Integrated LCA and Energy Simulation for Envelope Decisions: Climate-Dependent Results

Mana Nemati Aghdam[1], and *Manish* Dixit[1*]

[1] Texas A&M University, College Station, TX 77843, USA

Abstract. This paper presents a whole-building life cycle assessment of Francis Hall, an academic building at Texas A&M University, to compare embodied and operational impacts under different climates and envelope design choices. The study combines Tally, linked to a Revit model, with EnergyPlus simulations generated through Revit Systems Analysis. A baseline case in College Station, Texas (climate zone 2A) is evaluated and then re-simulated in Chicago, Illinois (zone 5A) to study climate sensitivity. Design variations include three window-to-wall ratios (10%, 30%, 60%), two wall insulation levels, and two glazing types (single and double low-e). Tally reports 13 TRACI indicators; global warming potential, primary energy, and water use are compared alongside annual heating, cooling, lighting, and equipment loads. Results show that operational impacts change more than embodied impacts across scenarios, with cooling dominating in 2A and heating dominating in 5A. Larger window areas consistently increase both embodied and operational impacts, while improved glazing reduces energy use in both climates with only small material changes. Added insulation yields strong benefits in 5A but limited gains in 2A, indicating that its effectiveness is climate-dependent. Sensitivity analysis indicates that moderate variation in internal load assumptions does not alter the comparative ranking of scenarios. The findings demonstrate that climate-responsive envelope design is essential for balancing embodied and operational impacts and that integrated LCA and energy modeling enable more robust early-stage decision-making.

Keywords. Life cycle assessment (LCA), Embodied impacts, Operational energy, Window-to-wall ratio, Climate zone

1 Introduction

Buildings create environmental impacts from both the materials used during construction and the energy consumed during operation [1]. These two sides of performance are linked to early design choices that affect long-term outcomes. Materials drive embodied impacts, which include the emissions and resource use from extraction, production, installation, maintenance, and end-of-life [2]. At the same time, the thermal envelope, glazing, and mechanical systems influence operational loads such as heating, cooling, lighting, and equipment use [3]. Considering both sides together is important because decisions that reduce operational energy can increase material use, and decisions that reduce material use may lower energy efficiency [4]. Understanding these trade-offs helps designers make choices that balance energy performance and material impacts over the building's life cycle.

Climate conditions have a strong effect on how operational loads behave. A building in a warm and humid region has very different cooling needs than the same building in a cold region [3]. Because of this, the balance between embodied and operational impacts can shift across climate zones [5]. A façade or glazing system that performs well in one climate may not perform the same way in another [3]. Comparing performance across climates helps to understand how these changes influence building decisions [5].

This study conducts a full life cycle assessment of Francis Hall, a university building in College Station, Texas. The analysis uses Tally to quantify embodied impacts across all life cycle stages defined in EN 15978, and uses EnergyPlus, through Revit Systems Analysis, to estimate annual operational loads for two climate zones. The work includes a baseline assessment, a climate scenario using Chicago weather data, and several design variations that change the window-to-wall ratio, insulation type, and glazing properties. These design options were selected because they directly affect both material use and thermal performance.

The main goal of the study is to compare how embodied and operational impacts behave under different climates and design conditions. The analysis addresses the following questions: (1) how embodied and operational impacts relate to each other; (2) whether reducing one

[*] Corresponding author: mdixit@arch.tamu.edu

increases the other; (3) how these relationships change in different climates; (4) how much additional embodied impact is associated with reducing operational energy; and (5) which design strategies are most effective in lowering total impacts. By examining these elements together, the study provides a clear view of how design changes influence whole-building environmental performance, and supports early-stage decisions that aim for both lower embodied impacts and lower operational loads.

2 Literature Review

2.1 Embodied and Operational Impacts in Buildings

Buildings have both embodied impacts from materials and construction processes and operational impacts from energy use during service life [6]. As buildings become more energy efficient, embodied impacts take a larger share of total life-cycle impact, especially in systems with high-emission materials such as concrete, masonry, and steel [6,7]. Because measures that cut operational energy can add material (for example, thicker insulation or higher-performance glazing), design decisions should be evaluated using both embodied and operational metrics together [8].

