

**OPTIMIZING THERMAL PERFORMANCE OF WINDOW
FRAMES FOR ENERGY EFFICIENCY IN HOT CLIMATES**

BY

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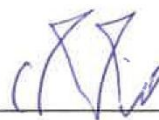
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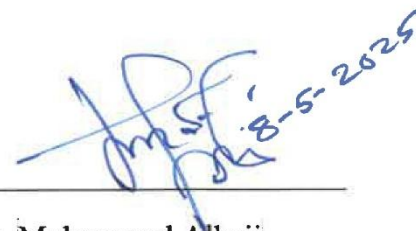
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Dedication

“And He found you lost and guided [you].”

— Qur’an, Surah Ad-Duhaa (93:7)

I dedicate this to Allah (SWT), the One who never left me, even when I struggled to find my way— seeking His acceptance and guidance in all that I do.

To my dearest family—your faith in me lit the path when my own steps faltered. Mom and Dad, your silent prayers and constant sacrifices are written between every line of this thesis.

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LIST OF ABBREVIATIONS

Abbreviation	Full Term
ANN	Artificial Neural Network
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEM	Building Energy Modelling
BIM	Building Information Modelling
CAD	Computer-Aided Design
CEN	European Committee for Standardization
CFD	Computational Fluid Dynamics
DGU	Double Glazing Unit
EPS	Expanded Polystyrene
FEA	Finite Element Analysis
FEM	Finite Element Method
FGR	Frame-to-Glass Ratio
GA	Genetic Algorithm
GFRP	Glass Fiber Reinforced Polymer
GWP	Global Warming Potential
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LBNL	Lawrence Berkeley National Laboratory
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
NFRC	National Fenestration Rating Council
NMBE	Normalized Mean Bias Error
PCM	Phase Change Material

PS-TIM	Pressure-Sensitive Transparent Insulation Material
PUR	Polyurethane Foam
R-Value	Thermal Resistance Value
RMSE	Root Mean Square Error
RS	air film resistances
SEEC	Saudi Energy Efficiency Centre
SBC	Saudi Building Code
SHGC	Solar Heat Gain Coefficient
SRBEC	Saudi Residential Building Energy Code
U-Value	Thermal Transmittance Coefficient
UF	Frame Thermal Transmittance (U-factor of Frame)
UG	Glazing Thermal Transmittance (U-factor of Glazing)
UPVC	Unplasticized Polyvinyl Chloride
UT	U-value of Total Assembly
UW	Window Thermal Transmittance (Overall U-value)
VIPs	Vacuum Insulation Panels
WFR	Window-to-Floor Ratio
WWR	Window-to-Wall Ratio
XPS	Extruded Polystyrene

ABSTRACT

Full Name : [Sara Ahmad Daás]

Thesis Title : Optimizing thermal performance of window frames for energy efficiency in hot climates

Major Field : [Architectural Engineering]

Date of Degree : [May, 2025]

In regions with extreme climatic conditions, such as Saudi Arabia, the thermal performance of building envelopes plays a critical role in energy efficiency, particularly for cooling-dominated residential structures. This study investigates the optimization of window frame designs to reduce energy consumption by addressing the high thermal transmittance (U-value) of conventional aluminum frames, which contribute significantly to cooling loads. Through a combination of computational modeling and energy simulations, the research evaluates the efficacy of alternative materials (U-PVC, fiberglass), thermal breaks, and frame-to-glass ratios across Saudi Arabia's climatic zones, including the hot-humid environment of Dhahran and the moderate climate of Abha.

Using Therm and Window software, U-values were calculated for diverse configurations, revealing that while increasing gauge thickness or adding cavity insulation had minimal impact, non-metallic materials such as U-PVC and Fiberglass reduced frame U-values by 79–85% compared to aluminum. Thermal breaks, particularly aerogel-integrated designs, further enhanced performance, lowering aluminum frame U-values by 56–67%. Energy simulations in EnergyPlus demonstrated that these optimizations reduced annual cooling consumption by 9.5% in Dhahran and 7.5% in Abha. Larger window sizes ($\geq 1.7 \times 1.7$ m) in hot climates amplified savings by leveraging glass's lower U-value, while material

substitutions proved more impactful in milder climates. Economic analysis confirmed short payback periods (as low as 2–3 months for U-PVC frames) and meaningful CO₂ emission reductions (up to 3,700 kg/year).

The findings underscore the importance of climate-specific design strategies: prioritizing U-PVC and thermally broken frames in hot regions and single breaks in aluminum in moderate zones. Policy recommendations include revising the Saudi Building Code to mandate thermal breaks and incentivizing non-metallic materials. This study contributes to both theoretical understanding and practical application by addressing the overlooked thermal impact of window frames. It advocates for policy updates in the Saudi Building Code, provides designers with data-driven guidelines, and proposes educational inclusion of frame performance analysis. Ultimately, the findings offer a pathway for more sustainable and energy-efficient residential architecture in hot climate regions.

ملخص الرسالة

الاسم الكامل: سارة احمد دعاس

عنوان الرسالة: تحسين الأداء الحراري لإطارات النوافذ لتعزيز كفاءة الطاقة في المناخات الحارة.

التخصص: هندسة العمارة

تاريخ الدرجة العلمية: مايو, 2025

في المناطق ذات الظروف المناخية القاسية، مثل المملكة العربية السعودية، تلعب كفاءة الأداء الحراري لغلاف المبنى دورًا حاسمًا في تحسين كفاءة استهلاك الطاقة، لا سيما في المباني السكنية التي تعتمد بشكل كبير على التبريد. تهدف هذه الدراسة إلى تحسين تصاميم إطارات النوافذ لتقليل استهلاك الطاقة، من خلال معالجة معدلات النفاذية الحرارية العالية (U-Value) لإطارات الألمنيوم التقليدية، والتي تسهم بشكل كبير في الأحمال الحرارية للتبريد.

من خلال النمذجة الحاسوبية والمحاكاة الطاقية، تم تقييم فعالية استخدام مواد بديلة مثل U-PVC والألياف الزجاجية (Fiberglass)، بالإضافة إلى استخدام فواصل حرارية (Thermal Breaks)، وتحليل نسب الإطار إلى الزجاج، في مناطق مناخية مختلفة في المملكة، مثل البيئة الحارة في الظهران والمناخ المعتدل في أبها. باستخدام برنامجي Window وTherm، تم حساب قيم النفاذية الحرارية (U-Values) لعدة تكوينات، حيث أظهرت النتائج أن زيادة سماكة الألمنيوم أو ملء التجاويف الداخلية بالعزل لها تأثير طفيف. في المقابل، أدى استخدام مواد غير معدنية مثل U-PVC والألياف الزجاجية إلى تقليل U-Value للإطار بنسبة تتراوح بين 79% و 85% مقارنة بالألمنيوم. كما أدت الفواصل الحرارية المدمجة بمواد عازلة مثل Aerogel إلى خفض قيمة النفاذية الحرارية بنسبة تتراوح بين 56% و 67%.

أظهرت محاكاة الأداء الطاقية باستخدام برنامج EnergyPlus أن هذه التحسينات ساهمت في تقليل استهلاك التبريد السنوي بنسبة 9.5% في الظهران و 7.5% في أبها. كما بيّنت النتائج أن النوافذ الكبيرة (1.7×1.7 متر) أدت إلى زيادة وفورات الطاقة في المناخات الحارة بفضل انخفاض U-Value للزجاج مقارنة بالإطار، بينما كانت المواد البديلة أكثر تأثيرًا في المناخات المعتدلة.

وأكد التحليل الاقتصادي فترات استرداد قصيرة (تصل إلى 2-3 أشهر لإطارات U-PVC) وانخفاض كبير في انبعاثات ثاني أكسيد الكربون (تصل إلى 3700 كجم / سنة).

تؤكد هذه النتائج أهمية تبني استراتيجيات تصميم مخصصة للمناخ، حيث يُوصى باستخدام إطارات من U-PVC أو الألياف الزجاجية مع فواصل حرارية في المناطق الحارة، والاكتفاء بفواصل حراري واحد في إطارات الألمنيوم في المناطق المعتدلة. توصي الدراسة بتحديث كود البناء السعودي ليشتمل اشتراطات الأداء الحراري للإطارات، وتشجيع استخدام المواد غير المعدنية. كما تسهم هذه الدراسة في تعزيز الفهم النظري والتطبيق العملي لمساهمة إطارات النوافذ في تحسين كفاءة الطاقة.

Chapter 1

Introduction

1.1 Background

In an era marked by a global energy crisis, which is characterized by increasing demand, waning of non-renewable energy sources reserves, and the undeniable threat of the climate change, it goes without saying that there is an urgent need to reconsider the energy use patterns across all sectors [1]. Awareness of anthropogenic harm to the environment has significantly expanded in recent years, particularly over global warming and unregulated greenhouse gas emissions [2]. The escalation of deleterious gasses from heightened human activity has resulted in considerable environmental contamination, presenting serious global ecological challenges[3]. In response, numerous environmental programs have been enacted during the past two decades with the primary aim of advancing the energy transition towards low-carbon economies [4]. The construction sector, which utilizes 50% of worldwide electricity and contributes to 38% of overall carbon emissions, is considered one of the largest energy consumers, which makes it a critical sector requiring energy optimization [5].

Building energy efficiency pertains to the creation of a more energy-efficient structure through functional design and energy-conserving behaviours [6]. The latter cannot be regulated before to construction; however, the former can be enhanced by sustainable

design, meticulous planning, and thoughtful decisions to manage the thermal comfort of buildings, hence improving electric energy efficiency and decreasing energy consumption [7]. In discussions of thermal control, the building envelope is a critical component for optimization [8]. The building shell serves as a physical barrier between conditioned inner zones and harsh exterior environments, playing a crucial role in managing energy flows. its design immediately influences heating, cooling, and ventilation requirements, rendering it a crucial factor in reducing energy waste [9].

This is particularly noticeable in hot climates, where elevated temperatures and intense solar radiation impose significant demands on cooling systems, constituting nearly 50% of a building's energy usage in cooling-centric areas like the Middle East and North Africa [10].

Improving the thermal performance of various envelope components (walls, floors, roofs, ceilings, windows, etc.) can be accomplished through strategies such as optimizing geometry, utilizing effective insulation, properly selecting materials—considering reflectance, thermal mass, and colour—and implementing shading techniques [11]. It is important to acknowledge that any methodology lacking constraints on heat gain will be ineffective [12]. Neglecting to identify the origin of heat gain via the building envelope and mitigate energy usage corresponds to bailing water from a boat instead of repairing the leak [13]. Thus, a fundamental energy-efficiency technique is to employ optimal materials and components to minimize the thermal transmittance (U-factor) of the building envelope, so reducing heat transfer from the hot exterior to the cool interior and subsequently decreasing cooling energy consumption in hot environments [14].

Predictably, Recent rules and codes frequently mandate a highly insulated envelope [15]. Among the various shell components, windows serve as a double-edged sword; they are essential for natural lighting and ventilation, however, frequently function as thermal hazards due to elevated thermal transmittance (U-Values) [16].

Typically, windows comprise just one-eighth to one-sixth of the building envelope area; yet they considerably impact the heating and cooling energy consumption of residential structures [17]. A study concluded that around 30-40% of the total energy used for conditioning residential buildings is due to heat transmission through windows [18]. In the context of thermal transmittance values, fenestration often exhibits a U-value between 2 W/m²K and 4.5 W/m²K; even high-performance windows generally have a U-value ranging from 0.8 W/m²K to 1.5 W/m²K [19], which is significantly greater than the U-value of the opaque sections of the envelope, as Walls and roofing can readily attain U-factors of 0.10–0.20 W/(m² K) or less [20].

In recent years, the window-to-wall area ratio of buildings has progressively risen due to enhanced aesthetics and concerns regarding indoor environments comfort [21]; thus, the enhancement of thermal insulation efficiency in windows has become essential and has garnered considerable attention [22].

The glass and window frame constitute the primary components of a window, and both their thermal properties directly influence the energy efficiency of the entire window system [23]. However, most research has concentrated on enhancing the glazed section, while window frames, which cover 20–30% of a window's surface area [24], remain notably underexamined [5]. Consequently, with the ongoing optimization of window

glass—from single-layer to double-layer and now to advanced energy-efficient options such as insulating glass [25], vacuum glass, colour-changing glass [26], and photovoltaic integrated glass [27]—the U-factor of glass continues to decrease, reaching values below 1 W/(m²K) and even below 0.5 W/(m²K) [28], while the U-factor of conventional window frames exceeds 1.0 W/(m²K) or even above 8 W/(m²K) for aluminium window frames [29]. Consequently, window frames possess enhanced energy-saving capabilities.

To attain window frames with low U-factors, various solutions may be investigated. The enhancement of window frame geometry [30], substituting highly conductive metals, such as aluminium, with more sustainable materials exhibiting lower thermal conductivity, like U-PVC and fiberglass [31] [32], and utilizing materials with low thermal conductivity as thermal breaks within the structural framework to diminish conductive heat transfer (e.g., broken-bridge window frames) [33], exemplify such strategies. Despite studies indicating that frames account for up to 40% of a window's total heat transfer [34], highlighting their capacity to either diminish or improve glazing performance, optimization strategies for frames remain inadequately analysed in practical applications, particularly in the Gulf region [35].

In countries with harsh climatic conditions such as Saudi Arabia, air-conditioning systems account for approximately 65% of the electric energy consumed in buildings [36], in contrast to around 22% and 21% in the United States and Australia, respectively [37]. This can be related to the harsh climatic conditions of Saudi Arabia and the poor performance of building systems, including the construction and efficiency of the building envelope. Consequently, thermal optimization of the building envelope is of paramount importance. However, the construction codes in Saudi Arabia lack adequate regulations regarding

window frames, focusing mainly on the glazed elements. The prevalent utilization of aluminium frames, which prevail in markets due to their durability and cost-efficiency [38], exacerbates the issue due to insufficient insulation, resulting in inadequate thermal performance and significant environmental harm from energy-intensive production and high embodied carbon [39].

This thesis addresses the previously addressed key research and regulatory voids by exploring ways to maximize the thermal performance of window frames for energy efficiency in hot climates. By means of computer modelling and comparative analysis, the research assesses the effectiveness of novel frame designs including geometric thermal breaks, advanced insulation materials, and frame to glass ratios in order to enhance thermal performance of window frames and reduce heat gain. By bridging the disconnect between glazing-centric research and frame design, this work aims to inform policy changes, empower architects and engineers with evidence-based solutions, and improve the thermal performance of buildings in climates where energy efficiency is not only a sustainability goal but also an existential need.

1.2 Problem Statement

Though window technology has advanced significantly, especially in terms of glass component optimization, window frames have remained a rather understudied field, especially in areas like Saudi Arabia with extreme climates. Up to 30% of a window's surface area can be accounted for by window frames, which also show great thermal transmittance or U-values that significantly affect building total energy efficiency. Optimizing the thermal performance of window frames is essential in Saudi Arabia, where

the severe temperature causes air conditioning systems to consume around 65% of the power in buildings. But because of their great conductivity and low insulating value, the widely used aluminium frames—which are preferred for their affordability and durability—cause poor thermal performance. This worsens energy inefficiencies, hence raising energy consumption, CO₂ emissions, and environmental effect. Modern building rules mostly concentrate on glazing instead of thorough window design, therefore ignoring the possibility of frames to greatly improve energy efficiency.

Clearly among the primary factors influencing not only the thermal performance of the frame but also the overall window system is the material, geometry, insulation, and ratio of the frame. Still, the optimization of these elements and their composite influence on the thermal transmittance and energy consumption, especially in extreme hot environments like Saudi Arabia, remain a major research vacuum.

This thesis aims to address these critical gaps by proposing and assessing creative window frame designs using advanced materials, efficient thermal breaks, and frame to glass ratios to drastically lower the U-value of window frames. By means of computer modelling using Therm, Window and EnegyPlus software, and comparative analysis this study will investigate how well different frame designs lower heat gain and improve building thermal performance in hot environments. This study intends to influence policy changes, provide practical, evidence-based solutions for architects and engineers, and ultimately contribute to the sustainability and energy efficiency of buildings in areas where cooling needs dominate energy consumption patterns, by changing the research focus from glazing to include frame design.

1.3 Aim and Objectives

This study aims to improve the thermal performance and energy efficiency of window frames in hot climates, specifically throughout the various climatic zones of Saudi Arabia. This project aims to reduce the U-values of window frames by investigating and assessing new designs that utilize advanced materials, efficient thermal breaks, and optimum frame-to-glass ratios.

This aim was decomposed into three specific objectives as identified below.

- 1- To investigate the thermal and energy performance of different window frames.
- 2- To examine the impacts of window frames on energy saving in Residential Building of Hot climates.
- 3- To conduct Techno-Economic analysis.

1.4 Research Questions

To achieve the aim of this study, the following research questions deserve critical attention:

- 1- How do different materials used in window frames affect their thermal performance (U-value) in hot climates?**

This question aims to understand the impact of material selection (like aluminium, U-PVC, and fiberglass) on the thermal properties of window frames.

- 2- To what extent do different frame gauge thicknesses affect the thermal performance of Aluminium window frames?**

This question seeks to assess how varying gauge thicknesses that are mostly used in KSA (2mm, 1.8mm, 1.5mm, and 1.3mm) impact the thermal transmittance of the window frame.

3- What impact does the integration of insulation materials into window frame designs have on their thermal characteristics and performance?

This question explores how different insulation materials incorporated into the window frame design influence the frame's thermal resistance and overall energy efficiency metrics.

4- What impact does integrating a thermal break into the window frame design have on its thermal performance?

This question seeks to evaluate the effectiveness of a window frame design featuring a thermal break, focusing on its potential to enhance thermal insulation and reduce energy transfer compared to traditional frame designs.

5- To what extent will the optimized window frame designs impact the energy consumption in residential buildings situated in the different climatic zones of Saudi Arabia?

This question seeks to quantify the energy savings that can be achieved through the use of advanced window frame designs, exploring how changes in frame geometry, insulation, and frame-to-glass ratios influence the cooling loads and overall energy consumption in buildings.

6- What are the economic impacts and feasibility of implementing advanced window frame technologies in the construction sector of Saudi Arabia?

Focusing on the techno-economic analysis, this question addresses the cost-effectiveness, and potential economic benefits of adopting new window frame designs.

1.5 Scope of the study

The scope of this thesis encompasses a detailed analysis aimed at optimizing window frame designs to enhance its thermal performance and reduce its thermal transmittance and hence improve the energy efficiency of window systems in hot climates, specifically focusing on residential buildings. The research will use a double-glazed sliding aluminium window frame as the base case, reflecting the most commonly used window configuration in Saudi residential buildings. This study will not cover the glazed portion of the window but will instead focus on the frame components and the overall window system U-value.

The research focuses on evaluating various materials for window frames, specifically examining their thermal performance and suitability under local conditions. It critically assesses the impact of frame gauge thicknesses on the thermal properties of the frames. Additionally, the role of insulation materials integrated into frame designs is investigated, exploring how they affect the thermal characteristics and performance of the frames.

A key component of this research is the exploration of thermal breaks within the frame design, assessing their effectiveness in reducing thermal bridging and improving overall energy performance. The influence of frame-to-glass ratios on the energy efficiency of window systems is also analysed. By using advanced energy simulation tools, the research develops and compares different scenarios and combinations of frame materials, insulation, thermal breaks, and frame-to-glass ratios.

The study aims to identify the most energy-efficient window frame configurations and will propose a new frame design. However, the structural aspects of this proposed design will not be discussed in this thesis and could be explored in future research. These optimized frames will then be applied to a case study involving a residential building in various Saudi climatic zones to evaluate potential energy savings and provide region-specific recommendations for designing sustainable window systems.

1.6 Originality and significance of the study

The significance of this study unfolds in five main aspects. To begin with, this thesis presents an innovative frame design that integrates sophisticated materials—such as Aerogel, U-PVC, and Fiberglass—along with an effective thermal break and optimum frame-to-glass ratios, specifically engineered for hot climates like those in Saudi Arabia. The proposed design aims to significantly diminish the thermal transmittance of sliding window frames, an aspect often neglected.

With this being said, it is worth mentioning that this research tackles substantial gaps in the existing literature, specifically the insufficient emphasis on window frames relative to glazing in the context of envelope thermal optimization and building energy efficiency. This study enhances the understanding of the effects of frame materials, thicknesses, and the inclusion of thermal breaks on thermal performance.

Moreover, this study transcends theoretical research by addressing practical design practices, contrasting conventional window frame designs with an innovative proposed frame design through extensive simulations. This illustrates the potential energy savings from enhanced frame designs and provides a comprehensive assessment of their

performance across the many climate zones of Saudi Arabia. therefore, it enhances professional practices in the industry by informing industry professionals about effective strategies for optimizing window components and can assist architects and builders in choosing and executing more efficient window frames, hence, enhancing the overall energy performance of residential structures.

Furthermore, this thesis will serve as a valuable resource for future architectural and engineering curricula, highlighting the critical role of window frames in building energy efficiency and emphasizing the importance of analysing and optimizing the thermal characteristics of the entire window system rather than concentrating on a single element.

Finally, as current construction codes in Saudi Arabia primarily overlook the optimization of window frames, emphasizing glazing elements instead, this thesis emphasizes regulatory control and presents substantiated evidence to advocate for more comprehensive building rules that include window frame designs.

1.7 Organization of the thesis

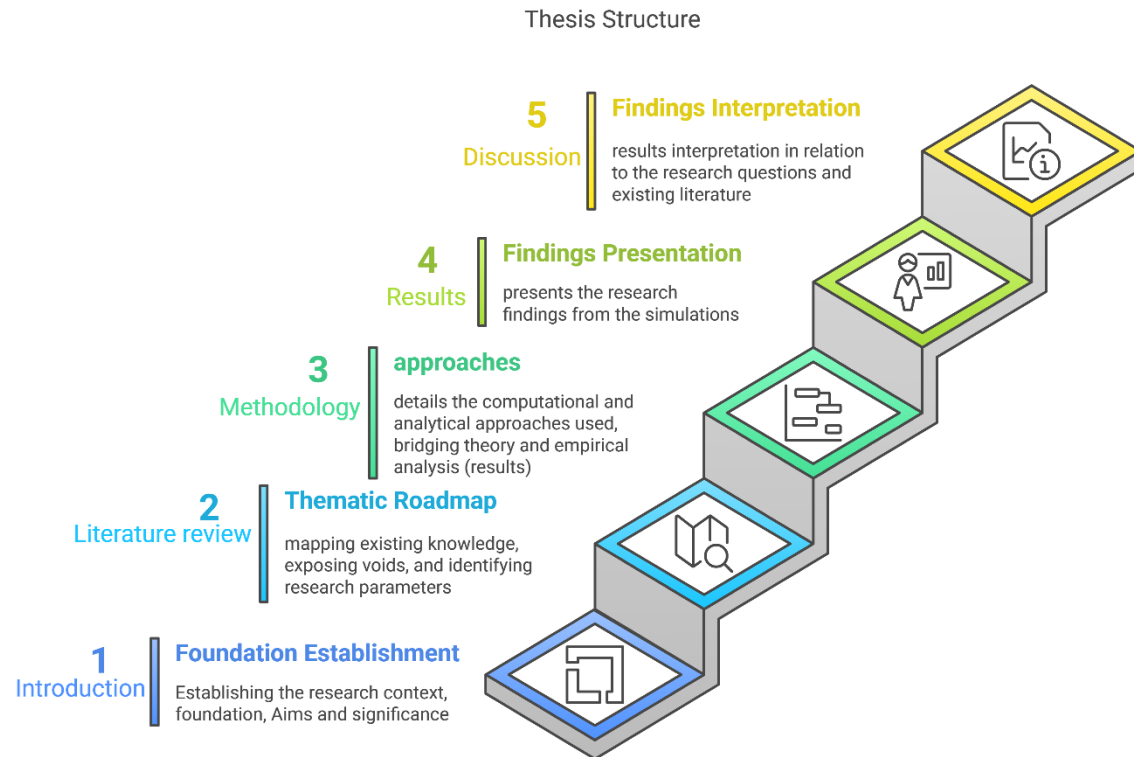


Figure 1.1 Organization of thesis chapters

This thesis, which unfolds into six main chapters, is structured to comprehensively address the research aim of optimizing window frame thermal performance for energy efficiency in hot climates, focusing on Saudi Arabia’s residential buildings context. It begins with the introduction chapter which sets the stage and define the context by providing a detailed background about the global energy crisis, the construction sector’s role in carbon emissions, and the critical gap in window frame optimization and their role in thermal optimization of the envelope. In addition to identifying the study’s objectives, questions, and significance. Chapter two, which is the literature review section, provides information

about the existing literature on building energy efficiency, thermal optimization, and window systems. It emphasizes the disproportionate focus on glazing over frames and highlighting gaps in Saudi building codes. Moreover, it provides the necessary knowledge about factors influencing frames, simulation tools to be used, and methods to be followed. Chapter three is the methodology chapter, which highlight the approaches used to achieve the goals of the study. It describes the methods used to transform theories into results with the help of computational modelling, using Therm, Window, and Rhino software to simulate U-values and energy consumption, parametric analyses of materials (aluminium, U-PVC, fiberglass), gauge thicknesses, insulation integration (e.g., aerogel), thermal breaks, and frame-to-glass ratios. The results of this study will be presented in chapter four. Results will include U-values of different frames configurations, energy results, and techno-economic analysis. This will be followed with a discussion in chapter five, which will provide results interpretations within the context of the reviewed literature and research questions. The thesis ends with chapter six, which is the conclusions and recommendations chapter. This section encapsulates the study's findings, reiterates the research contributions, and provides actionable recommendations, aiming to influence policy and practice.

1.8 Summary of chapter

This chapter sets the study into context and establishes the foundation by addressing the global energy crisis, while highlighting the drastic role of the construction sector in energy consumption and carbon emissions. It emphasizes the urgency of optimizing building envelope thermal efficiency and the critical role of window frames in enhancing the

thermal properties of the window system, thus reducing the energy consumption. This chapter puts the lens on the important research gaps around window frames, which have been largely overlooked. moreover, it delineates the specific problem of inefficient window frame designs in residential buildings, particularly in the harsh climates of Saudi Arabia, where traditional materials like aluminium contribute to significant energy losses.

Furthermore, the introduction outlines the thesis's aim to improve the thermal performance of window frames in Saudi Arabia's diverse climates through innovative materials and designs. It defines specific objectives and research questions focused on material selection, frame thermal breaks, and advanced insulation techniques. The scope is clearly stated, with a focus on window frames, and whole window system rather than glazing to identify and test solutions that could substantially lower the U-values of window systems. It also notes that while proposing a new frame design, the structural aspects will be suggested for future research.

Lastly, the significance of the research is articulated across five dimensions: originality, theoretical contribution, practical impact, policy implications, and pedagogical value. Each aspect is explored to demonstrate how the thesis will contribute not only to academic knowledge but also offer practical solutions and influence policy changes, thereby addressing a critical gap in the field of building energy efficiency.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents a comprehensive review of existing literature focusing on optimizing the thermal performance of window frames to enhance energy efficiency, particularly in residential buildings situated in hot climatic regions such as Saudi Arabia. The primary objective of this literature review is to contextualize and critically assess prior research and practices related to building envelope optimization, with special emphasis on window systems and their influence on overall energy consumption. A thematic structure has been adopted to systematically address and analyse the key aspects relevant to this research, including the thermal characteristics of window frames, commonly utilized frame materials, innovative insulation strategies, thermal break technologies, frame-to-glass ratio (FGR) optimization, economic and environmental impacts, and the application of computational simulation tools. This thematic arrangement is justified as it provides a clear, coherent narrative that connects various interrelated topics, facilitating a holistic understanding of current knowledge, trends, and gaps. By exploring international research contexts alongside region-specific practices and standards, this chapter aims to clearly identify research voids and highlight the significance of this study's contribution to both theoretical knowledge and practical applications in building energy performance optimization.

2.2 Energy Efficiency in Buildings: Global Context and Significance

The building sector accounts for 36% of global final energy consumption, 37% of energy-related CO₂ emissions, and about 65% of material accumulation globally, making it a pivotal arena for climate change mitigation [40]. As urbanization accelerates and global temperatures rise, particularly in hot regions, improving energy efficiency in buildings has emerged as a critical strategy to curb greenhouse gas emissions while enhancing thermal comfort and reducing operational costs. The Intergovernmental Panel on Climate Change (IPCC) identifies buildings as a key leverage point for achieving the Paris Agreement's goal of limiting global warming to 1.5°C, emphasizing that energy-efficient retrofits could reduce building-sector emissions by up to 60% by 2050 [41].

Understanding the patterns and drivers of energy consumption in buildings is essential for developing effective efficiency strategies. Household energy use represents a significant portion of building-related energy consumption, with households responsible for more than 70% of total global greenhouse gas emissions through their consumption behaviour [42]. Within households, energy use for space heating and cooling typically constitutes the largest share of consumption, followed by water heating, appliances, and lighting.

According to IEA statistics, active space cooling and air conditioning systems alone consume approximately 16% of the building sector's final electricity consumption and contribute 3.94% of global greenhouse gas emissions[43]. As global temperatures rise due to climate change, the demand for cooling is expected to increase dramatically, making this an area of particular concern for future energy use.

Approximately 2 billion air conditioning systems are presently operational worldwide, making space cooling a substantial factor in the rising electricity demand within buildings. Notwithstanding continuous progress in cooling technologies and diminished carbon emissions from electricity generation, the indirect release of CO₂ emissions associated with space cooling has significantly increased, nearly tripling from 1990 to surpass 1 gigaton of CO₂ in 2022 [44]. The heightened demand for power and CO₂ emissions underscores the need of energy conservation for achieving thermal comfort in buildings efficiently and sustainably [45]. Two primary ways are generally utilized to enhance energy efficiency in buildings: Active and Passive.

Improving the efficiency of existing HVAC systems and integrating on-site renewable energy sources are active tactics employed to attain optimal thermal comfort in buildings. The passive technique entails enhancing the design and construction of buildings in accordance with local climate conditions while minimizing energy consumption [43]. The building envelope is essential in passive technologies for maintaining indoor thermal comfort by acting as a barrier against varying outside conditions in any project. Improving a building's thermal mass can be accomplished by altering the materials and design of its envelope, resulting in less electricity usage for heating or cooling [46].

Despite the clear benefits of building energy efficiency, policy implementation remains inconsistent globally. The 2023 Global Status Report for Buildings and Construction emphasizes the urgent need for governments to develop and enforce climate action roadmaps for buildings and construction, noting that 161 nations still have pending roadmaps. Building energy codes must be strengthened to enhance efficiency, and despite economic hurdles, investment in building decarbonization should increase [47].

2.3 Building Energy Trends in Saudi Arabia

Saudi Arabia (KSA) is one of the largest energy consumers globally, with its building sector playing a dominant role. Due to its extreme desert climate—characterized by high cooling demands—the residential and commercial building stock accounts for a significant portion of total electricity consumption [48]. Despite abundant fossil fuel resources, there is an increasing push towards energy efficiency, sustainable building practices, and green building codes to align with Vision 2030 and global climate agreements.

According to the Saudi Energy Efficiency Centre (SEEC) [49], buildings consume approximately 80% of the nation's total electricity, with air conditioning alone responsible for nearly 70% of residential energy use. A study by [50] highlights that Saudi Arabia's per capita energy consumption is among the highest worldwide, largely driven by inefficient building envelopes and outdated HVAC systems. The IEA (2023) notes that Saudi households consume nearly double the global average for space cooling [45].

Residential buildings constitute the largest energy-consuming sector in KSA, accounting for 50% of total building stock electricity use [51]. A 2021 survey of Saudi households revealed that air conditioning systems consume 75% of residential energy, with average summer thermostat settings at 22°C despite outdoor temperatures exceeding 40°C [52]. This cooling demand is exacerbated by architectural designs ill-suited to the local climate as 38% of Riyadh's residential structures use single-pane windows with U-values above 5.0 W/m²K, compared to the Saudi Residential Buildings' Envelope Code (SRBEC) mandate of 2.8 W/m²K [53]. Cultural practices further intensify consumption; extended family gatherings and 24/7 occupancy patterns lead to continuous HVAC operation, with

67% of households reporting AC runtime exceeding 18 hours daily during peak summer [52].

Electricity consumption in the residential sector is projected to double by 2025 due to factors including population growth, rapid economic expansion, and low tariffs [54]. Consequently, an increase in demand for energy resources in residential buildings, coupled with rapid and unregulated economic and population growth, has been anticipated.

Furthermore, the energy demand of the residential structures sector is anticipated to rise substantially in the future due to projected climate change. Anticipated climatic change and fluctuations may adversely affect energy use [55]. The Kingdom of Saudi Arabia is situated in a hot climatic zone, and indications point to a prospective increase in temperature relative to present levels. [56] observed that the increase in temperature in Saudi Arabia every decade ranges from 0.63 °C (minimum) to 0.80 °C (maximum), with an average of 0.72 °C. This is anticipated to rise to a range of 2.0 to 2.75° by 2050. These statistics demonstrate Saudi Arabia's ranking among the world's warmest countries, with projections indicating an increase in temperature in the future. Consequently, it is imperative for structures to possess the capability to mitigate climate change in the future, and it is probable that individuals will consume substantial energy for air conditioning indoors due to extreme temperatures.

The recognition of energy efficiency as a critical issue in KSA began in the early 2000s, driven by the high energy consumption patterns in the residential sector [57]. Initial efforts focused on understanding the energy use patterns and the applicability of energy efficiency technologies. The government recognized the need for a comprehensive approach to

address the energy consumption in residential buildings, leading to the establishment of the Saudi Building Code (SBC) [58].

The Saudi Building Code (SBC) was introduced to set standards for the design, construction, and maintenance of buildings. The code aimed to reduce heat transfer through building components and external elements, with specific recommendations for thermal insulation, double and heat-reflecting glass, and light exterior colours [53]. The implementation of the SBC resulted in significant energy savings, with operating costs reduced by almost 44% in compliant buildings [58].

The SBC also emphasized the importance of the building envelope, particularly walls, roofs, and windows, in reducing heat absorption and energy consumption. The code mandated the use of thermal insulation and high-performance glazing systems, which became critical components of the energy efficiency standards [59]. The code also emphasized the importance of window performance, with a focus on reducing heat gains through advanced glazing technologies. However, it lacks regulation regarding the window frame performance [60].

The implementation of energy efficiency standards has had a profound impact on the residential building sector in KSA. Key outcomes include:

- **Energy Savings:** Compliance with the SBC has resulted in significant energy savings, with studies indicating reductions in annual energy consumption ranging from 14% to 40% [59].

- **Cost Savings:** The long-term economic benefits of energy efficiency measures have been significant, with payback periods for thermal insulation ranging from 3.7 to 8.8 years, depending on the climatic region [61], [62].
- **Environmental Benefits:** The reduction in energy consumption has also led to a decrease in carbon emissions, with studies indicating that thermal insulation can reduce CO₂ emissions by up to 66 kg/m²/year [63].
- **Improved Thermal Comfort:** The use of advanced glazing systems and thermal insulation has improved indoor thermal comfort, reducing the need for excessive air conditioning [64].

Despite the significant progress made, there are challenges and opportunities for further improvement in energy efficiency standards for residential buildings in KSA.

- **Climate Change:** The impact of future climate change scenarios on the effectiveness of current energy codes remains a concern. While the current codes have been shown to reduce energy consumption, they may not be sufficient to mitigate the effects of rising temperatures [57].
- **Retrofitting Existing Buildings:** The majority of the existing building stock in KSA does not comply with current energy efficiency standards. Retrofitting these buildings to meet the new codes presents a significant challenge but also an opportunity for energy savings [65].
- **Material Selection and Cost:** The selection of appropriate insulation materials and glazing systems that balance thermal performance and cost remains a challenge. Studies have shown that the law of diminishing returns applies to insulation

thickness, with beyond a certain point, additional insulation does not provide significant energy savings [66].

These challenges open a path for new opportunities for improvement:

- **Advanced Window systems:** The use of nanogel-filled polycarbonate windows and low-emissivity coatings offers significant potential for further reducing energy consumption [64], in addition to optimizing the window frame performance through thermal breaks and suitable materials selection.
- **Passive Design Strategies:** Incorporating passive design elements, such as shading devices and green roofs, can further enhance the energy performance of residential buildings [67].
- **Integration of Renewable Energy Systems:** The use of building-integrated photovoltaic systems can help reduce the reliance on grid electricity and further lower carbon emissions [67].

Table 2-1 Summary of Building Envelope Features and Energy Efficiency Strategies with Supporting Literature

Feature	Description	Citation
Thermal Insulation	Mandated use of thermal insulation in walls and roofs to reduce heat transfer	[58], [62]
	Use of double and heat-reflecting glass to reduce heat gains	
Window Performance		[58], [64]

	Roof insulation contributes	
Roof Insulation	significantly to reducing cooling loads	[68]
	Use of ETICS and shading	
Facade Retrofitting	devices to enhance energy efficiency	[69], [67]
	Advanced glazing systems	
Nanogel Windows	incorporating nanogel layers for improved performance	[64]
	Incorporation of shading	
Passive Design Strategies	devices and green roofs for enhanced thermal comfort	[67]
	Use of photovoltaic systems	
Building-Integrated PV Systems	to reduce reliance on grid electricity	[67]

2.4 Thermal Performance of Building Envelopes

2.4.1 Thermal Transmittance (U-Value)

The building envelope serves as the critical interface between indoor and outdoor environments, playing a fundamental role in energy efficiency, thermal comfort, and building sustainability [70]. The thermal performance of a building envelope is a

cornerstone of energy efficiency, dictating how effectively a structure resists heat transfer between its interior and exterior. Central to this performance is the concept of thermal transmittance, or U-value ($\text{W/m}^2\cdot\text{K}$), which quantifies the rate of heat flow through a material or assembly under steady-state conditions [71]. A lower U-value indicates superior insulation, making it a critical metric for evaluating components like walls, roofs, and windows. U-values are inversely related to the thermal resistance (R-value) of building components. In hot climates such as Saudi Arabia, where cooling demands dominate, optimizing U-values is essential to minimizing energy consumption and enhancing occupant comfort [72].

Multiple factors influence the U-values of building envelopes, starting with Building Materials and Construction Components as the selection of materials and construction components significantly impacts the thermal performance of building envelopes. Different materials possess varying thermal properties that directly influence heat transfer rates through the building fabric. The inherent thermal conductivity of construction materials plays a fundamental role in determining U-values. Materials with lower thermal conductivity provide better insulation and result in lower U-values. Wall conductivity has been identified as one of the critical parameters affecting heating consumption, particularly when the uncertainty of building-related parameters increases [73]. Therefore, the choice of construction materials requires discrete analyses and decision-making processes to optimize sustainability performance [74].

Window Systems and Glazing Technologies are also critical factors. Window components significantly influence the overall U-value of building envelopes. Multiple regression analysis of window system components reveals that the configuration (single or double)

has the greatest effect on U-value among all window components [75]. Advanced glazing technologies have been developed to enhance thermal performance, with vacuum and aerogel glazing systems exhibiting superior thermal insulation properties, achieving U-values below 1 W/m²K [76].

Another important factor is Insulation Strategies and Configuration. Insulation thickness demonstrates a direct relationship with thermal performance, with thicker insulation generally resulting in lower U-values. However, this relationship is not linear, as there are diminishing returns beyond certain thicknesses. The balance between insulation thickness and overall building performance must consider both operational and embodied energy implications [77]. Different insulation materials with varying thermal conductivities affect the required thickness to achieve target U-values.

Furthermore, thermal bridging plays a significant role in the thermal transmittance conversation. [78] Reported that thermal bridges can increase overall heat transfer by 10–20%, negating insulation improvements.

The literature review on the factors affecting thermal transmittance in building envelopes reveals a rich tapestry of research that highlights the critical role of building envelope components in determining energy performance and indoor thermal comfort.

[79] provides foundational insights into how modifications to building envelopes can significantly influence indoor air temperatures, particularly in tropical climates. This work underscores the necessity of understanding the interplay between various envelope elements and their contribution to energy consumption, emphasizing the importance of climate-responsive design in enhancing thermal performance.

Continuing this exploration, [80] examines the lifecycle energy implications of building envelope design, advocating for a holistic approach that integrates sustainable practices with aesthetic considerations. This study reinforces the idea that the performance of envelope components, including insulation and sealing, is paramount in minimizing operational energy use and enhancing occupant comfort. The focus on the interconnectedness of materials and their performance in specific climatic contexts is a recurring theme that is crucial for effective building design. [81] further delve into the thermophysical properties of wall materials, particularly the roles of thermal insulation and heat storage. Their findings reveal that the effectiveness of these materials can vary based on the thermal conductivity of the wall, suggesting that a nuanced understanding of material properties is essential for optimizing energy performance. This study adds depth to the discussion by differentiating the roles of insulation and heat storage in various scenarios, thus highlighting the complexity of thermal transmittance factors. [82] address the practical implications of building fabric performance, revealing a significant gap between designed and actual thermal performance in low-energy housing. Their meta-study illustrates how construction quality defects, such as air leakage and thermal bridging, can drastically increase heat loss. This research emphasizes the need for rigorous quality control and integrated design approaches to bridge the performance gap and enhance overall energy efficiency. In a more technical exploration, [83] proposed a method for determining optimum insulation thickness, emphasizing the balance between cost and energy savings. Their innovative approach to modelling heat transfer offers a pathway for optimizing thermal performance, showcasing the potential for simulation-based strategies in improving building energy efficiency.

