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Development of a Cost-Comfort Optimisation Indicator (CCOI) for Early-Stage Building Envelope Design Evaluation

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ABSTRACT

Building envelope decisions made during early design stages strongly affect construction expenditure, operational energy demand, and occupant comfort, yet available evaluation tools often treat these criteria separately. This study addresses the lack of a simple cost-sensitive decision-support metric for prioritising envelope alternatives before detailed design. It develops a Cost-Comfort Optimisation Indicator (CCOI) and tests it through DesignBuilder v2025 parametric simulations for a two-storey 750 m² office shoebox model in New Delhi's composite climate. A one-variable-at-a-time approach assessed four wall assemblies, five glazing types, and eleven window-to-wall ratios from 20% to 70%, using annual comfort hours, cooling energy, and envelope construction cost as inputs. Results show that the super-insulated wall assembly achieved the highest wall-category performance, with 7,677.5 comfort hours, 157,210 kWh cooling energy, INR 3,318,800 envelope cost, and CCOI of 0.864. Double grey argon glazing ranked highest among glazing options, reaching 7,688 comfort hours, 163,942 kWh, and CCOI of 0.856. Most WWR increases above the 30% baseline produced negative CCOI values, indicating inefficient cost-performance trade-offs. The framework supports cost-conscious envelope selection, improves infrastructure efficiency, reduces energy-related operating burdens, and strengthens urban economic resilience through better resource allocation in growing cities.

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Highlights:	Contribution to the field statement:
- Revealed super-insulated walls deliver highest comfort-energy gains despite greater costs. - Found grey double glazing maximises comfort and cooling efficiency economically. - Increasing window area raised costs while reducing comfort and efficiency. - Confirmed cost penalties preserve rankings across tested sensitivity levels consistently. - Improved envelope choices strengthen urban productivity through lower cooling costs.	This study introduces a simple Cost-Comfort Optimisation Indicator that helps designers compare envelope choices by balancing comfort, energy use, and construction cost. Tested in New Delhi simulations, it identifies cost-effective wall and glazing options, filling a gap in early design and supporting affordable, productive, energy-efficient, resilient urban building investment decisions.

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1. Introduction

Building envelope design decisions made during the early phases of a project have profound and long-lasting implications for both initial construction costs and long-term building performance. The building sector accounts for approximately 40% of global energy consumption and 36% of CO_2 emissions, making the optimisation of passive design strategies essential for achieving sustainability targets and near-zero energy building (nZEB) standards (Attia et al., 2020; Diakaki et al., 2008; Lam et al., 2010). Buildings also play a central role in advancing urban sustainability, which further highlights the need for systematic approaches capable of evaluating and optimising design decisions at the earliest possible stage (Achour-Younsi et al., 2022; Biswas et al., 2022). However, early-stage building design involves complex trade-offs: energy-efficient envelope solutions often increase initial construction expenditure, whereas cost-minimisation strategies may compromise operational energy performance and occupant thermal comfort (Aste et al., 2015; Hamdy et al., 2013; Kaynakli, 2012).

The building envelope, comprising walls, roofs, floors, windows, and doors, forms the primary interface between indoor spaces and the external environment. Its thermal characteristics are therefore critical to the effectiveness of passive design strategies and to the overall environmental performance of buildings (Bano et al., 2020; Tian et al., 2015). During early design phases, envelope-related parameters are among the main variables available to designers before detailed mechanical air-conditioning system sizing and technical specifications are finalised (Hopfe & Hensen, 2011; Heiselberg et al., 2009). Among the wide range of passive design parameters, including wall insulation, roof properties, window characteristics, shading devices, orientation, thermal mass, and ventilation strategies, three parameters consistently emerge in the literature as having disproportionate influence on building performance: wall thermal transmittance (U-value), window-to-wall ratio (WWR), and glazing properties (Mirrahimi et al., 2016; Goia et al., 2013; Ihm & Krarti, 2012). These parameters are particularly important because they are determined at the earliest design stages, are difficult and costly to modify after construction, are directly linked to both construction cost and operational energy performance, and are highly climate-sensitive, requiring different optimal values across geographic regions (Ascione et al., 2017; Tian et al., 2015; Ihm & Krarti, 2012).

Given the substantial influence of envelope characteristics on building performance, designers require simple, reliable, and interpretable tools to compare, assess, and prioritise alternative envelope design options during the early design stage. Numerous studies have examined the effects of envelope parameters on thermal comfort and energy consumption, and some have proposed optimisation methods to identify energy-efficient interventions. However, most existing studies focus primarily on post-occupancy comfort and operational energy performance, while comparatively limited attention has been given to the associated variation in construction costs. Although some studies incorporate economic evaluation through life-cycle costing or multi-objective optimisation frameworks, these approaches usually require detailed data, extensive modelling, and substantial simulation effort, which may not be readily available during early-stage design decision-making (Hamdy et al., 2013; Hopfe & Hensen, 2011).

Consequently, a methodological gap remains in the development of a simple and easily interpretable decision-support tool that simultaneously accounts for construction cost and performance outcomes in the evaluation of early-stage building envelope alternatives. This gap is particularly significant for decisions related to wall construction, glazing specification, and window-to-wall ratio, as these design choices have long-term cost, comfort, and energy implications and are difficult to alter once construction has been completed. Addressing this gap is essential not only for improving building-level performance but also for supporting more cost-effective and resource-efficient urban development, where cumulative decisions across buildings influence energy demand, infrastructure efficiency, urban productivity, and long-term economic resilience.

To address this gap, this study aims to develop a Cost-Comfort Optimisation Indicator (CCOI), which can be used as a simple decision-support tool for prioritising building envelope design alternatives based not only on energy implications but also on construction cost considerations. The study is presented as a preliminary methodological proposal and is validated through early-stage parametric simulations using DesignBuilder. The proposed indicator provides a unified framework for comparing alternative building envelope design options by integrating thermal comfort, energy performance, and construction cost into a single evaluative metric. In doing so, the CCOI enables designers and decision-makers to identify envelope solutions that provide proportionate performance benefits relative to their cost implications.

This paper addresses three core research questions: (1) Which early-stage building envelope parameters have the greatest influence on comfort and energy performance? (2) How do variations in these parameters affect the trade-off between construction cost and building performance? (3) How can a unified Cost-Comfort Optimisation Indicator (CCOI) be formulated and validated through parametric simulations? The significance of the study lies in the development of an easily applicable decision-support tool for early-stage passive design decision-making. Unlike conventional approaches that evaluate comfort and energy performance independently, the proposed CCOI integrates performance and cost considerations into a single framework, thereby supporting more informed, cost-conscious, and performance-oriented envelope design decisions.

The remainder of this paper is organised as follows. Section 2 reviews the literature related to building envelope parameters and identifies the key research gaps. Section 3 presents the research methodology and overall simulation framework. Section 4 describes the simulation model, input variables, and performance metrics. Section 5 introduces the formulation of the proposed CCOI. Section 6 presents and discusses the simulation results, and Section 7 concludes the paper by summarising the key findings and implications for future research. Figure 1 presents the overall structure of the paper.