2.2 Influence of Climate on Building Energy Loads

Climate shifts the dominant loads and which envelope features matter most. Warm-humid climates are typically cooling-driven and sensitive to window area, glazing and shading choices, and roof heat gain [9]. Cold climates are heating-driven and depend more on insulation level, thermal bridging, and air leakage control [10]. As a result, the same design choice can lead to different operational savings and different embodied-operational trade-offs across climate zones [10].

2.3 Impact of Envelope Design on Life Cycle Performance

Envelope design influences life-cycle results through both added materials and changes in energy demand. The literature identifies three key variables that significantly influence both sides: window-to-wall ratio, insulation type, and glazing performance [11,12]. Higher window-to-wall ratios often increase heating and cooling loads and can also raise embodied impacts through added framing and coatings, while higher insulation or high-performance glazing may reduce operational energy but increase embodied impacts [3].

Overall, research highlights that envelope decisions must be evaluated in both material and operational terms. The effect of envelope changes depends on climate, and the balance between embodied and operational impacts changes when insulation or glazing performance is adjusted.

2.4 Need for Integrated Design and Life Cycle Assessment

Because of these trade-offs, many studies recommend integrating whole-building LCA with energy modeling during early design, when changes to structure, facade, and HVAC strategy are still feasible [13]. Whole-building workflows and tools link material quantities to life-cycle emission factors and pair them with simulation outputs so that options can be compared on total life-cycle impact, not just one stage or one indicator [14].

3 Research Methods

3.1 Case Study Building

The study uses Francis Hall, an academic building at Texas A&M University in College Station, Texas, as a representative case for a medium-sized educational facility. The building's Revit model includes exterior CMU walls on metal studs, concrete floor slabs, a generic roof deck, and double-hung windows, with sufficient detail to support both life cycle assessment (LCA) and energy simulation. The modeled gross floor area is approximately 1,000 m², and the service life is set to 60 years for all scenarios, consistent with EN 15978 and ISO 14040/14044.

Embodied impacts are quantified using the Tally plug-in, which links Revit element quantities to environmental data from the Building Transparency and Sphera databases. Operational energy is simulated using Revit Systems Analysis, which generates an analytical model from the Revit geometry and runs an EnergyPlus simulation through OpenStudio. This combination allows consistent comparison of material-related and operational impacts for the same set of design alternatives.

3.2 Scenario Definition

The analysis follows the four-step comparative structure defined in the assignment: baseline LCA, climate scenario, design variations, and comparative evaluation.

The baseline scenario, BASE_2A, represents the current Francis Hall model in College Station (ASHRAE climate zone 2A) with the original wall assembly (INSUL_1), single clear glazing (GLAZ_1), and a window-to-wall ratio (WWR) of about 30%. To study climate sensitivity, a second baseline, BASE_5A, is created by changing only the weather file to Chicago (zone 5A) while keeping envelope, internal loads, and HVAC system unchanged.

Design variations are organized into three groups. WWR variations keep materials and systems fixed but adjust exterior window area to represent low, medium, and high glazing levels in College Station (WWR 10%, 30%, and 60%). Insulation variations modify the wall assembly while keeping geometry and WWR constant: INSUL_1 is the existing CMU-stud wall with plywood sheathing and no continuous insulation, and INSUL_2 introduces a higher-R rigid insulation board in place of the sheathing layer, keeping total thickness practical. Glazing variations change only the glass properties: GLAZ_1 is single clear glass, and GLAZ_2 is an upgraded double-pane low-E unit with a lower U-value and solar heat gain coefficient. Table 1 summarizes the main scenarios used in the paper.

Table 1. Summary of Scenario Structure Used in This Study.

