow concrete block walls, the percentages were 29%, 17%, and 25.4% for the same orientations respectively.

Results were less notable on the northern façade since cooling loads were comparatively low in summer due to the effective effect of prevailing wind from the natural ventilation as shown in trials 13 and 14.

As for winter simulations for trial 13, those had also proven a reduction of heating loads by 42.5%, 35%, 39.6%, and 37.6% for northern, eastern, southern, and western orientations respectively. While in trial 14, for stone cladded hollow concrete block walls, the same winter simulations had proven even better performances of 40%, 33%, 39.5%, and 36.5% for the same orientations respectively.

Results have shown a significant enhancement for all orientations in winter, especially the northern façade. This could probably be in response to it being the orientation with minimum solar intake in winter, therefore, the coldest and most heating loads consuming.

4.7.7 Condensation analysis

The enhancement of the external walls extends to evaluate the potential of condensation accumulation all year long. The condensation accumulation results when the dampness absorbed during winter is larger than the evaporating dampness in summer, which causes a remaining amount of vapor within the envelope’s layers. Condensation accumulation causes potential mold growth, which in terms affects the human respiratory system and health.

Selecting a relatively efficient solution depends on balancing the previously explained thermal properties, insulation efficiency, and consumed heating and cooling loads along with the possibilities of vapor condensation. Therefore, the study checks the most efficient solutions in terms of the potential of condensation accumulation along a year interval, in addition to the previously evaluated thermal performance and energy saving for additional validation of the selected wall interventions.

The evaluation depends on comparing the building's external wall in terms of evaluation of the thermal quality, the mold growth potential, the number of condensation interfaces- which is the number of points accumulating vapor-, each interface distance from the outer wall surface, and the amount of accumulated vapor. Results of condensation simulations were explained in Appendix E.

Results have shown that the common building practice -base case- was proven to be free of condensation. However, it is very poor in terms of thermal properties and energy consumption. Similarly, despite applying 7 and 10 cm hollow blocks produces no condensation, these interventions provide low thermal efficiency as shown previously in Tables 4-25 to 4-29.

Insulating materials could perform differently in terms of vapor trapping depending on the external wall components and order. In response, the same insulator may positively or negatively affect the vapor accumulation. Therefore, condensation analysis could not be carried out irrelevantly from the thermal evaluation. For example, trial 7 of rock wool performed worse in terms of condensation, 50.11 g/m^2 cumulated within the internal layers of the stone-concrete walls. On the contrary, rockwool performed better stone-concrete block envelopes causing only 5.90 g/m^2. Another example is the installation of Polystyrene boards, results have also shown different results for both building patterns of 41.02 g/m^2 and 23.24 g/m^2 for concrete walls and hollow block respectively, which classified it as a less-efficient condensation reducing material. While Polystyrene boards and rockwool panels caused larger amounts of condensation probably due to the lack of porosity, those had reduced vapor accumulation amounts for both common and proposed building patterns giving lower vapor values of 8.11 g/m^2 for stone-concrete walls and 7.25 g/m^2 stone-hollow concrete block walls.

Finally, trial 14 of the PU foam outer insulation with double hollow concrete block performed best in terms of thermal enhancement and scored no accumulation of condensation in the internal layers of external walls.

In conclusion, the condensation analysis confirms the necessity of a complete comprehensive evaluation of the external wall composition to conclude to the best performing composite. While some insulators have performed as efficient thermal insulating materials, they have fallen short of solving the vapor accumulation, which confirms the inability of validating the thermal performance evaluation apart from the condensation analysis.

Hollow concrete block is considered a porous material that allows the penetration of vapor through the external walls' layers. trials applying hollow concrete block either as the main construction material as in the proposed construction pattern, or as an insulating layer as in the first trial for concrete walls had performed better in terms of condensation accumulation, and therefore require shorter periods for the complete evaporation.

Composites with no solid insulators preventing vapor trapping had lower amounts of cumulative condensation. Therefore, concrete hollow block walls' interventions, shown in cases 9, 10, 11, 12, and 13, had the least values of condensation, and case 9 of double block walls with no insulator had a minimum of 4.35 g/m^2. followed by PU-foam and rock wool depending on each material's density.

4.8 Energy saving and payback period

The energy costs savings and payback period determination are considered essential for validating the feasibility of insulation materials for different external wall interventions as the study explains. Energy cost savings were generally more significant for colder climates and colder orientations and in cases that consume more energy (Ucar & Balo, 2010).

The payback period was calculated by dividing the total cost of each intervention for the external wall area of the analysed space (ILS) by the total amount of annual energy saving after using certain insulators (ILS/year). The annual energy saving cost was calculated by multiplying the annual energy consumed for maximum cooling and heating (KW/H) by the energy price, which was considered as the average residential price for energy consumption (0.65 ILS) in reference to the Electricity company prices in Hebron. Fixed costs including grid connections were neglected since they do not change while changing the consumed energy levels.

Insulation materials applied in the previously analysed interventions' costs were determined depending on the local market as follows, costs have included the installation and co-requested materials costs. Insulating hollow block, 50 ILS, Polystyrene boards 20 ILS, rockwool 30 ILS, and Polyurethane foam 35 ILS. In reference to these prices the total intervention costs, energy saving, and payback period for each orientation and external wall composites were illustrated in Table 4-31 as follows.

Table 4-31: Payback period calculations

			Orientation							
			North		**South**		**East**		**West**	
Case number	**Case description**	**Intervention cost (ILS)**	Annual energy saving cost for heating & cooling (ILS/year)	Pay-back period (Year)	Annual energy saving cost for heating & cooling (ILS/year)	Pay-back period (Year)	Annual energy saving cost for heating & cooling (ILS/year)	Pay-back period (Year)	Annual energy saving cost for heating & cooling (ILS/year)	Pay-back period (Year)
2	Installation of a 7 cm concrete hollow block	400	99.75	4.60	70.80	5.60	199.6	2.00	257.0	1.50
3	Installation of a 10 cm concrete hollow block	443.7	96.30	4.60	94.60	4.60	199.8	2.20	263.9	1.60
4	installation of a 10 cm concrete hollow block and 3 cm cavity	443.7	95.47	4.60	90.70	4.60	199.8	2.20	266.4	1.60
5	installation of a 10 cm concrete hollow block and 5 cm cavity	443.7	95.47	4.80	103.6	4.20	198.8	2.20	266.4	1.60
6	Void air cavity replacement of compressed polystyrene boards	621.2	91.27	6.00	105.2	5.90	209.3	2.90	268.2	2.20
7	Void air cavity replacement of rock wool rolls	710.0	102.7	7.00	105.4	6.70	202.7	3.50	275.9	2.50
8	Void air cavity replacement of 4 cm polyurethane foam	745.7	101.0	10.8	70.60	10.6	140.1	5.30	275.9	2.70

9	double hollow concrete block layers with no insulators	443.7	69.70	4.80	89.90	4.90	183.4	2.40	243.3	1.80
10	Void air cavity replacement of compressed polystyrene boards	621.2	88.03	7.00	88.50	7.00	180.9	3.40	234.5	2.50
11	Void air cavity replacement of rock wool rolls	710.0	63.72	11.1	87.00	8.10	178.9	3.90	243.5	2.90
12	Void air cavity replacement of 4 cm polyurethane foam	745.7	82.30	9.10	85.64	8.80	177.1	4.20	243.0	3.10

The energy saving and payback period for various insulation materials were more notable for the highest energy consuming orientations as the efficiency of the insulation performed as maximum.

The levels of energy saving were between 70 to 100 ILS for north and south, while it reached from 180 to 270 ILS for east and west depending on the insulation material. PU foam's energy costs had the lowest values for hollow block walls while it had relatively low costs for concrete walls. Energy saving were generally less for heating loads after the application of insulation materials. Therefore, the study confirms the efficiency of natural ventilation in climates like Hebron city.

The payback period for north-oriented apartments ranged from 4.6 to 11 years depending on the insulator type. For PU foam which was the best performing insulator in terms of thermal comfort and energy saving for stone-concrete walls the payback period was 10 years, while for stone hollow block walls the period was 4.8 years, however, installing rockwool rolls to achieve maximum energy saving requires 11 years to return its costs. For south-oriented apartments achieving the maximum energy saving for stone-concrete walls using PU foam requires around 10 years as a payback period. For hollow block walls it requires around 8.80 years.

East-oriented apartments achieve relatively lower payback periods when comparing the energy saving to the intervention cost. For example, for PU foam installation it takes 5 years and for hollow block walls it takes 4 years to return costs. Moreover, west-oriented apartments consume the highest levels of initial energy; therefore, insulation was found to be most effective. The payback period for the best performing insulting material was 2.7

for stone concrete walls and 3 for stone-hollow block walls. The payback period is expected to be reduced when reducing consumed energy, hereby, applying natural ventilation is expected to reduce the payback period as it lowers the cooling loads in summer as shown in the previously analyzed cases in Table 4-29.

The payback period for apartments with more than one main orientation could consider the maximum payback period for the used insulation material among its orientations when using the same insulating material for all its external walls. New technologies of heating and cooling allow separate load determination for each space connected to a main central HVAC unit, like the concept of VRF systems, this in terms allow variable payback period determination for each space depending on the orientation of its external walls.

4.9 Conclusion

This chapter has discussed and illustrated the external wall interventions performed for the most common building practice in Hebron city, which is the externally cladded concrete walls. The chapter also explains interventions proposed to enhance another building practice, however less common. Interventions aim to enhance the performance of stone-concrete external walls and encourage using stone-hollow block walls by proving their effectiveness in insulation and energy saving.

