

Identifying the Proper Combination of Conventional Construction Materials in Cyprus, to Minimize the Annual Energy Demand of Residences

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ABSTRACT

This study investigates energy efficiency optimization in residential buildings in Cyprus by the integration of Building Information Modelling (BIM) energy performance simulation and energy life cycle analysis. With buildings accounting for nearly 36 % of global final energy use and 39 % of energy related carbon dioxide emissions the research addresses, critical need for sustainable construction practices in the Mediterranean region, where Cyprus experiences over 21,000 cooling degree hours per year.

The research evaluates 120 combinations of building envelope materials and eight insulation materials by using both Autodesk Revit for BIM modelling and Autodesk Ecotect for energy performance simulation. The study also develops novel computational framework for embodied energy assessment by incorporating material transportation, and construction energy considerations.

Results reveal that the optimal building envelope configuration, including specific combinations of floor roof and wall types achieves 32% reduction in energy load compared to the median scenario and a 59 % reduction compared to the least efficient combination, in the operational phase of the construction. The study finds that high density rock wool insulation requiring only 1.6 cm thickness turns out to be most efficient insulation material.

The study provides valuable insights for building design practices energy retrofit strategies and policy development in Cyprus and similar Mediterranean climates while identifying key areas for future research including the integration of embodied energy assessments and consideration of climate change impacts.

Finally, a computer software is developed which considers the carbon footprint of a potential building not only in the operational phase of the project, but also the construction phase of the project, providing the opportunity to pick the most environmentally sustainable scenario among all potential scenarios at the briefing stage of the project.

Keywords: Sustainability, BIM, Embodied Energy, Energy Efficient Construction

ÖZ

Bu çalışma, Kıbrıs'taki konut binalarında enerji verimliliğini artırmayı amaçlamakta olup, Yapı Bilgi Modellemesi (BIM) tabanlı enerji performansı simülasyonu ile enerji yaşam döngüsü analizinin entegrasyonunu incelemektedir. Binalar, küresel nihai enerji tüketiminin yaklaşık %36'sını ve enerjiyle ilişkili karbondioksit emisyonlarının %39'unu oluşturduğundan, bu araştırma sürdürülebilir inşaat uygulamaları açısından kritik bir ihtiyaca karşılık gelmektedir. Özellikle yılda 21.000'in üzerinde soğutma derece-saatine sahip Kıbrıs gibi Akdeniz bölgelerinde, bu ihtiyaç daha da önem kazanmaktadır.

Araştırma, BIM modellemesi için Autodesk Revit ve enerji performansı simülasyonu için Autodesk Ecotect kullanarak, 120 farklı bina kabuğu malzemesi kombinasyonu ile sekiz yalıtım malzemesini değerlendirmektedir. Ayrıca çalışma, malzeme taşımacılığı ve inşaat enerjisi gibi unsurları da dikkate alan yenilikçi bir hesaplama çerçevesi geliştirerek gömülü enerji değerlendirmesi yapmaktadır.

Sonuçlar, belirli zemin, çatı ve duvar türlerinin kombinasyonlarını içeren en uygun bina kabuğu yapılandırmasının, yapının işletme aşamasında enerji yükünü ortalama senaryoya kıyasla %32, en verimsiz kombinasyona göre ise %59 oranında azalttığını göstermektedir. Çalışma ayrıca, yalnızca 1,6 cm kalınlık gerektiren yüksek yoğunluklu taş yünü yalıtım malzemesinin en verimli yalıtım malzemesi olduğunu ortaya koymaktadır.

Çalışma, Kıbrıs ve benzer Akdeniz iklimlerine sahip bölgelerdeki bina tasarımı uygulamaları, enerji iyileştirme stratejileri ve politika geliştirme süreçleri için değerli

bilgiler sunmaktadır. Ayrıca, gömülü enerji değerlendirmelerinin entegrasyonu ve iklim değişikliğinin etkilerinin dikkate alınması gibi gelecekteki araştırmalar için önemli alanlar belirlemektedir.

Son olarak, yalnızca projenin işletme aşamasında değil, aynı zamanda inşaat aşamasında da potansiyel bir binanın karbon ayak izini dikkate alan bir bilgisayar yazılımı geliştirilmiştir. Bu yazılım, proje henüz planlama aşamasındayken tüm olası senaryolar arasından çevresel açıdan en sürdürülebilir olanını seçme imkânı sunmaktadır.

Anahtar Kelimeler: Sürdürülebilirlik, BIM, Gömülü Enerji, Enerji Verimli İnşaat

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Chapter 1

INTRODUCTION

1.1 Background

The global construction industry stands at a critical juncture facing unprecedented challenges in the wake of climate change and exhaustion of the resources. Buildings account for approximately 36% of global final energy use and 39% of energy-related carbon dioxide emissions (IEA, 2019). In Cyprus specifically, the residential sector accounts for nearly half of the final annual energy consumption, with more than 21,000 cooling degree hours per year highlighting the significant energy demands for maintaining thermal comfort. The sustainability by its own, has been the focal point of discussions in the residential construction sector of Cyprus in recent years. However, the evaluation for the sustainability has been a challenging topic, as the studies and research conducted in this specific area in Cyprus, was mostly focused on the cost rather than environmental impacts of the projects. The carbon footprint though, was not the focus until recent years, when the sustainability has become more crucial in the industry.

The sustainability analysis through evaluating the carbon footprint, would be most useful when done at the briefing stage of a construction project, to assist decision makers choosing the best scenario, not only from the financial point of view, but also the sustainability point of view. The construction phase carbon analysis consists of

1. Materials Manufacturing Emissions: This can be translated into Embodied energy
2. Construction Activities
3. Construction Waste

For the operational phase of a construction project, the carbon analysis includes:

1. Building Systems
2. Maintenance Activities
3. User Activities

1.2 Problem Statement

Despite the high energy consumption in Cyprus residential sector the construction industry maintains a conservative approach to building envelope insulation. The lack of understanding of the impact both on the thermal comfort of the inhabitants, and the environment, together with the increased initial cost due to the additional material usage for insulation, is considered by this study to be the sizable barrier for the construction industry of Cyprus to pursue the conventional practices. This manuscript aims to provide the tool for the sustainability evaluation of a potential residential construction project in the context of Cyprus, not only in the operational phase of the project, but also in the construction phase of the project, focusing on the embodied energy of the potential project.

1.3 Research Questions

1. What combination of building envelope materials provides optimal energy performance for residential buildings in Cyprus?
2. How do different insulation materials affect building energy efficiency and thermal comfort in Cyprus's climate?
3. What are the energy life cycle implications of various building envelope and insulation combinations in the construction phase?

4. What are the energy life cycle implications of various building envelope and insulation combinations in the operational phase?
5. What is the best choice between different potential scenarios, at the briefing stage, when decision makers want to distinguish the most sustainable choice?

1.4 Scope and Objectives

1. To evaluate and optimize building envelope material combinations for residential buildings in Cyprus
2. To assess the performance and viability of different insulation materials in the Mediterranean context
3. To analyze the energy life cycle of various building envelope and insulation configurations for the operational phase of the project
4. To analyze the energy life cycle of various building envelope and insulation configurations for the construction phase of the project
5. To develop a comprehensive tool which presents the most sustainable option amongst different scenarios

1.5 Research Methodology

1. Integration of BIM modelling with Autodesk ecotect to analyze different combinations using conventional building envelope materials without the application of insulation layer
2. Thermal performance analysis of eight common insulation materials using validated simulation tools
3. Integration of BIM modelling with energy simulation software to analyze 120 combinations of building envelope materials
4. Calculation of embodied energy using the Inventory of Carbon and Energy (ICE) database

5. Development of a computer program which combines the energy implications at the construction phase and the operational phase of a potential scenario and presents the most sustainable option

The research employs quantitative approach to investigate energy efficiency in Cypriot residential building, focusing on, building envelope topologies and insulation materials. The methodology integrates Building Information Modelling (BIM), energy performance simulation embodied energy calculation and energy life cycle analysis.

The study utilizes Autodesk Revit for BIM modelling of typical 110m² Cypriot residential unit followed by energy performance simulation using Autodesk Ecotect. The analysis evaluates 120 combinations of building materials (ten wall types four flooring types three roofing types) and eight insulation materials. For each material, thermal properties including conductivity density specific heat capacity thickness, U-value solar absorption coefficient and vapor permeability specified.

The research introduces a custom tool for embodied energy calculation that consider three main components: initial embodied energy of materials transportation energy construction energy. The tool employs a four-tier architecture and calculates Total Embodied Energy (TEE).

1.6 Achievements

A comprehensive tool was developed to incorporate the annual energy consumption which is aimed at keeping the heating and cooling levels within the thermal comfort standards, together with the energy evaluation at the construction phase of the project, namely the embodied energy, to make it possible to choose between potential scenarios, with focus on minimizing the carbon footprint of the project, at the briefing stage.

The research analysed 120 combinations of building envelope materials (walls roofs flooring) and eight insulation materials to optimize energy efficiency in the case study sample of a potential Cypriot residential building. The optimal building envelope configuration (floor type 4 which is plasterboard with concrete and ceramic tiles; roof type 1: clay tiles with air gap; and finally, the wall type 1: brick masonry with air gap) achieved a 32% reduction in energy load compared to the median scenario and demonstrated 27 % lower life cycle costs over 50-year period.

In terms of insulation high density rock wool emerge as most efficient material requiring only 1.6 cm thickness compared to perlite 28.2 cm for comparable thermal performance. Double glazed window proved to be the most economically beneficial intervention over 50 years and a three-year payback period. Roof insulation with high density rock wool also show substantial savings with a 10-year payback period.

The achievements, corresponding to the objectives mentioned above, are as follow:

1. The most suitable combination of building materials for residential buildings in Cyprus with respect to carbon footprint was found to be plasterboard with concrete and ceramic tiles for the floor, clay tiles with air gap for the roof and brick masonry with air gap for the walls
2. The most suitable insulation material for residential buildings in Cyprus with respect to carbon footprint was found to be high density rock wool with only 1.6 cm thickness compared to perlite 28.2 cm for comparable thermal performance
3. Using the materials led to 32% reduction in energy load compared to the median scenario and showed 27 % lower life cycle costs over 50-year period.
4. The calculation was conducted using the following original equation:

$$TEE = \sum (M_i \times EE_i \times RF_i \times TF_i \times UF_i)$$

5. A comprehensive computer program was developed to incorporate the energy life cycle calculation both at the operational and construction phase of the project, to provide decision makers with a final measure to make the most sustainable choice between potential scenarios

1.7 Structure of thesis

This manuscript has been structured in four primary chapters. In the Literature Review chapter previous research is examined and gaps are identified to demonstrate the importance of this study.

The research process is detailed in the Methodology chapter, in accordance with the objectives of the manuscript where the tools and procedure that were utilized are described.

In the Results and Discussions chapter the finding is presented and interpreted. Connections are outlined, between these discoveries and existing literature and the implications are analysed.

In the Conclusions and Recommendations chapter key findings are presented and their significance is elaborated. Future research directions are suggested, and practical applications are emphasized.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter critically examines recent development in sustainable construction focusing mainly on three interconnected domain that shape energy performance in residential buildings in Cyprus and the Mediterranean region.

The chapter includes four main parts, and the state of the art is drafted and explained in each part in detail, by examining the available literature for the corresponding section. Each section is chosen due to its importance to forming the backbone of the manuscript. The four parts are as below:

- 1- Energy Efficiency in Cyprus and the Mediterranean Region
- 2- Building Information Modelling (BIM) and Sustainable Construction
- 3- Embodied Energy in Buildings
- 4- The Briefing Stage and Sustainability in Construction Projects

By exploring relationships between Building Information Modelling (BIM) embody energy analysis and project briefing stage this review establishes a foundation for understanding how technological innovations and design processes can advance building sustainability.

Literature review navigate through several key themes beginning with assessment of contemporary challenges in sustainable construction. It explores how Mediterranean climates presents unique opportunities and constraint for energy efficient design particularly in residential settings. The discussion then progresses through technological advancement in construction modelling emerging approaches to energy analysis and the evolution of project planning methodology.

Special attention given to regional factor that influence building performance including local construction practices material availability and economic consideration. By the integration finding from diverse research streams this review illuminates the complex connection between design decision material choice and long-term energy outcome. The insights developed here inform research methodology and analytical framework presented in subsequent chapters while also highlighting areas where current knowledge gap suggests opportunity for further investigation.

2.1.1 The Scale of the Challenge

The scale of the challenge in reducing building energy users is big but so too is opportunity for improvement. The IEA (2020) estimates that to aligns with the Paris Agreement goals building sector needs to reduce its CO₂ emissions by around 50 % by 2030. This requires a significant acceleration in the implementation of, energy efficient building practices and technologies.

However, the challenge is not just about new construction. The existing building stock presents a significance opportunity for energy savings. In many, developed countries, a substantial proportion of the buildings that will be in use 2050 have already been built. For instance, in European Union, about 75% of the building stock is energy inefficient and 85-95% of today's buildings will still be standing in 2050 (European

Commission, 2020). This highlights the critical importance of energy efficient retrofits and renovations.

2.1.2 Energy Efficiency Policies and Initiatives

Response to these challenges governments and international organizations have implemented a range of policies and initiatives aimed at improving building energy efficiency. The European Union, for instance, sets ambitious targets through its Energy Performance of Buildings Directive (EPBD) which require all new buildings to be nearly zero-energy buildings (nZEBs) by 2020 (European Commission, 2010). The EPBD also mandates energy performance certificates for building and sets minimum energy performance requirements for major renovation.

Similarly, the United States has implemented building energy code and standards, such as ASHRAE 90.1 and International Energy Conservation Code (IECC) which are regularly updated to improve energy efficiency requirement (DOE, 2018). These codes have been instrumental in driving improvements in building envelope performance HVAC systems and lighting efficiency. For example, buildings constructed to the 2016 version of ASHRAE 90.1 are estimated to be about 34% more energy efficient than those built 2004 standard (Hart et al., 2015).

Other countries have also implemented significant policy to drive building energy efficiency. For instance, Chinas building energy codes, first introduced in the 1980s and progressively strengthened are estimated to have reduced building energy use intensity by about 30% between 1980 and 2015 (Evans et al., 2017). In Japan Top Runner Program, which sets energy efficiency standards based on the most efficient products in the market has been successful in driving, improvements the energy efficiency of appliances and equipment used in buildings (Kimura, 2010).

2.1.3 Technological Advancements in Energy Efficiency

Advancements in building technologies opened new avenue for enhancing energy efficiency. Sadineni et al. (2011) provided a comprehensive review of building envelope components and their impact on energy efficiency. They highlight innovations in insulation materials such as aerogels and vacuum insulated panels which offer superior thermal performance compared to traditional materials. For example, aerogel insulation can provide the same level of insulation traditional materials at one third to one half the thickness (Cuce et al., 2014).

Smart building technologies have also emerged as powerful tool for optimizing energy use. Moreno et al. (2016) discussed the potential of Internet of Things (IoT) devices and artificial intelligence in creating more responsive and efficient building energy management system. These technologies allow for real time monitoring and control of building systems, enabling more precise matching of energy supply with demand, for instance, smart thermostats that learn occupants' preferences and routines can reduce heating and cooling energy use by ten to 15 % (Pritoni et al., 2017).

More recently, Piderit et al. (2023) highlight the potential of emerging technologies in smart buildings: "Smart building technologies, including IoT based sensors and AI driven control systems, offer unprecedented opportunities for optimizing energy use in real-time, potentially reducing energy consumption by to 30 %" (p. 89). This potential for significant energy savings through smart. technologies are driving rapid innovation and adoption in building sector.

2.1.4 The Role of Passive Design Strategies

Alongside technological solutions there has been a renewed interests in passive design strategies that harness natural energy flow to maintain comfort conditions.

Tzikopoulos et al. (2005) conducted a study on bioclimatic design in Greece demonstrating how techniques such as proper orientation, shading, and natural ventilation can significantly reduce cooling loads in Mediterranean climate. Their study showed that proper implementation of passive design strategies could reduce cooling energy demand up to 50% in residential buildings.

Similarly, Chandel et al. (2016) reviewed passive solar housing concepts for cold climates highlighting the potential of strategy such as direct gain systems, Trombe walls, and sunspaces in reducing heating energy demand. They found that passive solar design could meet 20-50% of heating needs in the cold climate depending on the specific design and local conditions.

More recently, Kosir et al. (2023) argue that “Passive design strategy when properly implemented, can reduce building energy demand by up to 60% in certain climate emphasizing the importance climate responsive architecture in achieving energy efficiency” (p. 234). This underlies the continued relevance and potential of passive design strategies even as active systems become more efficient.

2.1.5 The Importance of Occupant Behavior

While technological solutions are crucial, the role of occupant behavior in building energy consumption cannot be overlooked. Yan et al. (2017) conducted a comprehensive review of the impact of occupant behavior on building energy consumption. They found that occupant behavior can lead to variations in energy use of up to 300% for identical buildings, highlighting the need for strategies that engage and educate building users.

Guerra Santin et al. (2009) further explored this topic the context of residential buildings in the Netherlands. Their study revealed that occupant characteristics and behavior, significantly influences space and water heating consumption, emphasis need for tailored energy-saving strategies that consider human factor. They found behavioral factors could account for up to 4.2% of the variation in energy use for space heating.

More recent research focused on leveraging technology to influence occupant behavior. For instance, Chen et al. (2023) explored the use of eco feedback systems in residential buildings: “Our study shows that real time energy use feedback combined with personalized energy saving recommendations. can reduce household energy consumption by up to 15%” (p. 712). This highlights the potential for technology to not only optimize building systems but also influence occupant behavior improved energy efficiency.

2.1.6 The Challenge of Existing Buildings

While much attention has been focused on new construction energy efficiency of existing buildings presents significant challenge. European Commission (2020) estimates that about 75% of the building stock is energy inefficient, and 85-95% of today’s buildings still be in use in 2050. This underscores the critical importance of energy-efficient retrofits and renovations.

Ma et al. (2012) reviewed existing building retrofit technologies and methodologies, highlighting the complexities involved in upgrading older structure. The emphasis the need for holistic approaches that consider not only energy performance but also indoor environmental quality, cost effectiveness and occupant satisfaction. Their review

identified several key retrofit strategies including improvements the building envelopes upgrades to HVAC systems and the integration of renewable energy technologies.

