

COMPARATIVE EVALUATION OF FAÇADE SYSTEMS BASED ON ENERGY PERFORMANCE AND EMBODIED CARBON USING BIM-BASED SIMULATION

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ABSTRACT

Façade design plays a critical role in reducing both operational energy demand and environmental impacts of buildings. In recent years, increasing attention has been given to life cycle-oriented approaches that jointly consider operational and embodied carbon emissions. This study presents a comparative assessment of five façade scenarios—base masonry wall, externally insulated wall (ETICS), curtain wall, double-skin façade, and enhanced ETICS with shading—applied to a representative office building located in a Mediterranean climate context.

Building energy performance was evaluated through BIM-based simulations using Autodesk Revit and OpenStudio, focusing on annual heating and cooling energy consumption. In parallel, a carbon assessment was conducted using the Carbon Insights tool to estimate embodied carbon (A1–A3) and operational carbon (B6) over a 20-year building lifespan.

The results indicate that façade configurations with extensive glazing significantly increase cooling energy demand and embodied carbon, while enhanced opaque wall systems combined with shading devices provide notable reductions in both operational energy use and embodied carbon emissions. The findings highlight the importance of integrating early-stage energy and carbon assessments in façade design decisions and demonstrate the potential of BIM-based tools for supporting sustainable architectural design processes.

Keywords: Façade systems, Energy performance, Embodied carbon, Life cycle assessment, BIM.

BİM TABANLI SİMÜLASYON KULLANILARAK CEPHE SİSTEMLERİNİN ENERJİ PERFORMANSI VE GÖMÜLÜ KARBON AÇISINDAN KARŞILAŞTIRMALI DEĞERLENDİRİLMESİ

ÖZET

Cephe tasarımı, binaların işletme enerjisi gereksiniminin ve çevresel etkilerinin azaltılmasında kritik bir rol oynamaktadır. Son yıllarda, işletme ve gömülü karbon emisyonlarını birlikte ele alan yaşam döngüsü odaklı yaklaşımlara olan ilgi giderek artmaktadır. Bu çalışmada, Akdeniz iklim koşullarında yer alan temsili bir ofis binası için beş farklı cephe senaryosu—taşıyıcı yığma duvar, dıştan ısı yalıtımlı duvar (ETICS), giydirme cephe, çift kabuk cephe ve gölgeleme elemanlarıyla geliştirilmiş ETICS—karşılaştırmalı olarak değerlendirilmiştir.

Bina enerji performansı, Autodesk Revit ve OpenStudio yazılımları kullanılarak BİM tabanlı simülasyonlar aracılığıyla analiz edilmiş ve yıllık ısıtma ve soğutma enerji tüketimleri hesaplanmıştır. Buna ek olarak, Carbon Insights aracı kullanılarak 20 yıllık bina kullanım ömrü boyunca gömülü karbon (A1–A3) ve işletme karbonu (B6) değerlendirilmiştir.

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Elde edilen bulgular, yüksek cam oranına sahip cephe sistemlerinin soğutma enerjisi gereksinimini ve gömülü karbon miktarını önemli ölçüde artırdığını; buna karşılık, geliştirilmiş opak cephe sistemlerinin gölgeleme elemanlarıyla birlikte kullanıldığında hem işletme enerjisi tüketimini hem de karbon emisyonlarını belirgin şekilde azalttığını göstermektedir. Çalışma sonuçları, cephe tasarım kararlarında erken tasarım aşamasında enerji ve karbon değerlendirmelerinin entegrasyonunun önemini vurgulamakta ve BIM tabanlı araçların sürdürülebilir mimari tasarım süreçlerini destekleme potansiyelini ortaya koymaktadır.

Anahtar Kelimeler: Cephe sistemleri, Enerji performansı, Gömülü karbon, Yaşam döngüsü değerlendirmesi, BIM.

GENİŞLETİLMİŞ ÖZET

Araştırma Problemi

Binalar, küresel enerji tüketimi ve karbon emisyonlarının önemli bir bölümünden sorumludur. Cephe sistemleri ise hem işletme enerjisi performansını hem de yapı malzemelerinden kaynaklanan gömülü karbon emisyonlarını doğrudan etkileyen temel yapı bileşenlerinden biridir. Literatürde bina enerji performansı ve yaşam döngüsü değerlendirmesi üzerine çok sayıda çalışma bulunmasına rağmen, işletme enerjisi gereksinimi ile gömülü karbon emisyonlarını birlikte ele alan bütünlük ve karşılaştırmalı cephe değerlendirmeleri sınırlı sayıdadır. Bu durum, tasarımın erken aşamalarında çevresel açıdan dengeli cephe kararlarının alınmasını güçleştirmektedir.

Araştırma Soruları

Bu çalışma aşağıdaki araştırma sorularına yanıt aramaktadır:

- Farklı cephe sistemleri yıllık işletme enerjisi gereksinimi açısından nasıl bir performans göstermektedir?
- İncelenen cephe alternatifleri arasında gömülü karbon değerleri nasıl farklılaşmaktadır?
- İşletme enerjisi performansı ile gömülü karbon emisyonları arasında ne tür ödünleşimler (trade-off) bulunmaktadır?
- BIM tabanlı simülasyon araçları, erken tasarım aşamalarında cephe tasarım kararlarını nasıl destekleyebilir?

