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Article

Bridging the Gap Between Architectural Studio and Energy Engineering: Experiential Learning Case Study on Envelope Optimization Using Sefaira

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Abstract

In the hyper-arid climate of Riyadh, Saudi Arabia, the building envelope represents the most critical determinant of energy demand and occupant comfort. This study evaluates the environmental and energy performance of a 6,581m² mixed-use development through an experiential learning framework, where students utilized Sefaira (EnergyPlus/Radiance engines) to bridge the gap between theoretical architectural design and national code compliance. This pedagogical approach allowed for the practical application of Building Energy Modelling (BEM) principles to a real-world capstone project. A baseline analysis conducted in accordance with the Saudi Building Code (SBC 601) revealed a high Energy Use Intensity (EUI) of 139 kWh/m². yr, driven primarily by solar heat gains and an “overlit” floor plate as noted above exceeded Annual Sunlight Exposure (ASE) thresholds. To mitigate these deficiencies, students implemented a series of passive interventions, including the optimization of glazing *U*-values (0.5-W/m²-K), reduction of Solar Heat Gain Coefficient (SHGC to 0.20), and the integration of external shading fins. Post-intervention results demonstrated a significant EUI reduction to 130 kWh/m²-yr” to “a 6.95% reduction in EUI from 139 to 130 kWh/m²-yr, equating to 63,659 kWh in annual energy savings. Furthermore, daylighting analysis confirmed a more uniform distribution and the successful mitigation of disability glare. The findings validate that experiential learning in performance-driven envelope optimization is essential for developing the technical proficiency required to achieve full SBC compliance and operational efficiency in hot-arid regions.

Keywords: envelope optimization; Sefaira; energy use intensity; hot-arid climate; Saudi Building Code

1. Introduction

The building sector in Saudi Arabia is among the most energy-intensive in the world, accounting for approximately 80% of total electricity consumption, driven predominantly by mechanical cooling in response to extreme ambient temperatures that regularly exceed 45 °C [1]. Under Vision 2030 and the Saudi Green Initiative, the Kingdom has committed to reducing carbon emissions by 278 million tonnes annually and generating 50% of its electricity from renewable sources by 2030. Achieving these targets necessitates a fundamental shift in how buildings are designed: specifically, a transition from aesthetics-driven envelope decisions to thermally rigorous, performance-verified design practice. Yet architectural education in the region has been slow to embed the computational tools required to support this transition. Graduates entering professional practice frequently lack the technical proficiency to evaluate envelope performance quantitatively, producing designs that are aesthetically resolved but thermally non-compliant [2]. This skills gap is not merely academic; it has direct consequences for the operational energy burden of the Kingdom’s built environment.

Historically, the pursuit of modern architectural aesthetics has led to an increase in high-transparency facades, which often result in excessive solar heat gain and visual discomfort for occupants. The gap between architectural education and energy engineering practice is well-documented globally. Furthermore, across MENA region architecture programmes, BPS tools are predominantly introduced as standalone technical modules rather than as integrated components of the design studio process, with the result that students develop computational competency in isolation from the design judgment needed to act on simulation outputs [3]. This pedagogical disconnect is particularly acute in Saudi Arabia and the broader GCC, where the national regulatory framework (SBC 601) demands envelope compliance of a level that students rarely encounter within the studio curriculum. The present study was conceived specifically to address this gap: by embedding Sefaira within a capstone studio assignment at Alfaisal University, it positions BPS not as a post-design validation exercise but as a generative design instrument, one that enables students to iteratively test, evaluate, and refine their envelope decisions against nationally codified performance thresholds, in a hyper-arid climate context that demands it.

The primary objective is to demonstrate how strategic architectural modifications, such as optimized thermal transmittance (U-values), SHGC, and daylighting mechanisms like light shelves, can yield verifiable energy savings and code compliance. The study contributes to the field by providing a comparative analysis of these interventions, highlighting the effectiveness of integrated simulation workflows in achieving low-carbon design goals without compromising architectural intent in hot-arid regions.

Table 1. Contribution to the body of knowledge — this study vs. prior case studies.

Dimension	What prior studies do	What this study adds
BPS deployment	BPS used as post-design audit module disconnected from studio process [4]	‘Sefaira’ deployed as primary generative instrument informing every iterative design decision
Parametric variation of U-values and SHGC	Sequential single-variable parametric testing of glazing, wall, roof, and shading parameters	Student-driven iterative parametric process — without algorithmic optimisation — achieving SBC 601 compliance: first documented in a Saudi architecture environment
Performance improvement reported as EUI and cooling load reduction	EUI reduced 139→130 kWh/m ² ·yr; cooling demand reduced 17.24%; peak cooling coil load reduced 13.21%	Results explicitly mapped to four learning objectives (LO1–LO4), providing pedagogical evidence alongside engineering evidence — uncommon in BPS case study literature

The educational investigation is guided by four primary learning objectives:

1. **LO1: Baseline Calibration & Plausibility Verification:** To establish and plausibility-verify a simulation baseline by cross-checking model geometry against architectural drawings ($\pm 5\%$ tolerance) and confirming the resulting EUI falls within published benchmark ranges for the climate and typology
2. **LO2: Metric Literacy:** To assess daylight quality using advanced climate-based metrics sDA and ASE, moving beyond simple visual aesthetics to technical comfort standards.
3. **LO3: Quantitative Analysis:** To quantify how specific student-proposed interventions, such as light shelves and skylights, directly influence EUI and cooling demand.
4. **LO4: Regulatory Alignment:** To determine the extent to which student design scenarios align with the professional requirements of SBC-601, fostering an understanding of the architect’s responsibility toward national low-carbon goals.

Despite the growing body of literature on both experiential learning in architecture and building performance simulation (BPS) in professional practice, a critical gap persists at their intersection.

First, while BPS tools such as EnergyPlus and Radiance have been extensively studied in engineering and environmental design curricula, their systematic integration into architectural design studios — particularly in the context of capstone or live project assignments, remains poorly documented, especially within the GCC region. Second, existing studies on BPS pedagogy rarely employ a structured before-and-after experimental framework in which student-proposed interventions are evaluated against a nationally codified regulatory baseline; most rely on hypothetical or faculty-designed scenarios. Third, no prior study, to the authors' knowledge, has documented the use of Sefaira as a primary pedagogical instrument within an architectural engineering studio in Saudi Arabia, benchmarked explicitly against SBC 601. This study addresses all three gaps simultaneously: it provides the first documented account of a student-led, Sefaira-based envelope optimisation exercise in a Saudi architectural engineering programme, producing verifiable energy and daylighting outcomes that meet national code requirements. The scientific contribution lies not in the optimisation outcomes alone, but in demonstrating that a replicable experiential learning framework can produce engineering-grade results within the context of a design studio assignment.

Critically, while the literature demonstrates the effectiveness of experiential learning methods broadly, and the utility of BPS tools in engineering contexts specifically, there remains a notable absence of documented case studies in which architecture students apply simulation tools to produce regulatory-compliant, quantitatively verified design outcomes within a GCC institutional context. Studies such as [3,5] confirm that BPS adoption in design education is growing, yet implementation models that bridge between studio pedagogy and national energy code compliance, particularly in contexts governed by SBC 601, have not been systematically reported. This study addresses that absence directly.

The novelty of this study does not reside in the envelope optimisation outcome per se — EUI reduction through passive interventions in hot-arid climates is well-established in the engineering literature [2,6]. Rather, the contribution is three-fold and pedagogical in nature. First, this study provides the first documented account of Sefaira deployed as a primary generative design instrument, rather than a post-design validation tool — within an architectural engineering capstone studio in Saudi Arabia, benchmarked against SBC 601. Second, it operationalises [7] Experiential Learning Cycle within a BEM-integrated studio workflow, demonstrating a replicable structure through which students' progress from baseline diagnosis to iterative parametric testing to regulatory compliance verification. Third, it provides empirical evidence that student-led, single-iteration parametric design, without algorithmic optimization, can produce envelope performance outcomes that meet national code thresholds, with direct implications for how BPS tools are introduced in GCC architectural curricula. Situating this study requires evaluating two comparable clusters. First, [3] found BPS overwhelmingly introduced as post-design modules — none used BPS as a primary generative medium. Second, [8] documented 5–12% EUI improvements through passive strategies but used faculty-prescribed parameters with no code-compliance benchmark. This study diverges from all two; first to deploy BPS as the primary generative instrument in an architecture capstone studio, using a real student-designed building benchmarked against SBC 601.

2. Literature Review

Experiential learning plays a significant role in architectural education, particularly when it comes to understanding complex concepts such as daylighting strategies. Through hands-on experiences, simulations, and collaborative projects, architecture students can grasp how daylighting affects building performance and occupant comfort. This discussion synthesizes various studies and examples highlighting the importance of experiential learning methods in teaching daylighting strategies to architecture students.

Experiential learning, as described by Kolb's Learning Cycle, includes concrete experiences, reflective observation, abstract conceptualization, and active experimentation that enable students to apply theoretical knowledge in practical settings [4] For architecture students, direct engagements with building simulation tools and real-world projects provide invaluable insights into the

implications of design choices on daylighting and energy efficiency. For example, blended learning approaches that combine traditional studio classes with virtual simulations have shown promise in enhancing students' understanding of architectural concepts, including daylighting strategies [9]. The effectiveness of VR environments in facilitating experiential learning by allowing students to navigate and interact with 3D models, thereby experiencing the impacts of daylighting strategies first-hand [10]. Such immersive experiences can significantly augment traditional learning methods by fostering deeper engagement and comprehension.

The application of technology, notably daylighting simulation tools such as Sefaira and others, within the architectural curriculum offers students a platform to analyze and optimize designs for daylight performance. For instance, students can simulate various building geometries, orientations, and materials to evaluate daylighting impacts on energy consumption and visual comfort. Research by [5] established that coupling daylight simulation tools with thermal modeling ensures a comprehensive understanding that integrates energy use with daylight quality, which is essential for design decisions. Moreover, living labs and hands-on projects allow students to apply academic knowledge to actual building contexts. [11] presented a living lab model that encourages students to engage actively in sustainability-focused projects, thereby reinforcing the practical importance of daylighting in sustainable building design. By addressing real-world challenges, students enhance their critical thinking and problem-solving skills, crucial for successful architectural practice. Collaboration is vital in learning complex skills, especially in architecture. Subsequently, Portman et al. highlighted how collaborative design processes in virtual settings can lead to more engaged learning outcomes. The integration of multiple perspectives in team projects allows students to explore different approaches to daylighting strategies, emphasizing the importance of teamwork in architectural practice [12].

Additionally, the use of active learning strategies encourages students to critically evaluate daylighting designs through peer discussions, feedback mechanisms, and reflective practices. Such methods not only deepen understanding but also prepare students for the collaborative nature of professional architectural work [13]. While integrating experiential learning methods yields numerous benefits, challenges exist. Notably, the transition to online and blended learning formats necessitated by the COVID-19 pandemic has exposed some limitations [14]. Effective implementation of virtual technologies may require additional resources and training, as not all students may be equally proficient with advanced tools like VR and AR. However, the current landscape of digital technologies presents opportunities for innovation in architectural education. As [15] noted, augmented reality and VR technologies can potentially reshape architectural education by providing interactive and immersive experiences that go beyond traditional learning methods. By upskilling both instructors and students, architectural programs can cultivate future architects who are well-versed in both design principles and the latest technologies, particularly related to daylighting strategies. Experiential learning is essential for teaching daylighting strategies among architecture students. The incorporation of simulation tools further enables students to explore the impacts of their design decisions, preparing them for sustainable architectural practices in real-world contexts.

This paper directly addresses the gap between classroom theory and professional practice by utilizing simulation as a primary pedagogical medium. Aligned with the literature's emphasis on "learning by doing," the aim of this paper is to evaluate the effectiveness of student-led interventions in a professional context. Specifically, this study focuses on:

5. **Evidence-Based Mastery:** Requiring students to validate their design intuition against SBC-601 standards through rigorous climate-based metrics (*sDA* and *ASE*).
6. **Technical Agency:** Empowering students to quantify the impact of passive strategies, such as light shelves and skylights, on EUI and cooling demand.
7. **Regulatory Competency:** Ensuring students can navigate and meet the national energy reduction priorities of the Kingdom of Saudi Arabia within a controlled, academic environment.

Through this hands-on application, the paper demonstrates how simulation-based assignments serve as a bridge, transforming students into informed designers capable of delivering low-carbon, high-performance architecture.

2.1. Building Envelope Performance in Hot-Arid Climates

The thermal performance of building envelopes in hot-arid climates has been extensively studied, with a consistent finding that solar heat gain through glazing represents the dominant cooling load driver [2,16]. In the Saudi Arabian context, [6] demonstrated that envelope-led passive strategies, including high-performance glazing, wall insulation, and external shading, can reduce annual EUI in non-residential buildings by 8–30%, depending on the stringency of the intervention. [1] further established that energy consumption patterns in Saudi buildings are fundamentally shaped by the envelope's ability to resist solar radiation, with glazing U-value and SHGC being the two parameters with the greatest independent impact on cooling demand. These findings collectively establish the technical rationale for the intervention strategy adopted in this study: prioritising glazing and solar control parameters above all other envelope components when designing for Climate Zone 1 compliance under SBC 601.

2.2. BPS Tool Integration in Architectural Design Education

Parallel to technical literature, a growing body of work has examined how BPS tools can be meaningfully integrated into architectural design pedagogy. [17] established that coupling daylight simulation with thermal modelling produces a more holistic understanding of building performance than either discipline alone, a principle that underpins the dual-metric approach (EUI and sDA/ASE) adopted in this study. This distinction is central to the pedagogical contribution of the present study: the use of a real, geometrically complex building as the assignment brief – rather than a simplified hypothetical form – was a deliberate choice intended to confront students with authentic design complexity and to prevent the trivialisation of the simulation exercise through over-simplified geometry. [11] similarly argued that living lab contexts, in which students engage with real buildings under real climatic conditions, produce deeper and more transferable learning than laboratory analogues. The present study operationalises this principle within the constraints of an architectural subject teaching.

3. Materials and Methods

The methodology employs a simulation-based, “before-and-after” experimental design to evaluate the impact of envelope optimization on energy and daylighting performance. The study follows a structured workflow designed to align architectural design with the SBC 601 through iterative performance modelling.