Hence, understanding the mechanisms of heat transfer through building envelopes is essential for designing energy-efficient structures that can meet increasingly stringent environmental standards. Heat transfer in building envelopes occurs through three primary mechanisms: conduction, convection, and radiation.

2.4.2 Conduction Heat Transfer in Building Envelopes

Conduction is the primary mechanism of heat transfer through solid building materials, occurring when thermal energy moves from higher-temperature regions to lower-temperature regions within a material or between materials in direct contact. This process is governed by Fourier's law of heat conduction and is fundamental to understanding how building envelopes respond to temperature differences [84].

Thermal conductivity of materials plays a significant role in determining the rate of heat transfer. Materials with low thermal conductivity, such as insulation, are effective in reducing heat transfer via conduction. Research has shown that the thermal transmittance of building envelopes can be significantly reduced by incorporating materials with low thermal conductivity. For instance, aluminium window frames, with a thermal conductivity of 160–210 W/m·K, act as highly conductive pathways, enabling rapid heat exchange between indoor and outdoor environments [78]. In contrast, materials like UPVC (0.16–0.22 W/m·K) or fiberglass (0.25–0.35 W/m·K) resist conductive transfer, making them superior insulators in hot climates [85].

Moreover, the use of expanded polystyrene (EPS) insulation in exterior walls has been shown to reduce thermal transmittance by up to 45% compared to conventional wall structures [86]. Similarly, the application of vacuum insulation panels (VIPs) has been

demonstrated to reduce the thermal transmittance of walls by approximately 50% due to their extremely low thermal conductivity [87]. The effectiveness of conductive heat transfer is also influenced by the distribution of materials within the building envelope. For example, the use of hollow autoclaved aerated concrete (AAC) blocks has been shown to reduce heat transfer through walls by creating air-filled cavities that inhibit conduction [88]. However, the presence of thermal bridges, such as Windows, columns and beams, can significantly reduce the overall thermal resistance of the envelope, leading to increased heat transfer via conduction [89].

2.4.3 Convection Heat Transfer in Building Envelopes

Convection involves the transfer of heat through the movement of fluids. In building envelopes, convection occurs both internally and externally, with air movement playing a crucial role in heat transfer. Natural convection is driven by buoyancy forces, while forced convection is influenced by wind and other external factors [90].

The role of convection in building envelopes is complex and often coupled with other modes of heat transfer. For example, in the case of double-glazed windows, convection within the air gap between the panes can significantly influence the overall heat transfer coefficient (U-value) of the window [91]. Similarly, convection in air chambers within building envelopes can lead to increased heat transfer, particularly in hot climates [92].

Research has also highlighted the importance of convective heat transfer in the thermal performance of building envelopes. For instance, the use of reflective coatings and radiant barriers has been shown to reduce convective heat transfer by minimizing the interaction between the building envelope and the surrounding environment [93]. Additionally, the

application of external insulation has been demonstrated to reduce convective heat transfer by creating a thermal barrier that inhibits air movement near the building surface [94]. In window systems, convective loops can form between glazing panes or around frame edges, exacerbating heat gain in hot climates. For example, poorly sealed frames allow outdoor hot air infiltration, increasing cooling loads by 10–15% [95].

2.4.4 Radiative Heat Transfer in Building Envelopes

Radiation is the transfer of heat through electromagnetic waves. In building envelopes, radiation plays a significant role in both heat gain and heat loss. Solar radiation is a primary source of heat gain during the day, while thermal radiation from the building to the sky contributes to heat loss at night.

The impact of radiation on building envelopes is influenced by the emissivity and reflectivity of materials. Materials with low emissivity, such as low-e coatings, are effective in reducing radiative heat transfer by minimizing the emission of thermal radiation [86]. Similarly, reflective insulation materials, such as aluminium foil, can reduce radiative heat transfer by reflecting solar radiation away from the building envelope [92]. Research has shown that radiative heat transfer can account for a significant proportion of total heat transfer in building envelopes. For example, in hollow block walls, radiation has been shown to contribute up to 21% of the total heat transfer, while conduction and convection contribute 65% and 14%, respectively [86].

Engineering procedures have been developed to calculate effective thermal conductivity that accounts for both convective and radiative components [92].

2.4.5 Thermal Bridges in Building Envelope

Thermal bridges are regions where heat transfer occurs more easily due to discontinuities in insulation, particularly at interfaces of materials with varying thermal conductivity coefficients. A crucial region is the intersection of windows and walls [96]. At these junctures, the interface between materials with differing thermal characteristics establishes channels for heat dissipation, hence amplifying overall energy loss [97]. Thermal bridges substantially affect the insulation efficacy of building envelopes, compromising overall energy efficiency. Research indicates that they constitute almost 40% of the overall heat loss from windows [98].

The impact of thermal bridges can be significant, with studies indicating that they can increase energy consumption by up to 30% in some cases [99]. Various strategies have been explored to mitigate these effects, such as the use of thermal bridge breakers, which have been shown to reduce heating and cooling loads by 15–27% in residential buildings [100]. Different wall types also exhibit varying levels of susceptibility to thermal bridging, with systems like the Exterior Insulation and Finish System (EIFS) proving more effective in reducing heat transmission compared to traditional wall types [94].

[101] conducted a study focusing on double brick wall constructions in Greek buildings, emphasizing the detrimental effects of thermal bridges on energy demand. Their findings suggest that addressing thermal bridges can lead to substantial energy savings, particularly in older buildings that may benefit from renovation measures.

In the context of energy simulation, [102] explored different modelling methods for thermal bridges in flat heterogeneous roofs within Italian climates. Their comparative

analysis of accuracy underscores the importance of selecting appropriate modelling techniques to accurately predict energy performance, which is essential for effective building design and renovation.

Furthermore, numerical calculations and simulations, such as those using Therm and Flixo software, have been employed to optimize window placement and reduce thermal bridging by determining the optimal installation depth, which can minimize heat flux and even achieve negative psi-values, indicating reduced heat loss [103]. It was also found that the position and material of window frames, including the use of innovative materials like monolithic silica aerogel, play a crucial role in mitigating thermal bridges by enhancing the thermal performance of window systems [104]. Lastly, [105] investigated the thermal properties of window-to-wall connections, aiming to identify the most energy-efficient window positions to minimize thermal bridging effects. This study underscores the significance of design choices in mitigating thermal bridges and enhancing overall building energy efficiency.

2.5 Window Systems and Their Role in Energy Performance

windows play a significant and complex role in the energy performance of buildings. While they serve essential functions like providing daylight and ventilation, they often represent a major pathway for unwanted heat transfer, making them a critical component in determining a building's overall energy efficiency [106], [107]. Comprising both transparent and opaque parts, windows must be carefully engineered to deliver optimal thermal performance and minimize energy losses [108]. As a result, the detailed design of each window component is crucial for enhancing energy efficiency and lowering the

building's total energy demand. This has led to the continuous development and commercialization of increasingly sophisticated window systems [109]. Key design considerations include window-to-wall ratio (WWR), orientation, materials, glazing types, thermal properties, and façade integration. Among these factors, glazing characteristics have received the most extensive academic and practical attention [110].

2.5.1 Windows as a Primary Source of Heat Loss and Gain

Windows are frequently identified as the weakest element of the building envelope [39]. Despite often occupying a relatively small fraction of the total wall area (e.g., 1/8 to 1/6), they can be responsible for a substantial portion of heat loss [5]. Estimates suggest windows alone contribute from 25% to 40% of the heat loss through a typical building assembly [31]. In summer, they can be responsible for significant heat gains [111]. This high rate of heat transfer is due to their thermal transmittance (U-value) generally being much higher than that of opaque walls [78]. In well-insulated buildings where wall U-values can be between 0.1 and 0.2 W/(m²·K), even the best windows typically have U-values ranging from 0.7 to 1.5 W/(m²·K) [14]. With modern buildings featuring higher window-to-wall ratios (WWR), the impact of windows with high U-values on exacerbating heat losses and poor building energy performance becomes even more pronounced [106].

The energy performance of windows is governed by a range of interrelated design parameters, which must be simultaneously optimized to balance energy efficiency, indoor thermal comfort, and visual performance [108]. Despite this complexity, a substantial portion of the existing research adopts a single-objective focus. For instance, [112] analysed both construction and operational energy use in office buildings in Shanghai to propose appropriate window-to-wall ratio (WWR) values across orientations and material

types. In colder climates, [113] optimized building envelope features—including window type, WWR, wall insulation, and shading elements—for nearly zero-energy buildings in Estonia. Similarly, [114] examined how factors like window orientation, WWR, and the room’s width-to-depth ratio impact the energy use of commercial office buildings. [115] investigated five Asian climates through dynamic simulations, assessing the influence of WWR, U-value, solar heat gain coefficient (SHGC), orientation, and visible transmittance on annual energy consumption. [116] adopted a multi-objective approach to optimize WWR, orientation, and window material combinations for improving energy performance in residential buildings.

Beyond energy alone, a growing body of research has integrated multi-objective optimization frameworks to also account for daylighting and visual comfort [117]. For example, [118] optimized window dimensions to balance energy savings with visual quality, while [119] assessed how size, orientation, and glazing characteristics influence heating demand, daylight access, and overall thermal comfort. In educational buildings, [120] employed a multi-objective genetic algorithm to optimize both thermal and daylight performance in cold climate zones. Methodologies across these studies vary widely and include single- or multi-objective optimization strategies [112], [113], graphical and sensitivity analyses [115], [117], and simulation techniques such as EnergyPlus [118], artificial neural networks (ANN), and genetic algorithms (GA) [120], with some studies integrating multiple tools in a hybrid modelling framework [116]. These studies highlight the significant impact of window properties on indoor thermal environments and building energy consumption across various climates.

Table 1 summarizes some studies that exemplify both single- and multi-objective approaches to window optimization across various climates and building types. These studies provide valuable insights into the diverse parameters influencing window performance and highlight the methodologies employed to achieve energy-efficient design solutions. It can also be noticed that most studies focus on the glass portion of the window.

Table 2-2 Comparative Summary of Window Design Optimization Studies

Study	Climate Zone	Building Type	Key Parameters	Methodology
[112]	Warm	Office	WWR, Orientation, Window Materials	Energy Analysis
[113]	Cold	Nearly Zero Energy (nZEB)	Window Type, WWR, Insulation, Shading	Optimization
[114]	Mixed/Temperate	Commercial Office	WWR, Orientation, Room Geometry	Energy Simulation
[115]	Various Asian Climates	Various	WWR, U-value, SHGC, Orientation,	Graphical Analysis

			Visible Transmittance	
[116]	Cold	Residential	WWR, Orientation, Materials	Multi-objective Optimization
[118]	Temperate	Office	Window Size, Visual Comfort	EnergyPlus
[119]	Cold	Nearly Zero Energy (nZEB)	Size, Orientation, Glazing Properties	Simulation and Evaluation
[120]	Cold	School	Thermal and Daylighting Performance	Genetic Algorithm (GA)

2.5.2 Key Factors Influencing Window Energy Performance

The thermal and energy performance of a window system are influenced by several interactive design factors and the surrounding environment. These include:

- Thermal Transmittance (U-value): A measure of how well a window conducts heat. A lower U-value indicates better insulation and reduced heat transfer [85]. Reducing the U-value of windows is considered critical for reducing building energy consumption [121].

- Solar Heat Gain Coefficient (SHGC): Represents the fraction of solar radiation that passes through the window as heat [30]. SHGC is a significant factor, particularly in determining cooling loads, and its importance varies with climate and orientation [111].
- Window-to-Wall Ratio (WWR): The proportion of the façade covered by windows [106]. Higher WWR can lead to increased heat loss or gain, although it is necessary for daylighting and visual comfort [108]. Economic feasibility analysis, such as Life Cycle Costing (LCC), can help identify optimal WWR ranges that balance energy performance with other factors [122].
- Climate and Orientation: The optimal window design and its impact on energy consumption depend heavily on the climate zone and the orientation of the façade [30]. Furthermore, strategies suitable for cold climates (minimizing heat loss) may differ from those for hot climates (minimizing heat gain) [108].

Many researchers have studied the effect of these factors on the thermal and energy performance of window systems. For instance, studies have shown that larger window sizes can balance energy and daylight requirements when paired with energy-efficient products and well-designed shading systems [123]. The window-to-floor ratio (WFR) and window-to-wall ratio (WWR) are critical parameters in optimizing energy performance, with specific ratios like 0.23 in subtropical regions proving effective in reducing energy consumption by up to 34.47% when combined with appropriate shading devices and glazing options [124], [125]. Their findings suggest that careful consideration of window size is essential for achieving high energy performance in building designs. [80] builds upon this foundation by examining the balance between window area and thermal

properties of the building envelope. The study underscores the importance of selecting high-performance windows and considers various performance metrics, such as U-factor and Solar Heat Gain Coefficient, which are crucial for optimizing fenestration placement and sizing. The insights from this case study further reinforce the critical role of window selection in enhancing overall building energy performance.

In addition to WWR, the materials and technologies used in window systems also play a vital role in energy efficiency. [126] examined the daylight performance of a glazing system incorporating Parallel Slat Transparent Insulation Material (PS-TIM). Their research highlighted how variations in slat pitch, tilt angles, and materials can affect both optical performance and energy efficiency, emphasizing the importance of innovative glazing technologies in enhancing indoor environmental quality. The selection of appropriate glazing materials is crucial. Double- or triple-glazed windows with low-e coatings are highly effective in reducing heat transfer while maintaining daylight transmittance [127]. Advanced Glazing Technologies are also a vital aspect of research, for instance, [128] concluded that silica aerogel-filled windows can achieve U-Values as low as $1.0\text{--}1.1 \text{ W/m}^2\text{K}$, significantly improving energy efficiency. Incorporating nanomaterials like nano vacuum insulation panels (VIPs) or nanogel glazing can further reduce U-Values. These materials offer exceptional thermal insulation, with nanogel glazing achieving U-Values lower than those of conventional double-glazed windows [129]. Moreover, Windows with spectrally selective coatings or liquid-filled solutions can effectively block near-infrared and ultraviolet radiation while maintaining high visible transmittance. Such designs are particularly beneficial in hot and humid climates, as demonstrated by a novel liquid-filled window concept in Hong Kong [130].

Additionally, the integration of shading devices, such as switchable glazing or dynamic shading systems, can optimize daylighting and thermal comfort by adjusting to changing solar conditions [125]. Furthermore, the integration of building information modelling (BIM) and building energy modelling (BEM) can assist in optimizing window design and energy performance. These tools enable architects and engineers to simulate various window configurations and evaluate their impact on energy consumption and cost [131]. Another effective strategy is retrofitting existing windows with optimal U-Values and solar heat gain coefficients, which can significantly reduce energy consumption. [132] Found that for poorly insulated houses, lowering the U-Value of windows can decrease annual heating and cooling energy demand by 7.9–16.7%

In summary, the literature indicates that window systems are a crucial component in the quest for energy-efficient buildings. Factors such as window-to-wall ratio, material properties, and innovative glazing technologies significantly influence energy performance and occupant comfort. However, it can also be noticed that all focus has been on the glazed component on the window system, Although the thermal performance of window frames and the interaction between glazing and frames can significantly impact overall window system efficiency.

2.6 Window Components and Their Thermal Role

A window is composed of different elements, primarily the glazing and the frame, each with distinct thermal properties [30].

2.6.1 Glazing

It is the transparent part of the window. The advancements in window glazing systems have garnered significant attention over the past two decades, reflecting a growing understanding of their impact on energy efficiency, thermal performance, and occupant well-being. The literature reveals a trajectory of research that not only explores innovative glazing technologies but also emphasizes the importance of integrating these advancements into building design for optimal performance. Significant research and development have focused on improving glazing thermal performance through technologies like double and triple glazing [133], low-emissivity (low-e) coatings [134], gas fills (e.g., argon, krypton) [135], vacuum glazing [136], and more recently, smart window technologies like thermochromic or semi-transparent photovoltaic glazing [111]. These advancements have greatly reduced heat transfer through the glass pane itself [32].

Early investigations focused on enhancing the thermal performance of windows using low-emissivity coatings in conjunction with plastic films. [137] demonstrated through simulation that highly infrared transparent plastic films are well-suited for use as intermediate glazing when combined with a low emissivity coating. This early work highlighted the potential of advanced materials to improve window insulation.

In recent years, smart glazing technologies have gained considerable attention. Electrochromic (EC) glazing, which allows for dynamic control of light and heat transmission, has been investigated for its impact on glare and energy consumption. [138] conducted experimental tests on EC-glazing, revealing its effect on discomfort glare from windows. The study utilized a double-glazing unit (DGU) with an EC device exhibiting a visible transmittance range of approximately 7-70%. The results demonstrate the potential

of EC glazing to mitigate glare while maintaining visual comfort.[139] proposed an optimized electrochromic glazing control parameter and value to improve the energy performance and sustainability of medium-sized commercial building in different climates. [140] and [141] have also investigated gasochromic and plasmochromic smart windows, respectively, for building applications, focusing on improving indoor comfort and achieving energy conservation.

Other approaches to enhance window performance include the use of aerogels and photonic crystals. [142] described the development of double pane glazing systems with monolithic silica aerogel in their cavity, noting that while aerogel blankets have shown promise in retrofitting projects, glazing systems with aerogel are still in the research stage. [143] introduced a photonic crystal glazing (PCG) system capable of dynamically controlling near-infrared (NIR) reflection without affecting visible light transmittance. The PCG system demonstrates the potential for reduced energy consumption.

The thermal performance of windows has been a central focus of many studies. [144] investigated the thermal transmittance of secondary glazing products, including plastic film and low-E glass, as a retrofit alternative for single-glazed windows. Their measurements on a typical New Zealand single-glazed aluminium window provided insights into the effectiveness of different retrofit options. [145] emphasized the importance of thermal transmittance (U-value) in evaluating the insulating properties of glazing materials.

Furthermore, the impact of window size and glazing properties on energy consumption has been assessed. [146]evaluated the impact of different window sizes and glazing types on

heating and cooling energy needs in a hospital patient room, concluding that wider windows with appropriate glazing can lower energy demand.

In the context of Saudi Arabia, [147] reported that the use of double-pane low-E glass has been found to reduce cooling loads by up to 20% compared to single-pane glass.

Studies examining buildings in the Qassim region demonstrated that northern-oriented windows showed lower energy consumption compared to other orientations, while specific WWRs and glazing U-values significantly affected energy loads [148]. These findings confirm that glazing system selection and design are fundamental considerations for enhancing building energy efficiency in Saudi Arabia's challenging climate. The SBC specifically addresses energy conservation requirements, including standards for glazing systems [149]. These regulations aim to minimize heat transfer through building components and external elements, with explicit requirements for double-glazed and heat-reflecting windows [150]. The code recognizes the significant impact of glazing on cooling loads and establishes minimum performance standards to reduce energy consumption.

Research comparing buildings designed according to SBC standards versus conventional construction has shown that SBC-compliant buildings demonstrate substantially lower operational costs-approximately 44% less than non-compliant buildings [150]. This dramatic improvement stems largely from reduced cooling requirements achieved through more effective building envelope performance, including improved glazing systems.

2.6.2 Window Frame

The window frame serves a dual function: it structurally supports the glazing and anchors the window to the building envelope. Although frames account for a relatively small

portion of the total facade area, their contribution to thermal losses is disproportionately large [151]. This issue has become more critical in recent years as glazing technologies have advanced significantly, achieving much lower U-values than those typical of frame materials [32]. Consequently, improving the thermal performance of window frames has become essential.

Despite this, technological progress in window design has predominantly focused on glazing, often overlooking the frame component [107]. At present, aluminium—known for its high thermal conductivity—is the most commonly used framing material in Saudi Arabia. Alternatives composed of low-conductivity materials are sometimes criticized for their lower mechanical strength and the need for wider profiles, which may reduce visible transmittance. However, such concerns are not always supported by robust empirical evidence [152]. Regardless, the role of window frames in influencing the overall energy performance of buildings remains substantial and demands greater attention in both research and practice [108].

2.6.3 Frame Materials and Design for Improved Performance

The choice of material significantly impacts the thermal performance of window frames. Common materials include wood, aluminium, vinyl (PVC), fiberglass, and composite materials [153].

- **Aluminium Frames:** They are durable and lightweight but have high thermal conductivity, leading to significant heat transfer (160 W/m·K compared to 0.17 W/m·K for PVC) [154]. To achieve better thermal performance, aluminium frames require the integration of thermal breaks. These breaks interrupt the conductive

path, reducing heat transfer between the interior and exterior [155]. Studies have shown that aluminium frames with thermal breaks can achieve U-values comparable to those of less conductive materials [7]. However, aluminium frames are noted for high environmental impacts compared to materials like wood or PVC [111].

- Polyvinyl Chloride (PVC) / Vinyl Frames: Offers relatively good thermal performance due to its lower conductivity compared to aluminium [152]. PVC frames are considered suitable options due to their lower cost, thermal efficiency, fewer environmental impacts, and recycling possibilities [111]. Their thermal performance can be improved by optimizing the geometry of internal cavities, applying low-emissivity coatings on cavity surfaces, or filling cavities with insulation like polyurethane foam [156]. Research has demonstrated that filling the cavities of vinyl frames with insulation materials like polyurethane foam can reduce their thermal transmittance by up to 10% [157].
- Fiberglass Frames: They are made from glass fibres embedded in a polymer matrix, offering a balance between durability and thermal performance [32]. They have lower thermal conductivity than aluminium and can be designed with internal cavities for additional insulation. Studies have shown that optimizing the geometry and insulation of fiberglass frames can significantly reduce their U-values [14].
- Wooden Frames: Wooden frames are traditional and offer good thermal insulation due to wood's low thermal conductivity. However, they require maintenance to prevent rot and insect damage [153]. Research indicates that the thermal

conductivity of wood varies by species and anatomical direction, with hardwoods generally performing better than softwoods [158].

- **Composite Materials:** Combine different materials like aluminium and wood or aluminium and plastic [152]. For example, [153] found that aluminium-clad wood is considered a sustainable option with versatile applications. Another example is GFRP (Glass Fiber Reinforced Polymer), which have been shown to achieve low thermal transmittance while maintaining structural integrity [159].

The literature on window frames in building energy performance highlights the critical role that frame materials and designs play in enhancing energy efficiency in buildings. A variety of studies have explored the impact of various window frame materials on overall building energy consumption.

[160] focused on defining material performance targets for window frames, emphasizing the need for improved thermal performance beyond current market offerings. Their simulation studies revealed how variations in surface emissivity and frame material conductivities significantly affect the thermal performance of window frames, underscoring the importance of material selection in energy-efficient design.

[161] conducted a comprehensive analysis of various window frame types, including PVC, wood, and wood-aluminium, using both numerical simulations and experimental methods. Their findings indicated that different frame materials exhibit distinct thermal characteristics, which can influence the overall energy efficiency of buildings. This study contributes to understanding how specific frame designs can be optimized for better thermal performance.

[162] conducted long-term experimental measurements comparing three windows with triple glazing but different frame types-one wooden and two plastic frames with varying thermal properties. Their research, conducted in laboratory conditions with constant indoor boundaries and real outdoor climate exposure, provided valuable insights into the comparative performance of different frame materials under identical conditions

Similarly, [162] evaluated three different windows suitable for low-energy or passive houses. All windows featured triple glazing but varied in frame type-two plastic frames and one wooden frame, with one plastic frame incorporating thermal insulation. Their assessment based on inner surface temperatures and thermal transmittance differences revealed significant performance variations attributable to frame design and materials.

In a study comparing aluminium, uPVC, and wood frames with a 1 m² glazing area, the U-values were significantly different: 11.86 W/m²K for aluminium, 2.11 W/m²K for uPVC, and 1.85 W/m²K for wood. This study found wooden frames performed better thermally than uPVC and aluminium frames [107].

Changing window frame material can lead to a quantifiable reduction in annual energy consumption. For instance, changing from an aluminium frame to a composite frame resulted in an approximate 0.11–1.26% decrease in annual energy consumption, while changing from aluminium to PVC resulted in a larger decrease of approximately 1.49–3.55% [154]

2.6.4 Frame Cavities

Selecting the appropriate material alone does not guarantee optimal thermal properties for window frames [32]. Achieving a low U-value requires the frame's design to be optimized for thermal performance.

Frames air cavities involve complex heat exchange mechanisms that have been studied through various approaches. [163] analysed air cavity profiles with rectangular geometries using CFD simulations in natural convection, comparing the results with infrared thermography surveys to assess temperature trends on cavity outer surfaces. This comparison revealed a strong correlation between experimental and numerical results.

The NTNU research group simulated five different frames to investigate the effects of cavities surface emissivity and material conductivity on U_f -value reduction, following numerical approaches described in ISO standards [160]. They found that coatings with an emissivity of 0.05 reduced the U_f -value due to radiative heat transfer by 11%, often proving more beneficial and cost-effective than increasing frame thickness.

Filling frame cavities with insulation materials, such as polyurethane foam, can significantly reduce thermal transmittance. For example, filling the cavity of a vinyl frame with polyurethane foam has been shown to lower its thermal transmittance by 10% [157]. Similarly, subdividing cavities with vertical walls or filling them with insulation can further enhance fiberglass frames performance [32].

Research comparing different optimization approaches-radiant insulation panels, insulation material filling, and low surface emissivity treatments-shows that adding RIPs in the cavity can reduce the U-factor by more than 7.43%, slightly lower than the 8.97%

reduction achieved by filling the cavity with insulation, but significantly higher than the 0.81% reduction from low-emissivity treatments [5]. This suggests that a combination of these approaches might offer optimal results for frame thermal performance enhancement.

Recent advancements in window technology, such as the integration of phase change materials (PCM) in window frames cavities, were examined by [108]. Their research demonstrated that innovative designs could lead to significant energy savings, particularly in climates with extreme temperatures, further emphasizing the importance of window frame design in achieving energy efficiency. [106] concluded that Filling existing empty cavities of window frames with aerogel granules could reduce the frame thermal transmittance (Uf-value) by 4–29% depending on the frame type.

2.6.5 The Effect of Thermal Bridges and Thermal Breaks

Thermal bridges are areas or components within the building envelope with significantly higher thermal conductivity, creating pathways for increased heat flow [96]. In windows, the frame itself, especially if made of conductive materials like metal, and the edge connection between the glazing and the frame (edge effect) are notable thermal bridges [164]. Metal reinforcements within frames or components like bolts in curtain walls can also act as thermal bridges [165]. The effect of thermal bridges is to significantly increase heat transfer, leading to higher U-values and reduced energy efficiency [164]. Tools like infrared thermography and computer modelling are used to identify and analyse these heat flow concentrations [96]. This approach enables visualization of heat flow patterns and quantification of thermal bridge effects, leading to more effective optimization strategies.

Thermal breaks are materials with low thermal conductivity that are inserted between the inner and outer parts of the frame to reduce heat transfer [39]. An average window frame available on the market could be improved by 50% to 64% through the implementation of solid material thermal breaks, division of cavities, modification of central gaskets, and insulated cavities [166]. For instance, [7] designed an innovative aerogel-based thermal break for a composite window frame made of aluminium and wood. The study showed a 25% reduction in the U_w -value compared to traditional frames, significantly impacting building energy balance. A comprehensive numerical investigation by [106] on 48 window frames filled with various foams and aerogel indicated that replacing existing insulation with monolithic aerogel panes could reduce the U_f -value by 29% to 42%, depending on the frame material. Similarly, [167] simulated the thermal efficiency of aerogel in PVC frames, comparing it to standard insulating materials. The study concluded that filling one chamber (approximately 1 cm thick) with aerogel resulted in a 10% reduction of the U_f -value, lowering it from 0.90 W/m²K with standard insulation to 0.81 W/m²K. A significant 14% reduction in the U_f -value was achieved for PVC frames without steel reinforcement, suggesting that aerogel could offset the additional heat losses caused by the necessary reinforcements in this type of frame.

Thermal breaks are particularly important in hot climates where the temperature difference between indoors and outdoors is significant. By reducing heat transfer through the frame, thermal breaks can help maintain indoor thermal comfort while reducing the need for air conditioning. For example, in a study conducted in Turkey, the use of thermal breaks in window frames was found to reduce heat loss by up to 25% [168].

2.6.6 Frame to Glass Ratio

The frame-to-glass ratio, which refers to the proportion of window frame area to glass area, plays a significant role in determining the energy performance of buildings. This ratio influences heat transfer, solar gain, and daylighting, which are critical factors in various climatic conditions [169].

Studies have shown that lower FGRs can lead to significant energy savings in both heating and cooling seasons. For example, in a study conducted in China, it was found that optimizing the FGR can reduce energy consumption by up to 15% in the cooling season and up to 10% in the heating season [170]. Similarly, in a study conducted in Turkey, it was found that increasing the glass area while reducing the frame area can lead to significant reductions in heat loss [171].

The reason behind this phenomenon can be explained through Fourier's law as window frames typically have lower insulation (higher U-values) than high-performance glazing. Increasing the frame area (higher frame-to-glass ratio) usually increases overall heat transfer, reducing insulation and increasing energy loss or gain through the facade [172].

For energy efficiency, a balance is needed. Too much frame increases thermal bridging, while too much glass can lead to excessive heat loss or gain depending on climate and glass performance [173].

Studies suggest that reducing frame area and using high-performance glazing and thermally broken frames can significantly improve energy performance [174].

2.7 Environmental Impact of Window Frames

The environmental impact of different window frames is a significant consideration in building sustainability, analysed primarily through concepts like Life Cycle Assessment (LCA), embodied energy, and carbon footprint [107]. The environmental impact of window frames is primarily related to their energy efficiency and the materials used in their construction. Energy-efficient windows can reduce the need for heating and cooling, which in turn reduces greenhouse gas emissions [175].

Furthermore, the use of sustainable materials in window frames can also reduce their environmental impact. For example, [176] conducted a multi-objective optimization study focusing on building envelope design, which included window types and frame materials. Their findings indicated that the selection of window frames, alongside insulation materials and wall thermal resistance, plays a crucial role in reducing life cycle environmental impacts.

[80] examined the energy efficiency of building envelopes, detailing the thermal performance of various window frames, including fiberglass and aluminium. This study highlighted the importance of responsible sourcing of materials to minimize environmental impact.

Aluminium window frames are known for their durability and long service life but have a high environmental footprint. The production of aluminium is energy-intensive, with studies indicating that aluminium frames consume 73.06% of their lifecycle energy during the production stage [177]. Despite these challenges, aluminium's recyclability offers opportunities for reducing its environmental impact. Recycling aluminium reduces energy

consumption and greenhouse gas emissions, making it a more sustainable option in scenarios where recycling rates are high. Studies have shown that well-maintained aluminium frames can achieve a 68% reduction in GWP compared to PVC frames when recycling is considered [178].

PVC window frames are another popular option, offering a balance between cost, durability, and environmental performance. For example, PVC frames have been found to have a GWP of 48 kgCO₂eq/FU, which is lower than aluminium but higher than wood [152]. On the other hand, fiberglass window frames are emerging as a sustainable alternative to traditional materials. Fiberglass frames have a lower GWP than both aluminium and PVC, with some studies indicating a GWP of 45 kgCO₂eq [179].

Composite window frames, such as aluminium-clad wood, offer a combination of durability and low environmental impact. These frames typically have a GWP of 50 kgCO₂eq/FU, which is lower than aluminium but higher than wood [152]. The environmental impact of composite frames is influenced by the materials used in their production, with wood contributing to lower embodied energy and aluminium contributing to higher energy consumption.

2.8 Economic Analysis of Window Frames

The economic analysis of window frames involves considering both the initial cost of the windows and their long-term energy savings [180]. This analysis helps determine the most economically advantageous options, balancing initial investment against long-term operational benefits. While energy-efficient windows may have a higher initial cost, they can lead to significant savings over time due to reduced energy consumption [111].

Life Cycle Costing (LCC) is a widely used economic assessment tool that evaluates the total cost of a window system throughout its life cycle, from acquisition to operation and disposal [180]. LCC considers initial investment costs (materials, transportation, labour) and compares them against energy savings over the building's lifespan. LCC considers initial investment costs (materials, transportation, labour) and compares them against energy savings over the building's lifespan [85]. Studies integrate LCC with Life Cycle Assessment (LCA) to provide a holistic view, balancing environmental impacts with economic costs [153].

Cost-Benefit Analysis approach specifically focuses on determining whether the benefits (primarily energy savings) justify the initial investment in improved windows [108]. It often involves calculating the payback period, which is the time it takes for the accumulated energy cost savings to equal the initial additional investment cost of the more efficient window [85]. One study in a severe cold climate found that an optimal window configuration (with specific WWRs and a plastic-steel frame containing PCM) saved about 20% heating cost and energy, with a calculated payback period of 5.2 years [108].

2.9 Simulation Tools and Methodologies

Simulation tools and methodologies for assessing the thermal and energy performance of window frames are crucial for optimizing building energy efficiency. Computer simulation is described as more economical, repeatable, and not limited by time or place compared to experimental tests, making it generally adopted by scholars. Various approaches have been developed, each with its strengths and limitations. Numerical simulations, often based on ISO standards like ISO 10077-2 and ISO 15099, are widely used to evaluate the thermal

transmittance (U-value) of window frames, providing a good overall agreement with experimental results [181]. Computational Fluid Dynamics (CFD) simulations are employed to investigate convection and radiation effects within frame cavities, offering detailed insights into heat transfer processes [182]. Simplified tools have also been developed to predict the thermal behaviour and energy-saving potential of ventilated windows, validated by full-scale experiments and numerical simulations [183].

Two-dimensional (2D) heat transfer analysis is considered an efficient and accurate method to obtain results compared to CFD simulations and hot box testing [106]. It is a common approach, supported by the evidence that one dimension of a window frame is considerably larger than the other two [39]. A detailed numerical simulation should consider a three-dimensional approach to account for all heat transfer modalities (conduction, convection, radiation) with fluid-solid coupling. However, a complete 3D CFD analysis requires high computing power or long simulation times. Vertical window frames (jambs) specifically require 3D geometries for full CFD analysis [78].

Finite Element Method (FEM) is a widely used numerical technique for simulating heat transfer [5]. Some studies compared FEM results with CFD simulations, finding reasonable agreement, although accuracy can decrease with high-performing frames with complex geometries [32].

For window frames with internal cavities, heat transfer involves conduction, convection, and radiation [78]. Simplified approaches, common in previous work, treat cavities as solid materials with effective thermal conductivity [32]. This effective conductivity accounts for

the combined effects of conduction, convection, and radiation. Some software packages automatically calculate effective conductivity based on international standards.

THERM which is developed by the Lawrence Berkeley National Laboratory (LBNL) in the United States, is a common software using a 2D heat transfer FEM approach to solve steady-state conduction, convection, and radiation heat transfer [5]. THERM automatically generates a mesh and calculates thermal transmittance and surface temperatures [106]. It's widely used for studying window frame thermal properties and has shown accurate results that validate adopted methodologies [85].

THERM software is a widely used tool for modelling the thermal performance of window frames, offering detailed simulations that help optimize energy efficiency in building designs. It is particularly effective in evaluating the heat transfer characteristics of window frames, as demonstrated in various studies. For instance, [5] utilized THERM to analyse the thermal performance of broken-bridge aluminium window frames, incorporating radiant insulation panels to reduce the U-factor, a measure of heat transfer rate, by more than 7.43%. Similarly, [184] employed THERM alongside WINDOW software to assess the impact of triple-pane glass on the thermal performance of windows, finding significant reductions in heat transfer coefficients and solar heat gain coefficients, which are crucial for energy savings. [185] highlighted the importance of material choice in window frames, using THERM to simulate the effects of different materials on energy consumption, emphasizing the role of low thermal conductivity materials like wood and Low-E glass in reducing heat transfer. [186] further validated the accuracy of THERM simulations by comparing numerical results with experimental data, confirming its reliability in calculating linear thermal transmittance in aluminium alloy windows. The software's utility

extends to predicting condensation resistance, as demonstrated by [187], who used THERM to model indoor surface temperatures and refine condensation resistance ratings. Additionally, the THERM 5/WINDOW 5 NFRC Simulation Manual provides comprehensive guidance on using these programs for certified simulations, underscoring their importance in the industry [188].

2.10 Global Standards and Regulations

Numerous standards and certification systems have been established globally to ensure and verify window frame thermal performance. In the United States, the National Fenestration Rating Council (NFRC) provides standardized ratings for windows, including frame performance [189]. The ENERGY STAR program sets performance thresholds that vary by climate zone, driving the adoption of thermally optimized frames [190].

In Europe, the Passive House Institute has established particularly rigorous standards for window frames, requiring U_f values below $0.8 \text{ W/m}^2\text{K}$ for certification in cold climates [191]. These standards have pushed manufacturers to develop ultra-high-performance frame solutions. The European Committee for Standardization (CEN) has developed comprehensive testing methodologies under EN ISO 10077-2 specifically for frame thermal performance evaluation [192].

Moreover, Window frame thermal performance is governed by various standards that vary by region. In Europe, UNI EN ISO 10077-2:2012 establishes thermal performance requirements [193]. It is used for the numerical method for calculating the thermal transmittance of window frames [106]. It is often used as the basis for frame U-value calculations in simulation software like THERM [14].

ISO 15099 is a Standard for detailed calculations of the thermal performance of windows, doors, and shading devices [194]. It defines procedures for radiation and natural convection in air cavities and calculations of convection and radiation coefficients for frame cavities. Considered more accurate than some other methods [39].

NFRC 100 is a Procedure for Determining Fenestration Product U-factors used in North America [106]. While CSA-A440 is a North American Fenestration Standard / Specification for windows, doors, and skylights [194].

2.11 Conceptual Framework

2.11.1 Theoretical Linkages: A Unified Framework

The interplay between thermal performance, economic feasibility, and environmental impact forms the cornerstone of this study's conceptual framework. As illustrated in Figure 2.1 these dimensions are interconnected:

- Thermal Performance drives energy efficiency, reducing cooling loads and operational costs.
- Economic Feasibility determines the viability of material upgrades through metrics like payback periods and lifecycle savings.
- Environmental Impact quantifies CO₂ reductions, linking energy savings to national sustainability goals.

Conceptual Framework

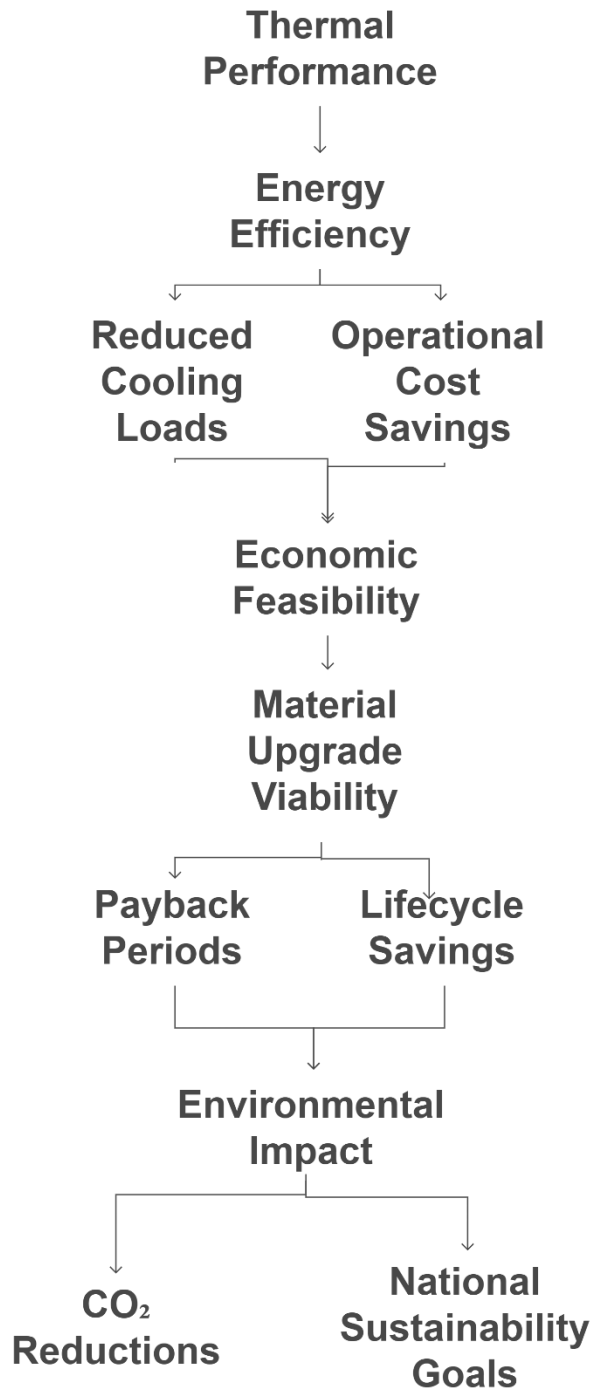


Figure 2.1 Conceptual Framework

2.11.2 Factors Affecting the Thermal Performance of Window Frames

This framework synthesizes the primary factors influencing the thermal performance of window frames, integrating material properties, design elements, climatic conditions, and socioeconomic considerations, as visualised in fig Figure 2.2. It is structured to guide analysis and decision-making for optimizing energy efficiency in hot climates like Saudi Arabia.