The chapter had explained the simulations for external walls interventions performed using the Design-builder software. The chapter further illustrates a summarized comparison between the best performed interventions for each orientation. Additional trials for applying the effect of natural ventilation and changing the location of the insulating surfaces installed. The final part of the chapter discusses the condensation in external walls happening as a result to internal and external temperature differences and evaluates the thermal condition of each trial along with the evaluation of mold formation potential.

The interventions performed were proven to be efficient in reducing the heating loads in winter and increasing the indoor operative temperatures, interventions were evaluated by enhancing the external wall performance during summer or maintaining the base case results of not increasing the internal heat due to the application of thermal insulators. Optimum solutions were selected for each orientation serving single or multiple directions-oriented residence. Polyurethane foam had proven its efficiency in reducing energy loads for most orientations. Moreover, it has significantly contributed to reducing condensation when applied to existing stone-concrete walls and could be applied to create a condensation-free stone-concrete hollow block walls. With a reasonable payback period ranging around 9 to 10 years for north and south, and 2 to 3 years for east and west.

Such analysis and measures were found very helpful as it directs the external walls initial design for newly designed buildings or interventions for previously constructed buildings. The presented analysis serves as a guiding manual for achieving more thermally responsible designs that better consider occupants’ comfort, furthermore, more energy efficient buildings.

The final chapter illustrates the conclusions and recommendations for this study to serve the generalization of its findings for similar cases in Hebron and other cities with the same climatic conditions.

Chapter 5

Conclusions and Recommendations

Chapter 5

Conclusion and Recommendations

5.1 Introduction

External walls design is a main design requirement for a properly designed building envelope. This chapter answers the research questions introduced in Chapter 1. Results have proven that applying thermal insulators is very essential. This thesis proposes passive interventions that have accomplished the control of thermal comfort and have achieved the energy saving through reducing the needed cooling and heating loads for mid-floors apartments in residential buildings in Hebron. The study had proven that the results could be generalized to other Palestinian cities having similar climatic conditions.

5.2 Conclusion

Occupants' comfort and energy saving are becoming more dominant requirements of buildings' design along with the continuous depletion of natural resources, increasing energy consumption rates, and the spread of awareness toward these parameters saving. However, common buildings practices remain to fall short to fulfill such requirements. This study highlights the main role of external walls' enhancement for developing the performance of buildings' envelopes by introducing and evaluating a variety of simple and relatively more precise external walls interventions.

In response to the research aims and objectives, this thesis aimed to enhance the compositions of external walls through the installation of insulating materials and the reduction of condensation resulting within the internal layers of external walls as a main part of the building envelope; to further reduce the consumed levels of energy toward a more efficient, affordable, and thermal comfort achieving envelopes of apartment buildings in Hebron, Palestine.

The study introduces an evaluation of different insulators' effect on enhancing the internal operative temperature along with maintaining reasonable humidity rates classified within the comfort measures, an assessment of seasonal heating and cooling loads, and the occupants' discomfort seasonal hours. Tubelo, et al. have conducted a similar study using the method of sensitivity analysis for analyzing the thermal comfort in residential buildings in Brazil, which allows understanding the effect of different heat insulators separately in the envelope. The study starts with an extended analysis depending on the data derived from a built house calibrated with empirical data collected from monitoring. The study was developed using thermal analysis simulation to measure the magnitude of thermal response of each envelope combination investigated. The simulation model used performs as a representative model of the mass housing typology in the country. The study depended on ASHRAE standards for the results of the simulation model analysis with reference to a thermal comfort limit of 20-25°C (Tubelo, et al., 2018).

The study presented an initial evaluation for a typical apartment in buildings constructed from concrete walls and cladded with stone with an average thickness of 3cm as commonly constructed. Such apartments were evaluated with a probability of indoor overheat in summer with temperatures averages of 26 °C compared to an outer temperature of 22 °C, and cold interior with averages between 13 °C and 16 °C in winter compared with 7.8 °C external temperature. This implies higher burdens of energy consumed for maximum seasonal cooling (314 kW/h) for western spaces and maximum seasonal heating for northern spaces (104 kW/h) for northern spaces.

This study aims at controlling thermal comfort and saving energy. Therefore, 12 external walls composites for insulators' interventions were applied for the main building practice of apartment buildings in Hebron in summer and winter while neglecting the effect of natural ventilation, to assess the effect of these insulators on the above-mentioned indoor environment comfort measures. Additional simulations were carried out for the best initially evaluated composites with the effect of natural ventilation applied in summer to reduce cooling loads. The same simulations were performed to help evaluating another less commonly used building pattern in apartment buildings. These pattens included stone cladding for concrete walls and concrete hollow block walls presented in different composites.

The simulation trials were continued to include the effect of changing the location of the insulating layer from the inner to the outer side of the wall. All the analyzed interventions were evaluated for the four main orientations resulting in a total of 104 simulation trials were performed to conclude to the thermal analysis of the external walls' enhancement criteria. Results of the energy saving performed by the best performance interventions were summarized in Table 5-1 and 5-2 for both building patterns as follows.

Table 5-1: energy saving results summary for stone cladded concrete walls

Building pattern	**Orientation**	**Intervention (trial) No.**	**External walls intervention**	**U-Value (W/m^2. k)**	**Insulator location**	**Cooling loads saving (neglecting natural ventilation)**	**Cooling loads saving (applying natural ventilation)**	**Heating load energy saving**
Stone cladded- concrete walls	North	8	Stone cladded concrete wall, with 4 cm polyurethane foam	0.493	Inner insulation	-6.0%	6.0%	41.5%
		13		0.50	Outer insulation		9.2%	42.5%
	South	8	Stone cladded concrete wall, with 4 cm polyurethane foam	0.493	Inner insulation	15.0%	15.0%	40.0%
		13		0.50	Outer insulation		30.0%	39.6%
	East	8	Stone cladded concrete wall, with 4 cm polyurethane foam	0.493	Inner insulation	30.0%	27.5%	34.0%
		13		0.50	Outer insulation		16.0%	35.0%
	West	8	Stone cladded concrete wall, with 4 cm polyurethane foam	0.493	Inner insulation	-15.0%	24.5%	37.0%
		13		0.50	Outer insulation		26.0%	37.6%

Table 5-2: energy saving results summary for stone cladded hollow concrete block walls

Building pattern	**Orientation**	**Intervention (trial) No.**	**External walls intervention**	**U-Value (W/m^2. k)**	**Insulator location**	**Cooling loads saving (neglecting natural ventilation)**	**Cooling loads saving (applying natural ventilation)**	**Heating load energy saving**
Stone- hollow concrete block wall	North	12	Stone cladded hollow concrete block wall, with 4 cm polyurethane foam or rock wool	0.470	Inner insulation: rockwool	-6.0%	15.0%	40.0%
		14		0.475	Outer insulation: PU foam		15.0%	42.5%
	South	12	Stone cladded hollow concrete block wall, with 4 cm polyurethane foam	0.470	Inner insulation	10.0%	11.0%	39.0%
		14		0.475	Outer insulation		29.0%	39.5%
	East	12	Stone cladded hollow concrete block wall, with 4 cm polyurethane foam	0.470	Inner insulation	3.5%	3.4%	33.5%
		14		0.475	Outer insulation		17.0%	33%
	West	12	Stone cladded hollow concrete block wall, with 4 cm polyurethane foam	0.470	Inner insulation	-15.0%	16.5%	36.0%
		14		0.475	Outer insulation		25.4%	36.5%

The study concludes to multiple findings depending on the measures in Tables 5-1, and Table 5-2 above shown, related to each building pattern toward different orientations, the following conclusions were given depending on controlling thermal comfort along with saving energy, which were summarized for each orientation as follow:

1. For north-oriented concrete walls cladded with stone, applying the insulating air cavity had reduced the heating energy by 31.5%, 34.6% by rockwool, and 41.5% by polyurethane foam (PU-foam). As for hollow concrete block walls percentages were 55.9% when applying rockwool, and 40.8% using PU-foam when compared to the base case concrete walls. These best performing insulators have also increased the indoor operative temperature in winter while conserving comfortable humidity rates. It is worth mentioning that these insulators did not cause an excessive increase in the cooling energy in summer for naturally ventilated spaces.

2. For south-oriented concrete walls cladded with stone, these had relatively similar results. Insulators of Polystyrene boards, rockwool, and Polyurethane foam have lowered the heating loads with percentages of 24%, 32%, and 39.6% respectively. Similarly, for stone-hollow block walls percentages were 23.6%, 31.1%, and 38.8%. Relating to this, PU foam had been proven to be the best insulating material for southern orientations for both building patterns. It provided warmer interiors in winter. In summer, applying PU foam (while natural ventilation effect was active) required a maximum cooling load of 71.86 kW/h in concrete walls, and 94.39 kW/h for hollow-block walls, which are considered in the range of to the base case cooling load (84.40 kW/H), and not requiring additional levels of cooling energy, also maintains the indoor temperature around 25.5 °C.

3. East oriented external concrete walls were proven to be enhanced when installing PU foam, the heating loads were reduced by 34% and cooling loads were lower by 30% neglecting the natural ventilation effect. Additional saving could be achieved in summer in naturally ventilated spaces saving 27.5% when compared to the base case model of natural ventilation independent spaces. On the contrary, in hollow block walls despite PU foam had reduced the heating loads by 33.5% did not reduce

cooling loads even when applying natural ventilation in summer. Hereby, for eastern oriented spaces of hollow block walls applying no insulation material will probably perform better in terms of energy consumption in both seasons achieving saving rates of 7% in summer, and 15% in winter when compared to the base case model.

4. As for west oriented external walls, it scored a maximum level of both heating and cooling loads, trial have proven the efficiency of PU foam in reducing heating loads for both construction patterns with a percentage of 36%. It, however, caused an increase in cooling loads while no natural ventilation applied. Additional simulation for applying natural ventilation had proven that cooling loads could be notably lowered.

