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A BIM-based method for identifying the most cost-effective and energy efficient external wall materials and systems within the UK over the buildings life cycle

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I certify that this dissertation reports original work carried out by the author during my final year project and that all researched materials is correctly referenced in accordance with the Harvard referencing style.

Signature Date

Seyed Mohammad Hosein Mehraban **06/09/2023**

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1- Abstract

The building envelope, separating a structure's interior and exterior, greatly impacts a building's cost and energy performance throughout its life cycle. Researchers have increasingly focused on factors influencing building envelope performance, with Building Information Modelling (BIM) offering a way to assess and improve it.

External wall materials and systems, as integral components of building envelopes, play a pivotal role in shaping construction costs and energy consumption. This research adopts a systematic approach, utilizing Building Information Modelling (BIM), to assess and identify the most cost-effective and energy-efficient external wall materials and systems within the UK, specifically focusing on the unique regional conditions in London. The analysis extends over the entire building life cycle, aiming to optimize sustainability and economic performance.

The process begins with interviews with construction experts to identify commonly used external wall materials in London, resulting in six distinct external wall scenarios. Autodesk Revit and BIM principles are used to extract data on wall surfaces and quantities for each material. Detailed cost assessments, covering materials and labour, determine the total construction cost for each system.

Additionally, Autodesk Green Building aids in extensive energy analysis, gathering data on natural gas and electricity consumption for heating and cooling in each scenario. This data helps calculate monthly and annual energy costs, factoring in local energy rates. The life cycle cost analysis considers both energy and construction costs, enabling a comprehensive evaluation of cost-effectiveness and energy efficiency.

The research reveals significant differences between traditional walls and alternative systems. Structural insulated panels (SIPs) show a potential 51% improvement in energy consumption and a 50% reduction in life cycle costs. Concrete block cavity walls with insulation exhibit a potential 29% reduction in construction costs and a 48% decrease in life cycle costs.

To address energy-inefficient solid brick walls, retrofitting options are explored. Internally insulating external walls could reduce energy bills by 46% with an 11-year payback period.

Implementing this method offers broad benefits. Local governments can recommend viable wall systems to boost builders' profits. Building residents enjoy lower utility bills, while society benefits from reduced energy consumption and greenhouse gas emissions, fostering a more sustainable built environment.

2- Introduction:

In the pursuit of sustainable and energy-efficient building practices, the choice of an appropriate external wall, a key component of building envelopes is paramount. Serving as the interface between a building's interior and exterior environments, the building envelope exerts a substantial impact on energy consumption, operational expenses, and occupant comfort. This research introduces an innovative BIM-based methodology designed to pinpoint the most cost-effective and energy-efficient external wall materials and systems within the United Kingdom throughout the building's lifecycle.

2-1 Aim and Objectives

The primary aim of this research is to leverage the capabilities of Building Information Modeling (BIM) and simulation tools to compare commonly used wall system in the UK with alternative options that vary in terms of thickness, material composition, insulation, and other relevant parameters. By utilizing BIM simulations, the energy performance and life cycle costs of different walls will be assessed, allowing for a comprehensive evaluation of their cost-effectiveness and energy efficiency. The specific objectives of this study are as follows:

1. To review and analyse existing literature and industry standards concerning wall materials, life cycle cost analysis, energy performance assessment, and sustainable construction practices within the UK context.
2. To identify commonly used wall systems in the UK, and gather data on material costs, labour costs, and construction costs associated with each option.
3. To assess the energy performance of different external walls through BIM simulation, considering parameters such as heating and cooling loads, energy consumption, and thermal performance.
4. To evaluate the life cycle costs of wals by considering not only immediate construction costs but also long-term energy costs, maintenance expenses, and potential retrofitting requirements.
5. To develop a set of evaluation criteria that encompasses economic, environmental, and social parameters, and assign appropriate weights to each criterion based on stakeholder input.
6. To compare and rank the identified walls based on their cost-effectiveness and energy-efficiency using quantitative analysis and multi-criteria decision-making techniques.

To achieve this objective, three key parameters will be considered: economical, environmental, and social factors.

2-2 Economic Parameters

The **economic parameters** of a construction project include immediate construction costs, such as materials, labour, and expenses associated with various building envelope options. Additionally, the analysis incorporates life cycle costs to account for long-term financial implications, considering energy costs over the building's lifespan. This evaluation facilitates the identification of the most financially viable wall system options.

Cost efficiency is a primary concern in construction projects, with the building envelope comprising a significant portion of the total construction cost. Studies indicate that more than 20% of a building's construction cost is allocated to the building envelope, encompassing components like walls, roofs, windows, and doors. Thus, selecting appropriate materials and design strategies for the building envelope can have a considerable impact on overall project costs. For example, investing in high-quality insulation materials and efficient windows can lead to long-term energy savings and reduced operational expenses.

However, evaluating the cost efficiency of different building envelope options requires considering not only the initial construction cost but also the life cycle cost of the building. Life cycle cost analysis encompasses ongoing operational expenses, maintenance costs, and energy consumption throughout the building's lifespan. By comprehensively evaluating these factors, stakeholders can make informed decisions regarding the building envelope to minimize long-term costs and maximize energy efficiency.

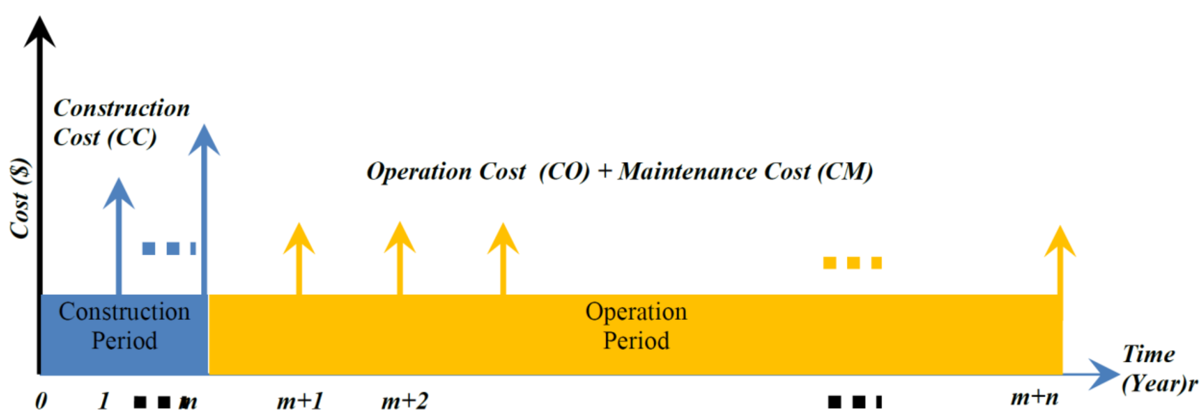

Figure 1– Cost lifecycle of building envelopes

2-3 Environmental Parameters

The **environmental parameters** focus on the sustainability aspects of the building envelope, particularly energy efficiency, carbon footprint reduction, and alignment with sustainability goals. Through a systematic analysis of building envelope materials and designs, their environmental impact is assessed to identify the most energy-effective options.

Buildings' environmental impact, especially in terms of energy consumption and carbon footprint, has gained significant attention due to climate change and resource concerns. The external wall plays a crucial role in achieving energy efficiency by minimizing heat transfer, optimizing insulation, and reducing air leakage. By selecting energy-efficient materials and designs for external walls, significant energy savings and reduced greenhouse gas emissions can be achieved.

Emphasizing thermal performance is key in designing an environmentally friendly building envelope. This includes using high-performance insulation materials, such as rigid or spray foam insulation, to minimize heat transfer through walls, roofs, and floors. Additionally, incorporating advanced glazing systems with low-emissivity coatings helps minimize heat gain or loss through windows, further enhancing the energy efficiency of the building envelope.

2-4 Social Parameters

The **social parameters** encompass the functional and aesthetic aspects of the building envelope. It evaluates how well the chosen materials and design meet factors such as durability, maintenance needs, thermal comfort, and occupant satisfaction. The research aims to identify wall solutions that optimize energy performance, cost-efficiency, functionality, and user experience.

The building envelope significantly impacts the indoor environmental quality (IEQ) of a building. Poorly designed or constructed envelopes can lead to issues like moisture intrusion, mold growth, and inadequate indoor air quality, negatively affecting occupant health. Implementing moisture control measures, ventilation systems, and ensuring airtight construction contributes to a healthier indoor environment.

Considering the social dimension of the building envelope is as important as economic and environmental factors. It should fulfil functional requirements, provide thermal comfort, and be durable and easy to maintain. Evaluating the social parameters ensures occupant satisfaction and well-being.

In conclusion, the selection of an appropriate building envelope specially external wall systems are a critical decision with far-reaching implications. It affects the cost efficiency, energy performance, environmental impact, and social dimension of a building. By carefully considering factors such as cost optimization, energy efficiency, occupant comfort, and sustainability, stakeholders can make informed decisions that result in a well-designed and high-performing building envelope. This not only benefits the building occupants but also contributes to global efforts in achieving energy efficiency, environmental sustainability, and the creation of healthy and liveable built environments. Through continuous research, technological advancements, and collaboration, the building industry can further improve building envelope design and construction practices, leading to a more sustainable and resilient future.

3- literature review

The choice of building envelope materials and insulation types holds significant implications for the cost and energy performance of buildings. Studies suggest that more than 20% of the total construction cost is allocated to the building envelope. Acting as a boundary between the interior and exterior of the building, the envelope facilitates heat exchange during operation. Extensive research efforts have been dedicated to exploring the effects of different materials and insulation options in order to enhance overall building efficiency. This section aims to provide a comprehensive analysis of various studies that have investigated the cost and energy performance implications of building envelope materials and insulation types. By delving into these studies, a deeper understanding can be gained, contributing to the advancement of sustainable and economically viable building practices.

3-1 Studies on Building Envelope Materials and Insulation:

In their study, Pakand and Toufigh (2014) conducted a comparison of the energy efficiency between low-cost rammed earth wall materials and high-cost alternatives such as expanded polystyrene insulation (EPS) and phase change materials. The study revealed comparable performance between the low-cost rammed earth walls and the high-cost insulation options, highlighting the potential of low-cost materials in achieving energy efficiency targets.

Hasan et al. (2018) discovered that the implementation of phase change envelope materials in buildings effectively reduces energy consumption. These materials, capable of storing and releasing heat, contribute to improved thermal performance and enhanced energy efficiency.

The research conducted by Domínguez et al. (2012) focused on exploring the potential energy savings that can be achieved by making appropriate choices of insulation materials in the city of Seville, Spain. Their study identified the possibility of up to 27% energy savings by carefully choosing insulation materials. This finding emphasizes the significance of considering insulation materials as a means to optimize energy performance and reduce operational costs throughout the life cycle of a building.

Echarri (2018) implemented thermal ceramic panel walls in a detached residential building in Spain, resulting in a 10% reduction in annual energy consumption. This research demonstrates the effectiveness of innovative materials in enhancing the energy performance of buildings and reducing their environmental footprint.

In their study, Song et al. (2019) focused on analyzing the effects of EPS (Expanded Polystyrene) insulation materials on the energy consumption of an office building located in Southern China. The research findings demonstrated substantial energy savings achieved through the implementation of EPS insulation. This outcome further highlights the significant role of insulation materials in enhancing energy efficiency within buildings. By utilizing EPS insulation, building owners and designers can capitalize on the potential to reduce energy consumption, contributing to sustainable and environmentally conscious practices in the built environment.

Hoseini et al. (2016) conducted a study in Tehran, Iran, investigating the application of fiberglass insulation in brick walls and ceilings, along with the use of double-glazed windows. Their findings indicated a remarkable 49% reduction in energy consumption, demonstrating the effectiveness of this insulation type in improving energy efficiency. This research highlights the importance of considering the specific regional context when selecting building envelope materials, as the effectiveness of different materials can vary depending on climate and other regional factors.

The study conducted by Rahbar and Saadati (2017) focused on exploring the utilization of polystyrene insulation layers in buildings situated in the hot and dry climate of Semnan, Iran. Their findings revealed that the incorporation of polystyrene insulation had the potential to enhance the energy performance of buildings by up to 6.5%. This research highlights the significance of selecting insulation options tailored to the specific climatic conditions of a region in order to maximize energy savings.

Cheung et al. (2017) in the context of the hot and humid climate of Hong Kong, focused on the potential energy consumption savings achievable through the use of extruded polystyrene (XPS) insulation layers in the tall skyscrapers. Their study revealed that the incorporation of XPS insulation resulted in an average energy consumption reduction of 31%. This significant reduction emphasizes the role of insulation in improving the energy performance of buildings, especially in regions with extreme climatic conditions.

Braulio-Gonzalo and Bovea (2013) conducted a study in Spain to assess the energy-saving potential of mineral and glass wool insulations. Their research confirmed the high effectiveness of these insulation types in improving energy efficiency and reducing operational costs. The study highlights the importance of considering insulation materials as a means to achieve significant energy savings in buildings.

Sawhney et al. (2013) conducted a comprehensive study comparing the cost-effectiveness of highly energy-efficient materials (referred to as Five Star) and super energy-efficient materials (referred to as Five Star Plus) in Michigan, USA. Their research demonstrated that Five Star materials had a shorter payback period, indicating a higher return on investment, compared to Five Star Plus materials. This finding highlights the importance of considering the cost implications of different materials when making decisions regarding building envelope design.