Literatür Değerlendirmesi

Mevcut çalışmaların büyük bölümü cephe sistemlerini ya işletme enerjisi performansı ya da yaşam döngüsü temelli gömülü karbon değerlendirmesi açısından incelemektedir. Son yıllarda BIM tabanlı simülasyon araçları sürdürülebilir bina performans analizlerinde giderek daha fazla kullanılmaktadır. Bununla birlikte, özellikle Akdeniz iklim koşullarında farklı cephe sistemlerini enerji performansı ve gömülü karbon açısından bütünlük BIM tabanlı iş akışlarıyla karşılaştıran çalışmalar sınırlıdır. Bu

araştırma, cephe performansının karşılaştırmalı ve bütünlük değerlendirmesine yönelik bir çerçeve sunarak literatüre katkı sağlamayı amaçlamaktadır.

Yöntem

Çalışma kapsamında beş farklı cephe sistemi BIM ortamında modellenmiş ve karşılaştırmalı olarak analiz edilmiştir. Yıllık ısıtma ve soğutma enerji gereksinimlerinin belirlenmesi amacıyla Autodesk Revit ve OpenStudio yazılımları kullanılarak bina enerji simülasyonları gerçekleştirilmiştir. Bunun yanında, malzeme miktarları ve yapı katmanları esas alınarak Carbon Insights aracı ile gömülü karbon değerlendirmesi yapılmıştır. Analizlerde işletme soğutma enerjisi gereksinimi ile A1–A3 yaşam döngüsü aşamalarını kapsayan gömülü karbon etkileri değerlendirilmiş; cephe saydamlığı, yalıtım stratejileri ve malzeme yoğunluğu arasındaki çevresel ödünleşimler karşılaştırmalı olarak incelenmiştir.

Bulgular ve Sonuç

Araştırma bulguları, cephe sistemleri arasında hem işletme enerjisi performansı hem de gömülü karbon emisyonları bakımından önemli farklılıklar bulunduğunu göstermektedir. Özellikle geniş cam yüzeylerine sahip giydirme cephe ve çift kabuk cephe sistemleri daha yüksek soğutma enerjisi gereksinimi ve gömülü karbon değerleri üretmiştir. Buna karşılık, optimize edilmiş opak cephe sistemleri ile dış gölgeleme elemanlarının birlikte kullanıldığı senaryolar en başarılı çevresel performansı sağlamıştır.

Elde edilen sonuçlar, cephe sistemlerinin yalnızca tek bir performans ölçütü üzerinden değil, işletme enerjisi ve gömülü karbonun birlikte değerlendirildiği bütünlük bir yaklaşımla ele alınması gerektiğini ortaya koymaktadır. Ayrıca çalışma, BIM tabanlı simülasyon iş akışlarının sürdürülebilir cephe tasarımında erken tasarım aşamalarında karar destek aracı olarak etkin biçimde kullanılabileceğini göstermektedir.

1. INTRODUCTION

The building sector is among the most energy-intensive sectors globally and represents a major contributor to greenhouse gas emissions. Buildings and construction activities account for approximately 39–40 % of global energy-related CO₂ emissions, including both operational energy use and embodied emissions associated with building materials and construction processes (IEA, 2019; UNEP, 2020). While reducing operational energy consumption has long been a primary objective of sustainable building design, recent studies further emphasize that embodied carbon is becoming increasingly dominant in high-performance buildings as operational energy demand decreases (Kuittinen et al., 2023; Huang et al., 2024). Previous studies also highlight the importance of low-carbon and low-embodied-energy material strategies in reducing the overall environmental impact of buildings (Cabeza et al., 2014).

Façade systems play a critical role in both operational and embodied environmental performance, as they directly influence thermal behaviour, solar heat gains, daylight availability, and material intensity. Different façade typologies—including masonry walls with external insulation, curtain wall systems, and double-skin façades—exhibit substantially different performance characteristics depending on climate conditions, glazing ratios, insulation strategies, and material composition (Tzempelikos and Athienitis, 2007; Pomponi and Moncaster, 2016). Several studies have demonstrated that façade-related design decisions made at early design stages can significantly affect heating and cooling energy demand as well as life cycle carbon emissions (Gervasio and Dimova, 2018; Simonen et al., 2017).

In cooling-dominated and Mediterranean climate regions, façade design becomes particularly critical due to high solar radiation levels and prolonged cooling periods. Previous research indicates that excessive glazing ratios in office buildings significantly increase cooling loads, even when high-performance glazing is employed (Grynning et al., 2013; Ascione et al., 2016). Conversely, opaque façade systems with enhanced thermal insulation have been shown to reduce cooling energy demand and improve overall thermal stability in warm climates (Dixit et al., 2010; Cuce et al., 2019).

Curtain wall and highly glazed façade systems are widely used in contemporary office architecture due to their architectural transparency and daylighting potential. However, numerous studies report that such systems are associated with higher embodied carbon impacts due to the intensive use of aluminium framing systems and coated glazing units, in addition to increased operational cooling demand (Azari and Abbasabadi, 2018; Ibn-Mohammed et al., 2013). Double-skin façades have been proposed as an alternative solution aiming to balance transparency and thermal performance through ventilated cavities. Nevertheless, their effectiveness strongly depends on design parameters such as cavity depth, ventilation strategy, orientation, and climate context (Saelens, 2002; Gratia and De Herde, 2007). Life cycle-based studies further suggest that the additional material use required for double-skin façades may outweigh

their operational benefits in certain contexts, resulting in higher overall carbon impacts (Pomponi et al., 2017).