This thesis extends to highlight one of the main problems facing insulation in external walls in buildings in general, the condensation phenomena resulting due to dampness absorption and accumulation within the layers of the external walls. The study proposes external walls composites resulting no water vapor accumulation, therefore solving the mold formation. The economic evaluation for the analyzed building pattern was performed by calculating the energy cost savings to further calculate the needed time for returning the interventions' costs, defined as the payback period.

Results have shown that external walls should be properly designed, and insulation materials should be carefully chosen depending on the apartment orientation. Moreover, thermal and physical properties of the external walls should be considered. It was proven by simulation trials and external wall interventions presented in the study that walls with lower thermal transmittance (U-value) perform better in terms of achieving thermal comfort and reducing energy consumption.

Applying the effect of natural ventilation enhances thermal performance in summer in a similar climatic context of Hebron city. Results had proven additional enhancements by the reduction of cooling loads in summer for all orientations when applying polyurethane foam as shown in Tables 5-1 and 5-2.

5.3 Results validation

The external walls interventions have achieved thermal performance enhancement due to reducing the thermal transmittance factor. The U-Value was reduced from 3.15 W/m^2. k to 0.493 W/m^2. k by applying PU foam to stone-concrete walls, and 0.470 W/m^2. k by applying the same insulator for the stone-double hollow block walls, achieving an enhancement percentage of 60.8% and 63.8% when compared to the target U-Value of 0.30 W/m^2. k. This had reduced the heating loads for both practices by around 40% for northern and southern orientations and exceeding 30% for eastern and western orientation. Generally, external walls composites with lower thermal transmittance coefficient provide better thermal performance and save larger amounts of energy. This was proved by a study conducted in Tehran, considering three alternatives for external walls' insulation with U-Values of 1.175, 1.040, and 0.492 W/m^2. K. Results have shown that the alternative with the lowest U-Value had performed an average of 20% more heating loads' saving than the other two alternatives using the Design-builder simulation software (Sadeghi, et al., 2019).

The proposed building pattern of a using double layers of hollow concrete block cladded externally with stone had proven to be slightly less energy consuming for nearly the same indoor temperatures and orientations, consuming a maximum cooling of (305 kW/h) and (86 kW/h) for heating, despite being slightly more expensive in the construction phase. Generally, hollow block had proven to be less energy demanding in terms of annual load consumption. That had been proven by a study conducted by (Dawoud, 2015), The study analyzes the effect of different external wall composites on indoor thermal comfort in Gaza. The study has analyzed three different wall details, these were: a) external stone cladding, internal hollow block, and plaster. b) both sides plastered hollow block wall. c) two layers of the hollow block with an air cavity in between and finished internally and externally with plaster. The U-value for the three trials were 2.33W/m^{2}k 2.51W/m^{2}k, and 1.60W/m^{2}k respectively. Initial evaluation had shown that (C) wall pattern consumes the least annual energy loads. Results have also shown that the air cavity of 5cm has reduced the energy consumption up to 50%; to reach comfort indoor temperature of 18-26°C.

External walls interventions had contributed to reducing the consumed energy levels especially in winter with lowering the necessary heating loads. However, insulating materials have performed differently depending on the orientation. Generally, applying insulation is considered significantly more efficient in winter when achieving an overall average energy saving exceeding 30%. Similar results using the Design builder software were conducted by (Monna, et al., 2016). The study had also analyzed the optimization of building envelopes to achieve energy efficiency using the Design-builder simulation software. Two buildings envelopes in Nablus were analyzed. Results have shown that energy consumption could be cut off to more than 50% by applying an optimized building envelope. This includes the installation of thermal insulators, proper glazing, shading devices, and natural ventilation. results have shown that the heating and cooling loads could be lowered by 40% and 10% respectively due to thermal insulation. Heat loads could also be reduced by 20% when installing double glazing, but cooling loads could increase by 5% using double glazing if the glazing was un-tinted or fixed (with no natural ventilation). Moreover, the shading devices assist in the reduction of cooling by 20% for southern windows.

Generally, PU foam has proven to probably be the most effective insulator, providing a more efficient effect when applied as an external insulating layer and maximum energy saving, which was proven by as study analyzing the influence of different insulating materials to the levels of energy consumed in Mediterranean regions as the best insulator and the most energy saving among others including polystyrene and rockwool (Cabeza, et al., 2010).

The study implies additional intervention regarding the location of the insulation, further interventions including the installation of insulation as an out layer were considered, results have shown that applying outer layer of PU-foam had proven a reduction averages of 20-30% of cooling loads, and heating loads reduction range of 33-40% for both construction methods for different orientations. This was confirmed by a study by (Haj Hussein, et al., 2021), the study described PU foam as an insulator giving a high thermal mass with the maximum thermal timing. His study had concluded to similar insulator behavior and similar energy saving percentages for the different orientations. Hence, results had explained the southern façade apart. The study validates the efficiency of using PU foam as an external insulating layer achieving the minimum levels of energy demand in different climates in Palestine. Additionally, PU-foam was also proven to be the least insulating material causing condensation accumulation within external walls, which minimizes the possibilities of mold growth.

5.4 Recommendations

The simulations performed had concluded to multiple recommendations summarizing the evaluation of the base case model for the external walls of a stone cladded buildings with backfill concrete and stone cladded - hollow concrete blocks walls. Recommendations were given for depending on the most effective simulation results for each orientation. Selected solutions. These recommendations could be summarized as the following:

For Stone cladded concrete walls:

- The study recommends the installation of 4 cm PU foam for stone cladded concrete walls oriented towards north for maximum energy saving exceeding 40%.
- Southern orientated walls insulated using PU foam have also performed best in saving heating energy by nearly 40%in winter. At the same time, it required reasonable amount of needed cooling energy when natural ventilation is available in summer.
- PU foam was significantly recommended for eastern oriented external walls, due to their high solar gains. A reduction of heating loads in winter exceeding 34% and of cooling loads by 27.5% when applying natural ventilation.
- The study recommends PU foam for west oriented walls for both building patterns while natural ventilation in summer is applicable to avoid overheating. PU foam reduced heating loads by 36%.
- Recommendations extend to include an outer installation of the foam layer allowing an additional energy saving by an average of 4% for all orientations for the heating

loads and cooling loads, this could be implemented in cases of newly constructed buildings while previous recommendations are more applicable for existing buildings.

For stone cladded- hollow block walls:

- For the proposed building practice, walls consisting of double layers of hollow concrete block and cladded with stone are recommended to be insulated using rockwool rolls when oriented toward North, whereas rockwool had a percentage of energy saving exceeding 55% with maintaining other comfort measure.

- The study recommends using PU foam for south oriented external walls, as it reduced the heating load with a percentage more than 38%. It also requires a slightly larger amount of cooling load in summer compared to the base case model.

- East oriented stone- hollow concrete block walls had achieved the best balance of lowering heating loads in winter without highly increasing the cooling loads in summer. The study recommends installing PU foam for eastern facades when natural ventilation could be taken into consideration. This has lowered the cooling loads by 18.6%.

- However, for eastern orientations when no natural ventilation effect is applicable the results recommend applying no insulation when natural ventilation in summer cannot be considered, since applying the proposed building pattern with no additional insulator offers heating and cooling loads saving by 15% and 7% respectively.

- Trials have proven the efficiency of PU foam in reducing heating loads for west oriented external walls for both construction patterns with a percentage of 36%. It, however, caused an increase in cooling loads while no natural ventilation applied.

- Outer application of PU foam for hollow block walls had proven better results giving the best thermal performance for all orientations with the lowest U-Value which considers it the most efficient intervention among all and therefore, their most recommended.

Previously analyzed simulation trials proved that insulation application highly assists the reduction of heating loads, it on the other hand may cause an increase in cooling loads due to heat retain in summer. This confirms the significance of natural ventilation effect in apartment buildings as a main passive thermal design tool in Hebron city climatic profile. Therefore, additional summer simulations were performed allowing an assessment of the effect of natural ventilation in lowering indoor operative temperatures and cooling loads.

It was also found that for common construction measures including the infiltration rate and WWR in mid-floors apartments, construction method using hollow concrete walls generally perform as better external wall composition providing better insulation rates and a thermally more efficient construction pattern solving the phenomena of condensation.

Results confirmed that relating the economic evaluation of the external walls to energy consumption is very important. Comparative analysis of factors including temperatures, humidity, energy saving, condensation evaluation, and payback period need to be integrally analyzed to achieve the best selection of each façade insulator separately. This could lead to different insulation practices for different external walls in the same apartment, which could save additional initial costs.

The research had proven its significance in providing helpful guidelines for architects through the proper design of external walls and the right selection of insulating material depending on the designed or executed apartment’s orientation. Results were intended to serve designing new buildings external walls or retrofitting external walls in existing buildings to help achieving thermally responsible building envelopes. The study also achieved the intended reduction of excessive heat and extreme cold indoor environment in contribution to the energy action plan for residential buildings, adopted by the municipality of Hebron since 2016.

Finally, the performed simulation and analysis are expected to be used as guidelines for designers, consumers, and local Municipality to achieve more responsible and occupants considering apartment buildings. Results could be explained in a manual to contribute to assist the design of external walls, such manuals could be generalized by local municipalities or related associations.

5.5 Future work

This thesis performs as an extended analysis for external walls enhancement interventions depending on the common building practice in Hebron. This study could be extended in future work to include a detailed analysis of other building envelope's components including internal partition, slabs, windows, and others. This study was intended to be specialized in external walls as a part of the building envelope. However, results are recommended to be extended in future works as integrated research for this study. Results of the study could be generalized to other types of housing units through the analysis of these units in future research. Advanced building interventions could be tested including active design solutions' evaluation in terms of efficiency, cost, and condensation analysis. Moreover, the study could be extended by evaluating the thermal bridging and thermal breakers solutions. Future works are recommended to evaluate the life cycle analysis (LCA) for thermal insulators to detect the expected time frame for each insulator performing as maximum efficiency.

