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RESEARCH

The Multi-Objective Optimisation for Energy Consumption and Daylight of Office Buildings in London: Meshed Façade Energy Study

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ABSTRACT

PURPOSE: Mesh façades have emerged as a dual-purpose solution that combines solar protection with visual transparency and aesthetic flexibility: leading architects are increasingly adopting them in non-residential buildings. This study evaluates their application as second-skin passive shading systems and their impact on energy and daylight performance in fully glazed office buildings in London, UK.

DESIGN/METHODOLOGY/APPROACH: A simulation-based multi-objective optimisation model was developed in Grasshopper using the Colibri plugin and evolutionary algorithms. Key variables, including mesh density, spacing, thickness, and standoff distance, were evaluated across four façade orientations. Trade-offs were analysed using Pareto fronts to select optimal solutions for each façade scenario, balancing cooling load, heating load, and daylight.

FINDINGS: Selective mesh application reduced energy demand by up to 20% (south), 19% (east), and 16.7% (west), while uniform application increased it by 20% due to high window-to-wall ratios. Heating remained the dominant energy load, highlighting the need to address thermal losses. The optimisation revealed trade-offs between energy and daylight performance, manageable based on a given project's specific design goals and constraints.

ORIGINALITY/VALUE: This study contributes to the architecture field by addressing underexplored mesh façade variables through a simulation-based optimisation framework. This enables architects to enhance façade design and performance during early digital modelling. It offers a practical method for improving energy and daylight outcomes based on orientation-specific strategies

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RESEARCH/PRACTICAL IMPLICATIONS: Findings support climate-responsive design and encourage further investigation into dynamic façades and broader performance metrics.

KEYWORDS: *Meshed Façade; Energy Demand; Daylight; Multi-Objective Optimisation; Genetic Algorithm; Building Performance Simulation; Grasshopper; Colibri*

INTRODUCTION

Global urbanisation and climate change have increased the demand for energy-efficient, resilient buildings. The sector contributes over one-third of global energy use and 40% of CO_2 emissions (IEA, 2021), mainly from heating, cooling, and ventilation. The net-zero 2050 target in the UK underscores the need to improve building performance (Johnstone and Holyoake, 2020). Urban centres such as London face heightened overheating risks from the urban heat island effect (Levermore and Parkinson, 2019). Fully glazed modern office façades enhance daylight and aesthetics but also raise solar gains and cooling load (CL). Orientation-specific passive shading can counter these effects, reducing energy use and improving visual comfort (Mahdavinejad *et al.*, 2024).

Mesh façade (MF) offers a dual-purpose solution, providing solar control, visual transparency, and design flexibility. Despite growing use in non-residential buildings, environmental performance remains underexplored (Fawaz *et al.*, 2025). This study addresses that gap by evaluating how variations in MF parameters, such as perforation percentage, vertical and horizontal density, thickness, and distance from glazing, influence annual heating load (AHL), annual cooling load (ACL), and average daylight factor (ADF) in fully glazed London office buildings. It also examines tools for early-stage design to improve energy efficiency and comfort.

The main objectives are to:

1. develop an MF optimisation model in Rhino 3D and Grasshopper to solve multi-objective optimisation (MOO) problems using parametric modelling and evolutionary algorithms;
2. explore design trade-offs between energy reduction, solar control, and daylight performance;
3. evaluate façade strategies' effectiveness in early-stage design;
4. benchmark and analyse performance across orientations.

LITERATURE REVIEW

Shading systems are vital components of building envelopes that control solar radiation, reduce CL, and enhance daylight levels and thermal comfort (Li *et al.*, 2020;

Al Tamimi and Fadzil, 2011). Fixed and movable devices such as overhangs, fins, and blinds are effective passive strategies, especially in high-exposure climates. Research demonstrates that optimised shading systems can achieve substantial energy savings, with overhangs reducing energy use intensity by up to 14.95% and side fins achieving 7.28% reductions (Abedini *et al.*, 2025). Performance depends on orientation, angle, and material (Middel *et al.*, 2021). Shading must avoid over-blocking daylight, which increases artificial lighting demand (Woo *et al.*, 2021). As shading design advances, MF is gaining attention for environmental and architectural benefits, contributing to sustainability goals, including Sustainable Development Goal (SDG) 11 (sustainable cities) and SDG 13 (climate action) (Fawaz *et al.*, 2024; Taveres-Cachat *et al.*, 2021).

Various perforated or woven metal options are now used, including expanded mesh, gratings, and fabrics. Expanded mesh reflects some solar radiation while allowing filtered penetration based on geometry and installation (Tsay *et al.*, 2019). MFs are commonly used on glazed buildings to reduce heat gain and glare, improve thermal comfort, and maintain outward visibility (Gourlis *et al.*, 2016). Forms such as diamond and square perforations enable design flexibility. Their durability and low maintenance suit new and retrofit projects, although their low insulation makes climate-based optimisation crucial (Mohamed and Bande, 2022). Prior studies have evaluated their energy-saving potential in countries such as Italy, Romania, and Taiwan (Tsay *et al.*, 2019; Mainini *et al.*, 2015; Udrea and Popa, 2019). Most research focuses on perforation rate, overlooking key variables such as thickness, density, and mesh-to-glazing distance addressed here. Table 1 presents a summary of key previous research findings on MF and perforated building façades (PBFs).

Table 1 Summary of Key Previous Research Findings on Mesh Façade and Perforated Building Façades

Reference	Focus	Key Findings
Fawaz *et al.*, 2025	Parametric design of PBFs using Grasshopper and ClimateStudio	PBFs improved energy efficiency by 26.91% over glazed façades; early-stage modelling and perforation geometry are critical
Fawaz *et al.*, 2024	Historical and practical role of PBFs in sustainable architecture	PBFs enhance ventilation, daylight, and energy use; integration in early design improves indoor air quality and sustainability
Tsay *et al.*, 2022	Daylight and energy simulation of expanded metal mesh in Taiwan	Optimal solar heat gain coefficient (SHGC) (50%), laminated glass, and 21% perforation achieved energy balance; window-to-wall ratio and SHGC are key variables
Fan *et al.*, 2019	Perforation impact on energy via ENVLOAD, OTTV, and ETTV	Low-perforation mesh with single-pane glass outperformed low-E glazing; cost-effective passive strategy

Reference	Focus	Key Findings
Blanco *et al.*, 2016	Double-skin systems with perforated panels across Spanish climate zones	Energy savings vary with perforation, material, and colour; zone-specific recommendations provided
Mainini *et al.*, 2015	Energy savings of perforated sheets in office curtain walls	Noted significant energy savings with varying opening ratios, especially in curtain wall systems
Blanco *et al.*, 2014	Impact of perforation shape, material, and colour	Energy performance influenced by emissivity, distribution, and material choice

Source: Constructed by author

Multi-Objective Optimisation

Early-stage design decisions influence 80% of a building's energy performance (Sun *et al.*, 2015). With increased computing power, simulation and optimisation tools now offer rapid feedback on metrics such as energy use, daylight, thermal comfort, and indoor air quality (Wang and Zhai, 2016). Multi-objective optimisation (MOO) provides an efficient framework for exploring high-performing design alternatives (Shen *et al.*, 2018).

MOO refers to a generative design process that explores trade-offs between competing goals such as reducing energy demand, maintaining adequate daylight, and lowering costs (Omid and Golabchi, 2019). The process typically follows six iterative steps (Shen *et al.*, 2018):

- identifying design variables and constraints;
- creating a baseline model;
- setting objectives;
- selecting an optimisation algorithm;
- running simulations;
- evaluating results.

It accommodates various parameters, including orientation, geometry, energy, and daylight metrics (Jafari and Valentin, 2018). Pareto front optimisation identifies optimal solutions; improving one metric does not compromise another (Machairas *et al.*, 2014; Lavin, 2015). This approach was adopted in the current study to evaluate MF configurations. Figure 1 shows a Pareto front example for a two-objective minimisation problem.

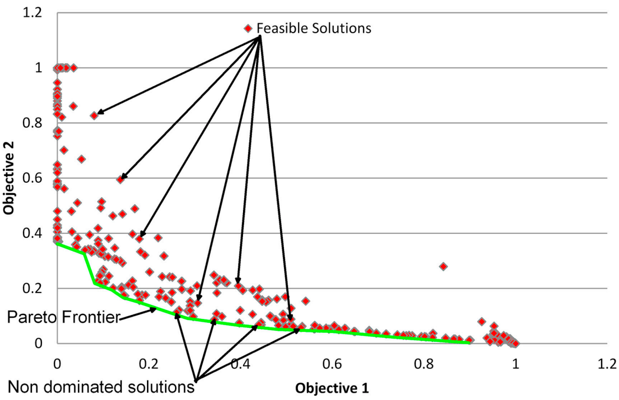


Figure 1 A Pareto Front Example for Two-Objectives Minimisation Problems
Source: Machairas *et al.*, 2014

Genetic algorithms are particularly suitable for solving complex, non-linear design problems. Introduced by Holland (1992), they simulate natural evolution through selection, crossover, and mutation. In this study, a genetic algorithm was applied to identify façade designs that minimise heating load (HL) and CL while preserving daylight performance.

Findings from Literature Review and Knowledge Gap

The literature highlights that external meshed shading systems offer functional and aesthetic benefits by reducing solar gain and enhancing façade design. Energy and daylight performance depends on factors such as window-to-wall ratio, glazing type, and climate-responsive shading. Although genetic algorithms show promise for early-stage optimisation, standard methods are lacking. Gaps remain in selecting input parameters, defining population size, and setting convergence criteria. Research on MF is also limited, with most studies focusing only on perforation rate. Critical variables such as mesh density, thickness, and spacing from the glazing are often overlooked. This study addresses those gaps by incorporating these underexplored variables into a simulation-based optimisation framework to support early design decisions.

METHODOLOGY

This study adopts a simulation-based optimisation framework to evaluate MF performance in a high-rise London office building. It aims to reduce total energy demand and enhance daylight distribution, using a MOO approach supported by environmental simulation tools. The MF is applied as a fixed second skin to the east, west, and south façades. The north façade is excluded due to limited solar exposure, consistent with literature findings.