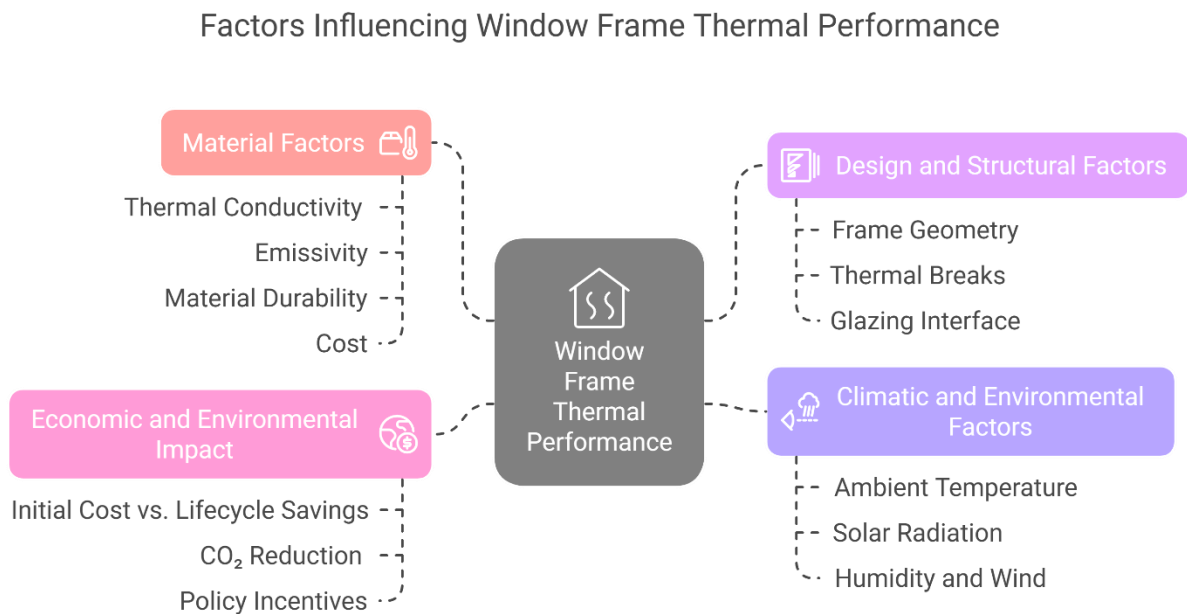


Figure 2.2 Factors influencing the thermal performance of window frames

2.12 Gaps in the literature

- Limited focus on window frame optimization relative to glazing: A disproportionate number of studies concentrate on glazing (glass) technologies while treating the window frame as a static element. This emphasis on glazing has led to relatively few investigations aimed at optimizing the frame's design or

thermal properties. By focusing heavily on glazing, the literature may be overlooking significant energy-saving opportunities associated with frame enhancements.

- Inadequate research into practical applications of thermal break integration in the Gulf region: limited studies have examined thermal break implementation in the Gulf region's building projects.
- Unaddressed climate-specific performance: KSA region's extreme climate—characterized by intense heat, high solar radiation, and, in some areas, humidity and dust—presents unique challenges for window frame performance. However, little research has been directed at how window frame technology copes with or benefits from these specific conditions.
- Limited guidance for local adoption: Due to the above gaps, architects and engineers in KSA have limited region-specific evidence or guidelines on integrating thermal breaks into standard practice. Moreover, SBC lack regulations regarding window frames performance.
- Need for holistic techno-economic analysis: The combined consideration of technical performance, economic factors, and emissions is largely missing in regional research. In other words, few studies adopt a holistic “techno-economic” approach that would provide a comprehensive evaluation of new window frame solutions.
- There is a lack of studies that simultaneously evaluate multiple factors affecting window frame performance. This fragmented approach leaves uncertainty about how different parameters might interact when combined in one design.

Collectively, these identified gaps underscore the need for more exhaustive research into window frame design within the context of energy-efficient buildings, particularly for hot climates like the Gulf region. Addressing these gaps would not only balance the current research emphasis between glazing and frame components but also provide region-specific insights into cost-effective and low-carbon window solutions.

2.13 Summary of the chapter

This literature review systematically explores current research on optimizing the thermal performance of window frames to enhance energy efficiency, particularly within residential buildings situated in hot climates such as Saudi Arabia. The review was thematically organized to address critical areas, including global and regional building energy trends, thermal transmittance of building envelopes, window systems, frame materials, insulation strategies, thermal break technologies, frame-to-glass ratios, and economic and environmental impacts, alongside computational simulation tools.

Globally, buildings significantly contribute to energy consumption and CO₂ emissions, highlighting the necessity of optimizing building envelopes, particularly in regions with high cooling demands. In Saudi Arabia, residential buildings dominate national energy use primarily due to air conditioning, exacerbated by inefficient envelope designs, outdated systems, and growing climate challenges. The Saudi Building Code has implemented standards improving building envelopes, yet regulations specifically targeting window frame performance remain underdeveloped.

The review identified window frames as critical yet often neglected components influencing building thermal performance. While glazing technologies have advanced

significantly, reducing heat transfer through frames remains less explored. Conventional aluminium frames, widely used despite high thermal conductivity, contrast sharply with alternative materials such as U-PVC and fiberglass, which offer superior insulation.

Innovative insulation strategies, particularly thermal breaks, significantly reduce heat transmission through window frames, enhancing energy performance in hot climates. Studies highlighted materials like aerogel for their potential to significantly lower frame U-values. Additionally, optimizing frame-to-glass ratios emerged as crucial, revealing that minimizing frame area relative to glazing typically improves energy efficiency.

Economic analyses underscored the cost-effectiveness of investing in energy-efficient window frames despite higher initial costs, demonstrating rapid payback periods. Environmentally, materials like U-PVC and fiberglass showed lower carbon footprints compared to traditional aluminium frames, aligning with broader sustainability goals.

Critical gaps identified in the existing literature include an insufficient emphasis on window frame optimization relative to glazing, limited practical research on thermal breaks in Gulf climates, and a general scarcity of integrated techno-economic and environmental analyses. These gaps underline the necessity for comprehensive, region-specific studies evaluating combined effects of multiple optimization strategies.

This review positions the current research as a pioneering effort to bridge these gaps by:

- Prioritizing frame optimization over glazing in hot climates.
- Providing climate-specific, simulation-driven data for Saudi Arabia.
- Integrating economic feasibility (payback periods) with environmental impact (CO₂ reductions) into a unified framework.

addressing these gaps can significantly enhance building energy efficiency, providing a robust foundation for developing sustainable, economically viable, and environmentally friendly window frame solutions tailored to hot climatic conditions.

Chapter 3

Methodology

3.1 Overview of Research Approach

This study's methodology framework has been carefully developed to improve the thermal performance of window frames, therefore improving energy efficiency in residential buildings across Saudi Arabia's varied climatic zones. As illustrated in Figure 3.1, the approach has five distinct phases, each facilitating a thorough investigation of factors impacting window frame performance.

Phase one includes a comprehensive literature review and industry contact. It begins with an extensive literature review to understand the current state of window systems, focusing on existing studies and technologies, in addition to identifying the gaps in the existing knowledge around window frame optimization. This phase entails engaging with industry specialists to obtain practical insights and validate the theoretical data. This phase's deliverables encompass a comprehension of current situations, the selection of the base case scenario, the variables affecting window optimization, and the tools and standards presently employed in the industry.

The following phase, which is the simulation and optimization step, utilizes several simulation tools, including THERM and WINDOW, to model and optimize window frame designs. This phase explores various materials (aluminium, U-PVC, fiberglass), gauge thickness of aluminium frames (2mm, 1.8mm, 1.5mm, 1.3mm), different insulation

materials selected according to the Saudi building code recommendations, and gap thicknesses for thermal breaks (5mm, 10mm, 20mm). Each configuration is assessed to determine its impact on thermal performance.

Phase three commences based on the simulation outcomes; new window frame designs are proposed. This phase includes variations in frame-to-glass ratios and the incorporation of thermal breaks. The effectiveness of these designs is compared through various simulated scenarios to identify the most efficient configurations.

All the previous results will then be evaluated in phase four, where a residential case study that represent a typical detached house in Saudi Arabia is selected, modelled, and validated to apply the optimized window frame designs. This phase comprises energy modelling utilizing Rhino and EnergyPlus to verify the performance of the new designs in real-world situations, ensuring the theoretical models' applicability in practice.

Phase five concludes the methodology with a techno-economic evaluation of the suggested window frame designs. This analysis assesses the cost-effectiveness and prospective energy savings, offering a thorough evaluation of the economic and environmental effects of the new designs.

This thesis employs a comprehensive and iterative research approach, whereby each phase is influenced by the insights derived from the preceding phase, as illustrated further in Figure 4.1. Starting with a thorough literature analysis and industry insights ensures that the simulations remain grounded in current practices and technical realities. Advanced simulation techniques provide comprehensive modelling and optimization of window frame designs, considering diverse materials and design modifications.

The iterative nature of design and simulation facilitates continual improvement and optimization of window frames. The research guarantees that the proposed designs are both theoretically robust and practically feasible by validating them through case studies and techno-economic analysis.

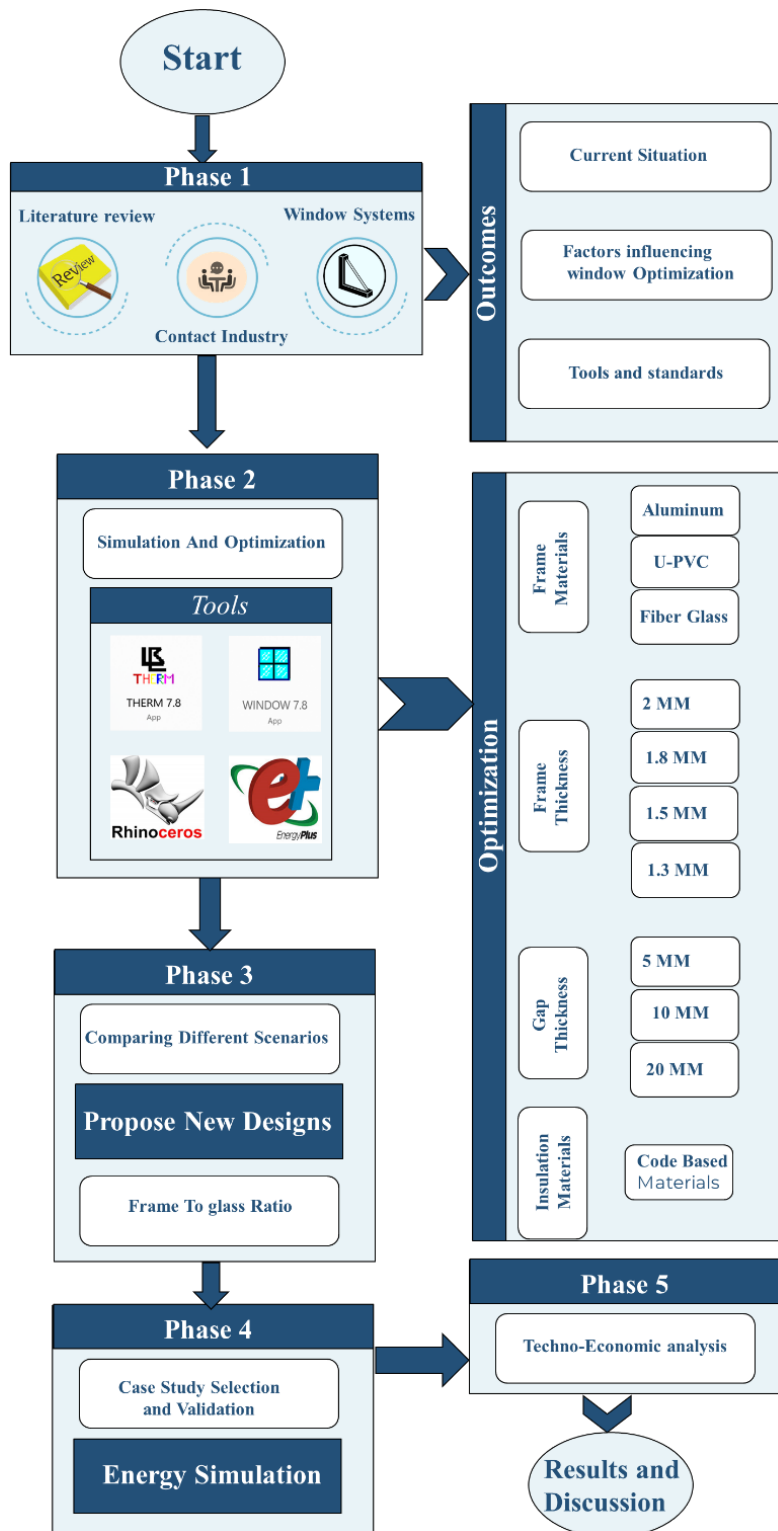


Figure 3.1 Methodology Framework

This methodical approach enhances comprehension of the elements influencing window frame performance and offers actionable strategies to markedly enhance energy efficiency in residential structures in hot climates.

3.2 Simulation Tools and Software

The structured approach for incorporating diverse simulation tools in the research, as illustrated in Figure 3.2, was intended to guarantee the dependability and precision of the simulation outcomes. The workflow begins by identifying the tools used: Therm, Window, Rhino, and EnergyPlus. Each selected for its specific capabilities in modelling, analysing, and simulating different facets of window and building energy performance. The subsequent phase involves outlining the inputs and outputs for each tool, guaranteeing that all required data is organized, and findings are accurately evaluated. We specify boundary conditions, setting outdoor and indoor temperatures at 45°C and 23°C, respectively, to closely mimic the climatic conditions of Saudi Arabia. Defining key variables entails establishing appropriate conditions for the simulations, including material characteristics and geometric configurations. The workflow seeks to attain precise simulations, wherein the interaction among these tools facilitates an exhaustive analysis of energy consumption and thermal performance, ensuring that the simulations yield realistic and applicable outcomes for optimizing window frame designs in dwellings in hot climates. This holistic strategy improves the thesis's methodological integrity and substantially enriches the depth and relevance of the study outcomes.

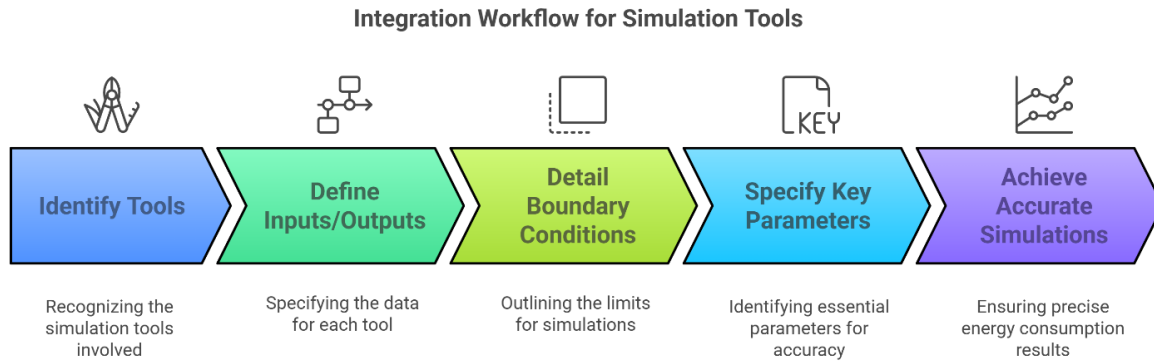


Figure 3.2 Simulation tools integration workflow

3.2.1 Therm Software

The thermal transmittance (U-value) of the window frames was calculated using Therm 7.8, a finite element analysis (FEA) software developed by Lawrence Berkeley National Laboratory (LBNL) [195]. Therm enables 2D heat transfer modelling of building envelope components, adhering to ISO 10077-2:2017 standards for steady-state thermal analysis. This software is critical for this study as it allows the modelling of the window frame sections and calculating the conductive, radiative and convective heat transfer across the frame. It calculates the Frame and edge- of- glass U-Values, which are later exported to window to calculate the total window system (Frame and Glass) U-Value. Cross-sectional profiles of the sliding window frames—including baseline and optimized designs with thermal breaks and insulation—were modelled in Therm. Boundary conditions were defined to replicate typical Saudi Arabian climatic extremes. Material properties including thermal conductivity and emissivity of materials followed ISO 10077-2:2017 standards. A mesh sensitivity analysis ensured grid-independent results, and an error estimator ensures that the error in each simulation run remain below 10% ensuring accuracy.

Per ISO 10077-2:2017 requirements, calculations must be executed on the examples specified in Annex D of the standard in order to validate the suitability of the calculation software employed. The simulated thermal transmittance must not differ from the values specified in the standard by more than 5%. Consequently, one of the examples, depicted in Figure 3.3, was chosen, thereafter modelled and simulated using Therm, as demonstrated in Figure 3.4, leading to a calculated U-value with a variance of 0.06%, shown in Figure 3.5.



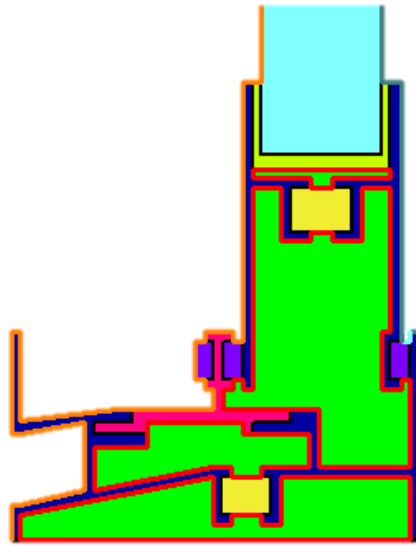


Figure 3.4 Therm's model for ISO 10077-2:2017 Frame

U-Factors							
	U-factor W/m ² -K	delta T C	Length mm	Rotation		Heat Flow W	Heat Flux W/m ²
frame ex	4.7576	20.0	95	N/A	Projected Y	9.0394	95.1514
Frame	4.6731	20.0	95	N/A	Projected Y	8.8788	93.4612

Display
☒ U-factor
☐ R-value

% Error Energy Norm 7.13%

Export
 OK

Table D.3 — Calculated thermal conductance L^{2D} and thermal transmittance

Example	L^{2D} W/(m·K)	U_f W/(m ² ·K)
Figure D.1	0,550 (0,007)	3,22 (0,06)
Figure D.2	0,263 (0,001)	1,44 (0,03)
Figure D.3	0,424 (0,006)	2,07 (0,06)
Figure D.4	0,346 (0,001)	1,36 (0,01)
Figure D.5	0,408 (0,007)	2,08 (0,08)
Figure D.6	0,659 (0,008)	4,67 (0,09)

Figure 3.5 U-Values of the Actual and simulated ISO Frame

The accuracy of the simulation procedure was tested by reproducing the work of Umberto Berardi et al. [31]. They employed Therm to model and simulate a PVC frame, as depicted in Figure 3.7 and Figure 3.6. Consequently, we re-modelled and simulated the section, yielding an inaccuracy of 2.3%, as depicted in Figure 3.8.

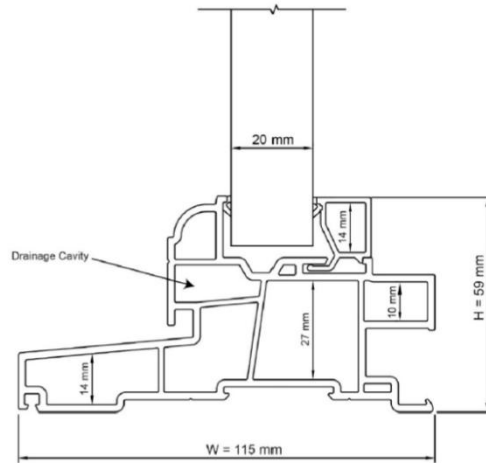


Figure 3.6 PVC Frame Configuration

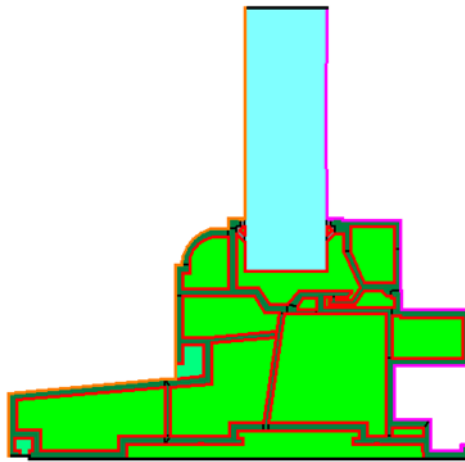
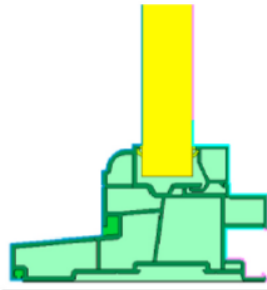


Figure 3.7 Therm's model of the PVC Frame

n results of the current PVC frame design.

Frame profile	Frame section	U-value W/m ² K
	Sill (below)	1.488

U-Factors							
	U-factor W/m ² -K	delta T C	Length mm	Rotation		Heat Flow W	Heat Flux W/m ²
frame ex	2.0474	20.0	43.272	N/A	Projected Y	1.7719	40.9477
Frame	1.4529	20.0	59.5015	N/A	Projected Y	1.7290	29.0578

Display
☒ U-factor
☐ R-value

% Error Energy Norm 2.50%

Export
OK

Figure 3.8 U-values of the actual and simulated PVC frame

3.2.2 Window Software

Window is a supplementary tool to Therm, also created by the Lawrence Berkeley National Laboratory, utilized to assess the whole energy performance of complete window systems [197].

The U-values for the centre-of-glass and the entire window systems (frame + glazing) were calculated using Window 7.8, which incorporates frame thermal data from Therm along with glazing characteristics. The total window system U-value is calculated using the following formula.

$$U_t = \frac{[\Sigma(U_f \times A_f) + \Sigma(U_d \times A_d) + \Sigma(U_e \times A_e) + \Sigma(U_{de} \times A_{de}) + \Sigma(U_c \times A_c)]}{A_{pf}}$$

Equation 1

Where:

U_t = Total product U-factor, W/m²-K

A_{pf} = Projected fenestration product area, m²

U_f = Frame U-factor, W/m²-K

A_f = Frame area, m²

U_d = Divider U-factor, W/m²-K

A_d = Divider area, m²

U_e = Edge-of-glazing U-factor, W/m²-K

A_e = Edge-of-glazing area, m²

U_{de} = Edge-of-divider U-factor, W/m²-K

A_{de} = Edge-of-divider Area, m²

U_c = Center-of-glazing U-factor, W/m²-K

The double-glazed unit (DGU) was designed with a 6 mm external pane, a 13 mm air-filled cavity, and a 6 mm internal pane. The double glass system was selected as it is the predominant glazing system utilized in residential structures in KSA; additionally, it meets the minimum standards established by the SBC [198]. window was utilized to simulate

various frame-to-glass ratios, ranging from 24% to 39%, to evaluate their impact on overall window U-values.

Window software is essential in this research as it offers a comprehensive analysis of the window's performance, integrating the impacts of both the glazing and the frame. The obtained total window thermal transmittance value is utilized in Rhino to evaluate the impact of frame optimization on the energy performance of the case study.

3.2.3 Rhino Software

The 3D geometry of the chosen residential structure was created in Rhinoceros 7 (Rhino), a 3D computer graphics and computer-aided design (CAD) software chosen for its accuracy in architectural modelling and compatibility with energy simulation tools and plugins. This thesis employed Rhino to precisely model the architectural elements of the chosen residential building, ensuring that the window frames were evaluated under appropriate structural and climatic conditions. The modelling procedure in Rhino encompasses the modelling of the building's geometry and the HVAC system. The simulation outcomes are subsequently exported to EnergyPlus for load computations.

3.2.4 EnergyPlus Software

EnergyPlus [199] is a whole-building energy simulation engine validated by the U.S. Department of Energy that models heating, cooling, lighting, ventilating, and other energy flows as well as water use in buildings. It is especially esteemed for its capacity to simulate the energy efficiency of structures over time, including fluctuating weather conditions and various HVAC and lighting options. This study utilized EnergyPlus to simulate the energy consumption of the entire residential building, emphasizing cooling energy needs while

incorporating the recommended optimal window designs. This tool offers insights into potential energy savings and quantifies the effect of enhanced window designs on the building's overall energy efficiency.

3.2.5 Integration and Workflow

The integration of these diverse tools in a sequential workflow, illustrated in Figure 3.9, allows for a robust analysis that spans from micro-scale components (window frames) to macro-scale systems (complete buildings). They ensure a comprehensive approach to optimizing the energy efficiency of window frames by starting with a detailed examination of frame thermal performance in Therm, extending to whole-window evaluations in Window, and culminating in building-scale energy simulations in Rhino and EnergyPlus.

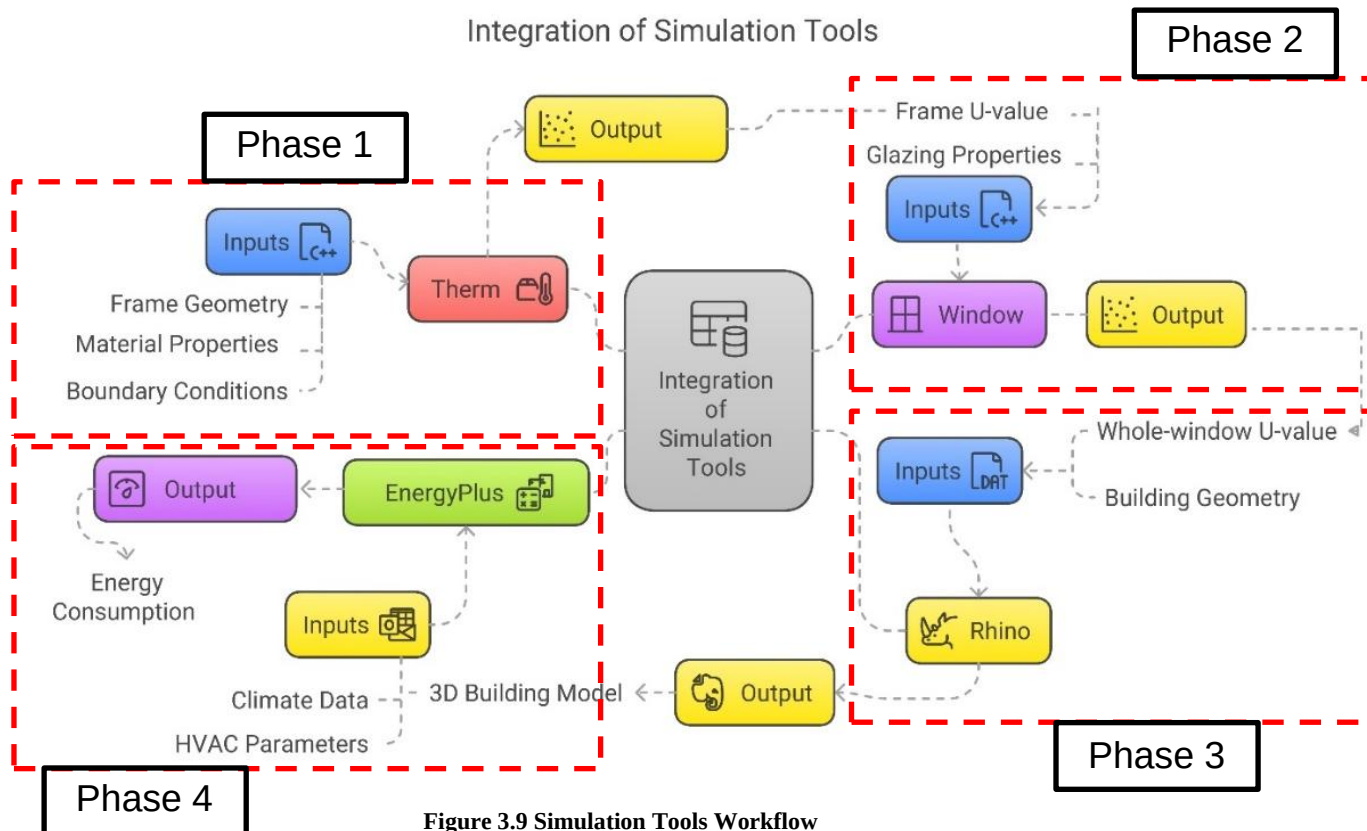


Figure 3.9 Simulation Tools Workflow

3.3 Materials and Boundary conditions

3.3.1 Frame's Materials

The selection of materials for window frames in this study was guided by several critical criteria aimed at addressing the specific demands of energy efficiency and environmental adaptability in Saudi Arabia. The key criteria encompassed:

- **Thermal Performance:** Materials were selected for their capacity to reduce thermal transmittance while boosting overall energy efficiency.
- **Durability:** Materials required to exhibit prolonged endurance to the severe environmental conditions' characteristic of Saudi Arabia, including excessive temperatures and solar radiation.
- **Cost:** Affordability was evaluated to guarantee that the recommended solutions are economically feasible for widespread implementation.
- **Availability:** Preference was accorded to materials that are locally accessible to minimize transportation emissions and promote local industry.
- **Sustainability:** Materials were chosen based on their environmental impact, including embodied carbon and recyclability potential.

consequently, the subsequent materials were chosen:

- **Aluminium (Baseline)**
 - **Rationale:** The reasoning for selecting aluminium as the base case material is its dominant utilization in Saudi Arabia. It is preferred for its structural integrity, corrosion resistance, extensive availability, and affordability. Nonetheless, its

elevated thermal conductivity presents a drawback regarding energy efficiency, which this study aims to solve through design enhancements.

- **U-PVC: unplasticized Polyvinyl Chloride (U-PVC)**

- Rationale: selected for its superior thermal insulation qualities, reduced thermal conductivity relative to aluminium, and its sustainability attributes. U-PVC is an advantageous option in KSA, as it utilizes Saudi Arabia's petrochemical industry, which manufactures U-PVC from oil byproducts. It is produced locally, so diminishing transportation emissions and promoting local economies. Nonetheless, it is prone to thermal expansion at temperatures over 80°C, but it is stabilized with additives for desert regions.

- **Fiberglass**

- Rationale: Chosen for its exceptional thermal insulation characteristics and durability, fiberglass frames provide diminished thermal bridging and outstanding resistance to weathering and thermal expansion, possessing a low thermal expansion coefficient ($\approx 7 \times 10^{-6}/^{\circ}\text{C}$) that guarantees stability amid temperature fluctuations. Nevertheless, it may be more expensive than U-PVC and aluminium.

It can be inferred from Table 3-1, which illustrates a comparison between the three selected materials, that aluminium is physically robust and cost-effective, although it possesses significant embodied energy and inferior thermal performance. Consequently, we maintain it as a benchmark to measure enhancements from innovative designs and materials. We select U-PVC due to its compatibility with Saudi petrochemical infrastructure and its almost 50% lower embodied carbon compared to aluminium. Nevertheless, it necessitates UV-resistant coatings to avert damage. Finally, we examine fiberglass's potential long-term

energy savings, despite its elevated initial expenses. It is optimal for minimizing thermal conduction and structural integrity, especially with thermal breaks.

Table 3-1 Frames Materials selection Criteria

Criteria Material	Thermal Conductivity (W/m·K)	Embodied Carbon (MJ/kg)	Life span	Cost	Tensile strength [Mpa]	Cooling Energy Savings
Aluminium	160	211	long	effective	300	7–15% (with RIPs)
U-PVC	0.17	45	medium	moderate	30	30–40%
Fiberglass	0.4	80	long	high	240	18–22%

3.3.2 Insulation Materials

This section outlines the insulation materials incorporated within the cavities of window frames to improve thermal efficiency. The materials—polyurethane (PUR), extruded polystyrene (XPS), expanded polystyrene (EPS), polystyrene rigid foam, and aerogel—were chosen for their adherence to the Saudi Building Code, their common usage in window frame studies, conformity with ISO 10077-2:2017 standards, and their appropriateness for extreme climatic conditions. As illustrated in Table 3-2, The material selection procedure was also informed by the following criteria:

- Thermal Performance: Reduced thermal conductivity (λ -value) to diminish heat transfer.
- Durability: Resistance to compression, dampness, and thermal degradation in elevated temperature conditions.
- Cost-Effectiveness: Accessibility and affordability in Saudi markets.

- Sustainability: Minimal embodied carbon and recyclability.
- Code Compliance: Adherence to SBC standards for building insulation.

Table 3-2 Insulation Materials selection criteria

Criterion Material	Thermal Conductivity	Sustainability	Cost	Durability	Toxicity
Polyurethane (PUR)	0.024	Moderate (high GWP agents)	Medium cost	moisture-resistant, and stable up to 120°C	High if not well-sealed
XPS	0.029	Low-Non-biodegradable but recyclable	affordable	resistant to moisture and sand abrasion	Moderate
EPS	0.028	Moderate-Recyclable	Low cost	Moderate	Moderate
Polystyrene Rigid	0.025	Moderate-Recyclable	Medium cost	Moderate - susceptible to UV degradation	Low
Aerogel	0.017	Low embodied carbon	High upfront cost	Resistant to moisture and UV degradation	non-toxic

3.3.3 Boundary conditions

Saudi Arabia possesses a primarily hot-arid desert climate, marked by harsh temperatures, low humidity, and high solar radiation, as illustrated in Figure 3.10. Inland places such as Riyadh and the middle Najd plateau often experience summer temperatures over 45°C, with maximum temperatures topping 50°C in locations like Al-Ahsa. Coastal regions, such as Jeddah and Dammam, encounter moderately elevated temperatures (30–45°C) alongside increased humidity (60–85%), intensifying thermal discomfort. The nation experiences

negligible annual precipitation (<100 mm), but solar irradiation averages 6–7 kWh/m²/day, resulting in substantial cooling requirements for structures. Sandstorms and airborne dust frequently affect the durability of building envelopes.

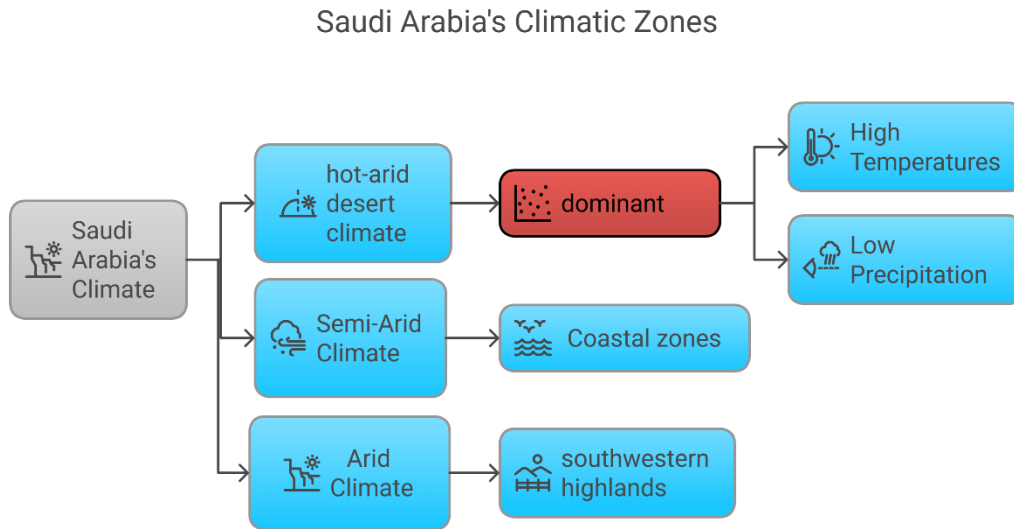


Figure 3.10 Saudi Arabia's Climatic zones

Consequently, for the simulation boundary conditions, an outdoor temperature of 45°C (indicative of peak summer extremes) and an inside temperature of 23°C (in accordance with ASHRAE comfort standards) were used to depict the severe cooling-dominated environment.

The outdoor and interior air film resistances, as presented in Table 3-3, were derived from ASHRAE comfort standards and the SBC [200].

Table 3-3 Simulation Boundary Conditions

Boundary	air film resistances (M2K/W)	Temperature
Outdoor	0.04	45c
Indoor	0.13	23c
Increased-indoor resistance	0.2	23c
Adiabatic	-	-

3.4 Case Studies Specification

3.4.1 Window Frame specification

This section details the window frame configurations analysed in this study, encompassing the baseline design reflective of current Saudi residential construction practices and experimental variations aimed at optimizing thermal performance.

The baseline window system was selected because it represents the most prevalent configuration in Saudi Arabian residential buildings, as confirmed through interviews with local window manufacturers and suppliers. The window system comprised a sliding aluminium frame with hollow cavities (no thermal break) and a double-glazed unit (DGU) with 6 mm inner clear glass pane, 13 mm air gap, and 6mm outer clear glass pane. The aluminium thickness (gauge) can vary from 1.3 mm to 2 mm; however, 1.8 mm was chosen for the base case model as it is the most used thickness in the residential market.

The aluminium frame's cross-sectional geometry (e.g., cavity dimensions, profile width) was replicated from specification sheets provided by a local window frame manufacture,

ensuring the study's relevance to current market trends in Saudi Arabia. This design prioritizes structural durability and cost efficiency but exhibits high thermal transmittance (U-value) due to uninsulated aluminium's conductive properties. The base case window size is 1.2 M by 1.2 M which reflects a frame to glass ratio of 61% glass and 39% frame.

Figure 3.11, illustrates the selected base case frame's sill section and its dimensions, while Figure 3.12, depicts the frame model from the simulation software Therm along with the boundary conditions and selected materials.