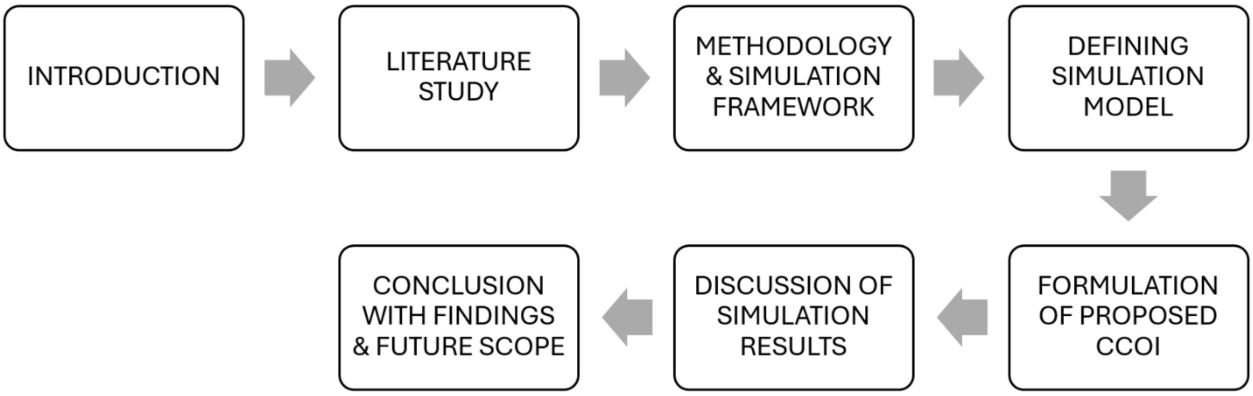

Figure 1. Structure of the Paper (Developed by the Authors).

2. Literature Review

2.1 Building Envelope Parameters in the Context of Indian Composite Climate

Under the climate classification framework adopted by the National Building Code of India (2016), India is divided into five major climate zones: hot-dry, warm-humid, temperate, cold, and composite. The composite climate zone, which includes major urban centres such as New Delhi, is characterised by pronounced seasonal variation and therefore presents a particularly complex context for passive building design. Buildings in this climatic setting must respond simultaneously to high solar heat gains during summer, elevated humidity during the monsoon, and heat-retention requirements during winter. This climatic diversity makes envelope optimisation a critical design concern, as a single building solution must balance thermal comfort, cooling demand, heating needs, and construction feasibility across different seasonal conditions.

The relevance of envelope performance is further amplified by India's rapidly expanding building sector, which currently accounts for approximately 33% of the country's total electricity consumption and is expected to increase substantially due to accelerating urbanisation and rising air-conditioning demand (Chaudhary et al., 2026). In this context, early-stage envelope decisions are not only technical design choices but also strategic interventions with implications for urban energy demand, infrastructure efficiency, operating costs, and long-term urban economic resilience. As Indian cities continue to expand, inefficient envelope design may intensify electricity consumption, increase cooling-related infrastructure burdens, and reduce the affordability and sustainability of buildings. Conversely, well-calibrated passive design strategies can contribute to lower operational energy use, improved indoor comfort, reduced pressure on urban energy systems, and more cost-effective building delivery.

Research in the Indian context has examined a broad range of passive design parameters, including building orientation, wall assembly and insulation, roof characteristics, shading devices, thermal mass, natural ventilation, and fenestration design. Among these, wall assemblies and insulation materials have received significant attention because of their demonstrated potential to reduce cooling and heating loads through improved envelope performance (Ahmed et al., 2023). However, despite the diversity of passive strategies investigated in the Indian composite climate, three parameters consistently emerge as the most influential and practically actionable during early design stages: wall assembly, including insulation type and thickness; glazing type, particularly U-value and Solar Heat Gain Coefficient (SHGC); and window-to-wall ratio (WWR). These parameters are especially important because they are typically fixed before detailed mechanical system design, carry substantial cost implications, and directly shape the thermal and energy performance of buildings.

Accordingly, the Indian composite climate requires an integrated evaluation approach that can assess envelope alternatives not only in terms of thermal comfort and energy reduction but also in relation to their construction cost implications. Such an approach is necessary because passive design strategies that perform well thermally may not always be economically efficient, while low-cost envelope choices may generate higher long-term energy burdens. Therefore, wall assembly, glazing type, and WWR provide a relevant basis for developing early-stage decision-support frameworks capable of linking building performance, construction expenditure, and broader urban sustainability outcomes.

2.2 Passive Design Parameters in Early-Phase Building Design

Passive design parameters can be classified into four broad categories: opaque envelope, fenestration, shading, and form-orientation parameters. Opaque envelope parameters include wall U-value, roof U-value, floor insulation, and thermal mass; fenestration parameters include WWR, glazing U-value, SHGC, visible transmittance, and frame type; shading parameters include overhang depth, fin depth, external blinds, and vegetation; and form-orientation parameters include building orientation, aspect ratio, floor plate depth, and surface-to-volume ratio. Among these categories, fenestration and opaque envelope parameters are generally determined during early-stage design and carry the highest construction cost implications (Hopfe & Hensen, 2011). These parameters therefore require particular attention in early design decision-making, where the opportunity to influence building performance is high but detailed technical information may still be limited.

Wall assembly, glazing type, and WWR dominate early-phase envelope design because of their irreversibility, cost-energy coupling, and climate sensitivity. First, they are difficult and costly to modify after construction; once structural walls are built and window openings are formed, changing wall construction type or WWR becomes prohibitively expensive (Tian et al., 2015). Second, these parameters simultaneously influence construction expenditure and operational energy performance, creating a direct cost-performance trade-off that must be addressed before design decisions become fixed (Ihm & Krarti, 2012; Goia et al., 2013). Third, their optimal values vary significantly across climatic zones, meaning that envelope solutions cannot be universally prescribed but must be calibrated to local environmental conditions (Ascione et al., 2017; Mirrahimi et al., 2016).

A key challenge in early-stage passive design is that improvements in thermal and energy performance often require additional capital investment. Higher wall thermal resistance may require thicker insulation or advanced materials; improved glazing performance may require more sophisticated glazing systems; and changes in WWR directly affect façade construction cost while simultaneously influencing solar heat gain, heat transfer, daylight availability, and cooling demand. Consequently, envelope design is inherently multi-objective and requires a balanced assessment of performance gains against additional construction expenditure (Chaturvedi et al., 2025; Mohamadi et al., 2024; Talaei et al., 2024). This balance is particularly important in cost-sensitive urban development contexts, where design decisions repeated across large building stocks can influence housing affordability, operational energy costs, electricity infrastructure demand, and overall resource allocation.