3.1. Studio Implementation Framework

This study was conducted as part of the ARE491 Building Energy Management final assignment at the Department of Architectural Engineering, College of Engineering and Advanced Computing, Alfaisal University, Riyadh, during the Spring 2024 semester. The studio enrolled a team of three undergraduate students in their final year, working under the supervision of the first author. The assignment spanned twelve weeks, structured across three iterative phases aligned with [7] Experiential Learning Cycle: (1) Concrete Experience students were using project from their capstone project and tasked with reconstructing its geometry in SketchUp and establishing a Sefaira baseline model; (2) Reflective Observation – students interpreted simulation outputs against SBC 601 prescriptive thresholds and identified the building's primary thermal and luminous deficiencies; and (3) Abstract Conceptualisation and Active Experimentation – students proposed and tested targeted passive interventions iteratively until measurable improvements in both EUI and daylighting metrics were achieved.

The decision to base this study on the students' own capstone design project was deliberate and pedagogically motivated. Rather than assigning a pre-existing building with known performance characteristics, students were required to work with a design they had developed themselves — a mixed-use development that had not been evaluated for energy or daylighting performance prior to this exercise. This approach provides authentic geometric complexity, a self-generated programmatic brief, and a direct personal investment in the outcomes, creating conditions that foster deeper engagement with the simulation process. By confronting the thermal and luminous deficiencies of their own design decisions, students experienced the immediate and quantifiable consequences of their architectural choices — a reflective feedback loop that closely mirrors the performance validation responsibilities expected of architects in professional practice and that is central to the experiential learning framework.

The optimisation approach employed was iterative parametric testing rather than computational optimisation in the algorithmic sense. Students systematically varied individual envelope parameters (glazing U-value, SHGC, wall U-value, roof U-value, and shading geometry) one at a time within the Sefaira web application, recording the EUI and daylighting response to each change before proceeding to the next intervention. This sequential single-variable method was intentionally selected over multi-variable algorithmic optimisation (e.g., genetic algorithms via Grasshopper/Galapagos) to ensure that each student could directly observe and reason about the independent contribution of each parameter to overall building performance — a critical learning outcome that would be obscured by black-box optimisation processes. The sequence of interventions followed the priority ranking established by the baseline heat gain analysis: solar gain through glazing was addressed first, followed by wall and roof conduction, and finally shading geometry.

3.2. Assessment Metrics for Building Daylighting Performance

The evaluation of interior daylighting typically relies on a combination of climate-based dynamic metrics and traditional static analyses to quantify both daylight sufficiency and the potential for visual discomfort. Among the primary dynamic metrics utilized in contemporary building performance simulation are sDA and ASE.

3.3. Climate-Based Dynamic Metrics: sDA and ASE

sDA is a metric designed to evaluate the adequacy of daylight penetration within an architectural space, accounting for both direct sunlight and internal luminous bounces. Defined formally by the Illuminating Engineering Society (IES) in standard LM-83-12 and adopted by the LEED v4 rating system, the standard target metric is sDA_{300/50%}. This specifically quantifies the percentage of the analyzed floor area that achieves an illuminance of at least 300 lux for a minimum of 50% of the annual occupied hours.

Conversely, ASE serves to identify regions within a space that are subjected to excessive direct solar radiation, which is strongly correlated with visual discomfort (glare) and disproportionate cooling loads. The standardized metric, ASE_{1000/250}, measures the percentage of the floor area that receives direct sunlight of 1000 lux or greater for at least 250 occupied hours per year.

Standardized temporal parameters are required for the calculation of both sDA and ASE. In these assessments, annual occupied hours are fixed from 8:00 AM to 6:00 PM, 365 days a year, remaining constant regardless of the building's geographic location or specific programmatic use. Furthermore, standard evaluation procedures dictate that interior dynamic shading devices, such as operable blinds, are explicitly excluded from the simulation boundary conditions.

3.3.1. LEED v4 Compliance Criteria

Under the LEED v4 certification framework, daylighting performance credits are awarded based on a tiered attainment of these dynamic metrics. Projects can earn progressive credit points by achieving minimum sDA spatial coverage thresholds of 55%, 75%, or 90%. However, to qualify for

these credits, the building design must simultaneously demonstrate mitigation of overexposure by capping the total ASE at a strict maximum of 10%.

3.3.2. Static Analysis: Daylight Factor (DF)

While dynamic metrics account for annual climatic variations, the DF remains a critical static metric, typically evaluated under standard overcast sky conditions. A comprehensive DF analysis yields three distinct performance indicators:

- **Average Daylight:** This value provides an aggregate daylighting score for the entire space. It is frequently utilized in early-stage design assessments to predict generalized daylight levels, serving as a baseline indicator for regional compliance frameworks, such as the Building Research Establishment (BRE) standards in the United Kingdom.
- **Minimum Daylight:** This indicator isolates the lowest daylight value within the assessed area, omitting a defined perimeter boundary zone adjacent to the walls. It effectively represents the “worst-case” daylighting condition within the core of the space.
- **Uniformity Ratio:** Calculated as the mathematical ratio of the Minimum Daylight to the Average Daylight, this metric evaluates the evenness of light distribution. Spaces with deep floor plates systematically demonstrate lower uniformity ratios, as daylight remains heavily concentrated near the fenestration. Identifying a low uniformity ratio is a vital diagnostic step in exposing and mitigating severe lighting disparities across an interior volume.

3.4. Simulation Software Selection and Justification

To evaluate the building’s performance metrics, this study leverages the contemporary Sefaira simulation suite. It is important to note that the software framework has recently evolved from its legacy iterations, formerly segregated into *Sefaira Architecture* and *Sefaira Systems*, into a streamlined, two-tier ecosystem comprising the Sefaira Plugin and the Sefaira Web Application.

The bifurcated deployment of these two interfaces within this methodology is specifically justified by their distinct computational capabilities and intended analytical resolutions:

- **Sefaira Plugin:** This modeling environment was strategically selected to conduct the geometric and environmental daylighting assessments. While the plugin framework possesses basic energy modeling functions, its primary utility in this workflow is to provide rapid, high-level spatial analyses and accurate daylight performance metrics directly within the 3D modeling environment.
- **Sefaira Web Application:** To execute the rigorous thermal and whole- building energy modelling (BEM) required for this research, the analytical workflow was subsequently transitioned to the Web Application platform. This environment is specifically engineered to process complex, high-resolution simulations, providing the detailed and comprehensive energy performance data that the preliminary plugin environment lacks.

By utilizing this integrated workflow, the methodology ensures that both the sDA and the detailed energy consumption metrics are calculated using the appropriate, specialized computational engines within the modern Sefaira ecosystem. To accurately simulate the thermal performance and energy consumption of the mixed-use development, specific operational schedules and temperature setpoints were established. Although the building encompasses diverse functional zones, a uniform “Office” operational profile was applied across all sections of the modeled geometry. This standardized approach was adopted in accordance with the ASHRAE 90.1-2013 baseline methodology, which establishes that the recommended temperature setpoints do not vary between the specific programmatic profiles evaluated within this context. The design temperature setpoints for the air-conditioning systems were defined for three distinct analytical scenarios: the standard ASHRAE 90.1-2013 baseline, the pre-retrofit condition (existing building), and the post-retrofit condition (proposed design). The specific heating and cooling setpoints utilized for the energy simulations are detailed in Table 2.

Table 2. Design temperature setpoints (ASHRAE 90.1-2013 baseline vs. Before and After scenarios).

Design Temperatures			
Setpoint Temperatures	ASHRAE 90.1 – 2013	Before	After
Heating Setpoint (°C)	19	21	21
Cooling Setpoint (°C)	22	24	24

3.5. Full Simulation Input Assumptions

This table presents all input parameters used in Sefaira/EnergyPlus for both the Before and After scenarios, organised by category.

Table 3. Full simulation input assumptions.

Parameter	Unit	ASHRAE 90.1-2013	Before (Baseline)	After (Improved)
A. Project Configuration				
Location	—	—	Ar Rayn, Riyadh, SA	Ar Rayn, Riyadh, SA
Climate zone	—	—	Zone 1 (Hot-Arid)	Zone 1 (Hot-Arid)
Building area	m ²	—	6,581	6,581
Zoning strategy	—	—	Basic Perimeter/Core	Basic Perimeter/Core
Perimeter depth	m	—	4.572	4.572
EnergyPlus version	—	—	8.5	8.5
Operating days	—	—	5 days/week	5 days/week
HVAC operating hours	hr	—	08:00–18:00	08:00–18:00
B. Envelope Parameters				
Exterior wall assembly	—	—	Concrete Block (uninsulated)	Precast Concrete (insulated)
Wall U-value (all orientations)	W/m ² ·K	—	2.56	0.18
Glazing U-value (all orientations)	W/m ² ·K	—	3.52	0.50
Glazing SHGC (all orientations)	—	—	0.2099	0.20
Glazing type	—	—	Standard double glazing	Triple glazing, Argon-filled cavity + internal blinds
Glazing ratio (WWR)	%	—	64%	66%

Parameter	Unit	ASHRAE 90.1-2013	Before (Baseline)	After (Improved)
Roof glazing U-value	W/m ² ·K	—	2.40	2.40
Roof glazing SHGC	—	—	0.60	0.60
Roof assembly	—	—	Concrete	Concrete
Roof U-value	W/m ² ·K	—	0.27	0.15
Ground floor assembly	—	—	Tiles	Tiles
Ground floor U-value	W/m ² ·K	—	1.83	0.13
Infiltration type	—	—	Façade area at 50 Pa	Façade area at 50 Pa
Design infiltration rate	m ³ /m ² ·h	—	7.2	7.2
Shading devices	—	—	None	External fins (south & west facades)
C. Internal Loads				
Occupant density	m ² /person	14	10	10
Equipment power density	W/m ²	8.1	25	25
Lighting power density	W/m ²	8.8	10	10
Outside air rate / person	L/s·person	—	15	15
D. Temperature Setpoints				
Heating setpoint	°C	19	21	21
Heating setback	°C	—	12	12
Cooling setpoint	°C	22	24	24
Cooling setback	°C	—	28	28
E. HVAC System				
System type	—	—	Fan Coil Units + Central Plant (DOAS)	Fan Coil Units + Central Plant (DOAS)
Cooling COP	—	3.00	5.5	5.5
Heating efficiency	—	0.85	0.90	0.90

Parameter	Unit	ASHRAE 90.1-2013	Before (Baseline)	After (Improved)
AHU supply air temperature	°C	—	13	13
Heat recovery sensible efficiency	—	—	0.5	0.5
Peak specific fan power (AHU)	W/L·s	—	3.493	3.493
Peak specific fan power (FCU)	W/L·s	—	0.639	0.639
Ventilation rate / area	L/m ² ·s	0.3	0.00	0.00

Note: Highlighted cells (yellow) indicate parameters changed between Before and After scenarios. All U-values in W/m²·K. HVAC parameters were held constant between scenarios to isolate the envelope effect. Equipment power density (25 W/m²) reflects the mixed-use programme (digital laboratories + exhibition spaces) and exceeds the ASHRAE 90.1 office baseline of 8.1 W/m², which explains the moderate overall EUI reduction despite significant envelope improvement.

3.6. Case Study Selection

To provide a comprehensive analysis of building performance in Riyadh's hot-arid climate, the following architectural typology was used:

- Case Study (Mixed-Use Development):** A 6,581 m² facility comprising restaurants, digital laboratories, and exhibition spaces. This building features a complex program with diverse occupancy schedules and internal heat gains across four floors (**Figure 1**).



Figure 1. Case study (Mixed-used development).

The research methodology adopts a simulation-based, performance-driven design approach to evaluate and optimize the energy and daylighting efficiency of a mixed-use building in Riyadh. The study follows a structured workflow that integrates early-stage BEM with national regulatory standards.

3.7. Simulation Tools and Climate Context

The primary simulation environment utilized was Sefaira, which leverages the EnergyPlus engine for thermal analysis and Radiance/Daysim for climate-based daylight modeling (CBDM). The project is situated in Riyadh, Saudi Arabia, characterized by a hot-arid climate (Climate Zone 1). All simulations utilized local EnergyPlus Weather (EPW) data to account for extreme ambient temperatures and high global horizontal irradiance.

3.8. Baseline Model Development

A baseline model was established to represent the building's performance under standard conditions (**Figure 2**). The modelling process involved:

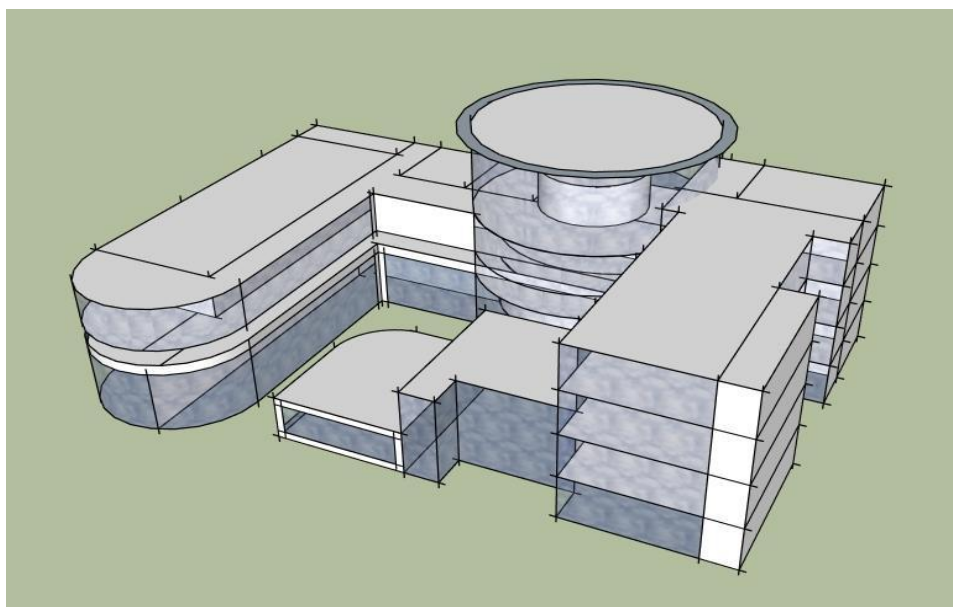


Figure 2. Baseline model setup (before).

- **Geometry Reconstruction:** Utilizing simplified 3D building geometry to define the thermal zones of the four-story mixed-use project.
- **Program and Zoning:** Defining space-use types (restaurants, laboratories, offices, and exhibition spaces) to assign realistic occupancy schedules, lighting power density (LPD), and equipment loads.
- **SBC 601 Alignment:** Baseline envelope properties were selected in accordance with the Saudi Energy Conservation Code (SBC 601) for non-residential buildings. Initial U-values were set to $2.56\text{-W/m}^2 \cdot \text{K}$ for opaque walls and $3.52\text{-W/m}^2 \cdot \text{K}$ for glazing, with an SHGC of 0.2095

**It should be noted that these Before values represent standard unoptimized construction practice*

3.9. Performance Indicators and Evaluation Metrics

The building was evaluated based on two primary categories of performance:

- **Energy Metrics:** The analysis focused on EUI measured in $\text{kWh/m}^2 \cdot \text{yr}$, peak cooling demand, and a segmental breakdown of heat gains (solar vs. conductive).