Simulations produced AHL, ACL, and ADF using a Chartered Institution of Building Services Engineers (CIBSE) Test Reference Year (TRY) weather file. The study investigates the two key design variables:

1. mesh density, including perforation percentage, vertical/horizontal spacing, and thickness;
2. distance from mesh to glazing surface.

The simulation follows four phases:

1. develop a base model without mesh as a benchmark;
2. apply mesh on selected façades and run optimisation using a genetic algorithm;
3. identify and analyse optimal Pareto front solutions;
4. present and interpret results.

Geometry and parametric controls were created in Rhinoceros 3D and Grasshopper. Performance analysis used Ladybug with Radiance, Daysim, and EnergyPlus. Optimisation was performed using the Colibri plugin, chosen for its efficiency, evaluated mesh variable combinations, and performance trends to guide decision-making. Results are visualised in Design Explorer, enabling comparison and selection of optimal solutions. Tables and graphs summarise outcomes, clearly evaluating energy and daylight performance across all scenarios. This approach supports early-stage façade design by using parametric modelling to identify mesh configurations that balance energy and daylight.

BASE CASE ANALYSIS AND RESULTS

Building Modelling in Rhino and Grasshopper

To conduct the simulations, a base model of the office building was created using Rhino and Grasshopper, followed by the integration of the MF geometry. The office building consists of three floors, each measuring 25m in width, 40m in depth, and 3m in floor-to-ceiling height, totalling 3,000m2; 90% of the east, west, and south façades are fully glazed. Figures 2 and 3 present the modelling workflow and geometry generation process. Figures 4 and 5 present the office building 3D models and the base case (BC) across all tested scenarios.

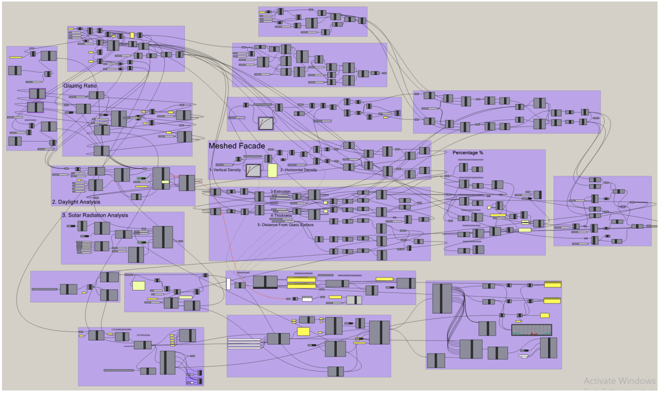


Figure 2 The Workflow of the Modelling Process in Grasshopper
Source: Constructed by author

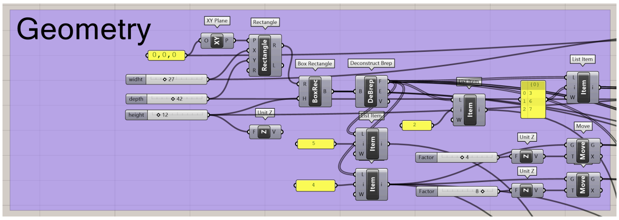


Figure 3 The Components used to Develop the Building Geometry
Source: Constructed by author

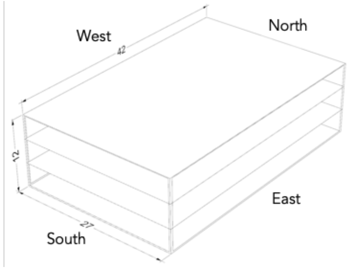


Figure 4 3D Model of the Office Building
Source: Constructed by author

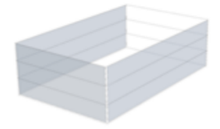
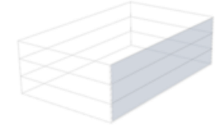
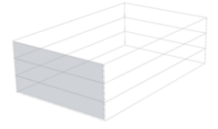
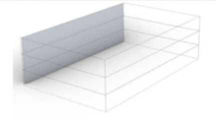
			
First Scenario: The glazed surface placed in three different orientations, east, west, and south façades.	**Second Scenario:** The glazed surface placed on the building's east façades.	**Third Scenario:** The glazed surface placed on the building's south façades.	**Fourth Scenario:** The glazed surface placed on the building's west façades.

Figure 5 3D Model of Base Case for all Scenarios

Source: Constructed by author

Solar Radiation Analysis

Solar analysis using Ladybug in Grasshopper identified façade exposure and overheating risks. The analysis showed that annual radiation exceeded 660kWh/m^2 on south-facing façades, followed by east and west, while the north had minimal exposure. This aligns with literature linking orientation to thermal gain (Middel *et al.*, 2021). Table 2 lists assumptions; Figures 6 and 7 show setup and outputs.

Table 2 Solar Radiation Assumptions

Parameter	Value
Grid size parameter	0.5m
Distance from the base	0.01m
Weather file	CIBSELondonHeathrowTRY.epw
Sky Density	1

Source: Constructed by author

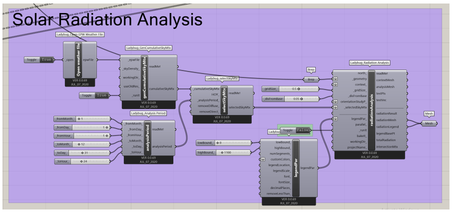


Figure 6 The Components used in Grasshopper to run the Solar Radiation Analysis

Source: Constructed by author

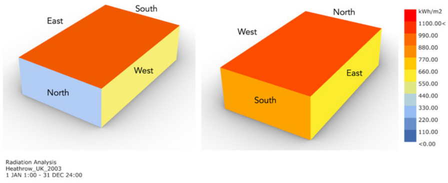


Figure 7 Solar Radiation Analysis Results

Source: Constructed by author

Average Daylight Factor Analysis

Daylight analysis is a climate-based method used to evaluate indoor light levels and visual comfort. Adequate daylight improves occupant well-being and reduces reliance on artificial lighting (Woo *et al.*, 2021). This study uses daylight factor (DF), which measures the percentage of indoor daylight under overcast sky conditions. BS EN 17037 recommends an ADF of 5% for spaces with good daylight and 2% for partial daylight. Values below 2% require artificial lighting. Using Honeybee in Grasshopper, ADF was simulated across all floors with 90% glazing and no shading, using a 0.5m grid at 0.85m above floor level.

The results show variation in daylight levels across the building. ADF values range from 9% to 18.2% on floors 1 to 3, indicating high daylight access. Near the glazing, ADF peaks reach 23.83%, exceeding recommended comfort limits. Minimum ADF was 3.85%, above the 2% threshold recommended by BS EN 17037, indicating sufficient daylight (BSI, 2008). These findings support Hwang *et al.* (2023), who noted that while larger glazed areas improve daylight in under lit spaces, they raise solar heat gain. The uneven distribution observed creates over lit zones prone to glare and overheating. Hwang *et al.* (2023) emphasised that window-to-wall ratio, glazing size, and placement are key to daylight and thermal performance. In such cases, active cooling becomes necessary. These results underscore the importance of using shading strategies to moderate daylight, reduce cooling and lighting loads, and enhance energy efficiency in over-glazed buildings. Table 3 and Figures 8-9 present set-up and results.

Table 3 Daylight Factor Assumptions

Parameter	Value
Grid size parameter	0.5m
Analysis grid height above floor level	0.85m
RAD material	Context_Material
Glazing RAD material	Exterior_Window
External walls RAD material	Exterior_Walls
Roof RAD material	Exterior_ Roof
Interior wall RAD material	Interior_Wall
Ceiling RAD material	Interior_Ceiling
Floor RAD material	Interior_Floor
Sky	Cloudy
Radiance parameters	-ab 2 -ad 1000 -as 20 -ar 300 -aa 0.1

Source: Constructed by author

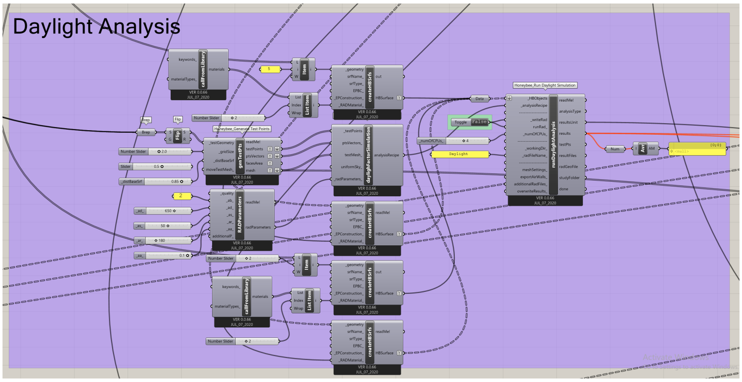
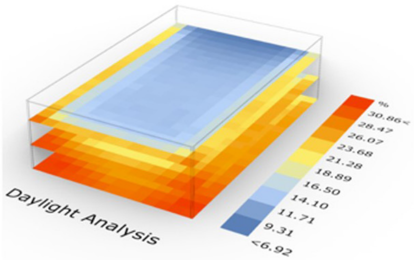
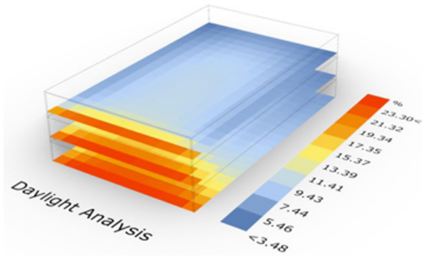


Figure 8 The Components used to run the Average Daylight Factor Analysis in Grasshopper

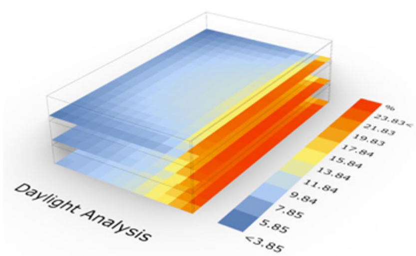
Source: Constructed by author

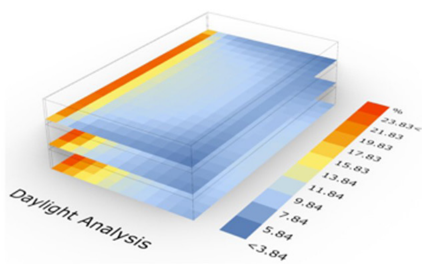




First Scenario (East, West and South Façade)
- The DF on floors 1 to 3 is between <6.92 and 30.68<.
- The ADF is 18.2%

Second Scenario (South Façade)
- The DF on floors 1 to 3 is between <3.48 and 23.30<
- The ADF is 9%





Third Scenario (East Façade)
- The DF on floors 1 to 3 is between <3.85 and 23.83<
- The ADF is 11.1%

Fourth Scenario (West Façade)
- The DF on floors 1 to 3 is between <3.84 and 23.83<
- The ADF is 11.3%

Figure 9 Daylight Analysis Results for the Base Case Scenarios (without Mesh Façade)

Source: Constructed by author

Cooling and Heating Load

A building's energy demand can be evaluated using its heating and cooling energy requirements. Heating load (HL) and cooling load (CL) represent the energy needed to maintain indoor temperatures. Estimating them during early design is crucial as geometry, orientation, layout, and envelope design strongly influence performance (González and Fiorito, 2015). In this study, Honeybee was used to simulate annual HL and CL across all three floors, modelled as a single thermal zone. The thermal envelope includes walls, roof, floors, and glazed façades. Mechanical cooling and ventilation were assumed. Simulations followed CIBSE Guide A (2019) and BS EN 16798-1:2019. EnergyPlus library schedules and internal loads were used to model a typical office profile. Materials followed ASHRAE 90.1-2010. Figure 10 shows the workflow; Tables 4 and 5 list assumptions.