A systematic synthesis of approximately 200 peer-reviewed studies has shown that wall thermal transmittance, expressed as U-value, WWR, and glazing type consistently emerge as the most critical parameters affecting both energy performance and construction costs in early-phase building design. Evidence from sensitivity analyses, parametric studies, and multi-objective optimisation research across different climate zones indicates that these three parameters account for a substantial share of energy performance variation and represent key cost-performance trade-off decision points (Albatayneh, 2021; Ascione et al., 2017; Talaei et al., 2024; Lapisa et al., 2022; Goia et al., 2013). However, many existing studies evaluate these parameters primarily through energy or comfort outcomes, while fewer provide a simple and interpretable framework that integrates construction cost with performance indicators at the early design stage.

This limitation indicates the need for an evaluative method that can assist designers in comparing envelope alternatives before detailed design information becomes available. Such a method should be transparent, adaptable, and capable of identifying whether additional construction expenditure produces proportionate gains in comfort and energy performance. Therefore, the literature supports the development of a unified cost-comfort evaluation framework focused on wall assembly, glazing type, and WWR as the most relevant early-stage envelope variables for performance-oriented and economically responsible building design.

2.3 Wall Assembly

Wall thermal transmittance (U-value, W/m²K) is one of the most important parameters governing conductive heat gain through opaque building envelope. The relationship between wall U-value and annual cooling or heating energy demand is well established (Kaynakli, 2012; Aste et al., 2015). Improving wall U-value typically requires additional insulation thickness, which directly increases construction costs.

The reviewed studies further indicate that reductions in wall U-value do not necessarily result in proportionate improvements in building performance. Initial improvements in insulation levels often produce substantial reductions in energy demand, whereas additional improvements beyond a certain threshold yield progressively smaller benefits. This phenomenon of diminishing returns has been observed across multiple climatic contexts and suggests that optimal envelope design cannot be determined solely by maximising thermal performance but must also consider the associated increase in construction cost (Aste et al., 2015; Mohamadi et al., 2024).

Despite the volume of research, significant gaps persist. Most studies report optimal insulation thickness rather than the corresponding wall assembly U-value, limiting cross-study comparison and development of a harmonised optimisation database. Additionally, of the 43 studies examining wall U-value, just 4 have examined U-value optimisation in tropical climates (Lapisa et al., 2022; Hernández et al., 2023). Cost integration remains limited, with only 18 of 43 including construction cost analysis, and merely 11 performing life-cycle cost optimisation.

2.4 Glazing Properties

Across the reviewed literature, Solar Heat Gain Coefficient (SHGC) consistently emerges as the most sensitive glazing parameter for energy performance, particularly in cooling-dominated climates. In mixed climates, optimal solutions balance moderate U and SHGC for best life-cycle cost outcomes, while SHGC remains the most influential single parameter when cooling load dominates building energy demand.

Like wall insulation, glazing performance exhibits diminishing return behaviour. While improvements in SHGC and U-value can significantly reduce energy loads, successive upgrades in glazing specification often generate progressively smaller performance gains relative to their additional cost. Consequently, glazing optimisation requires evaluation of both performance improvement and economic efficiency rather than selection based solely on maximum thermal performance (Ahmed et al., 2023; Talaei et al., 2024).

2.5 Window-to-Wall Ratio (WWR)

WWR is the ratio of glazed area to total façade area and is the most frequently studied passive design parameter in the reviewed literature (61, 68% in a total of 90). Its dominance is also driven by its implication on construction cost, as glazing is typically several times more expensive per m² than opaque wall construction (Goia et al., 2013; Ihm & Krarti., 2012; Mirrahimi et al., 2016). The optimal WWR varies substantially across climate zones (Goia et al., 2013; Ihm & Krarti., 2012).

WWR presents unique cost-energy dynamics because window area affects multiple cost components simultaneously. Altun (2022) demonstrated that increasing WWR from 10% to 50% increased initial construction costs by 8–15% depending on glazing type but also increased annual energy costs by 18–28% in Turkish climate conditions. The study concluded that WWR optimisation offers "double benefits" reducing both construction and operational costs, making it a high-priority parameter for cost-constrained projects.

Studies illustrate that, in case of WWR, higher expenditure does not always correspond to better performance outcomes. This highlights the need for evaluation methods capable of identifying unfavourable cost-performance relationships and penalising alternatives where additional expenditure yields limited or negative performance benefits (Altun, 2022; Goia et al., 2013). The most critical gap is the near-absence of studies that isolate the life-cycle cost effect attributable solely to WWR variation, independent of other envelope parameters.

2.6 Research Gap and Limitations in Existing Literature

Limited studies have adopted simulation-based approaches combined with economic and multi-criteria assessments to identify high-performing building design solutions (Ascione et al., 2017). Also, such approaches generally involve complex procedures which can be less suitable for rapid decision-making during early-stage design. The recurring observations of cost-performance coupling and diminishing returns across all three parameters suggest that design alternatives should be assessed not only on absolute performance outcomes but also on the efficiency with which those outcomes are achieved. This methodological gap provides the theoretical basis for the development of a Cost-Comfort Optimisation Indicator (CCOI) which integrates thermal comfort, energy performance, and construction cost within a single decision-support framework for early-stage building envelope design.

3. Methodology

3.1 Overview of Research Approach

The methodology is structured around the development and preliminary validation of a Cost-Comfort Optimisation Indicator (CCOI) using early-stage parametric energy simulations. The approach adopts 'one-variable-at-a-time' (OVAT) strategy to isolate the individual effects of the three most critical building envelope parameters identified from the literature, namely wall assembly, glazing type, and window-to-wall ratio (WWR).

This approach was adopted to isolate the individual contribution of each envelope parameter to the proposed CCOI. For methodological development studies, OVAT provides a transparent means of identifying the direct influence of individual variables while avoiding the complexities that may arise from simultaneous variation of multiple parameters (Tian et al., 2015; Heiselberg et al., 2009). Since the primary objective of this study is the development and preliminary validation of the CCOI framework rather than the identification of a globally optimal envelope configuration, isolating parameter specific cost-performance relationship was considered appropriate. Advanced optimisation approaches can capture interaction effects among variables, but these methods are generally employed when the objective is optimisation of final design solutions, rather than methodological validation (Talaei et al., 2024)

A baseline model is first established in DesignBuilder, and then each envelope parameter is systematically varied across its feasible range or discrete alternatives while all other parameters are held constant. The resulting simulation outputs are used to calculate the CCOI for each alternative, enabling ranked comparison of design options based on an integrated assessment of comfort, energy performance, and construction cost. The figure 2 given below summarises the methodology for this study.