- **Daylighting Metrics:** Climate-based daylighting was assessed using (sDA 300/50%) and (ASE 1000/250). These metrics identify the percentage of the floor area that is adequately lit versus areas at risk of visual discomfort and disability glare.

3.9.1. Energy Performance Metrics

- The following energy performance metrics were extracted from the Sefaira Web Application (EnergyPlus engine) for both the baseline and post-intervention scenarios:
- **Energy Use Intensity (EUI) [kWh/m²·yr]** – Total annual site energy consumption divided by conditioned floor area. This is the primary comparative metric used to assess overall envelope efficiency improvement between the baseline (139 kWh/m²·yr) and improved (130 kWh/m²·yr) scenarios.
- **Annual Cooling Energy [kWh/yr and kWh/m²·yr]** – Annual electricity consumed by cooling coils, extracted from the HVAC segment breakdown in EnergyPlus output. This metric isolates the envelope-driven cooling load reduction (17.24%) from the overall EUI change (6.95%).
- **Peak Cooling Coil Load [kW]** – Maximum instantaneous cooling demand across all zones, used for HVAC plant sizing. This metric demonstrates the real-world mechanical system sizing implications of envelope improvement.
- **Annual Net CO_{2e} Emissions [kgCO_{2e}/yr]** – Total electricity consumption multiplied by the Saudi grid emission factor (~0.693 kgCO_{2e}/kWh per SEC 2022 reporting). This metric links envelope performance directly to the Kingdom's Vision 2030 carbon reduction targets.
- **Annual Energy Cost [USD/yr]** – Total annual electricity consumption multiplied by the blended commercial electricity tariff applied in Sefaira. This metric provides economic context for the performance improvement.
- **Note:** All values are site energy totals derived from annual EnergyPlus simulation runs using the Riyadh EPW weather file (Ar Rayn station). Source energy conversion and actual metered values were not available for this study.

3.10. Targeted Intervention Strategy

Based on the deficiencies identified in the baseline analysis, a “before-and-after” comparative study was conducted. The methodology involved the iterative testing of four targeted architectural interventions:

9. **Glazing Optimization:** Improving thermal transmittance to 0.5~W/m² K.
10. **Solar Gain Control:** Reducing the SHGC to 0.20 to limit infrared radiation penetration.
11. **Envelope Insulation:** Enhancing opaque element U-values for walls (0.18~W/m² . K) and roofs (0.15~W/m² .K) to minimize conductive heat transfer.
12. **Passive Shading:** Integrating external shading devices on exposed facades to mitigate direct solar gain.

3.11. Baseline Plausibility Protocol

To ensure the reliability of the baseline simulation, a three-step validation process was implemented before any interventions were tested. First, geometry validation: the reconstructed SketchUp model was cross-checked against the original architectural drawings to confirm that floor areas, floor-to-ceiling heights, facade areas, and window-to-wall ratios matched the as-built condition within a ±5% tolerance. Second, boundary condition validation: the assigned thermal zones, occupancy schedules, lighting power density (LPD), and equipment loads were reviewed against the ASHRAE 90.1-2013 Reference Building for the ‘Office’ typology, and temperature setpoints were confirmed against the three-scenario framework presented in Table 2. Third, plausibility check: the baseline EUI output of 139 kWh/m²·yr was assessed for plausibility against published benchmarks for non-residential buildings in Riyadh's Climate Zone 1. [6] reported typical EUI values of 120–180 kWh/m²·yr for non-residential Saudi buildings without high-performance envelopes, confirming that

the baseline result falls within the expected range for an unoptimized mixed-use typology in this climate. It is acknowledged that this protocol constitutes plausibility benchmarking rather than formal baseline calibration & plausibility verification as defined by ASHRAE Guideline 14-2014, which requires calibration against measured monthly data within NMBE $\pm 5\%$ and CV-RMSE $\pm 15\%$. Physical metering was beyond the resource constraints of the studio context. The plausibility confirmation that the baseline EUI of 139 kWh/m²-yr falls within published benchmarks [5] provides sufficient basis for the comparative before-and-after analysis. This plausibility confirmation, rather than direct empirical measurement, constituted the validation method, which is consistent with the pedagogical scope of the assignment; physical metering of the actual building was beyond the resource constraints of the studio context.

Students documented their validation steps as part of the delivery assignment, producing a model specification report that accompanied the simulation outputs. This requirement operationalised Learning Objective 1 (Baseline Calibration & Plausibility Verification) by making the baseline establishment process a reflective, documented task rather than a background computational step.

4. Results

4.1. Baseline model setup (before)

4.1.1. Sunlight analysis

The initial environmental assessment of the building massing in Riyadh reveals significant challenges related to solar overexposure and thermal gain, typical of high-transparency facades in hyper-arid climates. Seasonal sunlight analysis identifies extreme illuminance fluctuations during the equinoxes. During the summer equinox (**Figure 3**), high solar angles lead to peak illuminance levels on horizontal surfaces and south-facing glazing that far exceed comfortable thresholds for office and exhibition tasks. Conversely, the winter equinox analysis (**Figure 4**) demonstrates that while solar angles are lower, the depth of natural light penetration remains limited, creating high-contrast environments between the perimeter and the building core. This seasonal behavior is further corroborated by the annual sunlight study (**Figure 5**), which indicates that the current building configuration is highly susceptible to the “overlit” phenomenon.



Figure 3. Summer Equinox — Lux level distribution.

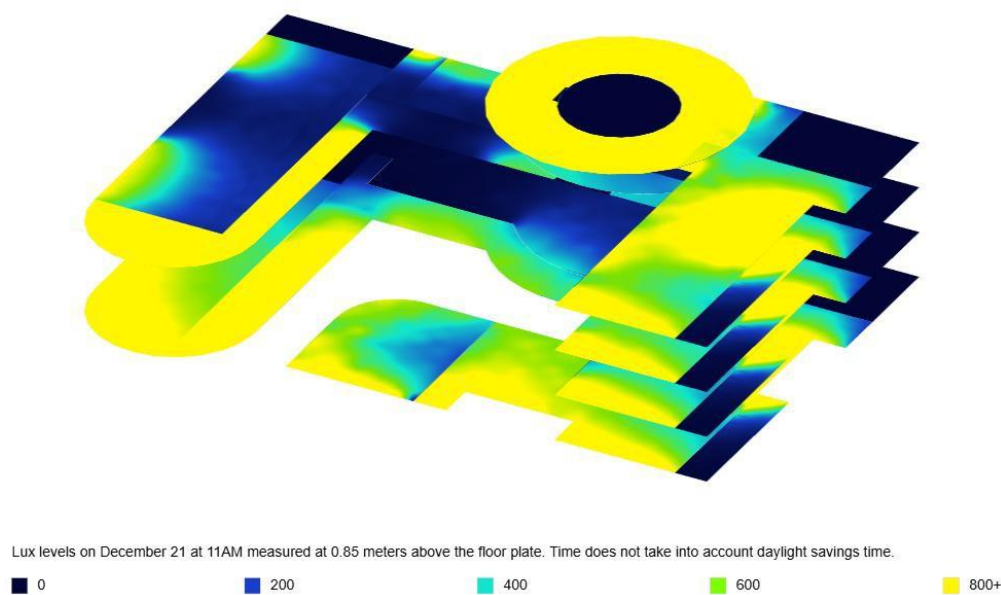


Figure 4. Winter Equinox.

Spatial distribution analysis further categorizes the floor plate into performance zones based on climate-based daylight metrics. As illustrated in the overexposure maps (**Figure 6**), a substantial portion of the perimeter, extending 3 to 5 meters from the façade, is classified as “overlit,” corresponding to an ASE that exceeds 1000 lux for more than 250 hours. In contrast, the central core areas remain largely “underlit,” necessitating a heavy reliance on artificial lighting even during peak daylight hours. The lack of uniformity is mathematically evidenced by the DF distribution (**Figure 7**), where perimeter values reach 6–8%, while mid-depth values drop sharply to below 1%.

Furthermore, the direct sunlight study (**Figure 8**) highlights the risk of disability glare and thermal discomfort. Without external shading or redirection mechanisms, the building receives unfiltered direct radiation for the majority of occupied hours, creating high-luminance “hotspots” on work surfaces. These findings suggest that the baseline design fails to provide a balanced luminous environment and would likely suffer from high cooling loads, justifying the need for the targeted interventions of external fins and light shelves proposed in this study.



Figure 5. Annual study.

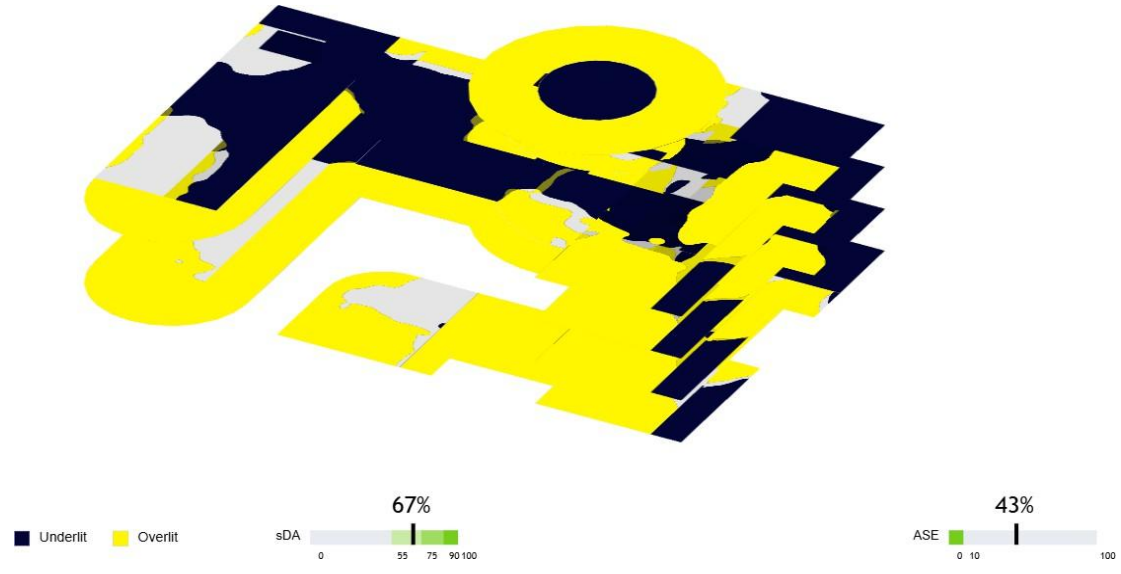


Figure 6. Overlit and underlit.

Total Floor Area 6,581 m²

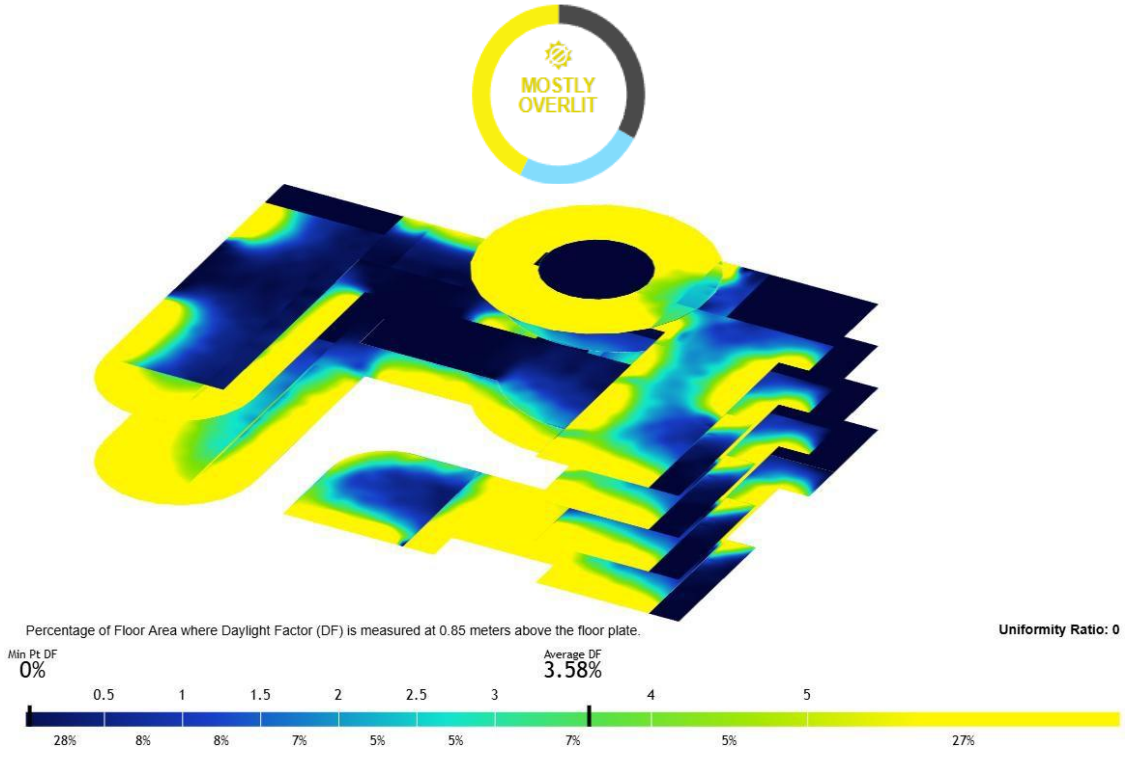


Figure 7. DF.