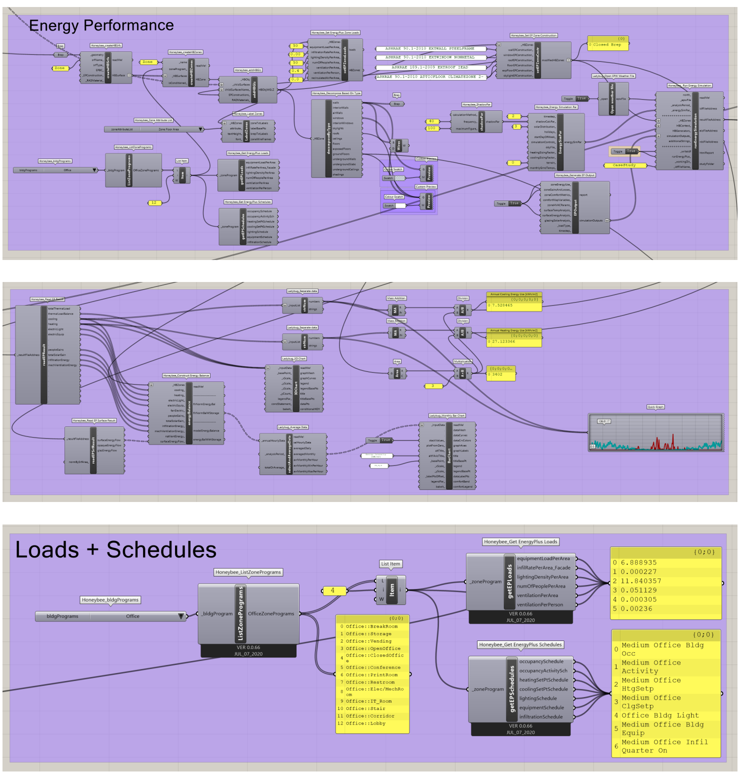


Figure 10 Grasshopper Workflow for Building Energy Performance Simulation

Source: Constructed by author

Table 4 Default Constructions used for Analysis

Type	ASHRAE Standard	U-value (W/m²k)
Wall	ASHRAE 90.1-2010 EXTWALL STEELFRAME CLIMATEZONE ALT-RES 7	0.38
Window	ASHRAE 90.1-2010 EXTWINDOW NONMETAL CLIMATEZONE 7-8	3.6
Roof	ASHRAE 189.1-2009 EXTROOF IEAD CLIMATEZONE 7-8	0.28
Floor	ASHRAE 90.1-2010 ATTICFLOOR CLIMATEZONE 2-7	0.15

Source: Constructed by author

Table 5 Simulation Assumptions

Density of occupation	4 person/m²
Lighting load	12W/m²
Equipment gains	12W/m²
Ventilation rate	10 l/s per person
Weather file	CIBSELondonHeathrowTRY.epw
Time steps per hour	4
Solar distribution	FullExteriorWithReflections
Terrain Type	City
Shadow calculation method	Default
Shadow calculation method	30
Shadow calculation overlap	3000

Source: Constructed by author

The simulations account for internal heat gains from occupants, lighting, equipment, and solar radiation, primary contributors to thermal load. Results for the BC confirm that heating consistently exceeds cooling, making HL is the dominant load. Table 6 summarises the ACL and AHL.

Table 6 Annual Cooling Load and Annual Heating Load

BC	ACL [kWh/m²]	AHL [kWh/m²]
First Scenario (East, West and South Façade)	7.52	27.12
Second Scenario (South Façade)	3.27	16.47
Third Scenario (East Façade)	2.67	19.55
Fourth Scenario (West Façade)	5.11	20.89

Source: Constructed by author

In the first scenario, where the east, west, and south façades are fully glazed, the HL reaches 27.12kWh/m^2 and the CL is 7.52kWh/m^2. Applying glazing to the south façade (second scenario) significantly reduces both loads to 16.47kWh/m^2 for heating and 3.27kWh/m^2 for cooling. The east-facing case (third scenario) further lowers the CL to 2.67kWh/m^2 but slightly increases the HL to 19.55kWh/m^2. The west-facing case (fourth scenario) records 5.11kWh/m^2 for cooling and 20.89kWh/m^2 for heating. All BC scenarios remain below the ASHRAE benchmark of 31.5W/m^2 (heating) and 47W/m^2 (cooling). The comparative chart in Figure 11 shows that although energy use remains within acceptable limits, heating remains the dominant load. These results reinforce the need for shading and window-to-wall ratio adjustments in highly glazed buildings.

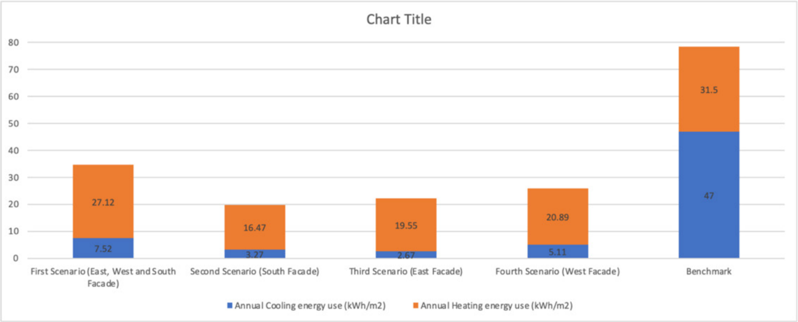


Figure 11 Comparison between the Annual Cooling Load and Annual Heating Load of the Base Case and the ASHRAE benchmark

Source: Constructed by author

MESHED FAÇADE ANALYSIS AND RESULTS

Modelling Meshed Façade

The MF was modelled in Grasshopper as a secondary skin system attached to selected orientations of a high-rise office building. The model incorporated parametric controls to adjust key design variables. The parametric setup enabled controlled variations of the MF properties while keeping the envelope geometry consistent. Figure 12 shows the geometry, while Figure 13 displays the components used to develop the MF.

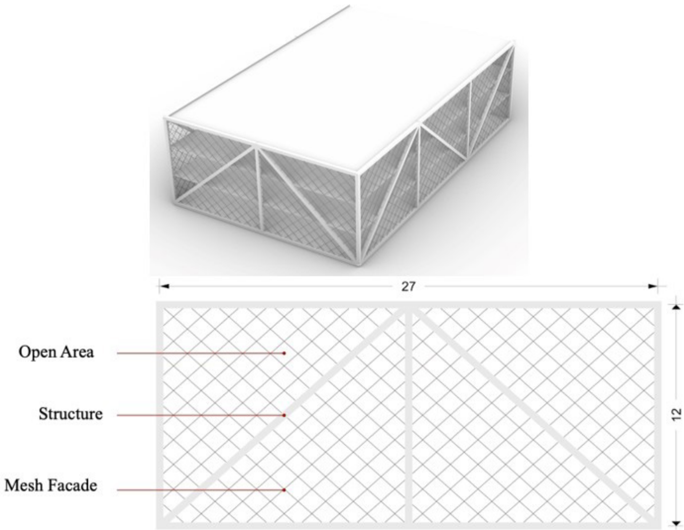


Figure 12 Geometry of the Case Study

Source: Constructed by author

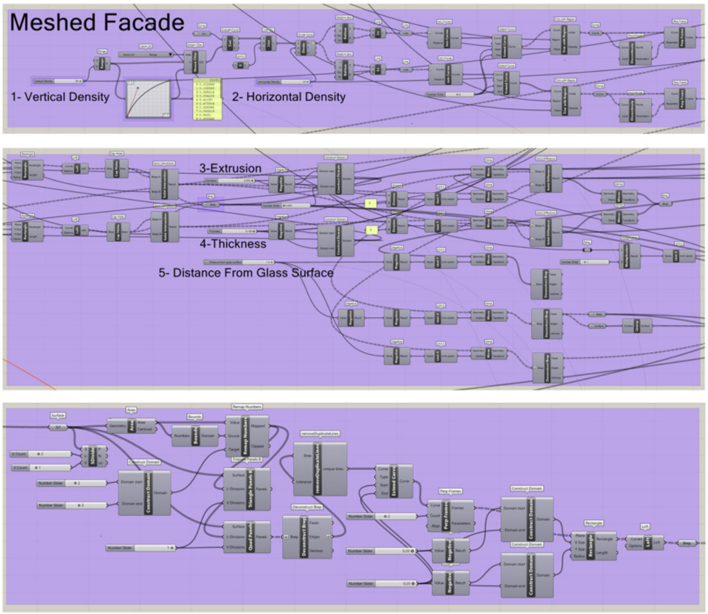


Figure 13 The Components used to build the Meshed Façade in Grasshopper

Source: Constructed by author

Optimisation Algorithm

A multi-objective genetic algorithm was employed to optimise the MF, aiming to minimise energy demand without compromising daylight levels. The optimisation was executed using the Colibri plug-in in Grasshopper, with each scenario run through Honeybee for simulation and Design Explorer for performance visualisation. Each mesh configuration required 4-6 hours to compute. Colibri generated multiple design iterations based on defined input variables, and Design Explorer was used to identify Pareto front solutions. These represent trade-offs, where improving one objective (such as reducing CL), compromises another (such as daylight access). As supported in the literature, daylight and energy variables are interdependent and cannot be optimised in isolation, justifying the use of an evolutionary optimisation approach.