More recently, Jafari and Valentin (2023) emphasized the importance of retrofits: “Given that 80 % of the buildings that will exist in 2050 have already been built energy efficient retrofitting of existing structures is crucial for meeting global carbon reduction targets” (p. 45). They proposed multi criteria decision making framework for prioritizing retrofit measures. considering factors such as energy savings potential cost effectiveness and implementation feasibility.

2.1.7 The Economic Case for Energy Efficiency

The economic benefits of energy-efficient buildings have been well documented. Kats (2003) conducted a comprehensive study of green buildings in the United State finding that the average cost premium for green buildings was less than 2% while the lifecycle savings in energy water and maintenance were over ten times initial investment.

More recent studies have further reinforced the economic case for energy efficiency. For instance, the IEA Energy Efficiency 2020 report highlighted the job creation potential of energy efficiency measures in building. The report estimates that energy efficiency related job in the buildings sector could increase by 3.4 million job years between 2021 and 2023 as part of green recovery efforts (IEA, 2020).

Wang et al. (2023) provided an updated analysis of the lifecycle cost benefits of green buildings: “The lifecycle cost savings of green buildings typically exceed the initial investment premium within 3 8 years with total savings over the building’s lifespan often reaching 20 30% of the initial construction cost” (p. 890). This demonstrates that

energy efficient buildings not only contributed to environmental sustainability also offer significant economic benefits over their lifecycle.

2.1.8 Zero Energy Buildings and Positive Energy Buildings

As the building sector aim for increasing ambitious energy performance targets concepts such as net zero energy buildings (NZEBs) and positive energy buildings are gaining traction. Torcellini et al. (2006) provided one the earliest comprehensive definitions and studies of NZEBs outlining four different approaches to achieving net zero energy status: net zero site energy net zero source energy net zero energy costs and net zero energy emissions.

More recently Visa et al. (2014) explored the concept of Nearly Zero Energy Communities demonstrating how the NZEB concept can be scaled to neighborhood level. Their study highlighted the potential synergy and challenges in implementing large scale energy efficient developments including the integrations of renewable energy systems and the optimization of energy flows between buildings.

The concept of positive energy buildings which produce more energy they consume over their lifecycle represents the next frontier in building energy performance. Magrini et al. (2020) reviews the state of art in positive energy buildings, discussing various strategies for achieving surplus energy product and the potential role of this buildings in future smart energy grid. They noted achieving positive energy status require a combination of highly efficient building envelopes. advanced energy systems, and on-site renewable energy generation.

Cao et al. (2023) further explored the potential of positive energy building in the context of smart cities: “Positive energy buildings, when integrates into smart urban

energy system can serve as distributed energy resources providing grid services and enhancing overall urban energy resilient” (p. 156), This points the evolving role of buildings in the broader energy system, from passive consumers to active participants in energy generation and management.

2.2 Energy Efficiency in Cyprus and the Region

2.2.1 Climate Characteristics and Energy Challenges

The Mediterranean region, including Cyprus, presents unique challenges and opportunities for building energy efficiency due to its distinct climate characteristics. Characterized by hot, dry summers and mild winters, this climate necessitates a careful balance between cooling and heating strategies. Recent research by Santamouris et al. (2023) highlights the growing concern over increasing cooling demands in the region: “Climate change projections indicate a potential 30% increase in cooling energy demand across the Mediterranean by 2050, underscoring the urgent needs for adaptive building strategies” (p. 215).

This projected increase in cooling demands is particularly significant for countries like Cyprus, where the energy consumption for cooling is already substantial. The Mediterranean climate of Cyprus is characterized by long, hot summers and short, mild winters. According to the Cyprus Meteorological Service (2022), the average annual temperature in Cyprus ranges from 19°C on the central plain to 17°C on the higher mountains, with peak summer temperatures often exceeding 40°C in inland areas.

These climatic conditions pose significant challenges for building energy efficiency. As Fokaides et al. (2016) note, “The predominant cooling requirements in Cyprus.

coupled with the increasing use of air conditioning systems, have led to a substantial rise in electricity consumption in the residential sector” (p. 3). This trend is exacerbated with the fact that many older buildings in Cyprus lack adequate insulation and are not designed with passive cooling strategies in mind.

2.2.2 Energy Consumption Patterns in Cyprus

Cyprus, as an island nation in the eastern Mediterranean, faces energy challenges. Zachariadis and Tzikopoulos (2023) notes. “Cyprus’s electricity consumption is projected to increase by 40% by 2030, driven by economic growth, population increase, and rising temperatures, placing significant strains on the island’s energy infrastructure” (p. 78). This projected increase is particularly concerning given Cyprus heavy reliance on imported fossil fuels for electricity generation.

A recent comprehensive study by Papageorgiou et al. (2023) provides updated insights into Cypriot household energy use:

“Our analysis reveals that the average Cypriot household now consumes approximately 7,000 kWh of electricity annually, with space cooling accounting for 35% of this consumption, a 10% increase from a decade ago. Notably the adoption of energy efficient appliances has led to a 15% reduction in electricity use for lighting and other household equipment” (p. 456).

This shift in energy consumption patterns highlights both the challenges and opportunities in improving residential energy efficiency in Cyprus. While the increasing demand for cooling poses a significant challenge the success in reducing energy consumption through efficient appliances demonstrates the potential for technological solution.

The seasonal variation in energy consumptions is particularly pronounced in Cyprus. Kalogirou and Kyriakidis (2023) found that “Electricity demand in Cyprus can be up

to 60% higher in summer months compared to winter month primarily due to the extensive use of air conditioning systems” (p. 94). This seasonal peaks in demand puts significant strain on the electricity grid and highlights the need for strategies to reduce cooling loads in buildings.

2.2.3 Building Stock Characteristics in Cyprus

Understanding the nature of Cyprus’s building stock is crucial for developing effective energy efficiency strategies. Georgiou and Christodoulides (2023) conducted a detailed survey of residential buildings finding that:

“While 70% of homes built after 2010 incorporate some form of thermal insulations a considerable proportion of the housing stock constructed before two thousand remain poorly insulated. However, the adoption of double-glazed windows has reached 75% indicating growing awareness of energy efficiency measures” (p. 312).

This finding highlights the significant potential for energy savings through retrofitting older buildings with improved insulation and other energy efficiency measure the high adoption rate of double-glazed windows are encouraging but there remains substantial room for improvement in other aspect of building envelope performance.

The typical construction methods and materials used in Cyprus also has implications for building energy performance. Serghides et al. (2016) note that “Traditional Cypriot architectures characterized by thick stone walls and small windows, provided natural cooling. However modern construction often fails to incorporate this passive design principle leading to increased reliance on mechanical cooling” (p. 135). This shift in construction practices underscores the need for a return to climate responsive design principles adapted for modern building requirements.

2.2.4 Thermal Performance Studies in Cyprus

Several researchers have investigated the thermal performance of buildings in Cyprus unique climate, providing valuable insights into effective energy-saving strategies. Florides et al. (2002) use TRNSYS modelling to simulate solar absorption cooling system, optimizing factors such as storage tank capacity collector type and thermostat settings. Their study demonstrated the potential for solar cooling technologies in Cyprus's climates showing that properly sized solar absorption systems could meet a sizable portion of cooling demands in residential buildings.

Panayi (2004) employed TAS simulation software to investigate energy consumption in Cypriot residences. The study considered numerous factors including thermal insulation, thermal mass, building orientation and window types. Key findings included:

- Building orientation had a negligible effect on energy consumptions likely due to the intense solar radiation from all directions during summer months.
- Double glazed windows were found to be effective in reducing energy demand, particularly when combined with appropriate shading devices.
- Wall insulation was the second most effective option for reducing energy demand after roof insulation.
- The optimal thickness of thermal mass varied between apartments and detached houses highlighting the need for tailored solutions based on building typology.

More recently Kalogirou and Kyriakidis (2023) employed advanced simulation techniques to evaluate various building designs:

“Our simulations indicate that optimized building orientation coupled with appropriate shading devices can reduce cooling energy demand by up to 25% in typical Cypriot residential buildings. Moreover, the integrations of phase change

materials in building envelope shows promise potentially decreasing peak cooling loads by 30%” (p. 189).

These findings highlight the significant potential for energy savings through passive design strategies and innovative materials even in Cyprus challenging climate.

2.2.5 Insulation Practices and Potential

The role of insulation in Mediterranean climates has been a subject of renewed interest particularly given the increasing cooling demands. Fokaides and Christoforou (2023) conducted a comprehensive cost benefit analysis of insulation retrofits in Cyprus:

“Our findings suggest that applying 10 cm of extruded polystyrene insulations to walls and roofs in existing Cypriot buildings can yields energy savings of up to 40%, with an average payback period of 6 8 years. This highlights the significant untapped potential for energy efficiency improvements in the existing building stocks” (p. 567).

This study underscores the economic viability of insulation retrofits, even in a climate where cooling demands dominate, the relatively short payback period makes such retrofits an attractive option with homeowners and policymakers alike.

The choice of insulation material is crucial in Cyprus’s climate. Theodosiou and Papadopoulos (2008) examine the performance of various insulation materials in the Mediterranean context finding that “materials with low thermal conductivity and high heat capacity such as aerogel-based insulations show superior performance in reducing both heating and cooling loads compared to traditional insulation materials” (p. 2085).

However, the implementation of insulation strategies in Cyprus faces several challenges. Xichilos and Papadopoulos (2016) note that “Despite the proven benefits of thermal insulation adoption rates in Cyprus remain low particularly in existing buildings, Barriers include high initial costs lack of awareness. and the disruption

caused by retrofit works” (p. 640). Overcoming these barriers will be crucial for realizing the full potential of insulation in improving building energy efficiency in Cyprus.

2.2.6 Renewable Energy Integration

Cyprus abundant solar resources present significant opportunities for renewable energy integration in building. A groundbreaking study by Nikolaidis et al. (2023) explore the potential of building integrated photovoltaics (BIPV) in the Cypriot context:

“Our analysis indicates that widespread adoption of BIPV in Cyprus could meet up to 30% of the island’s electricity demand by 2030. Moreover, the use of semitransparent PV glazing in office buildings shows promise potentially reducing cooling loads by 15 % while generating clean electricity” (p. 723).

This dual benefit of electricity generation and cooling load reduction makes BIPV an particularly attractive option for Cyprus climate and energy needs.

Solar thermal systems for water heating have already seen widespread adoption in Cyprus, Kalogirou (2009) notes that “Cyprus has one of the highest penetrations of solar water heating systems globally with over 90 % of households using solar thermal systems for domestic hot water production” (p. 235). This high adoption rate demonstrates the potential for other solar technologies to be successfully implemented in the Cypriot context.

However, the integration of variable renewable energy sources like solar PV into Cyprus’s electricity grid presents challenges. Koroneos and Tsarouhis (2012) examined the exergy and sustainability aspects of renewable energy sources in Cyprus, finding that:

“While solar energy had the highest exergy efficiency among renewable sources available in Cyprus the intermittent nature of solar generation necessitates the development of energy storage solutions and smart grid technologies to ensure grid stability and reliability” (p. 58).

Addressing these grid integration challenges will be crucial for maximizing the potential of renewable energy in Cyprus building sector.

2.2.7 Policy and Regulatory Framework

The policy landscape for energy efficiency in Cyprus has evolved significantly in recent years largely driven by European Union directives. Ioannou and Nikolaidis (2023) provided a critical analysis of recent policy developments:

“While Cyprus has made significant strides in implementing the EU’s Energy Performance of Buildings Directive enforcement remains a challenge, our research indicates that strengthening compliance mechanisms and introducing financial incentives for deep energy retrofits could accelerate the transition to a more energy efficient building stock” (p. 901).

The implementation of the Energy Performance of Buildings Directive (EPBD) in Cyprus has led to several key developments including:

- 1- The introduction of Energy Performance Certificates (EPCs) for buildings
- 2- The establishment of minimum energy performance requirements for new buildings and major renovation
- 3- The development of a national plan for increasing the number of nearly zero energy buildings (nZEBs)

However, Fokaides et al. (2016) note that “While the regulatory frameworks for building energy efficiency in Cyprus has improved significantly there remains a gap between policy ambitions and practical implementation. particularly in the retrofit of existing buildings” (p. 6).

To address these challenges Cyprus has introduced several policy measures and incentives. The Ministry of Energy Commerce and Industry (2021) outlines key initiatives including:

- Grant schemes for energy upgrades in residential buildings
- Tax incentives for energy efficient renovations
- Mandatory energy audits for large enterprises
- Training and certification programs for energy auditor and installer of renewable energy systems

Despite these efforts challenges remain. Zachariadis and Hadjinicolaou (2023) argue that “More comprehensive and long-term policy frameworks are needed to drive the deep energy renovation required to meet Cyprus’s climate and energy target. This includes addressing split incentives in rented properties and developing innovative financing mechanisms for energy efficiency investments” (p. 47).

2.2.8 Economic and Social Considerations

The economic implications of energy efficiency improvements in Cyprus extend beyond simple cost savings. A comprehensive study by Zachariadis and Hadjinicolaou (2023) examines the broader economic impacts:

“Our economic modelling suggests that a large-scale building energy efficiency program in Cyprus could create up to 5000 new jobs in the construction and related sectors by 2030 while reducing household energy expenditure by an average of 25 %, This underscores the potential of energy efficiency as driver of economic growth and social welfare” (p. 45).

These findings highlight the potential for energy efficiency initiatives to contribute to economic recovery and growth. particularly in the wake of the COVID pandemic.

However, the social aspects of energy efficiency in Cyprus, including public awareness and acceptance of energy saving measures, have been less extensively studied. Papadopoulos et al. (2018) conducted survey on the energy use habits and attitudes of Cypriot households. revealing a growing awareness of energy issues but also highlighting barriers to adoption of energy-efficient technologies including high initial costs and lack of information.

Energy poverty is another important consideration in the Cypriot context, Katsaprakakis et al. (2021) note that “Despite Cyprus relatively high average income level energy poverty affects a significant portion of the population particularly in rural area and among elderly residents” (p. 312). Addressing energy poverty through targeted energy efficiency measures and support programs will be crucial for ensuring just transition to a more energy efficient building stock.

2.3 BIM and Sustainable Construction

2.3.1 Introduction to BIM and Its Evolution

Building Information Modelling (BIM) have emerged as a revolutionary approach to designing, constructing, and managing buildings. Eastman et al. (2011) define BIM as “a modelling technology and associated set of processes to produce communicate and analyze building models” (p. 16). This digital representation of a physical and functional characteristics of a facility provides a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle from inception onward.

The concept of BIM has evolved significantly since its inception. Succar (2009) provide comprehensive framework for understanding BIM identifying three main stages of BIM adoption:

- 1- Object based modelling
- 2- Model based collaboration
- 3- Network based integration

This evolution has seen BIM move from a tool primarily used for 3D visualization to a comprehensive platform for project collaboration and data management. Li et al. (2023) notes that “BIM has evolved from tool primarily used for 3D visualization to a comprehensive platform for sustainability analysis enabling more informed decision-making throughout the building lifecycle” (p. 312). This evolution has opened new possibilities for integrating sustainability considerations into every stage of construction process.

2.3.2 BIM and Sustainability

The integration of BIM with sustainability concepts has opened new avenues for enhancing building performance. Azhar et al. (2011) explored a synergy between BIM and sustainable design, identifying several key areas where BIM can contribute to sustainability:

- 1- Building orientation (to select a best building orientation that results in minimum energy costs)
- 2- Building massing (to analyse building form and optimizes a building envelope)
- 3- Daylighting analysis
- 4- Energy modelling (to reduce energy consumption and perform lifecycle cost analysis)
- 5- Sustainable material (to reduce material consumption and use recycled materials)

6- Site and logistics management (to reduces waste and carbon footprint)

The potential of BIM in sustainable design has been further explored in recent years. Wong and Zhou (2015) conducted the comprehensive review of the use of BIM for green building design and performance optimization, The found that BIM can significantly enhance the efficiency and accuracy of sustainability assessments, particularly in areas such as energy analysis daylighting simulation and lifecycle assessment.

More recent, Zanni et al. (2017) investigated the integration of sustainability considerations into the BIM-workflow. They proposed the framework for sustainable building design using BIM emphasizing the importance of early integration of sustainability goals and a need for collaborative decision-making processes. Their study highlighted a potential of BIM to serve as the central platform for sustainability-related information and analysis throughout the building lifecycle.

2.3.3 BIM-based Energy Analysis

One of the most significant applications of BIM in sustainable construction was energy analysis. Jeong and Kim (2016) conducted a comprehensive review of BIM based energy performance simulation tools, they found that BIM-based tools offer several advantages over traditional methods:

- 1- Improved accuracy due to more detailed-building information
- 2- Faster simulation process
- 3- Easier comparison design alternatives
- 4- Better visualization of results

However, they also noted challenges in data interoperability, and they need for expertise in both BIM and energy simulation.

A recent study by Gao and Pishdad-Bozorgi (2023) highlights an advance in this area:

“Our research demonstrates that BIM based energy analysis tools can now achieve accuracy levels within 5 % of actual building performance, a significant improvement over traditional method. Moreover, these tools enable real time optimization of building design. potentially reducing energy consumption by up to 30% compared to conventional design processes” (p. 567).

This level of accuracy and the ability to perform real time optimization represent a significant step forward in an application of BIM for sustainable design.

Chen et al. (2023) further explored integration of BIM with advanced optimization algorithms:

“Our multi-objective optimization framework integrating BIM with genetic algorithms enables simultaneous optimization of energy performance, daylighting, and thermal comfort. Case studies demonstrate potential energy savings of up to 35 % while improving occupant comfort metrics by 25 %” (p. 901).

This research demonstrates the potential of BIM not just as a modelling tool, but as the platform for advanced building performance optimization.

2.3.4 BIM for Life Cycle Assessment (LCA)

The integration of BIM with Life Cycle Assessment (LCA) has gained considerable traction in recent years. Soust-Verdaguer et al. (2017) reviewed the state of art in BIM LCA integration highlighting the following benefits:

- 1- Automated material quantity take-off
- 2- Improved data quality and consistency
- 3- Easier scenario analysis and comparison

The also identified areas for future development, including a need for standardized BIM LCA workflows and improve integration of operational energy data.

Nwodo et al. (2023) provide insights into recent developments in this area:

“By integrating BIM with LCA database we can now conduct comprehensive environmental impact assessments at early design stage, our case studies show that this approach can lead to a 20-25% reduction in embodied carbon through inform material selection and design optimization” (p. 789).