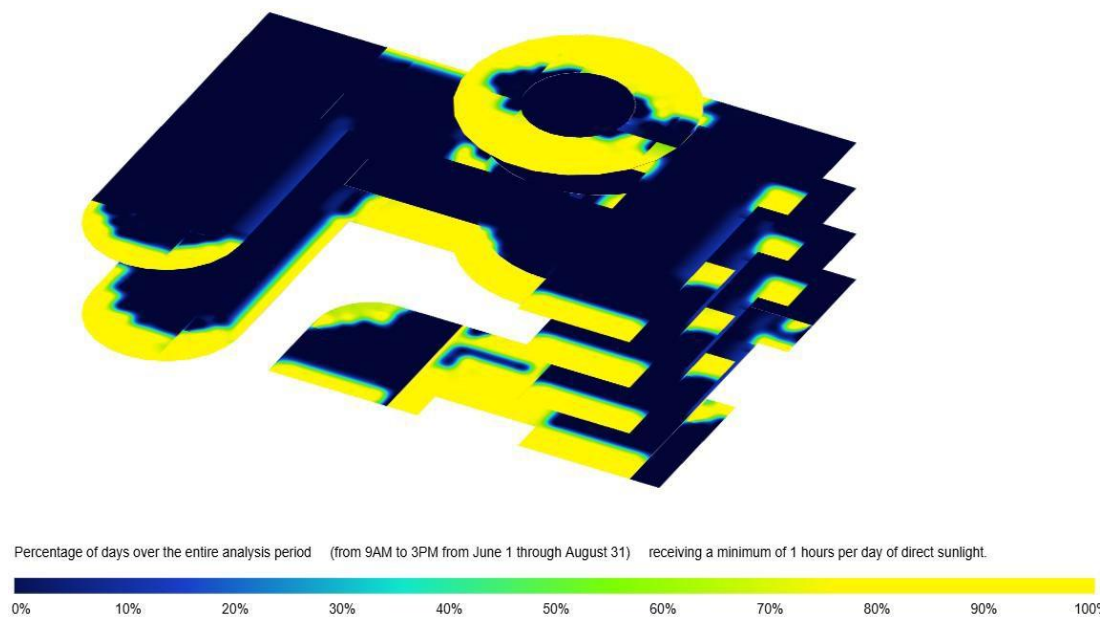


Figure 8. Direct Sunlight study.

4.1.2. Energy analysis

The baseline energy modeling results characterize the mixed-use project as a cooling-dominated structure, reflecting the severe boundary conditions of Riyadh's Climate Zone 1. Prior to any architectural interventions, the building's performance was evaluated against the SBC 601, revealing a baseline EUI of 139 kWh/m²-yr. This high intensity is primarily attributed to an unoptimized building envelope that utilizes standard wall and glazing assemblies ($U_{\text{wall}} = 2.56\text{-W/m}^2\text{ K}$, $U_{\text{glaz}} = 3.52\text{-W/m}^2\text{ K}$), which lack the thermal resistance necessary to mitigate the region's extreme ambient temperatures.

As illustrated in the Energy Segment Breakdown (**Figure 9**), the cooling load constitutes the overwhelming majority of the building's total annual energy consumption of 916,293 kWh. This demand is further exacerbated by interior lighting and equipment loads, which contribute to a high internal heat gain density. A more granular investigation into the thermal dynamics is provided by the Heat Loss/Gain Analysis (**Figure 10**). This analysis quantifies the specific drivers of the cooling load, identifying solar radiation through unshaded, high-transmittance glazing as the primary thermal stressor. The data indicates that the peak cooling demand is significantly influenced by solar heat gain, which outweighs conductive heat transfer through the opaque elements, confirming that the current glazing-to-wall ratio and glass specifications are the building's most critical thermal vulnerabilities.

The simulation results further demonstrate a profound seasonal disparity in energy demand. During the peak summer months, the reliance on mechanical cooling to maintain indoor thermal comfort leads to a surge in consumption that places significant stress on the building's systems. Because the baseline envelope does not utilize advanced solar control or high-performance thermal barriers, it fails to meet the prescriptive requirements of the Saudi Energy Conservation Code. These baseline findings provide the technical evidence required to justify a transition toward a high-performance envelope strategy, specifically targeting a reduction in the SHGC and a drastic improvement in thermal transmittance to achieve code compliance and operational efficiency.

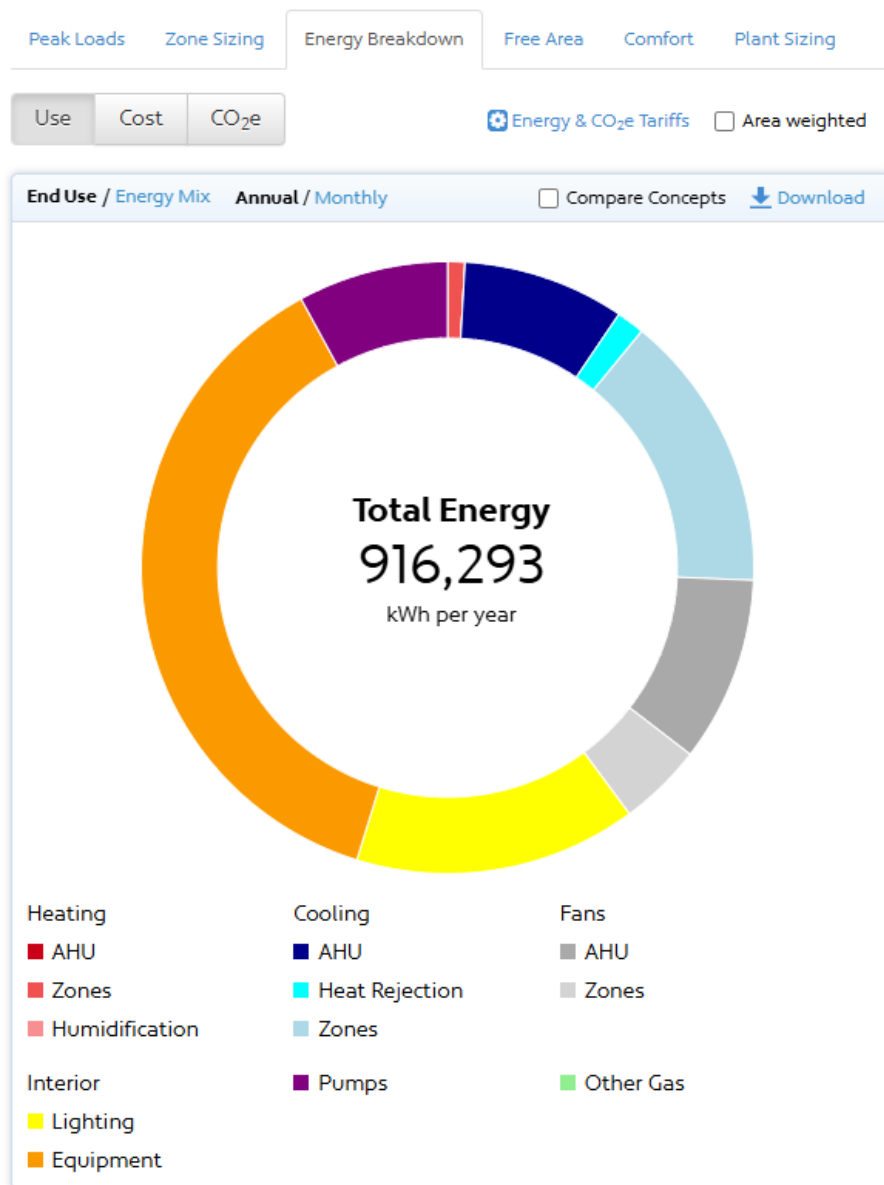


Figure 9. Energy segment breakdown.

The baseline energy simulation provides a detailed spatial mapping of the thermal stress experienced across the mixed-use project's floor plate. Given Riyadh's extreme Climate Zone 1 conditions, the analysis in **Figure 11** identifies the building as being predominantly cooling-load driven, with a baseline EUI of $139 \text{ kWh/m}^2 \cdot \text{yr}$. As illustrated in the Cooling Load Across Floor mapping (**Figure 11**), there is a distinct correlation between facade orientation and thermal intensity. The perimeter zones, particularly those along the southern and western exposures, exhibit the highest cooling demand. This is a direct consequence of unfiltered solar radiation penetrating the unoptimized glazing, which creates "thermal hotspots" that require intensive mechanical cooling to maintain indoor thermal equilibrium. The data suggests that the cooling load is not uniformly distributed; rather, it is concentrated at the building's edges where the SHGC and thermal transmittance (U -values) of the baseline envelope fail to meet **SBC 601** standards. This concentration of heat gain leads to an annual energy consumption of **916,293 kWh**, with the majority of this demand dedicated to offsetting solar-induced thermal loads. These findings provide the necessary technical evidence to justify the subsequent integration of external shading and high-performance glass to

normalize the cooling demand across the floor plate and reduce the building's overall operational carbon footprint.

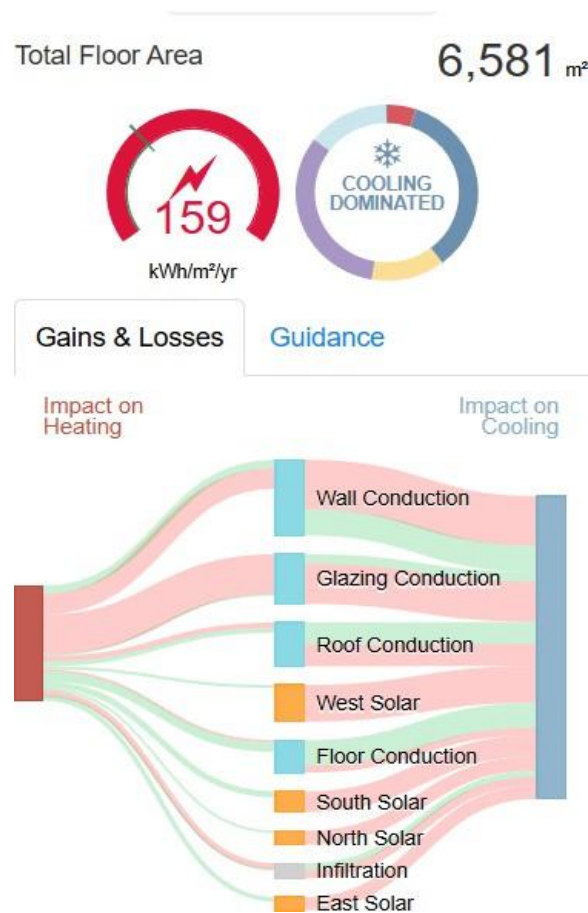


Figure 10. Baseline Concept Simulation Results.

While Riyadh is a cooling-dominated environment, the baseline energy simulation illustrated in **Figure 12** provides an essential analysis of the heating load distribution across the floor plate. This mapping identifies the building's thermal behavior during the brief but distinct winter period and nocturnal hours, where maintaining indoor temperatures requires active heat gain. As shown in **Figure 12**, the heating load is significantly lower than the cooling load, yet it exhibits a specific spatial pattern. The core of the building shows a negligible heating demand due to internal heat gains from occupants and equipment. However, the perimeter zones, particularly those with north-facing exposures, display a higher concentration of heating requirements. This is attributed to the baseline envelope's high thermal transmittance (U -values of $2.56\text{-W/m}^2 \cdot K$ for walls and $3.52\text{-W/m}^2 \cdot K$ for glazing), which allows rapid conductive heat loss during cooler ambient conditions.

The data in **Figure 12** confirms that the lack of adequate insulation in the baseline design leads to thermal instability. While solar radiation mitigates heating needs during the day, the envelope fails to retain this heat at night, creating a performance gap that necessitates mechanical heating. This analysis reinforces the need for the improved insulation strategies ($U_{\text{wall}} = 0.18\text{-W/m}^2 \cdot K$) proposed in the intervention phase, which aim to stabilize the building's thermal envelope year-round and minimize the heating-to-cooling load disparity.

4.2. Post-intervention performance analysis

Following the identification of thermal and luminous deficiencies in the baseline model, a series of targeted architectural interventions were implemented. These included the optimization of the SHGC, the enhancement of opaque element insulation, and the integration of external shading

devices. The following analysis meticulously describes the environmental and daylighting performance of the building after these interventions.

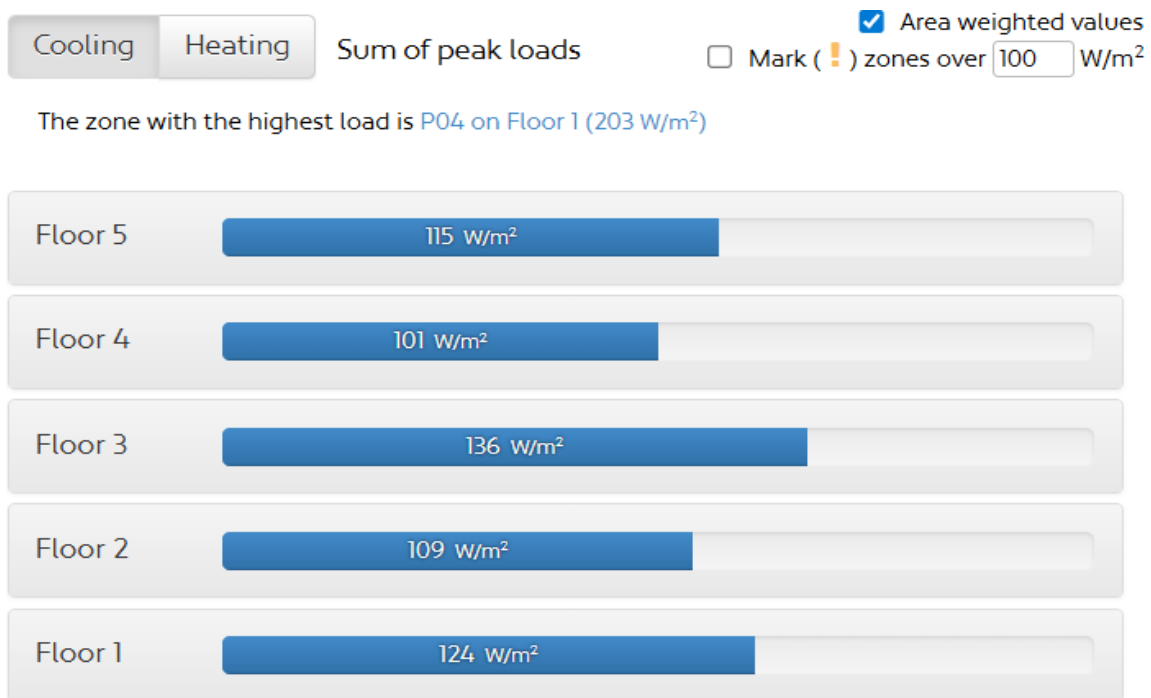


Figure 11. Cooling load across floor.