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APPENDICES

APPENDIX A

Questionnaire:

The evaluation of thermal comfort in residential apartments in Hebron city

جامعة بوليتكنك فلسطين
كلية البحث العلمي الدراسات العليا
ماجستير التصميم المستدام في العمارة

2019/2020

بسم الله الرحمن الرحيم

الموضوع: استبانة لتقييم الراحة الحرارية في المباني السكنية

تعتبر الراحة الحرارية في المباني السكنية من أهم عوامل راحة السكان ورضاهم، كما وتساهم في تقليل كميات الطاقة المستهلكة للتدفئة والتكييف. و يهدف هذا الاستبيان الى جمع معلومات حول مدى تحقيق الراحة الحرارية داخل الشقق والعمارات السكنية في مدينة الخليل والتعرف على أهم آثارها على قاطني هذه الشقق، جميع المعلومات في هذا الاستبيان يتم جمعها لأسباب بحثية صرفة ولن يتم استخدامها إلا لأغراض هذا البحث.

نشكر تعاونكم من خلال وضع اشارة X داخل الدائرة الخاصة بالاجابة المناسبة:

أولا: الخصائص الديموغرافية (اسئلة هذا القسم تخص الفرد الذي يقوم بتعبئة الاستبيان)

الجنس	○ ذكر	○ أنثى	
الفئة العمرية	○ 40-18	○ 60- 40	○ 60- فأكثر
عدد أفراد الأسرة	○ 3-1	○ 6-3	○ 6 فأكثر

ثانياً: معلومات عن المسكن

نوع السكن	○ ملك	○ إيجار		
ارتفاع المبنى السكني (عدد الطوابق)	○ 5-3	○ 6	○ 7 فأكثر	
عدد الشقق السكنية في الطابق	○ شقة واحدة	○ شقتان	○ ثلاثة شقق	○ أربع شقق
كثافة المباني في المنطقة المحيطة	○ قليلة	○ متوسطة	○ مكتظة	
موقع الشقة بالنسبة للمبنى (ترتيب الطوابق)	○ أرضية	○ وسطية	○ علوية (طابق أخير)	
موقع الشقة السكنية (بالمرجعية لإتجاه الشمال)	○ شمالي	○ شرقي	○ شمالي شرقي	○ شمالي غربي
	○ جنوبي	○ غربي	○ جنوبي شرقي	○ جنوبي غربي
مساحة الشقة السكنية (متر مربع)	○ أقل من 90 م^2	○ 120-90 م^2	○ 150-120م^2	○ 150 فأكثر
عدد الفراغات في الشقة	○ 4 أو أقل	○ 5 فراغات	○ 6 فراغات	○ 7 فأكثر

ثالثاَ: الراحة الحرارية (درجات الحرارة والتهوية) في الشقة السكنية

نشكر تعاونكم من خلال وضع اشارة X داخل الدائرة الخاصة بالاجابة المناسبة:

1. تقييمك لدرجة الحرارة في فراغات المنزل شتاءً	دافئة جداً ○	دافئة ○	مريحة ○	باردة ○	باردة جداً ○
2. تقييمك لدرجة الحرارة في فراغات المنزل صيفاً	حارة جداً ○	حارة ○	مريحة ○	باردة ○	باردة جداً ○
3. تحتوي الجدران الخارجية على العوازل	لا تحتوي ○	عازل حرارة ○			
4. نوع العازل الحراري المستخدم إن وجد (يمكن اختيار أكثر من نوع للعزل)	لا يوجد ○	طوب مفرغ ○	الواح الكلكل ○	عازل رغوي- Foam ○	
5. تقييمك لمستوى الراحة الحرارية داخل المنزل	معدومة ○	قليلة ○	متوسطة ○	جيدة ○	ممتازة ○
6. الحاجة الى التدفئة شتاءً	لا تحتاج ○	قليلة ○	متوسطة ○	كبيرة ○	كبيرة جداً ○
7. الحاجة الى التبريد صيفاً	لا تحتاج ○	قليلة ○	متوسطة ○	كبيرة ○	كبيرة جداً ○
8. وسيلة التكييف المستخدمة في الصيف	النوافذ ○	المراوح ○	المكيفات ○	جميعها ○	غير ذلك ○
9. وسيلة التدفئة المستخدمة في الشتاء	الكهرباء ○	الغاز ○	الحطب ○	جميعها ○	غير ذلك ○
10. الفتحات الخارجية في جدران الشقة	صغيرة جداً ○	صغيرة ○	متوسطة ○	كبيرة ○	كبيرة جداً ○
11. نوع الزجاج المستخدم في منزلك	طبقة واحدة ○	مزدوج ○	ثلاثي الطبقات ○		
12. تقييمك لمستوى التهوية الطبيعية في فراغات الشقة	معدومة ○	قليلة ○	متوسطة ○	جيدة ○	ممتازة ○
13. لو اتحيت لك فرصة تطبيق عوامل العزل لتحقيق راحتك، هل ستقوم بتطبيقها؟	لا ○		ربما ○	نعم ○	بكل تأكيد ○

اذا كانت إجابتك عن السؤال السابق بـ(لا)، لماذا؟

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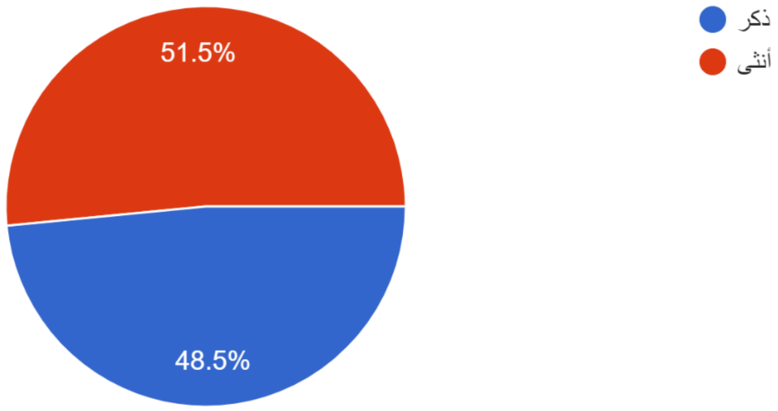
APPENDIX B

Questionnaire results analysis:

The illustrated graphs and figures show the results and responses of occupants regarding their satisfaction with their dwellings in terms of thermal comfort and their physical and thermal properties.