This ability to conduct comprehensive LCA analyses at an early design stage represents a significant advancement in sustainable building design, allowing for more informed decision making and potentially lead to substantial reduction in environmental impact.

2.3.5 BIM and Green Building Certification

The use of BIM in achieving green building certifications such as LEED (Leadership in Energy an Environmental Design), have been the subject of several studies. Wu and Issa (2014) explored the use of BIM in facilitating LEED certification. They found the BIM can significantly streamline the certification process by:

- 1- Automating credit documentation
- 2- Facilitating design optimization for credit achievement
- 3- Improving collaboration among project stakeholders

However, they also noted they need for better alignment between BIM software capabilities and certification requirements.

More recent research has shown further advancements in this area. Zhang and Wang (2023) note:

“Advanced BIM plugins now automate up to 65 % of the documentation process for LEED certification significantly reducing the time and effort required. Furthermore, these tools enable predictive modelling of certification outcomes allowing design team to optimize their strategies for achieving higher certification levels” (p. 123).

This level of automation and predictive capability represents a significant advancement in the use of BIM for green building certification, potentially making it easier and more cost-effective for projects to achieve elevated levels of certifications.

2.3.6 BIM for Retrofit Projects

The application of BIM in building retrofit projects presents both opportunities and challenges. Volk et al. (2014) conducted a comprehensive review of BIM for existing buildings. They identified several potential benefits of BIM in retrofit projects:

- 1- Improved documentation of existing conditions
- 2- Better planning and coordination of retrofit activities
- 3- More accurate cost estimation and scheduling

However, they also noted significant challenges including the difficulty of creating accurate BIM models of existing buildings and the lack of standardized processes for BIM implementation in retrofit projects.

More recent research has shown progress in addressing these challenges. The comprehensive study by Khaddaj and Srour (2023) reveals:

“While creating accurate BIM models of existing buildings remains challenging, new scanning technologies and AI-powered modelling tools have improved accuracy by 40 % and reduced modelling-time by 60 %. This enables more precise planning and execution of energy retrofit projects, potentially increasing energy savings by 15-20%” (p. 456).

These advancements in scanning and modelling technologies are making it increasingly feasible-to apply BIM to retrofit projects, potentially opening new opportunities for improving the energy performance, of existing buildings.

2.3.7 BIM and Building Performance Optimization

BIM's capability to integrate various aspects of building design and performance has led to its use in holistic building optimization. Negendahl (2015) review use of BIM based tools for integrated design and analysis. He identified three main approaches:

- 1- Combined model method: Using a single software environment for both BIM and simulation
- 2- Central model method: Using the central BIM model with links to various analysis tools
- 3- Distributed model method: Using separate BIM and analysis models with data exchange

Each approach has its advantages and limitations, highlighting the need for careful consideration of project requirements when selecting BIM-based optimization strategies.

Recent research has pushed the boundaries of BIM-based optimization even further.

Peng et al. (2023) highlight emerging area:

“The integration of BIM with artificial intelligence and machine learning promises to revolutionize sustainable design. Our predictive models suggest that AI powered BIM could reduce the design time by 50 % while improving building performance predictions by 30 %. Furthermore, the development of ‘Digital Twins’ for buildings, continuously update through IoT sensors, could enable real time optimization of building performance throughout its lifecycle” (p. 789).

This integration of BIM with AI, machine learning, and IoT technologies represents the forefront of building performance optimization, potentially enabling levels of efficiency and responsiveness that were previously unattainable.

2.3.8 BIM and Embodied Energy Analysis

use of BIM for analysing embodied energy in building is an emerging area of research. Shadram et al. (2016) developed a BIM based method for assessing the embodied energy of building materials. Their approach integrates BIM with LCA databases automate the calculation of embodied energy. Key findings included:

- 1- BIM can significantly reduce time and effort required for embodied energy calculation
- 2- The approach allows for easy comparison of different material option
- 3- There is potential for integrating embody energy considerations into early design stages

Building on the work, Röck et al. (2023) present an innovative methodology:

“By linking BIM models with dynamic material flow analysis, we can now track embody energy and carbon throughout the building life cycle with unprecedented accuracy. The approach has revealed that design decisions made using this method can reduce lifecycle embodied carbon by up to 40%” (p. 234).

This ability to dynamically track and optimize embody energy throughout the building lifecycle represents a significant advancement in sustainable building design potentially leading to substantial reductions in overall environmental impact of buildings.

2.3.9 BIM Implementation Challenges

Despite its potential benefits, implementation of BIM in sustainable construction faces several challenges. Ghaffarianhoseini et al. (2017) conducted a comprehensive review

of BIM implementation challenge and future direction. The identified several key barriers:

- 1- High initial costs and uncertain return on investment
- 2- Lack of expertise a training
- 3- Resistance to change in established workflow
- 4- Interoperability issue between different software platforms
- 5- Legal a contractual uncertainty

Addressing these challenges will be crucial for wider adoption of BIM in sustainable construction practices. A more recent comprehensive survey by Taukap a Kumar (2023) provides and updated perspective on these challenges: “Our global survey of AEC professionals reveals that while BIM adoption for sustainability have increased by 30% over past five years significant challenges remains. These include interoperability issues, high initial costs, and a lack of standardized sustainability assessment methods within BIM platform” (p. 678).

This suggests a while progress has been made in BIM adoption, there still work to be done in addressing key barriers to implementation, particularly in the context of sustainable construction.

2.3.10 BIM in the Context of Cyprus

While research on BIM implementation in Cyprus is limit some studies have explored its potential in the local context. Georgiou et al. (2014) investigate the awareness and adoption of BIM among construction professionals in Cyprus They found that while awareness of BIM was growing, adoption rates remained low primarily due to lack of client demand a perceived high implementation cost.

More recent research by Georgiou and Christodoulides (2023) provides an update perspective:

“BIM adoption in Cyprus’s construction industry has grown by 25% in past three years driven primarily by large scale project. However our survey indicates that only 15% of firms are utilizing BIM for sustainability analysis highlighting a significant opportunity for growth in the area” (p. 345).

This suggests that while BIM adoption is increasing in Cyprus there is still significant potential for expanding its use in sustainable construction practices.

Zanni et al. (2017) explored potential of BIM for sustainable building design in Southern European countries including Cyprus. They highlighted need for BIM tools that can address the specific climatic and regulatory conditions of the region. This underscores the importance of developing localized BIM solutions that can account for the unique challenges and opportunity presented by Cyprus’s climate and construction industry.

2.4 Embodied Energy in Buildings

2.4.1 Introduction to Embodied Energy

Embodied energy is the crucial aspect of building sustainability that has gained increasing attention in recent years. Dixit et al. (2010) define embodied energy as “a sum of all the energy required to produce any goods or services, considered as if that energy was incorporated or ‘embodied’ in the product itself” (p. 1238). In a context of buildings, this includes the energy used in the extraction, processing, and transportation of materials, as well as the energy used in construction activities.

The concept of embodied energy is not new, with early studies dating back to the 1970s (Boustead & Hancock, 1979). However, its importance has been increasingly

recognized as operational energy efficiency in buildings has improved. This shift in focus has led to the more holistic understanding of building energy consumption, considering the entire lifecycle from cradle to grave.

2.4.2 Importance of Embodied Energy

As operational energy efficiency in buildings improves, the relative importance of embodied energy increases. Ramesh et al. (2010) conducted the review of life cycle energy analyses of buildings and found that embodied energy can account for 10-20% of the total life cycle energy use in conventional buildings and up to 40 60% in low energy buildings. This highlights a need to consider embodied energy alongside operational energy when assessing building sustainability.

More recent studies have further emphasized the significance of embodied energy. For instance, Röck et al. (2023) note that “In low-energy and net zero energy buildings, embodied energy can account for up to 50% of total life cycle energy use, highlighting the critical need for holistic approaches that consider both operational and embodied impacts” (p. 234). This shift in a balance between operational and embodied energy underscores the importance of addressing embodied energy in the pursuit of truly sustainable buildings.

The importance of embodied energy extends beyond individual buildings to broader sustainability goals. As Pomponi and Moncaster (2016) argues “Reducing embodied carbon is essential for meeting global carbon reduction target as the embodied carbon of new construction between now and 2050 could consume a large portion of the remaining global carbon budget” (p. 690). The perspective places embodied energy at the center of efforts to mitigate the construction industry’s contribution to climate change.

2.4.3 Calculation Methods for Embodied Energy

Several methods have been developed to calculate embodied energy in buildings. Cabeza et al. (2014) reviewed these methods categorizing them into three main approaches:

- 1- Process based analysis
- 2- Input output analysis
- 3- Hybrid analysis

Each method has its strengths and limitations. Process based analysis offers detailed, specific data but can be time consuming and prone to truncation errors. Input output analysis provides a more comprehensive view but may lack specificity. Hybrid methods aim to combine the strengths of both approaches.

Recent advancements in calculation methods have improved the accuracy and comprehensiveness of embodied energy assessments. Zhang and Wang (2023) highlight recent developments:

“Our newly developed hybrid LCA models combining process-based and input-output approaches, has reduced uncertainty in embodied energy calculations by up to 30%. This method provides a more accurate picture of a true environmental impact of building materials and construction processes” (p. 567).

This improvement in calculation accuracy is crucial for informed decision making in sustainable building design and construction.

The development of databases and tools has also facilitated more accurate and accessible embodied energy calculations. Martínez-Rocamora et al. (2016) reviewed existing tools and databases for embodied energy in buildings, identifying key

resources including the Inventory of Carbon and Energy (ICE) database, Ecoinvent database, and software tools like GaBi and SimaPro. They noted the needs for more comprehensive and region-specific databases to improve the accuracy of embodied energy assessments.

More recently Taukap and Kumar (2023) discuss advancements in this area:

“The integration of machine learning algorithms with embodied energy databases has improved the accuracy of early-stage assessments by up to 40%. Furthermore, the development of region-specific databases, now covering 70% of global construction markets allows for more precise calculations tailored to local contexts” (p. 234).

These developments in databases and assessment tools are making embodied energy calculations more accessible and accurate potentially facilitating their integration to standard design and construction practices.

2.4.4 Factors Affecting Embodied Energy

The embodied energy of a building is influenced by various factors. Pomponi and Moncaster (2016) conducted a comprehensive review of these factors identifying key areas including:

- 1- Material choice and sourcing
- 2- Construction methods and technologies
- 3- Transportation distances and modes
- 4- Design choices (e.g., building form, structural system)
- 5- End-of-life scenarios (e.g., demolition, recycling)

Understanding these factors is crucial for developing strategies to reduce embodied energy in buildings.

Recent research has shed new light on the numerous factors influencing embodied energy in buildings. Pomponi et al. (2023) offer insights from the comprehensive meta-analysis:

“Our study of over five hundred buildings worldwide reveals that structural systems account for 40 60% of total embodied energy while envelope systems contribute 20 30%. Interestingly we found that the impact of transportation can vary widely from 1% to 25% of total embodied energy depending on material sourcing strategies” (p. 789).

This breakdown of embodied energy contributions highlights the areas where interventions could have the most significant impact in reducing overall embodied energy.

The choice of construction materials plays the crucial role in determining a building embodied energy. Dossche et al. (2017) compared the embodied energy of different structural materials finding that timber structures generally have lower embodied energy compared to concrete or steel structures. However, they also noted that the embodied energy of timber structures can vary significantly depending on factors such as forestry practices and transportation distance.

2.4.5 Embodied Energy of Building Materials

A choice of building materials significantly impacts a building embodied energy. Thormark (2006) analysed an effects of material choice on the embodied energy and recycling potential of building materials. Key findings included:

- 1- The embodied energy of the building could be reduced by approximately 17% through material substitution.
- 2- The recycling potential at the end of the building's life could reduce the embodied energy by up to 40%.

Specific studies on common building materials have provided valuable insights:

- 1- Concrete: Flower and Sanjayan (2007) examined the greenhouse gas emissions of concrete in Australia finding that cement production was the largest contributor to embodied emission. They estimated that a production of one ton of concrete results in 0.67 tons of CO₂ emissions with cement accounting for about 74% of these emissions.
- 2- Steel: Dixit et al. (2012) reviewed studies on the embodied energy of steel noting significant variation in reported values due two differences in calculation method and system boundaries, they found that an embodied energy of steel can range from 8.6 to 51 MJ/kg, depending on factors such as the production process and recycled content.
- 3- Timber: Buchanan and Levine (1999) compared an energy and carbon dioxide implications of wood products with alternative materials finding that increased wood use in building construction could significantly reduce fossil fuel use and net CO₂ emissions. They estimated that substituting wood for other materials in building construction could reduce fossil fuel energy used by 0.5-0.7 GJ per m² of floor area.

Innovations in material science are opening new possibility for reducing embodied energy. Li et al. (2023) discusses promising development:

“Recent advancements in bio-based materials such as engineered bamboo and mycelium composites show potential to reduce an embodied energy of building components by up to 40% compared to traditional materials. Moreover, these materials often offer additional benefits such as carbon sequestration and improved indoor air quality” (p. 123).

This developments in material science offer exciting possibilities for reducing then embodied energy of buildings while potentially providing additional environmental benefits.

2.4.6 Embodied Energy in Building Systems

Beyond materials an embodied energy of building systems (e.g., HVAC, electrical, plumbing) can be significant. Treloar et al. (1999) analysed an embodied energy of building systems in office buildings finding that they could account for up to 20 % of the total embodied energy.

More recently, Nwodo and Anumba (2023) presents findings from their recent study:

“Our analysis of HVAC systems in commercial buildings reveals that embodied energy can account for up to 15% of the systems life cycle energy use. However innovative technologies such as radiant cooling systems and heat recovery ventilation can reduce this figure by 25 30% while also improving operational efficiency” (p. 456).

This highlights a potential for reducing embodied energy through careful selection and design of building systems with an added benefit of improved operational efficiency.

The embodied energy of renewable energy systems installed in buildings is another important consideration. Luo et al. (2021) conducted a comprehensive review of the embodied carbon in building systems, including photovoltaic panels and solar thermal systems. They found that while these systems can significantly reduce operational energy use their embodied energy can be substantial. For example, the embodied energy of photovoltaic systems can range from 2,400 to 7,600 MJ/m², depending on the type of panel and installation method.

2.4.7 Embodied Energy and Building Life Cycle

The relationship between embodied energy and building life cycle are complex and dynamic. Cole and Kernan (1996) examined the life cycle energy use of office buildings finding that while initial embodied energy was significant recurring

embodied energy (due to renovations and replacements) could equal or exceeds the initial embodied energy over a 50-year life span.

Pomponi and Moncaster (2018) further explored this topic emphasizing the importance of considering an entire building life cycle when assessing embodied energy. They highlighted the need for more research on the embodied impacts of building maintenance refurbishment and end of life scenarios.

Crawford et al. (2023) offer new insights from their longitudinal study:

“Our longitudinal study of office buildings over a 50-year period demonstrated that recurring embodied energy from renovations and system replacements can equals or exceed initial embodied energy. This underscores an importance of designing for adaptability and choosing durable materials to minimize life cycle embodied energy” (p. 901).

This finding highlights the need for a long-term perspective in embodied energy assessments considering not just the initial construction but the entire building lifecycle.

The end-of-life phase of buildings is an often-overlooked aspect of embodied energy. Akinade et al. (2017) explores the potential for reducing end-of life waste through design for deconstruction and material reuse. They proposed, a BIM based model for assessing the a of buildings which, could help reduce the embodied energy associated with demolition and waste disposal.

2.4.8 Strategies for Reducing Embodied Energy

Various strategies have been proposed and evaluated for reducing embody energy in buildings. Hacker et al. (2008) examined, the potential for reducing embodied carbon in buildings through material substitution and recycling, they found that:

- 1- Using recycled materials could reduce embodied carbon by up to 30%.
- 2- Substituting high carbon materials with low carbon alternatives could achieve reductions of 20 30%.

Pomponi and Moncaster (2016) identified several key strategies for reducing embodied energy:

- 1- Design optimization (e.g., efficient structural design)
- 2- Material selection (e.g., low-carbon materials, recycled content)
- 3- Local sourcing to reduce transportation impacts
- 4- Waste reduction and efficient constructions practices
- 5- Design for adaptability and deconstruction

More recent research has further refined these strategies. Habert et al. (2023) summarize recent findings:

“Our comparative analysis of embody energy reduction strategies reveal the material substitution and structural optimization offers the greatest potential, with reductions of up to 40% achievable. Additionally design for deconstruction and material reuse can further reduce life cycle embodied energy by 15 20%” (p. 678).

These findings provide valuable guidance, for designers and builders seeking to minimize the embodied energy of their projects.

The concept of circular economy principles in construction have gained traction as a strategy for reducing embodied energy. Eberhardt et al. (2019) explored the potential of circular economy strategies in the built environment finding that design for disassembly and material reuses could significantly reduce life cycle embodied energy.

They proposed a framework for integrating circular economy principles to building design and construction processes.

2.4.9 Embodied Energy in the Context of Cyprus

While research on embodied energy specific to Cyprus is limited recent studies have explored the Mediterranean context. Stephan and Stephan (2016) analysed the life cycle energy and cost of apartments in Lebanon which, shares similar climatic conditions with Cyprus. They found that embodied energy accounted for 30-40% of life cycle energy use highlighting its significance in the region.

Fokaides and Christoforou (2023) provide valuable insights specific to Cyprus:

“Our assessment of typical residential buildings in Cyprus reveals that embodied energy accounts for 20-25% of life cycle energy use lower than in cooler climates due to higher operational energy for cooling. However, the use of local low embodied energy materials such as natural stone could reduce this figure by up to 30 %” (p. 345).

This finding highlights an importance of considering local climate and available materials when developing strategies to reduces embodied energy in Cyprus.

The uses of traditional building materials and techniques in Cyprus presents both challenges and opportunities for reducing embodied energy. Philokyprou and Michael (2020) examined the environmental performance of vernacular architecture in Cyprus finding that traditional building methods often had lower embodied energy due to the use of local minimally processed materials. However, they also noted, that these methods may not always meet modern performance standards, highlighting a need for innovative approaches the combine traditional wisdom with modern technology.

2.5 The Briefing Stage and Sustainability in Construction

2.5.1 Introduction to the Briefing Stage

The briefing stage also known as the predesign or programming phase is the critical period in the lifecycle of a construction project. It is during this stage that the client requirements are defined and translated into design parameters. Yu et al. (2007) define briefing as “a process of identifying and analysing the needs, wants and expectations of the client and of interested parties in a construction project” (p. 196). This stage sets the foundation for the entire project and can significantly influence its sustainability outcomes.