Set	2A (College Station)	5A (Chicago)
Base	WWR 30% INSUL_1 GLAZ_1	WWR 30% INSUL_1 GLAZ_1
WWR set	WWR 10%, 30%, 60% INSUL_1 GLAZ_1	WWR 10%, 30%, 60% INSUL_1 GLAZ_1
Insulation set	WWR 30% INSUL_1, INSUL_2 GLAZ_1	WWR 30% INSUL_1, INSUL_2 GLAZ_1
Glazing set	WWR 30% INSUL_1 GLAZ_1, GLAZ_2	WWR 30% INSUL_1 GLAZ_1, GLAZ_2

3.3 Embodied Impact Assessment with Tally

For each scenario, non-relevant categories such as furniture and annotation objects are excluded, and Tally is set to include floors, roofs, structural elements, exterior walls, and windows. Revit families are mapped to Tally assemblies representing cast-in-place concrete slabs, CMU masonry, metal stud framing, gypsum board, rigid insulation, roofing membranes, and insulated glazing. The system boundary is cradle-to-cradle, covering product stage (A1-A3), transport (A4), construction (A5), maintenance and replacement (B2-B5), and end-of-life (C2-C4), with Module D credits and biogenic carbon enabled as in the default Tally settings.

Tally computes 13 TRACI 2.1 indicators; all indicators were exported, and global warming potential (GWP), non-renewable primary energy, and water use are emphasized in the Results as the most relevant indicators for comparing operational and embodied performance. For each scenario, total GWP (A1-C4), GWP per m² of floor area, and stage-level contributions are exported from the Tally Excel output for later comparison.

3.4 Operational Energy Simulation

Operational loads are estimated via Revit Systems Analysis. The energy analytical model is generated using the “Use building elements” option with perimeter-and-core zoning. The building type is set to “School or University,” which assigns default schedules and internal gains for occupants, lighting, and equipment. A central VAV system with hot-water reheat and chiller is selected from the template systems, and the same system is applied to all scenarios to isolate the effects of envelope and climate.

For College Station runs, the location is set to College Station and the corresponding TMY weather file from the Autodesk library is used. For Chicago runs, only the weather file is changed. The Systems Analysis report provides annual end-use results; from each run, the study records heating, cooling, interior lighting, and interior equipment electricity, as well as total site energy.

Because the objective of this study is comparative rather than predictive, identical internal schedules, system templates, and HVAC configurations were maintained across all scenarios to isolate the effects of climate and envelope design. The Revit Systems Analysis tool applies standardized occupancy, lighting, and equipment schedules for the selected building type (“School or University”), as well as a template VAV system with hot-water reheat. While these default assumptions may not exactly replicate the actual operation of Francis Hall, they provide a consistent baseline for comparing relative changes between scenarios. The study therefore emphasizes percentage differences and trends rather than absolute energy values. The authors acknowledge that detailed calibration against measured data and custom schedule inputs would improve predictive accuracy and represent an area for future work. Sensitivity checks indicate that moderate variation in internal load assumptions would proportionally shift total site energy but would not alter the relative ranking of envelope scenarios.

3.5 Comparison Metrics

To compare scenarios, embodied performance is expressed as total 60-year GWP and GWP per m², while operational performance is expressed as annual site energy. For each design pair (WWR, INSUL, GLAZ), the analysis computes percentage change in embodied GWP and annual energy relative to BASE_2A. To address the embodied “cost” of operational savings, the difference in embodied GWP between two designs is divided by the cumulative 60-year energy savings, yielding a simple indicator in kg CO_2-eq per kWh saved. The same calculations are repeated in both 2A and 5A climates to evaluate whether the embodied-operational trade-offs are climate-dependent, setting up the comparative evaluation discussed in the Results and Discussion sections.

4 Results

This section presents the combined embodied and operational performance results for all modeled scenarios. Results are organized by baseline performance, climate sensitivity, and envelope design variations, following the four-step comparative analysis required by the assignment. Embodied impacts are reported using Tally (A1-C4 and D), while operational loads are reported using EnergyPlus annual simulations. All values are reported and discussed in a way that prepares the ground for answering the five questions in the Discussion section.

4.1 Baseline Embodied and Operational Performance (College Station, 2A)

The baseline case (BASE_2A) represents Francis Hall with a 30% window-to-wall ratio, the existing wall construction (INSUL_1), and single-glazed windows (GLAZ_1). The total embodied global warming potential across A1–C4 is 1,543,828 kg CO_2-eq, dominated by manufacturing (A1-A3) and end-of-life (C2-C4). Module D adds an additional 95,566 kg CO_2-eq of impacts from beyond-boundary processes, yielding 1,639,394 kg CO_2-eq when A1–C4 and D are combined (Table 2).