Sim and Sim (2015) conducted a comprehensive investigation into the energy performance variations among various wall materials in traditional Korean buildings. The study conducted a comprehensive analysis of various materials including mud brick, cement brick, autoclaved lightweight concrete block, cellulose fiber-reinforced cement board, and chaff charcoal. The results revealed significant variations in energy performance, indicating that the selection of appropriate materials is crucial for optimizing energy efficiency in traditional building designs.

3-2 Regional Impacts on the Building Envelope:

In addition to the choice of materials and insulation types, regional conditions and climate have a significant influence on the cost and energy performance of the building envelope. The studies discussed below highlight the importance of considering regional factors when evaluating the performance of building envelope materials.

Masoso and Grobler (2011) conducted a study on the use of XPS insulation with 80 mm thickness in buildings in hot and dry climates. Their research demonstrated energy savings of up to 26 degrees Celsius, indicating the effectiveness of insulation in mitigating heat transfer and reducing energy consumption in regions with high-temperature environments.

In a study by Pulselli et al. (2013), the energy performance of three building envelope materials was investigated across three European regions: Tuscany (Italy), Saxony (Germany), and Andalusia (Spain). The research emphasized that regional climate conditions play a crucial role in determining the performance of building envelope materials. The study highlighted the importance of conducting context-specific analyses and selecting materials accordingly to optimize energy efficiency.

Kurnaz et al. (2018) conducted a study in four cities in Turkey to investigate the life cycle cost savings associated with additional building insulation. The research revealed varying cost savings depending on the regional context, emphasizing the significance of considering regional factors when evaluating the economic viability of insulation options.

In an analysis by Ramesh et al. (2014), the energy savings potential of insulation materials was examined across five different climate zones in India. The study showcased energy savings ranging from 10% to 30%, underscoring the significant impact of regional climate on the performance of building envelope materials.

In a comparative study conducted by Friess et al. (2015), the impacts of insulation materials in typical office buildings were examined across three different regions: Malaga (Spain), Dubai (UAE), and El Dorado (USA). The study highlighted variations in energy consumption and cost savings, emphasizing the significance of considering regional factors when choosing building envelopes

In a study by Charisi (2017), the energy performance of various insulation materials in Greece was investigated. The research emphasized the significance of regional climate conditions and stressed the importance of selecting materials tailored to the specific context to optimize energy efficiency.

3-3 Integration of BIM in Building Energy Modeling:

Building Information Modeling (BIM) has emerged as a valuable tool for Building Energy Modeling (BEM) and has been widely employed to enhance the analysis and decision-making processes in building design and performance optimization. This section discusses the integration of BIM in BEM and the benefits it offers.

BIM provides a detailed, integrated multi-disciplinary design of buildings, facilitating the efficient collection of input data for BEM (Welle et al., 2011; Azhar et al., 2013). BIM models can capture regional and environmental impacts on building energy performance, enabling more accurate analysis (Heidari et al., 2014; Reinhart et al., 2017). By incorporating geographical information and climate data into BIM models, designers and engineers can assess the energy performance of buildings in a specific regional context.

The integration of BIM and Geographic Information Systems (GIS) has been explored to enhance regional energy-efficient building design in urban development. Niu et al. (2016) developed a web-based database that integrated BIM and GIS for this purpose, enabling the selection of optimal building materials and systems based on regional energy characteristics.

BIM proves valuable in construction for material quantity takeoff, cost estimation, and enhancing accuracy. Studies by Smith et al. (2013) and Wu et al. (2014) highlight its benefits. Integration of BIM with energy simulation tools enables effective evaluation of energy performance, leading to informed decision-making and optimized designs considering both financial and energy aspects.

The utilization of BIM as an information-based tool allows for the analysis of the effects of increased insulation, occupancy levels, and other factors on indoor environmental quality (Oduyemi and Okoroh, 2017). Integration of BIM with energy simulation and analysis enables practitioners to evaluate the influence of different factors on building performance, facilitating informed decisions to optimize energy efficiency.

BIM has been utilized by researchers to select efficient insulation materials and determine their optimal thickness, improving the cost and energy performance of existing buildings (Ahsan et al., 2019). BIM-based methods automate thermal value calculations and construction cost assessments for different building envelope options, enabling efficient analysis and decision-making (Lim et al., 2015).

The integration of BIM with energy simulation methods enables the identification of building spaces with abnormal energy consumption behavior, supporting the detection of inefficiencies and opportunities for improvement (Shalabi and Turkan, 2018). By visualizing and analyzing energy consumption patterns through BIM, practitioners can identify areas of high energy use and implement targeted energy-saving measures.

3-4 Research Gap and Proposed BIM-based Method:

Previous research has acknowledged the effectiveness of BIM in comparing different aspects of building envelope materials. However, a research gap still exists when it comes to providing a structured method for practitioners to select cost- and energy-efficient building envelope materials within a specific region over the life cycle of a building. To address this gap, this research proposes a novel BIM-based method that takes into account various regional conditions, including weather patterns, availability and costs of energy carriers, availability and costs of construction materials, and other relevant factors. By considering these factors, the method offers a systematic approach to assist practitioners in making well-informed decisions regarding building envelope materials and insulation types, with a focus on optimizing both cost and energy performance. The proposed method's effectiveness is validated through its application to buildings in the United Kingdom.

3-5 Conclusion:

The cost and energy performance of buildings are significantly impacted by the selection of building envelope materials and insulation types. Various studies have been conducted to assess the effects of different materials and insulation options on energy consumption and cost savings. Additionally, regional conditions, especially climate, play a crucial role in determining the effectiveness of building envelopes. The integration of Building Information Modeling (BIM) in efforts to improve building performance has shown promising outcomes. However, there is currently a lack of a systematic approach to assist practitioners in selecting cost- and energy-efficient building envelope options like different wall, roof, and façade systems, specific to a particular region throughout the building's life cycle. The proposed BIM-based method aims to bridge this research gap and offers a valuable tool for practitioners to optimize building envelope performance.

4- Methodology

The methodology to be employed in this study will aim to identify cost- and energy-efficient wall materials and system within the specific London region, considering various regional conditions such as climate conditions, energy and material availability, cost, and construction methods. It will recognize that materials identified as cost- or energy-efficient in one region may not necessarily hold the same efficiency in another. Therefore, the proposed method will accurately identify suitable external wall system by considering both material properties and the unique regional conditions.

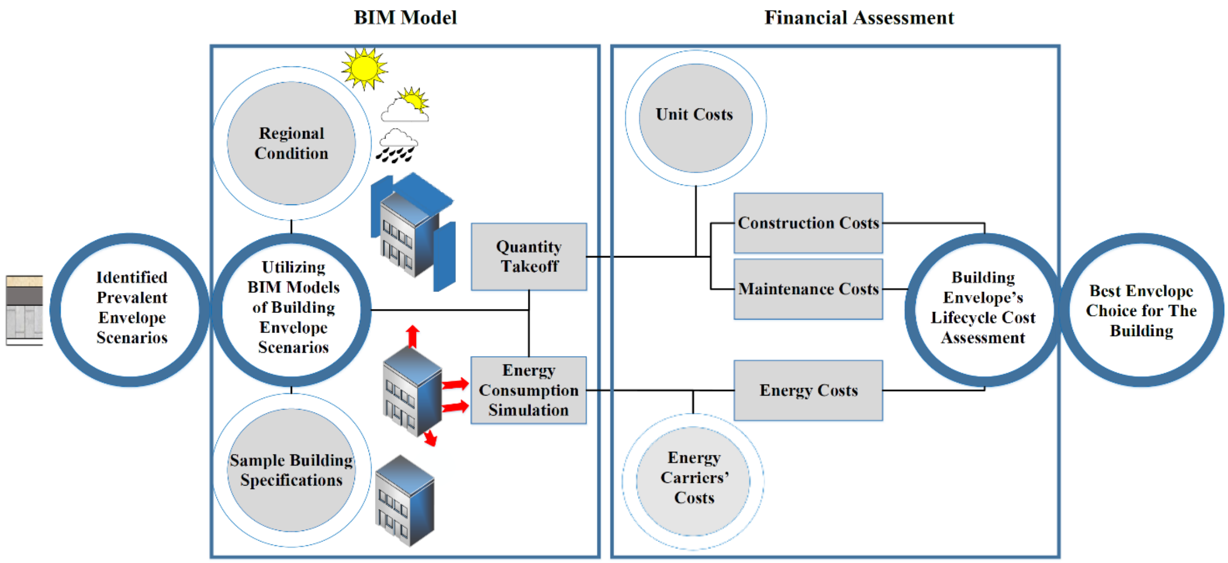

Figure 2 - Methodology explanation

4-1 Identification of Commonly Used and Accessible Materials:

To begin implementing the proposed method for the UK, the initial step involves determining the prevalence of materials available in the region. This is accomplished through a direct research approach that includes conducting a field survey among different building construction experts within the city. The primary objective of the survey is to identify the commonly used wall systems and materials for residential buildings. The region's exterior wall structures are categorized into three main groups, namely traditional system, new construction system, and industrial system.

4-2 Development of Building Information Models (BIM):

Once the suitable materials have been identified, the next part of the proposed method involves the development of Building Information Models (BIM) for a sample building. These BIM models provide a detailed representation of various wall scenarios. They encompass information such as the building's geometry, types of materials used, material density, and thermal conductivity. By incorporating such comprehensive details, the BIM models facilitate accurate estimation of the life cycle costs associated with the building's envelope.

4-3 Extraction of Material Quantities and Energy Consumption Simulation:

Moving forward, the methodology employs the BIM models to extract material quantities and simulate the annual energy consumption of the building for each envelope scenario. The extracted material quantities are then utilized to estimate the construction and maintenance costs of the building envelope. Local cost rates collected from the region are applied in these estimations to ensure accuracy. Furthermore, the energy consumption of the building is simulated, considering locally regulated cost factors of energy carriers, such as natural gas and electricity. By combining material quantities, cost rates, and energy consumption, a comprehensive evaluation of the life cycle costs for each scenario is achieved.

4-4 Estimation of Life Cycle Costs:

The estimation of life cycle costs encompasses various cost elements occurring at different stages of the building's life cycle. These include the construction cost, which covers the costs of materials, installation, and transportation during the construction phase. The maintenance cost comprises annual expenses associated with preventive and corrective maintenance activities required to maintain the building's desired level of service during its operational period. Additionally, the operational cost reflects the overall energy consumption cost of the building during its operational phase. By considering these diverse cost components, the proposed method provides a comprehensive evaluation of the life cycle costs associated with each scenario.

5- Implemented Method

London, as the thriving capital and most populous city of the United Kingdom, carries substantial significance within the country's context. The city's influence on the residential building construction sector, coupled with its vibrant urban landscape, makes it a fitting choice for the implementation of the proposed methodology.

In the scope of this research, the primary focus revolves around the evaluation of external wall materials in the context of regular residential buildings. Unlike the multistorey structures and skyscrapers found in certain regions, London's residential landscape is predominantly characterized by lower-rise constructions. Within this context, exterior walls continue to hold utmost importance in terms of energy dynamics.

The proposed methodology has been implemented to identify the optimal wall construction materials and systems for the residential building from among the various options available within the country. A comprehensive breakdown of these sequential procedures is provided in the subsequent section.

5-1 Identifying Prevalent Materials

The first step in implementing the proposed method was to gain an in-depth understanding of the prevalence of various types of external wall constructions and materials within the region. This understanding was crucial for establishing a comprehensive baseline for further analysis.

Through meticulous street-level observation, the prominent use of solid brick walls in the architectural landscape became readily apparent. However, recognizing the need for a rigorous validation of the collected data pertaining to the prevalent choices of external wall constructions in the UK, a series of focused field interviews were thoughtfully conducted. These interviews engaged a diverse group of building construction experts based in London. Care was taken to select experts representing a range of experience, specialization, and perspectives within the construction industry.

The engagement with these experts brought a valuable layer of authenticity to the research findings. Their practical insights, derived from hands-on involvement in various construction projects, offered nuanced perspectives on the external wall systems' selection criteria, considerations, and evolving trends. The experts' input not only validated the trends observed through observation but also provided insights into the intricacies of decision-making processes behind external wall choices.

The insights acquired through these interviews played a pivotal role in forming the foundational framework for developing comprehensive scenarios involving commonly utilized external wall systems. Additionally, the interviews shed light on two recently adopted systems in the UK with substantial potential for widespread utilization across the country, further enriching the research's applicability and relevance.

By incorporating direct insights from construction professionals, this research was able to bridge the gap between observational data and practical considerations, yielding a more robust and holistic perspective on the prevailing external wall construction landscape in the UK.

Subsequently, this compiled list was categorized into three primary segments:

- **Traditional systems**, which have been in use and constitute a significant portion of existing buildings.
- **New construction systems**, which align with the construction of the majority of recently erected buildings.
- **Industrial systems**, representing more intricate forms of external wall construction that necessitate skilled labour or innovative technology, offering the potential to address energy loss concerns.

This approach was formulated to inclusively cover both well-established and emerging building envelope materials.