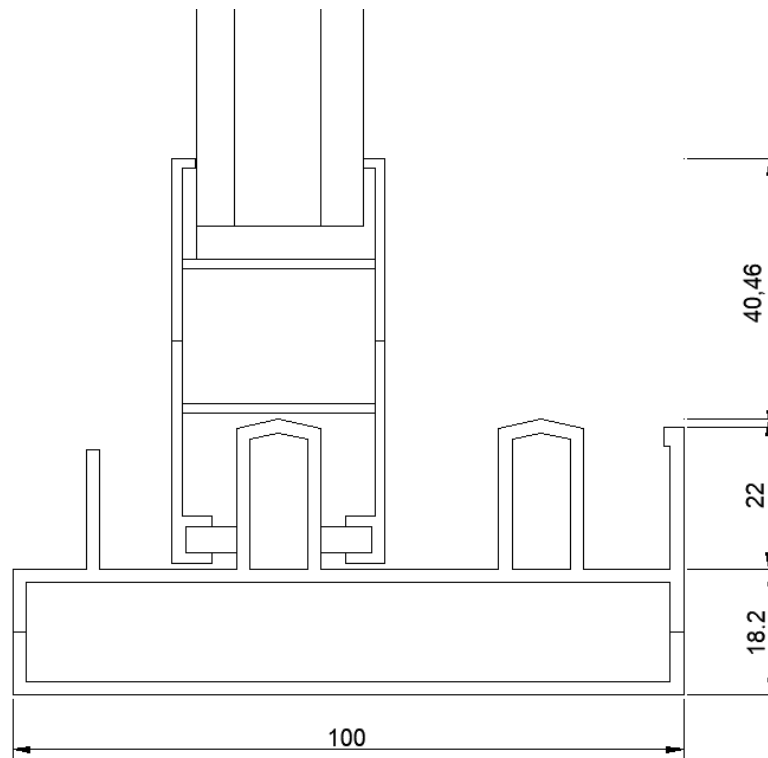


Figure 3.11 Sill Section of the Base Case Aluminium Window Frame

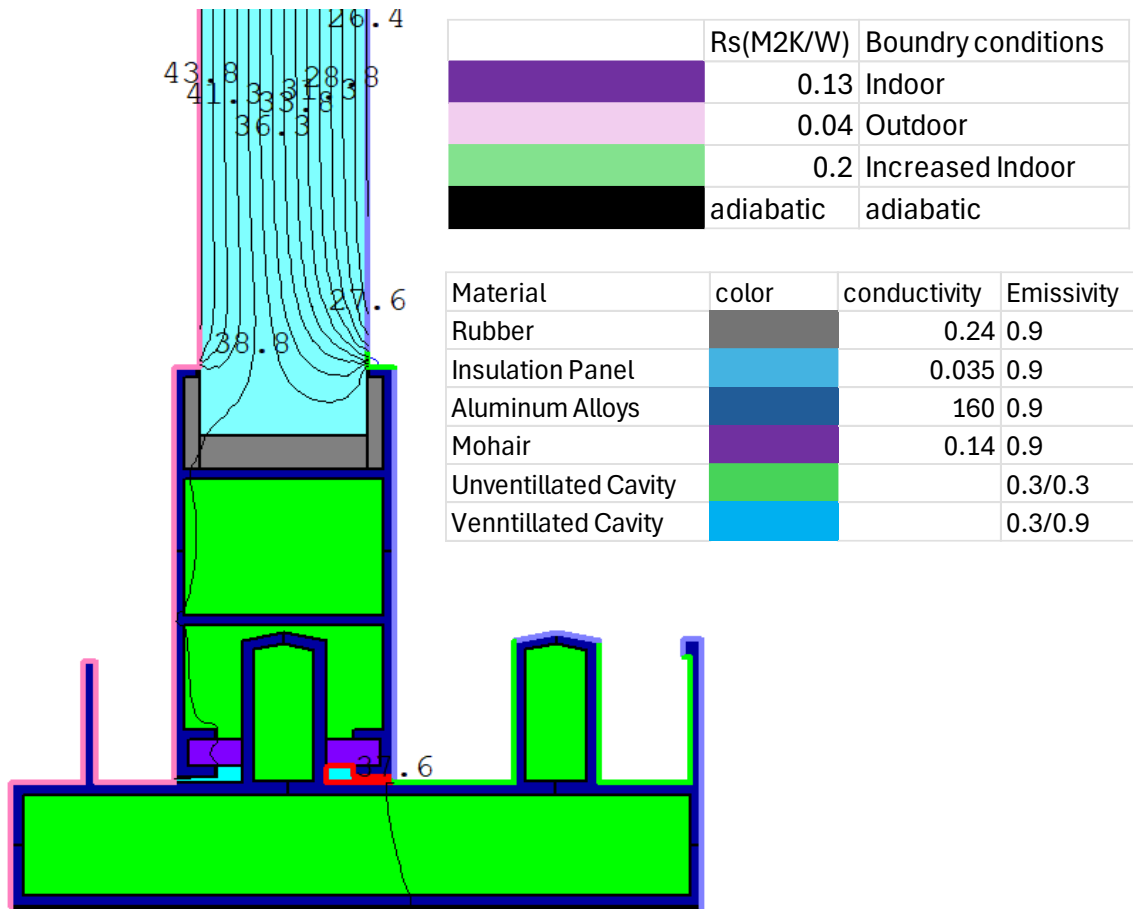


Figure 3.12 Therm's model and boundary conditions

Moreover, to assess the impact of material properties, gauge thickness, and insulation on thermal performance, the following experimental configurations, described in

Table 3-4, were tested: 1- Gauge thickness variations (1.3, 1.5, 1.8, and 2 mm). 2- insulated cavities designs. 3- alternative frame materials (U-PVC, and Fiberglass). 4- Thermal break integration. 5- different Frame- to- Glass ratios.

Table 3-4 experimental configurations

Configuration	Key Variables	Objective
Baseline aluminium	1.8 mm gauge, hollow cavities	Benchmark for current industry performance.
Gauge Thickness	1.3 mm, 1.5 mm, 1.8 mm, 2.0 mm	determine how frame thickness affects the thermal properties of the window
Insulated Cavities	PUR, XPS, EPS, Polystyrene, aerogel	Assess insulation efficacy in reducing U-value.
Alternative materials	U-PVC, Fiberglass	Compare materials' sustainability and thermal performance.
New design	Thermally broken Frames	Evaluate the effect of the thermal break on thermal performance.
Frame-to-glass ratio	Frame portion of the total window	Evaluate the effect of different ratios on energy consumption.

3.4.2 Residential Building Model

This study adopts a prototypical residential villa developed by Wahaj Yaqub et al. [201], based on a survey of Saudi housing typologies conducted by Alrashed and Asif, [202]. The model represents a single-family, two-story detached villa, a design that constitutes approximately 40% of Saudi Arabia's residential building stock. This configuration was

selected for its prevalence in the region and its alignment with local architectural practices, ensuring relevance to real-world energy performance analysis. Table 3-5, list the selected building's specific details.

Building Description

The villa spans a total floor area of 430 square meters and accommodates up to seven occupants. Its layout includes lounges and a kitchen on the ground floor, with private spaces such as bedrooms on the first floor. This layout, as can be seen in the floor plans in Figure 3.13, mirrors typical spatial arrangements found in Saudi homes, combining functionality with local architectural aesthetics.

Building Envelope Details

- Walls: The external walls are constructed without thermal insulation, comprising concrete blocks with a stucco finish. The total thickness of the wall section is 25 cm, resulting in a U-value of 2.23 W/Sqm-K, which highlights a potential area for thermal performance improvement. The walls are finished in a beige-yellow colour, typical of local residences.
- Roof: The roof structure featuring a 42 cm thickness composed of several layers, including terrazzo finish, a waterproofing layer, structural concrete, and an interior gypsum finish. The calculated U-value of 1.934 W/Sqm-K suggests moderate insulation properties.
- Windows: The villa's window-to-wall ratio is approximately 11%, utilizing typical rectangular windows without external shading. These are composed of single clear

glass with a high U-value of 6.1 W/Sqm-K, indicative of significant energy loss potential and an area ripe for optimization in terms of energy efficiency.

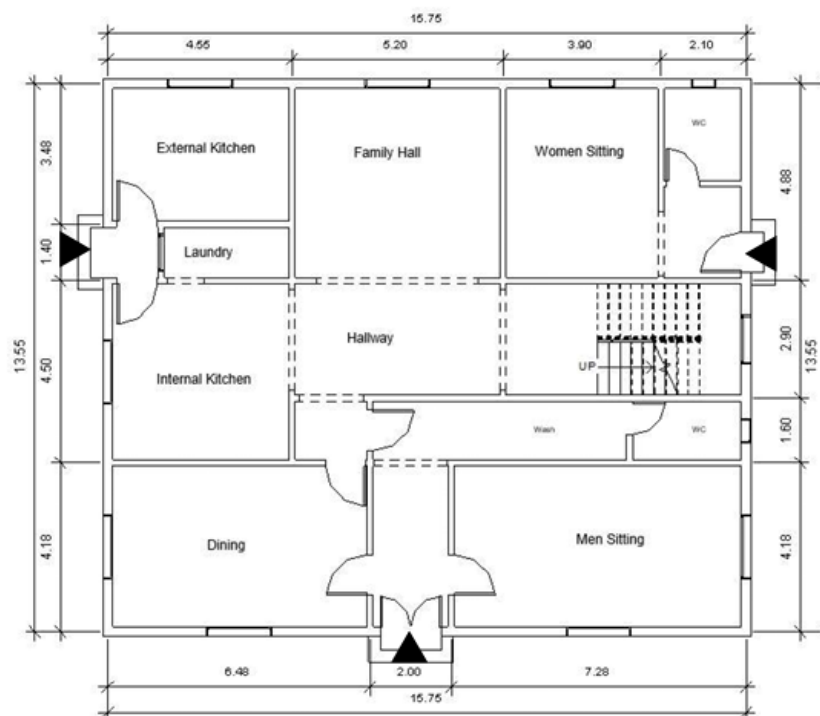
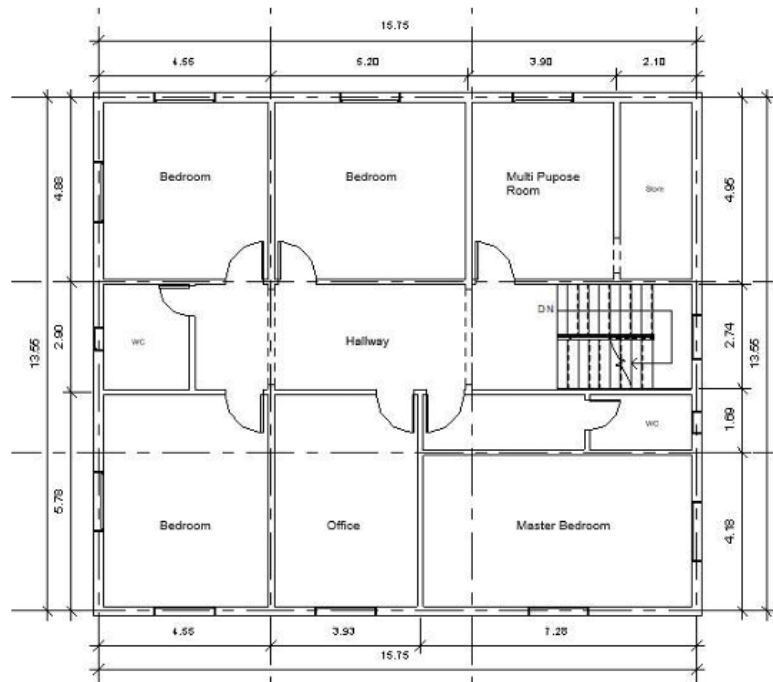


Figure 3.13 Villa Floor Plans. A. Ground Floor Plan. B. First Floor Plan

Table 3-5 Villa Case Study details description

Element	Description
Orientation	East-West
Shape	Square
Occupants	7
Floor Height	3.4 M
Total Floors	2
Total Built Area	430 Sq.m
Exterior Walls	25mm stucco, 75mm concrete block, 50mm air gap, 75mm concrete block, 25mm stucco, U-value: 2.23 W/Sq.m-K.
Finish Colour	Beige -Yellow
Interior Walls	25mm stucco, 100mm Concrete block, 25mm stucco.
Roof	25mm terrazzo, 25mm mortar, 5mm bitumen layer, 150mm cast concrete, 200mm concrete block, 15mm gypsum board, U-value: 1.934 W/Sq.m-K.
Ground Floor	150mm slab on grade
WWR	11%
Glazing	Single Clear, U-value: 6.1 W/Sq.m-K
Shading	None
HVAC	Window AC, COP=1.5, Total Units= 12
AC Set Point	22 C
Lighting	Fluorescent, 5 W,Sq.m
Equipment	Average Gain= 4 W/Sq.m

Infiltration	1.2 ac/h (poor construction)
EUI	148.83 KWH/Sqm/Year

HVAC Details

For this villa, a typical 2-ton window A/C unit with a coefficient of performance (COP) of 1.5 is employed, with a total of 12 units installed throughout the residence to ensure adequate cooling.

3.4.3 Energy Model Validation

The villa and its HVAC system were modelled using Rhino software and its plugins, as depicted in Figure 3.14. Rhino use the EnergyPlus engine to perform energy analysis, hence streamlining the energy simulation process. Furthermore, EnergyPlus is a widely utilized energy modelling engine among researchers owing to its precision. The simulation was conducted utilizing the meteorological information of Al-Dharhan city as the baseline instance.

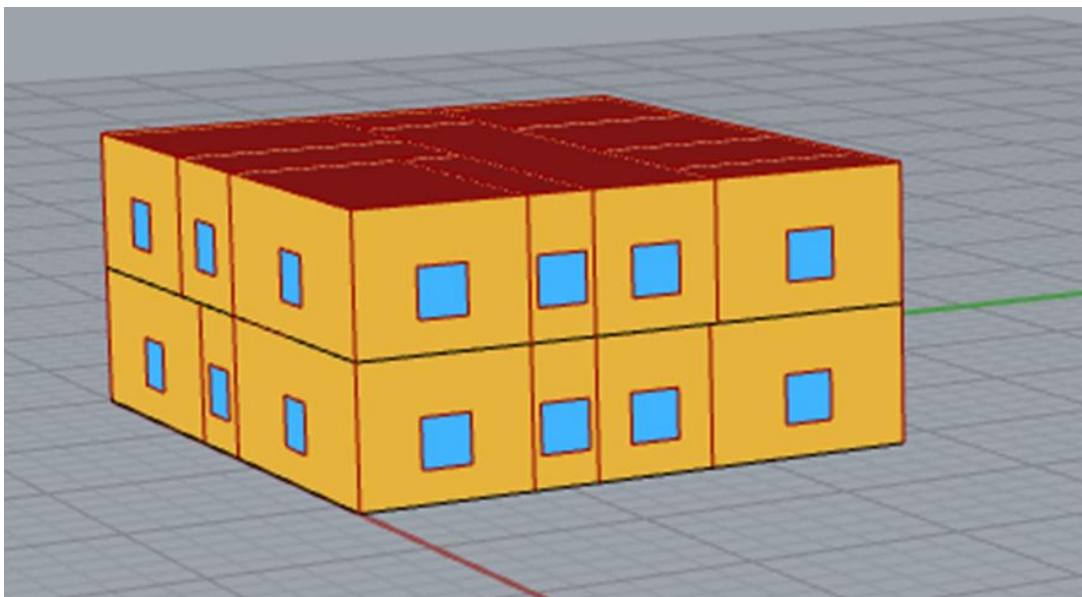


Figure 3.14 Villa 3D model Using Rhino

The energy model was calibrated by comparing the simulated monthly and annual energy usage with the data presented in the referenced publication, [201]. The villa utilizes 64,000.16 kWh of power each year. The simulated model in this research utilizes 63,972.02 KWh, reflecting a variance of 0.04%. Figure 3.15 and Figure 3.16 illustrate the annual and monthly energy use for both the actual and simulated models.

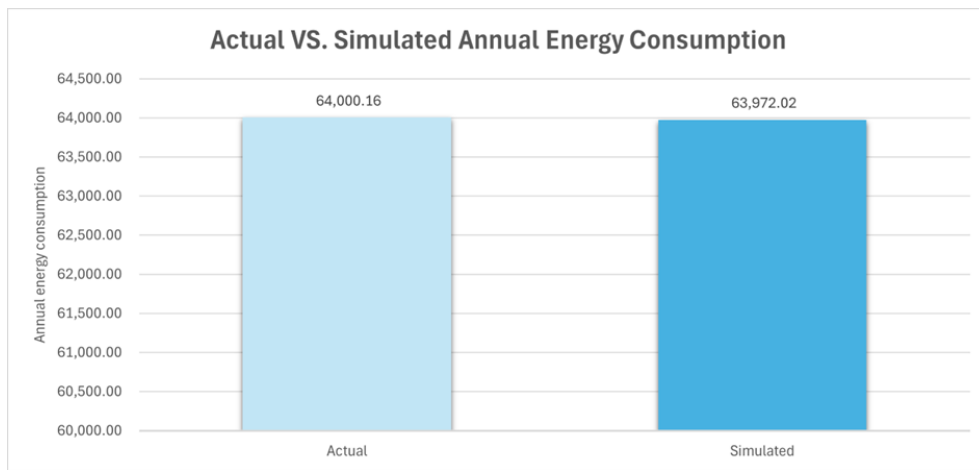


Figure 3.15 Actual VS Simulated Annual energy consumption

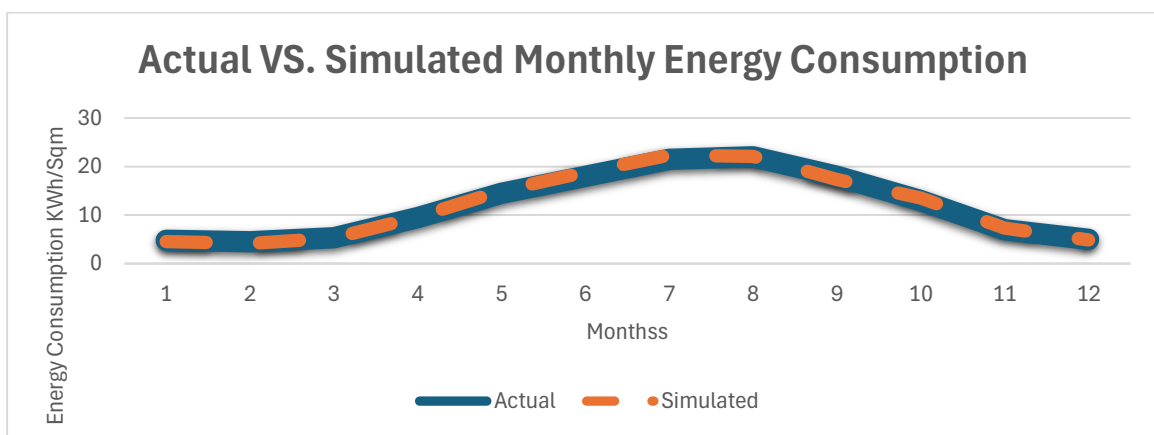


Figure 3.16 Actual VS Simulated Monthly energy consumption

ASHRAE standards mandate that calibration verification be conducted utilizing the normalized mean bias error (NMBE) and the root mean square error (RMSE), with permissible error thresholds of 5% and 15%, respectively. Table 3-6, indicates that the error % across all months remains within the permissible range.

Table 3-6 Energy Model Calibration

Month	Actual Monthly energy consumption KWh/Sqm	Simulated Monthly energy consumption KWh/Sqm	normalized mean bias error	Root Mean Square Error
January	4.8	4.6	5%	2%
February	4.5	4.1	5%	3%
March	5.3	5.3	0%	0%
April	9.5	9.6	1%	1%
May	14.5	15.0	4%	4%
June	18	18.8	5%	7%
July	21.5	22.4	4%	7%
August	22	22.1	0%	1%
September	18	17.3	4%	6%
October	13	13.5	4%	4%
November	7	7.3	4%	2%
December	5	4.9	3%	1%

3.5 Summary of chapter

Chapter Three outlines a thorough approach, incorporating computational modelling, material analysis, and energy simulations, to optimize the thermal performance of window

frames, hence improving energy efficiency in residential buildings in Saudi Arabia. The research commences with a literature review and industry consultations to validate baseline designs (1.8 mm aluminium frames with double-glazed units). It employs Therm (in accordance with ISO 10077-2:2017) and Window to simulate frame and overall window U-values under extreme conditions (45°C outdoors, 23°C indoors), examining variables such as materials (aluminium, U-PVC, fiberglass), gauge thicknesses (1.3–2.0 mm), insulation types (PUR, XPS, aerogel), and thermal breaks. Optimized designs are implemented on a prototypical Saudi villa (430 m², uninsulated walls $U = 2.23 \text{ W/m}^2\text{K}$, single-glazed windows $U = 6.1 \text{ W/m}^2\text{K}$), modelled in Rhino and simulated in EnergyPlus to assess cooling load reductions, resulting in a calibrated annual energy consumption of 63,972 kWh (0.04% deviation from reference data). A techno-economic analysis assesses cost-effectiveness.

This iterative method guarantees solid findings by merging theoretical insights with practical applications and economic assessments to provide actionable ideas for markedly improving building energy efficiency in hot regions.

Chapter 4

Thermal Performance Of Window Frames

4.1 Introduction

This chapter presents the thermal performance analysis of window frame configurations under Saudi Arabia's extreme climatic conditions, addressing the study's core objective of optimizing thermal performance through reduced thermal transmittance (U-values). Building on the methodological framework established in Chapter Three, this section evaluates the efficacy of varying design parameters—including frame material, gauge thickness, insulation integration, thermal breaks, and frame-to-glass ratios—in mitigating heat transfer. The simulations are structured to directly respond to the research questions outlined in Chapter One.

This chapter, as illustrated in Figure 4.1, is organized to reflect a systematic progression of simulations, beginning with the baseline aluminium frame (empty cavities, variable gauge thicknesses), followed by insulated aluminium frames, thermally broken aluminium designs, and finally alternative materials (U-PVC and fiberglass) with and without thermal breaks. Each configuration is tested across multiple frame-to-glass ratios (24–39% frame area) to assess scalability and practical applicability.

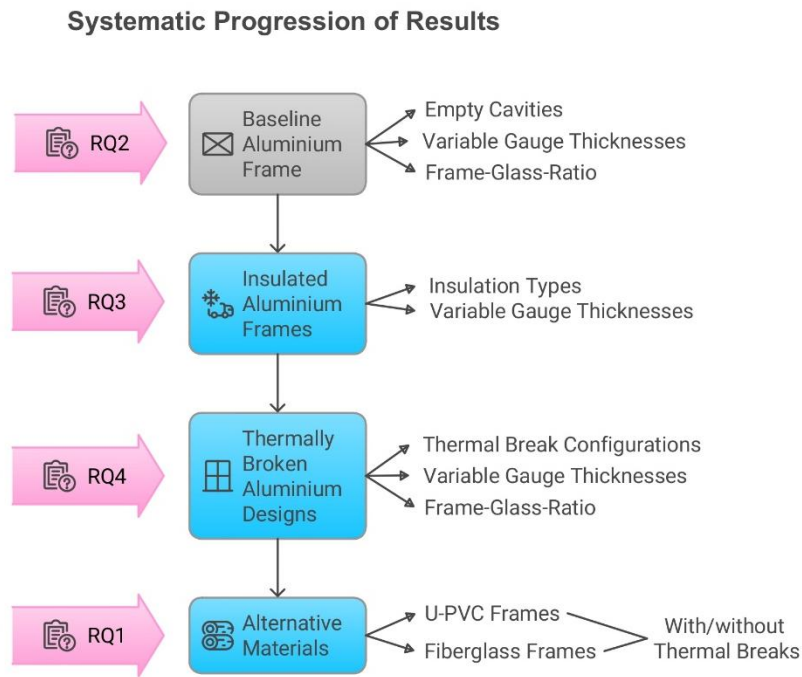


Figure 4.1 Systematic progression of results

4.2 Base Case: Aluminium Frames with Empty Cavities

The base case scenario, illustrated in Figure 4.2, focused on a sliding aluminium window frame with uninsulated cavities, reflecting common construction practices in Saudi Arabia for window frame, to establish a benchmark for thermal performance. To evaluate the influence of material thickness and window geometry on thermal performance, gauge thickness and frame-to-glass ratio were tested.

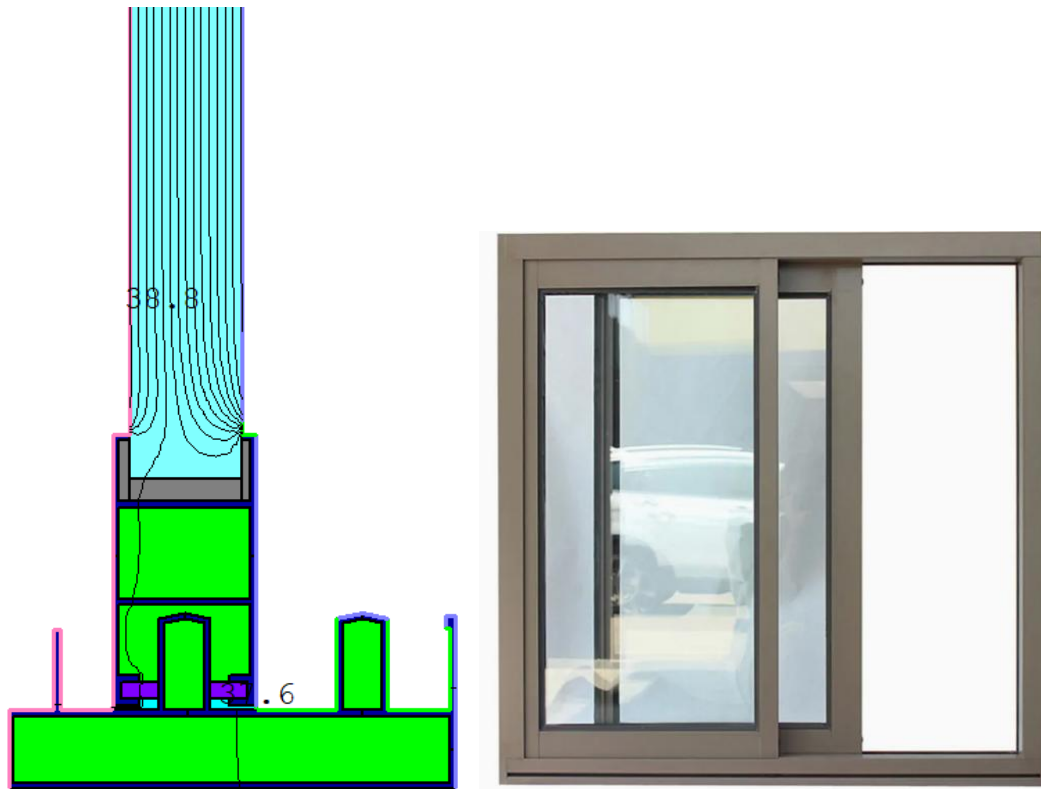


Figure 4.2 Base case frame: uninsulated aluminium frame

4.2.1 Gauge thickness

Four variations of aluminium gauge thickness were tested. These selected thicknesses (1.3 mm, 1.5 mm, 1.8 mm, 2.0 mm) were selected because they are the most used in residential buildings according to the industry specifications. This setup aimed to determine the intrinsic thermal properties of the frames as influenced solely by their material thickness without any other enhancement.

The simulation outcomes depicts that the base case frame, which is widely used in residential buildings in KSA, has a very high thermal transmittance value (U-Value) of around 11.5 W/m²K. The U-values of the aluminium frames exhibited minimal variation across gauge thicknesses, ranging narrowly from 11.4 for the 1.3mm gauge to 11.6 W/m²K for the 2.0mm gauge, as shown in Figure 4.3.

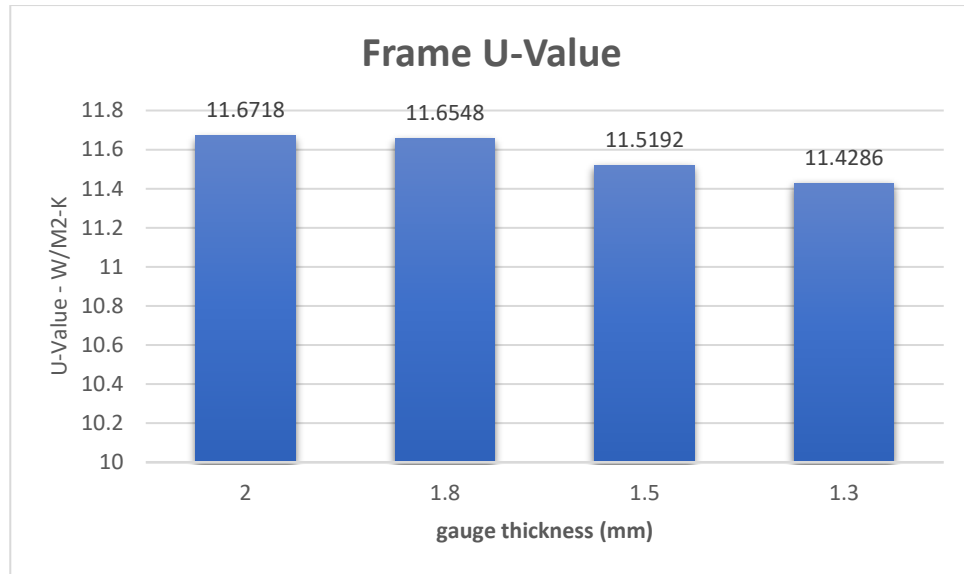


Figure 4.3 Base Case Frame U-values

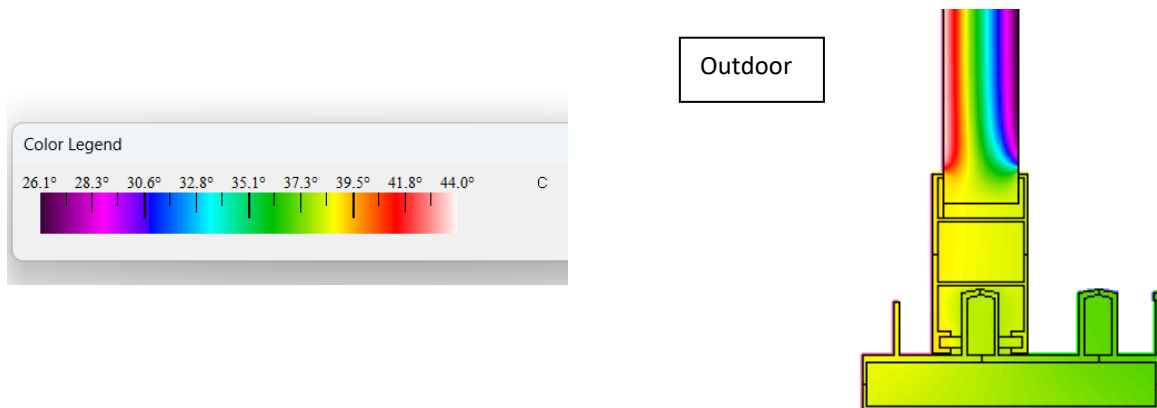


Figure 4.4 Temperature distribution across the frame on a typical summer day

These values indicate the level of thermal conductivity inherent to aluminium, which is generally considered high compared to more insulative materials. The results illustrate that variations in frame thickness have minimal impact on the overall thermal transmittance. These findings underscore the limited effectiveness of relying solely on aluminium's structural variations to achieve significant thermal performance improvements.

4.2.2 Frame-to-Glass Ratios

Further analysis examined how altering the frame to glass ratios affected the thermal performance of the window systems. This was tested by changing the window sizes, which adjusted the ratio of glass to frame surface areas. The software Window was used to model Seven window sizes (1.2×1.2 m to 2.0×2.0 m), as illustrated in Figure 4.5. U-values of the window frames were exported from Therm to Window and then simulated with double-glazed glass system, that has a U-Value of 2.781 W/m²K, to calculate the total window (Glass+ Frame) U-value. Figure 4.6 illustrates that the total window U-value was found to be around 5 W/m²K, again with minimal variation across different gauge thicknesses.

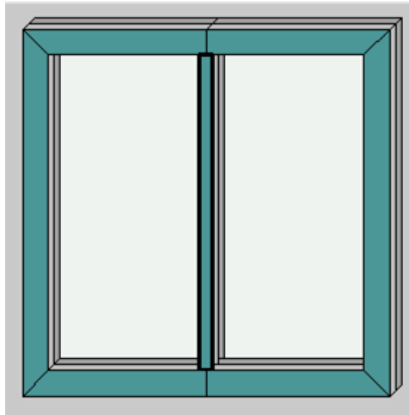


Figure 4.5 Whole window system Model

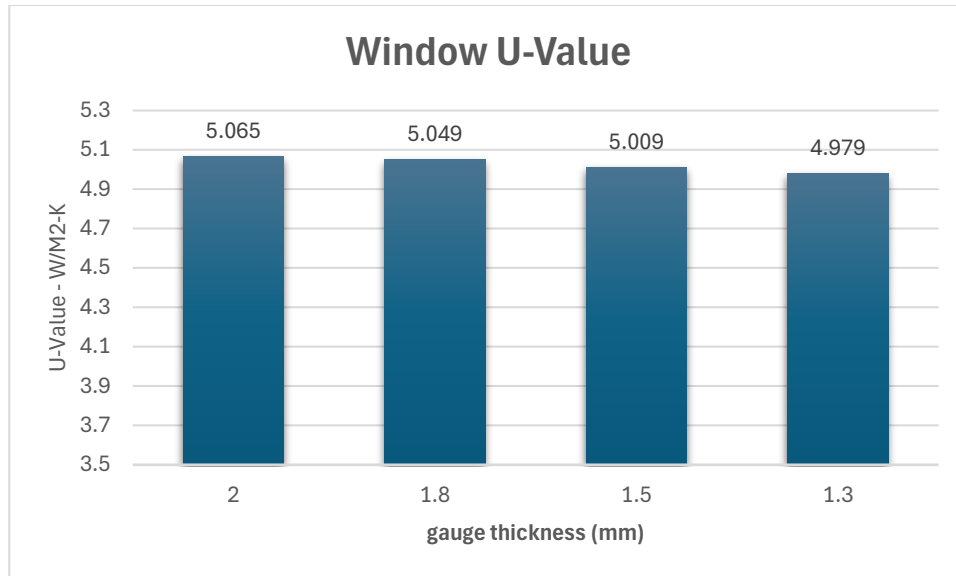


Figure 4.6 Total Window System U-Value- Window size 1.2*1.2m

As Figure 4.7 depicts, the selected window sizes yield glass-to-frame ratios ranging from 61% glass / 39% frame (smallest window) to 76% glass / 24% frame (largest window).

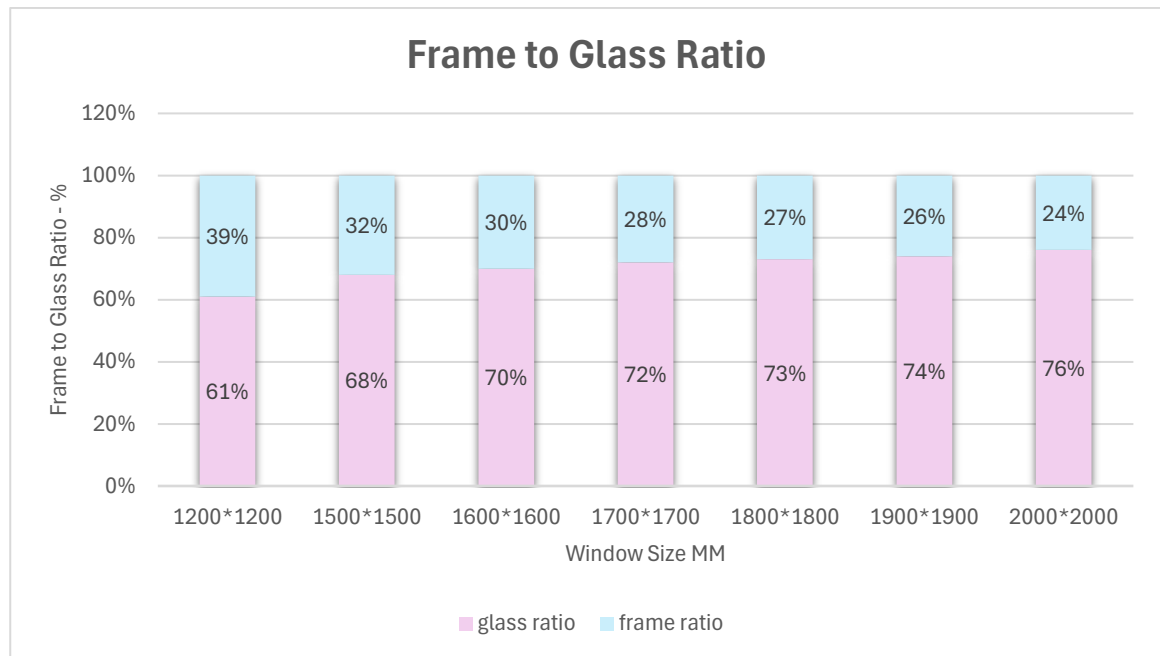


Figure 4.7 glass-to-frame ratios

The simulation results indicated a trend where larger window sizes, which correspond to a higher glass to frame ratio, exhibited lower U-values. This suggests that increasing the proportion of glass, which have much lower U-Value, relative to the frame can contribute to a reduction in overall thermal transmittance, enhancing the window's insulative properties. For instance, increasing the glass proportion from 61% to 76% decreased U-values by around 0.8 W/m²K. Figure 4.8 provides a clear visual representation of this inverse relationship, showing a gradual decrease in U-values as the frame area becomes less predominant in the window structure.

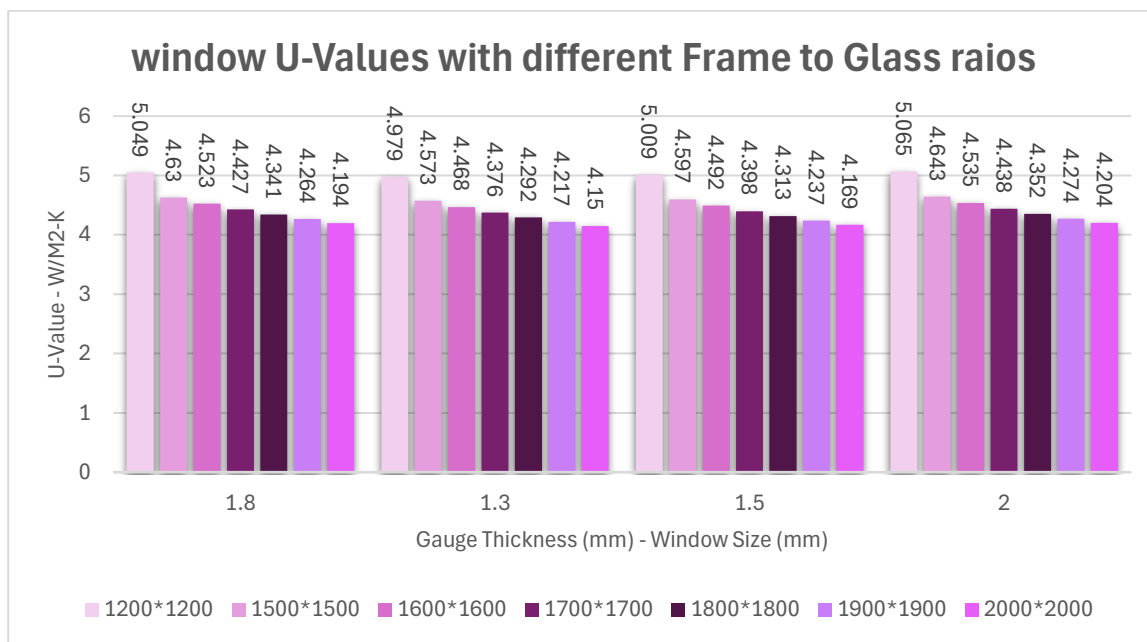


Figure 4.8 Total window U-values with different window sizes (Frame Ratios)

4.3 Insulated Aluminium Frames

To assess the potential of cavity insulation in mitigating aluminium's thermal inefficiency and reducing thermal transmittance, five insulation materials—polyurethane (PUR), extruded polystyrene (XPS), expanded polystyrene (EPS), polystyrene rigid foam, and

aerogel—were integrated into the hollow cavities of the baseline aluminium frames. These materials were chosen based on their thermal performance characteristics, compliance with the Saudi Building Code, and prevalence in window frame insulation literature. This modification was applied across all four tested gauge thicknesses: 1.3 mm, 1.5 mm, 1.8 mm, and 2 mm. Moreover, the insulation was inserted into the frame cavities without altering the frame’s external geometry, ensuring consistency in simulation comparisons, as illustrated in Figure 4.9.

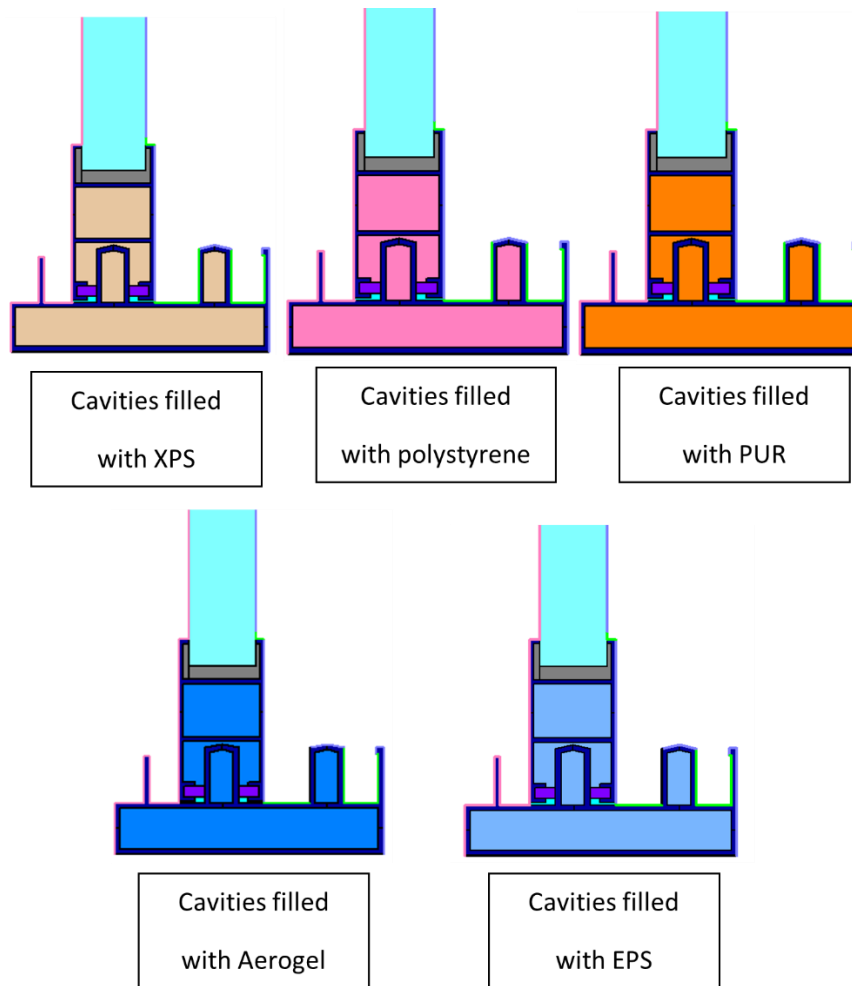


Figure 4.9 Aluminium Frame with insulation in cavities

Simulation outcomes, represented in Figure 4.10, shows that despite the integration of various insulation materials within the aluminium frame cavities, the impact on the overall thermal transmittance was minimal. The U-values remained relatively high across all configurations, showing only marginal improvements compared to the uninsulated base case. For example, even with high-performance materials like aerogel, which is known for its ultra-low thermal conductivity, the U-Value of the frame was only reduced to around 11.4 W/m²K, a mere 0.2% reduction compared to the base case hollow frame.