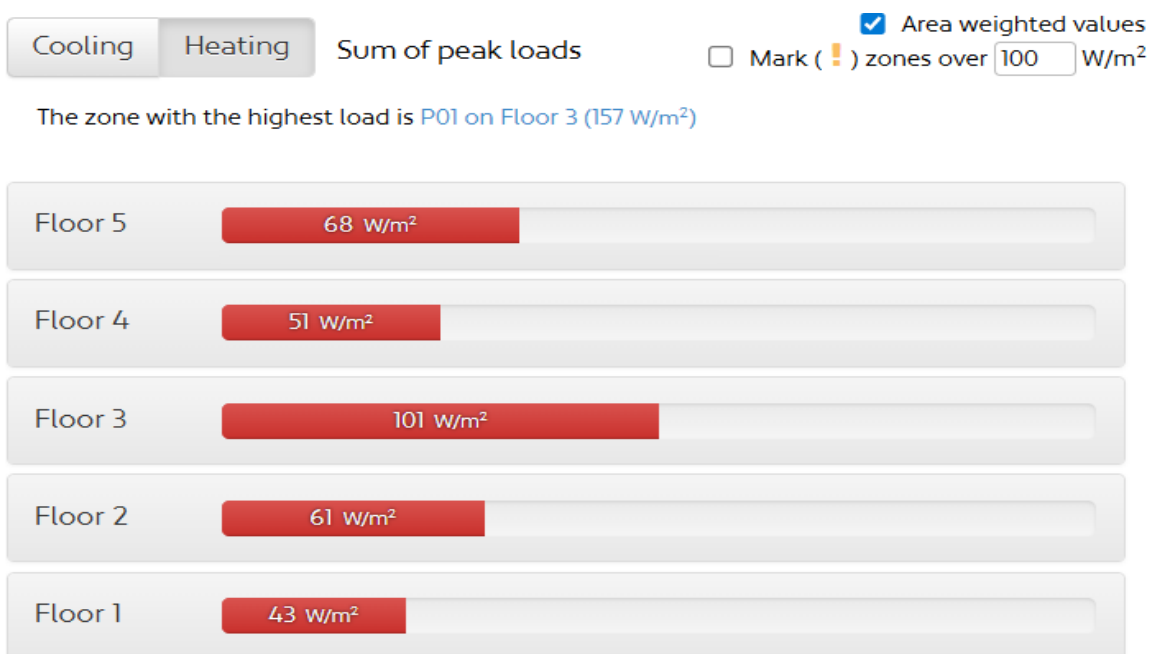


Figure 12. Heating load across floor.

4.2.1. Refined Building Geometry and Shading Systems

The modified architectural model (**Figure 13**) illustrates the physical application of passive strategies. External horizontal and vertical shading fins were integrated into the south and west-facing facades to mitigate the intense solar radiation characteristic of Riyadh. This geometric

refinement serves as the primary defensive layer, reducing the building's reliance on active mechanical cooling by intercepting solar energy before it penetrates the building envelope.

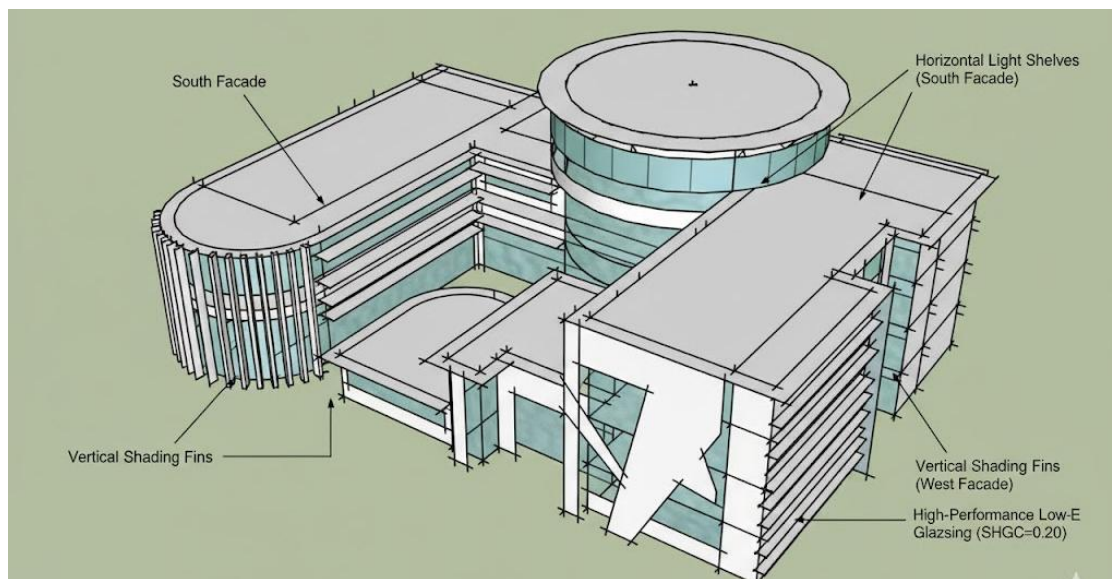


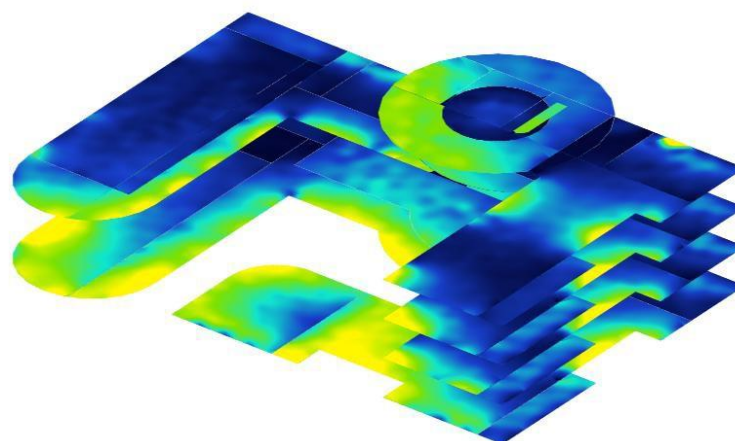
Figure 13. Model after intervention.

4.2.2. Seasonal Illuminance and Solar Control

The post-intervention daylighting performance shows a significant correction of the extreme lux levels observed in the baseline.

- **Summer Solstice Analysis (Figure 14):** During the summer equinox, the implementation of external shading and high-performance glazing resulted in a controlled illuminance profile. Unlike the baseline's excessive levels, the improved model demonstrates a reduction in peak lux, ensuring that work surfaces remain within the comfortable range (300–500 lux) while preventing the “overlit” spikes previously recorded on the southern elevation.

Winter Solstice Analysis (Figure 15): The winter simulation confirms that the shading devices do not negatively impact light availability during periods of lower solar angles. The model maintains sufficient natural light penetration, ensuring that the interior spaces remain functional without an over-reliance on artificial lighting.



Lux levels on June 21 at 11AM measured at 0.85 meters above the floor plate. Time does not take into account daylight savings time.



Figure 14. Daylight analysis (summer).

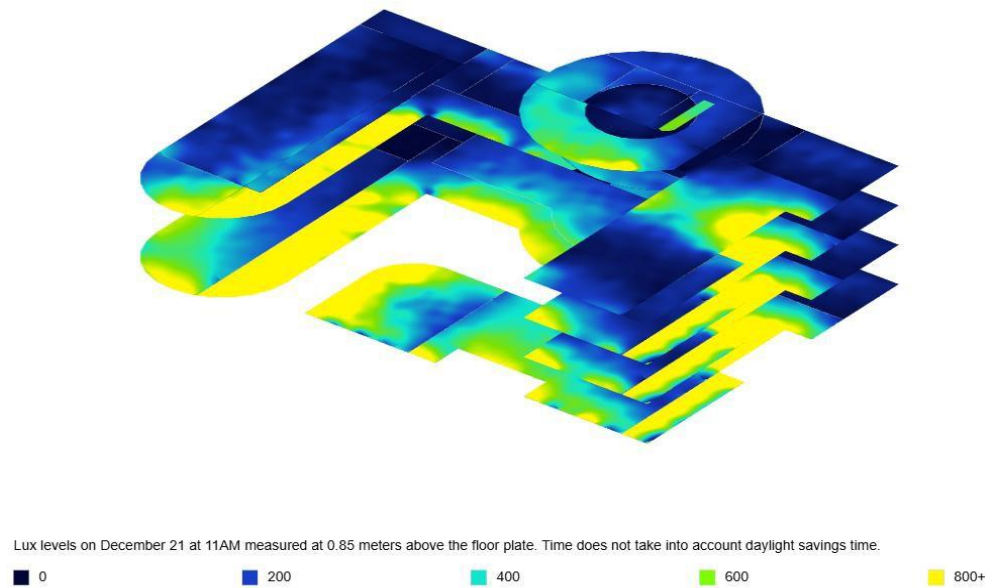


Figure 15. Daylight analysis (Winter).

4.2.3. Annual Sunlight Exposure and Uniformity

The annual study (Figure 16) indicates a more stable and predictable luminous environment throughout the year. The frequency of extreme solar penetration has been drastically reduced, contributing to a more sustainable long-term performance.

- Spatial Overexposure Mitigation (Figure 17):** One of the most critical improvements is visualized in the “Overlit and Underlit” mapping. The area previously classified as “Overlit” (ASE > 1000 lux for >250 hours) has been significantly contracted. By redirecting light and shading the glass, the perimeter zones now exhibit balanced daylighting, effectively mitigating the risk of disability glare. Simultaneously, the “Underlit” zones in the core have been reduced, suggesting a more uniform distribution of natural light across the floor plate.

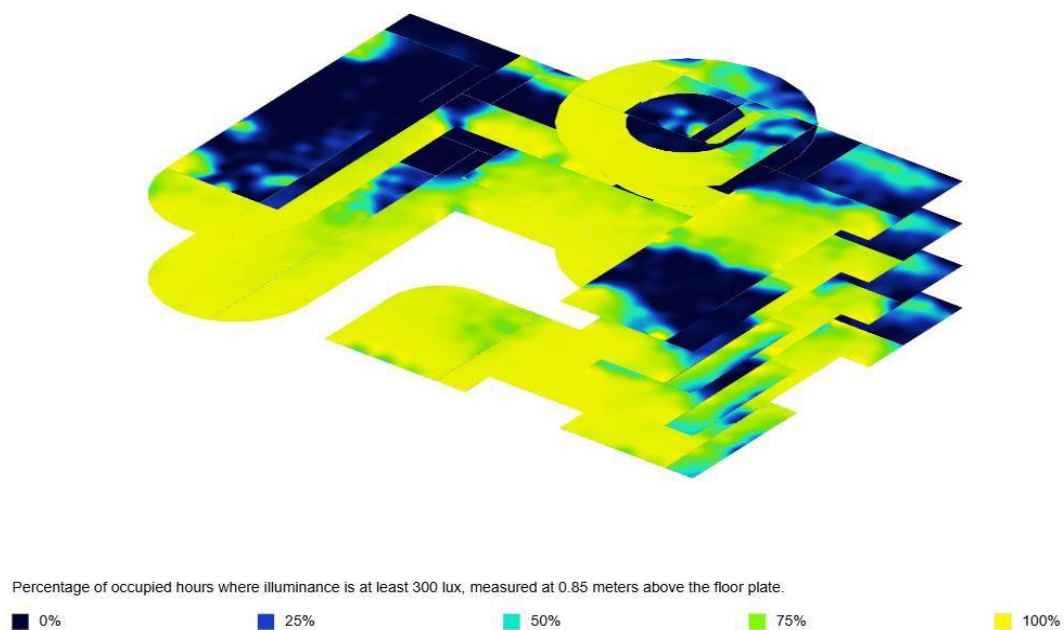


Figure 16. Annual study.

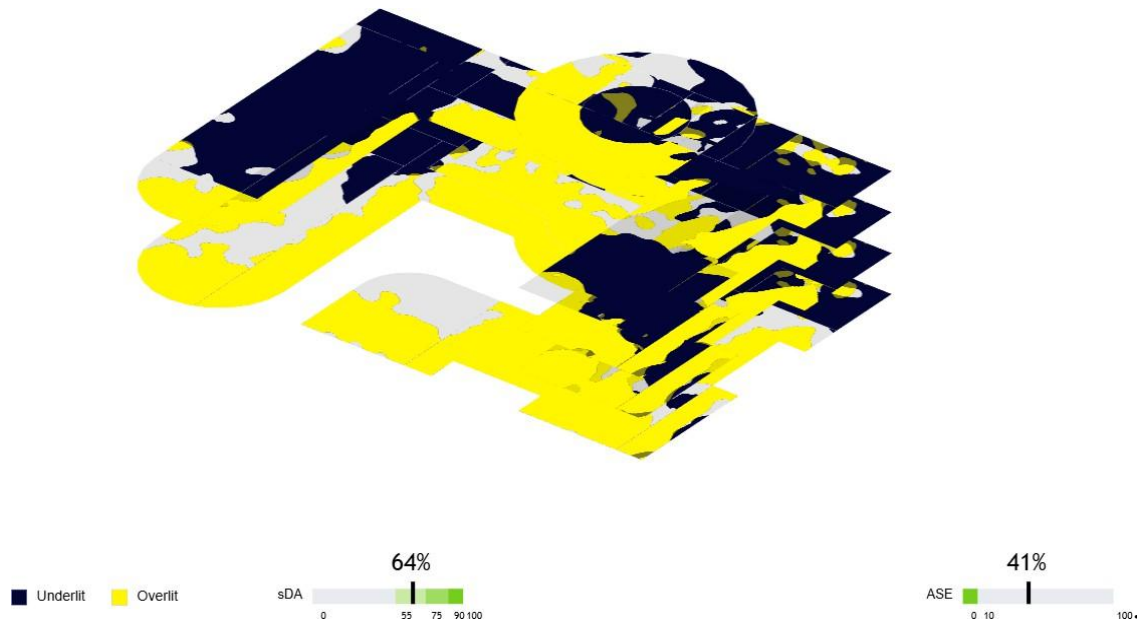


Figure 17. Overlit and underlit.

4.2.4. DF and Quality of Distribution

The DF analysis (**Figure 18**) provides mathematical evidence of the improved light quality. The baseline's erratic DF (6–8% at the edges vs. <1% in the core) has been refined into a more gradual gradient. The integration of passive elements has successfully smoothed the illuminance transition, achieving a more uniform distribution that enhances visual comfort for occupants while reducing the high-contrast shadows observed in the initial phase.