External shading devices and controlled glazing strategies have been identified as effective passive measures for reducing solar heat gains and cooling energy demand in office buildings. Several studies demonstrate that fixed shading elements combined with reduced glazing ratios can achieve substantial reductions in cooling loads without compromising indoor visual comfort (Olgay, 1963; Al-Tamimi and Fadzil, 2011). When integrated with well-insulated opaque façade systems, shading strategies can further enhance energy performance while limiting the use of carbon-intensive materials.

Life cycle assessment (LCA) has become an essential methodology for evaluating the environmental performance of building envelopes and façade systems. Integrated assessments combining operational energy use and embodied carbon are increasingly recommended to avoid burden shifting between life cycle stages (Zabalza Bribián et al., 2011; Anand and Amor, 2017). However, many façade-focused LCA studies remain limited to individual façade types or specific life cycle stages, restricting their usefulness for early design decision-making (Simonen et al., 2017). Recent studies further highlight the growing importance of BIM-LCA workflows for supporting embodied carbon assessment and early-stage environmental decision-making in building design (Keyhani et al., 2024).

In parallel, Building Information Modeling (BIM)-based tools have gained increasing attention as platforms for integrating geometric, thermal, and material data within a single digital environment. Recent BIM-integrated workflows also demonstrate the growing applicability of digital design environments for rapid environmental assessment and comparative decision-making during conceptual design stages (Santos et al., 2023). However, previous studies have often focused either on operational energy analysis or embodied carbon assessment separately, while integrated comparative evaluations of multiple façade systems remain relatively limited. Existing BIM-based studies generally concentrate on single façade typologies, specific performance criteria, or non-Mediterranean climatic contexts (Pomponi and Moncaster, 2016; Anand and Amor, 2017; Röck et al., 2020). Therefore, further comparative research combining operational energy demand and embodied carbon assessment within BIM-integrated workflows is still needed, particularly for cooling-dominated Mediterranean climates.

Against this background, this study presents a comparative evaluation of multiple façade systems using BIM-based energy simulation and life cycle-oriented carbon assessment. Five façade configurations—base masonry wall, externally insulated wall (ETICS), curtain wall, double-skin façade, and enhanced ETICS with shading—are analysed for a representative office building located in a Mediterranean climate. The study aims to (i) compare façade alternatives in terms of operational energy demand and embodied carbon emissions, (ii) investigate trade-offs between transparency, insulation, and material

intensity, and (iii) demonstrate the applicability of BIM-integrated tools for early-stage sustainable façade design decision-making.

2. MATERIAL AND METHOD

2.1 Case Study Description

The case study is based on a simplified, representative office building model developed to evaluate the impact of alternative façade systems on operational energy demand and embodied carbon emissions. The building geometry was intentionally kept compact and generic in order to isolate the effects of façade design decisions and ensure comparability between scenarios.

The reference building consists of a single-zone office volume with identical plan dimensions across all scenarios. All external walls are exposed to outdoor conditions, and the building orientation is fixed with the main façade facing south. Fenestration is limited to the south façade to better capture the influence of glazing ratio, shading strategies, and façade typology on solar heat gains and cooling demand. Each window has a clear opening of 1.5 m × 1.5 m and is positioned with a sill height of 0.90 m above floor level, reflecting common office design practice. In scenarios S1, S2, and S5, both the window dimensions and the window-to-wall ratio (WWR) were maintained identically in order to enable controlled comparison between insulation and shading strategies. Variations in cooling energy demand therefore primarily reflect differences in insulation properties, glazing performance, shading configuration, and façade transparency levels rather than changes in window geometry alone.

The building is located in a Mediterranean climate context, characterized by high solar radiation levels and cooling-dominated energy demand. Climate data used for energy simulations were derived from the standard weather file associated with the simulation engine embedded in the BIM workflow.

To ensure comparability between façade scenarios, all simulations were conducted under standardized operational assumptions. Occupancy schedules, internal equipment loads, lighting loads, thermostat settings, and ventilation assumptions were maintained consistently across all scenarios. The analyses focused specifically on façade-related design variations in order to isolate the influence of façade transparency, insulation level, glazing configuration, and shading strategies on operational energy demand and embodied carbon performance. Daylight-responsive lighting control systems were not included within the simulation workflow, and lighting schedules remained fixed throughout all scenarios.

2.2 Façade Scenarios

Five façade scenarios were developed and analysed in this study (Figure 1). All scenarios share the same building geometry, internal loads, occupancy assumptions, and orientation. Only façade-related parameters were modified between scenarios.