Subsequently, each of these systems was regarded as a distinct scenario, thereby forming the basis for further analysis. In the subsequent phases, each scenario is scrutinized with respect to both cost and energy considerations. A concise overview of each of these scenarios can be found on the subsequent pages.

Scenario 1

Traditional Wall (Solid brick wall + Plasterboard)

Solid brick walls have been a staple of British architecture for centuries, tracing back to the ancient art of brickmaking and masonry. This enduring construction technique reflects the craftsmanship of past generations, contributing to the iconic brick façades that characterize many British neighbourhoods. The use of solid brick walls in residential construction emerged during eras when energy efficiency was not a primary concern, making them emblematic of a bygone era's architectural sensibilities. However, as energy awareness and sustainability have gained prominence, the limitations of this approach have become more apparent.

While this traditional approach possesses merits such as aesthetic appeal and structural stability, it may present challenges in terms of energy efficiency due to limited insulation capacity, potentially leading to higher energy consumption for heating during colder periods. The interplay between the established strengths and potential limitations of this traditional wall construction makes it a compelling subject of analysis within the scope of this research. In the following, Figure 3 depicts a cross-section of a traditional wall system featuring solid brick and plasterboard as internal finishes, which has been created by the author.

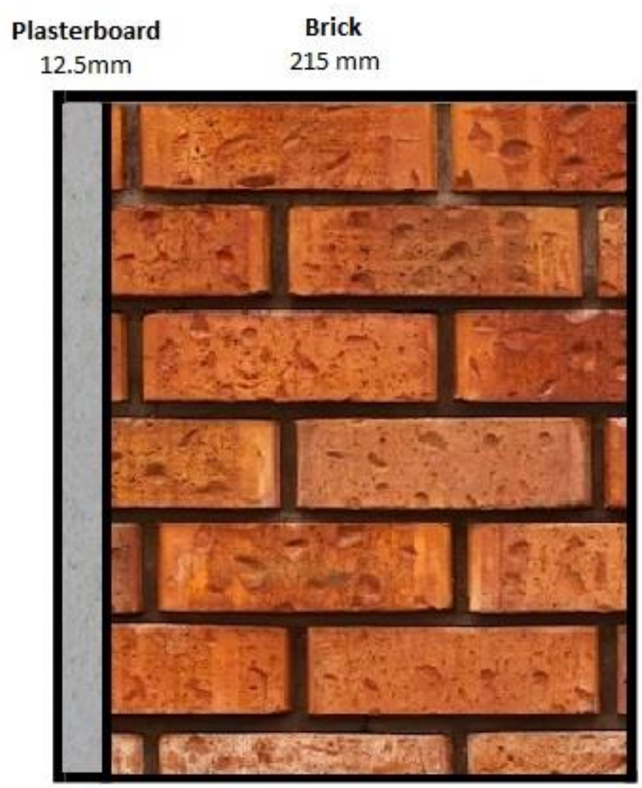

Figure 3 – Cross section of the traditional solid brick wall system

Scenario 2

Insulated Traditional Wall (solid brick wall + Rockwool + Plasterboard)

The "Insulated Traditional Wall" scenario, a refined iteration of the classic solid brick wall construction in the UK, marries historical resonance with contemporary energy-consciousness. Rooted in a legacy of solid brick craftsmanship steeped in British architectural heritage, this scenario introduces Rockwool insulation as innovative enhancement. These additions address a pivotal energy efficiency concern that the traditional solid brick wall encounters, presenting a robust solution to curb thermal losses. By leveraging modern insulating technology, this scenario endeavours to reduce energy consumption for heating during colder periods, thus aligning traditional aesthetics with progressive sustainability imperatives.

Figure 4 illustrates a cross-section of an insulated traditional wall system, which includes solid brick, a 50 mm rockwool insulator layer, and plasterboard as internal finishes, which has been created by the author.

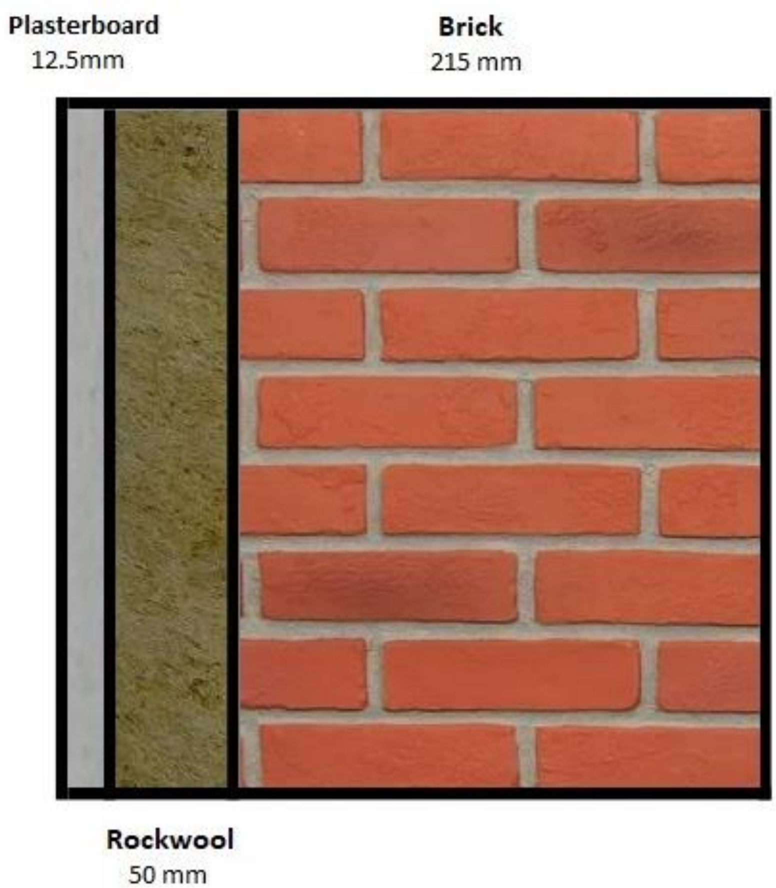

Figure 4 – Cross section of the insulated traditional solid brick wall system

Scenario 3

Cavity Wall (Half Brick Wall + rockwool + Half Brick Wall + Plasterboard)

This scenario strategically employs a dual-layered arrangement, leveraging the durability of half brick walls on either side. The incorporation of Rockwool insulation within the cavity serves as a pivotal measure to counter heat transfer, contributing to improved thermal performance. This approach also enhances the acoustic insulation attributes of the wall, potentially fostering a quieter indoor environment.

By fusing the classic qualities of brick with modern insulating technology, the "Cavity Wall" scenario addresses the energy loss challenges often associated with single-layered walls. The Rockwool insulation plays a vital role in reducing heat conduction across the wall assembly, thus aiming to decrease energy consumption for heating. With this integration of traditional and contemporary elements, the "Cavity Wall" scenario aligns itself with the evolving demands of energy-efficient residential construction, forging a path towards a harmonious equilibrium between tradition and innovation. Figure 5 presents a cross-section of the brick cavity wall system, which has been crafted by the author.

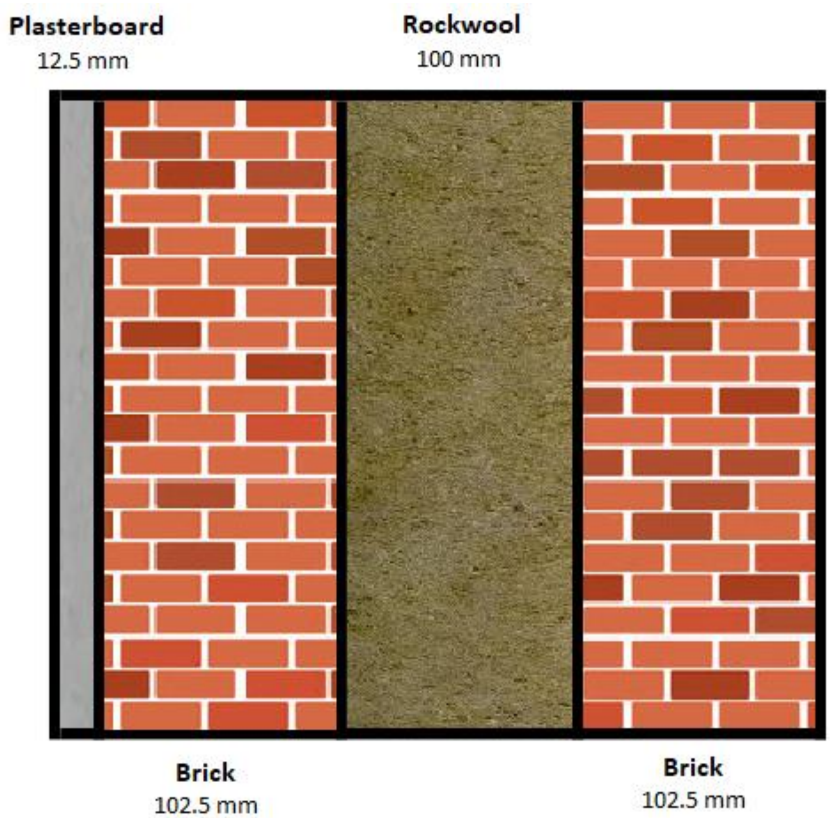

Figure 5 – Cross section of the brick cavity wall system

Scenario 4

Cavity Wall (Render + High Density Concrete Block + Phenolic Cavity Insulated Board + Low Density Concrete Block + Plasterboard)

The "Cavity Wall" scenario presents a distinctive departure from the conventional approaches seen in UK residential construction. This innovative configuration embraces a multi-layered composition designed to optimize energy efficiency and comfort. At its core, the scenario incorporates a combination of high-density concrete blocks, phenolic cavity insulated boards, and low-density concrete blocks, all strategically sequenced within the wall assembly. This meticulous arrangement aims to create an effective thermal barrier, minimizing heat transfer and enhancing insulation performance. Additionally, the application of render on the exterior surface adds a protective layer, contributing to weather resistance and visual appeal.

The integration of various materials in the "Cavity Wall" scenario serves to address energy loss concerns inherent in single-layered walls. By utilizing specialized insulation components like phenolic cavity insulated boards, this configuration effectively minimizes thermal bridging and optimizes insulation capacity. This holistic approach to energy efficiency aligns with modern sustainability objectives, making the "Cavity Wall" scenario a compelling avenue for exploration within the context of cost-effective and environmentally conscious residential construction. Figure 6 displays a cross-section of the concrete block cavity wall system, which has been crafted by the author.

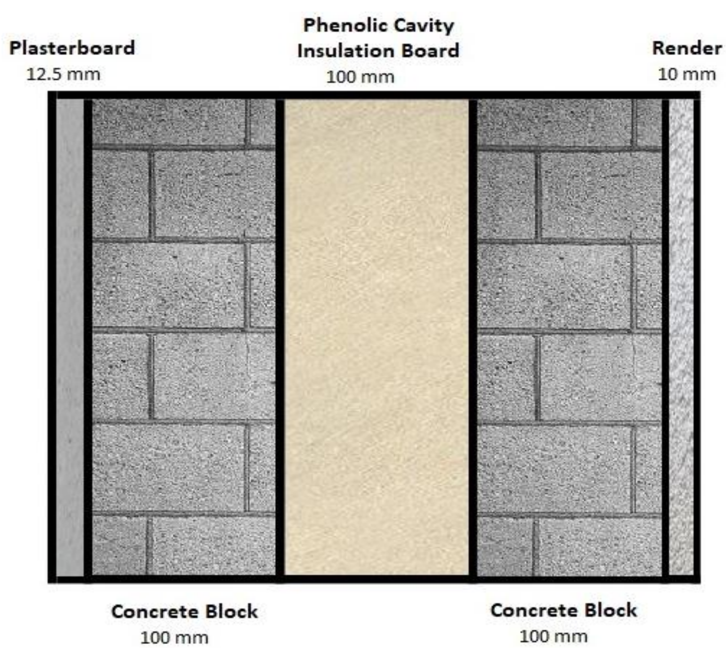

Figure 6 – Cross section of the concrete block cavity wall system

Scenario 5

Insulated concrete form (ICF) System

The "Insulated Concrete Form (ICF) System" scenario introduces a revolutionary approach to residential construction that places energy efficiency at its core. Departing from traditional methodologies, this system employs interlocking foam panels that serve as molds for poured concrete. These panels are designed with built-in insulation, contributing to a thermal envelope that significantly minimizes heat loss.

The ICF System presents an amalgamation of structural integrity and insulation prowess. The foam panels not only provide a stable framework but also create a continuous layer of insulation that envelops the structure. This seamless integration enhances energy efficiency, minimizing the need for excessive heating or cooling. Additionally, the ICF System offers noise reduction benefits, promoting a quieter indoor environment.

In embracing the ICF System, residential construction ventures beyond the familiar, embracing a contemporary paradigm that emphasizes sustainability. The insulation embedded within the system aligns with modern energy efficiency imperatives, potentially leading to reduced energy consumption and long-term cost savings. This scenario, with its innovative foundation, underscores the industry's strides toward innovative and eco-conscious building techniques. Figure 7 displays a Cross section of the Insulated concrete form (ICF) wall System, which has been drafted by the author.