The optimisation targeted the following performance objectives:

1. minimise total annual energy demand (CL and HL);
2. optimise average ADF;
3. explore trade-offs between daylight and energy performance;
4. identify optimal solutions for each façade orientation.

Each scenario involved 72 simulation runs. Fixed and variable inputs are summarised in Tables 7 and 8.

Table 7 Fixed Parameters

Fixed Parameters
Square metres
Glazing Ratio
Building materials and meshed façade material
Weather File

Source: Constructed by author

Table 8 Variables Parameters

Variable Parameters	Range
Vertical mesh density	1-15
Horizontal mesh density	1-15
Mesh thickness	0.01-1m
Extrusion depth	0.05-0.5m
Distance from glazing	0-1.5m

Source: Constructed by author

The main outcomes assessed during the optimisation were:

- differences in energy consumption between the BC and each mesh configuration;
- the performance impact of the meshed façade when applied to different orientations;
- the potential for overall energy savings and daylight balance using MF.

Multiple solutions were visualised and compared using Design Explorer and graphs. Results were interpreted through correlation analysis and benchmarked against the BC. Figure 14 illustrates the components used in the Colibri optimisation setup.

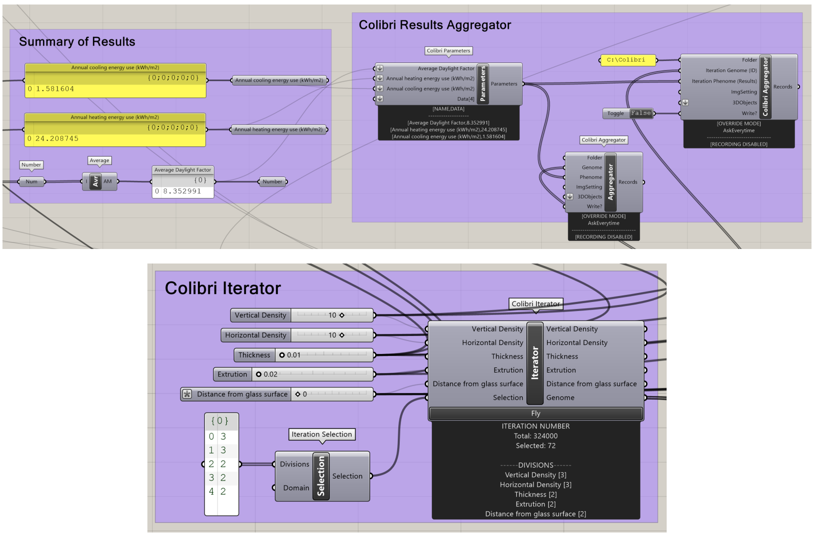


Figure 14 The Components used for the Optimisation Process (Colibri)
Source: Constructed by author

MULTI OBJECTIVE OPTIMISATION RESULTS

First Scenario

The MF is applied to the fully glazed east, west, and south walls (Figure 15). Based on Pareto front results, the greatest CL reduction (1.54kWh/m^2) was achieved using a 34% open area mesh, lowering CL by approximately 80% compared to the BC. Increasing mesh density and increasing the standoff distance further reduced CL, but also led to a 44.2% decrease in ADF and a 33% increase in HL (Figures 16-20).

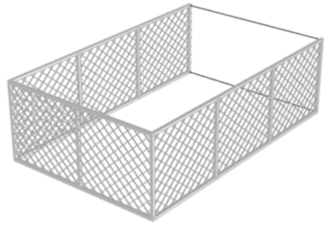


Figure 15 Base Case
Source: Constructed by author

Optimisation results

Figure 16 shows a multi-axes chart by Design Explorer, showing the simulation results of each run and trade-offs between CL, HL and DF, including each objective's minimum and maximum values.

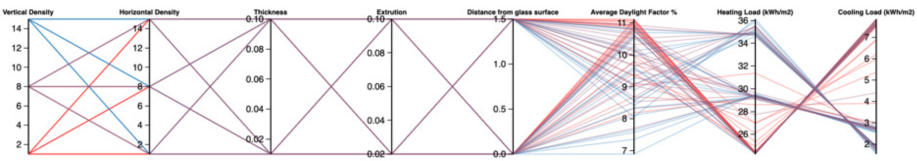


Figure 16 Multi-Axes Chart by Design Explorer
Source: Constructed by author

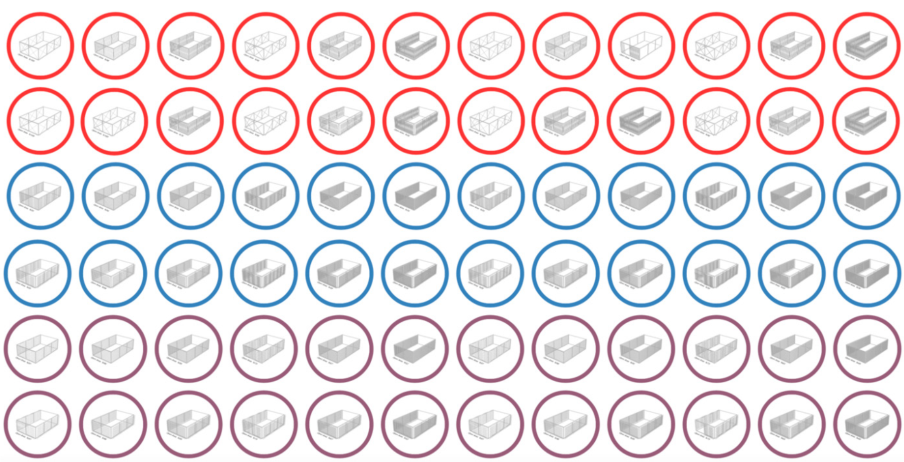


Figure 17 Visual Representation of the 72 Optimised Solutions for Office Building
Source: Constructed by author

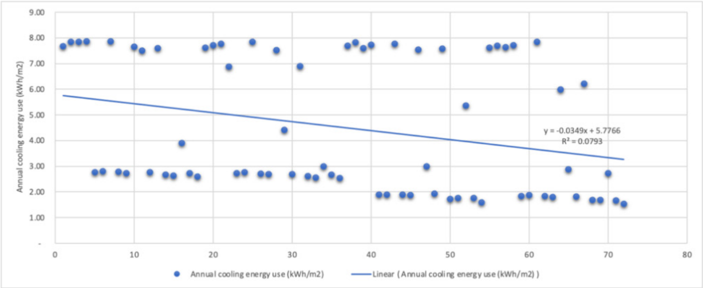
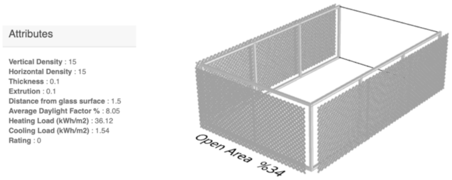


Figure 18 Annual Cooling Load

Source: Constructed by author



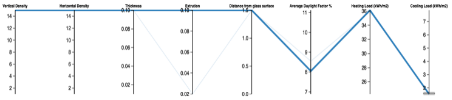


Figure 19 Optimal Solution for Cooling Load

Source: Constructed by author

Figure 20 Optimised Solutions for Cooling Load

Source: Constructed by author

Meshes with 96-98% open area achieved the lowest HL (24.27kWh/m²) and highest CL (7.86kWh/m²), with a 59.2% ADF drop. HL fell 10.5%; CL rose 4.5% compared to the BC (Figures 21-23).

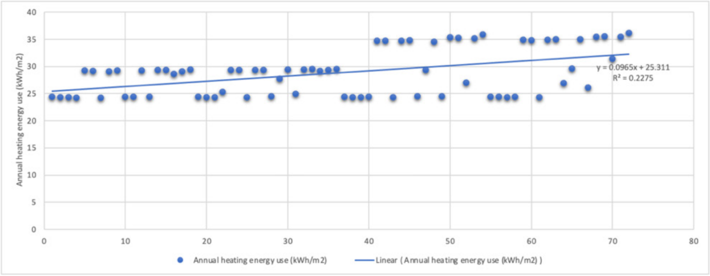


Figure 21 Annual Heating Load (Pareto Front Solutions)

Source: Constructed by author

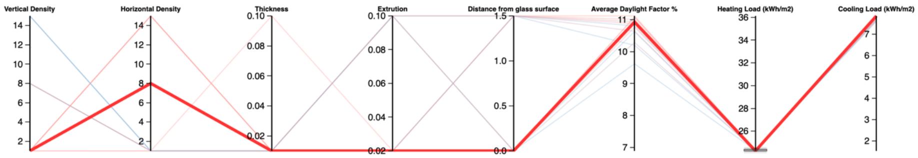


Figure 22 Optimised Solutions

Source: Constructed by author

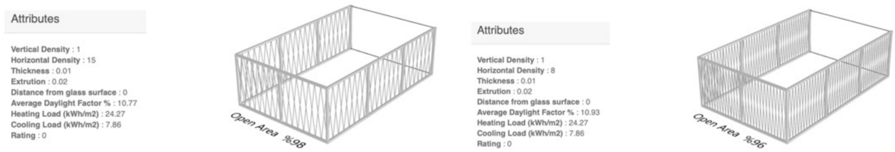


Figure 23 Optimal Solutions for Heating Load

Source: Constructed by author

The optimal ADF (6.89%) was also achieved using a 34% mesh, reducing ADF by 37.9% and raising HL by 9%. Lower mesh density and shorter standoff distance reduced both ADF and CL by 33.6% (Figures 24-26).