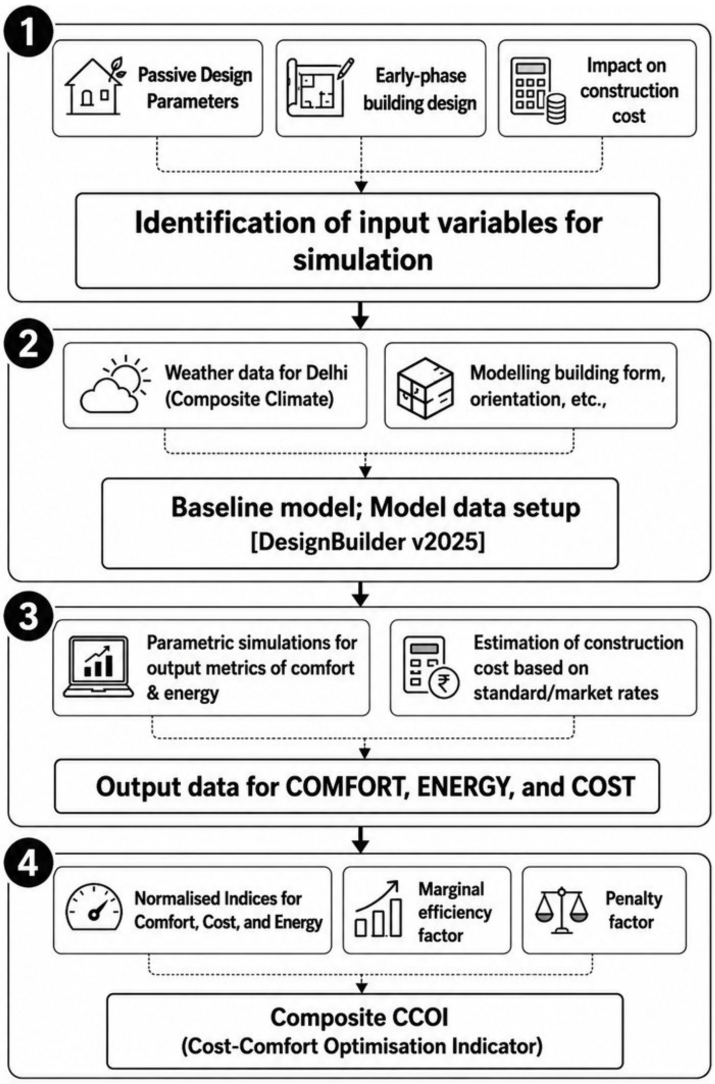

Figure 2. Research Methodology Framework (Developed by the Authors).

Unlike conventional approaches that evaluate comfort and energy performance independently, the proposed CCOI integrates normalised performance metrics with marginal cost efficiency and a diminishing returns penalty, enabling a more realistic and decision-oriented evaluation of early-stage design alternatives for building envelope. The focus of this paper is to develop this methodology in a form flexible enough to be applied to any variable in further studies.

4. Simulation Model and Data

This section discusses the baseline model setup, the input variables and their variation for the iterations in parametric simulation, and the output variables or metrics for the quantification of comfort and energy performance of the simulation iterations.

4.1 Baseline Model for Simulation

The baseline model for this study is a simple shoebox model for office building located in New Delhi, India; which is of composite climate. The baseline model building is rectangular in layout, with longer dimension along the East-West axis. It has two blocks, with single zone in each, where the first block is on Ground floor with floor area of 375 m² (size 25 meters x 15 meters) and the second block is on first floor with the same floor dimensions. The representative model and zone components and details of windows in building envelope are shown in the Figure 3 given below.

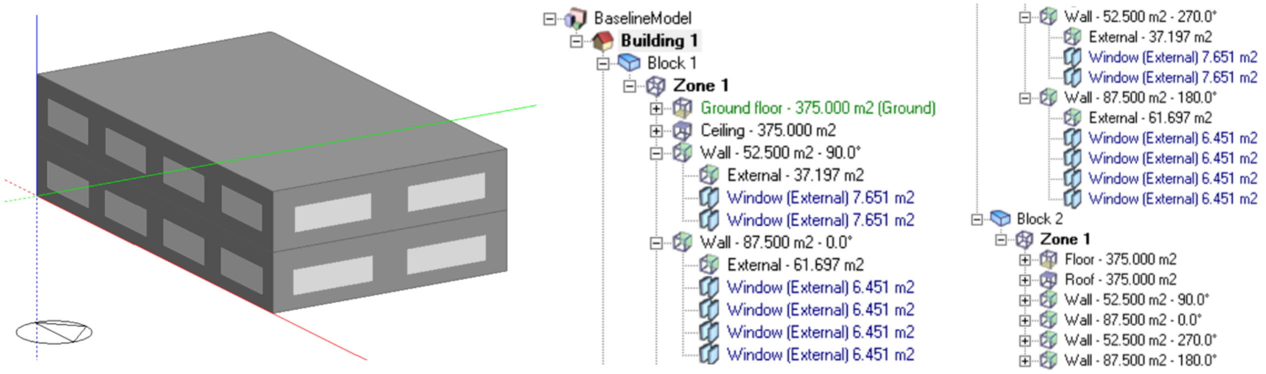

Figure 3. Baseline Model with Component details (Modelled by the Authors using DesignBuilder v2025).

A simplified shoebox model was adopted to provide a controlled basis for methodological validation of the proposed CCOI framework. Such simplified models are commonly used in building performance studies to isolate the influence of individual design parameters while minimising confounding effects resulting from geometry and operational complexity (Heiselberg et al., 2009; Tian et al., 2015).

The construction type for baseline model is composed of uninsulated walls, 200mm brickwork with 13mm plaster, for the external walls of building envelope. The roof is uninsulated flat roof composed of concrete slab with innermost layer of plaster. The windows in building envelope account to around 30% WWR, which are of single glazing type with 6mm grey pane.

The activity and schedule details are a simplified representation of a generic office. The occupancy for the baseline model was considered 0.1 person/m² (which is as per the occupant load factor standards of Part 4, Volume 1, National Building Code 2016). The cooling setpoint of 24°C and heating setpoint of 21°C were setup (Manu et al. 2016). The interior lighting level of 100 lux using suspended luminaire type is based on normalised power density of 5 W/sqm. The airtightness with infiltration of 0.5 ac/h is considered for simulation baseline model (ASHRAE Standard 140). The HVAC system is based on fuel type – electricity from grid, with default CAV, Air-cooled chiller as the HVAC type.

4.2 Simulation Parameters and Datapoints

An important step before running the simulations is defining the input variables to generate the design alternatives for each iteration of simulation and defining the output metrics to quantify the comfort performance and energy performance. Parametric simulations are conducted based on EnergyPlus, using DesignBuilder v2025.

4.2.1 Input Variables for Simulations

Based on the literature study, the three parameters based in the early-stage design of the building envelope and significantly impacting the performance potential are: 1. Wall assembly, 2. Glazing type, and 3. Window-to-wall-ratio (WWR).

Table 1: Values or discrete alternatives for variables in each iteration of parametric simulations.