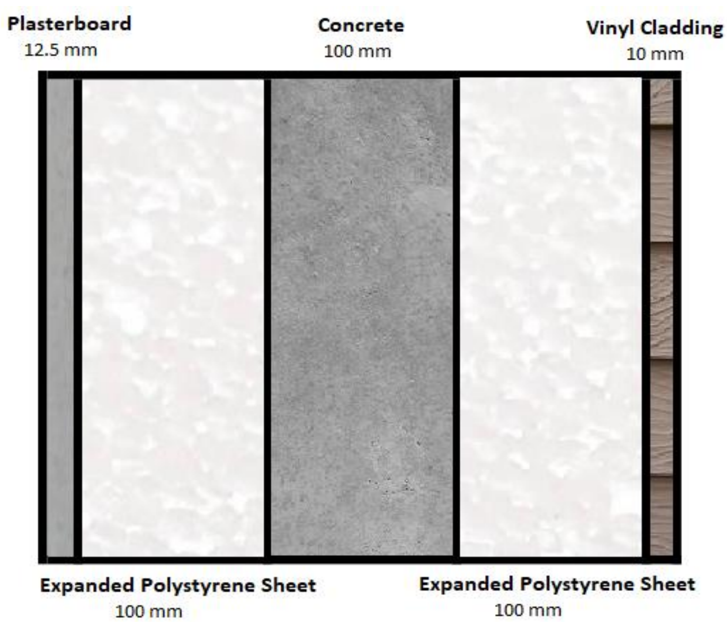

Figure 7 – Cross section of the Insulated concrete form (ICF) wall System

Scenario 6

Structural insulated panels (SIPs) System

The "Structural Insulated Panels (SIPs) System" introduces a cutting-edge approach to residential construction that emphasizes both structural integrity and energy efficiency. This innovative system replaces conventional framing with panels that integrate insulation between two layers of engineered materials.

SIPs offer a seamless blend of strength and thermal performance. The core insulation serves as a continuous barrier, effectively reducing heat transfer and minimizing energy loss. The interlocking design of SIPs ensures airtightness, further enhancing the system's ability to maintain a comfortable indoor environment.

By adopting the SIPs System, residential construction takes a forward leap into the realm of advanced building techniques. The integration of insulation directly into the structural elements aligns with modern energy efficiency goals, potentially translating into lower energy consumption and subsequent cost savings over time. This scenario underscores the industry's commitment to innovation and sustainability, offering a glimpse into a future where architectural prowess and environmental consciousness seamlessly coexist. Figure 8 displays Cross section of the Structural insulated panels (SIPs)wall System, which has been drafted by the author.

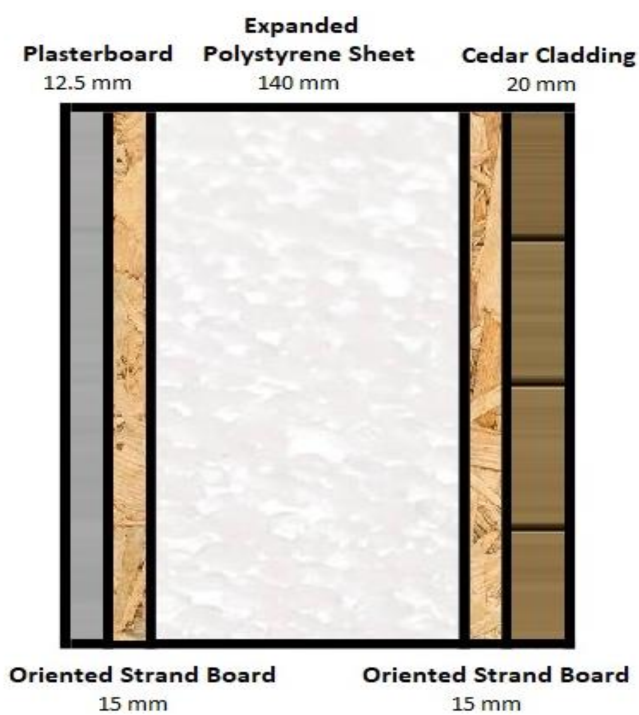

Figure 8 – Cross section of the Structural insulated panels (SIPs)wall System

5-2 Building Case Specification

For the purpose of this study, a typical four-bedroom residential building located in Kingston upon Thames within the Greater London area, United Kingdom, was chosen. The house, covering an area of 245 square meters, served as the primary model for analysis.

The cooling system adopted for the house entails the use of fans, providing effective temperature regulation. On the other hand, the heating system is based on a modern boiler, designed to efficiently maintain a comfortable indoor environment. These choices were influenced by the prevailing climate conditions and energy infrastructure in the London area.

In Figure 9 and 10, the floor plan and a 3D view of the selected house are presented, both of which were produced using the Autodesk Revit software.

Figure 9 – Floor plan of the selected building

Figure 10 – 3D view of the selected building

5-3 Wall Construction Cost

BIM-based 3D models of various building scenarios were developed, utilizing Autodesk Revit software. These models were designed with a level of detail of 300, encompassing comprehensive material specifications and the air conditioning system of the building.

For accurate volume assessments of different envelope materials, BIM technology was harnessed for material quantity take-off. The construction costs of different adopted scenarios were estimated based on the extracted quantities and prices for different scenarios. Table 1 outlines the estimated construction costs of different wall scenarios.

In the course of conducting cost estimation for the project, the author sought to acquire contemporaneous and precise data regarding material costs. To achieve this, the author referenced the websites of renowned construction material retailers in the United Kingdom, namely Jewson and B&Q. These retailers boast an extensive network of branches spanning across nearly every city within the country, thus ensuring access to the most current pricing information.

Given the project's location in Kingston upon Thames, the author took deliberate steps to ascertain the presence of Jewson and B&Q branches in the vicinity. This strategic consideration was undertaken with the specific objective of eliminating transportation costs from the overall cost estimation process.

To gain a more comprehensive insight into the intricacies of the cost estimation, unit price of each used material are compiled from introduced construction material retailers websites. These detailed documents are accessible in the appendix section for reference and in-depth analysis.

No	Material Cost	Labour Cost	Overall Construction Cost
Scenario 1	£22,678	£13,540	£36,218
Scenario 2	£25,002	£14,040	£39,042
Scenario 3	£27,340	£17,479	£44,819
Scenario 4	£15,661	£9,900	£25,561
Scenario 5	£25,424	£7,000	£32,424
Scenario 6	£15,176	£8,500	£23,676

Table 1 – The estimated construction cost of each scenario

- Across the spectrum of scenarios that were analysed, the Structural Insulated Panel (SIP) system emerged as the most economically favourable choice. This noteworthy discovery underscores the cost-effective nature of the SIP system concerning construction expenses in comparison to the other scenarios under examination. Particularly noteworthy is the substantial cost reduction of over 35 percent when juxtaposed with the base scenario, which involves the utilization of solid brick walls (Scenario 1). The rationale behind the lower labour costs associated with the SIP system lies in its modular composition, which can be transported to the site and assembled with minimal labour through the use of adhesives. In contrast, traditional wall construction methods require more time and incur higher costs.

- Scenario 5, utilizing the Insulated Concrete Form (ICF) System, may not be an immediate optimal choice considering construction expenses. However, the following energy analysis section investigates its potential effectiveness in terms of energy efficiency. This analysis seeks to determine whether the ICF System, despite its initial cost implications, provides a viable solution that aligns with long-term energy-saving objectives.

- Scenario 4, which utilizes a cavity wall constructed with concrete blocks, emerged as an economically viable choice. This finding aligns with current construction trends, as this configuration is widespread in new building projects, attesting to its cost-effectiveness.

- Additionally, it's noteworthy to mention that the cavity wall system of Scenario 4 presents a significant cost reduction of over 30 percent when compared to the base scenario of solid brick wall construction (Scenario 1). This substantial decrease in construction costs underscores the economic viability of the cavity wall system, thereby positioning it as an attractive option for external wall construction.

- Scenario 1 and Scenario 2, characterized by solid brick walls without insulation and walls with minimal insulation, respectively, present suboptimal choices in terms of construction costs. The labour-intensive nature of traditional construction methods and the need for additional materials in these scenarios result in elevated overall construction expenditures. When compared to more advanced construction techniques and integrated insulation systems, Scenario 1 and Scenario 2 demonstrate a comparative cost disadvantage, highlighting their inefficiency in achieving cost-effective outcomes.

- Among the evaluated scenarios, Scenario 3, which incorporates a cavity wall constructed with bricks, emerged as the most expensive choice for external wall construction. While bricks are generally considered cost-effective, the higher material requirement per square meter of wall for this scenario compared to using concrete blocks led to a less cost-efficient construction process.

Figure 11 provides a visual representation of the data presented in Table 1, illustrating the construction cost of each scenario. This graphical representation offers a clear and concise depiction of the comparative material and labour costs associated with the different scenarios examined.

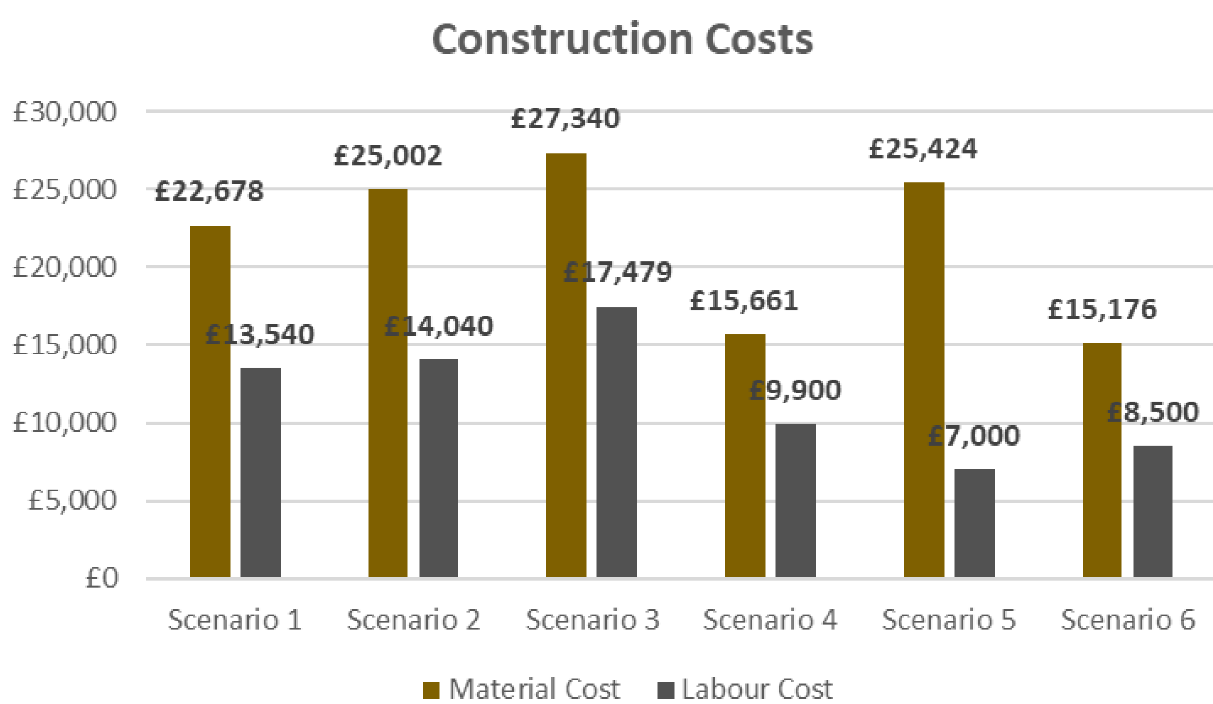

Figure 11 – Construction cost Distribution of each scenario

5-4 Energy Consumption Simulation

The thermal specifications inherent to the selected construction materials were meticulously sourced from the appropriate references and seamlessly integrated into the BIM models. To facilitate the simulation of energy performance for the buildings, the research opted for Autodesk® Green Building Studio software—a tool well-aligned with BIM models.

Incorporating the thermal attributes of materials and the spatial dimensions of the building, the simulation software harmoniously merged data from the BIM model. Regional climate data was sourced from the Hounslow weather station, identified by station code 142643 in London. A detailed depiction of this weather station's specifications, including location, monthly temperature variations, and wind speeds, is depicted in Figure 12, 13, and 14 which have been generated by Autodesk® Green Building Studio.