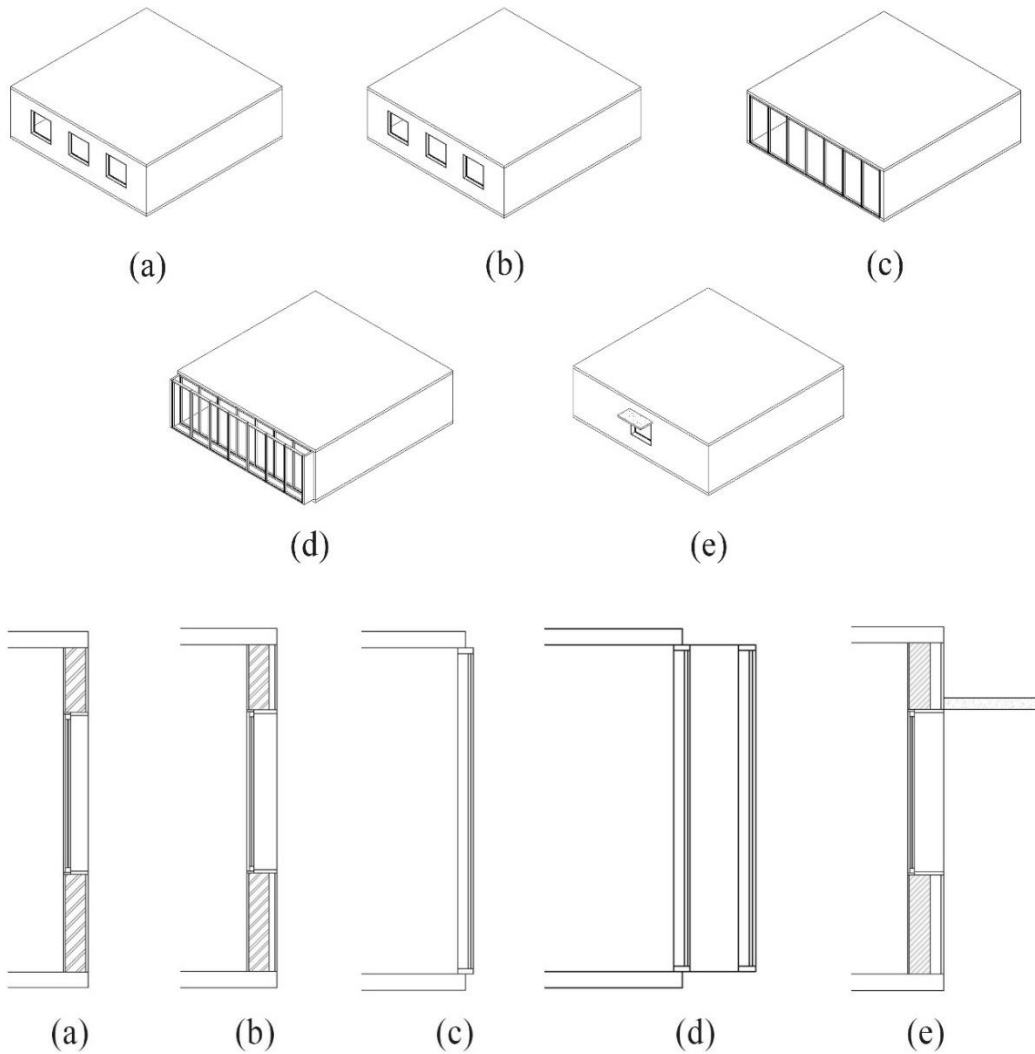


Figure 1. Architectural models of the analysed façade scenarios: (a) S1 – base masonry wall, (b) S2 – externally insulated masonry wall (ETICS), (c) S3 – curtain wall façade, (d) S4 – double-skin façade with ventilated cavity, and (e) S5 – enhanced ETICS with reduced glazing ratio and external shading devices.

- **S1 – Base Model:** Masonry external walls composed of 19 cm brick masonry with internal and external plaster layers. Standard double glazing is applied to south-facing windows.

- **S2 – ETICS:** The base masonry wall is enhanced with an external thermal insulation composite system (ETICS), maintaining the same window configuration and glazing properties as in S1.
- **S3 – Curtain Wall:** The south façade is replaced with a full-height curtain wall system, while the remaining façades retain the base masonry wall configuration.
- **S4 – Double-Skin Façade:** A secondary glazed façade layer is added in front of the primary curtain wall, creating a ventilated cavity with a depth of 0.60 m. The inner curtain wall remains room-bounding, while the outer layer acts as a climatic buffer.
- **S5 – Enhanced ETICS with Shading:** The ETICS wall configuration is further improved by increasing insulation thickness, reducing the glazing ratio compared to the curtain wall configurations while maintaining comparable window proportions with the base opaque façade scenarios, applying low-emissivity double glazing, and integrating fixed external shading devices on the south façade.

A summary of façade layer compositions and material thicknesses for each scenario is provided in Table 1.

Table 1. Summary of façade scenarios and construction layer compositions.

Scenario	Façade system description
S1 – Base	Internal plaster (15 mm) + Brick masonry (190 mm) + External render (20 mm)
S2 – ETICS	Internal plaster (15 mm) + Brick masonry (190 mm) + External insulation (50 mm) + External render (20 mm)
S3 – Curtain wall	Aluminium-framed curtain wall with double glazing
S4 – Double-skin façade	Inner aluminium-framed curtain wall with double glazing + 600 mm ventilated cavity + outer aluminium-framed curtain wall with double glazing
S5 – Enhanced ETICS + shading	Internal plaster (15 mm) + Brick masonry (190 mm) + External insulation (100 mm) + External render (20 mm) + low-emissivity double glazing + fixed external shading

The simulations aim to provide a comparative rather than absolute performance assessment. Therefore, standardized assumptions and default datasets embedded within the BIM-based tools were intentionally used to ensure consistency across scenarios. Energy simulations were conducted using Autodesk Revit in combination with OpenStudio-based analysis workflows. Annual heating and cooling energy demands were evaluated comparatively across all façade scenarios. Embodied carbon assessments were performed using the Carbon Insights tool based on material quantities and construction layer definitions embedded within the BIM environment. The assessment focused on cradle-to-gate embodied carbon impacts (A1–A3) over a 20-year building lifespan.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Operational Energy Performance

Annual operational energy performance results for all façade scenarios are summarised in Table 2. While both heating and cooling energy demands are reported, cooling energy demand represents the dominant component of total operational energy use for the analysed building and is therefore examined in greater detail.