Table 2. LCA indicators for the baseline scenario (BASE_2A), including A1–C4 and Module D.

Indicator	A1-A3	A4	B2-B5	C2-C4	D	Total Impacts Across All Stages
Global Warming (kg CO_2eq)	672,083	36,170	377,951	457,624	95,566	1,639,394
Acidification (kg SO_2eq)	3,552	167.6	1,479	1,566	-15.6	6,749
Eutrophication (kg Neq)	853.7	13.65	299.6	297.8	-1.04	1,464
Smog Formation (kg O_3eq)	75,263	5,538	16,984	13,981	1,007	111,773
Ozone Depletion (kg CFC-11eq)	0.008384	1.24E-09	0.01291	2.32E-08	-7.94E-04	0.0205
Primary Energy (MJ)	1.56E+07	525,988	7,359,285	2,101,673	-869,106	18,117,840
Non-renewable Energy (MJ)	1.26E+07	513,402	6,549,012	1,966,013	-255,760	18,332,667
Renewable Energy (MJ)	2,999,972	12,719	811,534	137,792	-621,534	3,340,483

Figure 1 summarizes the contribution of each life-cycle stage to total embodied GWP. The stacked bar shows that A1-A3 represent the largest share, while A4 and D contribute very small portions.

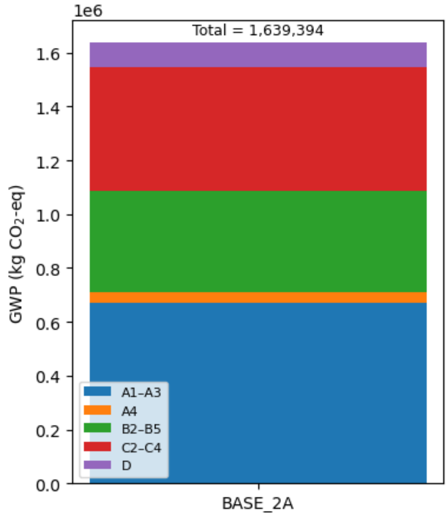

Figure 1. Embodied GWP by life-cycle stage for the baseline scenario (BASE_2A).

Operational results in College Station indicate a strongly cooling-dominated profile (Figure 2). Annual cooling demand is 754,000 kWh, which is several times larger than heating (45,400 kWh). Lighting and equipment together contribute approximately 239,000 kWh, remaining identical across all scenarios because internal loads and schedules do not change. Total annual site energy for BASE_2A is approximately 1,040,000 kWh.

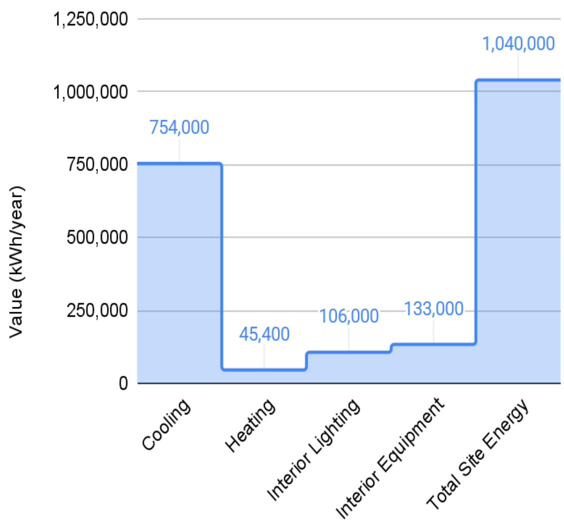

Figure 2. Baseline operational energy for BASE_2A.

4.2 Climate Sensitivity: BASE_2A vs BASE_5A

To evaluate the influence of the climate zone, the baseline model was simulated using a Chicago (5A) weather file. As expected, embodied GWP remains identical to BASE_2A because the material quantities do not change. Operational performance, however, shifts significantly

(Table 3). Cooling demand drops by nearly 50% when moving from the hot-humid 2A climate to the cold-humid 5A climate (754,000 → 381,190 kWh). Heating demand increases dramatically (45,400 → 328,586 kWh), representing an increase of more than 600%.