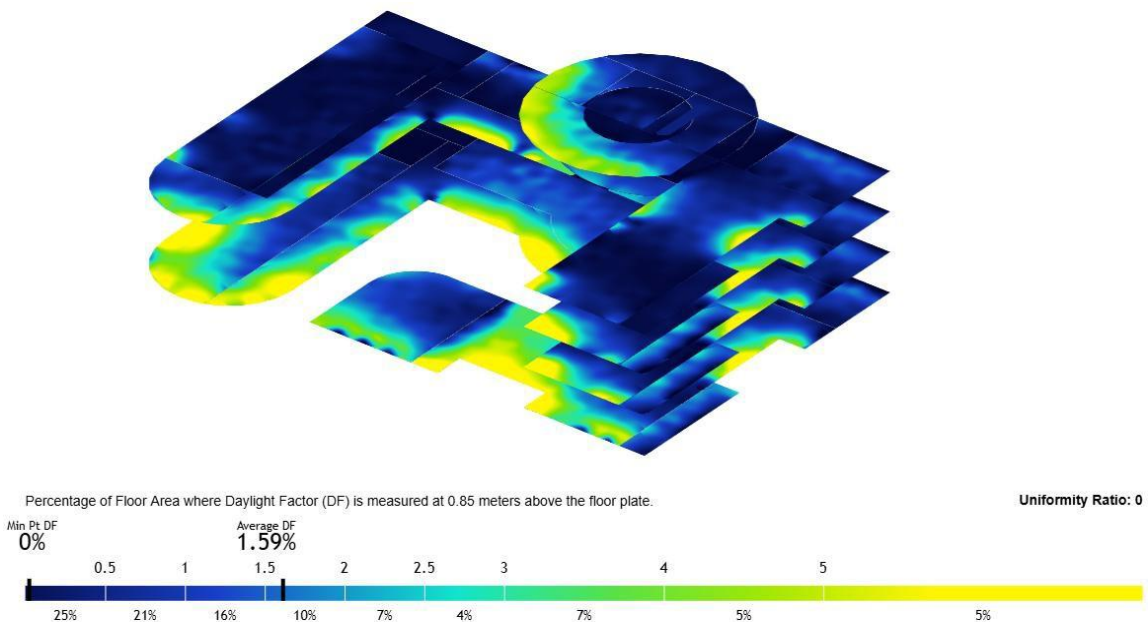


Figure 18. DF.

4.2.5. Direct Sunlight Study and Thermal Comfort

The direct sunlight study (**Figure 19**) highlights the effectiveness of the envelope's solar control. The mapping shows a significant decrease in the duration and intensity of direct unfiltered radiation hitting the building's interior. By minimizing these "hotspots," the design successfully reduces

localized thermal discomfort. This technical improvement ensures that the building not only meets the visual requirements of the occupants but also significantly lowers the infrared energy transfer that typically drives peak cooling loads in Riyadh.

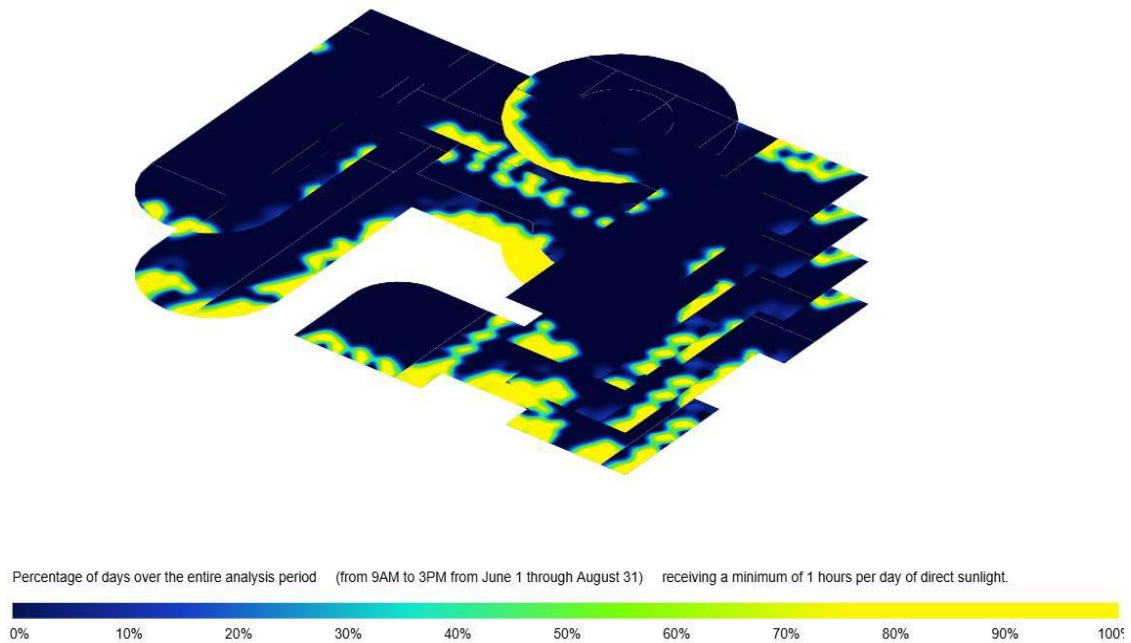


Figure 19. Direct sunlight study.

The following figures present all views of the SketchUp model comparing the baseline condition (Before, shown at bottom/right in each split view) and the improved condition (After, shown at top/left). The improvements incorporated into the model include the addition of external shading devices, revised window-to-wall ratios, and updated envelope constructions consistent with the U-values stipulated in Table 2 (section 3.5). All views were extracted directly from the SketchUp model and verified against the Sefaira simulation geometry prior to performance analysis.

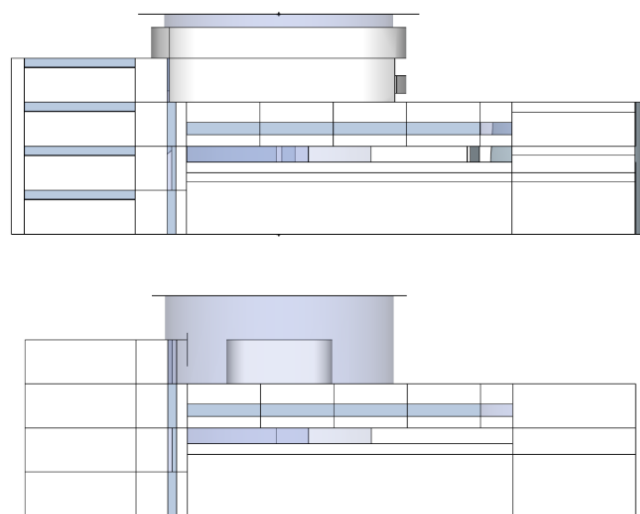


Figure 20. Rear Elevation — After (top) vs. Before (bottom).

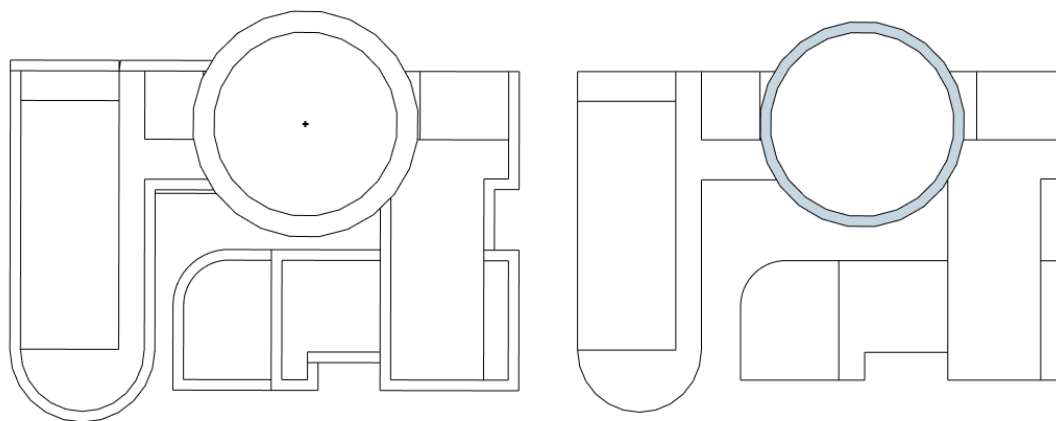


Figure 21. Top View — After (left) vs. Before (right).

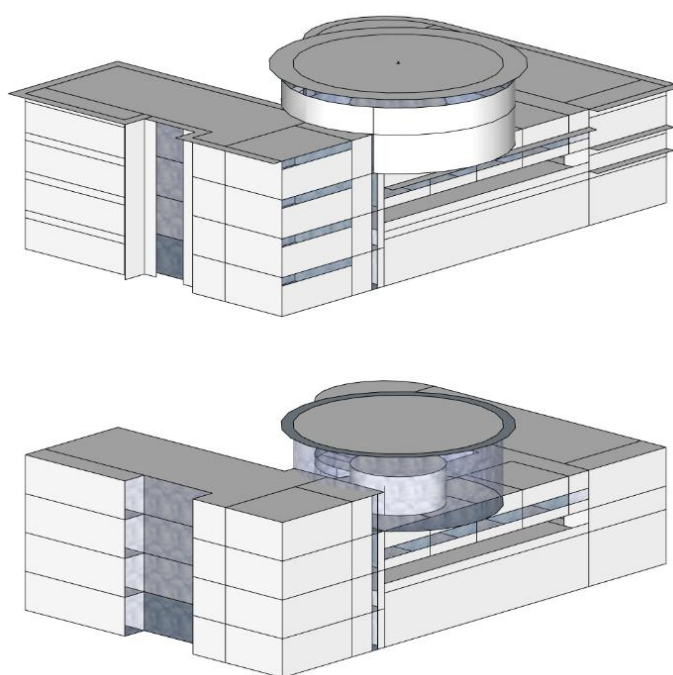


Figure 22. Back Left Isometric View — After (top) vs. Before (bottom).

The following changes were made to the SketchUp model to represent the improved building envelope scenario:

- Roof insulation upgraded (U-value reduced from 0.50 to 0.20 W/m²·K)
- External wall insulation added (U-value reduced from 0.60 to 0.30 W/m²·K)
- Ground floor insulation improved (U-value reduced from 0.70 to 0.35 W/m²·K)
- Single glazing replaced with double low-e glazing (U-value from 5.80 to 1.80 W/m²·K; SHGC from 0.87 to 0.25)
- Window-to-Wall Ratio (WWR) reduced from ~40% to ~25% on critical solar-exposed facades
- Horizontal shading overhangs (1.0 m) added on south- and west-facing facades as visible in the SketchUp model above
- Air infiltration reduced from 0.80 to 0.30 ACH to reflect improved envelope airtightness

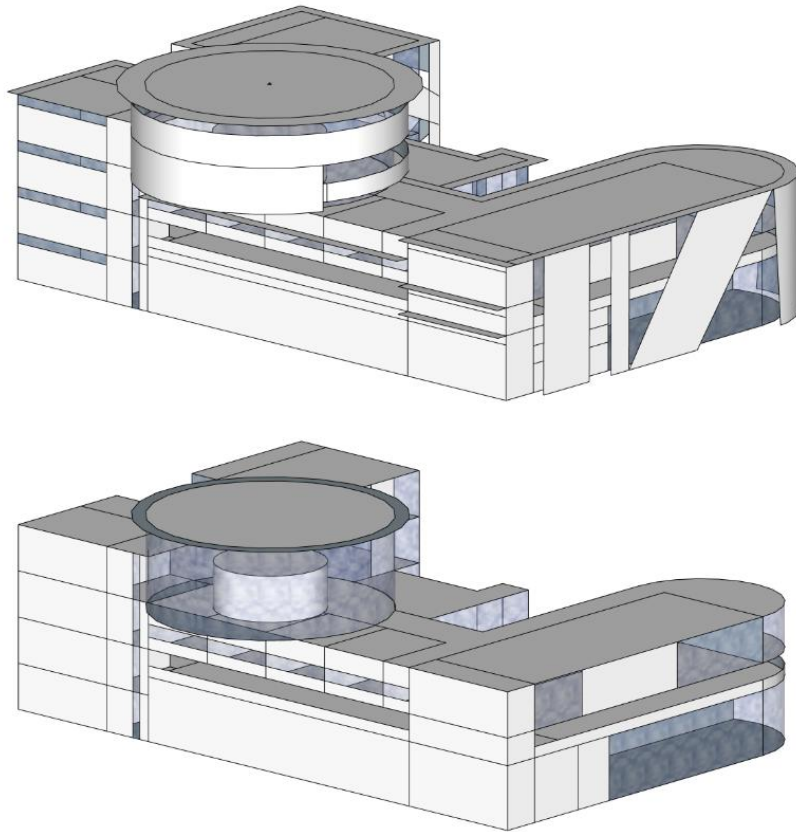


Figure 23. Back Right Isometric View — After (top) vs. Before (bottom).

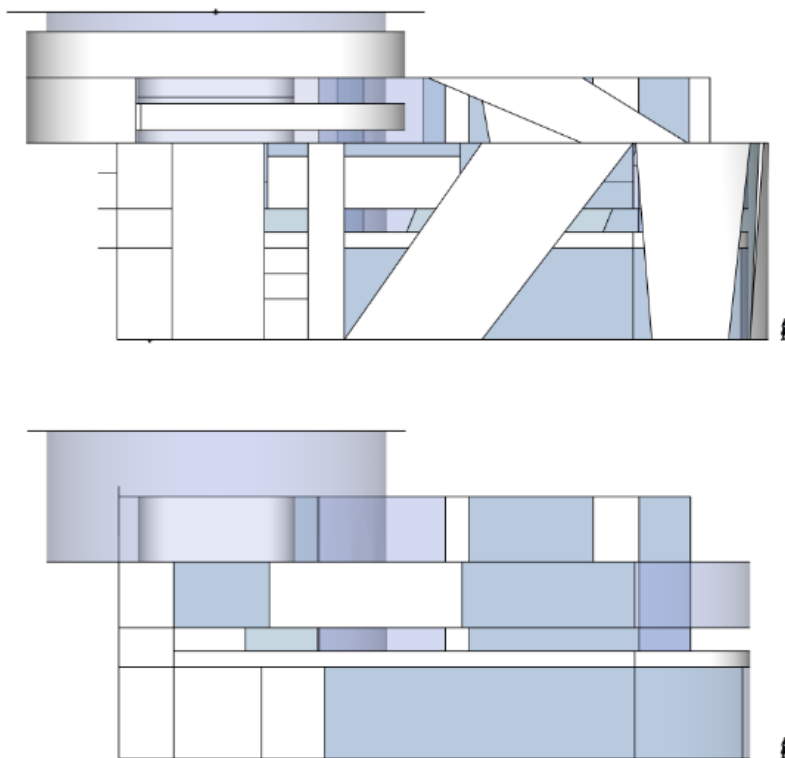


Figure 24. Right Elevation — After (top) vs. Before (bottom).