Table 2. Annual operational energy and internal load results obtained from BIM-based energy simulations.

Scenario	Heating (kWh)	Cooling (kWh)	Interior Lighting (kWh)	Interior Equipment (kWh)
S1 – Base	1,886	11,697	3,717	4,831
S2 – ETICS	1,883	11,669	3,700	4,811
S3 – Curtain Wall	2,047	24,417	3,753	4,881
S4 – Double Skin	2,281	20,658	3,753	4,881
S5 – Enhanced ETICS + Shading	1,964	9,344	3,692	4,800

Interior lighting energy values remained relatively similar across all façade scenarios because standardized lighting schedules and fixed internal lighting assumptions were maintained throughout the simulations. Daylight-responsive lighting control systems were not incorporated into the simulation workflow. Therefore, variations in façade transparency primarily influenced cooling energy demand rather than lighting-related energy consumption.

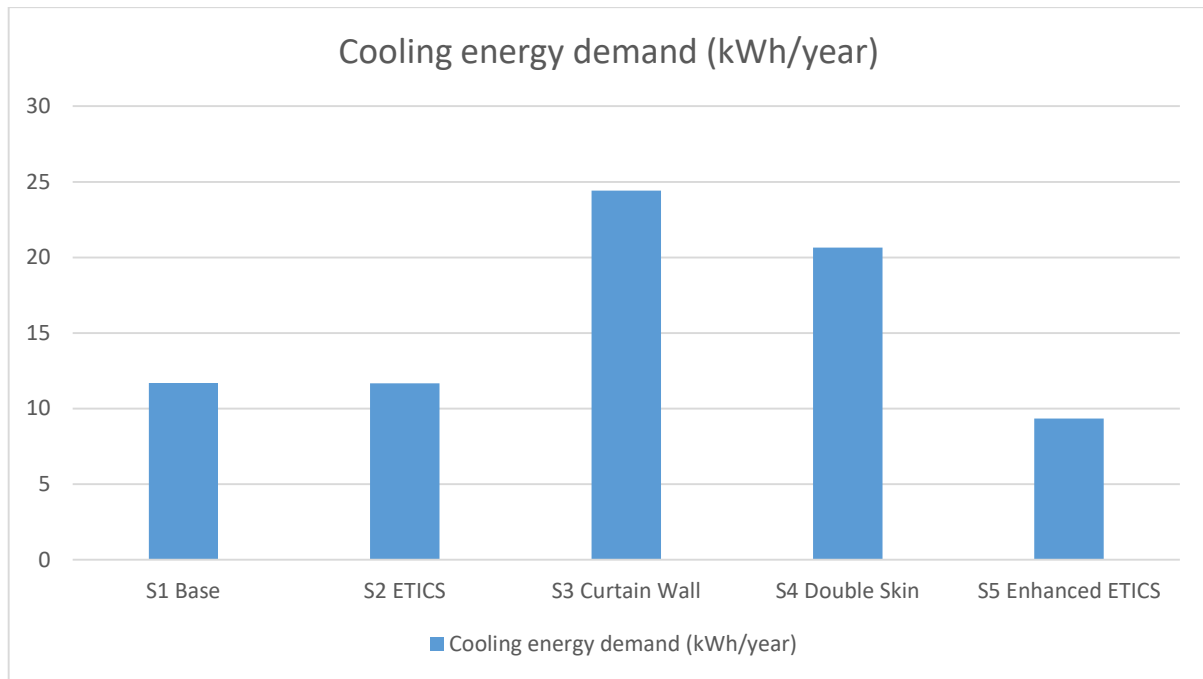


Figure 2. Comparative visualization of annual cooling energy demand across façade scenarios

A detailed comparison of annual cooling energy demand and percentage change relative to the base model (S1) is presented in Table 3, while the absolute cooling energy values are further illustrated in Figure 2. The base model (S1) exhibits an annual cooling energy demand of 11,697 kWh. The application of an externally insulated wall system in S2 results in a negligible change, with cooling energy demand slightly decreasing to 11,669 kWh. These results indicate that moderate insulation improvements alone have a limited influence on cooling demand under the examined climatic conditions.

Table 3. Cooling Energy Demand Comparison

Scenario	Cooling Energy (kWh)	Change Compared to Base (%)
S1 – Base	11,697	0%
S2 – ETICS	11,669	–0.24%
S3 – Curtain Wall	24,417	+108.7%
S4 – Double Skin	20,658	+76.6%
S5 – Enhanced ETICS + Shading	9,344	–20.1%

In contrast, the curtain wall scenario (S3) shows a substantial increase in cooling energy demand, reaching 24,417 kWh. The double-skin façade scenario (S4) partially mitigates this increase, reducing cooling energy demand to 20,658 kWh; however, this value remains significantly higher than that of the base model.

The enhanced ETICS scenario with external shading (S5) demonstrates the lowest cooling energy demand among all analysed scenarios, indicating the effectiveness of combined insulation and passive solar control strategies.

Overall, the results show that cooling energy demand is highly sensitive to façade transparency and solar control measures, while envelope insulation improvements alone result in only marginal reductions.