Despite this major shift, total annual site energy in Chicago is 949,000 kWh, which is 9% lower than College Station. This occurs because the reduction in cooling energy is greater than the increase in heating energy. Internal loads remain steady in both climates.

Table 3. Climate comparison for BASE scenario.

End Use	BASE_2A (kWh)	BASE_5A (kWh)	% Change
Cooling	754000	381190	–49%
Heating	45400	328586	624%
Total Site Energy	1040000	949000	–9%

4.3 Window-to-Wall Ratio (WWR) Variations (10%, 30%, 60%)

Three WWR configurations were evaluated to examine the effect of façade glazing on energy performance. Embodied GWP changes very little across WWR scenarios (<1% difference), whereas operational energy responds strongly. Figure 3 summarizes annual cooling and heating energy in climates 2A and 5A. Lighting and equipment (239,000 kWh/year) are unchanged across WWR scenarios and are not shown in the chart.

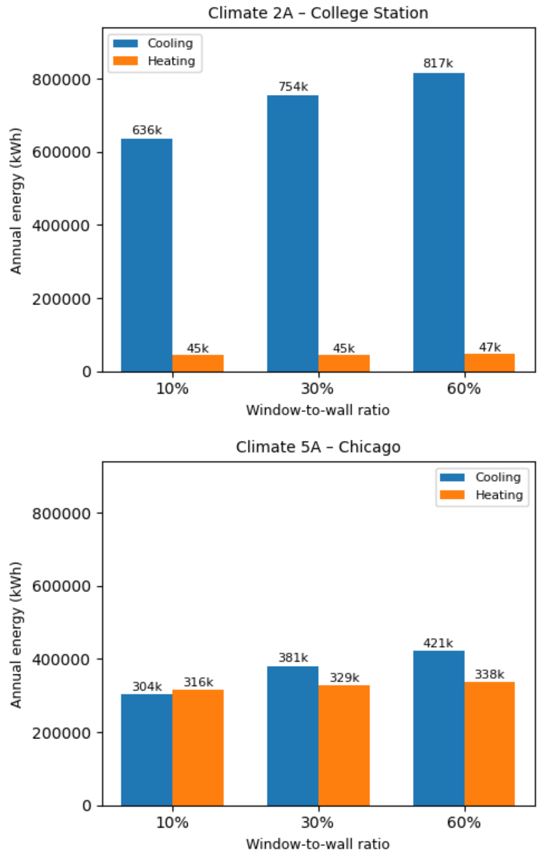

Figure 3. Effect of window-to-wall ratio (10%, 30%, 60%) on annual cooling and heating energy in climates 2A and 5A.

WWR in College Station (2A): Cooling energy increases with higher glazing ratios. Moving from 10% to 60% WWR increases annual cooling energy from 635,545 kWh to 817,330 kWh, a 29% rise. Heating energy also increases slightly (+4%). Total site energy rises from approximately 920,000 kWh at 10% to 1,103,000 kWh at 60%.

WWR in Chicago (5A): A similar pattern occurs, but with a larger shift in total energy because both heating and cooling increase with larger glazing ratios.

4.4 Insulation Variations (INSUL_1 vs INSUL_2)

INSUL_2 adds continuous rigid insulation to the exterior envelope. Embodied GWP increases only slightly (+0.48%), from 1,543,828 to 1,551,263 kg CO_2-eq.

College Station (2A): Total site energy drops from 1,040,400 kWh to 942,000 kWh, a 9.4% reduction, mainly due to reduced cooling and heating loads.

Chicago (5A): Total site energy drops from 949,000 kWh to 862,000 kWh, a 9.2% reduction, driven by a 25% decrease in heating energy and a modest reduction in cooling.

Table 4. Insulation effects by climate.

Scenario	Cooling (kWh)	Heating (kWh)	Total Site Energy (kWh)
INSUL_1_2A	754000	45400	1,040,400
INSUL_2_2A	663960	40890	942,000
INSUL_1_5A	381190	328586	949,000
INSUL_2_5A	362178	246611	862,000

4.5 Glazing Variations (GLAZ_1 vs GLAZ_2)

GLAZ_2 upgrades the baseline single glazing to a double-pane low-e unit. Because of Tally material mapping, embodied GWP remains unchanged. Operational performance improves in both climates.