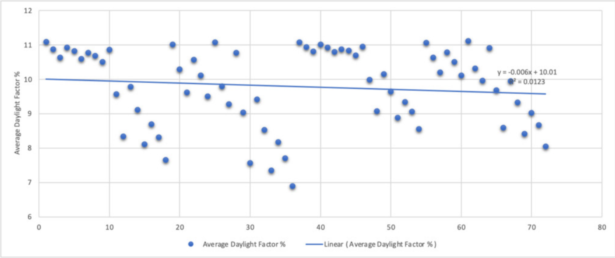


Figure 24 Average Daylight Factor

Source: Constructed by author

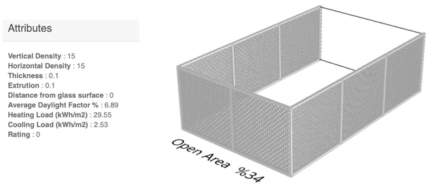


Figure 25 Optimal Solution for Average Daylight Factor

Source: Constructed by author

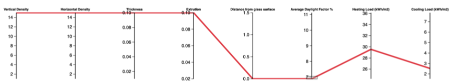


Figure 26 Optimised Solutions for Heating Load

Source: Constructed by author

SECOND SCENARIO

The MF is applied to the fully glazed south elevation (Figure 27). Based on Pareto front results, the greatest CL reduction (1.44kWh/m^2) was achieved using a mesh with 34% open area, lowering CL by approximately 44.1% compared to the BC. This configuration also led to an 8% increase in HL. Higher mesh density significantly reduced solar gain, resulting in a 20% ADF decrease (Figures 28-32).

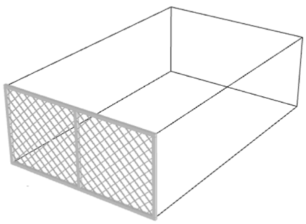


Figure 27 Base Case
Source: Constructed by author

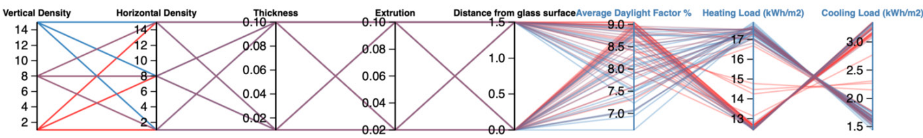


Figure 28 Multi-Axes Chart by Design Explorer
Source: Constructed by author

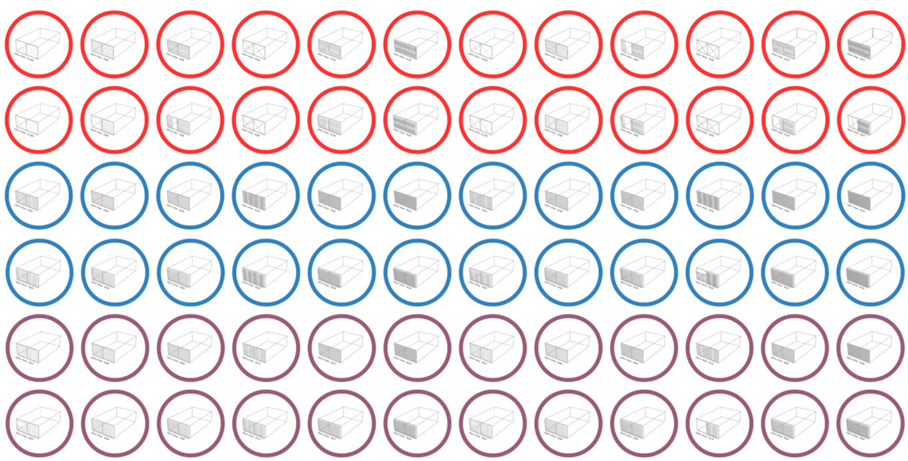


Figure 29 Visual Representation of the Optimised Solutions
Source: Constructed by author

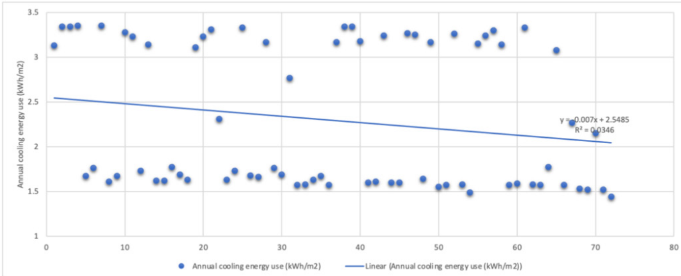


Figure 30 Annual Cooling Load

Source: Constructed by author

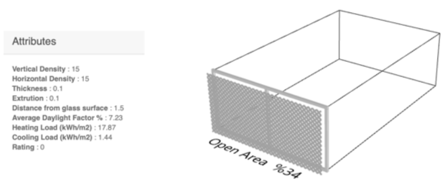


Figure 31 Optimal Solution for Cooling Load

Source: Constructed by author

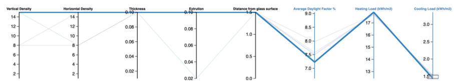


Figure 32 Optimised Solutions for Cooling Load

Source: Constructed by author

HL reached its lowest (12.43kWh/m²) and CL its highest (3.35kWh/m²) with 96%-98% mesh. These configurations reduced HL by 24.5%, raised CL by 2.5%, and slightly lowered ADF compared to the BC (Figures 33-35).

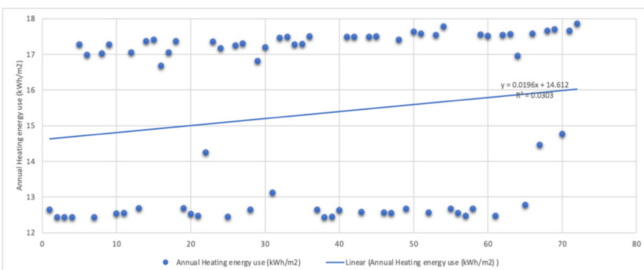


Figure 33 Annual Cooling Load

Source: Constructed by author

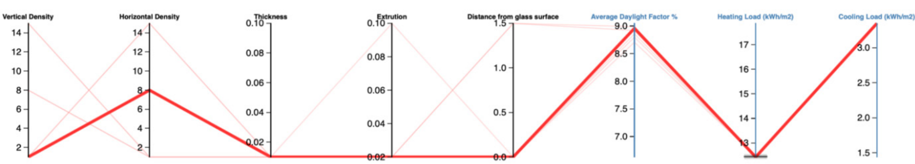


Figure 34 Optimised Solutions

Source: Constructed by author

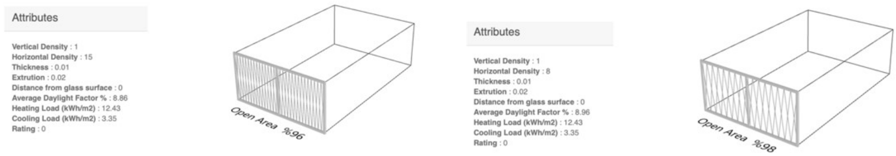


Figure 35 Optimal Solution for Heating Load

Source: Constructed by author

The optimal daylight (ADF 6.63%) was achieved with a 34% mesh, cutting ADF by 26.3%, CL by 52%, and raising HL by 6.3% (Figures 36-38).

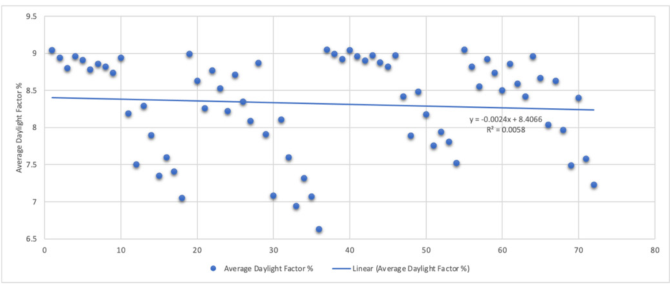


Figure 36 Average Daylight Factor

Source: Constructed by author

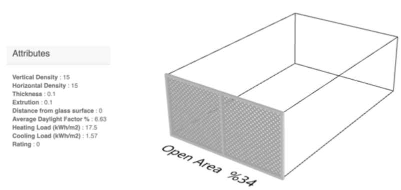


Figure 37 Optimal Solution for Average Daylight Factor

Source: Constructed by author

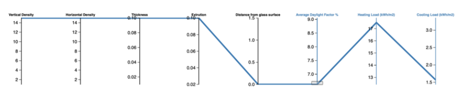


Figure 38 Optimised Solutions

Source: Constructed by author

THIRD SCENARIO

The MF is applied to the fully glazed east elevation (Figure 39). The lowest CL (1.45kWh/m^2) was achieved using a 34% open area mesh, as with previous scenarios (Figures 40-44), resulting in a 45.7% reduction in CL and a 9% increase in HL compared to the BC. Increasing mesh density and standoff distance further reduced CL, but also led to a 23.2% decrease in ADF.