1. Wall Assembly (Discrete alternatives)		**2. Glazing type (Discrete alternatives)**		**3. Window-to-wall-ratio (WWR) (Parametric step-metric based alternatives)**
(i)	**WA1:** Brickwork single leaf construction dense plaster (2 Layers Outer layer of 220 mm brickwork and inner layer of 13 mm dense plaster; U value 2.184 W/m^{2}K)	(i)	**GT1:** Dbl Clr Low Iron 5mm/13mm Air (SHGC of 0.818; U-value of 2.682 W/m^{2}K)	Starting at a minimum of 20% upto a maximum of 70% Step metric for each iteration of 5% Considering these, the WWR in each iteration of the parametric simulation will be: 20%, 25%. 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, and 70% respectively. The WWR for the baseline model is approximately 30%
(ii)	**WA2:** Uninsulated Wall, Medium weight (Baseline) (3 Layers Outer an inner layer of 100 mm brickwork. Innermost layer of 13 mm gypsum plaster; U value 2.071 W/m^{2}K)	(ii)	**GT2:** Project BIPV Window (SHGC of 0.691; U-value of 1.960 W/m^{2}K)	
(iii)	**WA3:** Wall, Mass, R-0.0 (0.00), U-0.350 (1.99) from ASHRAE Standards (Single layer 8 in. concrete at R-0.0625/in; U value 1.916 W/m^{2}K)	(iii)	**GT3:** Sgl Grey 6mm (Baseline) (SHGC of 0.602; U-value of 5.778 W/m^{2}K)	
(iv)	**WA4:** Super insulated brick/block external wall (4 Layers Outermost layer of 105 mm brickwork, 200 mm XPS Extruded Polystyrene, 105 mm concrete block and innermost layer of 15 mm gypsum plaster; U value 0.156 W/m^{2}K)	(iv)	**GT4:** Trp Clr 3mm/6mm Air (SHGC of 0.682; U-value of 2.178 W/m^{2}K)	
		(v)	**GT5:** Dbl Grey 6mm/13mm Arg (SHGC of 0.476; U-value of 2.511 W/m^{2}K)	

The three parameters identified through literature are taken as the input variables for the parametric simulations. These simulations are performed in 'one variable at a time' approach, which helps in isolating the cost-comfort trade-offs attributed to each design decision, particularly in the case of early-stage building envelope design.

Wall assembly and glazing type do not have a continuous numerical range. For these parameters, simulations are conducted as alternatives-based assessments where 4 discrete alternatives are considered for the input variable 'wall assembly' and 5 discrete alternatives are considered for the input variable 'glazing type'. For WWR simulations, a minimum value of 20% and a maximum value of 70% are adopted, with a parametric simulation interval of 5% for each subsequent simulation step. Table 1 summarises the discrete design alternatives considered for input variables in each iteration of the parametric simulations. In the case of each variable, the value or discrete attribute which has been used in the baseline model is also noted for reference.

4.2.1 Output Data from Simulations

Three output metrics are collected from each iteration of parametric simulation. These output metrics are further used in the analyses for calculation of the CCOI, the unified metric for determining the cost and performance optimised design alternative in the case of each input variable.

The three output metrics are: (1) 'Comfort Hours' for calculation of Normalised Comfort Index; (2) 'Cooling Energy (in kWh)' for calculation of Normalised Energy Index; and (3) 'Total Envelope Cost (in INR)' for calculation of Normalised Cost Index. The calculation of annual comfort hours is calculated as the complement of 'Discomfort Hours (all clo) as per ASHRAE 55' based on EnergyPlus, considering the default reporting period of DesignBuilder 'All Periods' which corresponds to annual duration of 8760 hours. Discomfort hours (all clo) aggregates every hour in which an occupied zone breaches the 80% acceptability threshold. This threshold corresponds to a Predicted Mean Vote (PMV) beyond the range of -0.5 to +0.5. 'All clo' specifies that the calculation accounts for seasonal variation in clothing insulation levels (measured in clo units, usually taken 0.5 for summer and ranging upto 1.0 for winter) (ASHRAE, 2023). 'Comfort hours' is taken as [8760 – Discomfort Hours (all clo)]. As all simulation iterations employed identical occupancy schedules and operating conditions, this metric provides a consistent basis for relative comparison of envelope alternatives, which is the primary objective of the proposed CCOI framework (Heiselberg et al., 2009; Tian et al., 2015).

Cooling energy is adopted as the representative indicator for operational energy performance of building envelope design alternatives in this study. This is driven by the fact that, in composite climate of India, cooling loads constitute a dominant share of building energy demand and are highly sensitive to envelope characteristics such as glazing, insulation, WWR, etc., (Chaturvedi, P. K., et al. 2025; Singh, M. K., et al. 2018; Rahbarianyazd & Raswol, 2018). Although heating demand occurs during winter months, its contribution to annual operational energy in considered climatic context is relatively small; consequently, cooling energy was taken as a suitable proxy for energy performance in this preliminary methodological study.

Table 2: Summary of the simulation outputs for comfort and energy.

Variable	Discomfort hours (all clo)	Annual comfort hours	Cooling energy (kWh)
1. Wall Assembly (Discrete alternatives)			
WA1	1224.75	7535.25	171786
WA2	1219.75	7540.25	170938
WA3	1197.00	7563.00	168260
WA4	1082.50	7677.50	157210
2. Glazing type (Discrete alternatives)			
GT1	1297.50	7462.50	178339
GT2	1241.50	7518.50	174167
GT3	1219.75	7540.25	170938
GT4	1214.50	7545.50	172085
GT5	1072.00	7688.00	163942
3. Window-to-wall ratio (WWR) in %			
20%	1027.50	7732.50	161730
25%	1125.50	7634.50	166249
30%	1219.75	7540.25	170938
35%	1286.00	7474.00	175799
40%	1346.00	7414.00	179409
45%	1404.75	7355.25	184105
50%	1459.75	7300.25	187426
55%	1507.25	7252.75	191410
60%	1548.75	7211.25	195230
65%	1584.25	7175.75	198911
70%	1619.25	7140.75	202694

Table 2 is a summary of the output data for the parametric simulations. Annual comfort hours in case of each iteration for each variable are calculated as annual hours (i.e., 8760 hrs) minus annual discomfort hours obtained from simulation. Cooling energy in kWh obtained from simulation are rounded off to closest integer.

Total Envelope Cost in INR is the construction cost attributed to a given design characteristic of an iteration. The costs are calculated based on Central Public Works Department (CPWD) Delhi Schedule of Rates (DSR 2023) and Plinth Area Rates (PAR 2025). Where CPWD rates were unavailable, prevailing market rates for Delhi were adopted. Costs correspond to total building envelope construction cost for each simulation iteration were determined while keeping all other parameters constant at baseline values.

Table 3 below is a summary of the total envelope cost in each iteration. The total envelope cost was calculated by multiplying the unit rate of each envelope component (external wall assembly and glazing system) with its respective quantity or surface area in the simulation model. The rates considered include material, labour, overhead, and profit expenses; which are based on PAR 2025 and or prevailing market rates.

Table 3: Summary of construction cost associated with each iteration.