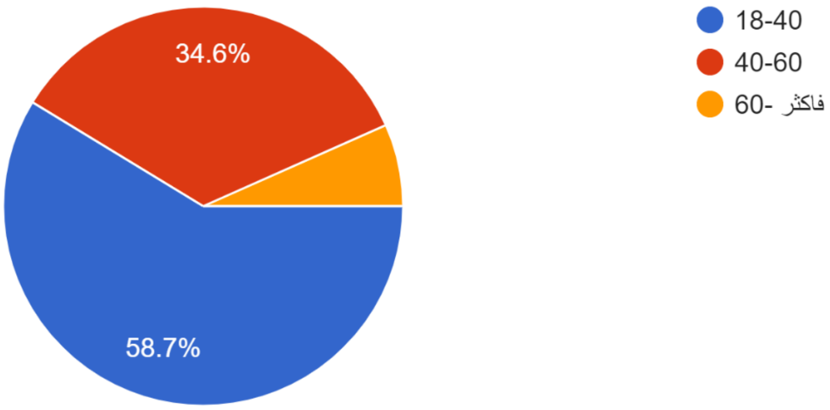
الجنس

390 responses



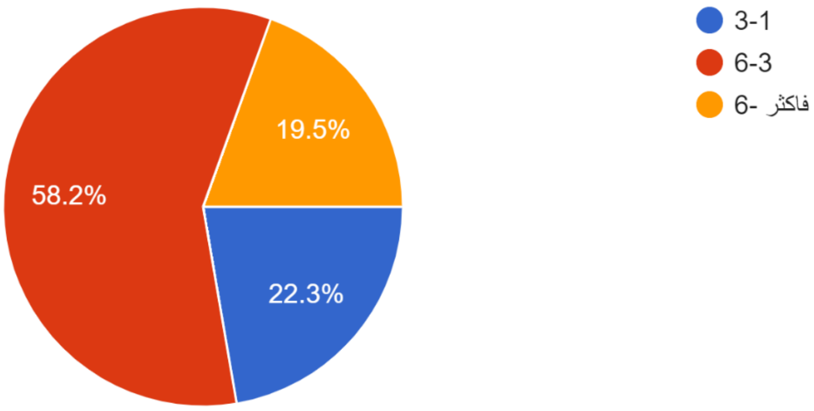
الفئة العمرية

390 responses



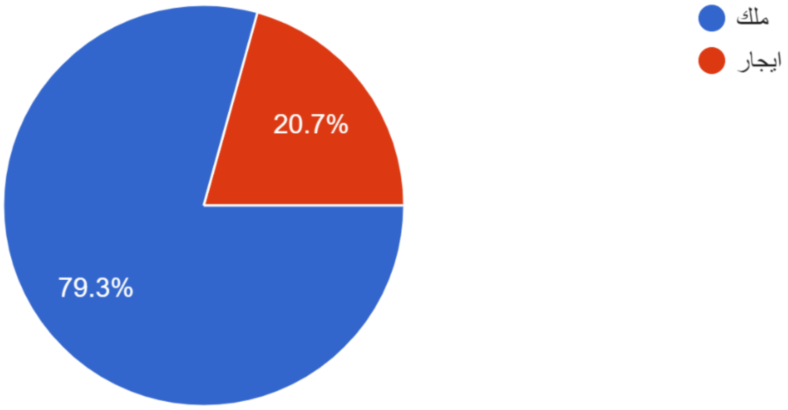
عدد افراد الاسرة

390 responses



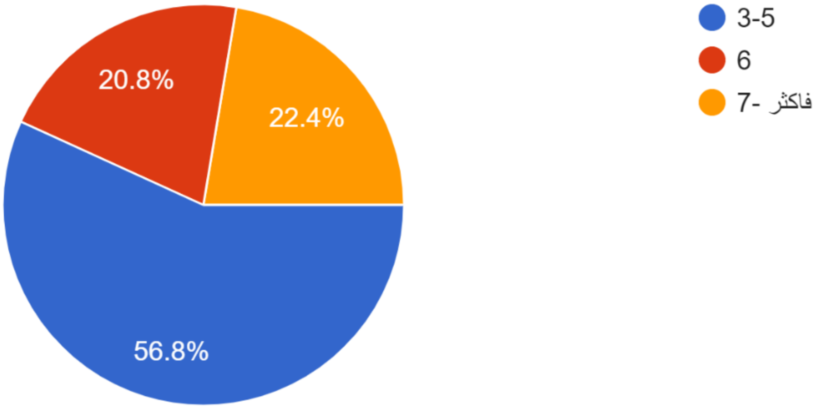
نوع السكن

387 responses



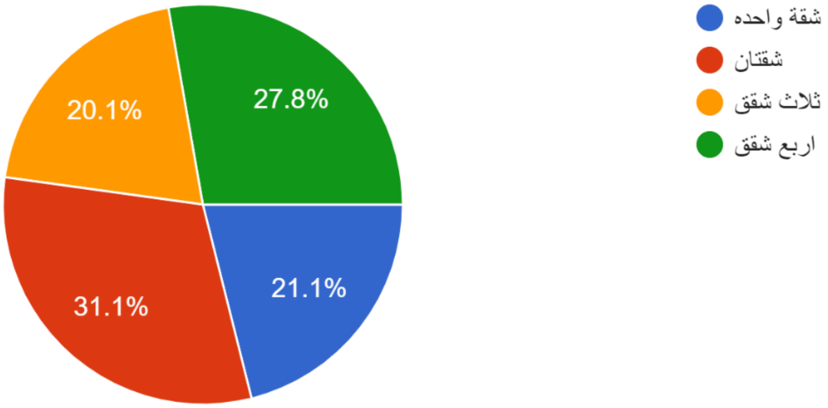
ارتفاع المبنى (عدد الطوابق)

389 responses



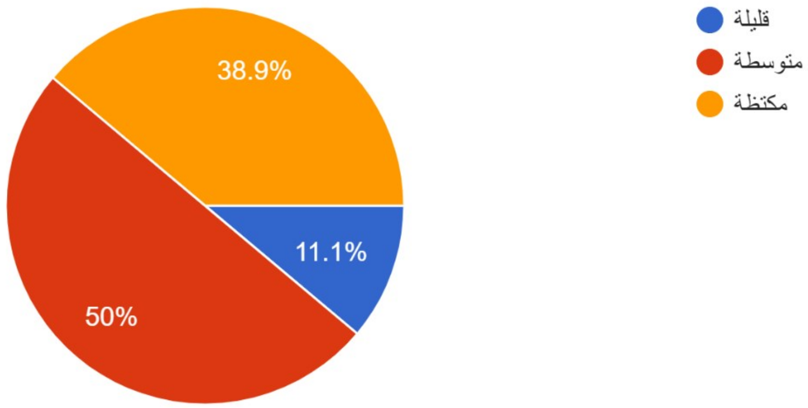
عدد الشقق السكنية في الطابق

389 responses



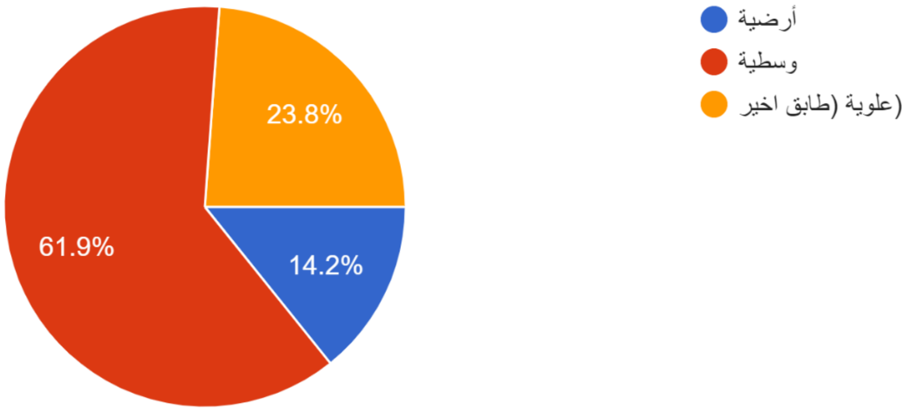
كثاقه المباني في المنطقة

386 responses



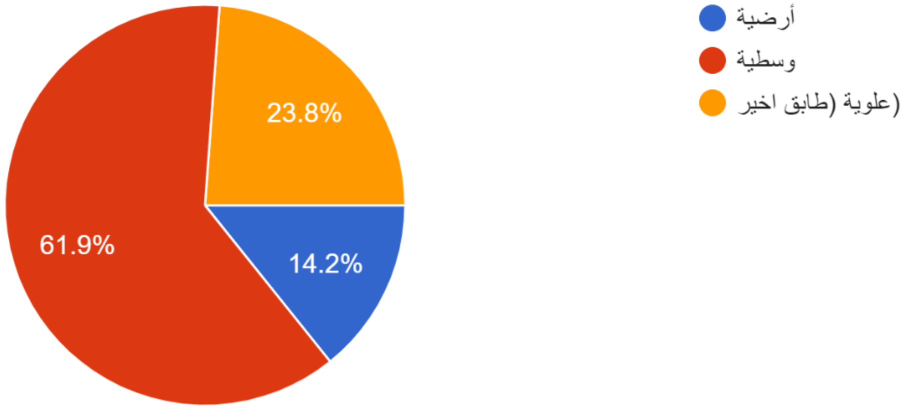
موقع الشقة بالنسبة للمبنى (ترتيب الطوابق)

386 responses



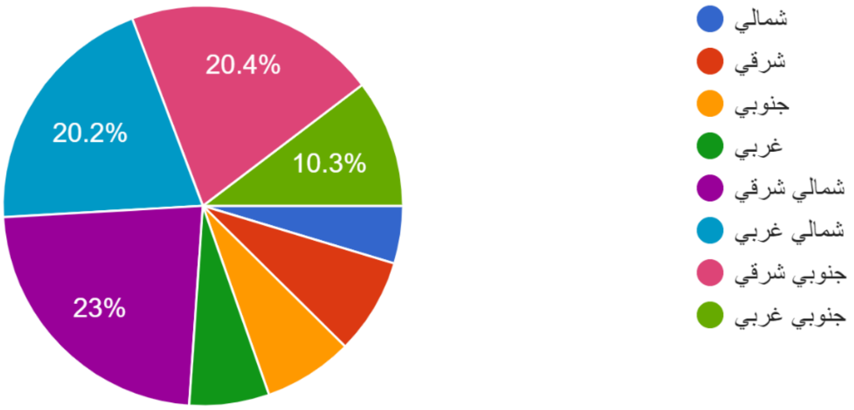
موقع الشقة بالنسبة للمبنى (ترتيب الطوابق)

386 responses



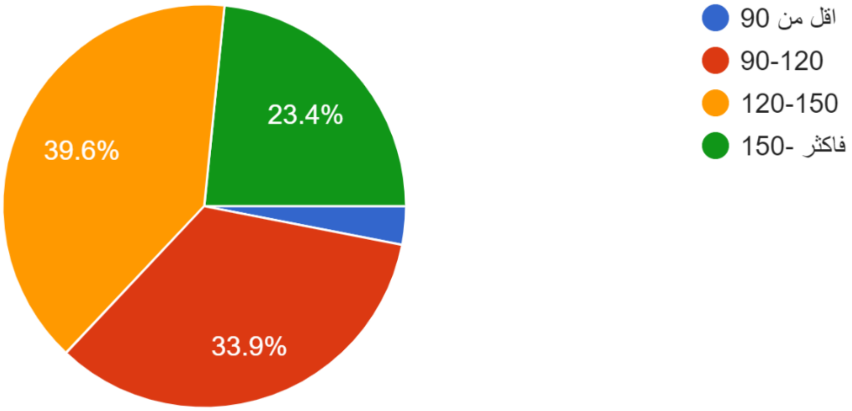
موقع الشقة السكنية (بالمرجعية لاتجاه الشمال)

387 responses



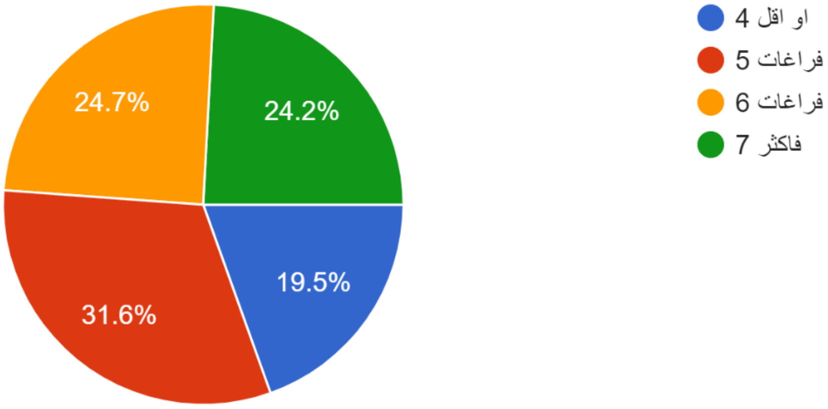
مساحة الشقة السكنية (متر مربع)