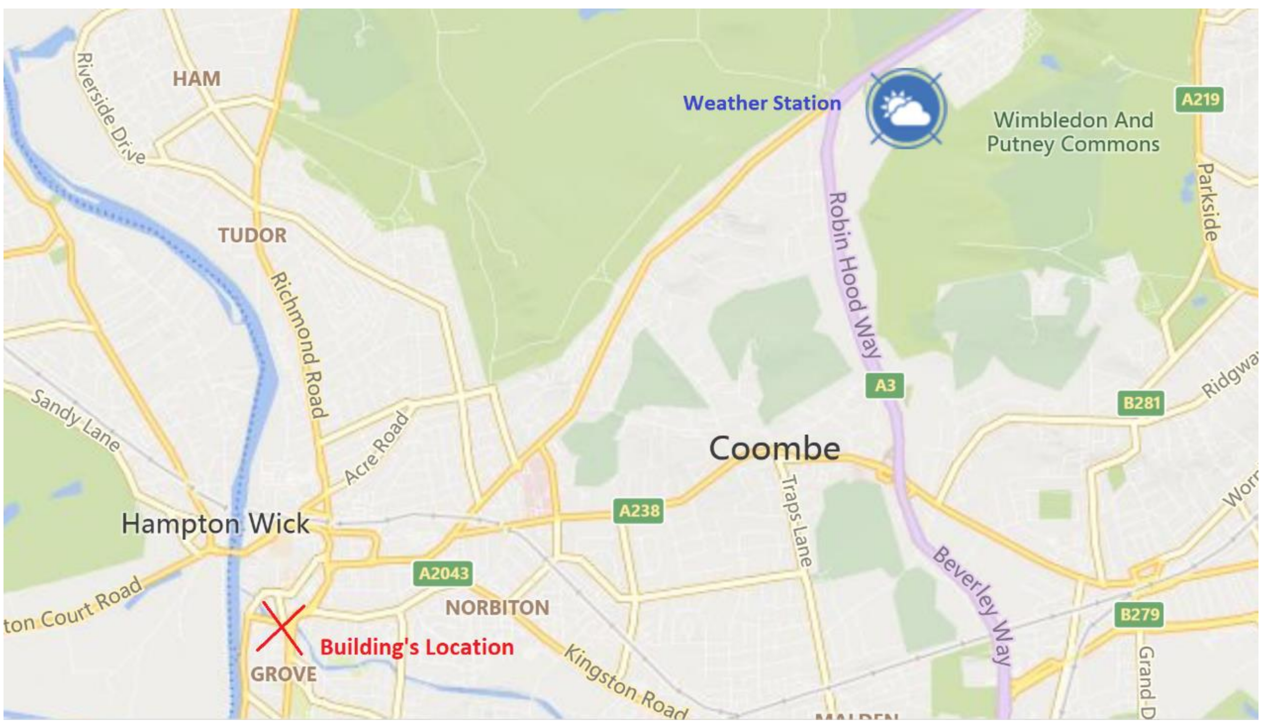

Figure 12 – Weather station and the building's location generated by Autodesk® Green Building Studio

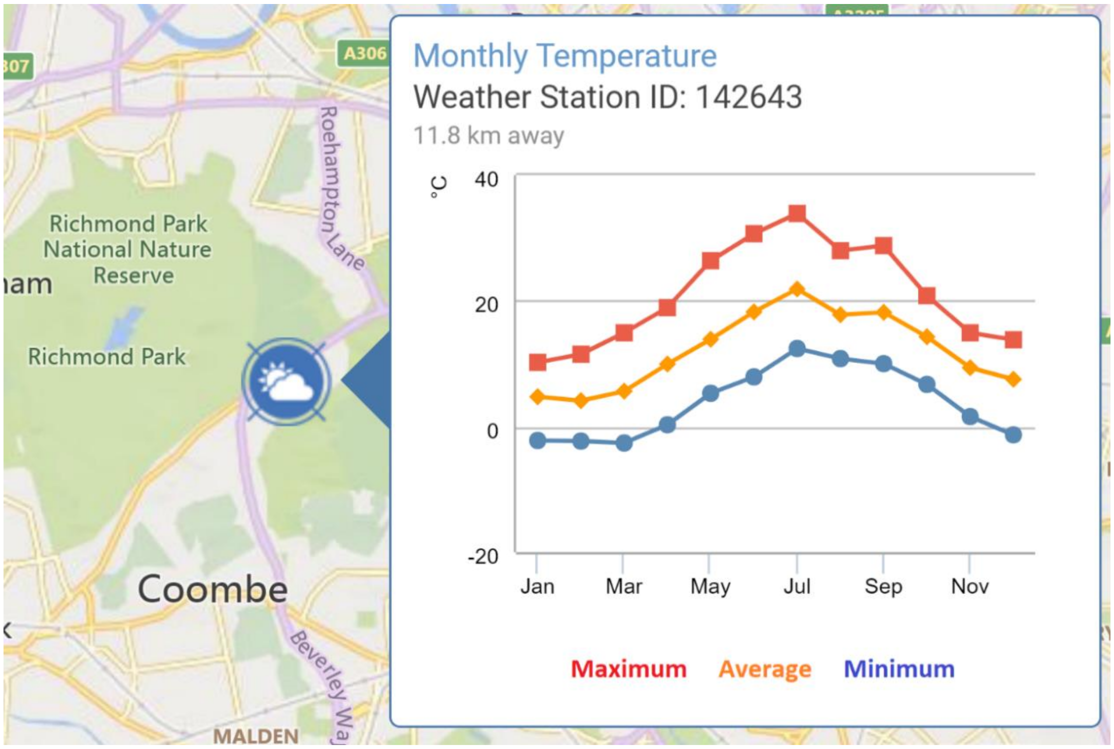

Figure 13 – Monthly temperature of the weather station generated by Autodesk® Green Building Studio

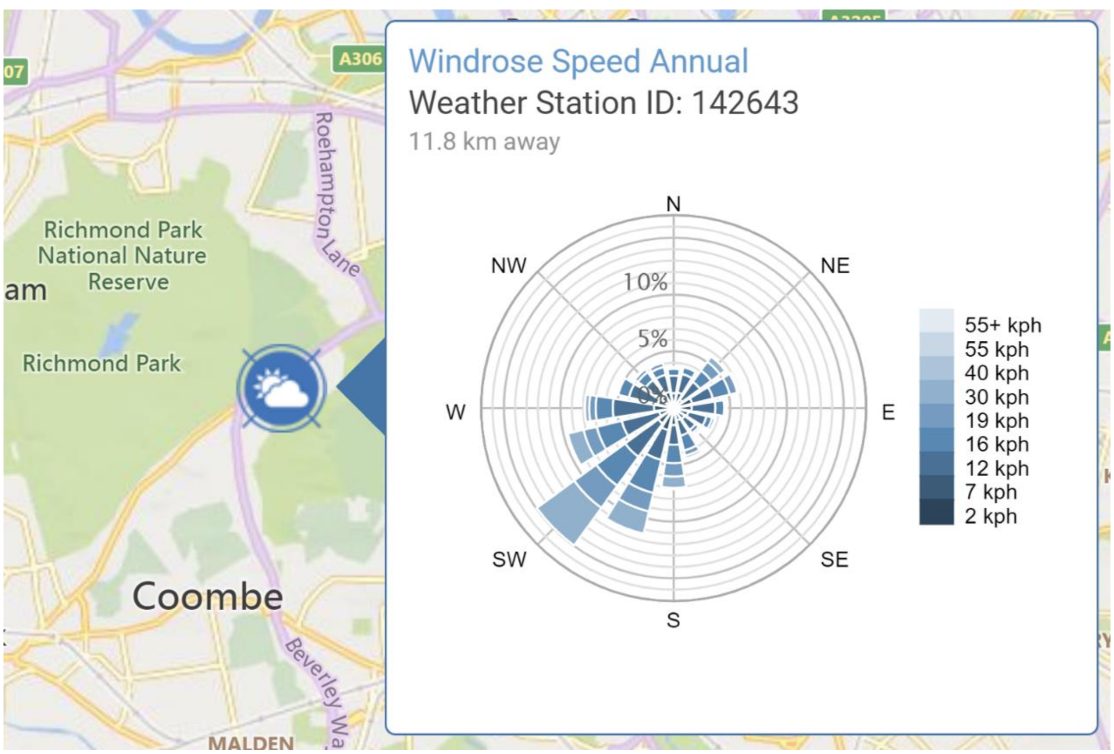

Figure 14 – Annual wind speed of the weather station generated by Autodesk® Green Building Studio

Subsequently, leveraging the power of BIM-based energy simulation software, monthly energy consumption projections for each distinct building scenario during operational phases were established. The extracted thermal specifications of the chosen construction materials are thoughtfully presented in Table 2, while table 3 and figure 15 present a comprehensive breakdown of monthly electricity and natural gas consumption generated by Revit for the varied scenarios.

Production Method	Scenario	Total Thickness (mm)	Thermal Resistance (R) (m^2.k)/W	Thermal Mass kJ/(m^2.k)
Traditional	1	227.5	0.4174	291.48
	2	277.5	1.888	298.58
New Construction	3	317.5	3.3453	294.55
	4	322.5	5.7626	332.52
Industrial	5	332.5	6.8818	170.01
	6	262.5	6.0105	80.76

Table 2 – Thermal properties of different scenarios

Thermal mass is a material's resistance to change in temperature. Thermal mass is crucial to good passive solar heating design, especially in locations that have large swings of temperature from day to night.

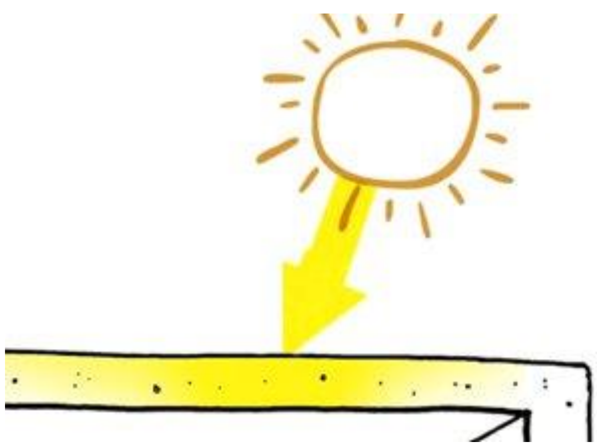

Figure 15 - Thermal mass can store energy absorbed from the sun and release it over time. Conversely, it can resist heating up too fast from solar radiation.

Objects with high thermal mass absorb and retain heat, slowing the rate at which the sun heats a space and the rate at which a space.

Thermal Resistance, often denoted as R-value (where R-value equals 1/U), quantifies a material's capacity to impede the flow of heat. It serves as a measure of how efficient a given material functions as an insulator. In practical terms, a higher R-value signifies that a wall or material possesses enhanced resistance to the dissipation of energy, thereby making it more effective at conserving heat and reducing energy loss.

Months	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
Jan	4,069	-	2,177	-	1,810	-	1,595	-	1,512	-	1,466	-
Feb	3,747	-	1,961	0	1,614	0	1,412	0	1,359	1	1,293	1
Mar	2,124	1	897	7	643	6	517	8	553	13	517	14
Apr	636	11	192	45	78	49	48	56	106	67	89	70
May	93	63	6	119	0	130	-	140	2	144	1	148
Jun	0	166		210		218		224	-	225	-	227
Jul		245		273		278		282	-	281	-	283
Aug	0	198		233		241		246	-	246	-	246
Sep	74	77	10	116	0	125	0	132	3	135	2	137
Oct	734	2	183	16	82	19	48	24	83	29	71	30
Nov	3,132	-	1,568	-	1,254	0	1,074	0	1,032	0	993	0
Dec	4,829	-	2,687	-	2,275	-	2,031	-	1,932	-	1,863	-
Total	19,440	763	9,681	1,019	7,756	1,066	6,724	1,113	6,582	1,141	6,297	1,156

Table 3 –Monthly electricity and natural gas consumption for each scenario generated by Autodesk® *Revit*