Variable	A = Cost of wall [Area of wall in m²] * [Rate in INR/m²]	B = Cost of window [Area of window in m²] * [Rate in INR/m²]	Envelope construction cost (INR) = A+B
1. Wall Assembly (Discrete alternatives)			
WA1	398*3200=12,73,600	162*5500=8,91,000	21,64,600
WA2	398*3300=13,13,400	162*5500=8,91,000	22,04,400
WA3	398*4200=16,71,600	162*5500=8,91,000	25,62,600
WA4	398*6100=24,27,800	162*5500=8,91,000	33,18,800
2. Glazing type (Discrete alternatives)			
GT1	398*3200=12,73,600	162*7500=12,15,000	24,88,600
GT2	398*3200=12,73,600	162*12,000=19,44,000	32,17,600
GT3	398*3200=12,73,600	162*5500=8,91,000	21,64,600
GT4	398*3200=12,73,600	162*9500=15,39,000	28,12,600
GT5	398*3200=12,73,600	162*8500=13,77,000	26,50,600
3. Window-to-wall ratio (WWR) in %			
20%	448*3200=14,33,600	112*5500=6,16,000	20,49,600
25%	420*3200=13,44,000	140*5500=7,70,000	21,14,000
30%	392*3200=12,54,000	168*5500=9,24,000	21,78,400
35%	364*3200=11,64,800	196*5500=10,78,000	22,42,800
40%	336*3200=10,75,200	224*5500=12,32,000	23,07,200
45%	308*3200=9,85,600	252*5500=13,86,000	23,71,600
50%	280*3200=8,96,000	280*5500=15,40,000	24,36,000
55%	252*3200=8,06,400	308*5500=16,94,000	25,00,400
60%	224*3200=7,16,800	336*5500=18,48,000	25,64,800
65%	196*3200=6,27,200	364*5500=20,02,000	26,29,200
70%	168*3200=5,37,600	392*5500=21,56,000	26,93,600

5. Proposed Cost-Comfort Optimisation Indicator (CCOI)

5.1 Rationale and Conceptual Basis

This study proposes the Cost-Comfort Optimisation Indicator (CCOI), which holistically integrates thermal comfort, energy performance, and construction cost within a unified framework. The proposed index incorporates three key advancements: (1) normalisation of performance indicators for comparability; (2) marginal efficiency of cost-to-comfort improvement; and (3) a penalty for diminishing returns at higher cost levels. This enables a realistic and decision-oriented evaluation of envelope design alternatives.

5.2 Normalisation of Performance Indicators

To ensure comparability across different metrics and scales, all performance indicators are normalised to a dimensionless range of 0 to 1 using minimum-maximum normalisation.

Normalised Comfort Index (Cm): Thermal comfort is represented using annual comfortable hours. Comfortable hours are calculated based on an annual simulation of 8,760 hours. Annual Comfortable Hours are calculated as discussed in Section 4.2.1

The Normalised Comfort Index is expressed as:

$$Cm_i = \frac{ACH_i - ACH_{min}}{ACH_{max} - ACH_{min}}$$

Equation 1. Normalised Comfort Index for ith simulation

where ACH_i is the annual comfortable hours for design iteration i, and ACH_{min} and ACH_{max} are the minimum and maximum annual comfortable hours across all simulated alternatives respectively. A higher Cm_i indicates better thermal comfort performance.

Normalised Energy Index (E): Energy performance is incorporated to account for operational efficiency. Since lower energy consumption is desirable, the normalised form is defined such that a higher value indicates better (lower) energy use:

$$E_i = 1 - \frac{CE_i - CE_{min}}{CE_{max} - CE_{min}}$$

Equation 2. Normalised Energy Index for ith simulation

where CE_i is the Cooling Energy (kWh) for design iteration i, and CE_{min} and CE_{max} are the minimum and maximum Cooling Energy (kWh) values across all simulated alternatives respectively.

Normalised Cost Index (Cs): The cost associated with each envelope configuration is normalised as

$$Cs_i = \frac{CC_i - CC_{min}}{CC_{max} - CC_{min}}$$

Equation 3. Normalised Cost Index for ith simulation

where CC_i is the actual construction cost for design iteration i, and CC_{min} and CC_{max} are the minimum and maximum actual construction costs across all simulated alternatives respectively. A higher Cs value indicates a more expensive alternative.

5.3 Marginal Efficiency Factor (η)

A key input for the proposed CCOI is the incorporation of marginal efficiency, which captures the incremental improvement in comfort achieved per unit increase in cost. This is expressed as:

$$\eta_i = \frac{\Delta Cm}{\Delta Cs} = \frac{Cm_i - Cm_{ref}}{Cs_i - Cs_{ref}}$$

Equation 4. Marginal Efficiency Factor for ith simulation

where ΔCm is the difference of normalised comfort index for ith simulation and normalised comfort index for the reference baseline case. ΔCs is the difference of normalised cost index for ith simulation and normalised cost index for the reference baseline case. This term reflects the effectiveness of investment, ensuring that solutions providing higher comfort gains per unit cost are favoured over those with diminishing returns.

5.4 Penalty Factor (P) for Cost Escalation

To account for diminishing returns at higher cost levels, a penalty factor is introduced:

$$P_i = 1 - e^{-\alpha . Cs_i}$$

Equation 5. Penalty factor for ith simulation

where α is the penalty sensitivity coefficient that controls the severity of the penalty applied to high-cost alternatives. This exponential penalty reduces the score of high-cost alternatives, even if they provide marginal improvements in performance, reflecting the practical reality that excessively costly envelope solutions are rarely adopted in early-stage design decisions.

For a balanced consideration of cost and performance α of 2 was adopted for calculating the CCOI. To assess the influence of α on the proposed CCOI, a sensitivity analysis was conducted using α values of 0.5, 1, 2, and 3. These values represent low to high levels of penalty based on cost sensitivity. The resulting CCOI values of design alternatives were compared to evaluate the robustness of the proposed framework.

5.5 Formulation of the Composite CCOI

The final Cost-Comfort Optimisation Indicator (CCOI) is defined as a composite index integrating all the above components:

$$CCOI_i = (w_1 \cdot Cm_i + w_2 \cdot E_i) * (1 - P_i) * \eta_i$$

Equation 6. Cost-Comfort Optimisation Indicator for ith simulation

where w_1 and w_2 are weighting factors for thermal comfort and energy respectively such that they add up to 1. Cm_i is the Normalised Comfort Index, E_i is the Normalised Energy Index. η_i is the Marginal Cost-Comfort Efficiency Factor, and P_i is the penalty factor for cost escalation.

5.6 Weighting Scheme

The weighting factors are assigned to reflect the primary objective of the proposed CCOI; with weighting of $w_1 = 0.6$ assigned to thermal comfort and $w_2 = 0.4$ assigned to energy performance. The higher weighting assigned to comfort is based on a widely recognised premise that thermal comfort is a primary indicator of building performance, with energy efficiency serving as a means of achieving comfort in a resource-efficient manner rather than an end in itself (Nicol and Humphreys, 2002).

Furthermore, the proposed weighting scheme is consistent with multi-criteria decision-making approaches in building performance evaluation, where weights are assigned to reflect the relative importance of evaluation criteria in accordance with the study objective (Wang et al., 2005). As this study aims to develop an optimisation indicator for cost-comfort rather than cost-energy, a modest preference was assigned to comfort while retaining substantial consideration for energy performance.