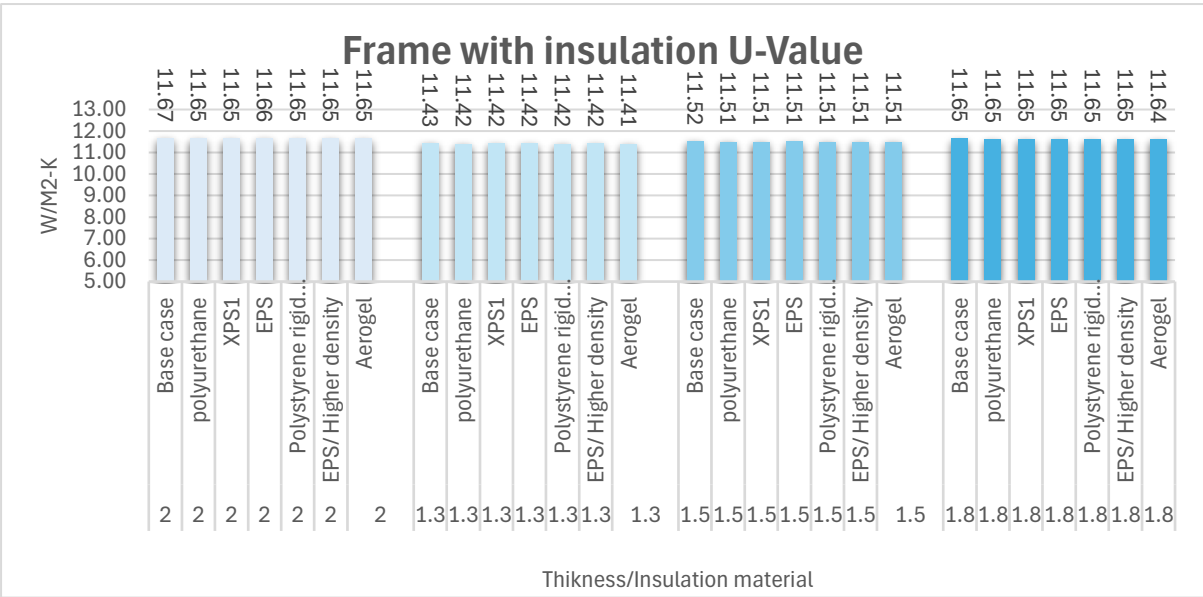


Figure 4.10 Frame filled with Insulation U-Value

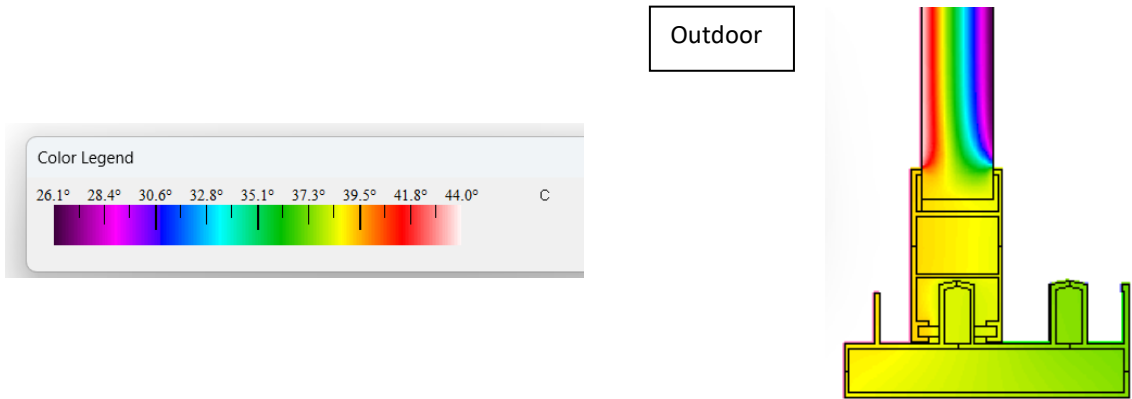


Figure 4.11 Temperature distribution across an insulated frame.

The total window U-value also reflects this limited effect. As Figure 4.12 shows, the maximum reduction in the total window system U-value does not exceed 0.2%.

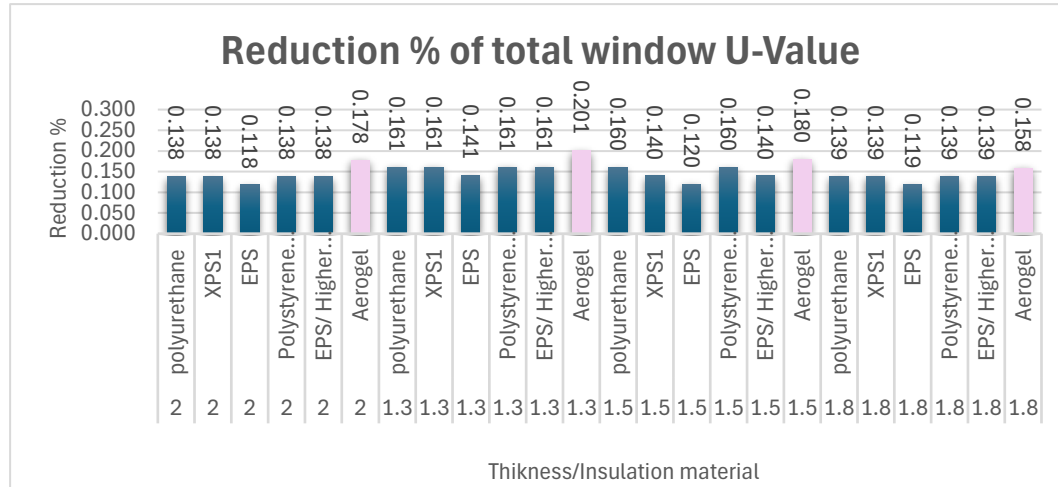


Figure 4.12 Reduction in Total Window U-Value with insulation

This limited performance gain can be attributed to aluminium's inherently high thermal conductivity, which dominates the heat transfer through the frame. In such configurations, heat bypasses the insulated cavities by traveling through the aluminium profile itself (thermal bridging), rendering the internal insulation less effective.

4.4 Thermally Broken Aluminium Frames

To overcome the high thermal conductivity of aluminium and address the thermal bridging inherent in aluminium frames, a series of thermally broken aluminium frame configurations were developed and tested. These configurations involved introducing a thermal break—a separation between the inner and outer aluminium sections of the frame—filled with aerogel, a super-insulative material known for its extremely low thermal conductivity ($\lambda = 0.017 \text{ W/m}\cdot\text{K}$). Three thermal break thicknesses were evaluated: 5 mm, 10 mm, and 20 mm, as illustrated in Figure 4.13. The break was placed centrally within the

cross-section of the fixed part of the aluminium frame, effectively interrupting the direct conductive path between the interior and exterior metal components. The simulations were subsequently evaluated across the same frame-to-glass ratios (24–39% frame area) and climatic conditions (45°C outdoor, 23°C indoor) as the baseline.

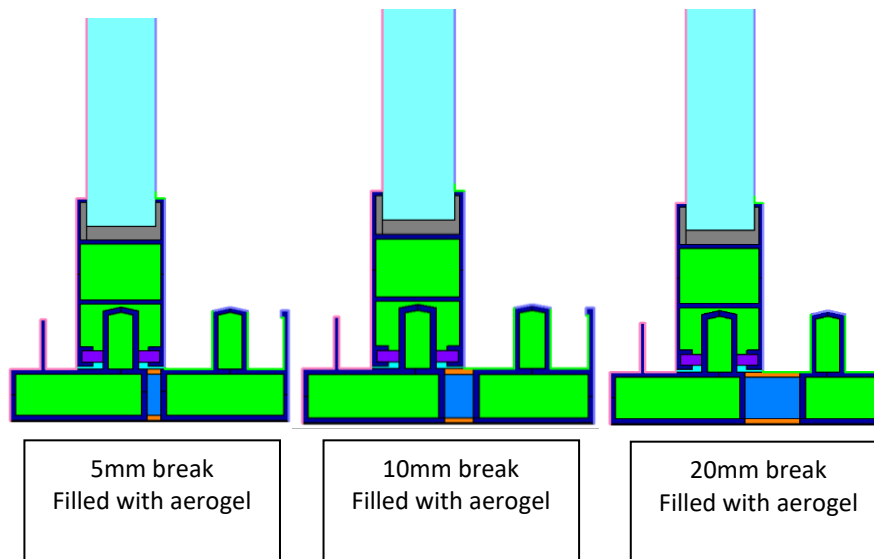


Figure 4.13 thermally broken aluminium frame configurations

The introduction of the thermal break had a significant impact on reducing the U-value of the aluminium frames, with performance improving as the break thickness increased. As shown in Figure 4.14, the 5 mm break yielded a noticeable but modest improvement, while the 10 mm break achieved a substantial reduction in thermal transmittance. The 20 mm break offered slightly better thermal performance than the 10 mm configuration; however, the marginal gain did not justify the additional material and manufacturing complexity. Hence, among the three tested configurations, the 10 mm aerogel-filled thermal break emerged as the most optimal solution, reducing the frame's U-value to approximately 5 W/m²K—representing a more than 50% reduction compared to the uninsulated base case. This thickness provided the best balance between thermal performance, and economic

feasibility, making it a viable option for practical implementation in energy-efficient window frame systems. These findings emphasize the critical role of thermal break design in enhancing the thermal resistance of aluminium frames and suggest that moderate break dimensions, when filled with high-performance materials, can yield substantial improvements without significantly increasing cost or design complexity.

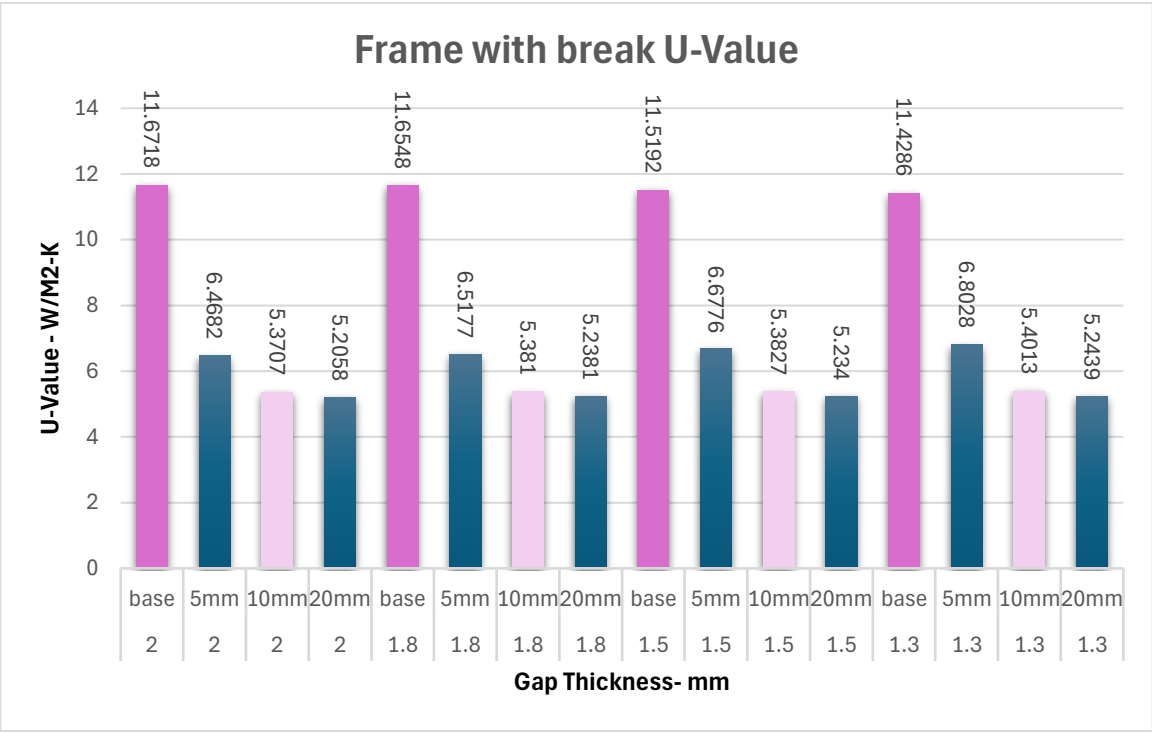


Figure 4.14 Thermally broken Frames U-Values

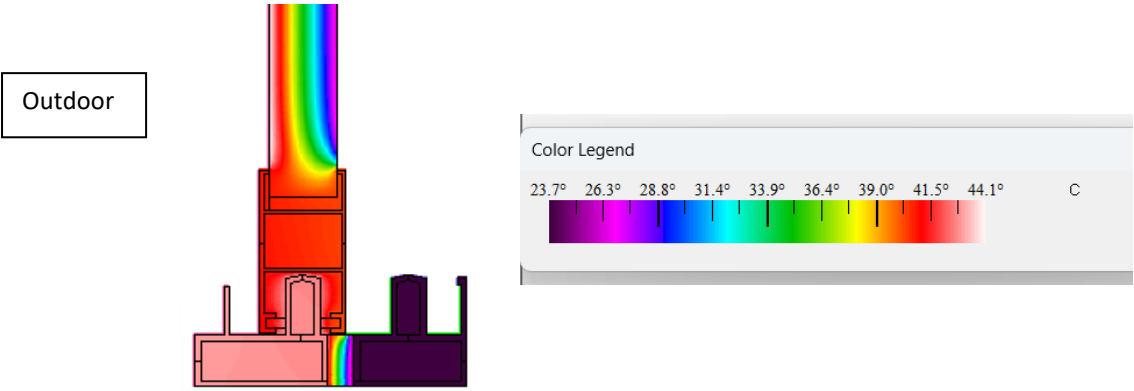


Figure 4.15 Temperature distribution across a thermally broken frame

When combining the thermally broken frame with double glazing, the U-value of the overall window system decreases due to the improved thermal performance of the frame. Figure 4.16 illustrates the percentage reduction of the total window U-values compared to the baseline hollow window frame.

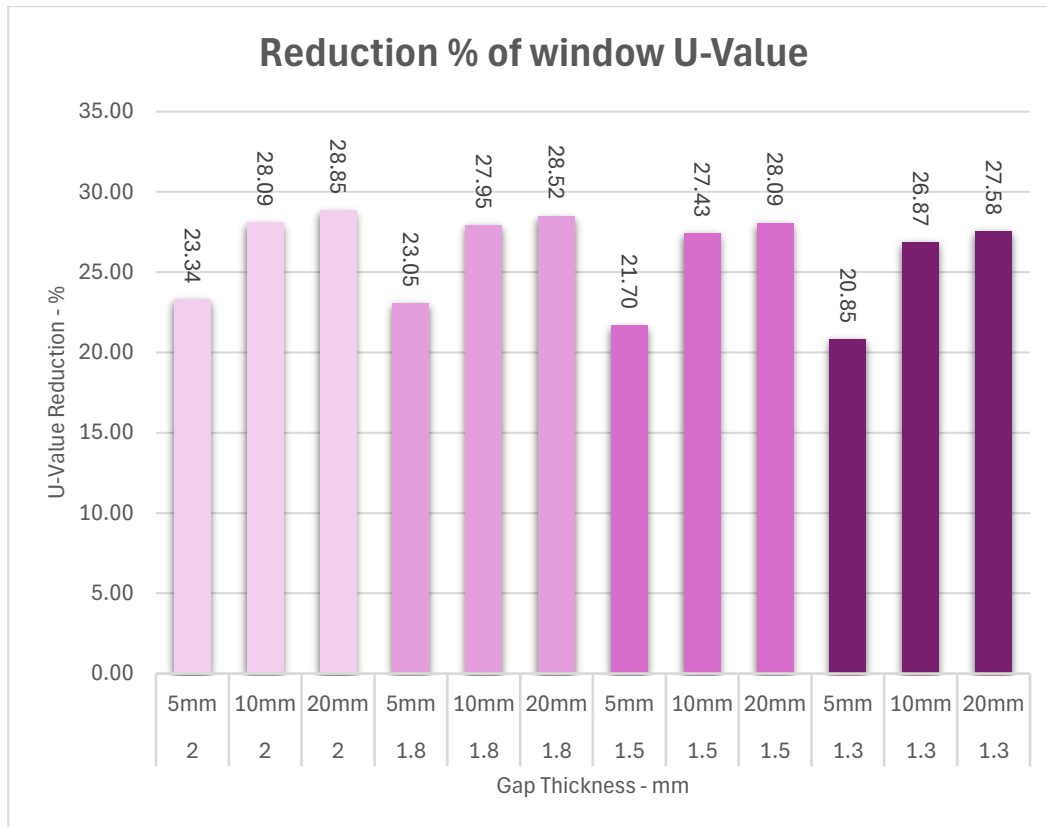


Figure 4.16 Reduction in total window U-Value with thermally broken Frame

As the 10mm gap was proven to be the optimum thickness, it was selected for the Frame to Glass ratio and energy simulations analysis. From Figure 4.17, it can be concluded that larger windows amplified thermal break efficacy. For instance, at 24% frame area (2.0×2.0 m), the U-value dropped to 3.33 W/m²K, a 10% reduction versus the window with 39% frame area (1.2×1.2m).

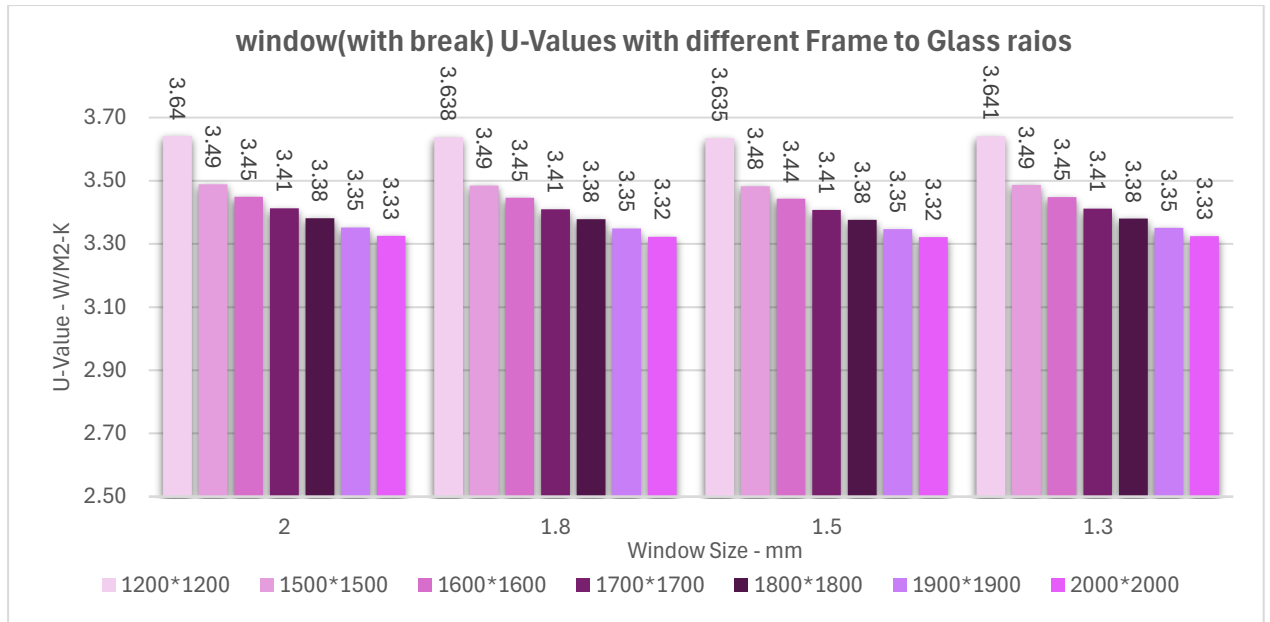


Figure 4.17 Total window U-Values with different thermally broken frame ratios

4.5 Alternative Frame Materials

4.5.1 U-PVC and Fiberglass base case frames

In addition to optimizing the aluminium frame, this study explored alternative materials for window frames with inherently better thermal performance. Two widely used low-conductivity materials were selected and tested: unplasticized polyvinyl chloride (U-PVC) and fiberglass, Presented in Figure 4.18 and Figure 4.19. Both materials were simulated across different gauge thicknesses—1.3 mm, 1.5 mm, 1.8 mm, and 2.0 mm—to maintain consistency with the aluminium configurations. Their thermal performance was also evaluated under varying frame-to-glass ratios, using the same range of window sizes tested in the base case.

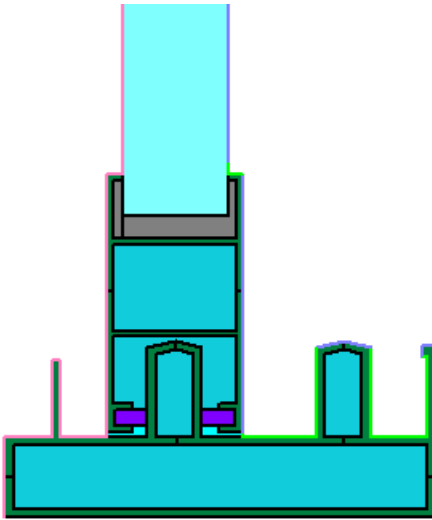


Figure 4.18 U-PVC Frame

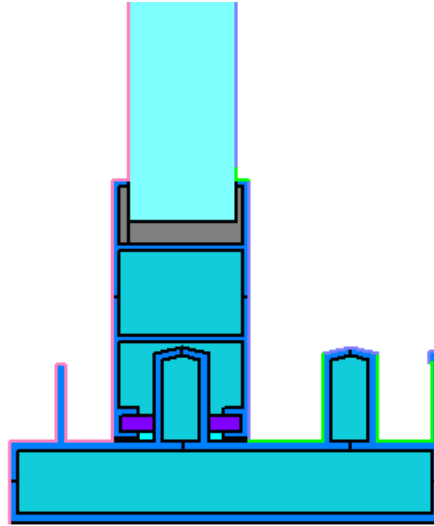


Figure 4.19 Fiberglass Frame

The U-PVC frames demonstrated remarkable thermal performance, maintaining an average U-value of approximately 2.4 W/m²K across all thicknesses, achieving a 79% reduction compared to baseline aluminium frames (11.5 W/m²K). Similarly, fiberglass frames showed slightly higher but still significantly improved thermal resistance, with an average U-value of 2.75 W/m²K, representing a 76% reduction compared to aluminium, as illustrated in Figure 4.20.

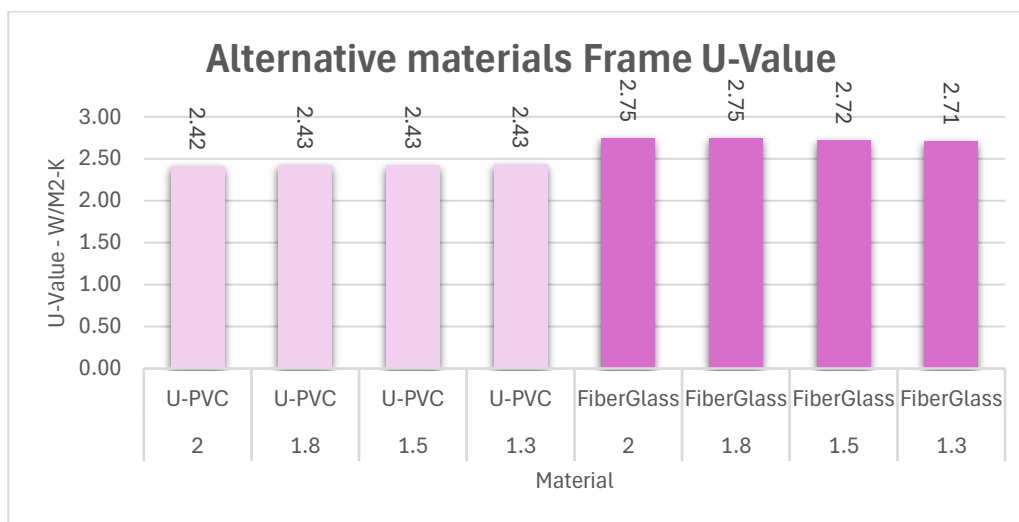


Figure 4.20 U-PVC and Fiberglass Frames U-Values

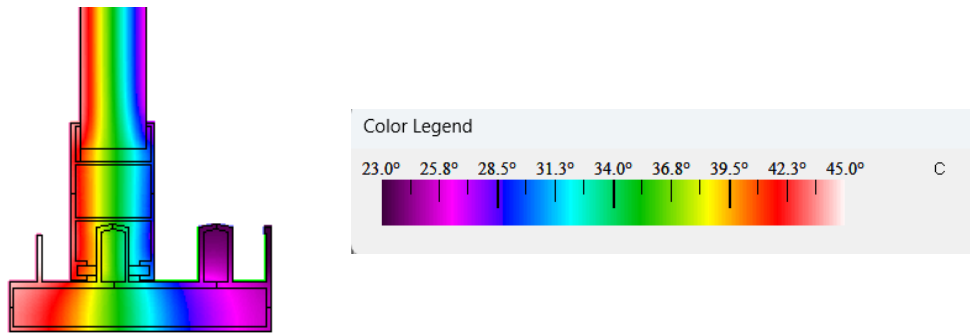


Figure 4.21 Temperature distribution across UPVC frame

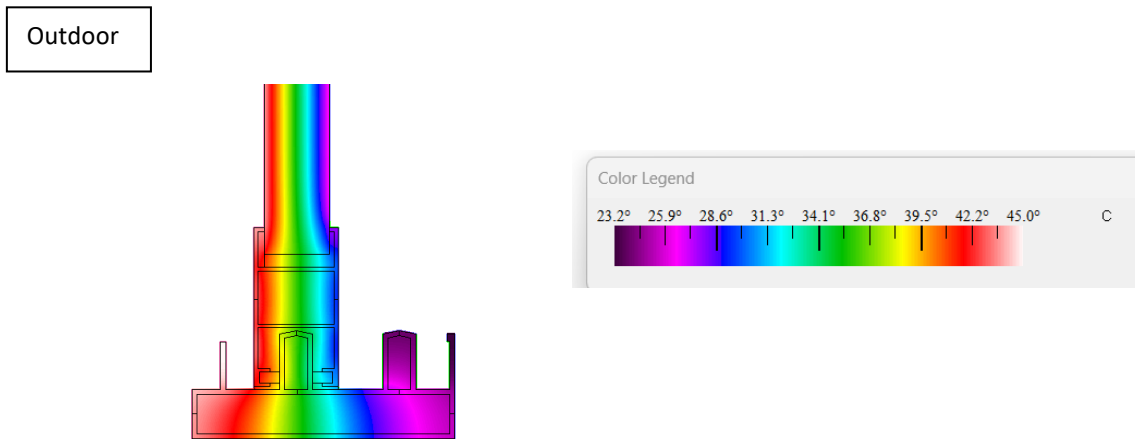


Figure 4.22 Temperature distribution across Fiberglass frame

Furthermore, the reduction in the whole window system U-value when using U-PVC and Fiberglass frames is remarkable. As Figure 4.23 shows, the reduction can reach up to 40% when compared to the base case aluminium frame. The results also confirmed the expected trend across both materials: the larger the window (i.e., the higher the glass-to-frame ratio), the lower the overall U-value, due to the reduced contribution of the frame area to total heat transfer, as Demonstrated in Figure 4.24 and Figure 4.25.

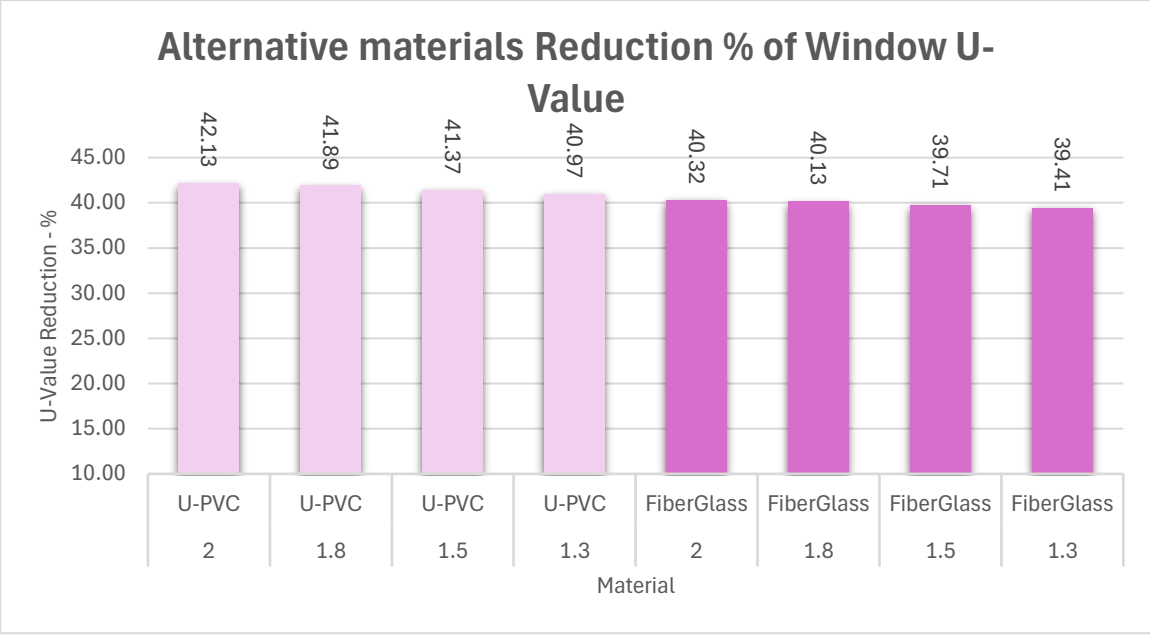


Figure 4.23 Total Window U-Value reduction with alternative materials compared to aluminium base case

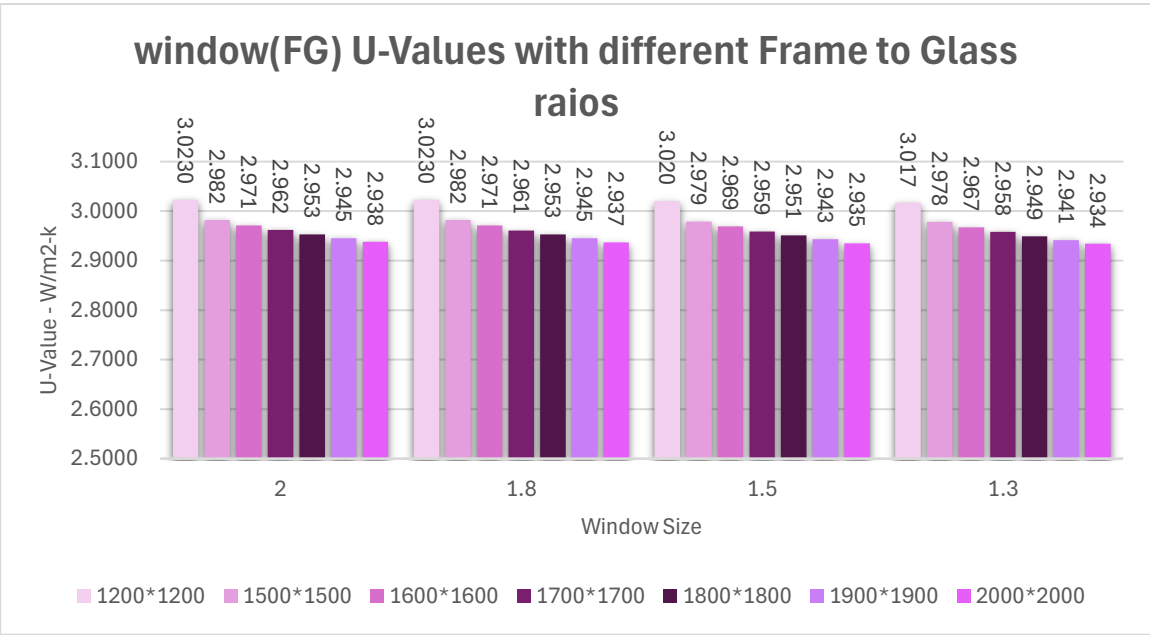


Figure 4.24 Different window ratios U-Values with Fiberglass frame

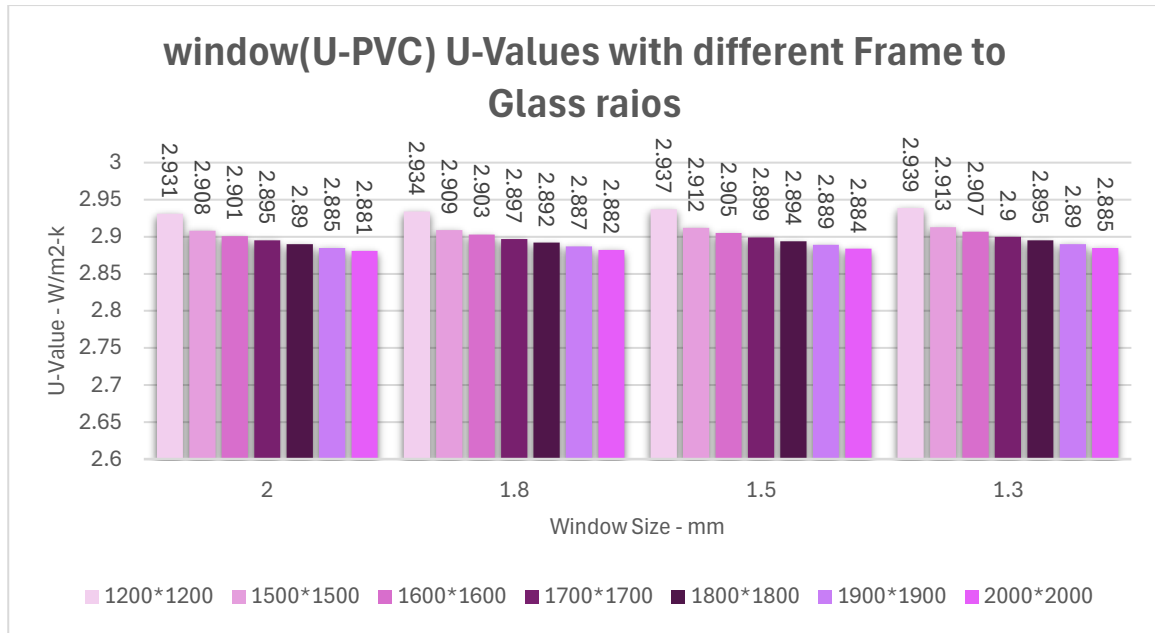


Figure 4.25 Different window ratios U-Values with U-PVC frame

4.5.2 U-PVC and Fiberglass thermally broken frames

To further enhance the thermal performance of low-conductivity frame materials, U-PVC and fiberglass window frames were tested with the addition of thermal breaks. As with the aluminium frame configurations, three thermal break gap sizes—5 mm, 10 mm, and 20 mm—were evaluated, with each break filled with aerogel to maximize insulation. These thermal breaks were strategically positioned to disrupt thermal bridging between the internal and external sides of the frame, as Visualized in Figure 4.26 and Figure 4.27.

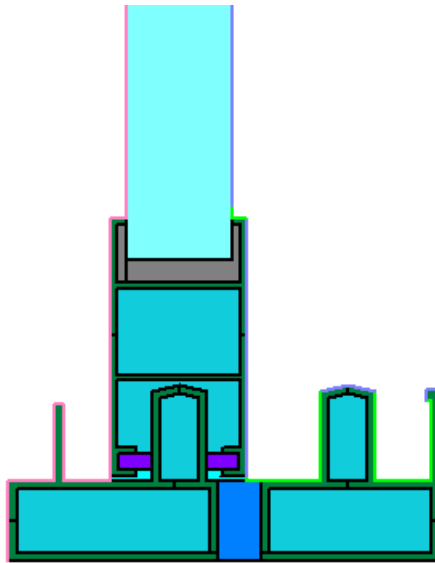


Figure 4.26 Thermally broken U-PVC Frame

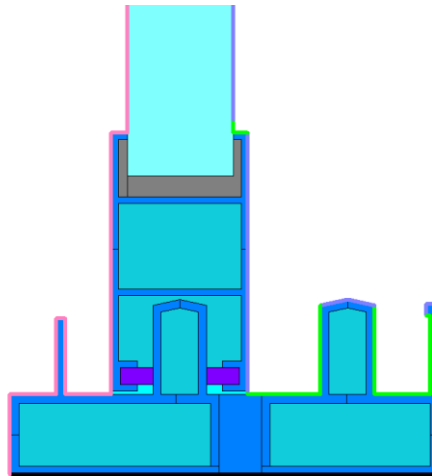


Figure 4.27 Thermally broken Fiberglass frame

The simulations revealed that the 10 mm thermal break offered the best balance between performance improvement and material economy for both U-PVC and fiberglass frames. The U-value of the U-PVC frame with a 10 mm thermal break was reduced from approximately 2.4 W/m²K to 1.7 W/m²K, achieving a further 28% reduction in thermal transmittance from the base case U-PVC frame, as illustrated in Figure 4.28. Similarly, the fiberglass frame with a 10 mm break exhibited a drop in U-value from 2.75 W/m²K to 1.9 W/m²K, representing a 27% reduction from the unbroken fiberglass configuration, as depicted in Figure 4.29.