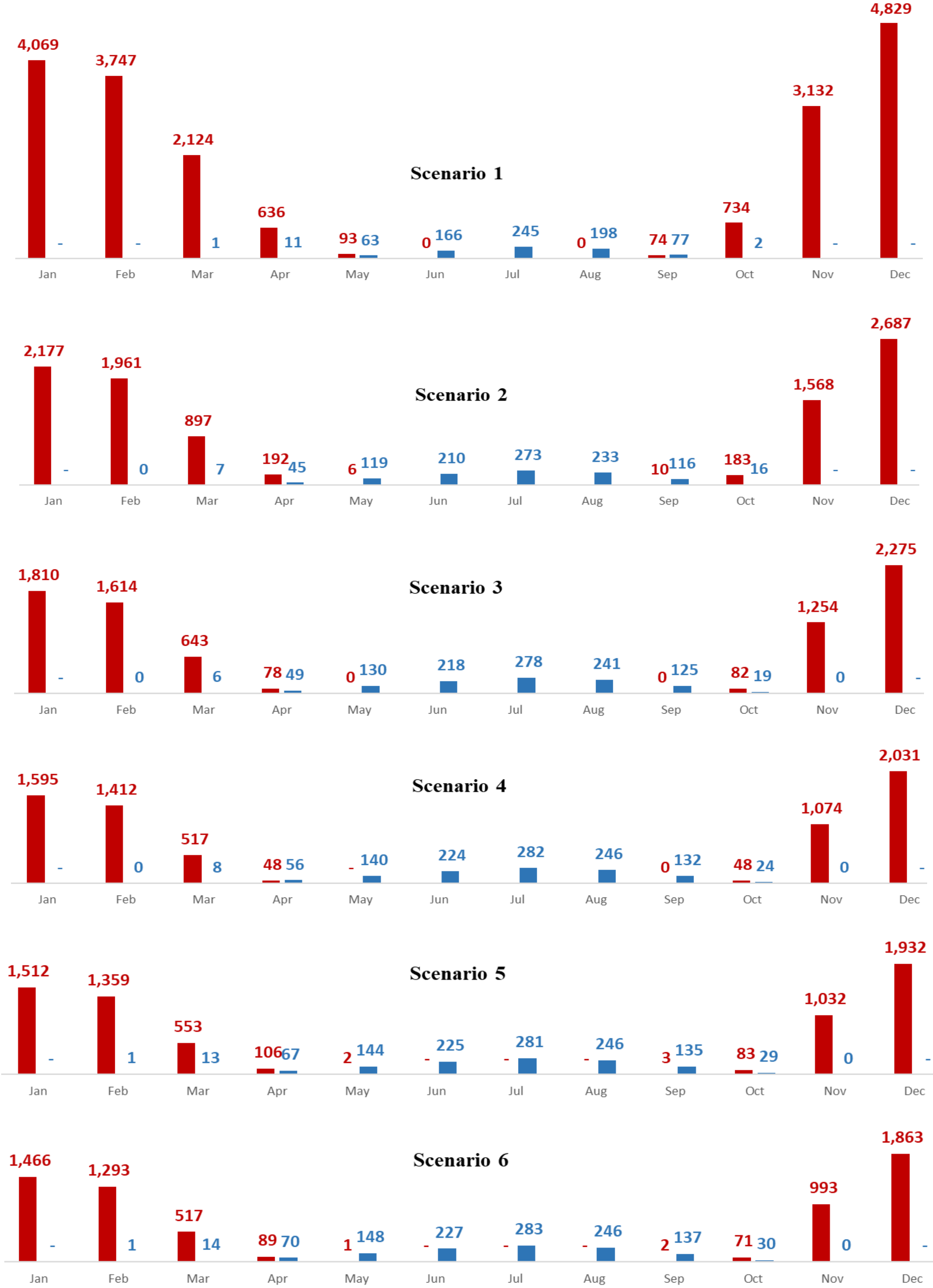

Figure 16 – Monthly electricity and natural gas consumption for each scenario

- An intriguing finding emerges from Scenario 1, where solid brick walls were utilized. This scenario revealed the highest overall energy consumption among the six distinct scenarios. This elevated energy consumption in Scenario 1 can be primarily attributed to significant natural gas usage for heating purposes. It's noteworthy that Scenario 1 also exhibited the lowest electricity consumption for cooling, which may indicate a relatively cooler indoor environment compared to the other scenarios.

- Scenario 2, which presents an insulated version of Scenario 1, offers a compelling insight. The inclusion of rockwool insulation in this scenario leads to a remarkable reduction of over 50 percent in energy expenditures. This finding underscores the substantial energy-saving potential that effective insulation strategies, such as rockwool, can bring to building performance, highlighting the significance of insulation in achieving significant energy bill reductions.

- Additionally, the results of Scenarios 5 and 6 are intriguing, as they embody industrial attributes and are conceived with a strong focus on energy conservation. These scenarios notably exhibited the lowest total energy consumption, indicating the efficacy of incorporating advanced energy-efficient concepts into building design for achieving significant energy savings.

- Scenario 3, featuring a brick cavity wall with a two-layer leaf and insulation in between, reveals a noteworthy finding. This scenario demonstrates that the utilization of a double layer of brick, along with insulation in the middle, is more effective in terms of energy performance than a wall with the same thickness but comprising only a single layer of leaf and insulation. Notably, Scenario 3 exhibits a substantial energy bill reduction of over 17 percent compared to Scenario 2, further emphasizing the importance of strategic wall design in achieving significant energy savings.

- Scenario 4, characterized by a concrete block cavity wall configuration, exhibited notably efficient energy consumption patterns. This scenario underscores an interesting observation: despite bricks having inherently higher thermal resistance than concrete blocks, the incorporation of Phenolic Cavity Insulated Board in the wall construction resulted in a remarkable energy consumption reduction of over 12 percent. This finding emphasizes the pivotal role of insulation materials in shaping energy efficiency outcomes.

5-5 Energy Consumption Cost

The UK government oversees and enforces regulations concerning the pricing and distribution of electricity and natural gas across various regions and seasons within the country. The floor unit prices for these utilities vary based on geographic location and payment methods. On average, the cost stands at approximately 34p per kilowatt-hour (kWh) for electricity and around 10.3p per kWh for gas.

Hence, the projected monthly energy consumption derived from BIM-based energy simulation software served as the basis for estimating the corresponding energy costs associated with the building. A comprehensive overview of the annual energy consumption costs across various scenarios is presented in Table 4. Additionally, Figure 16 visually represents the annual energy consumption outcomes determined through BIM-based energy simulation software.

No	Natural Gas Cost	Electricity Cost	Total Energy Cost
Scenario 1	£2,011	£261	£2,272
Scenario 2	£1,001	£348	£1,349
Scenario 3	£802	£364	£1,167
Scenario 4	£695	£380	£1,076
Scenario 5	£681	£390	£1,071
Scenario 6	£652	£395	£1,047

Table 4 – Annual energy consumption costs of each scenario

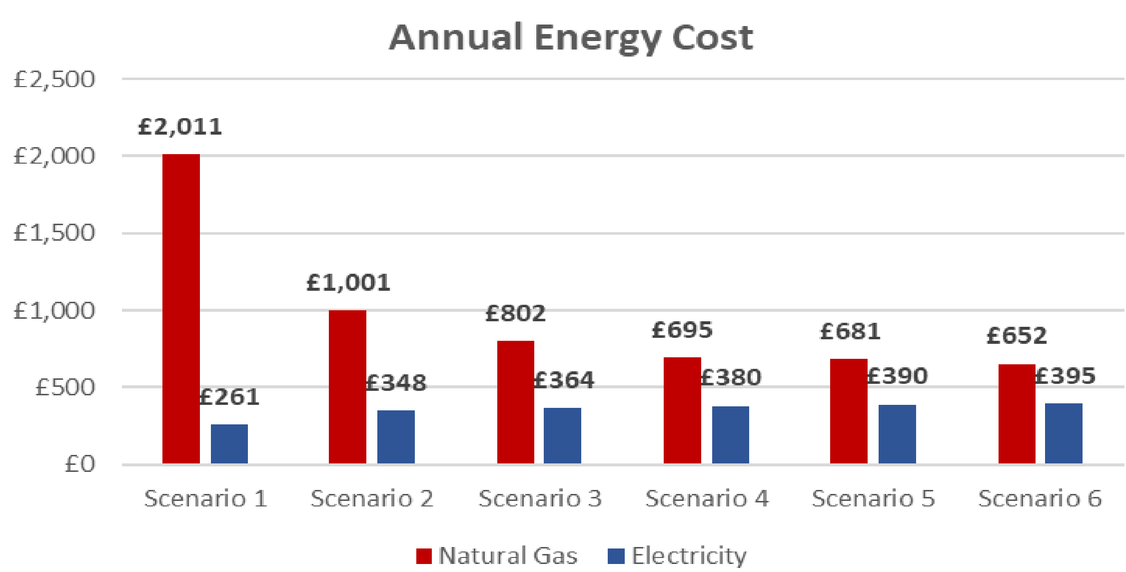

Figure 17 – Annual energy cost Distribution of each scenario

5-6 Financial Assessment

The life cycle cost assessment of the six distinct envelope scenarios was conducted through a comprehensive evaluation encompassing construction, and operational expenditures. The financial analysis captured the construction cost of walls as well as the anticipated annual energy consumption cost throughout the 75-year duration of the building's life cycle. Table 5 provides a comprehensive overview of the financial calculations across distinct scenarios. Additionally, Figure 17 visually presents the comparative ranking of these scenarios, evaluating them from various angles.

No	Overall Construction Cost	Total Energy Cost	Life Cycle Cost
Scenario 1	£36,218	£2,272	£206,583
Scenario 2	£39,042	£1,349	£140,246
Scenario 3	£44,819	£1,167	£132,313
Scenario 4	£25,561	£1,076	£106,244
Scenario 5	£32,424	£1,071	£112,728
Scenario 6	£23,676	£1,047	£102,207

Table 5 – Life cycle cost of each scenario

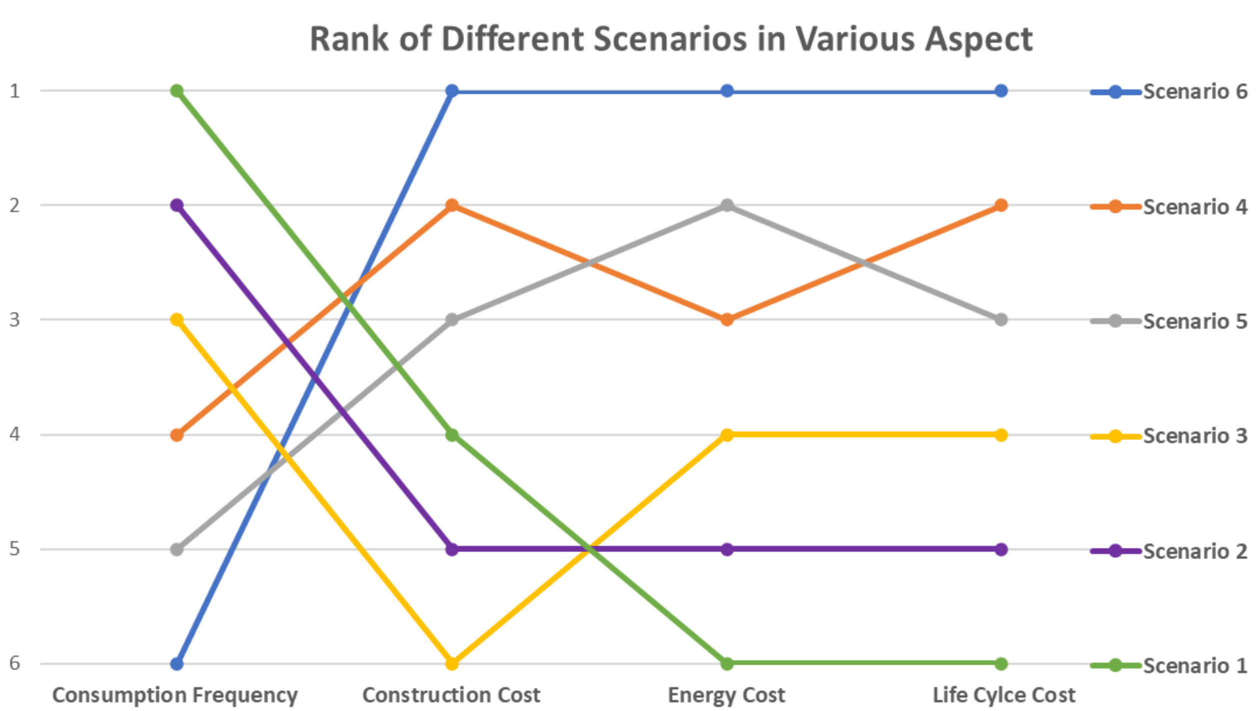

Figure 18 – Ranking of different scenarios in various aspects

The two traditional scenarios, namely the first and second, which are adopted most frequently, demonstrated the highest life cycle costs for the building envelope along with the lowest energy performance.

Scenario 6 utilizing the Structural Insulated Panels (SIPs) System, emerges with the most economical life cycle cost. Additionally, this scenario boasts the least energy consumption and construction cost compared to all other scenarios. While it occupies the 6th position in terms of frequency of adoption, indicating its limited current usage, the scenario's remarkable capacity for optimizing life cycle costs suggests promising prospects for substantially diminishing energy and construction costs for residential buildings in the UK.

The results derived from Scenario 6 underscore a noteworthy potential, indicating a potential reduction of construction costs by over 35% and a prospective decrease of more than 51% in energy consumption during the operational phase. Moreover, there is a promising possibility of lowering the overall life cycle cost of the building envelope by more than 50% in comparison to the baseline scenario (Scenario 1).

Scenario 4, employing the concrete block cavity wall system, emerges as having the second most cost-effective life cycle cost. Furthermore, this scenario ranks third lowest in energy consumption and second lowest in construction cost when compared to all other scenarios.

Utilizing a concrete block cavity wall system doesn't necessitate the latest technology, skilled labour, or complex equipment. This characteristic suggests that it could be an optimal choice for the external wall of residential buildings in the UK.

The findings from Scenario 4 highlight a substantial potential, with the potential for construction costs to decrease by over 29% and a prospective reduction of more than 49% in energy consumption during the operational phase. Additionally, there exists a promising opportunity to decrease the overall life cycle cost of the building envelope by more than 48% when compared to the baseline scenario (Scenario 1).

6- Results

The findings of this research hold substantial implications for both existing building and new construction in the UK's dynamic architectural landscape. The prevalence of solid brick walls in existing structures underscores the persistent challenge of enhancing energy efficiency in historically constructed buildings.

1- Based on the findings of this research, the **Structurally Insulated Panel (SIP)** system stands out as the most energy-efficient and cost-effective external wall option. Several factors contribute to this conclusion:

   - **Reduced Labor Costs and Construction Time:** SIPs are manufactured off-site with precise specifications, resulting in fewer on-site labour hours compared to traditional construction methods. The prefabricated nature of SIPs facilitates an efficient assembly process, as the panels arrive ready to install. This streamlined process minimizes the need for extensive on-site fabrication, thus reducing labour costs.