389 responses



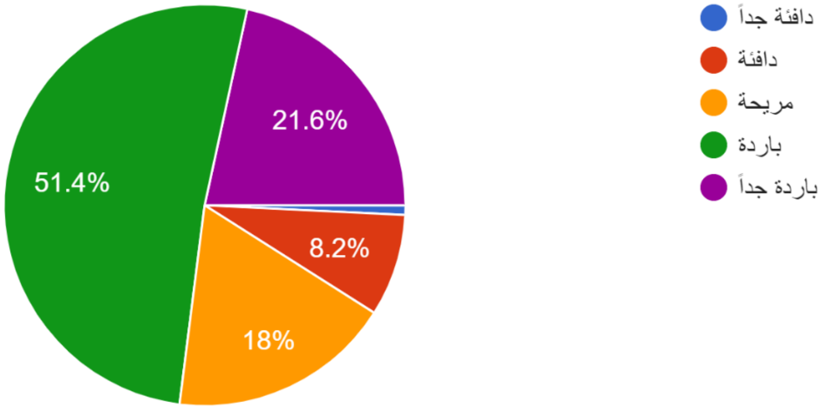
عدد الفراغات في الشقة

389 responses



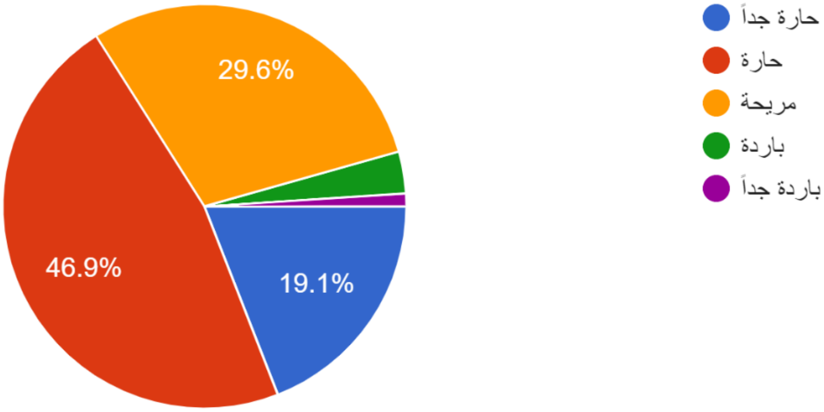
تقييمك لدرجة الحرارة في فرغات المنزل شتاءً

389 responses



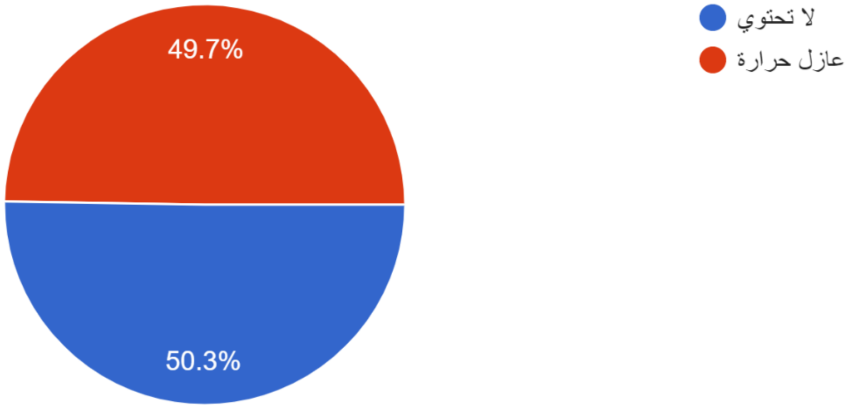
تقييمك لدرجة الحرارة في فراغات المنزل صيفاً

388 responses



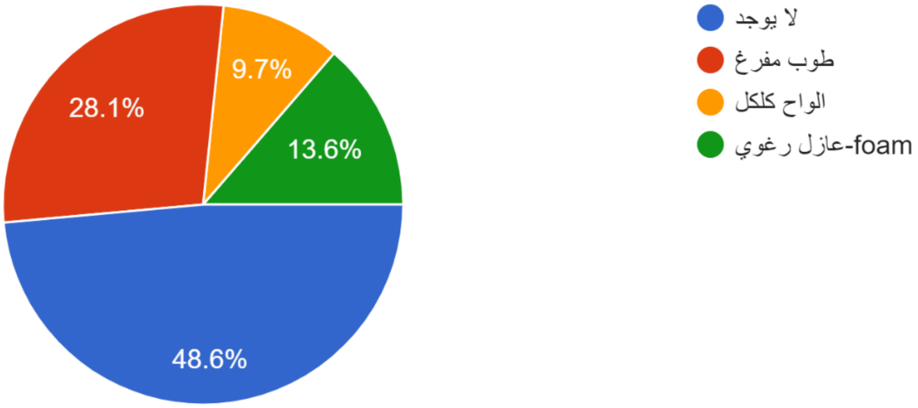
تحتوي الجدران الخارجية على العوازل

388 responses



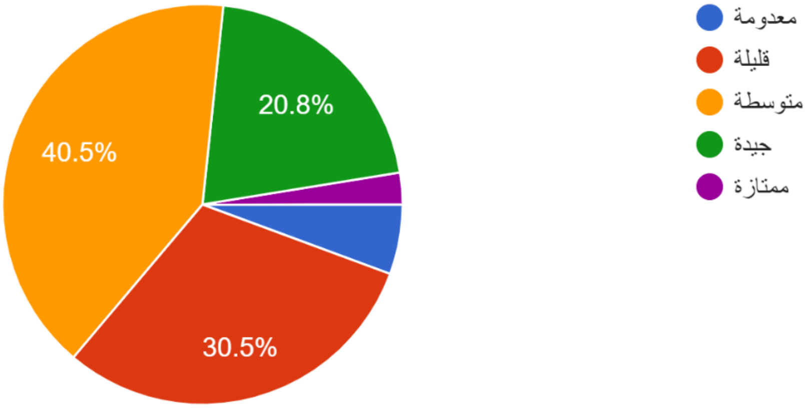
نوع العازل الحراري ان وجد

381 responses



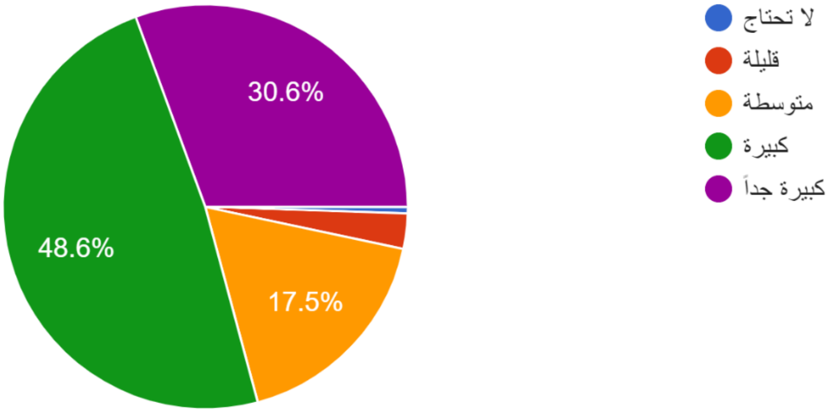
تقييمك لمستوى الراحة الحرارية داخل المنزل