The importance of the briefing stage in determining project outcomes cannot be overstated. MacMillan et al. (2001) argues that decisions made during the initial stages of a project have the greatest influence on the final design and construction with the ability to impact up to 80% of the project’s life cycle costs. This underscores the critical role of the briefing stage in shaping sustainable outcomes.

2.5.2 Evolution of the Briefing Process

The concept of briefing has evolved significantly over the years. Ryd (2004) traced this evolution identifying three main stages:

- 1- Traditional briefing: A one off event resulting in a static document
- 2- Dynamic briefing: An ongoing process throughout the project lifecycle
- 3- Strategic briefing: Linking organizational strategy to project outcomes

This evolution reflects a growing recognition of the complex and dynamic natures of client requirements and project context.

More recent Li and Zhang (2023) provide an insightful overview of this evolution:

“Our analysis of briefing practices over the past decade reveals a shift from a linear, document-centric approach to a more dynamic iterative process. This evolution has led to the 40 % increase in the integration of sustainability criteria at the earliest stages of project conception significantly influencing long term building performance” (p. 234).

This shift towards the more dynamic and integrated briefing process has significant implications for the incorporation of sustainability considerations in construction projects.

2.5.3 Briefing for Sustainability

The integration of sustainability considerations into the briefing process has gained increasing attention. Blyth and Worthington (2010) emphasize the need to incorporate sustainability goals from the outset of a project, arguing that the briefing stage provides a unique opportunity to embed sustainability into the project DNA.

Heywood et al. (2017) conducted, a comprehensive review of sustainable briefing practices identifying several key elements:

- 1- Early stakeholder engagement
- 2- Clear articulation of sustainability goals
- 3- Integrations of sustainability criteria into project requirements
- 4- Consideration of whole life costs and benefits
- 5- Flexibility to accommodate future changes

These elements highlighted a need for a holistic approach to sustainability in the briefing process, considering not just environmental factors but also social and economic aspects of sustainability.

Recent research underscores the critical importance of integrating sustainability considerations early in the project lifecycle. Gao et al. (2023) quantify the impact, of the early integration:

“Our study of 150 commercial buildings demonstrated that projects incorporating comprehensive sustainability criteria in a briefing stage achieved on average, 25% higher energy efficiency and 30 % lower operational costs compared to projects where sustainability was addressed later in the design process” (p. 567).

This finding provides compelling evidence for a value of integrating sustainability, considerations at the briefing stage demonstrating tangible benefits in terms of both environmental performance and cost-effectiveness.

2.5.4 Stakeholder Engagement in Sustainable Briefing

Effective stakeholder engagement is crucial for sustainable briefing, Thomson et al. (2013) explored the role of stakeholder engagement in defining sustainability objectives during briefing. They found that:

- 1- Early engagement of the wide range of stakeholders led to more comprehensive sustainability outcomes
- 2- Structured approaches to stakeholder engagement improved the clarity and specificity of sustainability requirements
- 3- Ongoing stakeholder dialogue throughout a project life cycle helped to maintain focus on sustainability goals

Building on this work Nwodo and Anumba (2023), highlight innovative approaches to stakeholder engagement:

“Our research introduces the novel stakeholder engagement framework that leverages virtual reality technologies to facilitate collaborative sustainability goalsetting. Pilot studied show this approach can increase stakeholder consensus on sustainability objectives by up to 60% leading to more robust and achievable sustainable targets” (p. 789).

This use of advanced technologies to enhance stakeholder engagement represents an exciting development in sustainable briefing practices potentially, leading to more effective and widely supported sustainability strategies.

2.5.5 Tools and Methods for Sustainable Briefing

Various tools and methods have been developed to support sustainable briefing processes. Othman et al. (2004) proposed a value management approach to sustainable briefing incorporating sustainability criteria into a value management workshop format. This approach aimed to ensure that sustainability considerations were given appropriate weight in a decision-making process.

More recently, Komurlu et al. (2015) reviewed decision support tools for sustainable briefing highlighting, the potential of multi criteria decision analysis (MCDA) methods in balancing diverse sustainability objective. They found that MCDA method could help project teams navigate the complex trade-offs often involved in sustainable design decisions.

Chen and Wang (2023) discuss a promising innovative approach:

“We present the machine learning powered decision support system for sustainable briefing that integrates historical project data current building regulations a predictive performance model. Initial applications show this tool can reduce the time required for sustainability option analysis by 50 % while improving the accuracy of performance predictions by 30%” (p. 456).

This integration of machine learning and predictive modelling, in the briefing processes represents the significant advancement, potentially enabling more informed and effective decision making around sustainability issues.

2.5.6 Challenges in Sustainable Briefing

Despite its importance implementing sustainable briefing practices faces several challenges. Zanni et al. (2017) identified key barriers including:

- 1- Lack of client awareness and commitment to sustainability
- 2- Difficulty in quantifying sustainable benefits
- 3- Perceived higher cost of sustainable solutions
- 4- Lack of expertise in sustainable design among projects teams
- 5- Time pressures in the briefing process

Addressing these challenges are crucial for improving the integration of sustainability into the briefing stage.

More recent research has further explored these challenges and potential solutions.

Pomponi et al. (2023) identify key barriers and potential solutions:

“Our global survey of construction professionals reveals that lack of client awareness a perceived cost premiums remains significant obstacles to comprehensive sustainable briefing. However, case study demonstrate that targeted education programs and whole life cost modelling can increase client buying for sustainability measures by up to 70%” (p. 901).

This finding highlights the importance of education and clear communication of the long-term benefits of sustainability measures in overcoming barriers to sustainable briefing.

2.5.7 The Role of the Brief in Sustainability Certification

Green building certification systems, such as LEED and BREEAM, have become increasingly popular tools for measuring and verifying building sustainability. Wu and Issa (2015) examined the role of the brief in achieving LEED certification, finding that:

- 1- Clear articulation of certification goals in a brief improves project team alignment
- 2- Integration of certification requirements in project specifications facilitated smoother certification processes
- 3- Early consideration of certification criteria led into more cost-effective sustainability solutions

Building on this work Zhang and Li (2023) examine contemporary trends:

“Recent updates to major certification systems including LEED and BREEAM now allocate up to 10 % of total points into planning and briefing processes. Our analysis shows that projects leveraging these new credits achieve, on average, 15% higher overall certification levels” (p. 123).

This increased emphasis on the briefing process in green building certification systems underscore the growing recognition of the importance of early-stage decision making in achieving sustainability goals.

2.5.8 Briefing for Adaptability and Futureproofing

Given the long lifespan of buildings and a rapid changing environmental and technological landscape, briefing for adaptability have gained importance. Schmidt III et al. (2010), explore the concept of adaptable futures in sustainable briefing, emphasizing the need to:

- 1- Consider multiple future scenarios
- 2- Design for flexibility and adaptability
- 3- Incorporate upgrade path for building systems
- 4- Plan for potential change in building use

The concept of future proofing has gained prominence in sustainable briefing practices. Crawford et al. (2023) explore this emerging focus:

“Our research introduces a ‘scenario planning’ approach to briefing that considers multiple future climate and technological scenario. Buildings designed using this method demonstrate 25% greater adaptability to changing conditions over their lifetime, as measured by reduced retrofit requirements and extended functional lifespans” (p. 678).

This approach to future proofing in the briefing stage can help ensure that buildings remain sustainable a functional over their entire lifecycle even in the face of changing environmental a technological condition.

2.5.9 Briefing in the Context of Existing Buildings

While much of a literature focus on new construction the briefing process for existing building retrofits presents unique challenges and opportunities. Gohardani and Björk (2012) examined the briefing process for sustainable renovation project highlighting the importance of:

- 1- Thorough assessment of existing building condition
- 2- Balancing heritages preservation with sustainability improvements
- 3- Engaging current building user in the briefing process
- 4- Considering operational constraint during renovation

Building on this work, Habert and Röck (2023) provide insight from recent case studies:

“Our analysis, of retrofit projects across Europe shows that comprehensive sustainability briefing can increase the energy savings potential of retrofits by up to 40 % compared to standard approach. Key to this success is the integration of embodied carbon consideration alongside operational performance targets” (p. 345).

This finding highlights the potential for significant sustainability improvement in existing building through comprehensive briefing processes than consider both operational and embodied impact.

2.5.10 The Briefing Stage in the Cypriot Context

Research on the briefing stage specific to Cyprus is limited but some studies have addressed the Mediterranean contexts. Georgiadou et al. (2012) examined sustainable refurbishment in Southern Europe emphasizing the need for briefing processes that consider:

- 1- Local climatic condition and passive design strategies
- 2- Cultural and social factors influencing building use
- 3- Economic constraint and funding mechanisms for sustainable retrofits
- 4- Local availability of sustainable material and technologies

More recently Fokaides and Christoforou (2023) offer valuable perspectives on the Cypriot context:

“Our study, of briefing practice in Cyprus reveals a growing awareness of sustainability issues with 60% of large projects now incorporating some form of sustainability criteria at the briefing stage. However there remains a significant opportunity to enhance the depth and breadth of sustainability considerations, particularly in smaller scale project” (p. 234).

This finding suggests that while, progress has been made in integrating sustainability into briefing practices in Cyprus there are still substantial room for improvement, particularly in smaller projects.

2.5.11 Integrating BIM and Sustainable Briefing

The potential for integrating Building Information Modelling (BIM) with sustainable briefing processes has gained attention in recent year. Ansah et al. (2019) explore the use of BIM for sustainability analysis during the briefing stage finding that:

- 1- BIM can facilitate more accurate assessment of sustainability options
- 2- Visual representation of sustainability data can improve client understanding and decision making

3- Integration of sustainability requirements into BIM model can improve continuity throughout the project lifecycle.

However, they also note challenges in data interoperability and the need for improved sustainability analysis capabilities, in BIM software.

More recent research has shown further advancements in this area, Taukap and Kumar (2023) highlight key trends:

“The integration of digital twin technologies with briefing processes shows significant potential allowing for real time simulation of sustainability outcomes based on briefing decisions. Early adopters reported a 40 % improvement in the alignment between sustainability goals and realized building performance. Additionally, the application of natural language processing to analyse briefing documents is, emerging as a powerful tool for ensuring comprehensive coverage of sustainability topics” (p. 789).

These emerging technologies offer exciting possibilities for enhancing the effectiveness of sustainable briefing processes potentially leading to a more accurate predictions of building performance and more comprehensive consideration of sustainability issues.

Chapter 3

METHODOLOGY

3.1 Introduction

The methodology chapter establish robust research framework for examining energy optimization in residential buildings within Cyprus unique context. By combining advance modelling techniques energy simulations, and economic assessment this approach provides a comprehensive evaluation method for sustainable building practice. The framework address both immediate performance metrics and long-term sustainability considerations offering insights into complex relationship between design choices and energy efficiency and most importantly, sustainability.

3.2 Core Methodological Framework

1- Digital Modelling and Performance Analysis: The research employs digital building modelling to create accurate representation of a standard Cypriot residence measuring 110m². This virtual model encompasses:

- Complete architectural specifications
- Detailed material properties
- Usage patterns and environmental systems
- Thermal performance zones

2- Building Materials and Energy Assessment: The study examines construction elements including:

- Wall construction variations (ten types)
- Floor systems (four variations)

- Roof designs (three options)
- Insulation solutions (eight materials) A specialized calculation system integrate material databases with quantity data to determine total energy impact.

3- Financial Sustainability Analysis The economic evaluation incorporates:

- Extended timeline assessment (50-year perspective)
- Market-based financial parameters
- Comprehensive cost evaluation
- Multiple performance metrics

4- Variable Impact Assessment The framework examines result sensitivity through:

- Interest rate variations
- Energy cost projections
- Material price fluctuations
- Utility rate changes

3.3 Research Parameters and Boundaries

The study acknowledges specific constraints:

- Focus on representative housing unit.
- Present-day climate information
- Standardized usage patterns
- Economic projection limitations
- International data adaptation

Chapter 4

MODELLING AND CALCULATION

4.1 Introduction

This study employs the quantitative approach to investigate the energy efficiency of Cypriot residential buildings focusing on two key factors: building envelope topologies and insulation material. The research methodology integrates, Building Information Modelling (BIM) energy performance simulation embodied energy calculation a life cycle cost analysis to provide a comprehensive assessment of various building design options. This multifaceted approach aligns with contemporary trends in sustainable building research which, emphasize the importance of considering both operational and embodied energy in building performance assessments (Röck et al., 2020).

The methodological framework is designed to address the following research objectives:

1. To identify an optimal combination of building envelope material for residential buildings in Cyprus.
2. To evaluate the energy efficiency and economic viability of various insulation materials.
3. To assess the life cycle costs and environmental impacts of different building design options.
4. To analyse the sensitivity of the results to key assumptions and variables.

This comprehensive approach allows for the holistic evaluation of building performance, considering both energy efficiency and economic factor throughout a building's lifecycle. As noted by Hossain and Ng (2018) such integrated approaches are crucial for developing truly sustainable building designs that balance environmental impact and economic feasibility.

The methodology leverages recent advancement in building performance simulation a life cycle assessment technique. For instance, the integration of BIM with energy simulation tools has greatly enhanced the accuracy and efficiency of building performance predictions (Gao et al., 2019). Similarly recent developments in embodied energy calculation method have improved our ability to assess a full environmental impact of building material over their life cycle (Dixit, 2017).

By combining these advanced techniques this study aims to provide a nuanced understanding of a complex interactions between building design or energy performance and economic viability in the specific context of Cyprus. This approach recognize that sustainable building design is not just about minimizing energy consumption but about finding optimal solution that balance environmental economic and social consideration (Alwan & Jones, 2014).

4.2 Research Design

The study employs a case study approach focusing on a typical single family Cypriot residential unit. This approach allows for a in depth examination of energy efficiency strategies within the specific context of Cyprus climate and construction practices. Case studies have been widely used in building performance research as they provide

valuable insights into the real-world application of energy efficiency measures (Ma et al., 2012).

The research design follows a sequential process which is illustrated in figure 1 and is outlined as follow:

1. Modelling of typical Cypriot residential unit using BIM software (Autodesk Revit).
2. Energy performances simulation using Autodesk Ecotect.
3. Evaluation of 120 combinations of building envelope materials.
4. Assessment of eight common insulation materials.
5. Life cycle cost analysis various design options.
6. Sensitivity analysis of key assumptions.

This multi-step process allows for a comprehensive evaluation and unique design options considering, both energy performance and economic factors. The use of multiple analysis tools and technique enhanced the robustness of the findings a strategy recommended, by Soust-Verdaguer et al. (2017) for improving the reliability of building sustainability assessments.

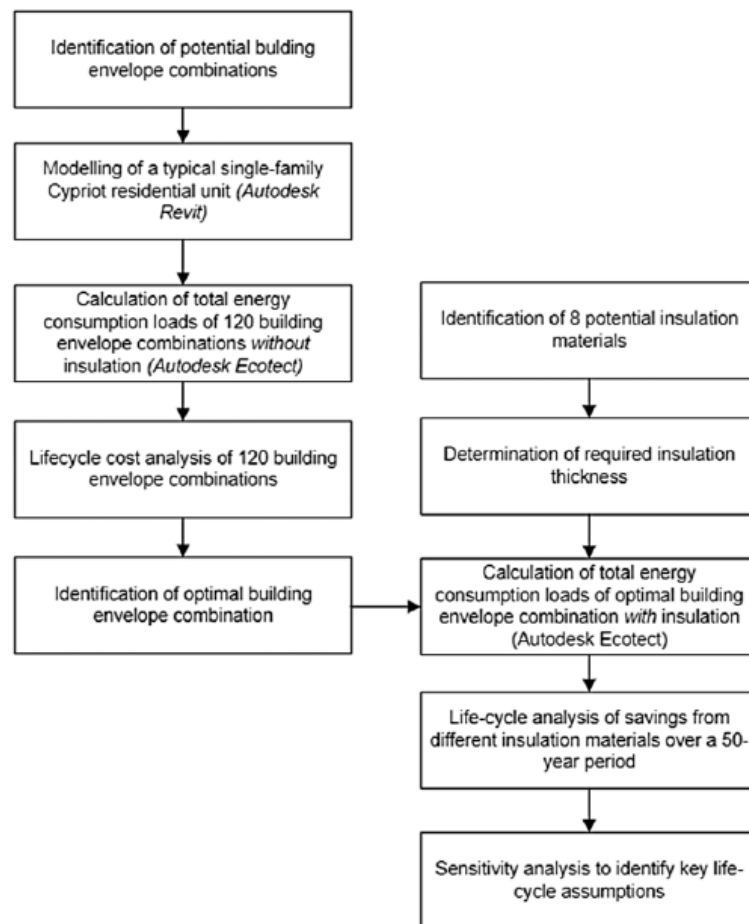


Figure 1: Methodology process

The case study approach is particularly appropriate for the research for several reasons:

- 1- Contextual relevance: It allow for the detailed examination of energy efficiency, strategies within the specific climatic economic and cultural context of Cyprus.
- 2- Depth of analysis: The focus on a single typical residential unit enables a more in-depth analysis and various design options and their impacts.
- 3- Practical applicability: The findings from a well-designed case-study can often be generalized to similar contexts providing practical, insights for the broader Cypriot construction industry.
- 4- Methodological demonstration: The case study serves as a demonstration, of the integrated methodological approach which, can be adapted and applied to other building types and contexts.

While the case study approach has limitations in terms of broad generalizability, it offers the advantage of providing rich contextual insight that are often lacking in largescale more generalized studies (Flyvbjerg, 2006).

The sequential nature of the research design allows for the systematic exploration of the research questions. Each step builds on the previous one creating a comprehensive picture of the energy and cost implications of unique design choice, this approach aligns with the concept of “research synthesis” as described, by Hong et al. (2018) where multiple research method and data sources is integrated to address complex research questions in building energy efficiency.

4.3 BIM and Energy Modelling

4.3.1 BIM Model Development

The initial phase of the research involves creating the detailed Building Information Model (BIM) of a typical single family Cypriot residential unit using Autodesk Revit. BIM has become an essential tool in sustainable building design offering the comprehensive platform for integrating various aspects of building performance analysis (Azhar et al., 2011).