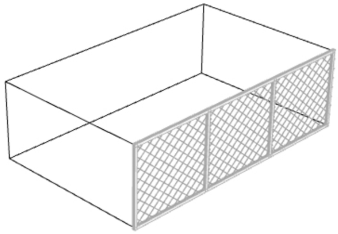


Figure 39 Base Case

Source: Constructed by author

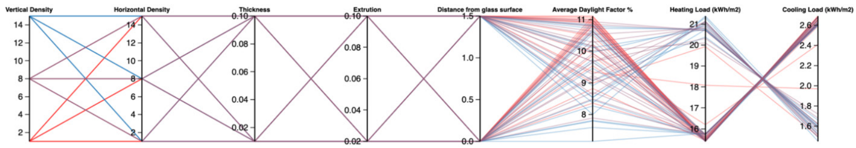


Figure 40 Multi-Axes Chart by Design Explorer

Source: Constructed by author

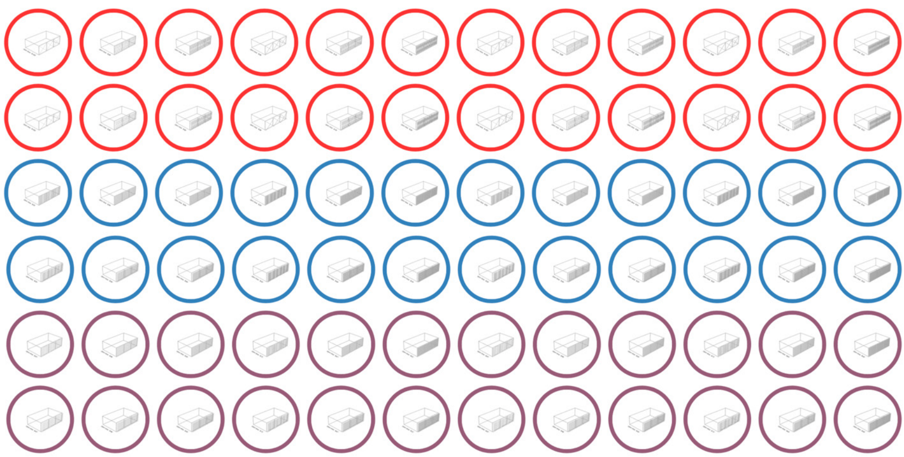


Figure 41 Visual Representation of the Optimised Solutions

Source: Constructed by author

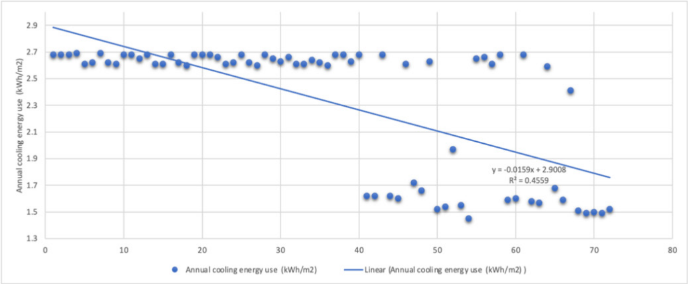


Figure 42 Annual Cooling Load

Source: Constructed by author

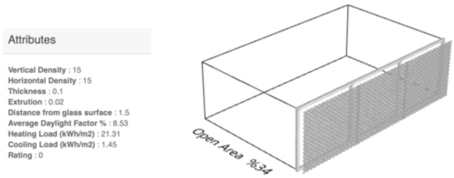


Figure 43 Optimal Solution for Cooling Load

Source: Constructed by author

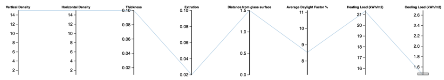


Figure 44 Optimised Solutions

Source: Constructed by author

A 97% mesh yielded the lowest HL (15.3kWh/m^2), with a 21.7% HL reduction, 0.01kWh/m^2 CL increase, and 1.8% ADF drop (Figures 45-47).

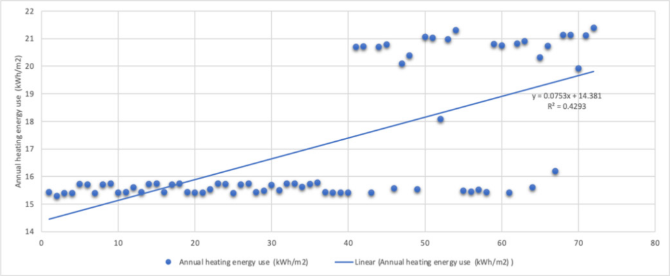


Figure 45 Annual Heating Load

Source: Constructed by author

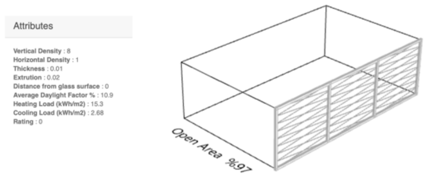


Figure 46 Optimal Solution for Cooling Load

Source: Constructed by author

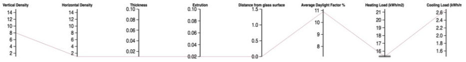


Figure 47 Optimised Solutions

Source: Constructed by author

The greatest ADF reduction (7.15%) came from a 34% mesh, cutting ADF by 35.6%, HL by 19.2%, and CL by 0.07kWh/m² (Figures 48-50). Results confirm that mesh geometry affects energy-daylight trade-offs.

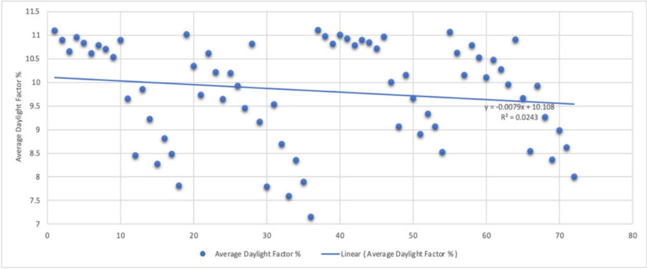


Figure 48 Average Daylight Factor

Source: Constructed by author

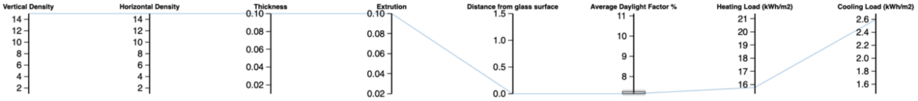


Figure 49 Optimised Solutions

Source: Constructed by author

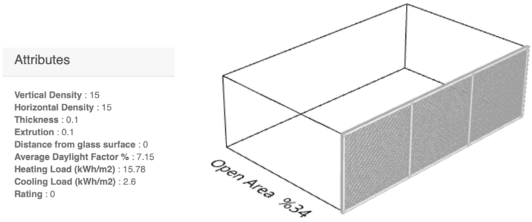


Figure 50 Optimal Solution for Average Daylight Factor

Source: Constructed by author

FOURTH SCENARIO

The MF is applied to the fully glazed west elevation (Figure 51). The lowest ACL (1.53kWh/m^2) was achieved using 34% and 49% open area meshes, resulting in a 70% CL reduction and a slight 1.2% HL increase compared to the BC. As in previous scenarios, increasing mesh density and distance from glazing further reduced CL but also caused a 23.3% drop in ADF (Figures 52-56).

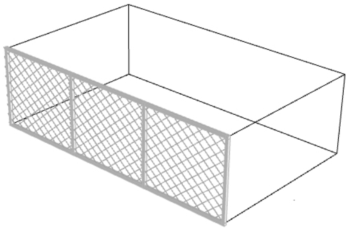


Figure 51 Base Case

Source: Constructed by author

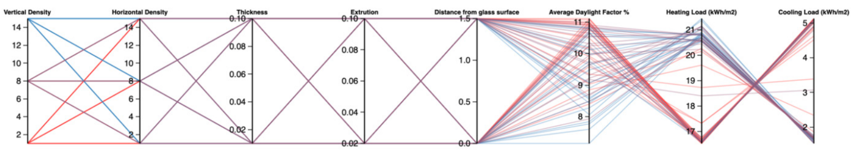


Figure 52 Multi-Axes Chart by Design Explorer

Source: Constructed by author

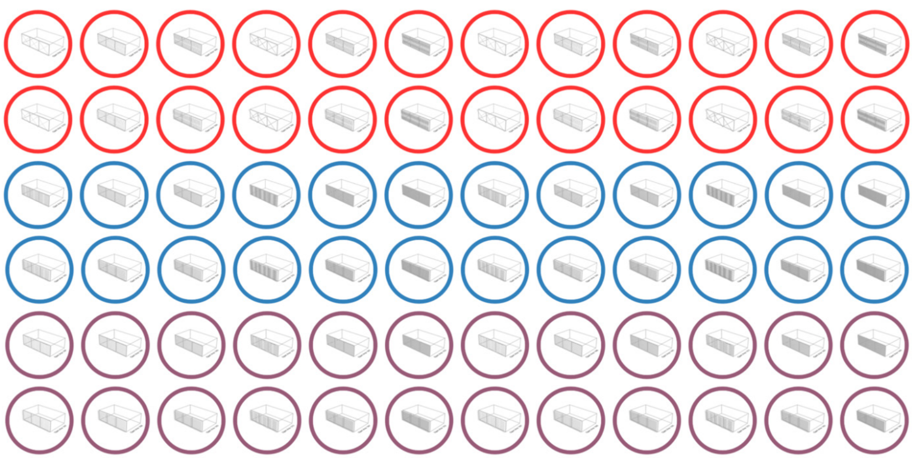


Figure 53 Visual Representation of the Optimised Solutions

Source: Constructed by author

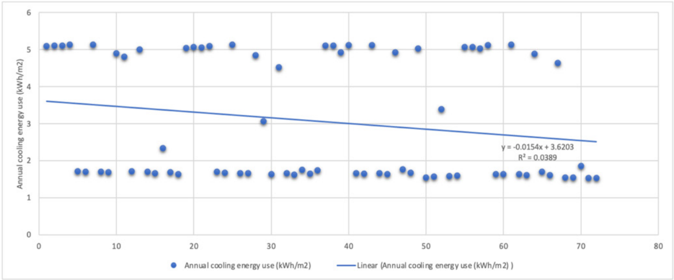


Figure 54 Annual Cooling Load

Source: Constructed by author

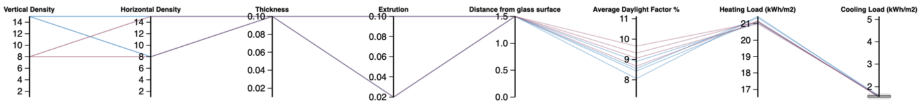


Figure 55 Optimised Solutions

Source: Constructed by author

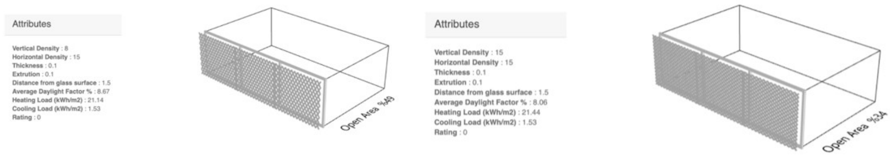


Figure 56 Optimal Solutions for Cooling Load

Source: Constructed by author

The lowest HL (16.53kWh/m^2) was achieved with 96-98% open area meshes, reducing HL by 20.9%, slightly increasing CL by 0.02kWh/m^2, and raising ADF by 3% compared to the BC (Figures 57-59).