390 responses



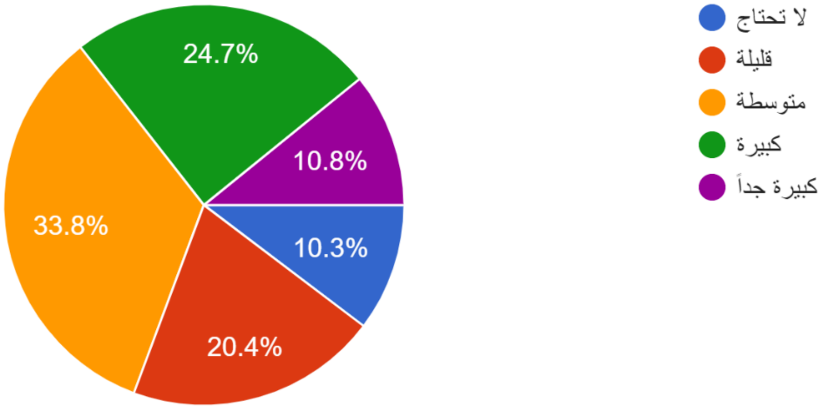
الحاجة الى التدفئة شتاءً

389 responses



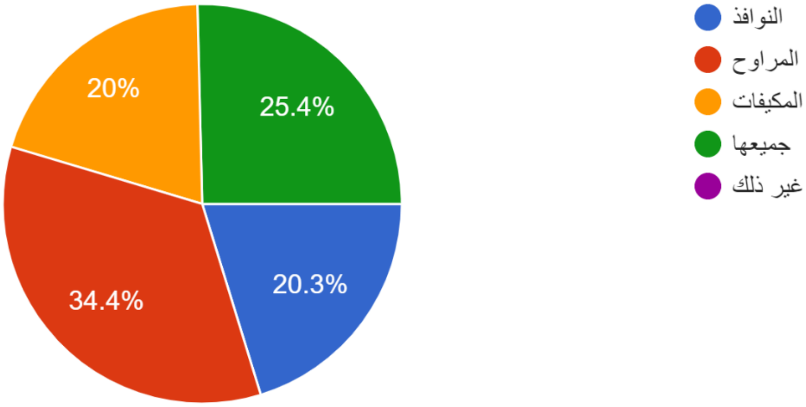
الحاجة الى التبريد صيفاً

388 responses



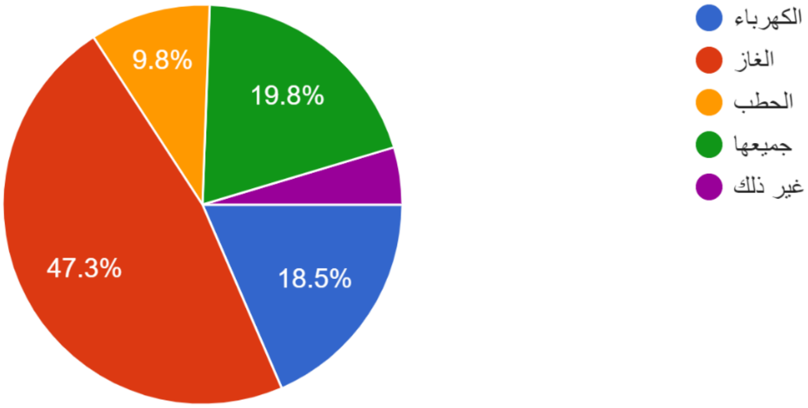
وسيلة التكييف المستخدمة في الصيف

390 responses



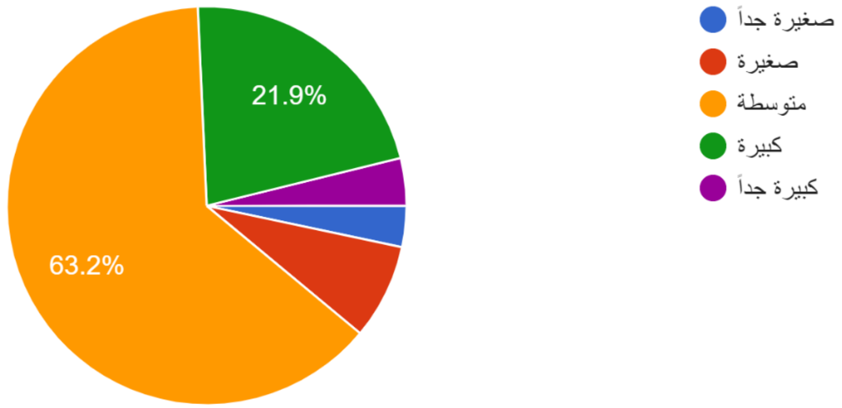
وسيلة التدفئة المستخدمة في الشتاء

389 responses



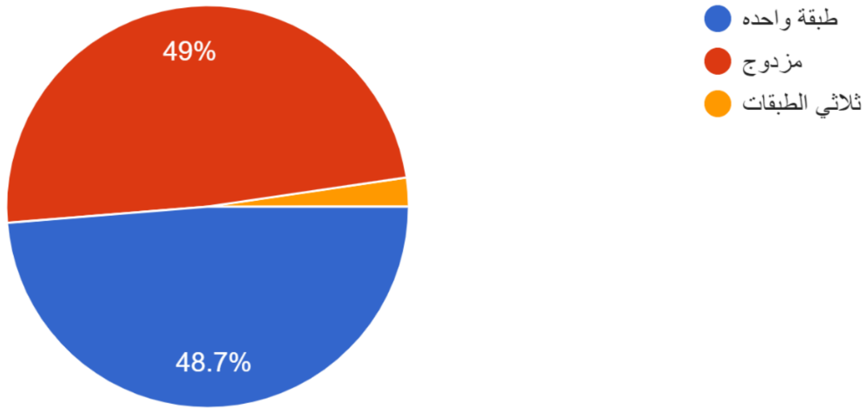
الفتحات الخارجية في جدران الشقة

389 responses



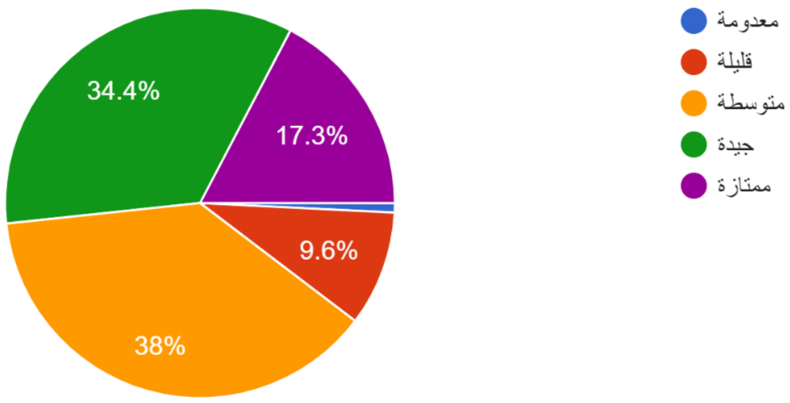
نوع الزجاج المستخدم في منزلك

388 responses



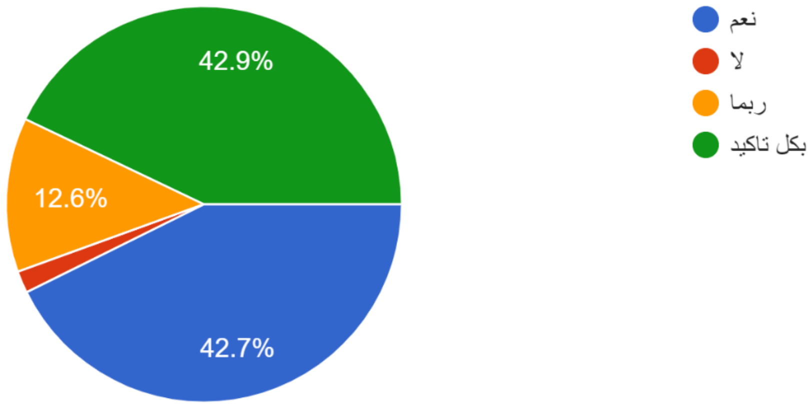
تقييمك لمستوى التهوية الطبيعية في فراغات الشقة

387 responses



لو اتيحت لك فرصة تطبيق عوامل العزل لتحقيق راحتك, هل ستقوم بتطبيقها؟

389 responses



APPENDIX C

Table:

Selected samples analysis:

An analytical description for the selected samples of residential buildings in Hebron considering the number of apartments on each floor, the components of the slabs, external cladding, internal partitions, and the year of construction.

Appendix C: Selected samples analysis:

Sample No.	No. of Apartments	WWR%	Slabs	Internal Partition	Exterior Cladding	Year
1	2	20	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
2	1	18	25cm RC, 7cm mortar, 0.6-0.8mm tiles	13cm Plastered concrete hollow block	stone	2019
3	4	33	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
4	2	30	25cm RC, 7cm mortar, 0.6-0.8mm tiles	13cm Plastered concrete hollow block	stone	2019
5	1	17.6	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2020
6	1	35	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
7	4	33	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
8	2	13	25cm RC, 7cm mortar, 0.6-0.8mm tiles	13cm Plastered concrete hollow block	stone	2018
9	2	14	25cm RC, 7cm mortar, 0.6-0.8mm tiles	13cm Plastered concrete hollow block	stone	2019
10	2	14.5	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
11	1	19.5	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2020
12	2	17.5	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2010
13	3	20.8	25cm RC, 7cm mortar, 0.6-0.8mm tiles	14cm Plastered concrete hollow block	stone	2014
14	2	19.2	25cm RC, 7cm mortar, 0.6-0.8mm tiles	14cm Plastered concrete hollow block	stone	2016
15	4	14	25cm RC, 7cm mortar, 0.6-0.8mm tiles	13cm Plastered concrete hollow block	stone	2019
16	2	16	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019

17	4	17	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
18	2	20	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
19	2	18	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12.8cm Plastered concrete hollow block	stone	2019
20	2	18	25cm RC, 7cm mortar, 0.6-0.8mm tiles	14cm Plastered concrete hollow block	stone	2020
21	2	16	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
22	4	17.3	25cm RC, 7cm mortar, 0.6-0.8mm tiles	13cm Plastered concrete hollow block	stone	2019
23	4	18	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
24	4	18	25cm RC, 7cm mortar, 0.6-0.8mm tiles	13cm Plastered concrete hollow block	stone	2019
25	2	20.2	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
26	4	14	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2020
27	2	17.8	25cm RC, 7cm mortar, 0.6-0.8mm tiles	13cm Plastered concrete hollow block	stone	2019
28	2	17.8	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
29	2	19	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
30	4	18	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019
31	4	14	25cm RC, 7cm mortar, 0.6-0.8mm tiles	13cm Plastered concrete hollow block	stone	2019
32	2	17	25cm RC, 7cm mortar, 0.6-0.8mm tiles	12cm Plastered concrete hollow block	stone	2019

APPENDIX D
Table:

Simulation results extended analysis:

Results for the simulations for external wall interventions of the 14 cases analyzed. Each case simulation was performed for the four orientations. Results include indices in summer and winter for the indoor operative temperatures, the outdoor temperature, relative humidity, levels of cooling and heating, and the hours of discomfort with all-clothing factors. The simulations were performed in the hottest months in summer and the coldest ones in winter.