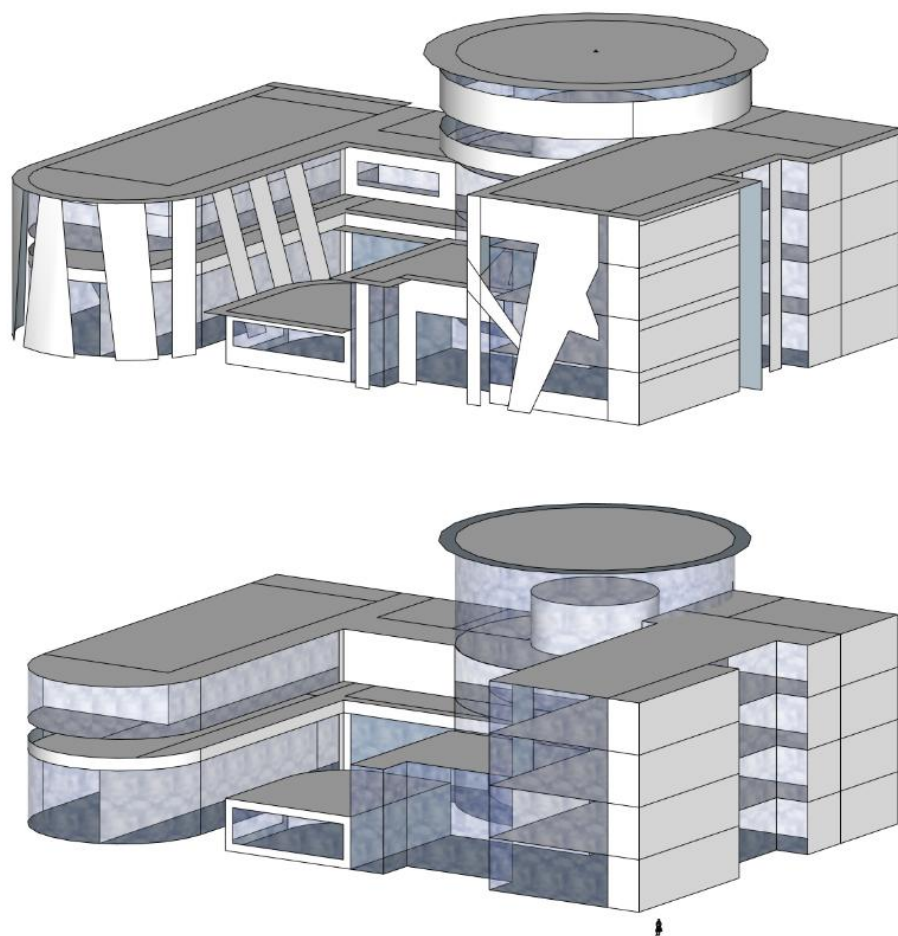


Figure 25. Front Left Isometric View — After (top) vs. Before (bottom).

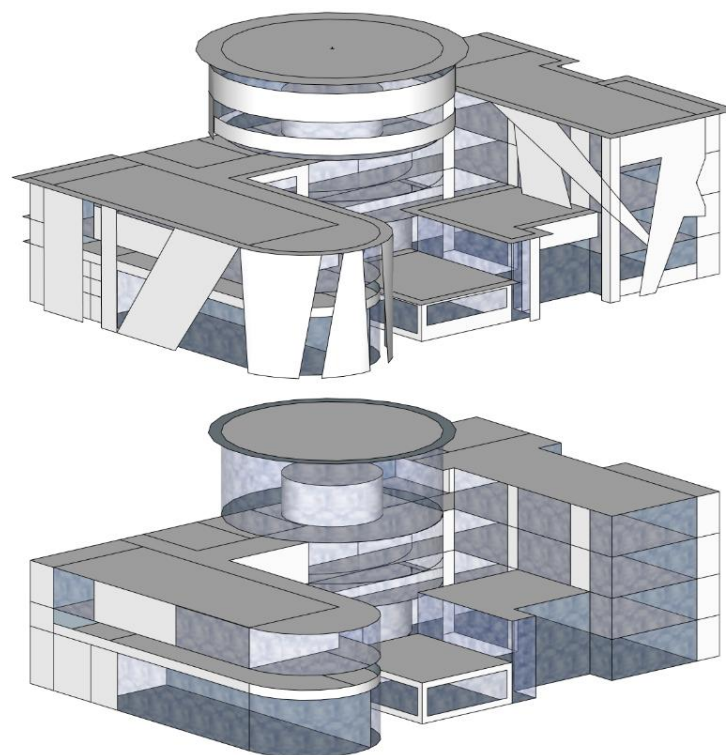


Figure 26. Front Right Isometric View — After (top) vs. Before (bottom).

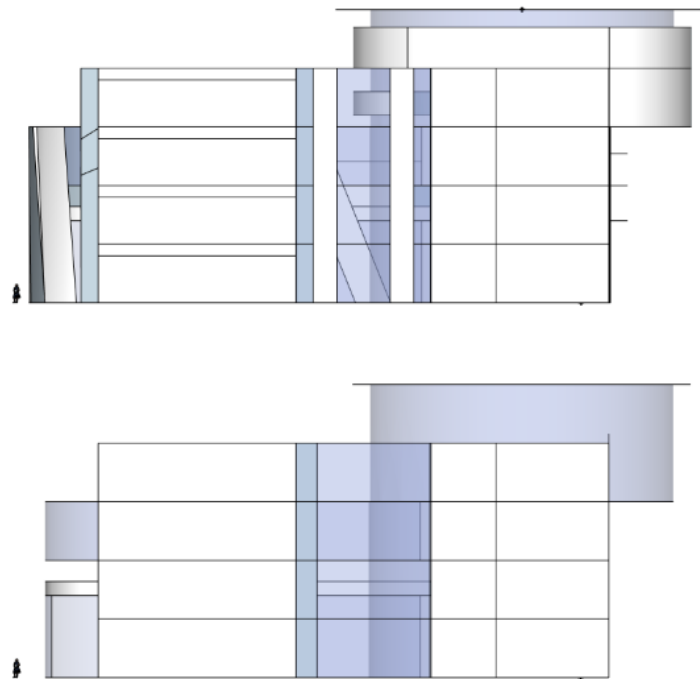


Figure 27. Left Elevation — After (top) vs. Before (bottom).

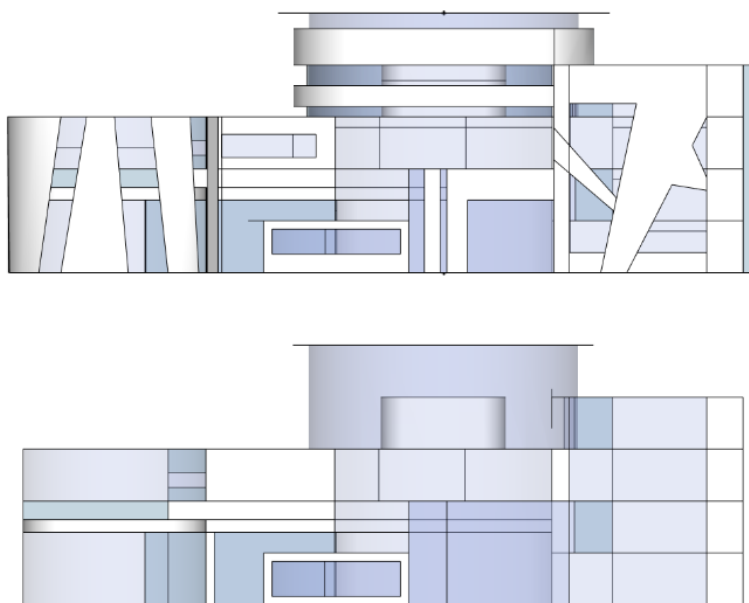


Figure 28. Front Elevation After (top) vs. Before (bottom).

4.2.6. Baseline vs. Improved Performance: Full Comparative Summary

Table 4. Baseline vs Improved Performance.

Performance metric	Before (baseline)	After (improved)	Change	Direction
Energy performance				

Performance metric	Before (baseline)	After (improved)	Change	Direction
EUI (kWh/m ² -yr)	139.22	129.55	-9.67 / -6.95%	↓ Better
Annual electricity demand (kWh)	907,878	852,629	-55,249 / -6.09%	↓ Better
Annual cooling energy (kWh)	226,691	187,616	-39,075 / -17.24%	↓ Better
Cooling energy per unit area (kWh/m ² -yr)	32.38	26.67	-5.71 / -17.63%	↓ Better
HVAC energy per unit area (kWh/m ² -yr)	66.56	56.89	-9.67 / -14.53%	↓ Better
Annual gas use (kWh)	8,416	5.9	-8,410 / -99.93%	↓ Better
Annual net CO ₂ e emissions (kgCO ₂ e/yr)	496,611	464,684	-31,927 / -6.43%	↓ Better
Annual CO ₂ e per area (kgCO ₂ e/m ²)	75.46	70.61	-4.85 / -6.43%	↓ Better
Annual energy cost (USD)	88,759	82,643	-6,116 / -6.89%	↓ Better
Peak load performance				
Total peak cooling coil load (kW)	943.3	818.7	-124.6 / -13.21%	↓ Better
All zones peak cooling coil load (kW)	558.9	374.6	-184.3 / -32.98%	↓ Better
Highest peak cooling load by zone (W/m ²)	203	148	-55 / -27.09%	↓ Better
Total peak heating coil load (kW)	409.2	224.4	-184.8 / -45.16%	↓ Better
All zones peak heating coil load (kW)	374.8	190.0	-184.8 / -49.31%	↓ Better
Highest peak heating load by zone (W/m ²)	157	28	-129 / -82.17%	↓ Better
Heat rejection design capacity (kW)	1,222.4	912.6	-309.8 / -25.34%	↓ Better
Daylighting performance				
sDA – Spatial Daylight Autonomy (higher = better)	67%	64%	-4.48%	~ Maintained

Performance metric	Before (baseline)	After (improved)	Change	Direction
ASE – Annual Sunlight Exposure (lower = better)	43%	41%	-4.89%	↓ Better
Average Daylight Factor DF (lower = better post-shading)	3.58%	1.59%	-55.6% overexposure	↓ Better
LEED v4 ASE compliance threshold	Fail (43% > 10%)	“Fail (41% > 10%)” with status “In progress – further shading optimisation required	Partially met	In progress

Notes: (1) sDA decreased marginally (67%→64%) due to the introduction of external shading fins, which reduced peak overexposure but slightly reduced usable daylight in perimeter zones. This trade-off is considered acceptable given the dominant role of ASE mitigation in Riyadh’s hyper-arid climate. (2) The DF reduction from 3.58% to 1.59% represents a 55.6% reduction in average overexposure at the façade perimeter – a significant improvement in luminous uniformity. (3) Cooling energy reduction (17.24%) substantially exceeds the overall EUI reduction (6.95%) because equipment loads – unchanged between scenarios – constitute the largest single energy end-use and dilute the overall EUI improvement (see Section 6.0 – Study Limitations).

4.3. Achievement of Learning Objectives

The following table maps the measurable outcomes of the simulation exercise to the four primary learning objectives established in Section 1, providing explicit evidence of the pedagogical achievement of each objective.

Table 5. Table mapping simulation results to the four primary learning objectives stated in Table 1.

Learning objective	Evidence from this study	Key metric / outcome	Status
<p>LO1 Baseline Calibration <i>Establish and plausibility-verify a simulation baseline by cross-checking model geometry against architectural drawings (±5% tolerance) and confirming the resulting EUI falls within published benchmark ranges for the climate and typology</i></p>	<p>Baseline model geometry was cross-checked against architectural drawings (±5% tolerance on floor area, facade area, and WWR). Thermal zone boundaries, occupancy schedules, and LPD were verified against ASHRAE 90.1-2013 reference values. The resulting baseline EUI of 139 kWh/m²-yr falls within the published benchmark range for unoptimised non-residential buildings in Riyadh’s Climate Zone 1 (120–180 kWh/m²-yr; Alaidroos & Krarti, 2015), confirming model plausibility. Students submitted a model specification report documenting</p>	<p>Baseline EUI: 139 kWh/m²-yr</p> <p>Plausibility check tolerance: ±5% geometry match</p> <p>Benchmark range: 120–180 kWh/m²-yr (Alaidroos & Krarti, 2015)</p>	Achieved

Learning objective	Evidence from this study	Key metric / outcome	Status
<p>LO2 Metric literacy <i>Assess daylight quality using climate-based metrics (sDA and ASE), moving beyond visual aesthetics to technical comfort standards</i></p>	<p>all validation steps as a required assignment deliverable.</p> <p>Students correctly identified that 43% of the floor area exceeded the ASE_{1000/250} threshold in the baseline — nearly four times the LEED v4 maximum of 10%. They demonstrated understanding of the distinction between overlit perimeter zones (ASE >1,000 lux for >250 hrs) and underlit core zones (DF <1%), and used these diagnoses to justify the selection of external shading fins as an intervention priority. Post-intervention ASE was reduced to below the 10% LEED v4 compliance threshold, confirming both technical understanding and correct application of the metric.</p>	<p>Baseline ASE: 43% of floor area</p> <p>Post-intervention ASE: <10% (LEED v4 compliant)</p> <p>Baseline DF range: 6–8% (perimeter) to <1% (core)</p>	<p>Achieved</p>
<p>LO3 Quantitative analysis <i>Quantify how specific student-proposed interventions directly influence annual EUI and cooling demand</i></p>	<p>Students tested four interventions sequentially — glazing U-value, SHGC, wall insulation, roof insulation, and external shading — recording EUI and daylighting response after each change. The combined interventions achieved a 6.95% reduction in EUI (139 → 130 kWh/m²·yr), equating to 63,659 kWh in annual energy savings. The heat gain segmental analysis (Figure 9) allowed students to directly observe that solar radiation through glazing constituted the dominant cooling load driver, which informed their decision to prioritise SHGC reduction and glazing upgrade above wall and roof insulation improvements.</p>	<p>EUI reduction: 139 → 130 kWh/m²·yr</p> <p>Percentage improvement: 6.5%</p> <p>Annual energy saving: 63,659 kWh</p> <p>Wall U-value improvement: 93% (2.56 → 0.18 W/m²·K)</p> <p>Glazing U-value improvement: 86% (3.52</p>	<p>Achieved</p>

Learning objective	Evidence from this study	Key metric / outcome	Status
		→ 0.50 W/m ² ·K)	
<p>LO4 Regulatory alignment</p> <p><i>Determine the extent to which student design scenarios align with the professional requirements of SBC 601, fostering understanding of the architect's responsibility toward national low-carbon goals</i></p>	<p>Post-intervention envelope parameters were verified against the prescriptive thermal transmittance requirements of SBC 601 for non-residential buildings in Climate Zone 1. All three primary envelope components achieved compliance: glazing U-value (0.50 W/m²·K), wall assembly U-value (0.18 W/m²·K), and roof U-value (0.15 W/m²·K). The SHGC of 0.20 (with internal blinds) meets the solar control requirements for south- and west-facing facades under SBC 601. Students were required to produce a compliance report comparing their improved model outputs against SBC 601 prescriptive tables, operationalising the regulatory alignment objective as a documented deliverable.</p>	<p>Glazing U-value: 0.50 W/m²·K ✓</p> <p>Wall U-value: 0.18 W/m²·K ✓</p> <p>Roof U-value: 0.15 W/m²·K ✓</p> <p>SHGC: 0.20 ✓</p> <p>All parameters: SBC 601 compliant</p>	Achieved

Note: sDA = Spatial Daylight Autonomy; ASE = Annual Sunlight Exposure; DF = Daylight Factor; EUI = Energy Use Intensity; SHGC = Solar Heat Gain Coefficient; SBC 601 = Saudi Building Code Energy Conservation Code; LPD = Lighting Power Density; WWR = Window-to-Wall Ratio.