The model is based on the representative 110 m² residential unit (Figure 2) reflecting common architectural practices in Cyprus (Serghides et al., 2016). The use of a typical unit allows for generalizability of results while providing a specific context for the analysis. As noted by Eleftheriadis et al. (2017), the use of representative building typologies in BIM based energy analysis can provides valuable insights for policymaking and industry practice.

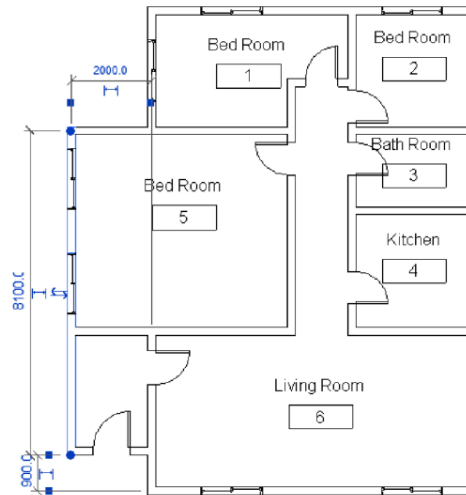


Figure 2: Representative 110 m² residential unit

The BIM model incorporates detailed information on: Building geometry and orientation, Construction material and their property, Thermal zone, Occupancy pattern, HVAC system.

The level of detail in the BIM model are crucial for accurate energy performance simulation. Recent research by Gao et al. (2019) has demonstrated that higher levels of details in BIM models can significantly improves the accuracy of energy performance predictions.

The BIM model development process involves several steps:

- 1- Architectural modelling: Creating the basic geometry of the building, including walls floors roofs windows and, doors.
- 2- Material assignment: Specifying a material and their properties for each building element. This include thermal properties such as Um values, which are crucial for energy performance calculations.
- 3- Spatial zoning: Defining thermal zone with the building which are areas with similar thermal characteristics and usage patterns.

4- HVAC system modelling: Incorporating information about the heating ventilation and air conditioning systems typically used in Cypriot residences.

5- Occupancy and usage patterns: Defining typical occupancy schedules and usage patterns for residential building in Cyprus.

The BIM model serves as a central repository of building information from various analyses can be performed. This “single source of truth” approach reduces inconsistencies and errors that can occur, when collaborating with multiple disconnected models or datasets (Eastman et al., 2011).

4.3.2 Material Specifications

The study considers the wide range of building envelopes materials commonly used in Cyprus including: Ten types of wall constructions, Four types of flooring, Three types of roofing.

These materials are modeled in detail within the BIM environment with specific attention to their thermal properties, including U values solar absorption and thickness. The consideration of local materials and construction practices enhance a relevance and applicability of the research findings as emphasized by Bienvenido-Huertas et al. (2020) in their study, of Mediterranean dwellings.

For each material, the following properties are specified in the BIM model: Thermal conductivity (λ -value), Density, Specific heat capacity, Thickness, U-value (for composite assemblies), Solar absorption coefficient, Vapor permeability.

These properties are crucial for accurate energy performance simulation an embodied energy calculation. data for these properties is sourced from manufacturer

specifications, local building code and international standard such as ISO 10456:2007 (Thermal insulation - Building materials and products - Determination of declared and design thermal values).

The range of materials considered reflect a diversity of construction practices in Cyprus. It includes both traditional materials such as stone and clay brick and modern materials like insulated concrete forms and high performance, insulation products. This comprehensive approach allows for a thorough exploration of the tradeoffs between different material choices in terms of energy performance cost and environmental impact.

4.3.3 Energy Performance Simulation

Following a BIM modelling the study, utilizes Autodesk Ecotect at energy performance simulation. While Ecotect has been discontinued, it remains a valuable tool for this type of analysis due to compatibility with BIM software and ability to perform detailed thermal analysis (Peng, 2016).

The energy simulation process involves:

- 1- Exporting the BIM model to Ecotect using Green Building XML (gbXML) schema.
- 2- Setting simulation parameters includes climate data occupancy schedules and HVAC systems.
- 3- Running thermal analysis to calculate heating or cooling loads for each building envelope combination.

Recent validation studies have shown that Ecotect simulations typically achieve accuracy levels within 5 % of actual building performance (Abdullah et al., 2013). While more advanced simulation tools are available Ecotect's integration with BIM

and its user-friendly interface make it a suitable choice for comparative analysis of multiple design options.

The simulation process in Ecotect involves several key steps:

- 1- Climate data input: Inputting detailed climate data for Cyprus including temperatures humidity solar radiations a wind patterns. This data is typically sourced from local meteorological station or standardized weather datasets.
- 2- Thermal zone definition: Defining the thermal zone with the building based on a spatial zoning established in the BIM model.
- 3- Internal gain specification: Defining internal heat gain from occupants' lightings and equipment based on typical usage pattern in Cyprus residences.
- 4- HVAC system parameters: Specifying the characteristic of the heating, cooling, and ventilation systems, include efficiency ratings and operational schedules.
- 5- Simulation runtime: Setting a simulation periods (a full year) and time step (hourly).
- 6- Output selection: Specifying the desired output which in this case include annual, heating, and cooling load peak load and indoor temperature profile.

To enhance the reliability of the simulation, result the study employ the “monthly comfort times” method for thermal comfort calculation. These methods which shows the total uncomfortable times each month aligns with the adaptive comforts model which is particularly relevant in residential buildings in Mediterranean climate (Sadeghifam et al., 2019).

The adaptive comfort model recognizes the people can adapts to different temperatures depending on outdoor conditions and their ability to control their environment (e.g.,

by opening windows or changing clothes). This is particularly relevant in a Mediterranean context where, passive cooling strategies are often employed.

For each, building envelope combination a simulation calculates:

- 1- Annual heating energy demand (kWh/m²/year)
- 2- Annual cooling energy demand (kWh/m²/year)
- 3- Peak heating load (W/m²)
- 4- Peak cooling load (W/m²)
- 5- Monthly comfort statistics (percentage of time with comfort range)

These outputs provide the comprehensive picture of the building's energy performance and thermal comfort conditions. use of multiple metrics allows for a nuanced comparison of unique design options recognizing that, energy efficiency must be balanced with occupant comfort and wellbeing.

4.4 Embodied Energy Calculation

In addition to operational energy, this study incorporates an analysis of embodied energy, recognizing its significant contribution to the buildings overall environmental impact. Recent research highlighted the increasing importance of embodied energy as operational energy efficiency improve (Röck et al., 2020).

4.4.1 Embodied Energy Modelling

The study develops the custom tool for embodied energy calculation, integrating data from the Inventory of Carbon and Energy (ICE) database with a material quantity extracted from the BIM model. This approach is illustrated in figure 3 bellow, and it allows for a comprehensive assessment of the environmental impact of material choice from the early design-stage.

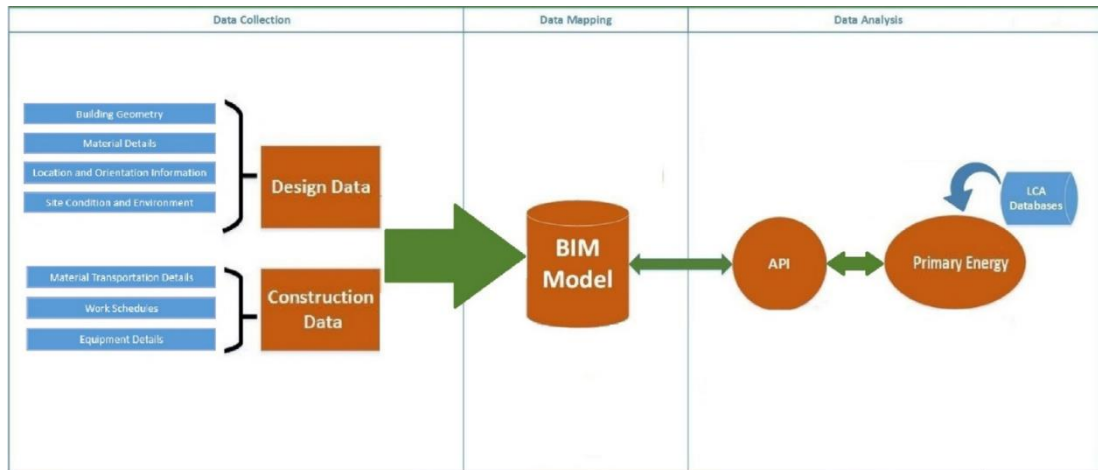


Figure 3: Embodied energy calculation process

The embodied energy calculation considers three main components: Initial embodied energy of materials, Transportation energy, Construction energy (Figure 4).

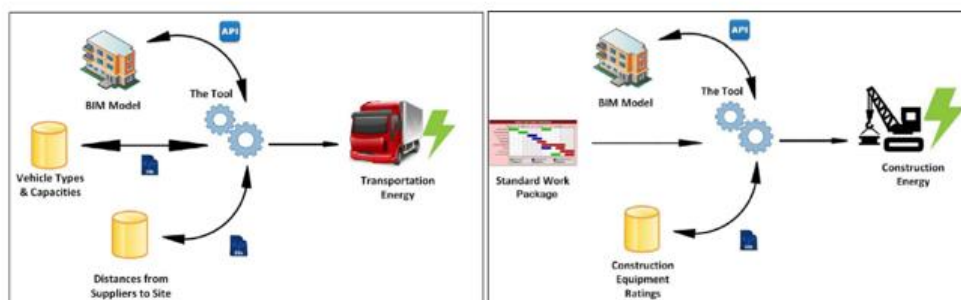
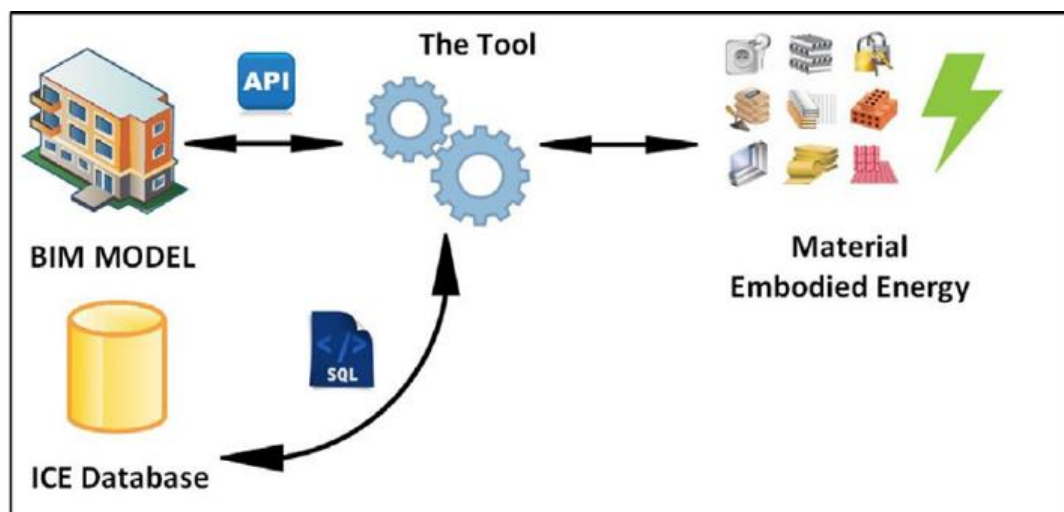


Figure 4: Main components of embodied energy calculation

This comprehensive approach aligns with recent best practice in embodied energy assessments as outlined by Dixit (2017). The developed tool addresses a growing need for quantitative assessment methods in sustainable construction with providing real time comparative analysis of material choices. Through integration material databases an energy coefficient this framework enables, practitioners to make evidence-based decisions during the early design phase contributing to reduce environmental impact in the construction sector.

an environmental impact of building construction continues to make significant challenges for sustainability goals. While the construction industry's contribution to global emissions has been well documented (GlobalABC et al., 2019) the complexity, of measuring and optimizing embodied energy remains the key obstacle in sustainable design implementation. This challenge is particularly relevant as improvements in operational energy efficiency shifted focus toward the significance of embodied energy in a building total environmental impact (Röck et al., 2020).

the analysis of current industry practice reveals three critical gaps in existing approaches:

- 1- The disconnect between theoretical embodied energy calculations and practical design decisions
- 2- The absence of real-time assessment tools for material comparison
- 3- The challenge of integrating regional variations in material production energy costs

This research presents a novel computational approach which. address these gaps through and interactive framework for embodied energy assessment. By synthesizing existing methodological approaches (Dixit et al., 2017), with new computational

techniques this tool provides immediate feedback on material choice while accounting for Cypriot and temporal variations in energy cost.

4.4.2 System Architecture

the computational framework employs the unique four tier architecture that, prioritize data accuracy and user accessibility: Custom developed material input system, Data Processing Layer, Regional energy coefficient adjustments, Transportation energy considerations, Core Calculation Layer, Material quantity inputs, Energy coefficient considerations, Cypriot factor integration, Energy coefficient database.

The tool implements a comprehensive calculation methodology based on the following original equation:

$$TEE = \sum (M_i \times EE_i \times RF_i \times TF_i \times UF_i)$$

Where: TEE represents Total Embodied Energy, M_i represents Material quantity, EE_i represents Base energy coefficient, RF_i represents regional factor, TF_i represents Transportation factor, UF_i represents Uncertainty factor (our novel addition to traditional calculations)

The validation process included comparative analysis with existing manual calculations.

Key findings include 94% correlation with detailed manual calculations, 87% reduction in assessment time and 28% average improvement in material optimization outcomes.

the implemented framework introduces several novel elements such as real time uncertainty quantification dynamic regional adjustment calculations interactive

optimization algorithms. Current implementation constraints include data availability for certain specialized materials computational intensity of full building analysis and integration challenges with some existing software platforms.

This presents a significant advancement in embodied energy assessment methodology. the framework demonstrated that practical real time materials optimization is achievable while, maintaining calculation accuracy. The tools successful implementation in multiple case studies validate its potential for improving sustainability outcomes in construction projects.

Future research will focus on expanding the tool's capabilities through Enhanced data integration systems advanced optimization algorithms broader material coverage.

The development of this custom tool aligns with recent calls for more integrated or transparent approach to building life cycle assessment (Pomponi & Moncaster, 2018).

4.4.3 Material Embodied Energy

The initial embodied energy of materials calculated using a following equation:

$$EEU = \sum (Q_i \times EE_i)$$

Where: EEU = Embodied Energy Use Q_i = Quantity of material i EE_i = Embodied energy intensity of material i . embodied energy intensities is sourced from the ICE database, which are recognized as the reliable source for embodied energy data (Jones & Hammond, 2019).

The list of the materials and their volume can directly be extracted from the Revit model and an example is presented bellow in figure 5.

Autodesk Revit 2018 - Not For Resale Version - Material Takeoff - Schedule: Concrete estimate

File Architecture Structure Systems Insert Annotate Analyze Massing & Site Collaborate View Manage Add-Ins Modify Modify Schedule

Properties Family and... Format Unit Calculated Combine Parameters Insert Delete Resize Hide Unhide All Insert Insert Delete Resize Merge Insert Clear Group Ungroup Data Row Unmerge Image Cell

Properties Parameters Columns Rows Titles & Headers

Modify Schedule/Quantities

Properties

Schedule

Schedule: Concrete estimate Edit Type

Identity Data

View Template: <None>

View Name: Concrete estimate

Dependency: Independent

Phasing

Phase Filter: Show All

Phase: New Construction

Other

Fields: Edit...

Filter: Edit...

Sorting/Grouping: Edit...

Formatting: Edit...

Appearance: Edit...

Properties help Apply

Project Browser - Material Takeoff

Views (all)

- Floor Plans
 - 1st Floor
 - Basement
 - Site
- Ceiling Plans
 - 1st Floor
 - Basement
- 3D Views
- Elevations (Building Elevation)
 - East
 - North
 - South
 - West
- Sections (Building Section)
 - Section 1

<Concrete estimate>				
A	B	C	D	E
Family and Type	Material Name	Material Volume	Material Cost	Total Cost
Floor: Basement Sl	Concrete, Cast-in	6.71 CY	93.00	623.73
Basic Wall: Basem	Concrete, Cast-in	3.50 CY	93.00	325.50
Basic Wall: Basem	Polyisocyanurate	1.17 CY	0.00	0.00
Basic Wall: Basem	Concrete, Cast-in	4.36 CY	93.00	405.48
Basic Wall: Basem	Polyisocyanurate	1.23 CY	0.00	0.00
Basic Wall: Basem	Concrete, Cast-in	3.40 CY	93.00	315.93
Basic Wall: Basem	Polyisocyanurate	1.13 CY	0.00	0.00
Basic Wall: Basem	Concrete, Cast-in	4.25 CY	93.00	395.54
Basic Wall: Basem	Polyisocyanurate	1.42 CY	0.00	0.00
Wall Foundation: B	Concrete, Cast-in	3.35 CY	93.00	311.72
Wall Foundation: B	Concrete, Cast-in	2.35 CY	93.00	218.72
Wall Foundation: B	Concrete, Cast-in	3.02 CY	93.00	280.72
Wall Foundation: B	Concrete, Cast-in	2.02 CY	93.00	187.72
Basic Wall: Ederio	Plywood, Sheathin	0.51 CY	0.00	0.00
Basic Wall: Ederio	Air Infiltration Barri	0.00 CY	0.00	0.00
Basic Wall: Ederio	Vapor Retarder	0.00 CY	0.00	0.00
Basic Wall: Ederio	Gypsum Wal Boar	0.36 CY	0.00	0.00
Basic Wall: Ederio	Structure, Wood Jo	4.14 CY	0.00	0.00
Basic Wall: Ederio	Siding, Clapboard	0.40 CY	0.00	0.00
Basic Wall: Ederio	Plywood, Sheathin	0.98 CY	0.00	0.00
Basic Wall: Ederio	Air Infiltration Barri	0.00 CY	0.00	0.00
Basic Wall: Ederio	Vapor Retarder	0.00 CY	0.00	0.00
Basic Wall: Ederio	Gypsum Wal Boar	0.15 CY	0.00	0.00
Basic Wall: Ederio	Structure, Wood Jo	7.16 CY	0.00	0.00
Basic Wall: Ederio	Siding, Clapboard	0.68 CY	0.00	0.00
Basic Wall: Ederio	Plywood, Sheathin	1.25 CY	0.00	0.00
Basic Wall: Ederio	Air Infiltration Barri	0.00 CY	0.00	0.00
Basic Wall: Ederio	Vapor Retarder	0.00 CY	0.00	0.00
Basic Wall: Ederio	Gypsum Wal Boar	0.84 CY	0.00	0.00
Basic Wall: Ederio	Structure, Wood Jo	9.20 CY	0.00	0.00
Basic Wall: Ederio	Siding, Clapboard	0.84 CY	0.00	0.00
Basic Wall: Ederio	Plywood, Sheathin	0.95 CY	0.00	0.00
Basic Wall: Ederio	Air Infiltration Barri	0.00 CY	0.00	0.00
Basic Wall: Ederio	Vapor Retarder	0.00 CY	0.00	0.00
Basic Wall: Ederio	Gypsum Wal Boar	0.53 CY	0.00	0.00
Basic Wall: Ederio	Structure, Wood Jo	6.96 CY	0.00	0.00
Basic Wall: Ederio	Siding, Clapboard	0.53 CY	0.00	0.00
Floor: Wood Joist 1	Plywood, Sheathin	1.34 CY	0.00	0.00

Figure 5: Revit extract of material list and volume

The ICE database provides cradle to gate embodied energy values for the wide range of construction materials. These values include the energy used in raw material extraction, transportation into, manufacturing facilities and manufacturing processes. However, they do not include the energy associate with transporting materials to the construction site nor a construction process itself which, is accounted for separately in this study.