5.7 Interpretation of the CCOI

The proposed index enables ranking of design alternatives based on integrated performance. A higher CCOI value indicates an optimal balance of comfort, energy efficiency, and cost, representing a design solution where performance improvement is proportionate to the cost increment. A lower CCOI indicates an inefficient design solution. Specifically, the index penalises: (1) high-cost, low-benefit solutions through the exponential penalty function; (2) energy-inefficient configurations through the normalised energy performance component; and (3) designs with poor thermal comfort performance through the normalised comfort component and the marginal efficiency term.

A simulation result where CCOI is negative implies that the case costs more and performs worse simultaneously. Such cases are ideally not considered optimal and are excluded from the ranking of preferred design alternatives. However, it may be noted that negative CCOI values may be a resultant of some benefit offered by the design alternative which is other than thermal comfort or energy performance; for example, increased natural lighting due higher WWR or increased on-site renewable energy production using BIPV glazing.

5.8 Applicability and Generalisation

The CCOI framework is flexible and can be adapted to different climatic contexts, alternative building typologies, and varying stakeholder priorities through weight adjustment. The ‘one variable at a time’ simulation approach adopted in this study can be extended to any number of envelope variables, making the framework directly applicable to future studies examining additional passive design parameters.

6. Results and Discussion

The CCOI values were calculated for all iterations corresponding to the three selected envelope design variables, namely wall assembly, glazing type and window-to-wall ratio (WWR), following the methodology and calculation procedure discussed in the previous section. The summary table (Table 4) presents the normalised performance indicators, marginal efficiency factor (η), penalty factor (P) based on α=2, and the resulting CCOI values to facilitate comparative evaluation of the different design alternatives.

Table 4: Compilation of CCOI values for all iterations of parametric simulation.

Variable	Normalized Comfort Index	Normalized Energy Index	Normalized Cost Index	Marginal Efficiency Factor	Penalty Factor for Cost Escalation	Cost-Comfort Optimization Indicator
	Cm	**E**	**Cs**	**η**	**P**	**CCOI**
1. Wall Assembly						
WA1	0.00	0.00	0.00	1.019	0.000	0.000
WA2	0.04	0.06	0.03	NA	0.067	Baseline/Reference
WA3	0.20	0.24	0.34	0.515	0.498	0.055
WA4	1.00	1.00	1.00	0.999	0.865	0.864
2. Glazing Type						
GT1	0.00	0.00	0.31	-1.12	0.460	0.000
GT2	0.25	0.29	1.00	-0.10	0.865	-0.022
GT3	0.34	0.51	0.00	NA	0.000	Baseline/Reference
GT4	0.37	0.43	0.62	0.04	0.708	0.011
GT5	1.00	1.00	0.46	1.42	0.603	0.856
3. Window-to-wall-ratio (WWR)						
20%	1.00	1.00	0.00	-1.62	0.000	0.000
25%	0.83	0.89	0.10	-1.59	0.181	-0.247
30%	0.68	0.78	0.20	NA	0.330	Baseline/Reference
35%	0.56	0.66	0.30	-1.12	0.451	-0.303
40%	0.46	0.57	0.40	-1.07	0.551	-0.296
45%	0.36	0.45	0.50	-1.04	0.632	-0.263
50%	0.27	0.37	0.60	-1.01	0.699	-0.220
55%	0.19	0.28	0.70	-0.97	0.753	-0.164
60%	0.12	0.18	0.80	-0.93	0.798	-0.107
65%	0.06	0.09	0.90	-0.88	0.835	-0.053
70%	0.00	0.00	1.00	-0.84	0.865	0.000

The results demonstrate the ability of proposed CCOI framework to rank envelope alternatives based on their combined comfort, energy, and cost performance. Higher CCOI values indicate that the improvement in thermal comfort and energy performance is justified by the associated construction cost. Accordingly, WA4 and GT5 emerge as the most favourable alternatives within the categories of wall assembly and glazing type respectively. These alternatives achieve the highest comfort and energy performance gains relative to their cost implications. In contrast, most WWR alternatives and GT2 yield negative CCOI values, indicating that an increase in construction cost is associated with reduced thermal comfort and/or increased cooling energy, compared to the reference case. Such alternatives are therefore less favourable from cost-comfort optimisation point-of-view.

However, negative CCOI values should not always be interpreted as grounds for outright rejection, as some alternatives may offer additional benefits which are beyond the scope of the present methodological framework. Few such additional benefits can include improved daylighting, glare control, and renewable energy generation. Consequently, the proposed CCOI is intended as a screening and prioritisation tool for early-design stages, rather than a standalone decision-making method.

To evaluate the influence of penalty sensitivity coefficient (α) on the proposed CCOI, sensitivity analysis is conducted using four values of α (0.5, 1, 2, and 3). The analysis is performed for all simulated alternatives. The resulting penalty factors and corresponding CCOI values are presented in Table 5. This analysis aims to assess the robustness of the proposed index and the effect of cost sensitivity variation on performance of design alternatives.

Table 5: Penalty Factors (P) and CCOI values for various penalty sensitivity coefficients (α).

Variable	**Considering α = 0.5**		**Considering α = 1**		**Considering α = 2**		**Considering α = 3**	
	P	**CCOI**	**P**	**CCOI**	**P**	**CCOI**	**P**	**CCOI**
1. Wall Assembly (Discrete alternatives)								
WA1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WA2	0.017	Baseline	0.034	Baseline	0.067	Baseline	0.098	Baseline
WA3	0.158	0.017	0.292	0.032	0.498	0.055	0.645	0.071
WA4	0.393	0.393	0.632	0.632	0.865	0.864	0.950	0.950
2. Glazing type (Discrete alternatives)								
GT1	0.143	0.000	0.265	0.000	0.460	0.000	0.603	0.000
GT2	0.393	-0.010	0.632	-0.016	0.865	-0.022	0.950	-0.024
GT3	0.000	Baseline	0.000	Baseline	0.000	Baseline	0.000	Baseline
GT4	0.265	0.004	0.460	0.007	0.708	0.011	0.842	0.013
GT5	0.206	0.293	0.370	0.525	0.603	0.856	0.750	1.064
3. Window-to-wall ratio (WWR) in %								
20%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
25%	0.049	-0.067	0.095	-0.130	0.181	-0.247	0.259	-0.354
30%	0.095	Baseline	0.181	Baseline	0.330	Baseline	0.451	Baseline
35%	0.139	-0.094	0.259	-0.174	0.451	-0.303	0.593	-0.399
40%	0.181	-0.098	0.330	-0.177	0.551	-0.296	0.699	-0.376
45%	0.221	-0.092	0.393	-0.164	0.632	-0.263	0.777	-0.323
50%	0.259	-0.082	0.451	-0.142	0.699	-0.220	0.835	-0.263
55%	0.295	-0.064	0.503	-0.109	0.753	-0.164	0.878	-0.191
60%	0.330	-0.044	0.551	-0.074	0.798	-0.107	0.909	-0.122
65%	0.362	-0.023	0.593	-0.038	0.835	-0.053	0.933	-0.059
70%	0.393	0.000	0.632	0.000	0.865	0.000	0.950	0.000

The results of the sensitivity analysis tabulated in Table 5 indicate that an increase in α increases the magnitude of penalty applied to cost-intensive alternatives, resulting in corresponding changes in

CCOI values. However, it can be observed that the relative trends within the alternatives mostly remain consistent even after a change in the magnitude of the penalty.