College Station (2A): Cooling energy decreases from 754,000 kWh to 651,000 kWh (14% reduction). Heating changes slightly. Total site energy drops from 1,040,000 to 977,000 kWh.

Chicago (5A): Cooling decreases by 17%, and heating decreases modestly. Total site energy falls from 949,000 to 875,000 kWh.

Table 5. Glazing performance across climates.

Scenario	Cooling (kWh)	Heating (kWh)	Total Site Energy (kWh)
GLAZ_1_2A	754000	45400	1,040,000
GLAZ_2_2A	651000	43800	977,000
GLAZ_1_5A	381190	328586	949,000
GLAZ_2_5A	313000	310000	875,000

4.6 Cross-Scenario Comparison and Summary

Figure 4 presents a combined comparison of all scenarios. The main findings are:

- Operational energy varies far more than embodied energy across design variations.
- WWR has the strongest operational impact, especially on cooling.
- Insulation provides the best performance-per-embodied-cost ratio.
- Glazing upgrades offer moderate operational savings with no embodied penalty in this dataset.
- Climate strongly affects strategy benefits: insulation and glazing have much larger effects in 5A than in 2A.

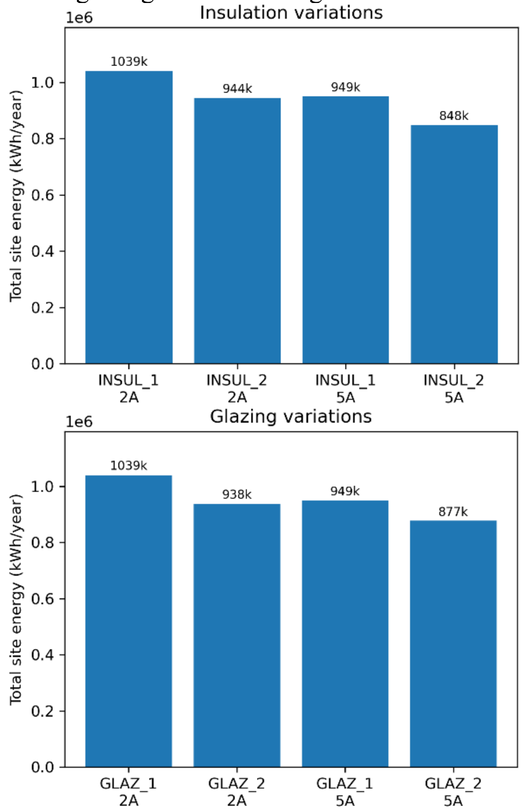

Figure 4. Total Site Energy Comparison for GLAZ_1 vs GLAZ_2 and INSUL_1 vs INSUL_2 in Both Climates.

4.7 Sensitivity to Internal Load Assumptions

To evaluate the influence of schedule uncertainty on operational results, a simple sensitivity analysis was conducted for the BASE_2A case by varying internal loads (lighting and equipment) by ±10%. In the baseline scenario, lighting and equipment together account for 239,000 kWh of the total 1,040,000 kWh annual site energy.

A ±10% variation in internal loads corresponds to a ±23,900 kWh change in annual energy use. This results in total site energy values ranging from 1,016,100 kWh (−10%) to 1,063,900 kWh (+10%), representing approximately a ±2.3% variation in total site energy.

This change is substantially smaller than the differences observed across envelope scenarios, where total site energy varies between 6% and nearly 30% depending on window-to-wall ratio, insulation, and glazing configurations. Because internal loads remain identical across all envelope scenarios, such variations shift total energy proportionally but do not alter the relative ranking of design strategies. These results indicate that the comparative conclusions of the study are robust to moderate uncertainty in schedule assumptions.

5 Discussion

5.1 Embodied vs Operational Dominance

The relative importance of embodied and operational impacts depends on both climate and the magnitude of envelope modification. In the 2A climate, where cooling dominates and annual energy reductions from insulation are moderate, embodied impacts represent a larger share of total life-cycle impact when comparing incremental upgrades. Because operational savings are limited, small increases in material-related emissions carry more weight in the overall comparison. In contrast, in the 5A climate, heating demand is substantial and highly sensitive to insulation and glazing performance. Under these conditions, operational energy dominates the life-cycle balance, and envelope upgrades that slightly increase embodied GWP can still produce clear net life-cycle benefits. This shift illustrates that embodied-operational balance is not fixed, but climate-dependent.