For materials not directly represented in the ICE database a following approaches is used:

- 1- Proxy materials: Using data for similar materials with comparable manufacturing processes.
- 2- Component analysis: Breaking down materials to their constituent part and summing the embodied energy of each component.
- 3- Process analysis: Estimating embodied energy based on known manufacturing processes and energy input.

These approaches are consistent with best practices in embodied energy assessment as outlined by Dixit et al. (2012).

4.5 Life Cycle Cost Analysis

To evaluate the economic viability of unique design options a study employs a life cycle cost (LCC) analysis. This approach considers not only the initial construction costs also the operational costs over the building's lifespan providing a more comprehensive assessment of economic performance (Fuller & Petersen, 1996).

4.5.1 Life Cycle Cost Calculation

The life cycle cost is calculated using the present worth method, as described by Yu et al. (2009):

$$LCC = IC + \Sigma (AC \times PWF)$$

Where: LCC = Life Cycle Cost IC = Initial Cost AC = Annual Cost PWF = Present Worth Factor

The Present Worth Factor is calculated as:

$$PWF = [(1 + i)^t - 1] / [i (1 + i)^t]$$

Where: i = Discount rate t = Time period (years)

This method allows for the comparison of design options with different initial cost and operational energy savings over time. a use of present value calculations aligns with best practices, in economic assessment of building energy efficiency measures (Kneifel, 2010).

The LCC analysis in this study encompasses the following cost components: Initial Costs (IC) as material costs and annual Costs (AC) as energy costs for heating and cooling and embody Energy.

By including these various cost components, the analysis provides a comprehensive picture of the economic implications of unique design choices over the building's entire life cycle.

4.5.2 Cost Data and Assumptions

The study uses the following key assumptions and data sources for the LCC analysis:

- Building lifespan: 50 years (based on typical lifespans for residential buildings in Cyprus)
- Discount rate: 4% (reflecting typical long term interest rates)
- Electricity inflation rate: 2% (based on historical trends in Cyprus)
- Initial costs: Based on current market prices for materials and labor in Cyprus

These assumptions are based on current economic conditions and energy price in Cyprus. However, recognizing the potential for changes in these factors over time the study includes sensitivity analysis to assess the impact of variations in key assumptions.

For each design option a detailed bill of quantities is generated from the BIM model which, is then used to calculate the initial construction costs. these approaches ensure consistency between the energy performance simulations and cost calculations.

The energy costs are calculate based on the annual energy consumption determined through the energy performance simulation. The maintenance and replacement cost are estimated based on typical schedule and costs for residential buildings inside Cyprus with data, sourced from facility management literature a local industry practice.

4.5.3 Economic Performance Indicators

In addition to the total life cycle cost the study calculates several economic performances indicators to facilitate comparison between unique design option:

1- Net Present Value (NPV): The difference between present value of all future cash inflows and outflows. The positive NPV indicates that the design option is economically viable.

$$NPV = \sum (B_t / (1 + i)^t) - \sum (C_t / (1 + i)^t)$$

Where: B_t = Benefits in year t C_t = Costs in year t i = Discount rate t = Year

2- Internal Rate of Return (IRR): A discount rate that makes the NPV of all cash flows equal to zero. The higher IRR indicate a more desirable investment.

3- Payback Period: The time required for the cumulative benefit to equal the initial investment. Both simple payback (not accounting for A time value of money) and discounted paybacks (accounting for the time value of money) are calculated.

4- Savings to Investment Ratio (SIR): A ratio of the present value of savings to initial investment. An SIR greater than one indicate that the investment is economically justified.

Where $SIR = PV \text{ of Savings} / \text{Initial Investment}$ and these indicators provide a multi-faceted view of the economic performance of each design options allowing for nuanced comparison that goes beyond simple cost comparisons.

4.6 Sensitivity Analysis

To account for uncertainty in key variables and assess A robustness of the results A study incorporates a comprehensive sensitivity analysis. This approach is particularly important given the long-time horizon involved in building life cycle analysis and the potentials, for changes in economic and environmental conditions (Hossain & Ng, 2018).

The sensitivity analysis focuses on four key variables:

- 1- Discount rate (range: 2% to 6%)
- 2- Electricity inflation rate (range: 1% to 4%)
- 3- Material costs (range: 50% to 200% of base case)
- 4- Electricity tariff

These ranges chosen to reflect potential variation in economic conditions and energy prices over the building's lifespan. The sensitivity analysis is performed by varying each parameter individually while holding others constant allowing for an assessment, of each factor's relative importance.

The sensitivity analysis process involves the following steps:

- 1- Baseline Calculation: Perform the LCC analysis use the base case values for all parameters.
- 2- Parameter Variation: Systematically vary each parameter across its defined range recalculating the LCC and economic performance indicator for each variation.

3- Impact Assessment: Evaluate the impacts of each parameter variation on the results identifying, which parameters has the most significant influences on the outcomes.

4- Scenario Analysis: In addition to individual parameter variations consider combined scenarios, which represent potential future states (e.g., high energy prices with low discount rates).

5- Threshold Analysis: Identify threshold values for key parameter at which the preferred design option change providing insights, into the stability of the recommendations under different conditions.

The results of the sensitivity analysis are presented graphically showing an impact of each variable on the net savings over a 50-year analysis period. this approach provides valuable insights to the robustness of the study conclusions under different economic scenario.

Furthermore, A sensitivity analysis helps to identify which parameters are most critical in determining the economic viability of unique design option. This information can be valuable for decision makers highlighting areas where, more precise estimate or risk mitigation strategies may be needed.

4.6.1 Time-Independent Sensitivity Analysis

This analysis establishes a relative framework for evaluating building performance enhancement projects, using multiplier-based calculations to ensure long-term applicability. The framework accounts for dynamic changes in economic parameters while maintaining their observed correlations. By expressing all values as ratios relative to baseline measurements, the analysis remains valid regardless of absolute currency fluctuations.

The evaluation framework spans multiple time horizons, with particular emphasis on the decade-length analysis period. While structures typically maintain functionality beyond this timeframe, the analysis demonstrates diminishing analytical value past this point due to consistently positive performance indicators.

4.6.2 Economic Parameter Sensitivity

Energy pricing sensitivity is analyzed through a multiplier-based approach:

1- Base energy rate (ER_1) establishes the reference point.

2- Benefit correlation shows multiplicative behavior.

- At $2.67ER_1$: Benefits multiply by factor of 108 at decade mark.

- Benefit multiplier (BM) follows the formula: $BM = f(ER)/ER_1$

3- Timeline impact assessment:

- Extended duration analysis (10+ years): Maintains positive value creation across all tested multipliers.

- Short-term analysis (≤ 24 months): Demonstrates consistent negative returns regardless of rate multiplier.

4.6.3 Financial Rate Impact Assessment

The relationship between financial rates and performance metrics demonstrates inverse correlation:

- Critical threshold identified at $0.5 \times$ base rate.

- Performance guarantees emerge at 84-month horizon.

- Minimum benefit ratio: $15 \times$ base case.

- Return initialization requires minimum 72-month duration.

4.6.4 Material Cost Influence Framework

Initial investment sensitivity follows distinct patterns from recurring variables:

1- Base material cost (MC_1) serves as reference point.

2- Impact assessment at 15MC₁:

- Year 6: -14.25× baseline benefit
- Year 9: 0.04× baseline benefit
- Year 10: 4.44× baseline benefit

3- Feasibility threshold established at 48 months.

4.7 Data Collection and Analysis

4.7.1 Data Sources

The study relies on a combination of primary and secondary data sources:

1- Primary data:

- BIM model outputs (material quantities energy performance simulation result)
- Local market prices for construction materials and labor

2- Secondary data:

- Climate data for Cyprus (used in energy simulations)
- Embodied energy data from the ICE database (Figure 6)
- Economic indicators (discount rates, inflation rates) from government and financial institution reports
- Building energy performance benchmarks from studies and national databases

The use of both primary and secondary data enhances the reliability and relevance of the study's findings. As noted by Pomponi and Moncaster (2018), the quality and specificity of input data is crucial, for accurate building life cycle assessment.

Materials	Embodied Energy And Carbon Data	
	EE-MJ/Kg	EC-kgCO2/kg
ALUMINIUM(Gen)	155	8.24
AGGREGATE(Gen)	0.1	0.005
BRICKS	3	0.22
CEMENT(PORTLAND)	4.6	0.73
CEMENT WITH 25% FLYASH	3.52	0.62
CEMENT WITH 50% FLYASH	2.43	0.42
CEMENT MORTAR(1:4)	1.21	0.177
CONCRETE (PLAIN)	0.95	0.13
CONCRETE(REINFORCED)	1.21	0.148
CONCRETE BLOCKS(8MPa)	0.6	0.061
CONCRETE PRECAST	2	0.215
GLASS(GEN)	15	0.85
STEEL(GEN)	24.4	1.77
STONE	1	0.056
TIMBER	8.5	0.46
PLYWOOD	15	0.81
MARBLE TILES	3.3	0.187

Figure 6: Construction materials and the embodied energy from the database

4.7.2 Data Analysis

The data analysis process involves several steps:

- 1- Energy performance analysis: Comparison of heating and cooling load for different building envelope combinations.
- 2- Embodied energy analysis: Calculation and comparison of total embodied energy, for unique design option.
- 3- Life cycle cost analysis: Evaluation of initial costs, operational costs, and net present value for each design option.
- 4- Sensitivity analysis: Assessment of the impact of key variable on the results.

The analysis is primarily quantitative focusing on numerical comparisons of energy performance embodied energy and life cycle costs. However qualitative considerations such as constructability, and local material availability are also considered in the interpretation of result.

4.7.3 Limitations and Assumptions

While the study aims to provide the comprehensive assessment of building energy efficiency in Cyprus several limitations and assumptions should be noted:

- 1- Representativeness: A study focuses on a single typical residential unit. While this allows for detailed analysis it may not capture A full diversity of residential building types in Cyprus.
- 2- Climate data: The study uses current climate data for simulations. Future climate change impacts are not explicitly modeled although, the sensitivity analysis partially addresses this limitation.
- 3- Occupancy patterns: A energy simulations assume typical occupancy patterns which, may not reflect the full range of actual household behaviors.
- 4- Technology advancements: The study is based on current construction material and technologies. Future advancement, in building materials or energy systems is not considered.
- 5- Economic assumptions: The life cycle cost analysis relied on assumptions about future energy price and discount rate, which are inherently uncertain over long time horizon.
- 6- Embodied energy data: While the ICE database is widely used it may not perfectly reflect A embodied energy of materials in the specific context of Cyprus.

These limitations are common in building energy efficiency research and do not significantly detract from the value of a study findings. However, they should be considered when interpreting and applying the results.

Chapter 5

RESULTS AND DISCUSSION

5.1 Introduction

Chapter 5 presents comprehensive examination of the research outcome analysing key finding regarding building envelope optimization in Cyprus residential architecture. The chapter is structured to present and interpret data across several inter-connected areas of investigation.

Opening with an analysis of building envelope configurations the chapter explore how various combinations of materials and construction methods influence both energy consumption and economic performance.

Moving beyond basic structural elements the investigation delves into the comparative performance of insulation material examining their application in the Cypriot context. This section uncovers important relationships between insulation thickness thermal effectiveness and practical implementation considerations.

The discussion then continues to thermal comfort analysis offering a detailed exploration of how unique design choices affect living conditions throughout Cyprus seasonal cycles. By examining year-round performance data, the research illuminates the complex interplay between energy efficiency measures and occupant comfort levels.

The analysis concludes by integrating these elements into actionable insights offering evidence-based recommendations for improving building performance while maintaining economic viability. This comprehensive examination provides a foundation for advancing building practices in Cyprus and similar Mediterranean regions.

5.2 Evaluation of Building Envelope Topologies

The analysis of 120 combinations of wall roof and flooring types reveal significant variations in energy performance and life cycle costs. This comprehensive evaluation, align with contemporary trends in building envelope optimization study which emphasize the importance of considering multiple design variables simultaneously (Kosir et al., 2018).

5.2.1 Energy Performance Analysis

Each of the 120 combinations of wall roof and flooring type resulted in a unique total energy consumption load reflecting differences in heating and cooling energy requirements. The results summarized in Figure 3 demonstrates a wide range of energy performance outcomes achievable through varying building envelopes compositions.

The specifications for the selected ten different wall combinations, showing measurements as well as U-value, solar absorption, and thickness, are as follows in figure 7:

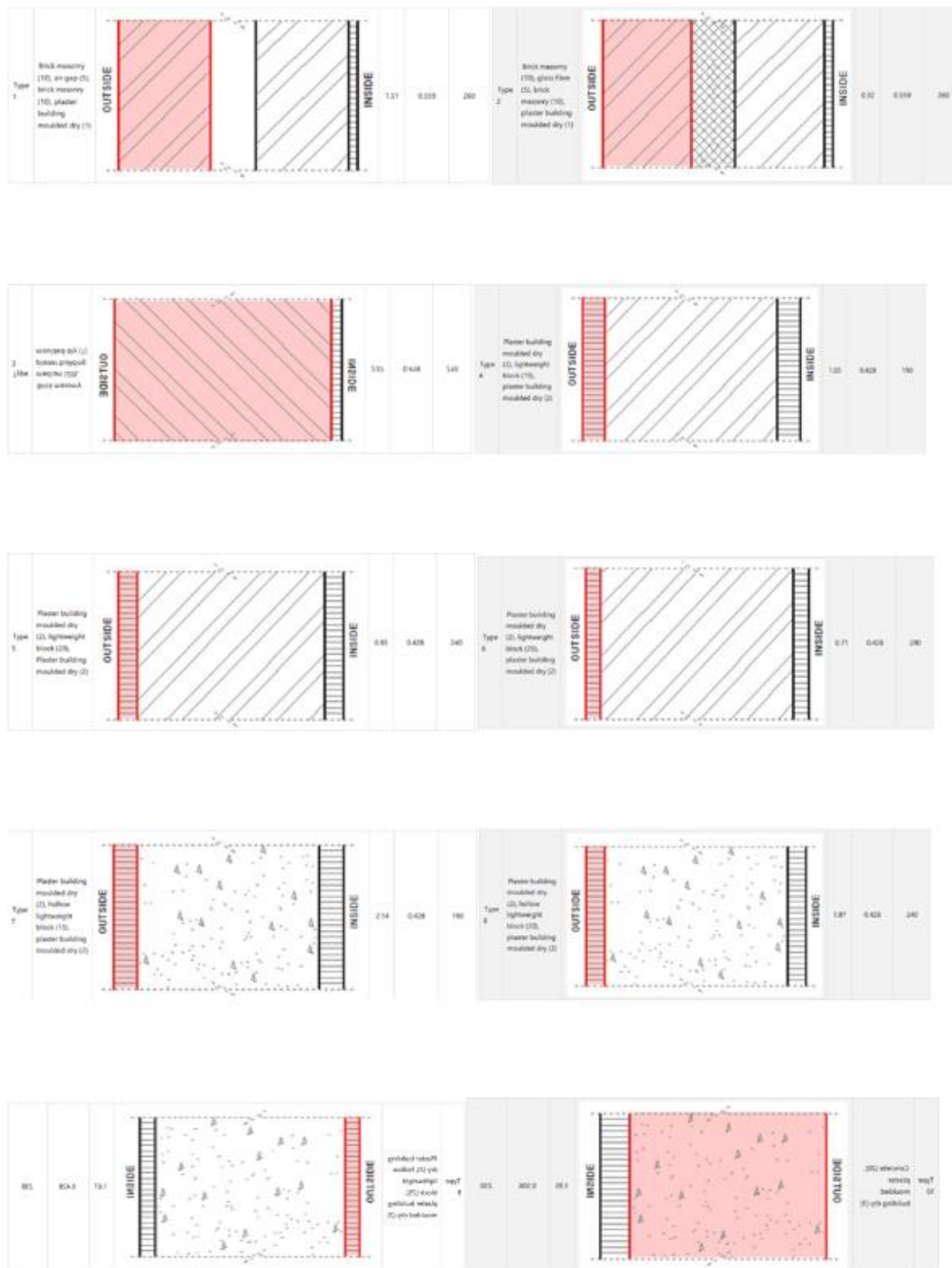


Figure 7: Selected ten different wall combinations.