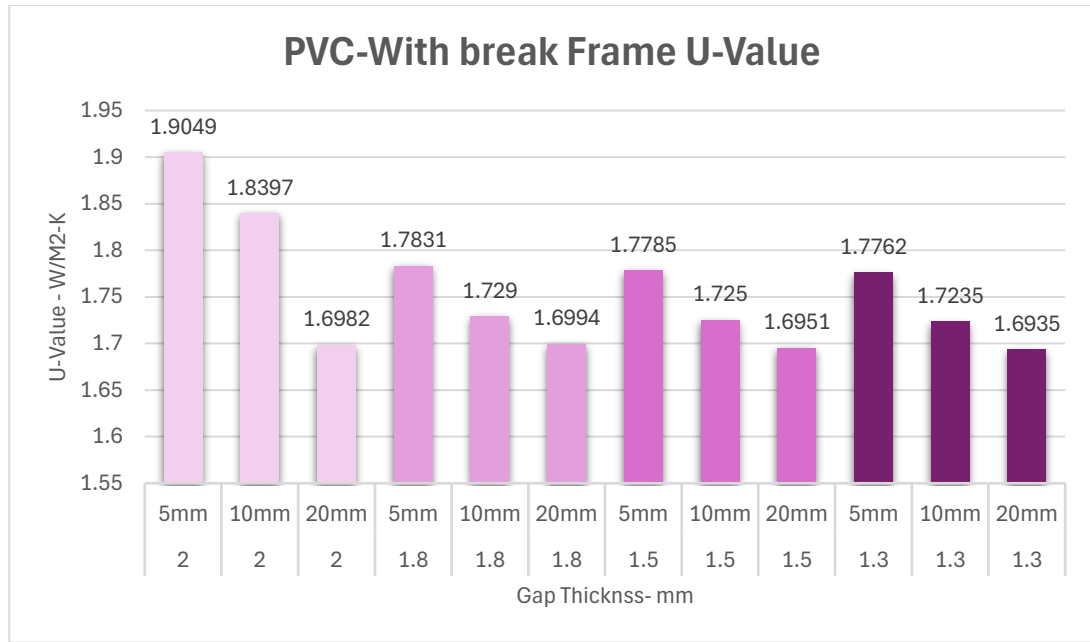


Figure 4.28 Thermally broken of different thickness in U-PVC Frame U-Values

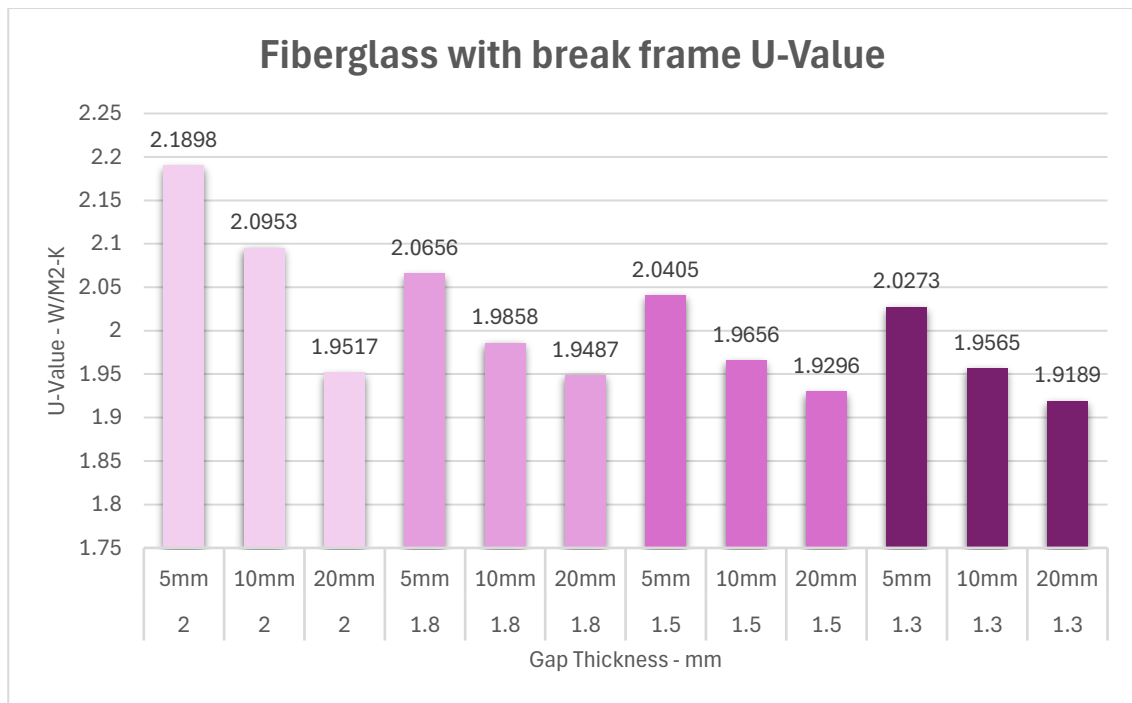


Figure 4.29 Thermally broken Fiberglass Frame U-Values

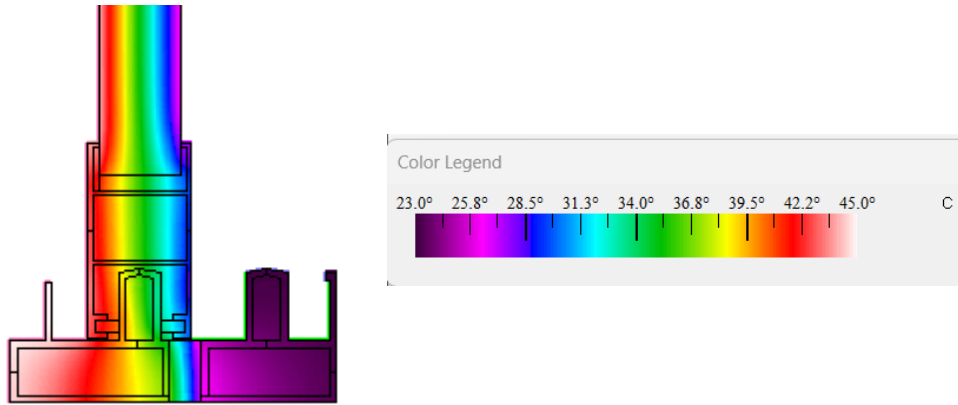


Figure 4.30 Temperature distribution across thermally broken UPVC frame

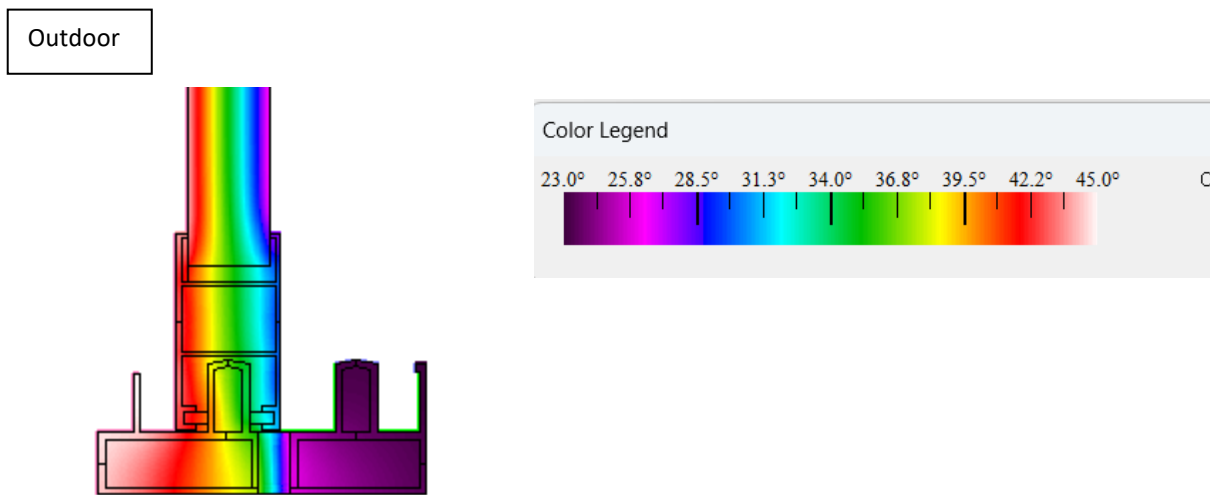


Figure 4.31 Temperature distribution across thermally broken Fiberglass frame

These configurations were also tested under varying frame-to-glass ratios, Portrayed in Figure 4.32 and Figure 4.33, and the trend of decreasing U-value with increasing window size remained consistent for thermally broken fiberglass frames. However, for the thermally broken U-PVC frames larger windows slightly increased the U-values (e.g., 76% glass: U-Total window = 2.8 W/m²K, compared to 61% glass and U-Total window of 2.796 W/m²K), contrasting with aluminium's consistent improvements. This is due to the low U-value of the optimized frame, which surpasses the performance of double glazing, which has a U-value of approximately 2.781 W/m²K. Consequently, as the window increases in size, the glass ratio rises, leading to a slight increase in the total U-value of the window.

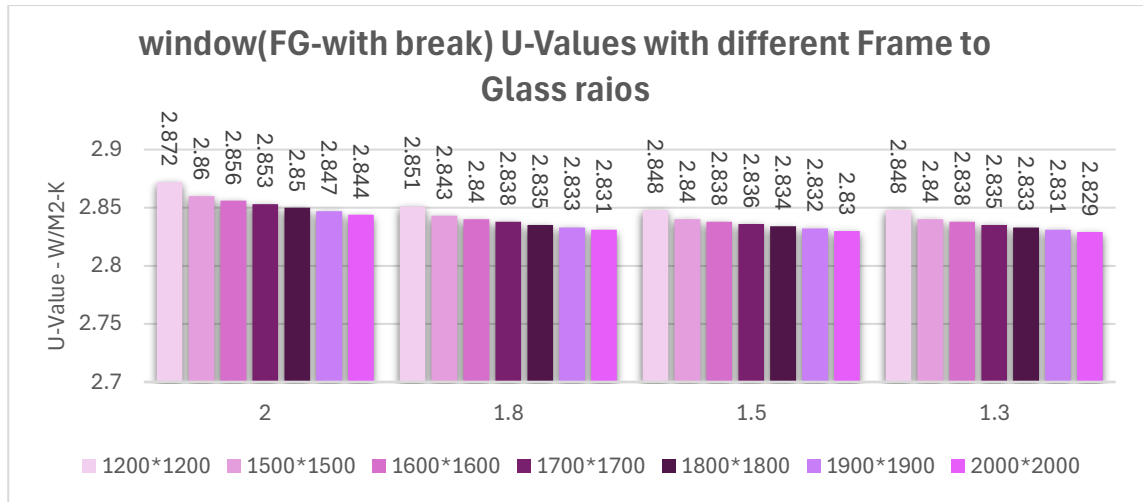


Figure 4.32 Different window ratios U-Values with Thermally broken Fiberglass frame

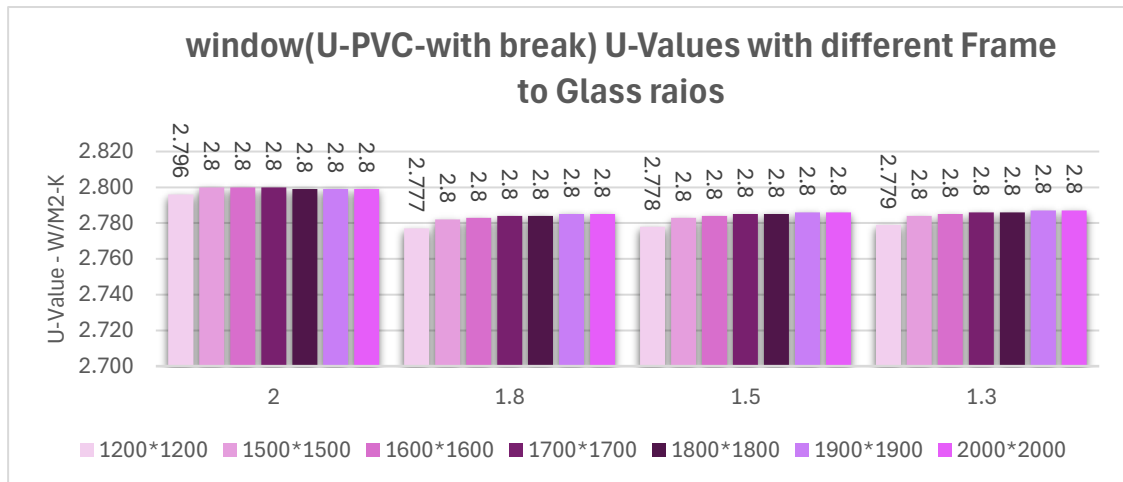


Figure 4.33 Different window ratios U-Values with Thermally broken U-PVC frame

4.6 Dual Thermal Breaks in Aluminium Frames

To push the thermal performance limits of aluminium frames further, an advanced configuration featuring dual thermal breaks was developed and tested. In this design, two separate thermal breaks were introduced: one in the fixed section of the sliding frame with a 10 mm gap, and another in the movable sash with a 5 mm gap, as visualized in Figure 4.34. Both breaks were filled with aerogel, chosen for its superior insulation

properties and minimal impact on structural integrity. This dual-break strategy aimed to completely disrupt conductive pathways at both critical junctions of the window assembly, hence, reducing the heat transfer from the outdoor to the indoor environment. Simulations replicated the methodology of earlier sections, evaluating performance across the same frame-to-glass ratios (24–39% frame area) under steady-state boundary conditions (45°C outdoor, 23°C indoor).

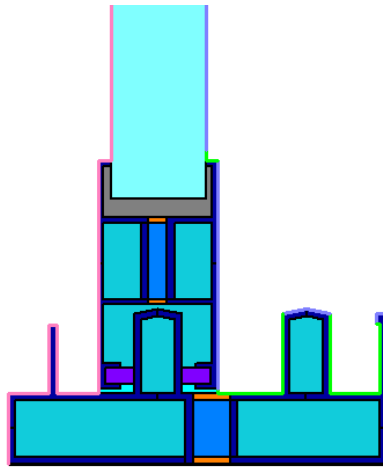
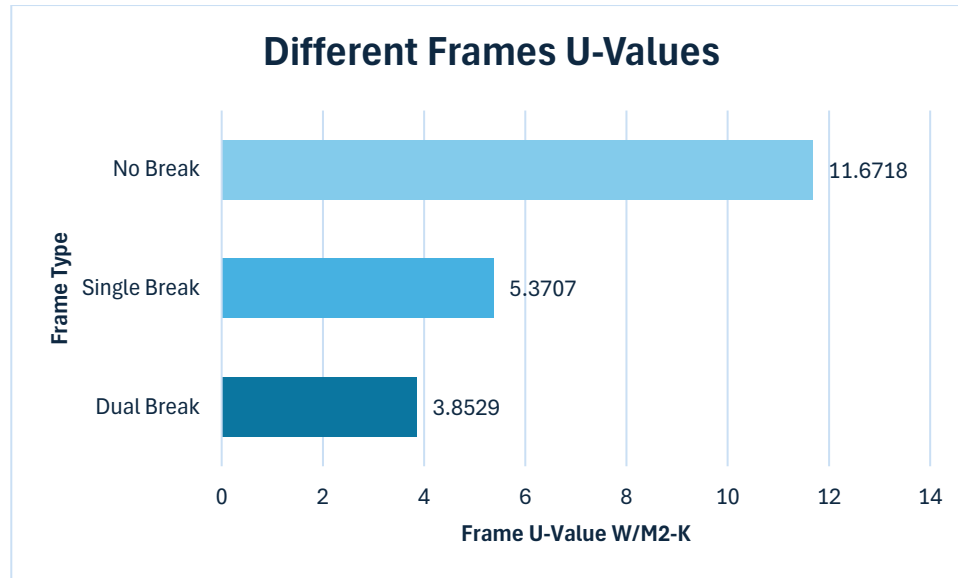


Figure 4.34 Aluminium Frame with dual thermal breaks

The implementation of this configuration led to a substantial improvement in thermal performance. The U-value was reduced to approximately 3.8 W/m²K, representing a 67% reduction compared to the base case aluminium frame with no thermal enhancement, and an 28% improvement over single-break designs (5.3707 W/m²K), as depicted in Figure 4.35.

This result demonstrates the effectiveness of combining multiple thermal breaks within different sections of the frame to address the inherent limitations of aluminium's high thermal conductivity.



Outdoor

Figure 4.35 Various Aluminium Frames U-Values

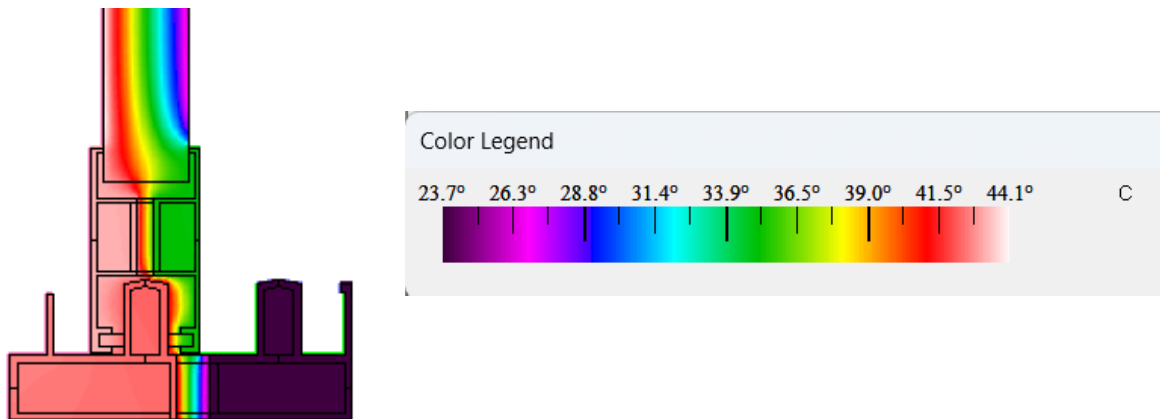


Figure 4.36 Temperature distribution across a frame with dual thermal break

The dual thermal break aluminium frame was further analysed under varying frame-to-glass ratios, using the same series of window sizes as in previous configurations. It can be analysed from Figure 4.37 that larger windows amplified performance gains, with the U-value dropping to 3.113 W/m²K at 24% frame area (2.0×2.0 m), a 6% reduction versus 39% frame area (1.2×1.2 m). This is due to the fact that glass typically has a lower U-value

than aluminium frames—even when the frames are thermally broken—so increasing the relative area of glass results in reduced overall heat transfer through the window system.

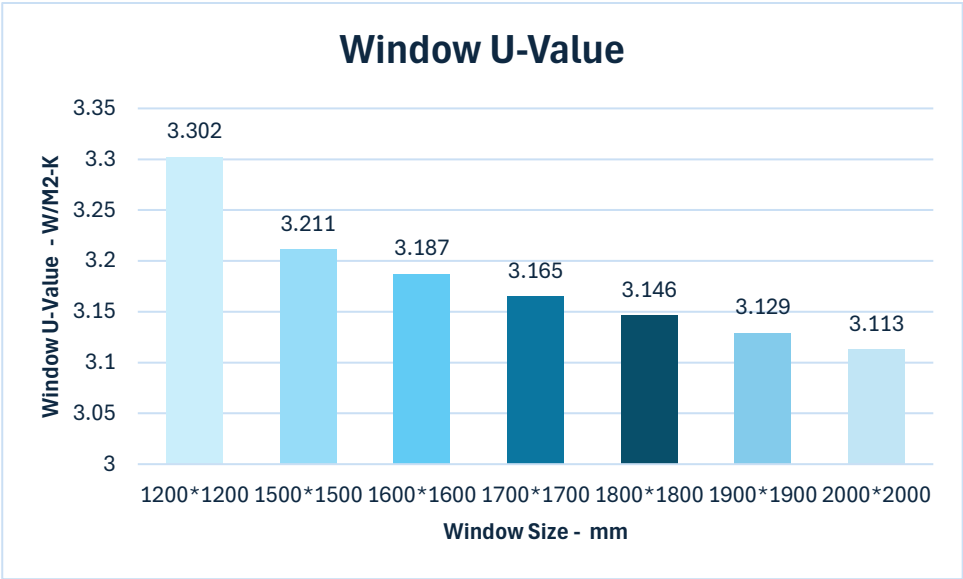


Figure 4.37 Various Total Window U-values with dual thermal break aluminium frame

4.7Synthesis of Results

The results of this study revealed several critical insights into the thermal performance of window frames and the effectiveness of various strategies to enhance their energy efficiency. The simulation configurations yielded significant variations in thermal performance, with material choice and thermal break integration emerging as primary determinants of U-value reduction. Key outcomes are highlighted in

Table 4-1.

Table 4-1 Thermal Performance Simulations Key Outcomes		
Configuration	Frame U-value (W/m²K)	Reduction vs. Baseline
Baseline Aluminium	11.6718	-

Aluminium + Insulation	11.10 - 11.66	0.065 - 0.107 %
Aluminium + 10mm Break	5.3707	53.98 %
U-PVC	2.42	79.30 %
Fiberglass	2.75	76.45 %
U-PVC + 10mm Break	1.8397	84.23 %
Fiberglass + 10mm Break	2.0953	82.04 %
Dual-Break Aluminium	3.8529	67%

These results underscore the transformative potential of non-metallic materials, thermal breaks, and hybrid designs in hot climates, where thermal bridging and solar gain dominate energy losses.

These findings directly address the four research questions guiding this section of the study:

- RQ1 (Material Impact): U-PVC and fiberglass significantly outperformed aluminium, reducing U-values by 76–79% due to their low thermal conductivity (0.17–0.35 W/m·K vs. aluminium’s 160 W/m·K).
- RQ2 (Gauge Thickness): Variations in aluminium gauge thickness (1.2–2.0 mm) had minimal impact on U-values (11.4–11.6 W/m²K), underscoring the dominance of material conductivity over geometric adjustments.
- RQ3 (Insulation): Cavity insulation (e.g., aerogel, XPS) in aluminium frames yielded negligible improvements ($\leq 2\%$ reduction), as thermal bridging negated insulation benefits.
- RQ4 (Thermal Breaks): Aerogel-based breaks (10 mm) reduced aluminium U-values by 56%, while dual breaks achieved a 67% reduction, demonstrating their viability for retrofits.

4.8 Summary of chapter

This chapter has presented a detailed evaluation of the thermal performance of various window frame configurations, with the aim of identifying effective strategies to reduce heat transfer through frames in hot climates such as Saudi Arabia. The findings confirm that conventional aluminium frames, even when tested at different gauge thicknesses, consistently demonstrate high U-values ($\sim 11.4\text{--}11.7\text{ W/m}^2\text{K}$), making them thermally inefficient. Filling aluminium frame cavities with insulation materials—including polyurethane, XPS, EPS, and aerogel—had minimal impact due to the dominant conductive heat flow through the aluminium itself.

In contrast, the integration of thermal breaks significantly enhanced performance, with a 10 mm aerogel-filled break emerging as the most effective and economically viable configuration, reducing U-values by more than 50%. Among the tested materials, U-PVC and fiberglass showed the most promise, with U-values of approximately $2.4\text{ W/m}^2\text{K}$ and $2.75\text{ W/m}^2\text{K}$, respectively. The incorporation of thermal breaks into these frames led to even greater reductions, with U-values dropping to $1.7\text{ W/m}^2\text{K}$ for U-PVC and $1.9\text{ W/m}^2\text{K}$ for fiberglass—representing up to 85% improvement over the base aluminium case. The dual thermal break aluminium design also achieved notable results, with a 67% U-value reduction, indicating a feasible strategy for thermally optimizing metal frames.

Across all configurations, except for thermally broken U-PVC frame, it was also observed that larger window sizes (higher glass-to-frame ratios) consistently led to lower overall U-values, highlighting the impact of architectural proportions on thermal performance.

The findings in this chapter directly address the research questions posed in Chapter One, confirming that material substitutions and thermal breaks—not gauge thickness or cavity insulation—are the most effective strategies for reducing cooling loads in Saudi residential buildings.

Chapter 5

Energy Performance of Window Frames

5.1 Introduction

This chapter presents the energy performance analysis of various window frame configurations by integrating the thermal transmittance values (U-values) derived in Chapter 4 into a whole-building simulation model. The primary aim is to assess how enhancements in window frame design can influence the annual energy consumption of a typical residential building in the context of Saudi Arabia's diverse climatic zones. By bridging thermal transmittance metrics (U-values) with whole-building energy simulations, the study addresses a critical gap in understanding the practical implications of window frame design in cooling-dominated environments.

The energy simulations, as visualized in Figure 5.1, were conducted using EnergyPlus, through its interface with Rhino, to evaluate whole-building energy consumption under realistic operational conditions. WINDOW software was also used to calculate the total window U-values (including both frame and glazing), by combining the Frame U-Values calculated using Therm software and the double-glazed U-value that is calculated using Window. All simulations were performed on a standardized two-story residential villa model with a total floor area of 430 m², as previously described in Chapter 3. Internal loads—including lighting, equipment, infiltration rates, and HVAC set points—were held

constant across all configurations to isolate the effect of frame modifications on energy performance.

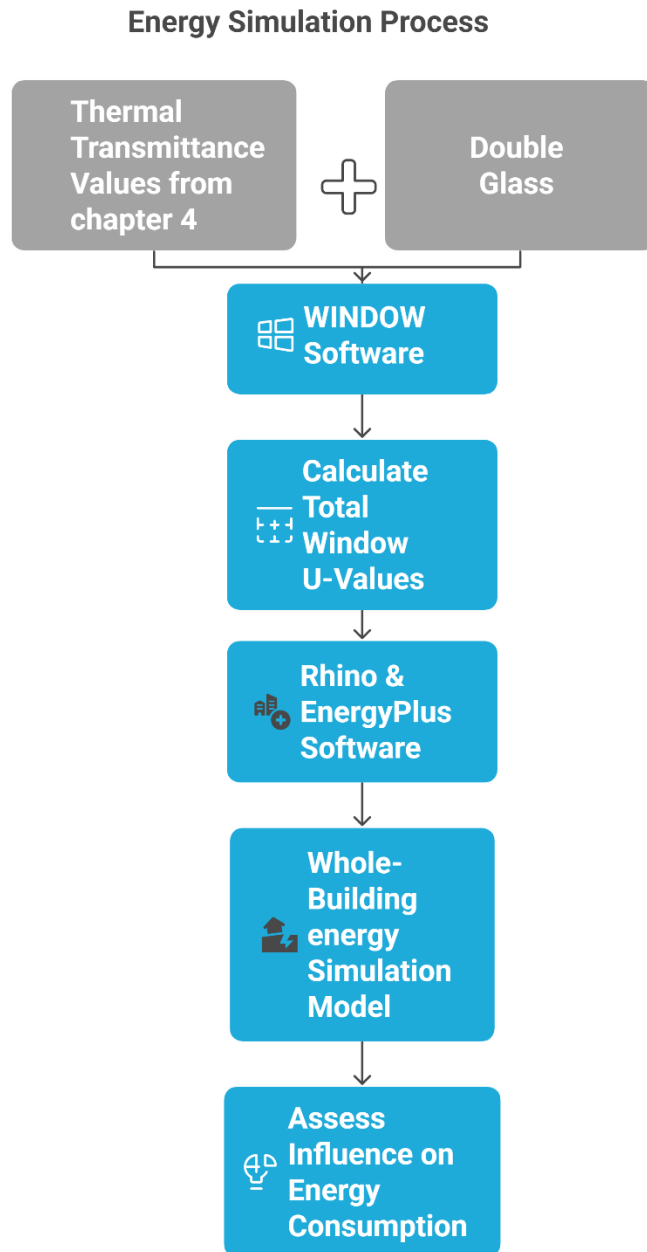


Figure 5.1 Energy simulation process

Two representative Saudi cities were selected to reflect the climatic extremes within the country: Dhahran, characterized by a hot and humid environment, and Abha, which exhibits a more moderate and cooler climate. This dual-location approach enables a comparative analysis of how climatic context affects the performance outcomes of thermally optimized window frames, and provides region-specific insights for architects, policymakers, and manufacturers seeking to enhance energy efficiency in Saudi Arabia's diverse built environment.

The structure of this chapter, as illustrated in Figure 5.2, is organized as follows: first, the base case (a conventional sliding aluminium frame (2.0 mm gauge thickness with double-glazed units and window size of 1.2*1.2m) energy performance is analysed to establish a reference point. Next, the impact of different frame modifications—including thermal break integration, the use of alternative materials such as U-PVC and fiberglass, and the implementation of dual thermal breaks—is examined. Subsequently, the influence of varying frame-to-glass ratios (seven window sizes (1.2×1.2 m to 2.0×2.0 m), reflecting frame-to-glass ratios of 24% to 39%) is evaluated, both independently and in combination with frame enhancements.

This chapter directly addresses the research aim of linking window frame thermal performance to real-world energy savings, offering actionable strategies for sustainable design in hot and moderate climates.

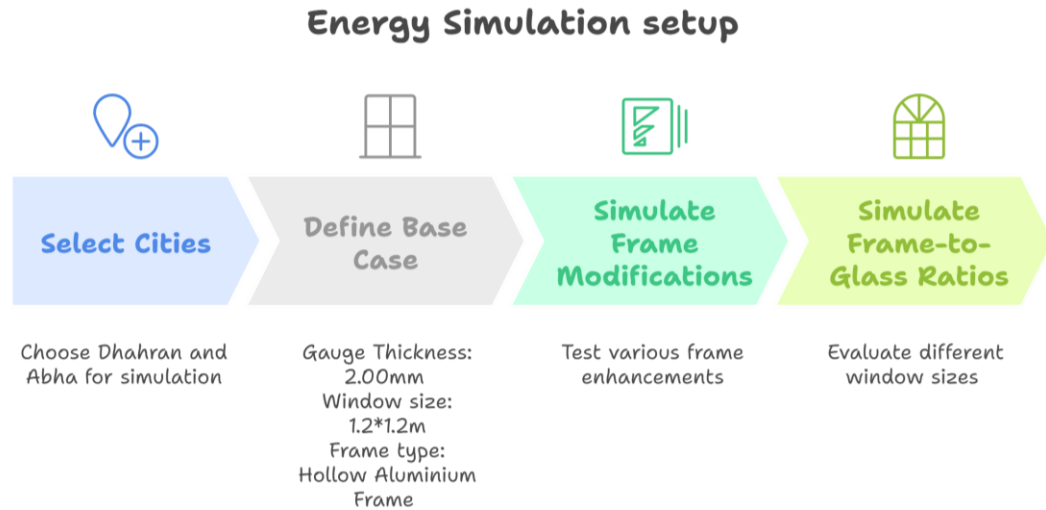


Figure 5.2 Energy Simulation Setup

5.2 Base Case Energy Consumption

5.2.1 Gauge Thickness Insignificance

Although four different aluminium gauge thicknesses were initially tested (2.0 mm, 1.8 mm, 1.5 mm, and 1.3 mm), the resulting differences in energy consumption were found to be negligible (less than 0.5%). For instance, a 1.3 mm frame consumed 733.08 kWh/M2-year in Dhahran, while a 2.0 mm frame used 734.54 kWh/M2-year—a mere 0.2% variance (Figure 5.3). This minimal discrepancy underscores aluminium's inherent thermal inefficiency: its high conductivity ($\lambda = 160 \text{ W/m}\cdot\text{K}$) dominates heat transfer, rendering geometric adjustments (e.g., thinner gauges) ineffective. Consequently, the 2.0 mm gauge aluminium frame was adopted as the standard for all subsequent simulations to streamline comparison across frame materials, insulation strategies, and frame-to-glass ratio variations.

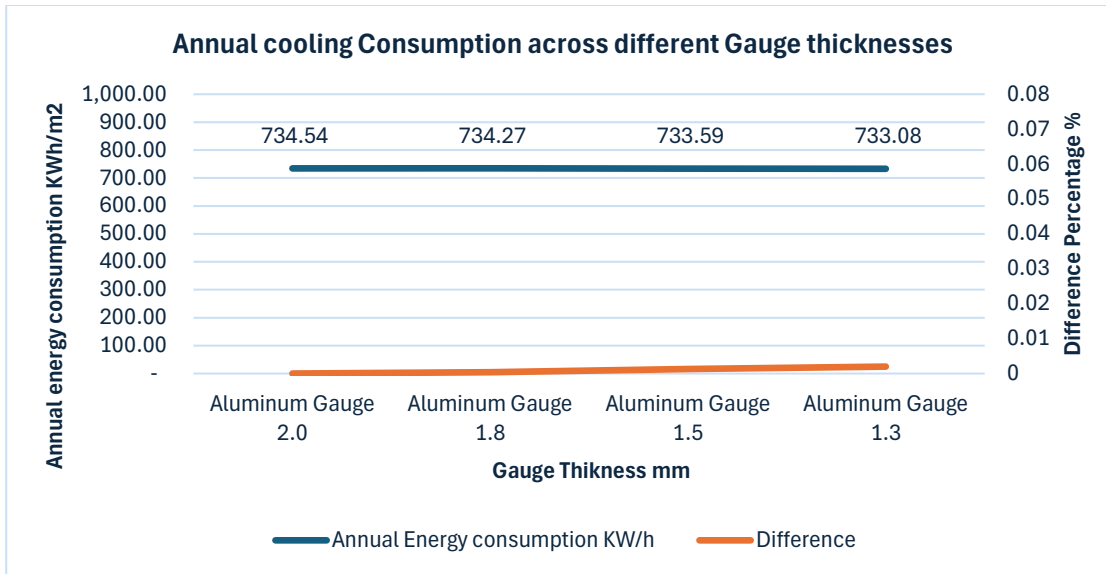


Figure 5.3 Annual cooling Consumption across different frame gauge thicknesses

5.2.2 Baseline Results

The base case simulation, which reflects the current standard 2.0 mm Aluminium window frame without any insulation or thermal break and a window size of 1.2 * 1.2 m, was used to establish a reference point for evaluating energy performance improvements. The annual energy consumption of the residential villa model using this base frame was approximately 734.54 kWh/M2-year in Dhahran and 552.87 kWh/M2-year in Abha, as depicted in Figure 5.4.

This notable difference of nearly 14,400 kWh/year (25% Difference) underscores the substantial influence of climate on energy demand. Dhahran, characterized by its hot-humid climate, experiences prolonged and intense cooling seasons, which significantly increases HVAC loads. In contrast, Abha's moderate and cooler climate results in a shorter cooling season and overall reduced energy demand.

These findings reinforce the critical importance of optimizing window frame thermal performance in hot climates, such as those prevalent across most of Saudi Arabia. Since the temperature differential between indoor and outdoor environments is a key driver of heat gain, inefficient window frames contribute heavily to cooling loads. Therefore, improving frame thermal properties presents a valuable strategy for reducing operational energy consumption in such regions.

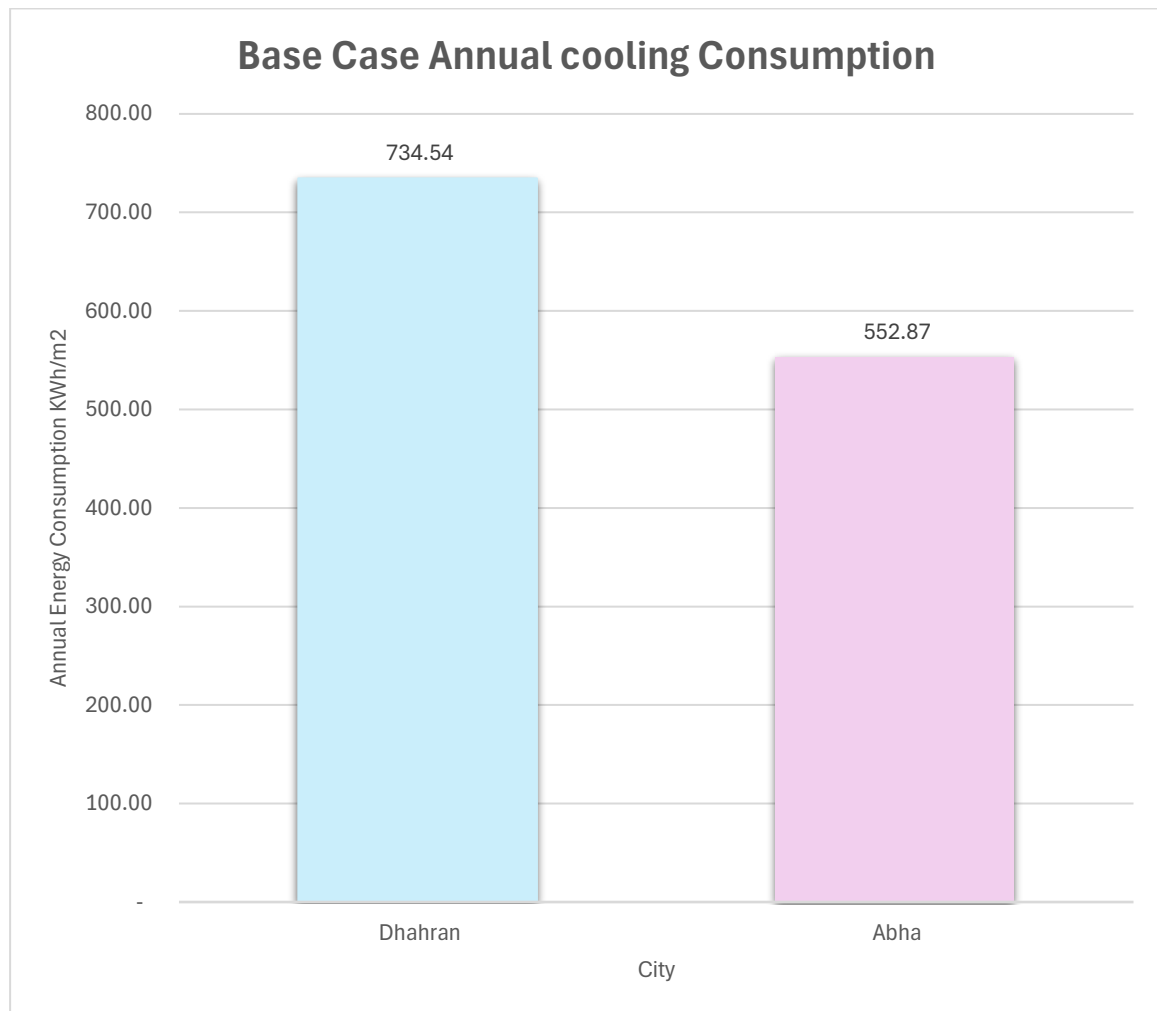


Figure 5.4 Annual cooling consumption for the base case aluminium window frame

5.3 Energy Performance of Window Frame Modifications

This section presents a comparative analysis of the energy savings achieved through various window frame modifications across two distinct Saudi Arabian climatic zones: Dhahran, representing a hot-humid climate, and Abha, characterized by a moderate-cool climate. The base case 2.0 mm aluminium frame with no insulation or thermal break and window size of 1.2*1.2 m served as the benchmark, against which all other configurations were evaluated.

It can be concluded from Figure 5.5 and Figure 5.6 that among the tested configurations, introducing a 10 mm thermal break filled with aerogel into the aluminium frame yielded a 7.5% reduction in energy consumption in Dhahran and a 4% reduction in Abha. This modification proved effective in disrupting the conductive heat transfer path across the metal frame, significantly reducing cooling loads—particularly in hotter climates where temperature differentials are more pronounced.

Switching the frame material to U-PVC or fiberglass further enhanced energy savings. Both materials achieved approximately a 9% reduction in Dhahran and 7% in Abha. U-PVC was particularly advantageous for the Saudi context due to its local production from petrochemical by-products, making it a sustainable and economically viable option. Fiberglass, although costlier, offered excellent structural stability and low thermal conductivity, making it a strong contender for high-performance applications.

When thermal breaks were added to these alternative materials, performance improved marginally. A U-PVC frame with a 10 mm thermal break reduced energy consumption by 9.5% in Dhahran and 8% in Abha, while fiberglass with a thermal break achieved

reductions of 9.1% and 7.2%, respectively. These results demonstrate the compounded benefits of combining low-conductivity materials with thermal isolation techniques, though the incremental gains were slightly lower than when applied to aluminium due to the already high performance of U-PVC and fiberglass.

The dual thermal break aluminium frame, featuring a 10 mm break in the fixed part and a 5 mm break in the movable sash, presented a notable advancement. It reduced energy consumption by 8.4% in Dhahran and 6% in Abha, offering a middle ground between material substitution and aluminium retention. However, this design introduces additional engineering complexity, which may affect its immediate adoption in mass-market applications. Nonetheless, it serves as a compelling alternative for manufacturers aiming to enhance aluminium frame performance without shifting to entirely new materials.

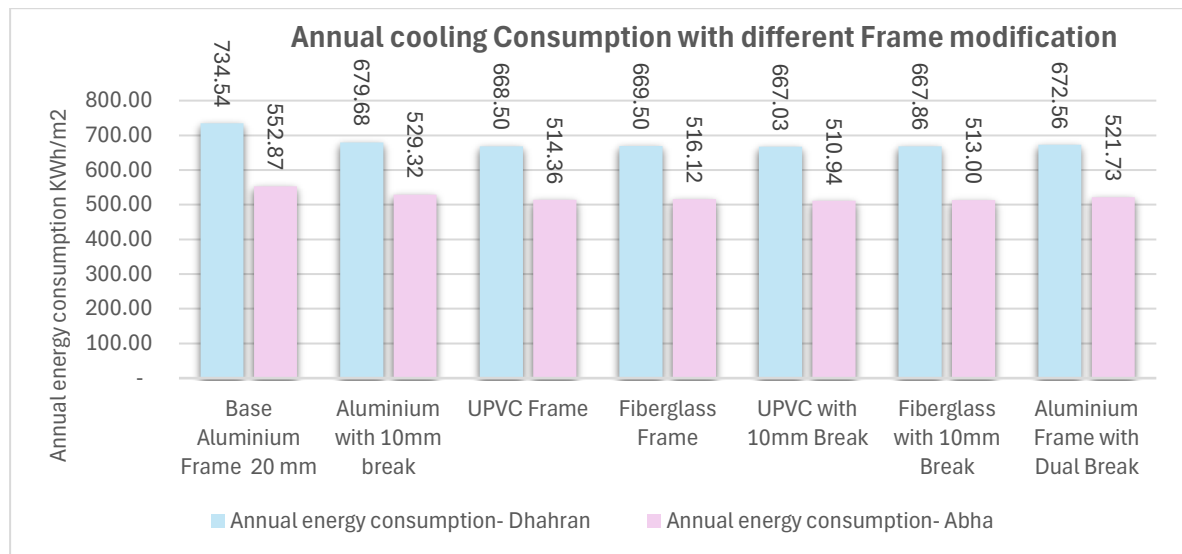


Figure 5.5 Annual Cooling Consumption with different Frame modification

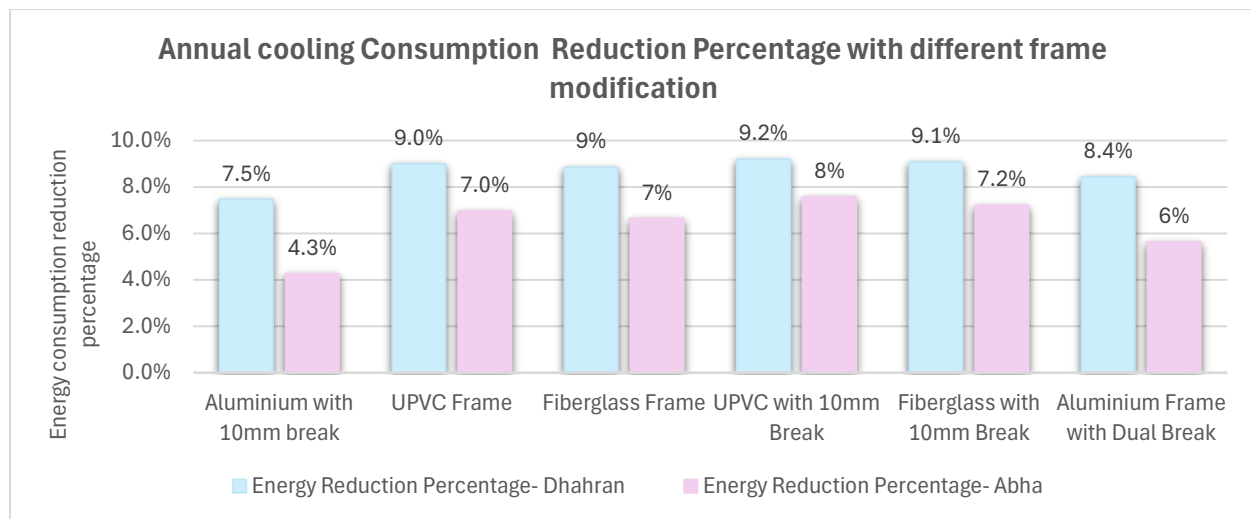


Figure 5.6 Annual Cooling Consumption Reduction Percentage with different frame modification

In summary, all frame modifications led to measurable reductions in energy use, with more pronounced savings in Dhahran due to the higher cooling demand. The most effective configurations were U-PVC and fiberglass frames with thermal breaks, although even simpler strategies such as incorporating a thermal break into aluminium frames yielded substantial improvements. Though savings were less pronounced in Abha than in Dhahran, these results highlight the importance of tailored solutions for diverse climatic zones, where material substitutions and hybrid designs remain viable pathways to energy efficiency despite lower heat flux. These findings affirm the critical role that frame design and material selection play in enhancing energy efficiency in residential buildings, particularly in hot climates.