3.1.2 Embodied Carbon Assessment of Façade Scenarios

The embodied carbon assessment focuses on cradle-to-gate impacts (A1–A3), as provided by the Carbon Insights tool, and does not include maintenance or end-of-life stages. The embodied carbon results of the five façade scenarios are presented in Table 4 and illustrated in Figure 3. The assessment focuses on the material-related embodied carbon of façade components, enabling a direct comparison between different envelope design strategies.

Table 4. Embodied carbon emissions of façade systems over a 20-year building lifespan for all analysed scenarios.

Scenario	Embodied Carbon (kgCO _{2e})	Change Compared to ETICS (%)
S1 – Base	19,268.77	+0.35%
S2 – ETICS	19,201.12	0% (reference)
S3 – Curtain Wall	20,150.35	+4.94%
S4 – Double Skin	20,367.83	+6.07%
S5 – Enhanced ETICS + Shading	19,023.62	–0.92%

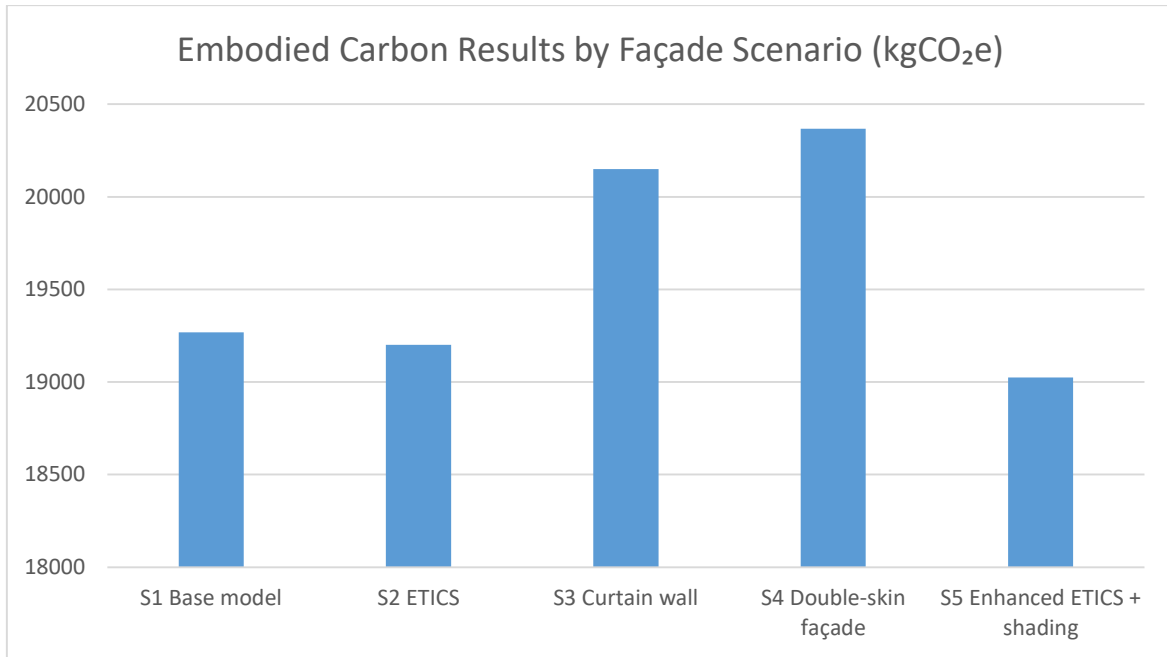


Figure 3. Comparative visualization of embodied carbon emissions across the analysed façade scenarios.

The base model (S1) exhibits an embodied carbon value of 19,268.77 kgCO₂e, which serves as the reference for evaluating alternative scenarios. The ETICS scenario (S2) shows a marginal reduction in embodied carbon, with a total value of 19,201.12 kgCO₂e.

In contrast, the curtain wall scenario (S3) demonstrates a noticeable increase in embodied carbon, reaching 20,150.35 kgCO₂e. This represents an increase of approximately 4.6% relative to the base model. The higher embodied carbon of this scenario can be attributed primarily to the extensive use of aluminium framing systems and high-performance glazing units, which are known to have carbon-intensive production processes.

The double-skin façade scenario (S4) exhibits the highest embodied carbon value among all scenarios, at 20,367.83 kgCO₂e. Compared to the base model, this scenario results in an increase of approximately 5.7%. Although double-skin façades are often promoted for their potential operational energy benefits, the results indicate that the additional material layers, structural elements, and glazing systems significantly increase embodied carbon impacts.

The enhanced ETICS scenario combined with reduced glazing ratio and external shading (S5) achieves the lowest embodied carbon value, amounting to 19,023.62 kgCO₂e. This corresponds to a reduction of approximately 1.3% relative to the base model and approximately 5.8% compared to the curtain wall scenario. The reduction is mainly associated with the lower quantity of high-impact materials, particularly glazing and aluminium components, as well as the use of relatively low-carbon insulation materials.

Overall, the embodied carbon assessment reveals that façade systems with higher transparency and complexity tend to increase embodied carbon, even when they are expected to improve operational performance. Conversely, scenarios prioritising compact envelope configurations, reduced glazing ratios, and moderate insulation enhancements demonstrate lower embodied carbon impacts. These findings highlight the importance of evaluating façade design strategies through a life-cycle perspective that balances both operational and embodied carbon considerations.