Appendix D: Simulation trials results' analysis toward different orientations

Case number	Case description and construction detail		U-value (W/m^2. k)	Orientation	Summer					Winter				
					Average operative indoor air temperature in Summer (°C)	Average outdoor air temperature in Summer (°C)	Relative Humidity in Summer (%)	Maximum sensible cooling loads in summer (KW/H)	Discomfort hours (all clothing) in Summer (hrs.)	Average operative indoor air temperature in Winter (°C)	Average outdoor air temperature in winter (°C)	Relative Humidity in Winter (%)	Total zone heating load in winter (KW/H)	Discomfort hours (all clothing) in Winter (hrs.)
1	Interventions to a stone-concrete wall	Stone cladding, concrete, no insulators	3.15	N	25.40	22.12	50.48	49.05	472.50	13.33	7.91	55.53	104.36	780.50
				E	26.90	22.12	44.53	218.89	819.00	14.04	7.91	53.57	91.98	698.50
				S	25.54	22.12	49.28	84.40	468.00	16.79	7.91	46.41	61.09	710.50
				W	26.99	22.12	43.57	313.95	860.00	15.03	7.91	50.75	81.47	780.00
2		Installation of a 7 cm concrete hollow block	2.54	N	25.63	22.12	49.59	56.78	464.00	13.60	7.91	54.79	91.38	784.50
				E	27.03	22.12	44.04	224.7	832.50	14.27	7.91	52.97	82.43	695.50
				S	25.66	22.12	49.07	61.51	444.00	17.51	7.91	44.50	47.50	714.50
				W	27.15	22.12	43.15	333.20	927.00	15.32	7.91	49.94	72.84	777.50
3		Installation of a 10 cm concrete hollow block	2.34	N	25.71	22.12	49.29	59.74	458.50	13.70	7.91	54.49	87.13	772.00
				E	27.06	22.12	43.88	228.06	841.00	14.36	7.91	52.69	79.43	695.00
				S	25.81	22.12	48.38	93.26	468.00	17.17	7.91	45.44	52.42	702.00
				W	27.19	22.12	43.04	339.95	947.00	15.43	7.91	49.67	70.01	777.00
4		installation of a 10 cm concrete hollow block and 3 cm cavity	1.64	N	25.71	22.12	49.29	59.74	458.50	13.70	7.91	54.49	87.13	772.50
				E	27.07	22.12	43.88	228.07	841.00	14.36	7.91	52.69	79.43	695.00
				S	25.81	22.12	48.38	93.26	468.00	17.18	7.91	45.44	52.43	702.00
				W	27.19	22.12	43.04	339.96	947.00	15.43	7.91	49.67	70.01	777.00
5		installation of a 10 cm concrete hollow block and 5 cm cavity	1.35	N	25.90	22.12	48.48	68.90	439.50	14.22	7.91	53.06	71.52	760.00
				E	27.15	22.12	43.57	237.15	859.50	14.82	7.91	51.47	68.70	687.00
				S	26.05	22.12	47.41	107.08	476.00	17.18	7.91	45.44	52.43	702.00
				W	27.24	22.12	42.84	353.17	974.50	15.94	7.91	48.38	59.58	770.00
6		Void air cavity replacement of compressed polystyrene boards	1.145	N	26.02	22.12	47.84	81.67	422.50	14.02	7.91	53.61	76.35	771.50
				E	27.17	22.12	43.41	250.14	887.50	14.57	7.91	52.12	71.93	687.00
				S	26.10	22.12	47.17	115.63	470.00	17.32	7.91	45.12	46.35	691.50
				W	27.24	22.12	42.85	362.23	963.00	15.67	7.91	49.05	62.31	770.00
7		Void air cavity replacement of rock wool rolls	0.849	N	26.09	22.12	47.47	87.26	407.50	14.37	7.91	52.62	68.21	734.00
				E	27.22	22.12	43.25	245.74	903.00	14.88	7.91	51.28	66.12	686.50
				S	26.17	22.12	46.89	120.76	461.00	17.63	7.91	44.39	41.50	676.50
				W	27.26	22.12	42.78	367.35	985.00	16.00	7.91	48.25	56.54	769.50
8		Void air cavity replacement of 4 cm polyurethane foam	0.493	N	25.39	22.12	50.59	46.19	445.50	14.78	7.91	51.51	61.04	710.50
				E	26.57	22.12	47.02	155.05	827.00	15.26	7.91	50.22	60.62	685.00
				S	25.44	22.12	50.25	71.86	491.50	17.93	7.91	43.66	36.88	649.50
				W	27.00	22.12	43.48	372.47	896.00	16.39	7.91	47.24	51.30	768.00

9	**Interventions to a stone-concrete hollow block wall**	double hollow concrete block layers with no installed insulators	1.41	N	25.38	22.12	50.18	55.18	456.50	13.67	7.91	45.57	85.70	779.00
				E	26.73	22.12	45.07	203.94	795.00	14.29	7.91	52.89	78.24	696.00
				S	25.47	22.12	49.31	87.00	464.50	16.92	7.91	46.06	51.41	709.50
				W	26.85	22.12	43.92	305.42	836.00	15.30	7.91	50.03	68.87	778.00
10		Void air cavity replacement of compressed polystyrene boards	1.03	N	25.29	22.12	49.83	58.65	453.50	13.94	7.91	53.81	76.78	720.50
				E	26.77	22.12	44.90	206.24	793.50	14.53	7.91	52.20	72.06	704.50
				S	25.54	22.12	49.06	89.50	434.50	17.17	7.91	45.47	46.65	689.50
				W	26.90	22.12	43.78	311.63	855.00	15.58	7.91	49.30	63.08	773.00
11		Void air cavity replacement of rock wool rolls	0.735	N	25.65	22.12	49.67	51.99	452.50	14.72	7.91	51.57	46.04	764.50
				E	26.81	22.12	44.72	208.72	797.50	14.82	7.91	51.43	66.53	684.50
				S	26.61	22.12	48.84	91.91	462.00	17.46	7.91	44.76	42.06	684.00
				W	26.93	22.12	53.67	316.84	870.00	15.89	7.91	48.51	57.84	771.00
12		Void air cavity replacement of 4 cm polyurethane foam	0.470	N	25.62	22.12	49.21	64.90	442.50	14.72	7.91	51.66	61.72	732.00
				E	26.85	22.12	44.59	211.37	800.00	15.21	7.91	50.35	61.15	684.50
				S	25.67	22.12	48.63	94.39	464.50	17.84	7.91	43.85	37.36	655.50
				W	26.97	22.12	43.57	321.87	880.50	16.30	7.91	47.47	51.97	786.50
13	**Stone-concrete wall**	Stone cladding, with outer 3 cm polyurethane foam concrete wall with 10 cm hollow block	0.50	N	25.35	22.12	50.75	44.51	440.00	14.82	7.91	51.39	59.96	760.50
				E	26.55	22.12	47.11	154.87	824.00	15.28	7.91	50.21	59.75	682.00
				S	25.41	22.12	50.39	70.74	486.50	17.95	7.91	43.53	36.90	625.50
				W	26.80	22.12	45.80	232.75	805.00	16.41	7.91	47.20	50.81	766.50
14	**Stone-block wall**	double hollow concrete block layers with outer 4 cm polyurethane foam	0.470	N	25.30	22.12	44.73	58.40	444.00	14.73	7.91	51.60	62.56	780.00
				E	26.50	22.12	47.29	156.04	829.50	15.21	7.91	50.35	61.43	687.00
				S	25.41	22.12	50.28	69.84	486.50	17.82	7.91	43.85	36.95	643.50
				W	26.84	22.12	45.64	234.15	814.50	16.30	7.91	47.44	51.69	766.50

APPENDIX E
Table:

Simulation results the evaluation of potential condensation cumulation in the investigated external wall interventions

Evaluation for the condensation that may occur between the layers of the external walls' interventions were evaluated to ensure the efficiency of the selected solutions as shown in Appendix E as follows. The determination of the distance, layer, and the amount of accumulative water vapor was found as explained.

Appendix E: Simulation results the evaluation of potential condensation cumulation in the investigated external wall interventions

Case number	Case description	Thermal quality	Mold growth probability	Interstitial condensation	Condensation interfaces	Distance of condensation interface from the external surface and layer within (m)		Cumulative condensation for condensation surface (g/m^2)
						Distance	Layer within	
1	Stone cladding, concrete, no insulators	Poor	Probable	Free of condensation	0	0.00	none	0.00
2	Installation of a 7 cm concrete hollow block	Good	Unlikely	Free of condensation	0	0.00	none	0.00
3	Installation of a 10 cm concrete hollow block	Good	Unlikely	Free of condensation	0	0.00	none	0.00
4	installation of a 10 cm concrete hollow block and 3 cm cavity	Good	Unlikely	Evaporates during summer	1	0.18	concrete	17.10
5	installation of a 10 cm concrete hollow block and 5 cm cavity	Good	Unlikely	Evaporates during summer	1	0.18	concrete	14.90
6	Void air cavity replacement of compressed polystyrene boards	Good	Unlikely	Evaporates during summer	1	0.18	concrete	41.02
7	Void air cavity replacement of rock wool rolls	Good	Unlikely	Evaporates during summer	1	0.18	concrete	50.11
8	Void air cavity replacement of 4 cm polyurethane foam	Good	Unlikely	Evaporates during summer	1	0.18	concrete	8.11
9	double hollow concrete block layers with no insulators	Good	Unlikely	Evaporates during summer	1	0.06	concrete outer-face	4.35
10	Void air cavity replacement of compressed polystyrene boards	Good	Unlikely	Evaporates during summer	1	0.06	concrete outer-face	23.24
11	Void air cavity replacement of rock wool rolls	Good	Unlikely	Evaporates during summer	1	0.06	concrete outer-face	5.90
12	Void air cavity replacement of 4 cm polyurethane foam	Good	Unlikely	Evaporates during summer	1	0.06	concrete outer-face	4.29
13	Stone cladding, with outer 3cm polyurethane foam concrete wall with 10 cm hollow block	Good	Unlikely	Evaporates during summer	1	0.06	Insulator PU-foam	7.25
14	double hollow concrete block layers with outer 4 cm polyurethane foam	Good	Unlikely	Free of condensation	0	0.00	none	0.00