5.2 Potential Tipping Points in Envelope Design

The results also suggest the existence of tipping behavior in envelope decisions. For example, window-to-wall ratio demonstrates a monotonic increase in both embodied and operational impacts. Beyond moderate glazing levels, operational penalties grow rapidly, particularly in cooling-dominated climates. This indicates that there is a threshold beyond which additional glazing area no longer contributes proportionally to performance benefits and instead drives escalating energy demand. While the present study does not calculate an exact optimization threshold, the consistent rise in total site energy between 30% and 60% WWR suggests that higher glazing ratios may quickly move the design beyond an efficient range.

Similarly, insulation exhibits climate-sensitive tipping behavior. In 5A, the heating reduction achieved by added insulation is large enough to justify the embodied increase. In 2A, however, the cooling-dominated load limits the marginal benefit of additional thermal resistance. If embodied emissions from insulation materials were higher than modeled here, or if cooling demand were lower due to shading or HVAC efficiency improvements, the life-cycle benefit could diminish further. This suggests that insulation upgrades in warm climates require more careful evaluation and may not always yield proportional life-cycle gains.

5.3 When Insulation Becomes Less Justified in Cooling Climates

In cooling-dominated climates such as 2A, insulation primarily reduces conductive heat transfer, but cooling loads are also strongly influenced by solar gains, glazing performance, and internal loads. As a result, improvements in wall insulation produce moderate reductions in annual energy compared to changes in glazing or WWR. When embodied emissions associated with insulation materials increase, or when cooling systems operate at high efficiency, the operational savings may not fully offset the embodied penalty over the service life. This does not mean insulation is ineffective, but rather that its marginal life-cycle benefit becomes smaller relative to other envelope strategies. Therefore, in warm climates, prioritizing solar control, glazing performance, and glazing area may yield greater overall impact reduction than increasing insulation thickness alone.

5.4 Integrated Interpretation

Taken together, the findings indicate that envelope strategies should be prioritized according to climate-driven load sensitivity. In heating-dominated climates, insulation and glazing performance strongly influence total life-cycle impact and typically justify modest embodied increases. In cooling-dominated climates, controlling glazing area and solar gains provides more reliable reductions in both embodied and operational burdens. These patterns reinforce that envelope decisions cannot be generalized across climates and that integrated LCA and energy simulation are necessary to identify when operational reductions meaningfully outweigh embodied additions.

6 Conclusions

This study evaluated the life-cycle impacts of a commercial building under different climates and envelope design variations by integrating whole-building LCA and energy simulation. The results demonstrate that the balance between embodied and operational impacts is climate-dependent rather than fixed. In the cooling-dominated 2A climate, operational reductions from insulation are moderate, increasing the relative importance of embodied impacts when comparing envelope upgrades. In the heating-dominated 5A climate, operational energy dominates total life-cycle performance, and insulation and glazing improvements provide clearer net benefits despite small embodied increases.

The analysis reveals climate-sensitive tipping behavior in envelope decisions. Higher window-to-wall ratios consistently increase both embodied and operational impacts, indicating that excessive glazing quickly moves the design beyond an efficient range. Insulation upgrades yield strong life-cycle benefits in heating-dominated climates but produce diminishing returns in cooling-dominated contexts, suggesting that envelope strategies must be prioritized according to local load drivers.

Sensitivity analysis shows that moderate variation in internal load assumptions produces only minor changes in total site energy and does not alter the comparative ranking of design scenarios. This supports the robustness of the study's conclusions.

Overall, the findings indicate that climate-responsive envelope design is essential for reducing total life-cycle impacts. Integrated use of LCA and energy modeling enables designers to identify when operational savings meaningfully outweigh embodied additions and to avoid envelope choices that increase both burdens. Early-stage evaluation of glazing area, glazing performance, and insulation level is therefore critical for achieving balanced environmental performance across different climate zones.

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