5.4 Impact of Frame-to-Glass Ratio (FGR)

The frame-to-glass ratio (FGR) was found to be a critical factor influencing overall window thermal performance and, consequently, the energy consumption of the building.

Simulations were conducted across a range of window sizes—from 1.2×1.2 m to 2.0×2.0 m, firstly for the base case Frame and secondly for the Frame modifications.

5.4.1 Impact of Window Size (FGR) With The base Case Frame

The influence of window size on energy consumption varied markedly between Dhahran and Abha, reflecting the interplay of climatic conditions and material thermal properties. Figure 5.7 and Figure 5.8 depict that in Dhahran's extreme climate, larger windows reduced energy use by diluting the aluminium frame's high thermal transmittance ($U = 11.5$ W/m²K) through a higher glass-to-frame ratio. For instance, increasing the window size to 1.7×1.7 m and 1.9×1.9 m yielded 4% ($734.54 \rightarrow 703.43$ kWh/M2) and 3.7% ($734.54 \rightarrow 707.07$ kWh/M2) reductions, respectively, as the lower U-value of glass (2.781 W/m²K) mitigated heat gain. This effect was amplified by Dhahran's high temperature differential ($\Delta T \approx 22^\circ\text{C}$), which intensified conductive losses through inefficient frames.

Conversely, in Abha's milder climate ($\Delta T \approx 10^\circ\text{C}$), While most larger windows resulted in minor reductions or negligible changes in energy consumption, the 1.7×1.7 m and 1.9×1.9 m sizes still provided modest savings by 1.4% ($552.87 \rightarrow 545.15$ kWh/M2) and 1.3% ($552.87 \rightarrow 545.95$ kWh/M2), respectively. For other window sizes, increasing the glazed area did not always lead to improved energy performance, likely due to the less severe climate and shorter cooling season, where heat gain through windows is not as dominant.

These findings underscore the importance of window proportions in energy-efficient design, particularly in hot climates where high-performance glazing can offset the thermal weaknesses of window frames. From a design perspective, selecting larger windows with lower frame-to-glass ratios—when paired with high-performance glazing—can be a simple

and effective strategy for reducing building energy loads. Moreover, these results underscore a climate-dependent strategy: hot climates like Dhahran benefit from larger windows to offset frame inefficiencies, while moderate climates like Abha prioritize material and thermal upgrades over size adjustments.

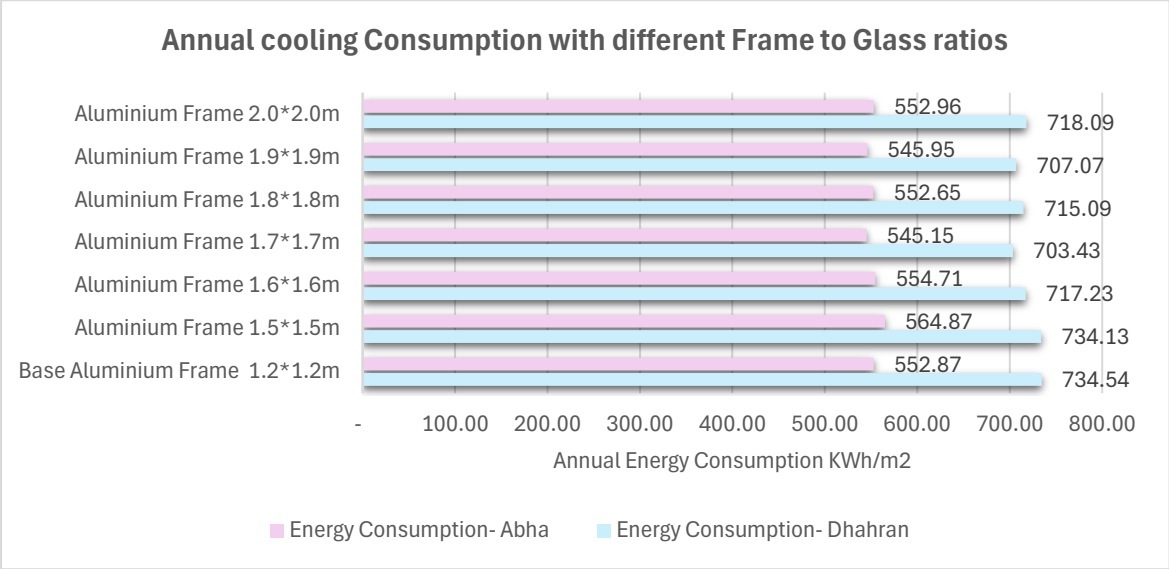


Figure 5.7 Annual Cooling Consumption with different Frame to Glass ratios

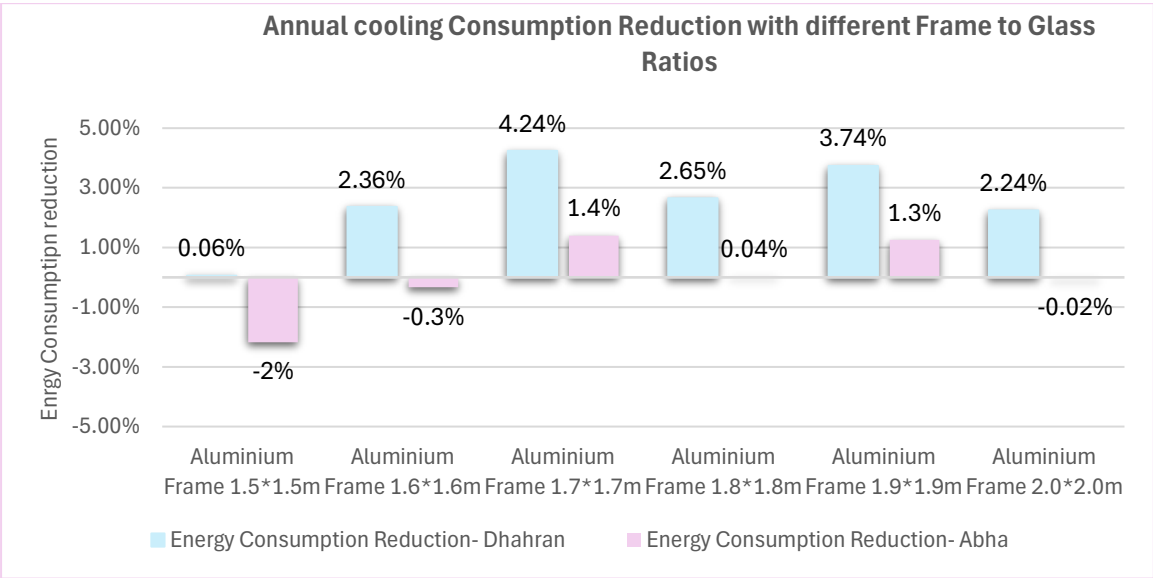


Figure 5.8 Annual Cooling Consumption Reduction with different Frame to Glass Ratios

5.4.2 Combined FGR and Frame Modifications

The energy savings from frame modifications exhibited a distinct sensitivity to window size, with smaller windows demonstrating the greatest responsiveness to thermal upgrades, as illustrated in Figure 5.9 and Figure 5.10.

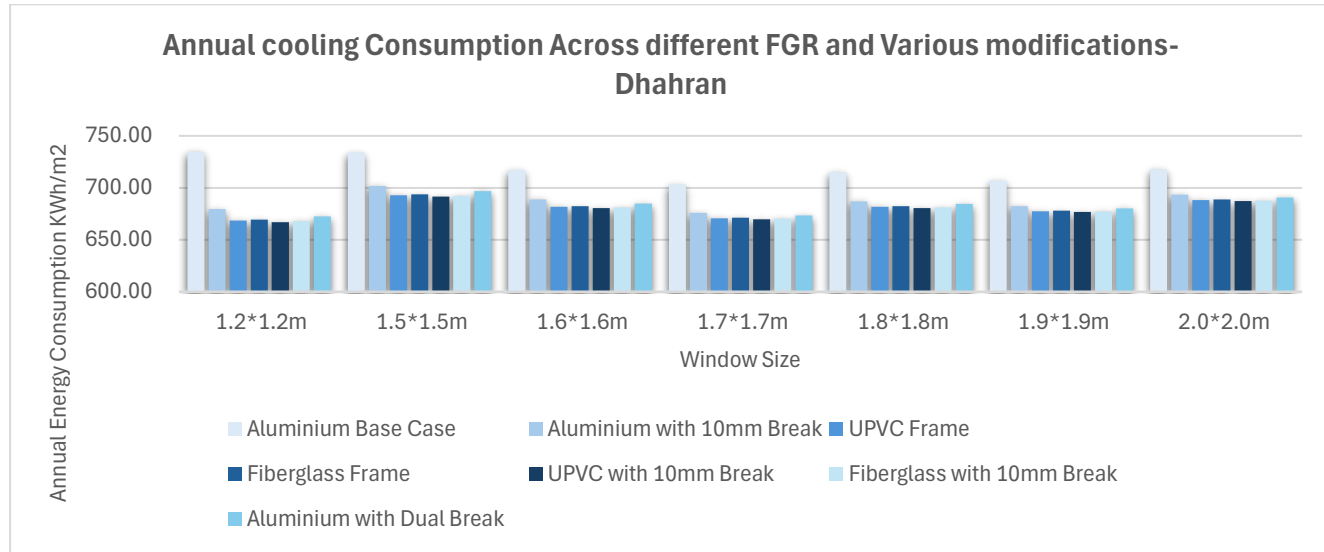


Figure 5.9 Annual Cooling Consumption Across different FGR and Various modifications- Dhahran

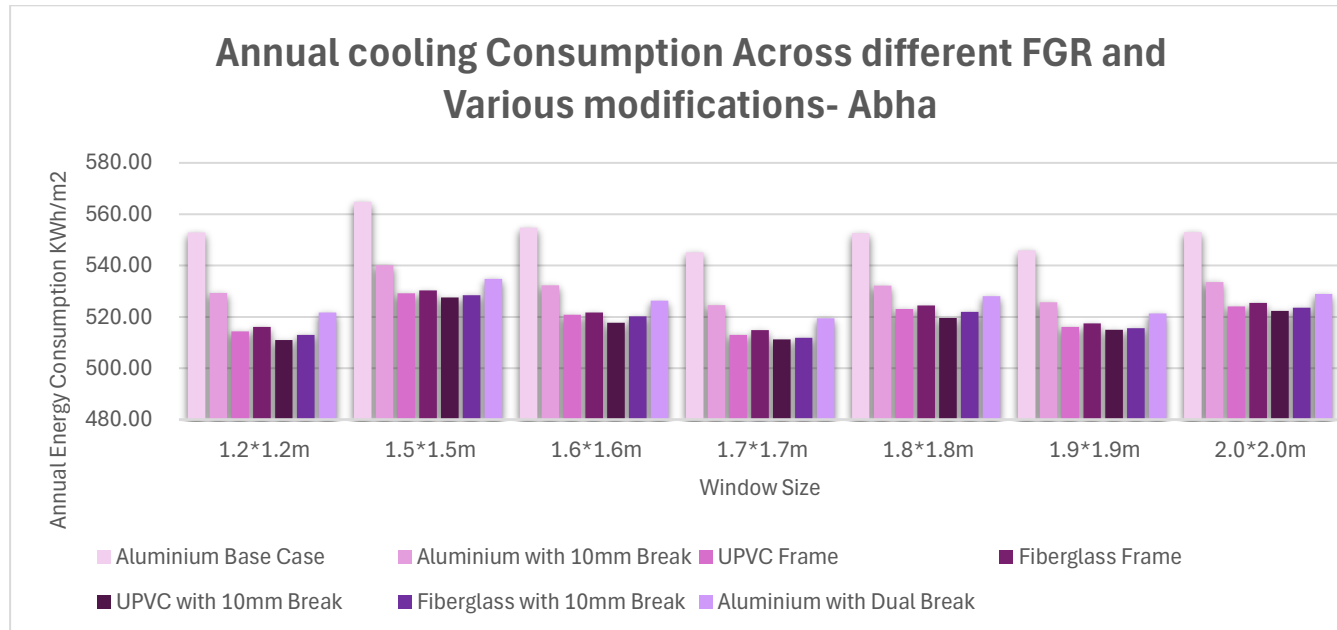


Figure 5.10 Annual Cooling Consumption Across different FGR and Various modifications- Abha

In Dhahran's extreme climate as well as in Abha, 1.2×1.2 m windows achieved the highest reductions: U-PVC frames with a 10 mm thermal break lowered energy consumption by 9.5% (Dhahran) and 8% (Abha) compared to an 4% and 6% reduction for 2.0×2.0 m windows, as visualised in Figure 5.11 and Figure 5.12. This trend reflects the higher frame-to-glass ratio in smaller windows, where the aluminium frame's thermal inefficiency ($U = 11.5 \text{ W/m}^2\text{K}$) dominates heat transfer. Optimizing the frame in such cases directly addresses the primary source of heat gain, yielding substantial savings. Larger windows, with their greater glass area (lower U-value), inherently dilute the frame's contribution, resulting in diminishing returns. Nevertheless, even at 2.0×2.0 m, optimized frames maintained meaningful energy savings, underscoring the universal benefits of thermal upgrades across sizes. The results emphasize that the combined approach of adjusting geometry and enhancing material performance consistently outperformed either strategy alone.

These findings highlight that maximizing window system efficiency requires a holistic design strategy, one that addresses both material selection and geometric configuration. For hot climate zones like Dhahran, combining low-conductivity frames with minimized FGRs offers significant cooling load reductions. Even in moderate climates such as Abha, applying both strategies delivers measurable efficiency improvements.

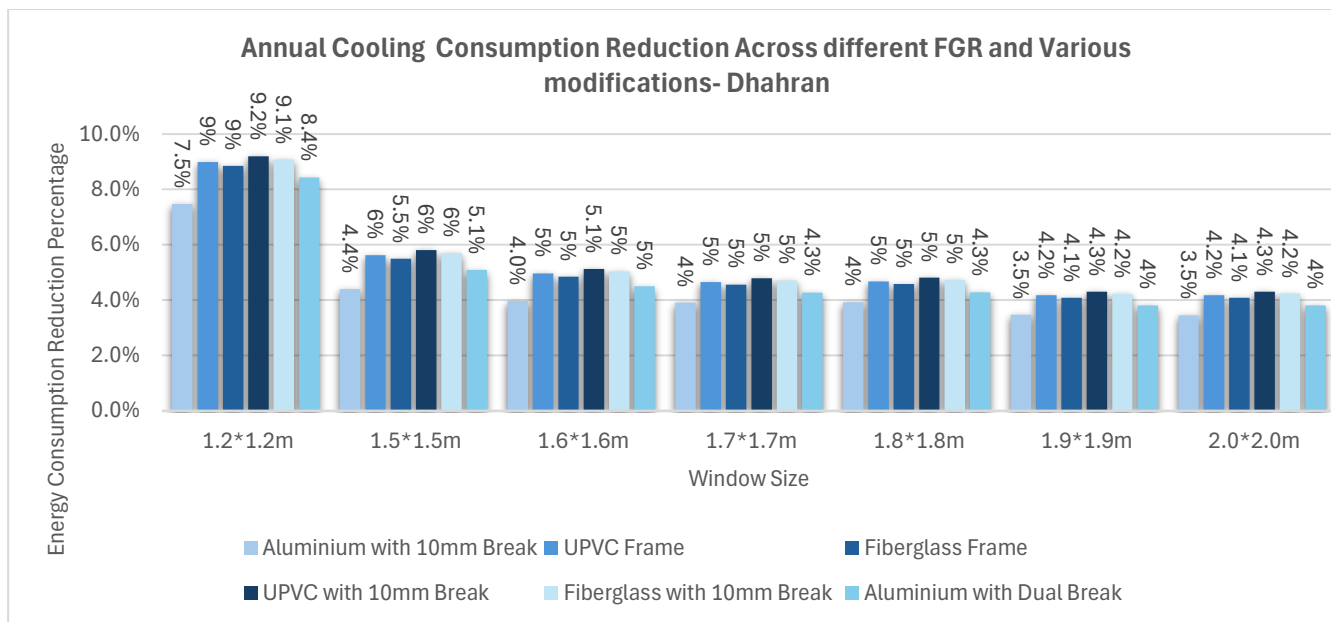


Figure 5.11 Annual Cooling Consumption Reduction Across different FGR and Various modifications- Dhahran

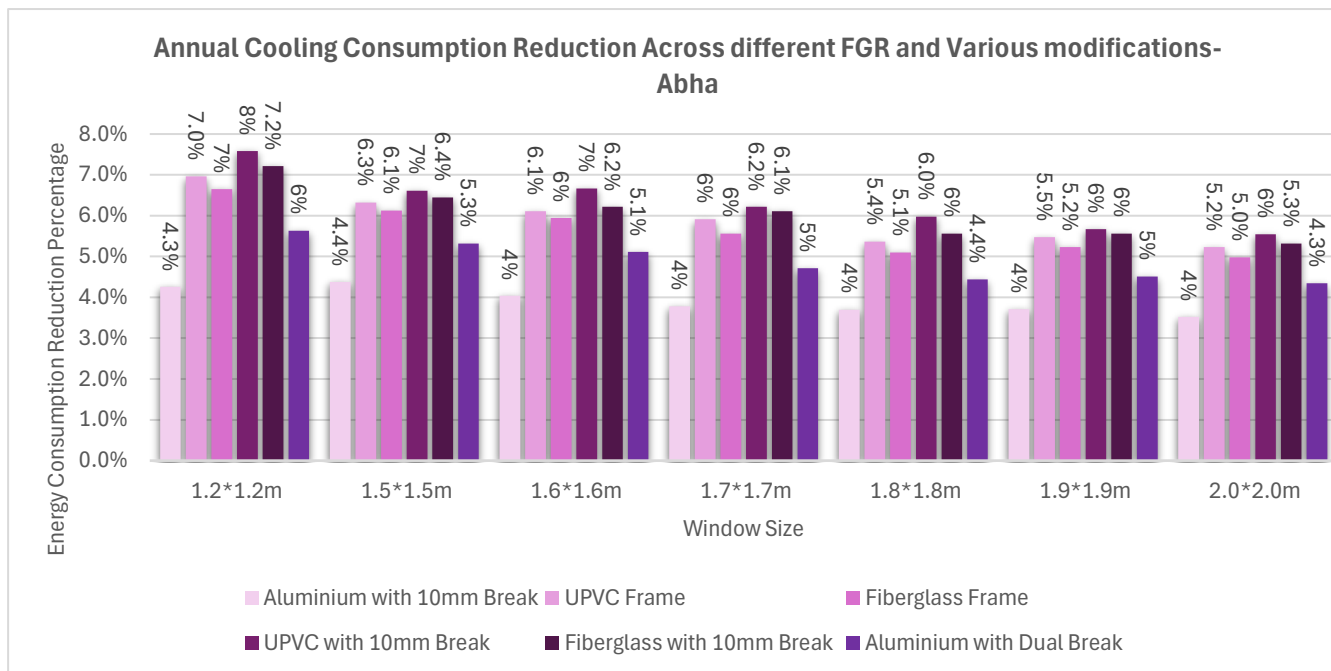


Figure 5.12 Annual Cooling Consumption Reduction Across different FGR and Various modifications- Abha

5.5 Economic feasibility and Carbon Reduction Analysis

5.5.1 Objectives of the analysis

The primary objective of this economic and environmental analysis is to evaluate the financial viability and sustainability impact of optimizing window frame designs for enhanced thermal performance in residential buildings located in hot climatic regions such as Saudi Arabia. Specifically, the analysis aims to achieve the following:

- **Compare Initial Costs:** Assess the initial market costs of conventional window frames—predominantly aluminium sliding frames—with the costs associated with modified configurations, including alternative materials (U-PVC, fiberglass) and the incorporation of thermal breaks.
- **Calculate the annual energy cost savings** resulting from reduced thermal transmittance and lower cooling loads to evaluate economic feasibility
- **Estimate CO₂ Emissions Reduction:** Quantify the environmental benefits of each configuration by estimating the reduction in carbon dioxide (CO₂) emissions achieved through energy conservation, using region-specific emission factors.

Together, these objectives contribute to identifying the most cost-effective and environmentally beneficial window frame designs, offering practical guidance for architects, policymakers, and developers seeking to enhance the energy performance of buildings in the Gulf region.

5.5.2 Data Collection and Assumptions

To ensure an accurate and contextually relevant analysis, this study relies on a combination of market data, standardized values, and simulation results. The following data sources and assumptions form the basis of the economic and environmental evaluation:

➤ Window Frame Cost Data

- Baseline Frame Cost: The cost of conventional commercial sliding aluminium window frames commonly used in Saudi residential construction was collected from local suppliers. Prices were standardized on a per-square-meter (m²) basis, as shown in Table 5-1.

➤ Modified Frame Costs

- The costs for alternative materials such as U-PVC and fiberglass were obtained through supplier interviews and market databases.

➤ Energy Cost Assumptions

- The residential electricity tariff in Saudi Arabia is assumed to be 0.18 SAR/kWh, based on current national rates for household consumers.

➤ Energy consumption data for each window frame configuration was derived from the simulations using EnergyPlus, based on the total annual cooling loads in two case study cities: Dhahran and Abha.

➤ CO₂ Emission Factor

- A standard CO₂ emission factor of 0.692 kg CO₂ per kWh was used to quantify emissions reductions. This value reflects the typical emissions associated with electricity generation in Saudi Arabia's current energy mix, dominated by fossil fuel sources, according to SBC 1001.

- Standardized Window Size and Configuration
- All economic and emissions calculations were based on a standard window size of 1.2 m × 1.2 m (1.44 m²). Simulations used the 2.0 mm aluminium frame gauge across all configurations, as analysis showed negligible variation in energy performance (<0.5%) across different thicknesses.

Table 5-1 Materials prices

Material	Cost
Aluminium Frame	500 SAR/M2
UPVC Frame	600 SAR/M2
Fiberglass	1000 SAR/M2
Aerogel	130 SAR/50 ML

5.5.3 Initial Cost Comparison

This section compares the market prices of conventional and optimized window frame configurations to evaluate the financial implications of thermal performance improvements, as represented in Table 5-2 .

Table 5-2 market prices of conventional and optimized window frame configurations

Frame Type	Cost	Notes
Uninsulated Aluminium frame	720 SAR	Commonly used in Saudi residential sector. very poor thermal performance.
UPVC frame	864 SAR	Locally produced, sustainable and excellent thermal performance
Fiberglass frame	1440 SAR	High cost, however, High strength and thermal stability
Aluminium frame with thermal break	1220 SAR	Enhanced insulation.
UPVC frame with thermal break	1364 SAR	Higher insulation performance.
Fiberglass frame with thermal break	1940 SAR	Very high cost but Higher insulation performance
Aluminium frame with dual thermal break	1480 SAR	Enhanced insulation, but Complex manufacturing design.

The results illustrate that while advanced configurations, especially those involving thermal breaks, incur higher initial costs, they also offer superior thermal insulation, which

translates into long-term energy and emissions savings as discussed in the following sections.

5.5.4 Energy Cost Savings Calculation

To assess the economic feasibility of each optimized configuration, the annual energy cost savings were calculated based on simulation results from EnergyPlus, using the energy consumption of the base case aluminium frame as a reference. The following equation was used:

Equation 2

$$\text{Annual Cost Savings (SAR)} = \text{Energy Saved (kWh/year)} \times \text{Electricity Tariff (SAR/kWh)}$$

Accordingly, the energy cost for the base case aluminium frame was found to be 10,471.65 SAR/ Year in Dhahran and 7,881.72 SAR/Year in Abha.

The Energy savings for the modified frames are summarized in Table 5-3 for both Dhahran and Abha:

Table 5-3 Energy savings for modified frames

Frame Configuration	Cost Savings	
	(Dhahran)	(Abha)
Thermally broken aluminium frame	782.10 SAR/Year	335.68 SAR/Year
UPVC Frame	941.58 SAR/Year	548.97 SAR/Year
Fiberglass Frame	927.22 SAR/Year	523.98 SAR/Year

Thermally broken UPVC Frame	962.49 SAR/Year	597.81 SAR/Year
Thermally broken Fiberglass Frame	950.69 SAR/Year	568.42 SAR/Year
Aluminium Frame with Dual thermal breaks	883.64 SAR/Year	443.94 SAR/Year

These figures clearly demonstrate that all the suggested modifications yield cost savings in the range of 800-1000 SAR/year in Dhahran and 400-500 SAR/year in Abha, emphasizing their role in reducing energy consumption. Furthermore, U-PVC and fiberglass offer the highest annual cost savings, making them ideal candidates for practical implementation, particularly in hot regions like Dhahran, where cooling loads dominate energy use.

The same method was also used to calculate the energy cost savings for different frame to glass ratios for both cities, as summarized in Table 5-4. The savings were compared to the reference base case frame with the size of 1.2 m * 1.2 m.

Table 5-4 energy cost savings for different frame to glass ratios

Window Size	Cost Savings (Dhahran)	Cost Savings (Abha)
1.5 * 1.5 m	5.90 SAR/Year	-171.12 SAR/Year
1.6 * 1.6 m	246.75 SAR/Year	-26.25 SAR/Year

1.7 * 1.7 m	443.53 SAR/Year	110.06 SAR/Year
1.8 * 1.8 m	277.37 SAR/ Year	3.15 SAR/Year
1.9 * 1.9 m	391.66 SAR/Year	98.64 SAR/Year
2.0 * 2.0 m	234.49 SAR/Year	-1.21 SAR/Year

It can be concluded from the results that in Dhahran, increasing the window size reduces the energy consumption, hence increasing the cost savings. Moreover, a 1.7 * 1.7m window size was found to have the highest cost reduction of around 450 SAR/year. On the other hand, increasing the window size in Abha doesn't necessarily decrease energy costs. However, 1.7 * 1.7m remained the best window size in Abha as well, achieving energy cost savings of 110 SAR/year.

5.5.5 Payback Period Analysis

The payback period is a critical metric for evaluating the economic feasibility of energy-saving investments. It represents the time required for the energy cost savings to offset the additional initial investment of the optimized window frame configurations compared to the conventional aluminium frame. This analysis was performed for all configurations using the following formula:

Equation 3

Payback Period (years) = Additional Initial Cost (SAR)/Annual Energy Cost Savings (SAR/year)

Where:

- Additional Initial Cost is the difference between the cost of the optimized frame and the base case aluminium frame.

- Annual Energy Cost Savings are based on the results from EnergyPlus simulations, previously calculated for both Dhahran and Abha.

The results of the payback period calculation, which were calculated based on a single window, are summarized in the Table 5-5 below for Dhahran and Abha:

Table 5-5 payback period for frame modifications

Frame Configuration	Payback Period, Dhahran (Years) – (Months)	Payback Period, Abha (Years)
Thermally broken aluminium frame	0.64 Years ➔ 8 Months	1.5 Years ➔ 18 Months
UPVC Frame	0.15 Years ➔ 2 Months	0.26 Years ➔ 3 Months
Fiberglass Frame	0.78 Years ➔ 9 Months	1.37 Years ➔ 16 Months
Thermally broken UPVC Frame	0.67 Years ➔ 8 Months	1.1 Years ➔ 13 Months
Thermally broken Fiberglass Frame	1.3 Years ➔ 16 Months	2.1 Years ➔ 25 Months
Aluminium Frame with Dual thermal breaks	0.86 Years ➔ 10 Months	1.7 Years ➔ 20 Months

In both climatic zones, optimized window frame configurations demonstrate remarkably short payback periods, generally under two years, reinforcing their strong economic appeal. As expected, Dhahran, with its longer and more intense cooling season, exhibits faster

payback periods due to greater energy savings. However, even in Abha’s moderate climate, all modifications offer solid financial justification, especially for U-PVC-based frames. The U-PVC frame alone offers the fastest return, achieving payback in just 0.15 years (about 2 months) in Dhahran, and 0.26 years (3 Months) in Abha. More advanced systems, such as aluminium frames with dual thermal breaks, also provide good returns, with higher initial costs and longer—but still reasonable—payback times. Moreover, even though fiberglass has a higher initial cost compared to U-PVC, it still delivers a payback period under 1.5 years in Dhahran and under 2.2 years in Abha.

These findings highlight that thermal optimization of window frames is not only environmentally sound but also economically viable, supporting large-scale adoption in both new construction and retrofit programs. The short recovery periods ensure that stakeholders—homeowners, developers, and policymakers—can achieve long-term energy and cost savings with minimal investment risk.

5.5.6 CO₂ Emissions Calculation

This section evaluates the environmental benefits associated with the optimized window frame configurations by quantifying the reduction in carbon dioxide (CO₂) emissions resulting from decreased energy consumption. Since electricity generation in Saudi Arabia predominantly relies on fossil fuels, reducing building cooling loads directly contributes to lowering greenhouse gas emissions.

The CO₂ savings were calculated using the following formula:

Equation 4

$$\text{CO}_2 \text{ Reduction (kg/year)} = \text{Energy Saved (kWh/year)} \times \text{Emission Factor (kg CO}_2\text{/kWh)}$$

Where the Emission Factor Used is 0.65 kg CO₂/kWh Based on the SBC 1001.

The savings were compared to the reference base case uninsulated aluminium frame with the size of 1.2 m * 1.2 m, which resulted in an annual Co₂ production of 40,257.67 Kg/Year in Dhahran and 30,300.84 Kg/Year in Abha.

Table 5-6 presents a summary of the CO₂ annual reductions for different frame modifications.

Table 5-6 CO₂ annual reductions for different frame modifications

Frame Configuration	CO ₂ Saved (Dhahran)	Reduction Percentage (Dhahran)	CO ₂ Saved (Abha)	Reduction Percentage (Abha)
Thermally broken aluminium frame	3,006.73 Kg/Year	7%	1,290.52 Kg/Year	4%
UPVC Frame	3,619.85 Kg/Year	9%	2,110.48 Kg/Year	7%
Fiberglass Frame	3,564.66 Kg/Year	9%	2,014.42 Kg/Year	7%
Thermally broken UPVC Frame	3,700.22 Kg/Year	9%	2,298.23 Kg/Year	8%

Thermally				
broken	3,654.88		2,185.25	
		9%		7%
Fiberglass	Kg/Year		Kg/Year	
Frame				
Aluminium				
Frame with Dual	3,397.10		1,706.69	
		8%		6%
thermal breaks	Kg/Year		Kg/Year	

The results clearly show that all optimized configurations contribute to significant reductions in CO₂ emissions, with the U-PVC and fiberglass frames achieving the highest annual reductions. These improvements prevent over 4000 Kg of CO₂ emissions per year per household, offering a compelling environmental justification for transitioning away from conventional aluminium frames.

These findings emphasize the dual benefit of thermally efficient window frames: not only do they lower operating costs, but they also align with Saudi Arabia's broader sustainability initiatives, including the Vision 2030 goals for environmental conservation and energy efficiency.

5.6 Synthesis of Results

The simulation configurations yielded significant variations in energy performance across different climatic conditions. The results demonstrate that material innovation, thermal break integration, and climate-specific design strategies collectively reduce energy consumption, though their efficacy is modulated by regional temperature differentials (ΔT) and cooling demands. Key outcomes are highlighted in Table 5-7 and Table 5-8.

Table 5-7 Energy Performance Simulations Key Outcomes

Configuration	Energy Savings – Dhahran (%) ($\Delta T \approx 22^\circ\text{C}$)	Energy Savings – Abha (%) ($\Delta T \approx 10^\circ\text{C}$)
Baseline Aluminium	58,175.82	43,787.34
Aluminium + 10mm Break	7.5	4.3
U-PVC	9	7
Fiberglass	9	7
U-PVC + 10mm Break	9.2	8
Fiberglass + 10mm Break	9.1	7.2
Dual-Break Aluminium	8.4	6

Table 5-8 Frame to glass ratio results summary

Window Size (FGR)	Energy Savings – Dhahran (%) ($\Delta T \approx 22^\circ\text{C}$)	Energy Savings – Abha (%) ($\Delta T \approx 10^\circ\text{C}$)
1.2*1.2 m (Baseline)	58,175.82	43,787.34
1.5*1.5 m	0.06	-2
1.6*1.6 m	2.3	-0.3
1.7*1.7 m	4.5	1.4
1.8*1.8 m	2.6	0.04
1.9*1.9 m	3.7	1.3
2.0*2.0 m	2.2	0.02

This synthesis quantifies the extent to which optimized window frames reduce energy consumption in Saudi Arabia's climatic zones, demonstrating that:

- The best performing configuration in both climates was the U-PVC frame with a 10 mm thermal break, offering a practical balance between affordability, local availability, and high thermal performance.
- The dual-break aluminium frame, while more complex in design and construction, still demonstrated substantial energy savings and offers a path forward for industries committed to retaining aluminium.
- In terms of window sizing, a frame-to-glass ratio corresponding to approximately 1.7×1.7 m windows proved to be optimal, delivering the highest energy savings due to the lower U-value of glazing relative to frame materials.
- The results underscore the climate sensitivity of window frame performance. Modifications yielded greater energy reductions in Dhahran, where extreme temperatures intensify cooling demands, while the same interventions showed moderate but still valuable effects in Abha's milder climate.
- All optimized configurations demonstrated a reduction in annual energy cost compared to the baseline aluminium frame. However, U-PVC and fiberglass frames delivered the highest energy cost savings, reaching up to 1000 SAR/year in Dhahran and 500 SAR/year in Abha.
- Optimized frame configurations significantly lowered annual carbon emissions, with up to 4000 kg CO₂/year saved in Dhahran and 2000 kg CO₂/year in Abha.

- In both climatic zones, optimized window frame configurations demonstrate remarkably short payback periods, generally under two years, reinforcing their strong economic appeal.

These results quantify the extent to which optimized window frames can affect energy consumption across Saudi Arabia's climatic zones, addressing RQ5 and demonstrating that material innovation and climate-specific design are pivotal to achieving national sustainability goals. Moreover, this study demonstrates that implementing advanced window frame technologies can lead to measurable economic benefits in Saudi Arabia's residential construction sector. Furthermore, these technologies contribute to significant CO₂ emission reductions, offering long-term environmental benefits aligned with Saudi Vision 2030 sustainability targets.

5.7 Summary of chapter

This chapter presented a detailed analysis of the energy performance of various optimized window frame configurations applied to a residential building model across two distinct Saudi Arabian climates: Dhahran (hot-humid) and Abha (moderate-cool). By integrating the U-values derived in Chapter 4 into whole-building energy simulations using WINDOW and EnergyPlus via Rhino, the impact of frame design, including material substitutions, thermal breaks, and frame-to-glass ratios, on annual energy consumption was quantified.

The results clearly demonstrated that optimizing the thermal performance of window frames—through strategies such as incorporating thermal breaks, switching to low-conductivity materials (U-PVC and fiberglass), and adjusting the frame-to-glass ratio—can significantly reduce energy consumption, particularly in hot climates. Key findings

reveal that non-metallic materials (U-PVC, fiberglass) significantly outperform conventional aluminium frames, reducing annual energy use by 9–9.5% in Dhahran and 7–7.5% in Abha. Thermal breaks further enhance savings, achieving 7.5–8.5% reductions in Dhahran and 4–6% in Abha, with dual breaks (fixed + movable sash) offering incremental gains at higher costs.

Window size optimization demonstrates climate-specific efficacy: larger windows (1.7×1.7 m) in Dhahran reduce energy use by 4% by diluting aluminium's thermal bridging, while in Abha's milder climate ($\Delta T \approx 10^\circ\text{C}$), geometric adjustments yield negligible benefits ($\leq 1.4\%$). Smaller windows (1.2×1.2 m) exhibit heightened sensitivity to frame modifications, achieving up to 11% savings in Dhahran with U-PVC + thermal breaks.

In addition to the energy savings, the chapter also evaluated the economic and environmental implications of these design modifications. The cost-benefit analysis showed that all modifications decreased the annual energy costs, with UPVC and fiberglass having the highest annual savings, reaching up to 1000 SAR/year in Dhahran and 500 SAR/year in Abha per household. Moreover, carbon emissions were significantly reduced, with CO₂ savings up to 4000 kg annually, highlighting the environmental viability of adopting these enhancements.

The results underscore the necessity of climate-tailored strategies:

- Hot climates (Dhahran): Prioritize U-PVC/fiberglass with thermal breaks and larger glazing areas.
- Moderate climates (Abha): Focus on material substitutions.

Overall, the findings of this chapter underscore the critical role of window frame optimization not only in reducing cooling loads, but also in achieving economic and environmental sustainability. The combination of material selection, thermal isolation, and intelligent sizing offers a pathway to more energy-efficient and climate-responsive residential design in Saudi Arabia. Furthermore, by bridging theoretical insights with regional practicality, this chapter advances actionable pathways for energy-efficient fenestration, aligning with Saudi Vision 2030 sustainability and economic diversification objectives.

Chapter 6

Discussion

6.1 Thermal performance discussion

The purpose of this section is to critically interpret and contextualize the results presented in Chapter Four, focusing specifically on the thermal performance of various window frame configurations tested under the climatic conditions of Saudi Arabia. By discussing these findings, the chapter aims to clearly illustrate how different materials, frame geometries, insulation strategies, and thermal break integrations affect window frame performance, addressing each of the study's core research objectives and questions.

The discussion is organized thematically, beginning with an analysis of the baseline aluminium frame configurations, followed by evaluations of insulation effectiveness, thermal break strategies, alternative frame materials (U-PVC and fiberglass), and advanced designs such as dual thermal breaks. The chapter then explores the implications of varying frame-to-glass ratios on thermal efficiency.

6.1.1 Base Case Performance

The initial tests conducted on the baseline aluminium sliding window frames revealed notably high thermal transmittance (U-values), consistently ranging from approximately 11.4 to 11.6 W/m²K across different gauge thicknesses (1.3 mm, 1.5 mm, 1.8 mm, and 2 mm). Such elevated values were also observed by studies conducted under several climatic conditions. For instance, [107] reported a U-value of 11.86 W/M²-K, under cold boundary

conditions, and [78] reported a U-value of 11.2 W/m²K. These findings clearly indicate aluminium's inherently poor insulation capacity, affirming that aluminium frames significantly contribute to heat transfer and thus exacerbate energy consumption.

Interestingly, the variations in aluminium gauge thickness had minimal impact on the U-values obtained. Despite a notable difference in gauge thicknesses tested, the thermal performance remained largely unchanged, suggesting that aluminium's extremely high thermal conductivity (approximately 160 W/m·K) dominates the heat transfer behaviour. Essentially, even significant variations in frame thickness offer negligible thermal insulation improvements due to the strong conduction path inherent in aluminium as a material. This aligns with prior studies highlighting metallic frames' susceptibility to thermal bridging, even with geometric adjustments [164],[203]. This finding reinforces the understanding that enhancing the thermal performance of aluminium frames requires more substantial modifications than simple adjustments to material thickness.