   - **Energy Efficiency and Long-Term Savings:** SIPs possess inherent energy-efficient qualities, attributed to their high thermal resistance and minimal air leakage. This inherent insulation leads to reduced energy consumption over the building's lifetime. Consequently, potential long-term cost savings are realized in the realms of both heating and cooling expenditures.

   - **Minimal Need for Secondary Insulation:** The integrated insulation within SIPs negates the requirement for additional insulation installation. This characteristic minimizes both material and labour costs associated with the inclusion of secondary insulation materials.

   - **Structural Integration:** SIPs possess robust structural integrity, reducing the necessity for additional load-bearing components such as extensive framing or support structures. The resulting decrease in materials and labour contributes to cost savings, making the SIP system economically viable.

In conclusion, the Structurally Insulated Panel (SIP) system presents a synergistic blend of energy efficiency and cost-effectiveness, making it a prudent choice for external wall systems in the pursuit of sustainable building practices.

2- The prevalent use of cavity walls, often with added insulation, in contemporary construction vividly illustrates the construction industry's commitment to infusing energy efficiency into modern architectural practices. This approach's twofold appeal—being cost-effective and offering substantial energy savings—makes it a compelling choice for projects of varying sizes. Additionally, the adaptability of cavity walls to different regions, along with the wide availability of concrete blocks, enhances the practicality of Scenario 4. Several key factors converge to firmly establish the Concrete Block Cavity Wall as the preferred option:

- **Affordability and Thermal Resilience of Materials:** Choosing concrete blocks is notable for its cost-effectiveness and durability. These attributes stem from their affordable procurement and ability to handle temperature changes well. This practical pairing of financial sensibility and long-lasting thermal performance strikes a balance in life cycle cost considerations.

- **Inherent Insulation:** The clever design of a cavity wall, incorporating an insulation layer between inner and outer sections, significantly boosts the wall's thermal insulation abilities. This design choice aligns with the contemporary push for energy efficiency and thermal stability.

- **Proven Effectiveness:** Concrete block cavity walls are widely used in modern construction for their practicality and proven track record. This widespread adoption underscores their reliability and effectiveness, further solidifying their appeal within the scope of life cycle cost evaluations.

In conclusion, the trajectory of cavity walls coupled with insulation embodies a strong commitment to incorporating energy efficiency into contemporary architecture. By merging economic feasibility, adaptability, and inherent thermal resilience, Scenario 4 becomes a practical choice. This strategic fusion of attributes positions the Concrete Block Cavity Wall as a prime example of a thoughtful selection—a convergence of practical materials, sustainable intent, and architectural sophistication.

7- Discussion

In recent years, the dominant choice for external walls in residential construction in the UK has been the cavity wall. This research has uncovered a significant insight into the favoured selection for new buildings in the region: the cavity wall, stands out as one of the most optimal options in terms of energy-efficiency and cost-effectiveness. This convergence of prevailing practices and research findings is truly promising, highlighting a harmonious equilibrium between industry standards and the principles of sustainable construction.

However, it is critical to address the pressing challenge posed by the existing building stock in the UK. Many of these structures feature solid brick or traditional walls lacking proper insulation, leading to substantial annual energy loss. To confront this issue, the research extends to explore the viability of enhancing energy efficiency through retrofits, particularly in relation to life cycle cost-effectiveness.

7-1 Retrofit Considerations

The endeavour to assess the cost-effectiveness of retrofitting existing brick walls unveiled intriguing findings. Two distinct options were explored for adding insulation to existing brick walls:

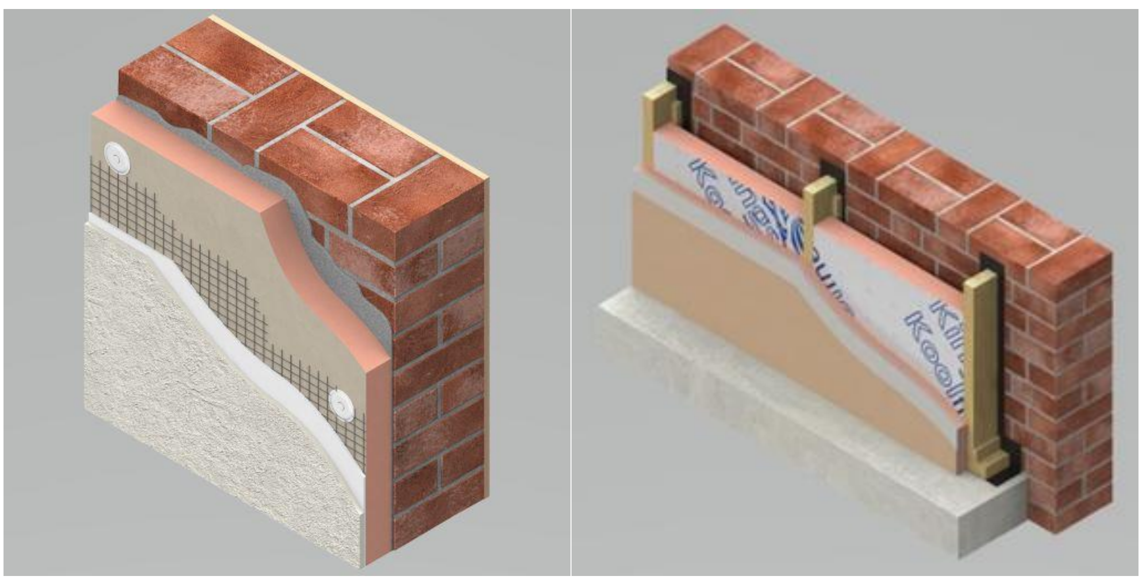

Figure 19– Wall cross section of the proposed external and internal retrofitting

1- **External Insulated Wall Board:** The application of a 100 mm external insulated wall board, affixed to the brick using bedding adhesive and mechanical fixing, and capped with a 20 mm render, was modelled and analysed using Revit.

The outcome of this refurbishment was undeniably positive: the annual energy cost demonstrated a remarkable decrease of over 52 percent. Nonetheless, it's essential to acknowledge that the cost of this approach amounts to £24,469, with a payback period of 21 years. While the energy savings are substantial, the relatively prolonged payback period might deter individuals seeking rapid returns on their investments.

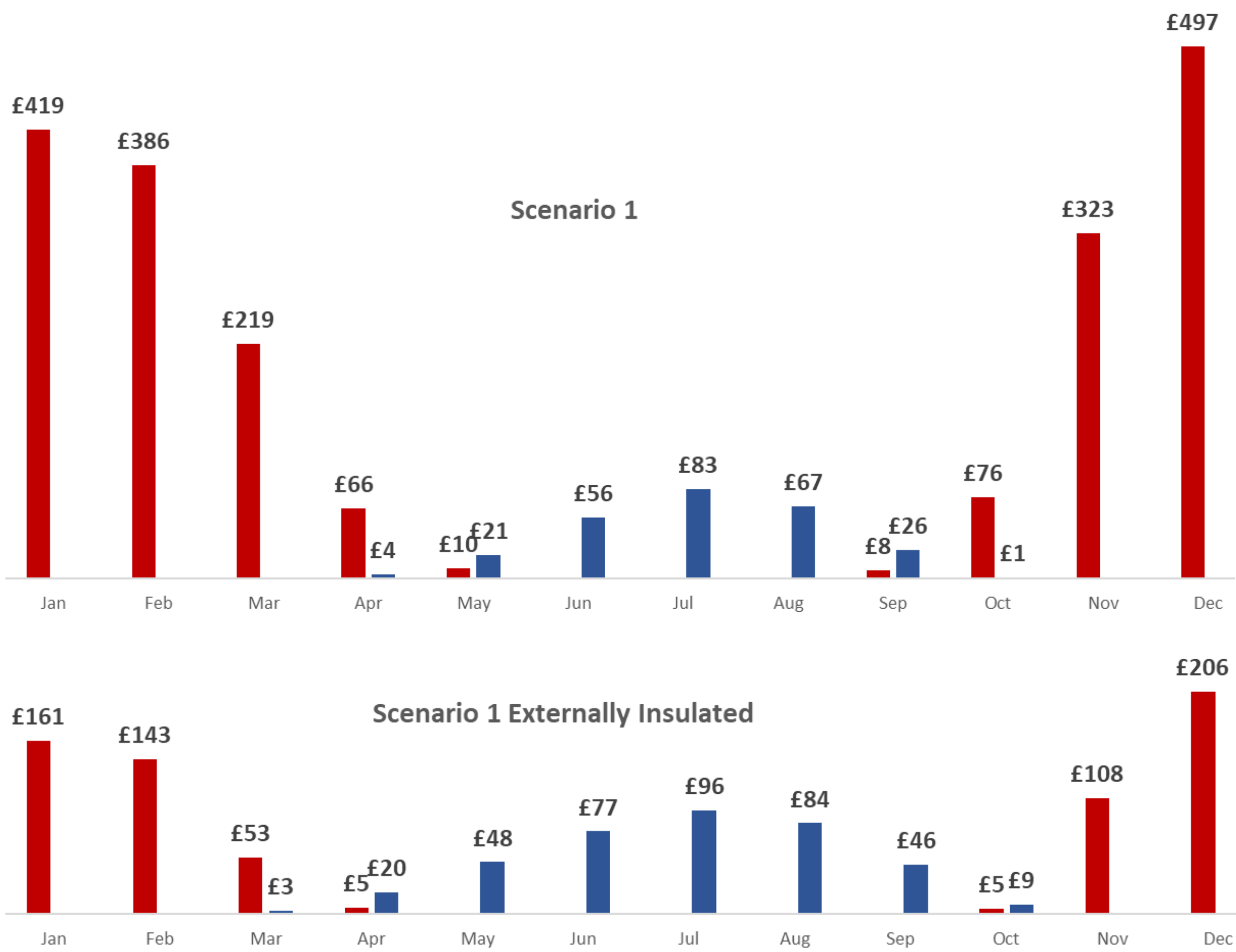

Figure 20 – Monthly electricity and natural gas consumption for scenario 1 and externally insulated wall

2- **Insulated Internal Plasterboard:** As an alternative, an internal approach was explored, involving the addition of 82.5 mm insulated plasterboard.

This method similarly yielded impressive results, with annual energy cost decreasing by over 46 percent. Remarkably, the cost of this option is significantly lower at £10,568, and the payback period is substantially reduced to 11 years. This internal approach offers a more attractive investment proposition, aligning with preferences for faster return on investment.

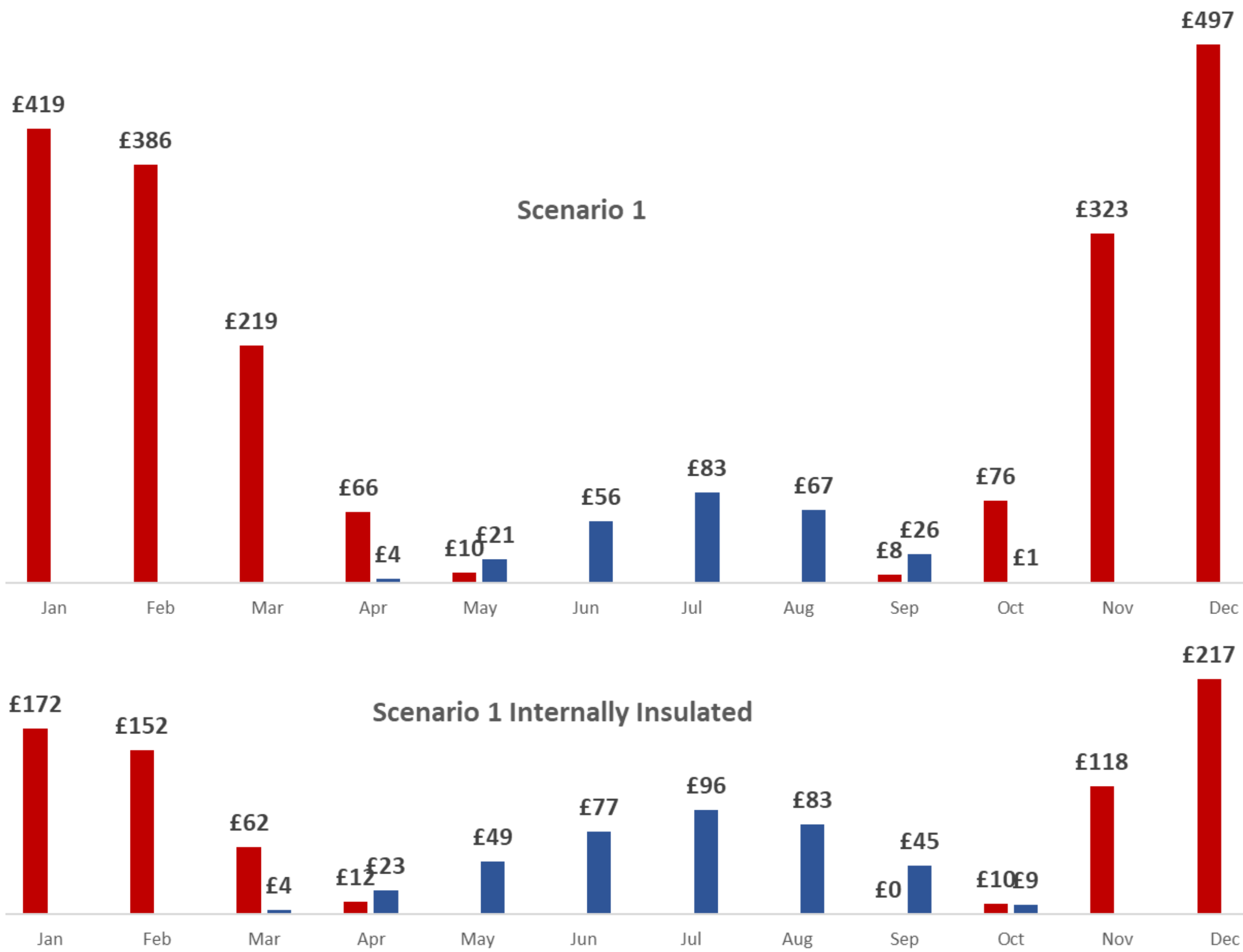

Figure 21– Monthly electricity and natural gas consumption for scenario 1 and internally insulated wall

The implications of these retrofit options extend beyond immediate financial considerations. By opting for insulated plasterboard internally, potential savings of over £75,000 can be realized over the building's life cycle, spanning 75 years. This not only emphasizes the significance of forward-looking investment decisions but also underscores the long-term financial benefits associated with energy-efficient retrofits.