3.1.3 Integrated Energy and Carbon Performance and Trade-off Analysis

While Sections 3.1 and 3.2 evaluate operational energy demand and embodied carbon separately, this section integrates both performance dimensions to assess the overall effectiveness of the façade scenarios. Table 5 presents a qualitative synthesis of cooling energy and embodied carbon performance, enabling a holistic comparison across all scenarios.

Table 5. Integrated assessment of façade scenarios based on cooling energy demand and embodied carbon performance, providing an overall qualitative evaluation of each design alternative.

Scenario	Cooling Energy Performance	Embodied Carbon Performance	Overall Assessment
S1 – Base	Medium	Medium	Baseline reference
S2 – ETICS	Medium–Low ↓	Low ↓	Balanced solution
S3 – Curtain Wall	Very High ↑↑	High ↑	Least efficient option
S4 – Double Skin	High ↑	Very High ↑↑	Energy improvement with carbon penalty
S5 – Enhanced ETICS + Shading	Lowest ↓↓	Lowest ↓↓	Best overall performance

The base model (S1) represents a medium-level performance in both operational and embodied terms and serves as the benchmark for subsequent comparisons. The ETICS scenario (S2) achieves a balanced performance, combining a moderate reduction in cooling energy demand with low embodied carbon impact. This indicates that conventional insulation-based improvements can enhance environmental performance without introducing significant material-related emissions.

In contrast, the curtain wall scenario (S3) demonstrates the weakest overall performance. Despite its architectural prevalence, this scenario exhibits very high cooling energy demand alongside high embodied carbon, primarily due to extensive glazing and aluminium components. The results suggest that fully glazed façades may represent an inefficient solution in terms of both operational and life-cycle environmental performance under the studied conditions.

The double-skin façade scenario (S4) presents a more complex trade-off. Compared to the curtain wall, cooling energy demand is reduced; however, this improvement comes at the cost of a further increase in embodied carbon. As summarised in Table 6, the transition from S3 to S4 results in a relatively small embodied carbon increase (+1.08%) while achieving a notable reduction in cooling energy demand (–15.4%). This highlights the partial effectiveness of double-skin façades, yet also reveals their material-intensive nature.

The enhanced ETICS scenario with reduced glazing ratio and external shading (S5) emerges as the best overall-performing option. This scenario achieves the lowest cooling energy demand and the lowest embodied carbon among all alternatives. As shown in Table 6, the transition from S2 to S5 results in simultaneous reductions in both embodied carbon (–0.92%) and cooling energy demand (–19.9%), demonstrating that low-tech, design-oriented strategies can outperform more complex façade systems.

Table 6. Quantitative trade-off analysis between operational cooling energy demand and embodied carbon emissions for selected façade scenario transitions.

Comparison	Embodied Carbon Change	Cooling Energy Change	Interpretation
S2 → S3	+4.94%	+109%	Glazing-intensive façade causes significant cooling energy increase
S3 → S4	+1.08%	–15.4%	Double-skin improves cooling at moderate embodied carbon increase
S2 → S5	–0.92%	–19.9%	Optimized opaque façade improves simultaneous environmental improvement
S4 → S5	–6.6%	–54.8%	Low-tech optimization superior integrated environmental performance

Overall, the integrated assessment confirms that façade solutions relying on increased material complexity and transparency tend to generate environmental trade-offs, whereas optimized opaque envelopes combined with shading strategies can deliver superior performance across both operational and embodied dimensions.

3.2 Discussion

The results of this study demonstrate that façade design decisions have a decisive influence on both operational cooling energy demand and embodied carbon emissions, particularly in cooling-dominated Mediterranean climate conditions. The integrated evaluation of multiple façade scenarios reveals clear

trade-offs between transparency-driven design approaches and more compact, insulation-oriented envelope strategies.

3.2.1 Influence of Façade Transparency on Cooling Energy Demand

The findings confirm that façade transparency is a critical driver of cooling energy demand. Scenarios with extensive glazing, particularly the curtain wall configuration (S3), resulted in a substantial increase in cooling energy consumption compared to the base model. This outcome is consistent with previous studies reporting that high glazing ratios significantly increase solar heat gains and cooling loads, even when advanced glazing systems are used (Ascione et al., 2016; Grynning et al., 2013). Similar findings have been reported in Mediterranean and cooling-dominated climates, where increased glazing ratios were associated with substantial cooling energy penalties despite improvements in glazing technology (Ascione et al., 2016; Grynning et al., 2013). The present study further supports these observations through a comparative BIM-based assessment framework.

Although the double-skin façade scenario (S4) achieved a partial reduction in cooling demand relative to the curtain wall, its performance remained considerably worse than opaque façade alternatives. This suggests that, under the examined conditions, the buffering effect of the ventilated cavity is insufficient to fully compensate for the high solar gains associated with large glazed areas. While façade transparency may also affect daylight availability and lighting-related energy consumption, the present study intentionally maintained fixed lighting assumptions in order to isolate the influence of façade systems on cooling energy demand and embodied carbon performance.

3.2.2 Embodied Carbon Implications of Complex Façade Systems

The embodied carbon assessment highlights the material-related implications of façade complexity. Curtain wall and double-skin façade systems exhibit higher embodied carbon values due to the intensive use of aluminium framing systems and multi-layer glazing assemblies. These findings are consistent with previous life cycle assessment studies emphasizing that aluminium-intensive and highly glazed façade systems tend to generate disproportionately high embodied carbon impacts compared to more compact opaque envelope solutions (Pomponi and Moncaster, 2016; Azari and Abbasabadi, 2018).