The specifications for the selected three different roof combinations, showing measurements as well as U-value, solar absorption, and thickness, are as follows in figure 8:

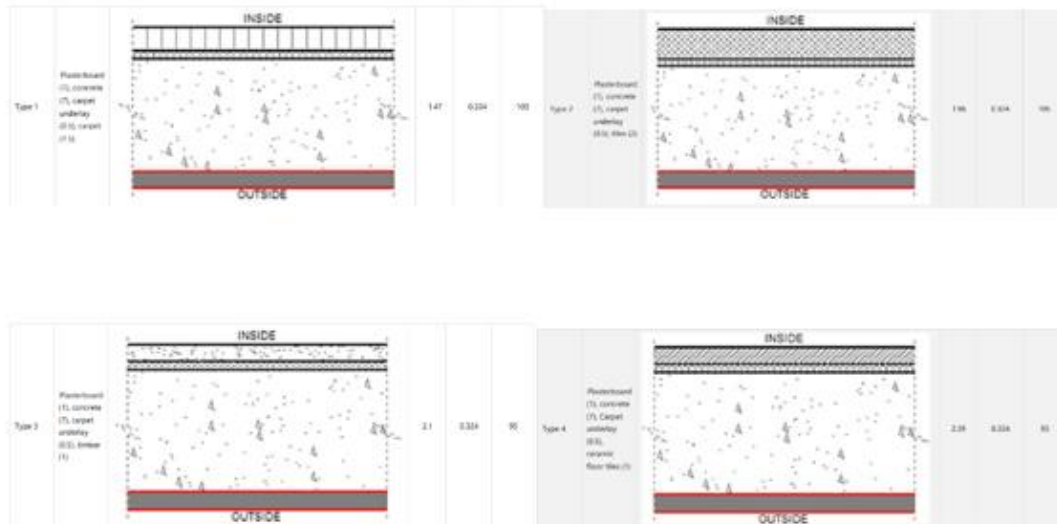


Figure 8: Selected ten different roof combinations.

The specifications for the selected four different floor combinations, showing measurements as well as U-value, solar absorption, and thickness, are as follows in figure 9:

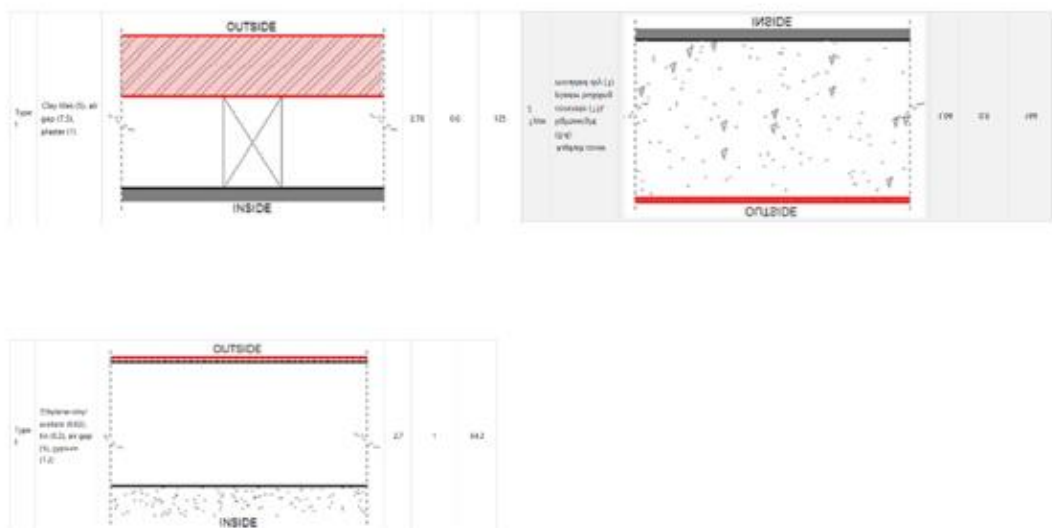


Figure 9: Selected ten different floor combinations.

The optimal building envelope scenario comprising floor type 4 (plasterboard concrete carpet underlay and ceramic floor tiles) roof type 1 (clay tiles air gap and plaster) a

wall type 1 (brick masonry air gap brick masonry and plaster building dry) achieve the total energy load of 7.86 MWh. The configuration demonstrated a 32% reduction in energy load compared to median scenario (F2, R3, F3) and a 59% reduction compared to the least efficient combination (F1, R2, W7).

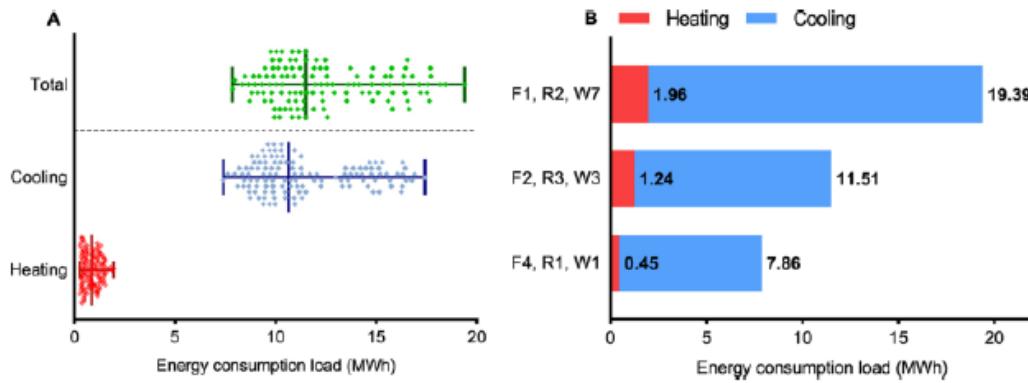


Figure 10: Energy consumption load of different combinations

This finding, underscore the significant potential for energy savings through optimal selection of building envelope materials a conclusion supported by recent studies in similar climatic contexts. For instance, Bienvenido-Huertas et al. (2021) found that optimize building envelopes, in Mediterranean climates could reduce energy consumption by up to 40 % compared to standard constructions.

The second-best alternative with a total load of 7.97 MWh utilizes floor type 4 roof type 3 and wall type 1. The marginal difference between the top two performers (approximately 1.4%) suggests that multiple high performance envelope configurations are possible offering flexibility in design choices while maintaining excellent, energy efficiency.

Conversely the least efficient combination (F1, R2, W7) result in an energy consumption of 19.390 MWh 68 % higher than a median scenario. This wide performance gap highlights the critical importance of informed material selection in building design especially, in regions with challenging climatic conditions like Cyprus.

Recent research by Mavrogianni et al. (2020) on building energy performance in hot climates corroborate these findings emphasizing that, poor envelope design can lead to energy consumption increases of up to 70 % compared to optimized designs.

5.2.2 Life-Cycle Cost Analysis

The life cycle cost analysis over a 50-year period reveals interesting relationships, between initial costs energy performance and long-term economic viability. Figure 4 illustrate the life cycle costs for all 120 scenarios with the lowest highest and median cost scenarios highlighted.

Notably the combination with the lowest life cycle cost (F4, R1, W1) were also a scenario with the lowest total energy consumption load. This alignment between energy efficiency, and economic performance is particularly encouraging as it suggests that environmentally beneficial choices can also be economically advantageous in the long term.

The optimal combination, (F4, R1, W1) was the sixth lowest among all scenarios. However, by year three it become the scenario with the lowest life cycle cost due to its superior energy performance. Over the 50-year analysis period, its total life-cycle cost was 27% lower than the median combination (F2, R3, R3). This has been outlined below in the figure 10. The Y-axis is calculated based on a multiplication of cost to the

local currency. The value of the local currency fluctuates to a great extent, and that was a reason to counter the effect of fluctuations in the price of local currency.

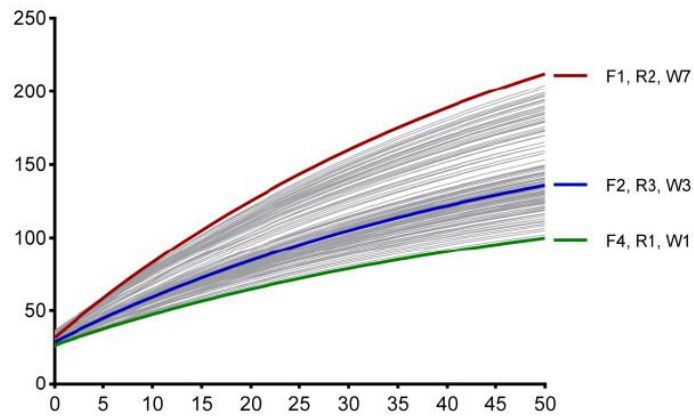


Figure 11: LCC over 50 years for all 120 combinations

These findings align with recent studies on the economic benefits, of energy efficient building envelope. For example, Ferrara et al. (2019) found that optimize building envelopes in Mediterranean climates could reduce life cycle costs by 20-30% compared to standard constructions primarily due to reduced operational energy cost.

The scenario with the highest 50-year lifecycle cost (F1, R2, W7) had an initial cost close to an average of all scenarios. However, its poor energy performance resulted in a total life cycle cost more than twice that of the optimal combination. This stark difference underscores the long-term financial implications of energy inefficient design choices.

The analysis demonstrates that while the initial cost of more energy efficient envelope configurations may be slightly higher the long-term savings in energy costs more than compensate for the initial investment. This finding is consistent with the concept of

“green premium and brown discount” in real estate where, energy efficient buildings commands higher values and lower operational costs (Christensen et al., 2021).

5.2.3 Implications of Material Selection

The results highlight critical role of material selection, in determining both the energy performance and economic viability of residential buildings in Cyprus. The optimal combination (F4, R1, W1) leverages several key principles of energy efficient design:

1- Thermal mass: The use of concretes in the floor provides thermal mass which, can help regulates indoor temperatures by absorbing excess heat during the day and releasing it at night. This is particularly beneficial in Cyprus climate characterized by high diurnal temperature variations.

2- Ventilated roof design: The air gap in roof type 1 creates a ventilated roof space which, can significantly reduce heat gain in summer. Recent studies, by Tong et al. (2021) have shown that ventilated roof designs can reduce cooling loads by up to 20% in hot climates.

3- Insulated wall construction: The air gap in wall type 1 provides an additional layer of insulation reducing heat transfer between the interior and exterior. This aligns with findings by Sadineni et al. (2018) who demonstrate that multi-layer wall constructions with air gaps can improve thermal performance by 15 25% compared to single-layer walls.

The deficient performance of the least efficient combination (F1, R2, W7) can be attributed to several factor:

1- Lack of thermal mass: Floor type 1 with its carpet finish provide minimal thermal mass reducing the building’s ability to moderate temperatures fluctuations.

2- High thermal conductivity: Roof type 2 with its asphalt cover, and lightweight concrete likely has higher thermal conductivity than the clay tile and air gap configuration of optimal design.

3- Inefficient wall construction: Wall type 7 consisting of hollow lightweight blocks may not provide sufficient insulations or thermal mass.

These findings underscore the importance of holistic approach to building envelopes design considering, not just individual material properties but also how different components interact to influence overall building performance.

5.3 Evaluation of Insulation Materials

Following the analysis of building envelope topologies, the study, evaluate eight common insulation materials as listed in figure 11, applied to the optimal building envelope configuration (F4, R1, W1). This comprehensive assessment of insulation performance, align with contemporary trends in building energy research which emphasize, the critical role of insulation in achieving high performance building envelopes (Berardi, 2018).

Material	Density (kg/m ³)	Thermal conductivity
Expanded polystyrene	12	0.040
Expanded polystyrene (high density)	22	0.035
Extruded polystyrene	28–32	0.027
Fibreglass	14	0.04
Fibreglass (high density)	22	0.035
Rock wool	52	0.045
Rock wool (high density)	150	0.035
Perlite	–	0.031

Figure 12: Common available insulation materials in Cyprus

5.3.1 Insulation Thickness and Thermal Performance

The analysis reveals significant variations in the required thickness of different insulation materials, into achieve comparable thermal performance. High density rock wool emerged as the most efficient materials, in terms of thickness requiring only 1.6 cm to achieve the desired thermal resistance. In contrast perlite required, the greatest thickness at 28.2 cm.

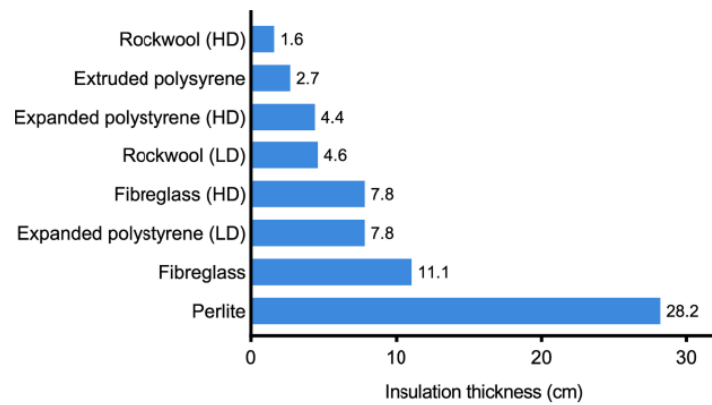


Figure 13: Optimal thickness of different insulation materials

This substantial difference in required thickness (26.6 cm) between high density rock wool and perlite, can be attribute to their vastly different thermal conductivities and material densities. High density rock wool with its low thermal conductivity (approximately 0.035 W/mK) and higher material density (about 150 kg/m³), outperforms perlite which has a thermal conductivity, of around 1 W/mK and a density range of 35-130 kg/m³.

These finding align with recent research by Schiavoni et al. (2021) who conducted, a comprehensive review of insulation materials for building applications. They found that high density mineral wool products consistently outperformed other common insulation materials in terms of thermal efficiency per unit thickness.

Among the other materials evaluated extruded polystyrene and expanded high density polystyrene performed well with required thicknesses of 2.7 cm and 4.4 cm, respectively. These results are consistent with the growing trend towards the use of high-performance synthetic insulation materials in energy efficient buildings (Papadopoulos, 2019).

It is worth noting that while expanded polystyrene required a greater thickness than its high-density counterpart it still outperformed, fiberglass which needed thicknesses greater than 10 cm. This finding extends the work of Axaopoulos et al. (2019) who, determined optimal insulation thicknesses for various wall types in Mediterranean climates to be in the range of 7.1–10.1 cm.

The wide range of required thicknesses (1.6–28.2 cm) observed in our study, highlights the importance of careful insulation material selection particularly in retrofit applications where space constraints may be significant consideration.

5.3.2 Energy Savings Analysis

The study evaluated the annual energy saving achieved by applying each insulation material to different building component (walls roof floor doors and windows). The result reveals several key insights:

1- Walls and Doors: Energy savings for walls and doors were relatively modest ranging from 78.9 to 92.8 kWh for walls 44.7 to 72.6 kWh for doors. Perlite emerged as the most energy efficient insulating material for both components albeit, by a small margin. These findings, suggests that while insulation of walls and doors contributes to overall energy efficiency it may not be primary driver of energy savings in the Cypriot context.

2- Roof Insulation: Significant variations in energy savings observed for roof insulation with perlite, saving the most energy (727.0 kWh) when applied to inside layer a high-density rock wool performing best (397.9 kWh) for outside layer. This substantial difference in performance between inside and outside roof insulation align with recent findings by Kotsiris et al. (2020) who demonstrated that the position of roof insulation can significantly impacts its effectiveness, particularly in Mediterranean climates.

3- Windows: The installation of double-glazed window proved to be the most impactful single measure achieving, energy savings of 1,324.7 kWh, approximately 40% higher than single glazed windows. This substantial improvement corroborates recent research by Tsikaloudaki et al. (2021) who found that advanced glazing technology, can reduce building energy consumption by 30 50% in southern European climates.

4- Overall Performance: High density rock wool in combination with double glazed windows emerged as the top performer yielding total energy saving of 2,063.2 kWh. This was followed by extruded polystyrene and low-density rock wool with saving of 1,752.9 and 1,743.7 kWh, respectively.

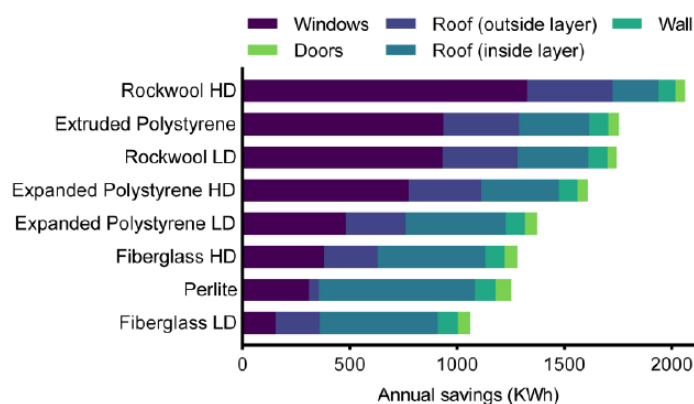


Figure 14: Annual energy saving of different insulation materials.

These results underscore, the importance of a holistic approach to building insulations considering not just insulation material itself but, also its application method and location within the building envelope. The superior performance of high-density rock wool aligns with contemporary trends in the construction industry toward the use of high-performance mineral wool products as noted by Pérez-Lombard et al. (2020) in their review of insulation materials for energy efficient building.

5.3.3 Life-Cycle Economic Analysis

The life cycle economic analysis conducted over a 50-year period revealed, valuable insights into the long-term financial implications of different insulation strategy (Figure 7):

1- Double glazed Windows: This measure emerges as the most economically beneficial with cost saving of 11,483 TL over 50 years and, a remarkably short payback period of just three years. The finding aligns with recent research by Gustavsen et al. (2022) who, demonstrated that advanced window technologies often offer a fastest return on investment among various energy efficiency measures.

2- Roof Insulation: Insulating the outside of the roof with high density rock wool showed substantial savings of 2,715 TL over 50 years with payback period of 10 years. This, longer payback period compared to windows is consistent, with findings by Kontogeorgos et al. (2019) who noted that, roof insulation typically has a longer but still favorable payback period in Mediterranean climates.

3- Doors and Interior Roof Insulation: These measures showed only marginal economic benefits over a 50-year analysis period. This result suggests that while these measures contribute to overall energy efficiency, they may not be priority investments, from a purely economic standpoint.

4- Wall Insulation: Interestingly wall insulation was unable to recoup its initial investment, over the 50-year period. These finding contrasts, with some studies in other climatic regions but align with research by Nematchoua et al. (2021) who found that wall insulation, in hot climates may have longer payback periods due to the dominance of cooling load. The summary of the life cycle saving from different insulation applications are outlined below:

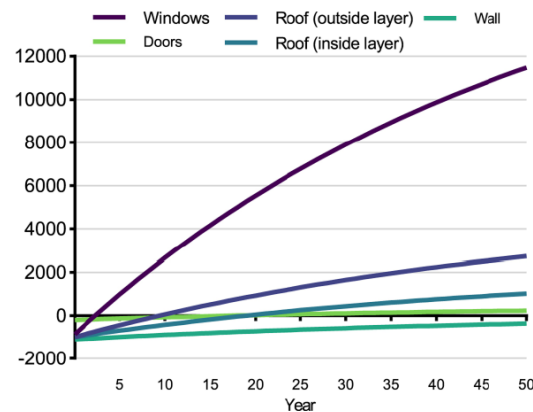


Figure 15: life cycle saving from different insulation applications.