These results directly address RQ2 (gauge thickness impact), The results confirm the limitations of aluminium as a standalone frame material from a thermal efficiency standpoint and underscore the necessity of incorporating more effective insulating strategies—such as introducing thermal breaks or using alternative materials—to achieve meaningful reductions in heat transfer in residential buildings in Saudi Arabia.

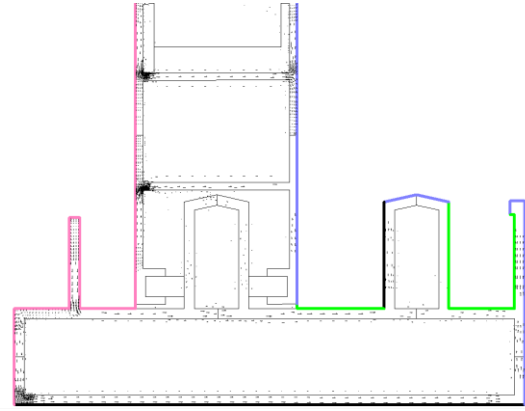
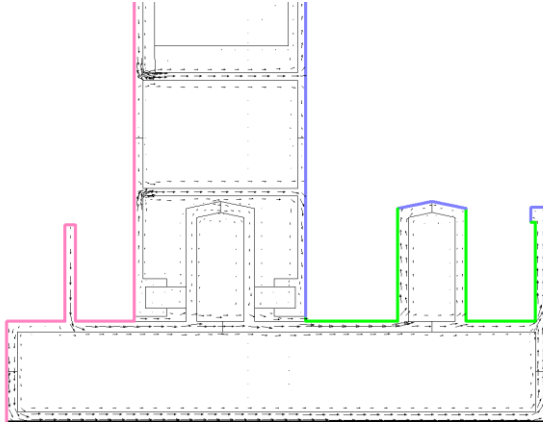
6.1.2 Insulated Aluminium Frames

The integration of insulation materials (polyurethane, XPS, EPS, rigid polystyrene, and aerogel) into the aluminium window frame cavities resulted in minimal improvements in thermal performance. Despite the use of highly effective insulating materials, including

aerogel—which is known for its exceptionally low thermal conductivity—the resulting U-values showed only marginal reductions, typically less than 2%. This limited improvement can be attributed primarily to aluminium’s inherently high thermal conductivity, which dominates the heat transfer mechanism within the frame.

As visualised in Figure 6.1, the dominant heat transfer path in aluminium window frames occurs through thermal bridging, whereby heat conduction takes place directly through the aluminium itself, circumventing the insulated cavities. Due to this, the internal insulation’s effectiveness is significantly diminished, as the aluminium frame acts as a direct conductor of heat, overshadowing the insulation’s contribution, as depicted in Figure 6.2. These findings align with previous studies reported in the literature (e.g., [7], [6]), confirming that internal cavity insulation alone is insufficient for significantly improving thermal resistance in metal frames, particularly aluminium.

However, as can be noticed from Figure 6.3 and Figure 6.4, the results contrast sharply with non-metallic frames (e.g., U-PVC or fiberglass) which have low thermal conductivity, thus, allows for heat transfer through the cavities as well as the frame itself. This aligns with the outcomes of [31] who were able to reduce the UF-value of a PVC frame by up to 40% by filling the cavities with aerogel.



Outdoor

Figure 6.1 flux vectors for hollow aluminium frames

Figure 6.2 flux vectors for insulated aluminium frames

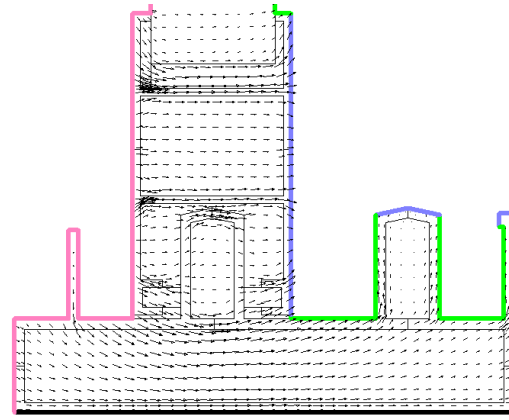
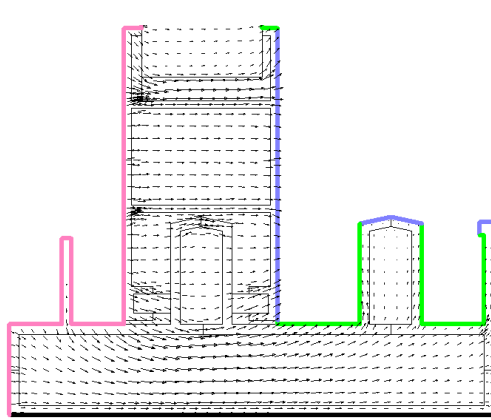


Figure 6.3 flux vectors for UPVC frames

Figure 6.4 flux vectors for Fiberglass frames

It can also be noticed that most research conducted around enhancing the thermal performance of metallic window frames who were able to enhance the UF-value ([106], [7]) were performed on high- performance frames (thermally broken frames, hybrid frames, etc.), emphasising that insulation can't be a standalone solution for aluminium frames.

Consequently, this result addresses Research Question 3, emphasizing the necessity of alternative strategies, such as thermal breaks or lower-conductivity frame materials, for achieving substantial thermal performance enhancements in window systems, especially within hot climate contexts.

6.1.3 Thermally broken aluminium frames

The integration of thermal breaks within aluminium window frames demonstrated substantial improvements in thermal performance. The significant reduction in the frame's U-value achieved through the implementation of thermal breaks can be primarily attributed to their ability to effectively interrupt the direct heat conduction path. Aluminium, characterized by its very high thermal conductivity, readily facilitates heat transfer between external and internal environments, creating a continuous thermal bridge. Introducing a thermal break filled with insulating material such as aerogel—known for its exceptionally low thermal conductivity, disrupts this conductive pathway, enhancing the thermal resistance (R-value) of the frame. Consequently, this results in a markedly lower U-value. Similar results were also achieved by other studies. For instance, [7], [6], and [78] reported that using thermal break can significantly enhance the thermal performance of aluminium frames, not only in U-value reduction but also in reducing the linear heat transfer between the frame and adjacent components.

Among the tested gap sizes (5 mm, 10 mm, and 20 mm) filled with aerogel insulation, the 10 mm thermal break proved to be the optimal configuration. This configuration achieved a notable reduction in the frame's U-value—from approximately 11.5 W/m²K in the baseline scenario down to roughly 5 W/m²K, signifying an impressive reduction of over 50%. Although the 20 mm break offered a marginally better thermal performance, the improvement was minimal relative to the significant increase in material cost and complexity in manufacturing.

The 10 mm gap was therefore identified as the optimal solution because it provided the best balance between performance enhancement and economic viability. It significantly improved thermal insulation while keeping additional costs manageable. This cost-performance trade-off is critical in promoting widespread adoption within the construction industry, especially in regions like Saudi Arabia, where affordability and practicality are key factors in the uptake of new technologies.

Furthermore, the dual thermal breaks demonstrated synergistic efficacy by isolating both fixed and movable frame components, effectively interrupting most of the conductive pathways. This contrasts with single-break designs, which only address one segment of the frame. The superior performance of dual thermal breaks (fixed + movable sash) stems from their ability to disrupt two critical conductive pathways in the window assembly. While a single 10 mm aerogel break reduced aluminium's U-value to 5.0 W/m²K, adding a second 5 mm break in the movable sash further lowered it to 3.8 W/m²K, achieving about a 67% reduction compared to the original unbroken aluminium frame. This dual interruption isolates the interior and exterior frame segments. However, this enhanced thermal performance comes with increased complexity in manufacturing, higher material costs, and potentially more challenging installation procedures compared to single-brake systems. While single break designs already deliver substantial reductions in thermal transmittance, dual thermal breaks add a further incremental benefit. Yet, designers and manufacturers must carefully weigh these marginal gains against the additional economic and practical considerations.

In comparison with single-break solutions, dual-break frames offer superior insulation performance, making them particularly suitable for scenarios demanding maximum energy

efficiency. Nevertheless, considering the Saudi Arabian construction context—where cost sensitivity, ease of production, and streamlined construction practices are important—single-break configurations may still present a more feasible and immediately applicable solution. For widespread industry acceptance and practical implementation, dual thermal breaks would require further economic optimization, careful evaluation of production capabilities, and possibly incentives or regulatory support.

These results directly address Research Question 4, affirming that strategically placed thermal breaks significantly reduce heat conduction across frames, making them highly effective in mitigating thermal bridges. This finding has important implications for window frame design, suggesting that even highly conductive materials like aluminium can achieve acceptable levels of thermal performance when appropriately modified. Thus, incorporating carefully designed thermal breaks is recommended as a standard practice for window frames in hot climates.

6.1.4 Alternative Frame Materials

The evaluation of alternative frame materials, specifically U-PVC and fiberglass, demonstrated significant improvements in thermal performance compared to traditional aluminium frames. Both U-PVC and fiberglass consistently achieved considerably lower U-values (approximately 2.4 W/m²K and 2.75 W/m²K respectively), representing substantial reductions of approximately 79% and 76% from the aluminium baseline (11.5 W/m²K). These results clearly illustrate the potential of these materials in enhancing window frame insulation, directly addressing Research Question 1, which examines the impact of frame materials on thermal performance. They also align with the broader research around window frames which reported that the selection of the frame material is

more of a crucial factor than the thickness of the material or insulating the cavities [78], [106].

The superior thermal performance of U-PVC stems from its inherently low thermal conductivity ($\lambda = 0.17 \text{ W/m}\cdot\text{K}$), which minimizes conductive heat transfer. The material itself—unplasticized polyvinyl chloride—is fundamentally different from regular PVC as it contains no plasticizers, resulting in a more rigid, durable material with excellent resistance to chemical degradation. This aligns with studies confirming U-PVC's efficacy as a frame material, where its non-metallic structure eliminates thermal bridging [111], [85]. Additionally, U-PVC's cost-effectiveness and reliance on Saudi Arabia's petrochemical byproducts position it as a sustainable, locally viable alternative to aluminium. Its compatibility with circular economy principles—owing to recyclability and reduced embodied carbon (45 MJ/kg vs. aluminium's 211 MJ/kg)—further bolsters its appeal for energy-efficient construction.

On the other hand, Fiberglass, while slightly less thermally efficient than U-PVC ($\lambda = 0.4 \text{ W/m}\cdot\text{K}$), offers superior structural reliability, durability, and resistance to weathering and thermal expansion [32]. These properties make fiberglass frames especially suited to demanding environmental conditions, such as the extreme heat and solar radiation characteristic of Saudi Arabia.

While its upfront cost may exceed U-PVC, its longevity and resistance to thermal expansion justify its use in high-stress environments. However, its higher embodied energy (80 MJ/kg) requires further consideration.

In practical terms, the adoption of these alternative materials presents compelling implications for the Saudi construction industry. U-PVC provides a cost-effective and environmentally friendly solution, aligning well with national sustainability goals and industry capabilities, whereas fiberglass offers enhanced mechanical strength and long-term stability, suitable for high-performance residential applications. Both materials effectively address critical gaps identified in current aluminium frame practices, reinforcing the importance of thoughtful material selection as a foundational step toward achieving energy-efficient building envelopes.

6.1.5 Alternative materials with thermal break

The integration of thermal breaks within low-conductivity materials such as U-PVC and fiberglass demonstrated a compounded improvement in thermal performance, exceeding the effectiveness of either strategy applied separately. The combination of inherently low thermal conductivity materials with strategically placed aerogel-filled thermal breaks produced U-values as low as 1.7 W/m²K for U-PVC frames and 1.9 W/m²K for fiberglass frames. This indicates further reductions of approximately 28% and 27%, respectively, compared to their already efficient unbroken configurations. Among tested thermal break sizes (5 mm, 10 mm, and 20 mm), the 10 mm aerogel-filled gap emerged as optimal, striking a suitable balance between cost, manufacturing practicality, and performance.

This compounded effect emphasizes that the most significant enhancements in thermal insulation are achieved by concurrently addressing material conductivity and thermal bridging. Low-conductivity materials significantly reduce conductive heat flow, while thermal breaks interrupt remaining conductive pathways, maximizing overall performance [31], [32]. The findings provide clear responses to Research Questions 3 and 4,

demonstrating the effectiveness of integrating insulation and thermal breaks in enhancing thermal characteristics, and emphasizing that performance is significantly improved when combining both strategies.

From a practical perspective, these results suggest that incorporating thermal breaks into low-conductivity frames should become a standard design approach, especially in regions like Saudi Arabia where enhancing thermal performance is critical.

6.1.6 Frame To Glass Ratio

A consistent trend observed across all configurations tested in this study was the inverse relationship between the frame-to-glass ratio and the total window U-value: increasing the glass proportion relative to the frame consistently resulted in lower overall U-values. This trend occurs because, typically, glazing units—particularly double-glazed configurations—have substantially lower thermal transmittance compared to metal frame materials, especially aluminium. Consequently, as the proportion of glazing increases, its relatively better thermal performance dominates, thereby reducing the cumulative U-value of the entire window system. These results align with existing research which highlighted the glass as the dominant factor in determining the total window U-value [111], [7], [108]. This finding underscores the importance of optimizing window geometry—not just material properties—in hot climates, where solar gain and conductive losses exacerbate cooling demands.

Moreover, this inverse relationship between frame-to-glass ratio and U-value further underscores the synergy between thermal breaks and glazing performance. As the glass area increases, the proportion of heat transfer attributed to the frame diminishes, amplifying

the thermal break's relative impact. This highlights the importance of holistic window design, where thermal breaks and glazing optimization jointly enhance energy efficiency.

Furthermore, the frame-to-glass ratio's impact varied between materials due to their contrasting thermal properties (Material-Specific Responses):

- Aluminium: Larger windows (76% glass) reduced UT-values by 16% ($5.065 \rightarrow 4.204 \text{ W/m}^2\text{K}$) because the low-conductivity glass fraction diluted the frame's dominant heat transfer contribution.
- U-PVC and Fiberglass: The ratio had negligible effects ($2.931 \rightarrow 2.881 \text{ W/m}^2\text{K}$), and ($3.02 \rightarrow 2.93 \text{ W/m}^2\text{K}$), respectively, as the material's inherent insulation capacity overshadowed geometric adjustments.

These findings advocate for material-specific design guidelines in hot climates:

- Aluminium Frames: Prioritize larger glazing areas ($\geq 70\%$ glass) to offset thermal bridging.
- Non-Metallic Frames: Focus on material selection and thermal breaks rather than geometric adjustments.

By tailoring standards to material behaviours, Saudi Arabia can optimize energy efficiency without compromising structural or aesthetic requirements.

6.1.7 Practical Implications

The practical implications of this study offer valuable guidance for architects, designers, engineers, and policymakers involved in residential construction in hot climates. First, the findings strongly advocate for careful material selection, highlighting U-PVC and

fiberglass as superior alternatives to conventional aluminium frames, particularly when combined with strategic thermal break integration. These materials not only significantly improve thermal performance but also align with sustainability goals, particularly in the context of Saudi Arabia's petrochemical-driven economy, where locally produced U-PVC offers significant economic and environmental advantages. Fiberglass on the other hand is Recommend for high-stress environments (e.g., coastal or desert regions) due to its durability and resistance to sand abrasion. Moreover, thermal breaks emerged as an efficient solution for aluminium frames which are widely used in KSA.

Additionally, the demonstrated importance of frame design optimization underscores the need for updating existing building codes and regulations, which currently lack specific guidelines on frame insulation and thermal bridging mitigation. Policymakers should incorporate clear performance criteria for window frames into national construction standards and green building guidelines (e.g. mandate thermal breaks in aluminium frames) to ensure systematic improvement in residential energy efficiency.

6.2 Energy Performance Discussion

This section interprets the energy performance outcomes of optimized window frame designs in Saudi Arabia's distinct climatic zones, contextualizing the results within broader theoretical frameworks, practical design considerations, and policy implications. By analysing the interplay between material properties, thermal breaks, window geometry, and climatic conditions, this discussion addresses the study's research questions and broader objectives while offering actionable strategies for energy-efficient fenestration.

6.2.1 Climatic Sensitivity and Heat Transfer Dynamics

The results confirmed that reducing the U-value of the window frame directly translates into measurable energy savings at the building scale. However, it was also concluded that the energy savings from window frame optimizations are intrinsically tied to climatic conditions, particularly the outdoor-indoor temperature differential (ΔT) and cooling demands. In Dhahran's hot-arid climate and prolonged cooling demand (8–10 months/year), where ΔT averages 22°C, conductive heat transfer through frames is amplified by high heat flux, making U-value reductions impactful. For instance, the 9.5% energy savings achieved by U-PVC + thermal break designs reflect the critical role of low-conductivity materials in mitigating heat gain under extreme conditions. Conversely, in Abha's moderate climate and shorter cooling season (4–6 months/year) ($\Delta T \approx 10^\circ\text{C}$), the lower temperature gradient reduces heat flux, diminishing the relative contribution of frame-driven losses. This explains why the same interventions yielded smaller savings (8% for U-PVC + break vs. 9.5% in Dhahran).

This disparity underscores the critical role of temperature differentials (ΔT) in determining the efficacy of window frame optimizations. As per Fourier's law of heat conduction ($Q=U \cdot A \cdot \Delta T$), Dhahran's larger ΔT amplifies conductive losses through frames, magnifying the energy savings from U-value reductions. Conversely, Abha's lower ΔT reduces heat flux, muting the benefits of thermal upgrades.

The findings reported in [172] affirm the foundational role of temperature difference (ΔT) in driving heat transfer through building elements, as described by Fourier's law. In their study, they demonstrated that the rate of heat conduction increases linearly with the thermal

gradient across a structure. This principle directly aligns with the energy performance outcomes observed in this research.

This climatic divergence underscores the necessity of region-specific design strategies, where interventions must balance energy savings, cost, and practicality.

6.2.2 Material and Design Efficacy

The superior energy performance of non-metallic materials (U-PVC: $\lambda = 0.17 \text{ W/m}\cdot\text{K}$; fiberglass: $\lambda = 0.4 \text{ W/m}\cdot\text{K}$) compared to aluminium ($\lambda = 160 \text{ W/m}\cdot\text{K}$) stems from their intrinsic ability to disrupt conductive heat transfer, a critical driver of cooling loads in hot climates. By minimizing thermal bridging, these materials reduce heat flux through window frames, directly lowering the energy required to maintain indoor thermal comfort.

In Dhahran's extreme climate ($\Delta T \approx 22^\circ\text{C}$), U-PVC frames reduced annual energy consumption by 9%, while fiberglass achieved comparable savings. These reductions reflect the materials' low thermal conductivity, which limits heat gain even under prolonged cooling demands. The 7% savings in Abha, though smaller, highlight their efficacy in moderate climates, where lower ΔT ($\approx 10^\circ\text{C}$) reduces but does not eliminate conductive losses.

Hybrid designs, such as U-PVC + 10 mm aerogel break, amplified savings to 9.5% in both climates by synergizing material insulation with conductive pathway disruption. This dual approach addresses both surface-area-driven heat transfer (via low-conductivity materials) and geometry-driven thermal bridging (via breaks). The results align with [85], which demonstrated that Non-metallic frames have a superior performance in hot climates, where

conductivity-driven losses dominate, which can greatly contribute to reducing cooling loads.

These findings underscore that material choice is not merely a component-level optimization but a systemic strategy to reduce cooling energy intensity in buildings, particularly in regions where windows account for 30–40% of envelope-driven heat gain,[111].

6.2.3 Frame-to-Glass Ratio Implications

The Frame-to-Glass Ratio (FGR)—the proportion of window area occupied by the frame versus glazing—plays a critical role in modulating energy performance, particularly in conjunction with material choice and climatic context. In Dhahran’s hot-arid climate, where conductive heat transfer dominates, increasing the glass area (lower FGR) amplifies energy savings by leveraging the lower U-value of double-glazed units ($2.7 \text{ W/m}^2\text{K}$) compared to aluminium frames ($11.5 \text{ W/m}^2\text{K}$). For instance, enlarging windows to $1.7 \times 1.7 \text{ m}$ (FGR = 24%) reduced energy consumption by 4%, as the glass-dominated assembly minimized frame-driven heat gain. This aligns with Fourier’s law ($Q=U \cdot A \cdot \Delta T$), where reducing the high-U frame area directly lowers total conductive losses, [172].

However, the benefits of low FGR are contingent on material selection. For example, while aluminium frames with low FGR (24%) achieved 4% savings, U-PVC frames with the same FGR delivered 9.5% savings, as their inherent low conductivity ($\lambda = 0.17 \text{ W/m}\cdot\text{K}$) further mitigates residual heat flux. This synergy between FGR and material properties underscores the importance of holistic design, as was also emphasized in the outcomes of [7].

In Abha's moderate climate, the impact of FGR is muted due to lower temperature differentials ($\Delta T \approx 10^\circ\text{C}$). Here, increasing glass area (1.7×1.7 m) reduced energy use by only 1.4%, as the smaller ΔT diminishes the relative contribution of frame conductivity. Instead, material upgrades (e.g., U-PVC) proved more impactful, achieving 7% savings regardless of FGR. This highlights the fact that in mild climates, material innovation outweighs geometric optimization.

6.2.4 Economic Feasibility: Balancing Costs and Returns

The payback period analysis demonstrates that thermally optimized window frames are financially viable, with most configurations recovering their additional initial costs within 2 months to 2.5 years. Among the evaluated options, UPVC frames emerge as the most economically attractive, achieving the shortest payback period of 0.15 years (2 months) in Dhahran and 0.26 years (3 months) in Abha. This rapid return on investment stems from UPVC's combination of low incremental cost (144 SAR over conventional aluminium) and high annual energy savings (941.58 SAR/year in Dhahran), making it a pragmatic choice for widespread adoption, particularly in cooling-dominated regions like Dhahran. Thermally broken aluminium frames, offer considerable energy savings but face longer payback periods (0.64–1.5 years) due to their higher upfront costs (500 SAR over baseline), rendering them as the second preferred option after UPVC. However, fiberglass frames present a trade-off: despite achieving energy savings comparable to UPVC (927.22 SAR/year in Dhahran), their significantly higher initial cost (1,440 SAR) erodes economic appeal, resulting in payback periods of 0.78–2.1 years. These findings underscore the importance of balancing material performance with affordability. For instance, aluminium

frames with dual thermal breaks, though enhancing insulation, are limited to specific applications due to their complex design and elevated cost (1,480 SAR).

The economic feasibility of these configurations is further influenced by regional climate variability. In Dhahran's hot climate, higher cooling demands amplify energy savings, enabling faster payback periods. For example, increasing the window size to 1.7×1.7m maximizes savings (443.53 SAR/year) by reducing heat gain. Conversely, in Abha's milder climate, lower cooling needs diminish returns, with larger window sizes (e.g., 2.0×2.0m) even increasing energy costs (-1.21 SAR/year). This divergence highlights the necessity for climate-specific design guidelines, ensuring that window configurations are tailored to local environmental conditions to optimize both energy efficiency and financial returns.

6.2.5 Carbon Reduction and Environmental Value

The environmental impact analysis underscores the alignment of optimized window frames with Saudi Arabia's Vision 2030 sustainability targets, demonstrating significant reductions in annual CO₂ emissions across all configurations. Thermally efficient designs reduce household emissions by 4–9%, with UPVC and fiberglass frames achieving the highest reductions. UPVC prevents 3,700 kg CO₂/year in Dhahran and 2,298 kg CO₂/year in Abha, while fiberglass delivers comparable savings of 3,654 kg CO₂/year in Dhahran, albeit at a higher initial cost. These reductions directly support national goals to curb greenhouse gas emissions and enhance energy efficiency in the built environment. At scale, widespread adoption of these configurations across Saudi households could offset millions of tons of CO₂ annually, positioning window frame optimization as a strategic lever for advancing the Kingdom's climate commitments and fostering a sustainable, low-carbon future. These results align with [154], who also emphasized that changing the material of

the window frame has a significant energy-saving impact, and a considerable amount of energy can be saved at the city scale.

6.2.6 Theoretical Implications

This research addresses a key gap in building energy performance literature by focusing on window frames, a component often overshadowed by the emphasis on glazing. By providing comparative, simulation-based evidence across different climatic contexts and frame configurations, this study contributes valuable data to guide holistic window system design. The findings reinforce the importance of including frame thermal performance in energy modelling and envelope optimization, particularly in hot climate regions where its influence is amplified.

Moreover, by extending the analysis beyond thermal metrics to include economic feasibility and carbon emissions reduction, this research offers a multidimensional framework for evaluating building envelope improvements. The integration of energy cost savings, payback periods, and CO₂ reduction metrics provides a more comprehensive understanding of the practical and environmental value of optimizing window frames. This holistic approach strengthens the theoretical argument for treating window frames as critical energy, economic, and sustainability components in future building design and retrofitting strategies, particularly in regions aiming to meet ambitious climate targets like Saudi Arabia's Vision 2030.

6.2.7 Practical Implications

The combined energy, economic, and environmental results of this study underscore the urgent need for climate-specific strategies and policy reforms to optimize window frame

designs in Saudi Arabia and similar hot climate regions. The findings highlight clear, actionable recommendations for building professionals, developers, and policymakers. First, in hot climates such as Dhahran, prioritizing U-PVC or fiberglass frames with thermal breaks for new constructions, coupled with the adoption of larger windows ($\geq 1.7 \times 1.7$ m), can achieve up to 9.5% reductions in annual cooling energy consumption. Furthermore, when aluminium frames must be used, integrating at least a single thermal break is essential to mitigate their high thermal conductivity. Conversely, in moderate climates like Abha, cost-effective retrofits—such as adding single thermal breaks to existing aluminium frames—can deliver 4–6% energy savings, consistent with the region’s lower temperature differentials ($\Delta T \approx 10^\circ\text{C}$) and shorter cooling seasons.

Second, the economic analysis reveals that most optimized configurations achieve remarkably short payback periods—typically under two years—further reinforcing their financial attractiveness. U-PVC frames, for example, pay back their additional cost in as little as 2–3 months, while more advanced systems like dual-break aluminium frames also show solid returns within acceptable timeframes. These fast recovery periods make thermal frame optimization not only technically feasible but also economically compelling for widespread adoption.

Third, the environmental analysis highlights significant CO₂ emissions reductions—up to 9% annually with U-PVC and fiberglass options—aligning with Saudi Arabia’s Vision 2030 sustainability targets. Reducing emissions by several tons per household per year through simple design adjustments magnifies the national environmental impact when scaled across thousands of homes.

To institutionalize these strategies, updates to the Saudi Building Code are recommended: mandating the use of thermal breaks in aluminium frames, encouraging the use of non-metallic frames (U-PVC, fiberglass), and tailoring standards based on climatic zones. In hot regions, material substitutions and larger glazing areas should be prioritized, while in moderate regions, enhancing existing frames with cost-effective thermal breaks may suffice.

By harmonizing material innovation, frame design optimization, and regulatory reforms, Saudi Arabia can drive significant, scalable improvements in building energy efficiency, balancing economic, environmental, and policy objectives in alignment with its broader sustainability agenda.

6.3 Limitations of the Study

While this research provides valuable insights into the thermal and energy performance of window frames, certain limitations must be acknowledged. First, the study focused solely on thermal performance, without addressing structural or mechanical properties of the newly proposed frame configurations. The feasibility of manufacturing and long-term structural behaviour, particularly for dual thermal break designs, remains unexamined and should be validated in future engineering studies.

second, the case study was limited to a single residential building typology (detached villa). While representative of a significant portion of Saudi housing, results may vary for other building types, such as apartments or mixed-use structures with different occupancy patterns or window orientations.

Lastly, the study did not incorporate life cycle assessments, embodied carbon analysis, or dynamic occupant behaviour (e.g., shading control, ventilation habits), which could further influence the true impact of frame optimization on building performance.

6.4 Future Research Recommendations

Building upon the findings and limitations of this study, several directions are proposed for future work:

- **Structural and Mechanical Validation:** Future research should include mechanical analysis and experimental testing of the proposed frame designs to assess durability, deformation behaviour, and resistance to sand, UV exposure.
- **Whole-Life cycle and carbon Analysis:** Expanding the study to include life cycle environmental assessments (LCA) will provide a more comprehensive view of the sustainability of each material and design option, particularly over long operational periods.
- **Integration with Adaptive and Smart Glazing:** Exploring the combined performance of optimized frames with advanced glazing technologies, such as electrochromic or vacuum-insulated glass, could lead to even greater energy efficiency gains.
- **Development of Local Design Guidelines:** The findings of this research could be used to initiate region-specific guidelines and performance benchmarks for window frame selection in hot climates. Collaboration with policymakers and standards authorities (e.g., SBC) is essential to formalize these recommendations.

- Broader Building Typologies: Extending the analysis to different residential and commercial typologies will enhance the generalizability of the results.
- Hybrid Material Designs: Investigate U-PVC/aluminium composites to synergize aluminium's structural robustness with U-PVC's thermal efficiency.

Chapter 7

Conclusion and Recommendations

7.1 Conclusion

This research aimed to optimize the thermal performance of window frames for enhanced energy efficiency in residential buildings situated in hot climates, with a particular focus on Saudi Arabia. The study addressed a critical gap in the building energy literature by shifting attention from the traditionally emphasized glazed components to the often-overlooked window frame, which can constitute up to 30% of the total window area and significantly influence overall thermal transmittance.

The methodology involved a multi-phase process including literature review, simulation-based modelling, and energy performance evaluation using tools such as THERM, WINDOW, Rhino, and EnergyPlus. A base case aluminium sliding window frame—common in the Saudi residential sector—was first modelled with four-gauge thicknesses then systematically enhanced through design modifications: adding internal cavity insulation, introducing thermal breaks of various sizes, substituting aluminium with alternative low-conductivity materials (U-PVC and fiberglass), and even implementing a dual thermal-brake system. The thermal performance of each design was quantified by calculating the frame U-values in THERM and incorporating them into full-window U-values using WINDOW. These values were then used in building-scale energy simulations

for a residential villa model located in two distinct Saudi climates: Dhahran (hot-humid) and Abha (moderate-cool) to evaluate their impact on annual cooling energy demand.

This study has demonstrated that optimizing the thermal performance of window frames in hot climates—particularly in the Saudi Arabian context—can lead to significant reductions in building energy demand and environmental impact. Among the tested configurations, the baseline aluminium frame had a U-value of $11.50 \text{ W/m}^2\cdot\text{K}$, which was substantially higher than optimized alternatives.

The study explored a variety of window frame design strategies to enhance the poor thermal performance of aluminium window frames and assess their effect on thermal, energy, and environmental performance. It was found that variations in frame metal gauge thickness had a negligible effect on thermal performance, with less than a 0.5% difference in U-value and energy consumption between the thinnest and thickest aluminium frames. However, from economic wise it can be concluded that choosing thin frames is a valid choice as the thermal performance won't be affected. Similarly, filling the aluminium frame's hollow cavities with insulation yielded minimal benefits (U-Value was reduced by less than 1%) due to aluminium's inherently high thermal conductivity, which overshadowed any insulating effects of the insert. In contrast, incorporating a thermal break within the aluminium frame proved highly effective. Introducing a 10 mm aerogel-filled thermal break in aluminium frames reduced the frame U-value to $4.35 \text{ W/m}^2\cdot\text{K}$, optimizing both thermal insulation and energy savings. This 10 mm break was identified as the most effective and cost-efficient option compared to smaller or larger variants.

Further enhancements were achieved by substituting aluminium with low-conductivity materials such as U-PVC and fiberglass. These materials led to reductions in frame U-value by up to 79% (U-Value reduced to $2.83 \text{ W/m}^2\cdot\text{K}$ and $2.91 \text{ W/m}^2\cdot\text{K}$, Respectively) compared to the baseline aluminium frame. The non-metallic frames successfully limited perimeter heat conduction, offering a practical solution for energy-efficient windows in hot climates. Notably, even when retaining aluminium, the use of dual thermal breaks led to approximately 67% reduction in U-value (achieved a U-value of $3.30 \text{ W/m}^2\cdot\text{K}$), albeit with added complexity and higher initial cost. These improvements in thermal performance contributed directly to a reduction in overall window U-values, enhancing the envelope's insulation capacity.

The study also highlighted the importance of geometric design, particularly the frame-to-glass ratio (FGR). Increasing the glass area relative to the frame improved window performance, especially when combined with advanced frame materials or thermal breaks. This points to the dual importance of material and proportion in optimizing thermal behaviour, emphasizing the importance of a holistic approach when designing window systems.

In terms of energy performance, the improvements in frame design translated into meaningful reductions in annual cooling loads. Compared to the baseline configuration, which led to energy use of $734.54 \text{ kWh/m}^2\cdot\text{year}$ in Dhahran and $552.87 \text{ kWh/m}^2\cdot\text{year}$ in Abha, the optimized frames reduced energy consumption by up to 9% in Dhahran and 7% in Abha. For instance, U-PVC frames achieved energy savings of 941.58 SAR/year in Dhahran and 548.97 SAR/year in Abha. Similarly, dual thermal break aluminium frames saved 883.64 SAR/year and 443.94 SAR/year in each city respectively. Even changes to

the frame-to-glass ratio, such as increasing window size to 1.7×1.7 m, contributed to additional savings of 443.53 SAR/year in Dhahran and 110.06 SAR/year in Abha, emphasizing the synergistic potential of geometric and material optimizations.

The economic analysis confirmed that all advanced configurations are financially viable, with payback periods ranging from 2–10 months in Dhahran and 3–25 months in Abha. U-PVC frames offered the shortest return periods due to their low cost and strong performance, while the more complex dual thermal break design remained justifiable with a payback of just over a year. These short payback periods reinforce the financial viability of investing in thermally efficient window frames, even when the upfront cost is slightly higher.

Environmentally, these frame improvements significantly cut CO₂ emissions. For a typical window in Dhahran, optimized frames reduced emissions by up to 3,700 kg/year, and up to 2,300 kg/year in Abha. The highest reductions were achieved with U-PVC and fiberglass frames, aligning with national sustainability goals.

In conclusion, the study establishes that strategic window frame modifications—through improved materials, thermal breaks, and frame-to-glass ratios—can dramatically reduce energy use, enhance economic outcomes, and contribute to carbon mitigation. Especially in Saudi Arabia’s climate, where cooling loads are dominant, integrating thermally efficient window frames into design standards and retrofit practices is both practical and essential.

Key findings of the study:

- Frame gauge thickness had negligible influence on U-values or energy consumption (<0.5% variation).
- Cavity insulation alone showed minimal improvement (< 1% reduction) due to aluminium's high thermal conductivity.
- Thermal break integration significantly reduced U-values to 4.35 W/m²·K and energy consumption by 7%, with a 10 mm aerogel-filled break offering the best cost-performance balance.
- U-PVC and fiberglass frames reduced U-values by up to 79%, and energy consumption by up to 9.5%.
- Dual-break aluminium frames achieved a 67% U-value reduction and an 8.4% energy savings, although at higher design complexity.
- Frame-to-glass ratio (FGR) adjustments demonstrated that larger glazing areas (i.e., less frame) improved thermal and energy performance, especially with optimized frame materials.
- Cost analysis revealed short payback periods for all enhanced configurations—ranging from 2 to 10 months in Dhahran and 3 to 25 months in Abha. U-PVC frames demonstrated the most rapid returns, while dual thermal breaks yielded robust savings despite higher initial costs.
- CO₂ emissions reductions reached up to 3,700 kg/year per window in Dhahran and 2,300 kg/year in Abha. U-PVC and fiberglass frames delivered the greatest environmental benefits, aligning with Vision 2030's goals for energy sustainability and carbon neutrality.

Overall, the combination of low-conductivity materials, thermal breaks, and intelligent frame-to-glass design led to significant reductions in annual energy consumption, particularly in hot regions where thermal differentials are more pronounced. The study confirms that window frames are a critical component of building envelope design and must be actively considered in both research and regulation to meet national sustainability goals.

7.2 Recommendations

To translate these findings into actionable outcomes, the following strategies are proposed:

- **Update Building Codes for Frames:** Revise the Saudi Building Code (SBC) and related energy regulations to incorporate explicit thermal performance standards for window frames (not just for glazing). This should include setting maximum allowable U-values for complete window systems and specific requirements for frame components. In particular, climate-specific code provisions are advised: for the hottest regions of Saudi Arabia, enforce more stringent frame performance criteria (Mandate maximum U-values for frames, $< 5.0 \text{ W/m}^2\cdot\text{K}$ for hot zones like Dhahran) while moderate zones may have slightly relaxed benchmarks yet still require improvements over current practice. By embedding frame efficiency into the code, all new buildings would be required to consider frame thermal performance at the design stage.
- **Mandate Thermal Breaks in Metal Frames:** Introduce regulations that mandate the use of thermal breaks in any aluminium (or other metal) window frame used in new construction and major renovations. For instance, the code could require a

minimum thermal break thickness (e.g. around 10 mm of insulating material) for aluminium frame profiles, which was proven to reduce the frame U-Value from 11 W/m²·K to 5 W/m²·K. This mandate would effectively reduce thermal bridging in metal-framed windows nationwide. Government enforcement and compliance checks should ensure that builders and window suppliers include certified thermal break technology in their products, especially for buildings in hot climate zones.

- **Incentivize Non-Metallic Frame Materials:** Develop incentive programs and standards that encourage the adoption of non-metallic, thermally efficient frame materials such as U-PVC and fiberglass, which were proven to reduce emissions by >2,000 kg CO₂/year.
- Policymakers could implement measures like financial incentives (rebates, tax credits) for projects that install high-performance frames, or fast-track permitting and certifications for buildings that exceed energy code minima through such innovations. Additionally, the building code can explicitly prioritize U-PVC and fiberglass frames in hot regions by recommending or crediting their use to meet compliance, as these materials showed around 9.5% energy savings, U-values < 2.9 W/m²·K, and the shortest payback (below 2 years). By acknowledging these materials' superior insulation performance, Saudi authorities would drive the market toward frames that substantially cut energy usage in air-conditioned buildings.
- **Adopt Optimized Frame Designs in Practice:** Stakeholders in the building industry, including developers, architects, and contractors, should prioritize optimized window frame designs as a standard part of energy-efficient construction. In

practical terms, this means specifying low-conductivity frame materials (U-PVC, fiberglass or composite frames) for projects in hot climates, instead of defaulting to traditional aluminium. Where aluminium must be used (for structural or cost reasons), it should be a thermally broken aluminium frame with at least a 10 mm insulating break to minimize heat flow. Moreover, architects should aim for low frame-to-glass ratios in the facade design (i.e. maximize the glazed area relative to the frame area, within daylight and structural limits) so that less heat is conducted through frame elements. By incorporating these considerations into design guidelines, specifications, and tender documents, the industry can ensure that window frame performance is optimized from the outset of each project.

- **Integrate Simulation-Based Evaluation:** To support the above design choices, simulation-based performance evaluations should be integrated into the building design process for all significant projects. Developers and design consultants are encouraged to use thermal analysis tools like THERM (for two-dimensional heat transfer analysis of frame cross-sections) and EnergyPlus (for whole-building energy simulation) when selecting window frame systems. By evaluating different frame options through simulation, professionals can quantitatively assess the impact on annual cooling loads, indoor temperatures, and overall energy use before finalizing decisions. This data-driven approach ensures that choices of frame material or the addition of a thermal break are justified by measurable energy savings, and it helps optimize the frame configuration for each project's specific climate and design conditions. Firms should include simulation results in their

design reports and value engineering exercises, thereby institutionalizing a culture of evidence-based envelope design.

- **Strengthen Local Supply Chains:** The construction industry, in partnership with manufacturers and government programs, should work to strengthen the local supply chain for energy-efficient window frame components. This involves investing in domestic production of U-PVC profiles, fiberglass composites, and thermal break materials (such as aerogel strips). By producing these materials locally (or sourcing them through reliable regional suppliers), costs can be reduced and availability improved for Saudi projects. Such an initiative aligns with Saudi Arabia’s economic diversification and Vision 2030 goals, creating potential local business opportunities while also removing logistical barriers to adopting advanced frames. In practice, industry groups could collaborate with material science companies to set up fabrication of insulated frames, and government incentives could support factories that produce high-performance fenestration products. Increased availability and lower cost of optimized frame systems will make it easier for developers and builders to implement the research recommendations at scale.

Table 7-1 Summary of Recommendations

Stakeholder	Action	Expected Impact
Policymakers	Revise SBC with U-value limits, Thermal break adoption and climate-specific standards.	Nationwide adoption of energy-efficient designs.
Manufacturers	Scale production of U-PVC/fiberglass and aerogel thermal breaks.	Reduced material costs and increased accessibility.

Architects	Specify low-conductivity frames and optimize window sizes in hot climates.	Enhanced building performance and compliance.
Researchers	Investigate hybrid materials and structural integrity.	Innovation in sustainable fenestration technologies.

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