In conclusion, the research underscores the harmony between prevalent practices and sustainable construction approaches in the UK. The imperative to address energy inefficiencies in existing buildings has led to the exploration of retrofit strategies, highlighting the potential of both external and internal insulation methods. The findings provide valuable insights for building owners, professionals, and policymakers as they navigate the intricacies of energy-efficient building transformations.

8- Summary and Conclusion

The building envelope, which separates the inside and outside of a structure, significantly influences a building's cost and energy performance over its life cycle. This importance has driven researchers to explore factors affecting the building envelope's performance. The rise of Building Information Modelling (BIM) in recent years has provided a way to assess and enhance building envelope performance. This study addresses the need for a clear method to help professionals identify the best building envelope system within a region throughout the building's life cycle.

Both the building envelope and weather conditions related to a specific location have a big impact on building costs and energy consumption. This research employs a structured approach that considers both the materials of the envelope and the regional conditions to find the most practical building envelopes. The study proposes a method that utilizes Building Information Modelling (BIM). Among all the building envelopes which have effect on a building’s cost and energy performance, this method identifies cost-effective and energy-efficient external wall systems based on the available wall material and weather condition specific to London, United Kingdom over the building's life cycle.

The process begins with the identification of commonly utilized external wall materials and systems in the London region through in-person interviews with construction experts. These identified materials are subsequently classified into six distinct external wall scenarios.

Autodesk Revit is utilized for the modelling of a standard four-bedroom residential building situated in the London area, United Kingdom. Employing Building Information Modelling (BIM) principles, data is systematically extracted regarding the surface areas and quantities of walls corresponding to each material within the confines of distinct wall scenarios. Subsequently, a meticulous assessment of costs, encompassing both materials and labour, is conducted for the various scenarios, culminating in the precise determination of the total construction cost for each individual system.

By employing Autodesk Revit in conjunction with Autodesk Green Building, an extensive energy analysis was conducted. This analysis facilitated the extraction of data pertaining to natural gas and electricity consumption specifically for heating and cooling within each scenario. Subsequently, utilizing the prevailing local energy rates, the monthly and annual costs associated with natural gas and electricity were calculated independently for each scenario with different thermal resistance.

In the calculation of the life cycle cost for each scenario, both energy costs and construction costs were taken into account. A comprehensive evaluation was performed to assess the strengths and weaknesses of each scenario concerning cost-effectiveness and energy efficiency. This thorough comparison allowed for a detailed analysis of the scenarios and their respective attributes in these critical aspects.

Applying this method in London, UK, reveals that the commonly used traditional walls (scenarios 1 and 2) are neither energy-efficient nor cost-efficient compared to other available wall systems.

The results reveal a noteworthy potential for enhancing energy efficiency, with an estimated 51% improvement in energy consumption, coupled with a substantial reduction exceeding 36% in initial construction expenses. This collective outcome underscores a significant 50% reduction in life cycle costs through the adoption of Structural Insulated Panels (SIPs) in lieu of conventional wall systems.

Similarly, Scenario 4 demonstrates a potential 29% reduction in construction cost with an estimated 50% improvement in energy consumption and a 48% decrease in life cycle cost by using concrete block cavity walls with insulation in between.

The findings indicate that Scenario 5, characterized by the utilization of an Insulated Concrete Form (ICF) wall system, harbours the capacity to curtail energy consumption and associated costs. However, owing to the substantial upfront construction expenses, it does not emerge as the most optimal choice over the course of the building's lifecycle.

In light of the energy inefficiency exhibited by conventional solid brick walls, this study investigates two prospective solutions for enhancing energy performance: the application of external and internal insulation to external walls during retrofitting processes. Externally applied insulation exhibits the potential to yield a substantial 52% reduction in energy costs and payback period of 21 years. Conversely, internally applied insulation demonstrates the ability to reduce energy costs by 46%, achieving a quicker payback period of 11 years. While the external insulation method appears to deliver a greater reduction in energy, an evaluation based on the payback period renders internal insulation as the more pragmatic choice.

Implementing this method can benefit various groups. Local governments can use it to recommend viable envelope materials to builders, enhancing their profits. Building residents will see lower utility bills, while society as a whole benefits from reduced energy consumption and greenhouse gas emissions.

9- Recommendations for Further Research

9-1 Expanding Building Envelope Elements

In the context of this research, the primary focus lies on external walls as the central parameter influencing energy consumption within the realm of building envelopes. However, there exists an opportunity to broaden the scope of this study, extending it beyond the sole examination of external walls.

This expansion could involve examining not only the impact of external walls but also considering other critical elements within the building envelope, including windows, roofs, doors, and floors. Incorporating these elements into the analysis has the potential to significantly enhance the precision of the energy analysis and extend the research's coverage to encompass a wider range of building envelope configurations.

By adopting this comprehensive approach, a more holistic understanding of how various elements within the building envelope collectively influence energy consumption throughout a building's life cycle can be gained. This, in turn, will enable construction industry to provide more nuanced and informed recommendations for optimizing energy efficiency in building design and construction.

9-2 Expanding Regional Analysis

In this research project, the primary focus is on London, the most populous city in the United Kingdom. The research entails conducting interviews related to the prevalent external wall systems used in this region and utilizing data from the Hounslow weather station in London for energy analysis.

However, there is potential to extend this research to encompass a more extensive geographical scope across the United Kingdom. This broader approach would involve examining major cities such as Edinburgh, Manchester, or Newcastle, each characterized by distinct weather patterns. The objective is to comprehensively evaluate the performance of building envelope materials and systems in diverse climate zones. The study can further delve into the specifics of each region, enabling the formulation of tailored recommendations for builders and policymakers.

9-3 Advanced Material Technologies

The construction industry has historically exhibited slower adoption rates of new technologies compared to other industries. Nevertheless, it remains imperative to maintain a vigilant watch on emerging building materials and construction technologies. This ongoing monitoring is essential for detecting potential revolutionary advancements in building envelopes. Consequently, comprehensive examinations should be carried out to evaluate the feasibility, long-term sustainability, and environmental implications of incorporating these materials into building designs.

9-4 Comprehensive Life Cycle Assessment

The scope of life cycle assessments for building envelope systems can be expanded by including additional factors such as environmental impacts, carbon footprint, and end-of-life considerations associated with building envelope systems.

To achieve this, it is advisable to develop a holistic model that provides a more accurate assessment of the overall impact of different systems over extended periods. This comprehensive approach will enable better-informed decisions in building design and construction, considering the full life cycle of these systems.

9-5 Retrofit Strategies for Historic Buildings

Within the context of this research, the investigation encompassed two distinct retrofitting approaches aimed at reducing energy consumption in traditional buildings, yielding encouraging results. To gain a more expansive perspective on the implications of retrofitting, it is advisable to explore specialized retrofit strategies specifically designed for historic and heritage buildings. Such structures frequently pose unique challenges owing to their architectural significance. Therefore, an inquiry into these specialized strategies is recommended to ascertain how energy efficiency can be enhanced within these edifices while concurrently preserving their historical and cultural value.

9-6 User Behaviour and Enhancing Occupant Comfort

It is recommended to investigate the impact of occupant behaviour on building envelope performance and energy consumption. This research should encompass an analysis of how occupant preferences, habits, and interactions with building systems influence the effectiveness of different envelope systems. Moreover, strategies should be developed to optimize user behaviour in order to enhance energy efficiency.

9-7 Exploring Advanced Building Information Modelling (BIM)

To advance the field, researchers should delve into the realm of advanced BIM applications and tools that harness real-time environmental data, predictive modelling, and artificial intelligence. These technologies have the potential to significantly improve the precision and efficiency of building envelope performance assessments. It is recommended to conduct a comprehensive investigation into the seamless integration of these cutting-edge BIM advancements within the construction industry.

9-8 Exploring Policy Implications and Incentives

Future research endeavours should involve a rigorous policy analysis aimed at evaluating the efficacy of government regulations and incentives in stimulating the adoption of energy-efficient building envelope systems. Additionally, it is advisable to conduct in-depth case studies focusing on regions or cities that have effectively implemented such policies, with a keen focus on identifying and elucidating best practices in this regard.

9-9 Advancing Sustainability Metrics

To keep pace with evolving sustainability objectives and certifications, it is recommended that sustainability metrics be expanded. These metrics should encompass a broader spectrum of environmental impacts, encompassing factors such as carbon emissions, resource utilization, and life cycle analysis, specifically in relation to various building envelope materials and systems. This alignment with evolving sustainability goals and certifications will enable a more comprehensive evaluation of environmental performance within the construction industry.

9-10 Long-term Building Performance Monitoring

To validate the predicted performance of recommended envelope systems, it is advisable to establish a long-term monitoring program for buildings constructed using these systems. This initiative should involve the collection of empirical data over extended periods. The objective is to refine recommendations and enhance the precision of predictions related to life cycle costs and energy savings. Such long-term monitoring will provide valuable insights into the actual performance of these envelope systems in real-world conditions.

Indeed, these recommendations collectively constitute a comprehensive roadmap for guiding future research endeavours within the domain of building envelope performance. Through diligent exploration of these avenues, researchers and industry experts can contribute to the advancement of sustainable, economically viable, and energy-efficient buildings.

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11- Appendix 1 (Material Costs)

The unit costs for all materials were sourced from two reputable construction material retailers in the United Kingdom: Jewson and B&Q. To enhance cost efficiency, the author conducted a comprehensive evaluation of the project's location in Kingston upon Thames, confirming the proximity of Jewson and B&Q branches. This strategic decision was made with the specific goal of minimizing transportation costs in the overall cost estimation process. Subsequently, the rates for each material used in the research are provided directly from the respective websites of these suppliers.

Brick

The cost per brick ranges from £1.08 to £2.04, with each pallet containing 500 bricks priced at £350.

Sand

Each 25kg bag of sand is available at prices ranging from £3.67 to £6.04, and there is also the option to purchase sand in bulk, with 850 kg priced at £59.75.

Cement

Each 25kg bag of Ordinary Portland Cement (OPC) is priced at £6.59.

Rockwool Insulation

- Rockwool insulation with a thickness of 50 mm and covering an area of 6.48 m² is available at prices varying between £44.05 and £51.13. On average, the cost per square meter (m²) can be estimated at £7.34.
- Rockwool insulation with a thickness of 100 mm and covering an area of 2.88 m² is available at prices ranging from £35.05 to £53.92. On average, the cost per square meter (m²) can be estimated at £15.45.

Plasterboard

Plasterboard with a thickness of 12.5 mm and covering an area of 2.88 m² is available at prices varying from £4.13 to £5.49. On average, the cost per square meter (m²) can be estimated at £1.67.

Metal Frame

A Drylining Metal Frame C Stud with a thickness of 50mm and a length of 2.4m is priced at £4.58.

Concrete Block

Each concrete block is priced at £2.15, and a pallet containing 72 bricks is available for £139.

Phenolic Cavity Insulated Board

- The Kingspan Kooltherm K108 Cavity Insulation Board, with the thickness of 100 mm and a coverage area of 2.7m², is priced at £25. On average, the cost per square meter (m²) is approximately £9.26.
- The Kingspan Kooltherm K108 Cavity Insulation Board, with the thickness of 50 mm and a coverage area of 2.7m², is available for £15. On average, the cost per square meter (m²) is approximately £5.56.

Polystyrene Insulation EPS70

Polystyrene Insulation EPS70 with a thickness of 100 mm and a coverage area of 2.88m² is priced at £84. On average, the cost per square meter (m²) is approximately £29.16.

Ready-mixed concrete

Ready-mixed concrete is priced at £100 per cubic meter, and this cost includes transportation to the construction site.

SIP Panel

Structural insulated panels with dimensions of 230x1200x3000 mm and a coverage area of 3.6m² are priced at £205.

Render

A 25kg tub of thin coat organic resin render, with a coverage area of 10 square meters, is priced at £86.