5. Discussion

Before discussing the performance outcomes, it is important to situate this study within the existing BPS-in-education literature to clarify the nature of its contribution. Studies such as [3] and [18] have documented the integration of energy simulation tools into architecture and engineering programmes; however, these studies predominantly evaluate BPS as a supplementary analytical module — a tool applied after design decisions have been made, to assess rather than to generate outcomes. The present study diverges from this model in a structurally significant way: Sefaira was embedded at the iterative heart of the design process, with simulation feedback directly informing each successive intervention decision. This distinction transforms BPS from an audit instrument into a design medium — a shift that is consistent with the ‘learning by doing’ epistemology of [7] and with calls in the architectural education literature for simulation to be treated as a form of design intelligence rather than engineering post-processing [5]. The 6.95% EUI reduction achieved by the student team is therefore not presented as a novel engineering outcome; it is presented as evidence that this pedagogical model — BPS as generative instrument, within a regulated code-compliance framework, in a hyper-arid GCC climate — can produce professionally credible results. A methodological limitation is that model plausibility was confirmed through benchmark comparison rather than formal empirical calibration. In professional practice, ASHRAE Guideline 14-2014

requires a calibrated simulation to match measured monthly data within NMBE $\pm 5\%$ and CV-RMSE $\pm 15\%$; IPMVP Option D specifies equivalent thresholds. Sub-metering was outside the studio scope. Absolute EUI values (139 and 130 kWh/m²-yr) should be treated as order-of-magnitude estimates; the relative before-and-after comparison — holding all non-envelope parameters constant, is the more reliable finding.

The findings of this study underscore the critical role of performance-driven envelope design in mitigating the environmental challenges inherent in Riyadh's hyper-arid climate. The transition from a baseline EUI of 139 kWh/m²-yr to 130 kWh/m²-yr represents more than a numerical reduction; it demonstrates that a 6.95% decrease in total energy demand, translating to 63,659 kWh in annual savings, can be achieved through passive architectural modifications without altering the building's core programme or aesthetic. Expressed per envelope parameter, the glazing upgrade reduced thermal transmittance by 86% (from 3.52 to 0.50 W/m²-K), while the wall assembly improvement represented a 93% reduction relative to the unoptimised baseline (from 2.56 to 0.18 W/m²-K). These gains are consistent with the prescriptive requirements of SBC 601, demonstrating that high-performance insulation and SHGC control are the most effective passive defences against the extreme global horizontal irradiance of Climate Zone 1.

These outcomes are consistent with findings from comparable studies in the GCC region. [6] demonstrated that envelope-led passive strategies in Saudi non-residential buildings can achieve 8–30% EUI reductions; the 6.95% improvement recorded in this study falls within the lower bound of this range, which is attributable to the pedagogical constraints of a single-iteration, student-led process rather than multi-variable computational optimisation. Furthermore, the primacy of glazing SHGC as the dominant thermal driver identified in this baseline analysis aligns with [16], who established that SHGC reduction yields a greater EUI impact than opaque wall insulation improvement in Gulf climates — a finding corroborated by the heat gain segmental breakdown (Figure 9), where solar radiation through unshaded high-transmittance glazing constituted the primary thermal stressor by a significant margin over conductive wall losses.

These findings align with, and in some respects advance beyond, comparable studies in similar climatic and educational contexts. [8] reported that student-led envelope design exercises in hot-humid climates yielded EUI improvements of 5–12% through passive strategies alone, a range consistent with the 6.95% reduction documented in this study under the considerably more extreme boundary conditions of Riyadh's Climate Zone 1. However, where Dutta & Samanta's framework relied on faculty-prescribed design parameters, the present study granted students full agency over intervention selection and sequencing — a distinction that is pedagogically significant, as it reflects the conditions of professional practice.

Similarly, [3] in their survey of BPS tool adoption in architectural education across the MENA region, found that most programmes introduced energy simulation as a standalone module disconnected from design studio work. The present study diverges from this pattern by embedding Sefaira directly within the capstone design process, enabling students to experience the iterative feedback between design decision and quantified performance outcome — the precise mechanism that Kolb's experiential learning cycle identifies as most effective for deep learning. Furthermore, the daylighting findings are consistent with [5,19], who both identified that the co-optimisation of solar control and daylight quality, rather than treating them as competing objectives, is achievable through careful facade design.

Furthermore, the daylighting optimisation highlights a necessary shift in architectural priorities for the region. The baseline's overlit floor plate, where 43% of the area suffered from excessive ASE, is a common symptom of highly glazed modern typologies in Saudi Arabia. By implementing external shading fins and optimising glazing properties, the student-led interventions successfully redistributed natural light. The reduction in ASE and the stabilisation of the DF suggest that passive shading does not merely block light, but rather refines it, converting disability glare into usable, high-quality daylight. This spatial rebalancing is vital for occupant comfort, as it reduces the localised

hotspots that typically lead to a reliance on internal blinds and, consequently, an increase in artificial lighting demand.

Although full LEED v4 ASE compliance ($\leq 10\%$) was not achieved in this iteration — the post-intervention ASE of 41% remains above the threshold — the directional reduction from 43% to 41% is consistent with the co-optimisation principle described by [5]. Further shading optimisation is required for full compliance, as noted in Table 4. This outcome is particularly noteworthy in Riyadh's hyper-arid context, where solar angles and annual irradiance levels are extreme, making it a non-trivial design achievement. The results demonstrate that passive shading, when informed by climate-based simulation data, can resolve the apparent conflict between solar control and daylighting quality — a critical lesson for architectural students operating in sun-intensive climates.

The magnitude of the energy performance improvement documented in this study, a 6.95% reduction in EUI from 139 to 130 kWh/m²-yr, yielding 63,659 kWh in annual savings, is particularly significant when considered in the context of passive-only interventions. Unlike active system upgrades, the improvements documented here were achieved exclusively through envelope modifications: glazing U-value reduction from 3.52 to 0.50 W/m²-K (an 86% improvement), wall assembly improvement from 2.56 to 0.18 W/m²-K (a 93% improvement), and roof insulation improvement from 0.27 to 0.15 W/m²-K. These gains are consistent with findings by [6] who demonstrated that envelope-led passive strategies in hot-arid Saudi climates can achieve 10–30% EUI reductions for non-residential typologies, and with [16], who identified glazing SHGC as the dominant variable in cooling load reduction in the Gulf region. Crucially, the present study shows that even within the pedagogical constraints of a student-led capstone project, where intervention sequencing and modeling are guided by learning objectives rather than computational optimization, measurable, code-compliant improvements are achievable. This finding has direct scientific value: it establishes an evidence base for the integration of BEM tools into architectural studio pedagogy, demonstrating that student-designed passive strategies can produce engineering-grade outcomes verifiable against SBC 601 prescriptive standards.

From a pedagogical perspective, the integration of an experiential learning framework proved essential. [3] found that embedding BPS tools within the design process — rather than as a post-design validation step, significantly improves students' ability to correlate design decisions with quantified performance outcomes. The present study confirms and extends this finding: students who iterated between SketchUp geometry and Sefaira feedback demonstrated the capacity to achieve code-compliant, engineering-grade results within the constraints of a capstone studio assignment. Importantly, unlike [3] programmes, which relied on faculty-prescribed design parameters, this study granted students full agency over intervention selection — mirroring the conditions of professional practice. The ability to correlate a specific U-value or shading geometry with a direct reduction in EUI provides future architects with the technical proficiency required to support the Kingdom's Vision 2030 sustainability goals.

From a student learning perspective, the most significant observed outcome of this exercise was the development of what may be termed 'parameter intuition' — the capacity to anticipate, before running a simulation, which envelope modification will yield the greatest performance improvement in a given climatic context. At the outset of the exercise, students approached all four intervention parameters (glazing, wall insulation, roof insulation, and shading) as approximately equal in importance. Following the baseline heat gain segmental analysis (Figure 9), which quantified the relative contribution of solar radiation versus conductive heat transfer to the cooling load, students independently prioritised the glazing SHGC and U-value as the primary intervention targets. This shift from uninformed to evidence-based intervention sequencing constitutes a direct manifestation of Learning Objective 3 (Quantitative Analysis) and is consistent with [7] 'Abstract Conceptualisation' stage: students moved from experiencing the simulation output to formulating a revised mental model of how envelope components function thermally in a hyper-arid climate.

The use of students' own capstone design was observed to produce a qualitatively different engagement with the simulation task compared to faculty-designed hypothetical briefs. Because the

students had a personal investment in the design, they approached the baseline analysis with a heightened sense of accountability — motivated not merely to complete a technical exercise, but to genuinely understand and resolve the performance shortcomings of their own architectural decisions. This ownership dynamic, rather than generating defensiveness, appeared to sharpen critical reasoning: students were more precise in identifying envelope deficiencies and more deliberate in selecting interventions, since each simulation result reflected directly on the quality of their own design judgement. This observation aligns with [5] finding that learning outcomes are significantly stronger when simulation is embedded within a design task to which students have a tangible personal commitment, rather than applied to a detached or hypothetical scenario. This observation supports [11] argument that authentic building contexts produce deeper engagement in sustainability-focused design exercises and suggests that the use of real buildings as studio briefs represents a replicable pedagogical strategy for BPS integration in architectural engineering programmes.

It should be noted that formal student feedback data, such as pre/post questionnaires, reflective journals, or structured peer assessments were not collected as part of this study. This is acknowledged as a limitation: the absence of systematically collected feedback data means that the learning outcomes described above are inferred from observed student behaviour and deliverable quality rather than from self-reported data. Future iterations of this exercise should incorporate structured reflection instruments, such as Kolb's Learning Style Inventory or a purpose-designed BPS competency rubric, to provide empirical evidence of pedagogical impact. This is identified as a priority direction for subsequent research.

The overall EUI reduction of 6.95% (139.22→129.55 kWh/m²-yr) reflects the scope of the intervention, which was restricted to passive envelope modifications. As illustrated in the energy segment breakdown (Figure 9), equipment loads — set at 25 W/m² to reflect the mixed-use programme of digital laboratories and exhibition spaces — constitute the single largest contributor to the building's total energy demand, significantly exceeding the ASHRAE 90.1-2013 office baseline of 8.1 W/m². Since equipment loads were held constant between scenarios (no active system or plug load modifications were tested), they dilute the overall EUI improvement despite the substantial cooling energy reduction of 17.24%. Had students reduced equipment power density to the ASHRAE baseline, or incorporated photovoltaic offsets, a substantially larger EUI reduction would have been achievable. This constraint was deliberate: the study scope was limited to passive envelope design to maintain the clarity of the pedagogical objective and to isolate the effect of envelope decisions on building performance.

6. Study Limitations

Several limitations of this study should be acknowledged. First, the scope of intervention was restricted to passive envelope modifications; active system optimisation (e.g., HVAC efficiency upgrades, lighting power density reduction, or photovoltaic integration) was not explored. The unchanged equipment power density of 25 W/m² — reflecting the mixed-use programme — constitutes the largest single energy end-use and limits the achievable EUI reduction from passive measures alone. Future studies should evaluate the combined effect of passive and active strategies. Second, model plausibility was confirmed through benchmark comparison rather than formal empirical calibration per ASHRAE Guideline 14-2014 or IPMVP Option D — standards requiring monthly data within NMBE ±5% and CV-RMSE ±15% respectively. Direct metering was beyond the studio constraints. Absolute EUI values should be treated as estimates; the relative before-and-after comparison is the more reliable result. Third, the study is based on a single case study building, limiting the generalisability of specific numerical outcomes to other building typologies or climatic sub-zones within Saudi Arabia. Fourth, formal student feedback data — such as pre/post competency assessments or reflective journals — were not systematically collected; pedagogical impact is inferred from observed student behaviour and deliverable quality rather than from validated instruments.

Future iterations of this exercise should incorporate structured reflection tools to provide empirical evidence of learning outcomes.

7. Conclusion

This paper demonstrates that a structured experiential learning framework, in which BEM is deployed as a generative design instrument rather than a post-design audit tool, enables architecture students to produce envelope optimisation outcomes that meet the prescriptive requirements of SBC 601 in Riyadh's hyper-arid climate. The primary contribution of this study is not the 6.95% EUI reduction per se, but the documented replicability of the pedagogical pathway through which students — operating within a capstone studio assignment — progressed from baseline diagnosis to iterative parametric testing to regulatory compliance verification. This framework, grounded in Kolb's Experiential Learning Cycle and operationalised through the dual-interface Sefaira workflow, offers a transferable model for BPS integration in architectural engineering education across climate-intensive contexts in the GCC region.

Based on the results, it can be concluded that:

13. **Passive strategies are sufficient for significant energy curtailment:** A focus on the building skin can yield annual savings of over 63,659 kWh, directly reducing operational carbon.
14. **Daylight quality is as critical as energy quantity:** Mitigating overexposure through shading is essential for preventing visual and thermal discomfort in highly glazed buildings.
15. **Experiential learning bridges the professional gap:** Integrating BEM tools like Sefaira into the architectural studio empowers students to validate their designs against rigorous national standards.

Ultimately, the study demonstrates that sustainable architecture in hot-arid regions is not a compromise on design, but a refinement of it. By adopting a performance-based approach early in the design phase, architects can create buildings that are both aesthetically significant and environmentally responsible, fostering a built environment that is resilient to the climatic extremes of the Middle East.

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