For wall assembly alternatives, WA4 consistently achieves the highest CCOI value across all tested α values, while WA3 remains substantially low. Similarly, in glazing type, GT5 consistently emerges as the most favourable alternative, and GT2 continues to exhibit low CCOI. These findings suggest that the proposed CCOI framework is reasonably robust to variations in the penalty sensitivity coefficient (α) and that the raking of alternatives is not influenced significantly by choice of α within the tested range.

7. Conclusions

This study developed and tested a Cost-Comfort Optimisation Indicator (CCOI) as a simple, transparent, and early-stage decision-support framework for evaluating building envelope alternatives through the integrated consideration of thermal comfort, cooling energy performance, and construction cost. The study responds directly to a critical gap in existing building performance research, where envelope design alternatives are often assessed primarily through energy or comfort outcomes, while the construction-cost implications of early design choices remain insufficiently integrated into comparative evaluation. By combining normalised comfort and energy indicators with marginal cost-comfort efficiency and a cost-escalation penalty, the proposed CCOI provides a structured basis for identifying envelope solutions whose performance benefits are proportionate to their additional investment.

The findings confirm that early-stage envelope parameters substantially influence the balance between construction expenditure and building performance. Among the wall assembly alternatives, the super-insulated wall achieved the strongest integrated performance, recording 7,677.5 annual comfort hours, 157,210 kWh of cooling energy, and a CCOI value of 0.864, despite its higher envelope cost. This result demonstrates that higher initial construction expenditure can be justified when it delivers proportionate gains in comfort and energy efficiency. Similarly, double grey argon glazing emerged as the most favourable glazing option, achieving 7,688 annual comfort hours, 163,942 kWh of cooling energy, and a CCOI value of 0.856. In contrast, most window-to-wall ratio increases above the 30% baseline generated negative CCOI values, indicating that additional façade expenditure was associated with declining thermal comfort and increased cooling energy demand. These findings show that costlier design alternatives are not inherently more efficient and that performance gains must be evaluated in relation to their economic justification.

The study addresses its research objectives by identifying wall assembly, glazing type, and window-to-wall ratio as critical early-stage envelope variables and by demonstrating how variations in these parameters affect cost-performance trade-offs in the composite climate of New Delhi. It also answers the methodological research question by formulating and testing a unified indicator capable of ranking envelope alternatives through a single interpretable metric. The originality of the study lies in its integration of construction cost, comfort performance, and cooling-energy performance into a practical screening tool for early design evaluation. Unlike complex optimisation frameworks that may require extensive input data and advanced modelling capacity, the CCOI is designed to support rapid comparative assessment when design information remains limited but key envelope decisions must already be made.

The theoretical contribution of the research is the conceptual advancement of early-stage envelope evaluation from a performance-only perspective toward a cost-performance efficiency perspective. By incorporating marginal efficiency and diminishing-return logic, the CCOI strengthens the analytical basis for understanding whether envelope improvements generate meaningful benefits relative to their cost. This is particularly important in climatic contexts where cooling demand is sensitive to envelope design and where inefficient design decisions can impose long-term energy and economic burdens. The framework therefore contributes to the broader literature on passive design, building performance simulation, and cost-conscious sustainable building design by offering a method that is both scientifically structured and practically interpretable.

The practical implications of the findings are significant for architects, engineers, planners, developers, construction professionals, and policy-oriented decision-makers. At the project level, the CCOI can help design teams compare wall, glazing, and façade alternatives before construction decisions become difficult or expensive to reverse. At the industry level, it can support more rational material selection, reduce overinvestment in poorly performing envelope options, and encourage performance-based design choices. For policymakers and urban development authorities, the framework can inform guidelines, incentive mechanisms, and early-stage assessment protocols that promote cost-effective energy efficiency in the building sector. In rapidly urbanising cities, such tools can improve the allocation of construction resources, reduce operational cooling burdens, and support more economically resilient building stocks.

The study also contributes to the urban economy by linking early building envelope decisions with long-term operating costs, energy demand, and infrastructure efficiency. In expanding urban contexts such as New Delhi, repeated design choices across office and commercial buildings can influence electricity consumption, cooling-related infrastructure pressure, and the affordability of building operation. By enabling the prioritisation of envelope alternatives that improve comfort and reduce cooling energy without unjustified cost escalation, the CCOI can support more productive indoor environments, lower operating expenses, and better resource allocation in urban construction. These outcomes are directly relevant to urban economic resilience, as energy-efficient and cost-conscious buildings can reduce financial pressure on occupants, owners, and urban energy systems.

Beyond its economic implications, the proposed framework has broader environmental and societal significance. By encouraging envelope decisions that reduce cooling energy demand while improving thermal comfort, the CCOI supports more sustainable building practices and contributes to reduced energy-related environmental pressures. Improved indoor comfort can also enhance occupant well-being and productivity, particularly in office buildings located in climates with high seasonal thermal variation. Therefore, the framework aligns with wider goals of sustainable urban development by connecting building-level design decisions with environmental performance, user comfort, and long-term urban resource efficiency.

Nevertheless, the findings should be interpreted within the limitations of the study. The validation was conducted using a simplified two-storey office shoebox model located in New Delhi's composite climate, and only three envelope variables were examined through a one-variable-at-a-time simulation strategy. The framework focused on annual comfort hours, cooling energy, and envelope construction cost, while other potentially relevant criteria, such as daylighting, glare, embodied carbon, maintenance cost, heating demand, occupant behaviour, and interactions among multiple design variables, were outside the scope of the present study. These limitations do not reduce the methodological contribution of the CCOI but indicate that its application should be extended and calibrated before broader generalisation.

Future research should apply the CCOI framework to different building typologies, climatic zones, occupancy patterns, and design stages to test its robustness across wider contexts. Further studies should also incorporate additional performance criteria, especially daylighting, glare, embodied environmental impact, and life-cycle cost, to develop a more comprehensive decision-support framework. Multi-variable simulations and advanced optimisation approaches may be used to examine interaction effects among wall assembly, glazing type, window-to-wall ratio, shading, orientation, and ventilation strategies. Refinement of the weighting scheme and penalty sensitivity coefficient through expert consultation, stakeholder preference modelling, or empirical calibration would further improve the reliability and adaptability of the indicator. Through these extensions, the CCOI can evolve into a more comprehensive tool for supporting sustainable, cost-effective, and performance-oriented envelope design in diverse urban development contexts.

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