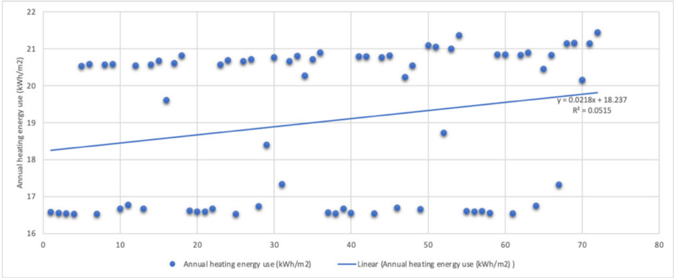


Figure 57 Annual Heating Load

Source: Constructed by author

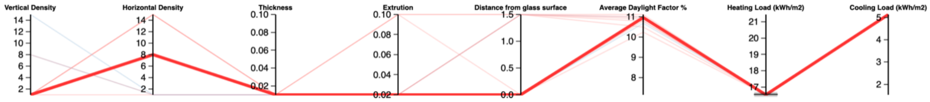


Figure 58 Optimised Solutions

Source: Constructed by author

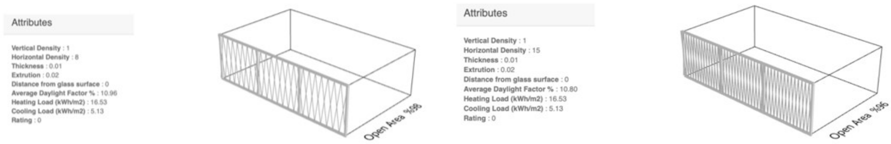


Figure 59 Optimal Solutions for Average Daylight Factor

Source: Constructed by author

The greatest ADF reduction (to 6.82%) was also achieved with a 34% open area mesh, leading to a 36.7% decrease in ADF, a 65.9% drop in CL, and a slight 0.01kWh/m^2 increase in HL (Figures 60-62).

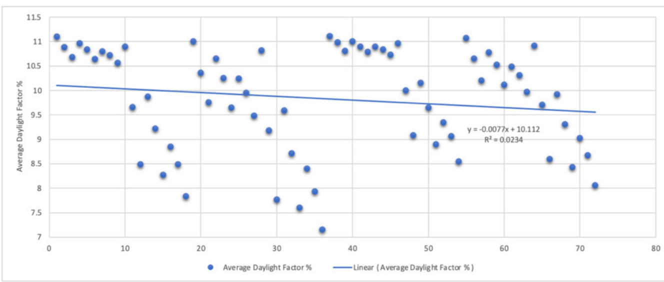


Figure 60 Average Daylight Factor

Source: Constructed by author

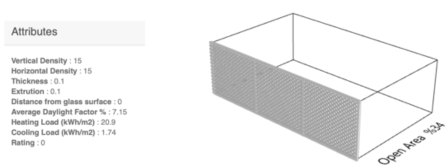


Figure 61 Optimal Solution for Average Daylight Factor

Source: Constructed by author

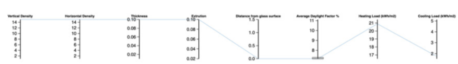


Figure 62 Optimised Solutions

Source: Constructed by author

DISCUSSION

This section interprets the BC analysis and optimisation results, identifying performance trends across scenarios. It examines the correlations among CL, HL, and ADF, and assesses the role of mesh parameters in achieving energy and daylight objectives.

Correlation between Heating Load, Cooling Load and Average Daylight Factor

A strong negative correlation was found between HL and CL across all scenarios: as shading reduced CL, HL increased, reflecting a typical trade-off. Conversely, CL and ADF showed a positive correlation: reducing CL through dense mesh also lowered ADF. In this study, the reduction in ADF was beneficial, as BC values exceeding 5% contributed to glare and overheating in the fully glazed model. Figures 63-70 illustrate these relationships.

First Scenario (East, West and South Façade)

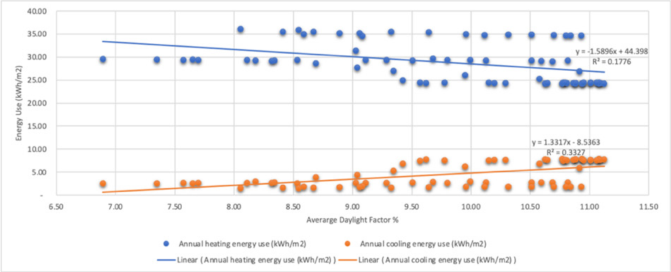


Figure 63 Correlation between Annual Heating Load and Annual Cooling Load

Source: Constructed by author

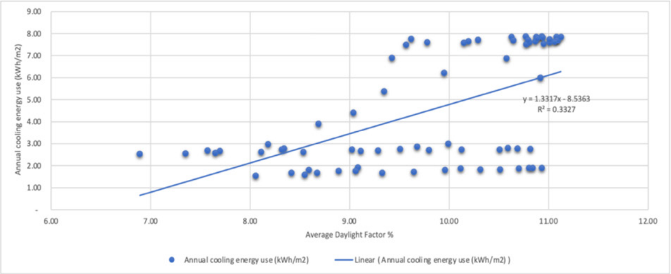


Figure 64 Correlation between Average Daylight Factor and Annual Cooling Load

Source: Constructed by author

Second Scenario (South Façade)

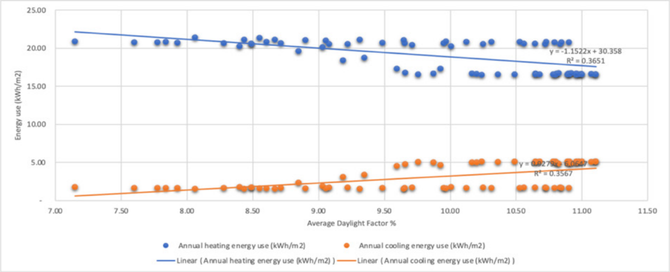


Figure 65 Correlation between Annual Heating Load and Annual Cooling Load

Source: Constructed by author

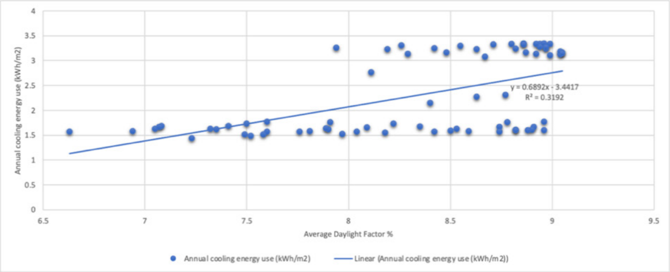


Figure 66 Correlation between Average Daylight Factor and Cooling Load

Source: Constructed by author

Third Scenario (East Façade)

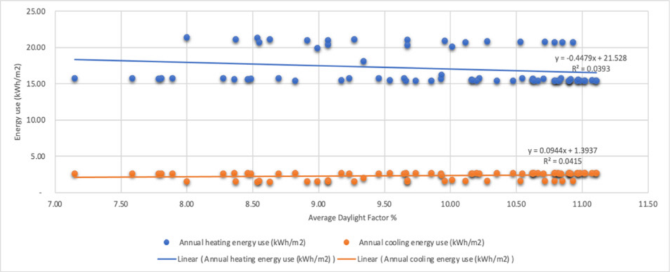


Figure 67 Correlation between Annual Heating Load and Annual Cooling Load

Source: Constructed by author

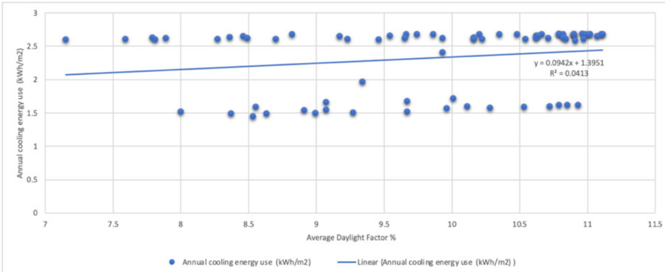


Figure 68 Correlation between Average Daylight Factor and Annual Cooling Load
Source: Constructed by author

Fourth Scenario (West Façade)

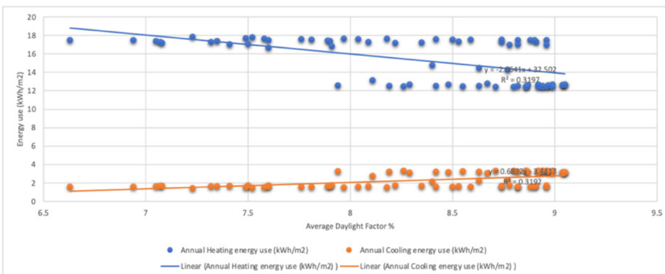


Figure 69 Correlation between Annual Heating Load and Annual Cooling Load
Source: Constructed by author

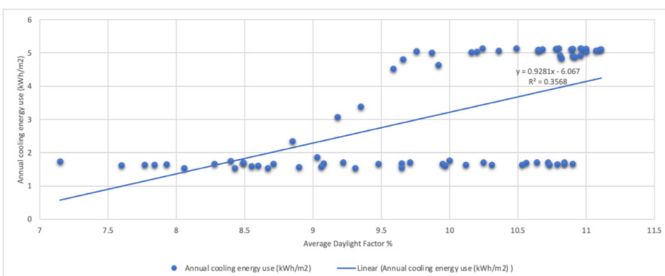


Figure 70 Correlation between Average Daylight Factor and Cooling Load
Source: Constructed by author

Finding the Optimal Solution

Optimal solutions were selected from the Pareto front based on balanced CL, HL, and ADF performance. Scenarios exceeding the BC in total energy use were excluded. Mesh open area and density had the greatest influence on results.

First Scenario (South, East and West (S, E, W))

The optimal mesh (95% open area) led to a 20% increase in total energy demand, equivalent to 7.95kWh/m^2 annually, including a slight CL increase of 0.08kWh/m^2 (Table 9). HL remained dominant. A 1.5m mesh distance was linked to higher HL, while reduced mesh density significantly lowered ADF (Figures 71-72). Table 10 summarises the correlations.