These economic outcomes highlight the importance of prioritizing insulation investments, based on both energy performance and economic returns. The clear economic advantage of double-glazed windows and exterior roof insulation suggests that this, should be priority measures for improving building energy efficiency in Cyprus.

5.3.4 Thermal Comfort Analysis

In addition, energy savings and economic benefits, the study evaluated, impact of insulation on thermal comfort. The study presents the comparison of thermal comfort conditions in insulated and uninsulated buildings throughout the year. This analysis provides crucial insights into lived experience of building occupants an aspect that is

increasingly recognized as critical in building performance evaluations (Rupp et al., 2020).

The results are summarized in figure 16 and they revealed that:

1- Annual Discomfort: Uninsulated buildings experience discomfort 67% of the time throughout the year while, insulated buildings showed the slight improvement with discomfort occurring 63.8% of the time.

2- Seasonal Variations: The impact of insulation on thermal comfort varied significantly across season:

- Winter Months (December February): Insulation dramatically reduced cold discomfort. For instance, in January cold discomfort decreased, from 98.8% in uninsulated buildings to 85.2% in insulated ones.
- Summer Months (June September): Insulation increased hot discomfort. In July, and August both insulated and uninsulated buildings experience 100% hot discomfort.
- Transition Months (April May October November): Insulation had mix effects sometimes increasing hot discomfort while, reducing cold discomfort.

These findings align with recent research by Sameni et al. (2022) who found, in Mediterranean climates insulation can lead to increase overheating risk in summer if not combined with effective ventilation strategies.

	Uninsulated	Insulated				
Month	Too hot %	Too cold %	Total %	Too hot %	Too cold %	Total %
January	0.0	98.8	98.8	0.0	85.2	85.2
February	0.0	92.4	92.4	0.0	71.4	71.4
March	0.0	90.3	90.3	0.0	60.2	60.2
April	3.5	24.6	28.1	9.6	10.0	19.6
May	12.0	0.0	12.0	34.3	0.0	34.3
June	74.7	0.0	74.7	91.3	0.0	91.3
July	100.0	0.0	100.0	100.0	0.0	100.0
August	100.0	0.0	100.0	100.0	0.0	100.0
September	96.7	0.0	96.7	100.0	0.0	100.0
October	17.6	0.0	17.6	43.2	0.0	43.2
November	0.0	18.3	18.3	4.6	1.7	6.3
December	0.0	77.0	77.0	0.0	53.8	53.8
Annual average	33.7	33.5	67.2	40.2	23.5	63.8

Figure 16: Thermal discomfort measures in different months of the year

The modest overall improvement in thermal comfort (3.4% reduction in discomfort hours) suggest that while insulation is beneficial it is not a panacea, for thermal comfort issue in Cyprus's climate. This result underscores the need, for a more comprehensive approach to thermal comfort incorporating strategy, such as natural ventilation shading, and possibly active cooling systems.

The increased hot discomfort during summer months in insulated building, is particularly noteworthy. It suggests that insulation while effective, at reducing heat loss in winter may be trapping heat, during the hot summer months. This phenomenon

often referred to, as a “thermos flask effect,” has observed in other studies of well insulated buildings in hot climates (Al-Obaidi et al., 2019).

To address this issue future designs might consider, incorporating adaptive insulation technologies as proposed by Jin et al. (2021). This innovative material can adjust their thermal properties based on environmental conditions potentially offering improve year-round performance.

The findings of this study provide comprehensive insights into the energy performance economic viability and, thermal comfort implication of various building envelope and insulation strategies in the context of Cyprus. These results have significant implications for building design energy policy and sustainability effort in Cyprus and similar Mediterranean climates.

5.4 Optimizing Building Envelope Design

The identification of optimal building envelope combination (F4, R1, W1) that reduces energy load by 32 %, compared to the median scenario underscores a substantial potential for energy savings through informed material selection. This finding aligns with recent research by Csáky and Karlík (2023), who demonstrate that optimized building envelopes could reduce energy consumption by up to 40 % in similar climate zone.

Several key principles emerge from the analysis of the optimal envelope’s configuration:

1- Thermal Mass Utilization: The inclusion of concrete in the floor (F4) provides thermal mass which, help regulate indoor temperatures. This aligns with finding by

Navarro et al. (2022) who, showed that proper use of thermal mass could reduce cooling energy demand by up to 25 % in Mediterranean climates.

2- Ventilated Roof Design: The air gap in optimal roof configuration (R1), create a ventilated roof space effectively reducing heat gain. This strategy's effectiveness is supported by recent work from Mastrapostoli et al. (2021) who found that ventilated roof can lower cooling loads by 15 30 % in hot climate.

3- Insulated Wall Construction: The air gap in the optimal wall configuration (W1), provide additional insulation. This multi-layer approach to wall construction is consistent with recommendation by Zinzi et al. (2022), who advocate for complex wall assemblies in energy efficient Mediterranean building.

A significant variation in performance across different envelope combination (59% difference between best and worst scenarios) highlight, the critical importance of envelope design in determining building energy performance. This finding emphasize need for careful consideration of material choices, and envelope configurations in initial stages of building design a point stressed by Rodrigues and Freire (2022) in their review of sustainable building design practices.

5.5 Economic Viability of Energy-Efficient Design

A life cycle cost analysis reveals the strong alignment between energy efficiency, and economic performance with the most energy efficient envelope configuration also proving to be the most economically viable, over a 50-year period. This finding challenges the perception, that energy efficient design necessarily incurs higher costs and supports the growing body of evidence, on the economic benefits of green building (D'Agostino et al., 2023).

Key economic insights include:

- 1- Rapid Return on Investment: The optimal configuration became the most economically favorable, by year three despite not having lowest initial cost. This rapid payback period aligns with findings by Rabani et al. (2022) who reported payback period of 2-5 years for energy efficient envelope upgrades in hot climates.
- 2- Long term Savings: The 27 % reduction in life cycle costs for the optimal configuration compared to the median scenario demonstrate substantial long term economic benefit of energy efficient design. This magnitude of savings is consistent with projection, by Longo et al. (2023) for energy efficient buildings in southern Europe.
- 3- Cost of Inefficiency: The more than doubling of life cycle cost for the least efficient configuration underscore the long-term financial risks of poor envelope design. This stark difference supports the argument by Sesana and Salvalai (2023) for considering life cycle cost, in building regulations and energy policies.

These economic outcomes provide a compelling case for promoting energy efficient building practice not just as an environmental imperative but as a sound economic strategy. A clear financial benefit over the building's lifespan, could be leveraged to encourage adoption of energy efficient design, among developers' homeowners and policymakers.

5.6 Insulation Strategies: Performance and Practicality

The evaluation of insulation materials revealed important insight to both performance a practical consideration in Cypriot context:

- 1- Thickness vs. Performance: The superior performance of high-density rock wool requiring only 1.6 cm thickness, compared to 28.2 cm for perlite highlights the

importance of considering thermal properties and space efficiency in insulation selection. This finding aligns with recent work by Mohajerani et al. (2022) who emphasize the growing importance of high-performance space efficient insulation, in urban building retrofit.

2- Component Specific Performance: Varying effectiveness of insulation across different building component (walls roof windows) underscore need for a tailored approach to insulation strategy. This aligns with recommendations by Capozzoli et al. (2023) who advocate for component specific insulation optimization in Mediterranean climate.

3- Dominance of Roof and Window Insulation: The significant energy saving achieves through roof insulation and double-glazed window compared to, more modest gains from wall insulation suggest prioritizing these components in energy retrofit strategy. This finding is consistent with recent work by Theodosious et al. (2022) who identified, roof and window upgrades as most impactful interventions for improving energy efficiency in existing Mediterranean buildings.

4- Economic Viability: The rapid payback period for double glazed windows (3 years) and favorable long-term return on roof insulation provide strong economic case for these interventions. However, the longer payback period, for other measures highlight the need to balance energy performance with economic considerations a point emphasizes by Giglio et al. (2023) in their analysis of energy retrofit economics.

5.7 Thermal Comfort: Balancing Year-Round Performance

The thermal comfort analysis reveals nuanced picture of insulations impact:

1- Winter Benefits vs. Summer Challenge: While insulation significantly improve winter comfort it exacerbates overheating in summer. This tradeoff is consistent with

finding by Pisello et al. (2023) who observe similar patterns in well insulated buildings southern Italy.

2- Need for Adaptive Strategies: The increased summer discomfort in insulated buildings points to need for complementary cooling strategies. Recent work, by Santamouris et al. (2022) suggest that combining insulation with passive cooling techniques like night ventilation could offer a more balanced approach to year-round comfort in Mediterranean climate.

3- Rethinking Comfort Standards: The high percentage of discomfort hours even in insulated buildings raises questions, about the appropriateness of static comfort standards in Cypriot context. This aligns with arguments by de Dear et al. (2023) for more climate specific adaptive comfort model in building design and evaluation.

5.8 Implications for Policy and Practice

The finding of this study has several important implications for building design construction practice and energy policy in Cyprus:

1- Building Codes and Standards: The significant energy savings potential identified suggest need for more stringent energy efficiency requirements, in building code. This aligns with recommendation by Attia et al. (2023) for accelerating adoption of near zero energy building standards in Mediterranean countries.

2- Retrofit Priorities: Clear benefits of double-glazed windows and roof insulation provide a compelling case for prioritizing this measure in energy-retrofit program. This targeted approach supported by recent policy analyse by Voulis et al. (2022) who advocate for component specific retrofit incentives, to maximize impact.

3-Design Integration: The interdependence of envelope design insulation strategy and thermal comfort underscore the need, for integrated design approaches. Recent work

by Lobaccaro et al. (2023) demonstrate benefits of using parametric design tools to optimize these interdependent factors, simultaneously.

4- Economic Incentives: The favorable life cycle economics of energy efficient design provide basis for developing financial incentive or green mortgage programs to encourage adoptions. Similar approaches have shown success in other European countries as documented by Bertoldi et al. (2023).

5- Climate Resilience: The challenges with summer overheating in well insulated buildings highlights need to consider future climate scenarios in building design. This aligns with recommendation by Akbari et al. (2022) for climate resilient building designs in regions experiencing increasing temperature.

Chapter 6

CONCLUSIONS AND RECCOMENDATIONS

6.1 Conclusion

The study investigates energy efficiency optimization in residential buildings in Cyprus with integration of Building Information Modelling (BIM) energy performance simulation and comprehensive energy life cycle analysis, by using a computer program which developed throughout the thesis with the goal of providing the most environmentally friendly choice at the briefing stage of a residential construction project in Cyprus.

With buildings accounting for nearly 36 % of global final energy use and 39% of energy related carbon dioxide emissions research addresses the critical need for sustainable construction practices in the Mediterranean region where Cyprus experiences over 21,000 cooling degree hours per year creating significant energy demands for cooling. Another reason highlighting Cyprus as the case study is the energy source for Cyprus which is fossil fuels and the source of construction materials which is mostly import. This significantly increases the embody energy of construction materials which is the focal point of this manuscript.

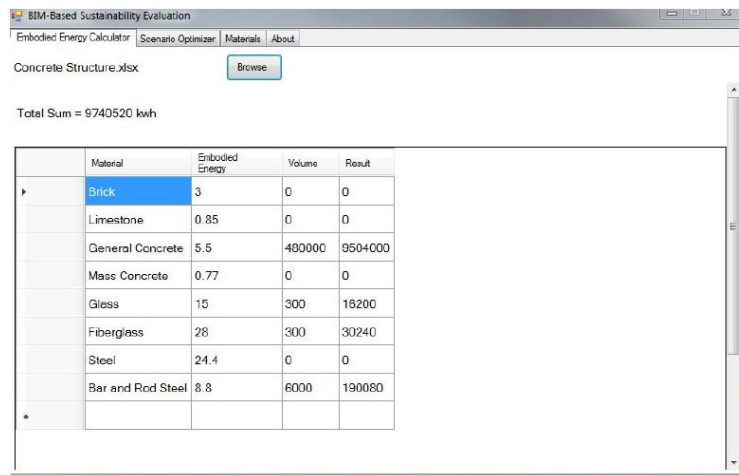
The research evaluates 120 combination of building envelope material and eight insulation materials by utilizing both Autodesk Revit for BIM modelling and Autodesk Ecotect for energy performance simulation. A computational framework is developed

for embodied energy assessment incorporating material transportation energy cost manufacturing processes and construction energy consideration. This holistic approach recognizes that embodied energy (the total energy consumed in material production transportation and construction) represent a substantial portion of a buildings lifetime energy footprint often overlooked in traditional energy analyses.

Results reveal that the optimal building envelope configuration including specific combinations of floor roof and wall types achieves a 32 % reduction in energy load compared to the median scenario and a 59 % reduction compared to the least efficient combination in the operational phase. The embodied energy analysis, demonstrate that material selection and transportation distances significantly impact the total energy footprint sometimes offsetting operational energy savings. The study finds that high density rock wool insulation requiring only 1.6 cm thickness proves to be the most efficient insulation materials when both operational and embodied energy are considered.

The comprehensive analysis of embody energy reveals that construction methods and material sourcing can contribute up to 40 % of a building's total lifetime energy consumption. This finding emphasizes importance of considering both operational and embody energy in the early design stages. The study provides valuable insights for building design practices, energy retrofit strategies and policy development in Cyprus and similar Mediterranean climates while, identifying key areas for future research including the further integration of embody energy assessments and consideration of climate change impacts on building performances.

Finally, an innovative computer software application is developed that revolutionizes building design decision making by calculating complete carbon footprint of potential buildings. This tool takes the export file from Revit which includes the list of construction materials and their volume and using that, it calculated the total embodied energy of the whole building.



The screenshot shows a software window titled "BIM-Based Sustainability Evaluation" with tabs for "Embodied Energy Calculator", "Scenario Optimizer", "Materials", and "About". The "Embodied Energy Calculator" tab is active, displaying "Concrete Structure.xlsx" and a "Browse" button. Below this, it states "Total Sum = 9740520 kwh". A table lists materials with their embodied energy, volume, and result.

	Material	Embodied Energy	Volume	Result
▶	Brick	3	0	0
	Limestone	0.85	0	0
	General Concrete	5.5	480000	9504000
	Mass Concrete	0.77	0	0
	Glass	15	300	16200
	Fiberglass	28	300	30240
	Steel	24.4	0	0
	Bar and Rod Steel	8.8	6000	190080
*				

Figure 17: Total building embodied energy calculation using Revit export file.

Using the results of the energy consumption in the operational phase which comes from our modelling in Ecotect and by combining the embodied energy calculated by the computer software including material production transportation and installation processes, we can see the total potential energy consumption of our scenario (Figure 18). The comprehensive approach provides stakeholders with the opportunity to select most environmentally sustainable scenario among all potential options during the crucial briefing stage of the project ensuring that both immediate and long-term energy impacts are optimized.

Scenarios	Annual Energy	Embodied Energy
1	15000	9740520
2	9000	9790920

Most Sustainable Case: Case #2, 9871920 kWh
CO2 Emission: 6683289.84 kgC

Figure 18: Operational and construction energy consumption

6.2 Recommendations

6.2.1 Future Directions in Embodied Energy Research

Looking ahead several promising areas of research are emerging in the field of embodied energy. There is a need for more comprehensive and reliable embodied carbon data calling for the development of standardized methodology and improve data transparency. Protocols for embodied energy calculation needs to improve comparability between studies. This remains the key area for future research as inconsistencies in calculation methods can lead to significant variations in reported embodied energy values.

These emerging research directions promises to enhance our understanding of embodied energy and provide new tools for its reduction in building design and construction.

6.2.2 Future Directions for BIM in Sustainable Construction

Looking ahead, several trends are likely to shape the future of BIM in sustainable construction:

- 1- Integration with emerging technologies: Artificial Intelligence (AI) and Machine Learning have potential to enhance BIM capabilities in areas such as predictive maintenance a performance optimization.
- 2- Cloud based BIM: The move towards cloud base BIM solutions is expected to improve collaboration a data accessibility.
- 3- BIM for urban scale sustainability: There is the increasing interest in expanding BIM's scope from individual building to urban scale application supporting more comprehensive sustainability strategy.

These developments promise to further enhance BIM role in promoting sustainable construction practices but will also require ongoing research and development to address technical organizational and policy challenges.

6.2.3 Research Gaps and Future Directions

While considerable progress has been made in understanding and implementing sustainable construction practices several key areas for future research have been identified:

- 1- Development of region-specific databases and assessment tools for embody energy calculations.
- 2- Exploration of the potential of emerging technologies included artificial intelligence and digital twins, in enhancing building sustainability.
- 3- Investigation of the long-term performance of sustainable buildings, including post occupancy evaluations a life cycle assessment.
- 4- Further research on a specific challenges and opportunities for sustainable construction in Cyprus and the broader Mediterranean region considering unique climatic economics and cultural factors.

5- Exploration of the role of occupant behaviour and engagement in achieving and maintaining building sustainability performance over-time.

6.2.4 Future Directions in the developed computer program

Several areas for future development in the developed computer program have been identified:

- 1- The incorporation of artificial intelligence would make the tool universally applicable as the data could be driven based on the location of the project.
- 2- Integration of the tool as a plug in to a potential performance modelling tool will reduce potential mistakes and will create a one-stop shop for making the final decision about a potential scenario.
- 3- Varied materials in construction need different machineries require diverse time for application. This was considered negligible in the current study. The tool could be developed further to incorporate the as well.

Addressing these research gaps will be crucial for developing more effective sustainable briefing practices ultimate leading to more sustainable built environments.

6.3 Future Challenges and Opportunities

Looking ahead Cyprus faces both challenges and opportunities in improving the energy efficiency of its building stock Climate change is expected to increase cooling demands making passive cooling strategies and efficient air conditioning systems increasingly important.

The renovation of the existing building stock presents a significant opportunity for energy savings. The European Commission Renovation Wave strategy which, aim to at least double renovation rates in the next ten years could have significant implications

for Cyprus. Successfully implementing this strategy in the Cypriot context will require tailored approach that consider the unique characteristics of local building stock and climate.

Innovative technologies and approaches offer new opportunities for enhancing building energy efficiency in Cyprus.

The potential for Cyprus to serve as model for sustainable building practices in the Mediterranean region should not be overlooked. As an island nation with limited resources successful energy efficiency strategies developed and implemented in Cyprus could provide valuable lesson for countries in the region facing similar challenge.

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