The double-skin façade scenario demonstrates the environmental trade-off between operational improvement and increased material-related carbon emissions. This outcome illustrates a common challenge in sustainable façade design: operational energy savings achieved through added layers and systems may be offset—or even outweighed—by increased material-related emissions (Pomponi et al., 2017).

3.2.3 Effectiveness of Low-Tech, Design-Oriented Strategies

Among the analysed scenarios, the enhanced ETICS with reduced glazing ratio and external shading (S5) consistently demonstrated superior performance across both operational and embodied dimensions. This observation aligns with recent sustainable façade research advocating passive and climate-responsive design strategies as effective alternatives to technologically complex building envelope systems.

The effectiveness of external shading in reducing cooling demand corroborates established passive design principles and previous research highlighting the role of solar control strategies in warm climates (Olgyay, 1963; Al-Tamimi and Fadzil, 2011). Importantly, the results suggest that optimizing façade geometry, glazing ratio, and shading configuration may deliver greater environmental benefits than introducing technologically complex façade systems.

3.2.4 Implications for Early-Stage Design and BIM-Based Assessment

The study also demonstrates the potential of BIM-based tools for supporting early-stage façade design decision-making. By integrating energy simulation and embodied carbon estimation within a single modeling environment, designers can rapidly evaluate alternative façade strategies before committing to detailed development. Recent research also indicates that simplified BIM-LCA workflows can effectively support early-stage environmental optimization despite certain limitations regarding data precision and full life-cycle coverage (Hoxha and Jusselme, 2024).

Although the embodied carbon assessment conducted using Carbon Insights does not represent a full ISO-compliant LCA, its use as a comparative tool proved effective in identifying relative performance differences between façade options. This finding is consistent with previous research advocating simplified LCA approaches at early design stages to guide strategic decisions (Soust-Verdaguer et al., 2017; Cavalliere et al., 2019).

From a design perspective, the findings highlight the critical role of early façade decisions in shaping both operational and embodied carbon performance. Parameters such as glazing ratio, façade transparency, shading configuration, and material selection were shown to have a greater influence on environmental outcomes than the introduction of complex façade systems.

The results suggest that low-tech, design-oriented strategies—such as optimized opaque envelopes combined with external shading—can outperform technologically advanced façade solutions in cooling-dominated climates. This has important implications for architects and designers, indicating that environmentally effective façade design does not necessarily require increased system complexity.

Furthermore, the study demonstrates the value of integrating simplified energy and embodied carbon assessments within BIM environments during early design stages. Such workflows enable designers to compare alternative façade strategies rapidly and make informed decisions before detailed development, when design flexibility is highest and environmental impact reduction potential is greatest.

3.2.5 Limitations and Future Research Directions

Several limitations of this study should be acknowledged. First, the case study is based on a simplified building model and a single climatic context, which may limit the generalizability of the results. Second, operational energy simulations rely on standardized assumptions for occupancy and internal loads, while embodied carbon values are based on default datasets embedded within the BIM tool.

Future research could expand the analysis to multiple climate zones, alternative building typologies, and longer life-cycle stages, including maintenance and end-of-life scenarios. In addition, coupling BIM-based assessments with detailed, ISO-compliant LCA tools would allow for more robust quantification of absolute environmental impacts. In addition, real operational behaviour and user-driven control strategies were not considered and may influence actual building performance.

4. CONCLUSION AND SUGGESTIONS

This study presents a comparative evaluation of alternative façade systems using a BIM-based workflow that integrates operational energy simulation and embodied carbon assessment. Focusing on a representative office building in a Mediterranean climate, five façade scenarios were analysed to investigate the environmental implications of façade design decisions at early design stages.

The results demonstrate that façade transparency is a dominant factor influencing cooling energy demand. Highly transparent façade systems were associated with increased cooling energy demand and embodied carbon impacts under the analysed climatic conditions. Although the double-skin façade provided partial cooling energy improvements relative to the curtain wall, this benefit was accompanied by increased embodied carbon impacts.

Embodied carbon assessment revealed that material-intensive façade systems, especially those relying on aluminium framing and multi-layer glazing, generate higher life-cycle carbon emissions. In contrast, externally insulated masonry façades exhibited lower embodied carbon values, particularly when combined with reduced glazing ratios and external shading devices.

Among the analysed scenarios, the enhanced ETICS façade with external shading emerged as the best overall-performing solution, achieving simultaneous reductions in cooling energy demand and

embodied carbon emissions. This finding highlights the effectiveness of low-tech, design-oriented strategies over technologically complex façade systems in cooling-dominated climates.

The study also demonstrates the applicability of BIM-based tools for early-stage performance evaluation. The integration of energy simulation and embodied carbon estimation within a single modeling environment enables rapid comparison of façade alternatives, supporting informed design decision-making before detailed development.

Despite its contributions, the study is subject to limitations related to simplified geometry, a single climatic context, and the use of default embodied carbon datasets. Future research should extend the analysis to additional climate zones, building typologies, and life-cycle stages, as well as explore the integration of BIM-based workflows with detailed, ISO-compliant LCA tools.

From a functional perspective, the findings also indicate that façade design decisions in office buildings directly influence cooling-related operational performance due to the combined effects of solar heat gains, occupancy conditions, and internal loads. While lighting-related energy consumption remained relatively stable under the standardized simulation assumptions adopted in this study, façade transparency and shading strategies demonstrated a significant impact on cooling energy demand within office-use scenarios.

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