Table 9 Base Case

Performance Metrics	BC	Optimised Case
Annual CL (kWh/m^2)	7.52	7.6
Annual HL (kWh/m^2)	16.47	24.35
Average DF %	18.2%	10.81%

Source: Constructed by author

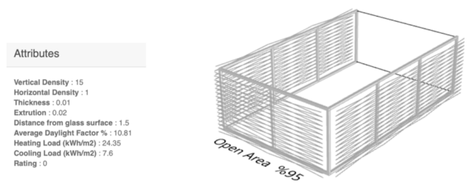


Figure 71 Optimum Solution

Source: Constructed by author

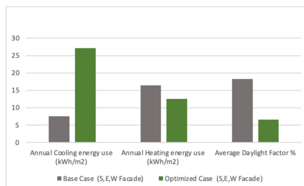


Figure 72 Comparison between the Optimised Case and the Base Case in Terms of Energy

Source: Constructed by author

Table 10 Correlation between Cooling Load, Heating Load and Average Daylight Factor and Design Parameters

Design Parameters	CL	HL	ADF
Mesh Density	Negative	Positive	Positive
Distance between glazed surface and mesh façade	Positive	Negative	Negative

Source: Constructed by author

Second Scenario (South Façade)

A 95% open area mesh achieved 20% energy savings (3.96kWh/m^2), with a minor CL increase of 0.03kWh/m^2. HL and ADF decreased as mesh density increased and standoff distance reached 1.5m (Figures 73-74; Tables 11-12).

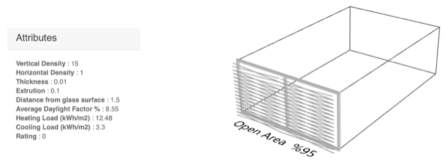


Figure 73 Optimum Solution

Source: Constructed by author

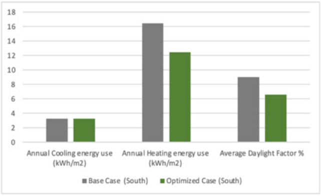


Figure 74 Comparison between the Optimised Case and the Base Case in Terms of Energy

Source: Constructed by author

Table 11 Optimisation Results

Performance Metrics	BC	Optimised Case
Annual CL (kWh/m^2)	3.27	3.3
Annual HL (kWh/m^2)	16.47	12.48
Average DF %	9%	6.6%

Source: Constructed by author

Table 12 Correlation between Cooling Load, Heating Load and Average Daylight Factor and Design Parameters

Design Parameters	CL	HL	ADF
Mesh Density	Negative	Positive	Positive
Distance between glazed surface and mesh façade	Positive	Negative	Negative

Source: Constructed by author

Third Scenario (East Façade)

A 97% mesh reduced energy demand by 4.22kWh/m^2 (19%). HL dropped, ADF improved slightly, and CL rose by 0.01kWh/m^2 (Figures 75-76; Tables 13-14).

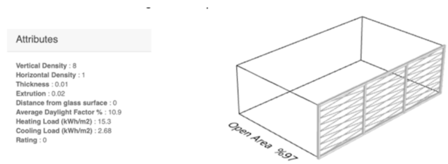


Figure 75 Optimum Solution

Source: Constructed by author

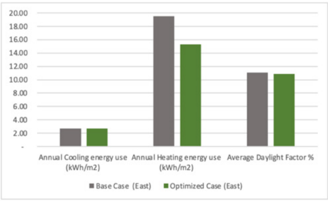


Figure 76 Comparison between the Optimised Case and the Base Case in Terms of Energy

Source: Constructed by author

Table 13 Optimisation Results

Performance Metrics	BC	Optimised Case
Annual CL (kWh/m^2)	2.67	2.68
Annual HL (kWh/m^2)	19.55	15.3
Average DF %	11.1%	10.9%

Source: Constructed by author

Table 14 Correlation between Cooling Load, Heating Load and Average Daylight Factor and Design Parameters

Design Parameters	CL	HL	ADF
Mesh Density	Negative	Positive	Positive
Distance between glazed surface and mesh façade	Negative	Positive	Positive

Source: Constructed by author

Fourth Scenario (West Façade)

Open area meshes of 96-98% achieved 16.7% energy savings (3.5kWh/m^2) with a 0.01kWh/m^2 CL increase. Reducing mesh density and setting standoff distance to 0.0m lowered HL and ADF (Figures 77-78; Tables 15-16).

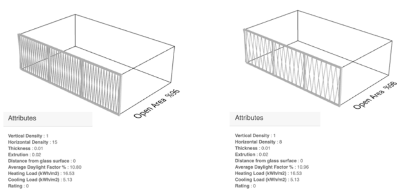


Figure 77 Optimum Solution

Source: Constructed by author

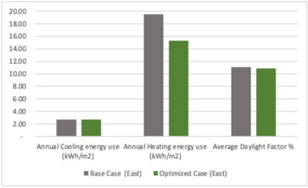


Figure 78 Comparison between the Optimised Case and the Base Case in Terms of Energy

Source: Constructed by author

Table 15 Optimisation Results

Performance Metrics	BC	Optimised Case
Annual CL (kWh/m^2)	5.11	5.13
Annual HL (kWh/m^2)	20.8	16.53
Average DF %	11.3%	10.8%

Source: Constructed by author

Table 16 Correlation between Cooling Load, Heating Load and Average Daylight Factor and Design Parameters

Design Parameters	CL	HL	ADF
Mesh Density	Negative	Positive	Positive
Distance between glazed surface and mesh façade	Negative	Positive	Positive

Source: Constructed by author

Comparative Outcomes

Among all scenarios, the south façade achieved the highest energy savings (20%) due to greater solar exposure, aligning with Middel *et al.* (2021). In contrast, Scenario 1 (all façades) led to a 20% energy increase, highlighting the drawbacks of excessive glazing and underscoring the need for orientation-specific shading (Middel *et al.*, 2021) (Figures 79-80).

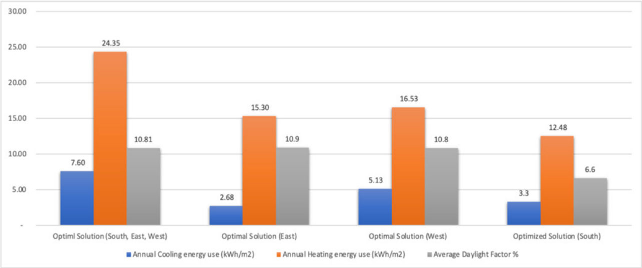


Figure 79 Comparison between all Scenarios in Terms of the Annual Heating Load, Annual Cooling Load and Average Daylight Factor

Source: Constructed by author

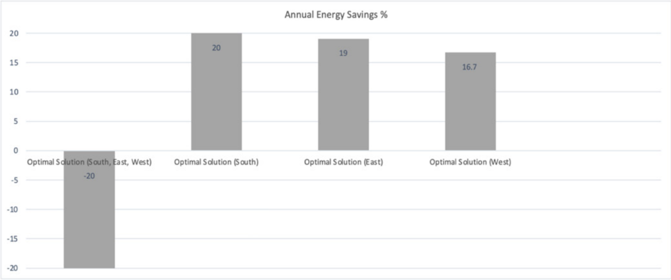


Figure 80 The Potential Total Annual Energy Savings Percentage for the Optimal Solutions

Source: Constructed by author

Compared with the ASHRAE benchmark, optimised designs significantly reduced total energy use and improved daylight distribution. Although heating demand increased slightly, it was offset by greater cooling reductions. Findings confirm MFs as a viable shading strategy for energy and comfort in London's temperate climate Gourlis *et al.* (2016). Figure 81 compares AHL and ACL across BCs, optimal designs, and the ASHRAE benchmark.

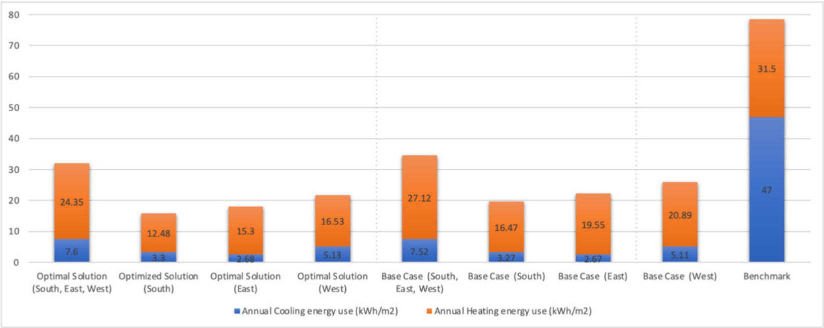


Figure 81 Comparison between Annual Heating Load, Annual Cooling Load across Base Cases, Optimal Designs, and the ASHRAE Benchmark

Source: Constructed by author

CONCLUSIONS

This study evaluated the performance of mesh façades (MF) as a passive shading strategy for a fully glazed office building in London. Using simulation-based multi-objective optimisation, the research assessed how mesh density and distance from glazing affect heating load (HL), cooling load (CL), and daylight factor (DF). Results demonstrate that MF significantly reduces CL and mitigates over-lit zones near glazing, offering a practical solution to enhance energy efficiency and visual comfort. Their flexibility allows performance to be tuned by adjusting parameters such as open area and standoff distance. The optimisation confirmed that improving one metric, such as reducing CL, may increase another, most often HL. These trade-offs should align with project-specific design goals and constraints. Despite their benefits, fixed mesh systems have limitations; low-density meshes may increase daylight penetration, raise the risk of glare and overheating. Minimal spacing between the mesh and glazing can obstruct outward-opening windows, while continuous shading may result in a dim interior environment.

Limitations

Computer-assisted optimisation helps architects address complex design problems efficiently. Although constrained by simulation runtime (72 simulation runs) and parameter ranges, the study yielded a robust set of optimised solutions. Conducting additional optimisation runs would improve reliability and further validate findings. This would require more time and computational power to explore wider design parameters. Nonetheless, the method adopted in this study demonstrated strong potential for supporting early-stage façade design decisions.

Future Research

To build on this study, further research is recommended in the following areas:

- **Climate adaptability:** Evaluate MFs performance across various climate zones to support context-specific design strategies.
- **Expanded design variables:** Investigate additional parameters such as mesh material, window-to-wall ratio, and geometry to assess effects on solar protection, insulation, and daylighting.
- **User comfort factors:** Integrate visual connectivity, glare probability, and natural ventilation potential to ensure occupant well-being.
- **Dynamic systems:** Explore the benefits of adjustable or responsive mesh shading compared to fixed installations.
- **Broader objectives:** Extend optimisation to include cost, life cycle performance, and environmental impact for a more holistic assessment.

ACKNOWLEDGEMENTS

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BIOGRAPHY

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