Reinforced Plastics
ISSN (print): 0034-3617 ISSN (online): 1873-1694

Energy, aesthetic, and thermal performance optimisation for building envelopes in China's hot summer and cold winter climate zones

E. Shambavi, A. Kanishka, R.Vihari
Department of Production Engineering,

Article Info

Received: 16-12-2025 Revised: 20-01-2026 Accepted: 02-02-2026 Published on: 12-02-2026

A B S T R A C T

Windows, apertures, shading, and materials are all part of the building envelope design elements that interact to greatly affect a structure's performance. Unfortunately, there is a lack of research on optimising all three of these characteristics at once to find the optimal balance between thermal comfort, interior daylighting, and energy usage. To explore the interplay between various building design and performance parameters, this study introduces a multi-objective optimisation (MOO) framework that assesses Useful Daylight Illuminance (UDI), Energy Use Intensity (EUI), and Thermal Discomfort Time Percentage (TDP) with a broad variety of parameters. This optimisation process takes into account the openable-window-area-ratio (OWR), window-wall-ratio (WWR), solar-heat-gain-coefficient (SHGC), louvre depth, and wall thickness. Using a building in the Hot Summer and Cold Winter Zone as an example, the results demonstrate that the optimal energy performance, taking thermal and visual comfort into account, is achieved by having a large south-openable-window-area-ratio (OWRs), south-window-to-wall-ratio (WWRs), SHGC, wall-thickness, a small north-window-wall-ratio (WWRn), and louvre depth. There is a clear improvement of 18% in EUI, 48.4% in TDP during the transition seasons, and 2.5% in UDI when compared to the first solution, thanks to the trade-off method. To construct sustainable cities, the results aid architects in finding the best solution for HSCW zone building envelope design, refurbishment, and renovation.

Keywords: Construction envelope Optimisation with multiple objectives Use of energy Thermal comfort and visual comfort

1. Introduction

Buildings, from an energy perspective, are representations of distributed, time-limited formations of energy in space [1]. The building envelope is the principal climatic negotiator in the energy exchange in structures, among all the building components. It might be quite useful for filtering out certain aspects of the weather (sunlight, humidity, precipitation, wind speed and direction, etc.) [2]. Building envelopes have evolved in response to energy's role as a powerful form-shaping component [3]. An environmentally friendly building envelope may keep occupants warm while reducing reliance on fossil fuels and making better use of renewable energy sources [4]. Due to the increased comfort expectations of well-resourced occupants, the energy consumption improving indoor environments of buildings in cities located within the HSCW zone in China is rapidly increasing [5]. The most effective passive strategies for enhancing the thermal environment inside buildings were discovered by Yao et al. Because it controls the interconnected exchanges of thermal energy, lighting, ventilation, moisture, and sound, the building envelope is the critical component that affects energy consumption and interior conditions [6,7]. The absorption and dispersion of heat are mostly dictated by the building envelope [8]. There may be a happy medium between thermal comfort and energy efficiency in the interface and void space created by the building envelope [9]. Decreasing energy dissipation and increasing solar radiation heat receipt through transparent interfaces in winter are two goals of an appropriate building envelope. In a similar vein, it acts as a thermal barrier, preventing the hot air from escaping while the cooled air remains within. To conserve energy in the HSCW zone, passive envelope design techniques, when used correctly, may prolong the non-heating and cooling time [5]. On the other hand, in most climates—and particularly in the HSCW zone—it is very difficult to achieve high performance levels for numerous metrics at once, including heating, cooling, and lighting. For example, although wide windows let more light in during the day, they may also dissipate heat too quickly in the winter and too much in the summer [10]. Early exploration of envelope design options is generally achieved using the combined methodologies of algorithm optimisation, building performance simulation, and parametric design [11–13]. Finding the minimal or highest value of a function by selecting many variables under certain restrictions is known as optimisation [14]. Using a single performance indicator as its only focus, single-objective optimisation studied the interplay of many parameters [15].

The energy performance for heating, cooling, and lighting has been the primary focus of studies, among other criteria. The interaction effects between distinct goals, such as visual, energy, and thermal performance, are ignored in these single-objective optimisation studies, even though they provide thorough examination of the impact of the building envelope on a specific performance measure.
To make it easier to test out different facade designs taking glare and illumination into account, Gagne and Andersen [19] suggested a genetic algorithm-based tool.

Table 1
Typical research on the building envelope design optimization.

Researchers	Variables	Objectives	Methods of research	Tools of research	Aim of research
Mitterer et al. [4]	Building envelope, building services system, operation strategies.	Energy consumption.	Step-by-step optimization	EnergyPlus.	Minimize the energy demand.
Zhai et al. [11]	WWR, orientations, glass type, filling gas of the window.	Annual total thermal load, the total number of discomfort degree hours, UDI <500lux.	Multi-objective optimization	EnergyPlus, Matlab, NSGA-II.	Obtain a balance between energy consumption, thermal environment, and visual performance.
Echenagucia et al. [12]	Number, position, shape, and type of windows, the thickness of the masonry walls.	The energy need for heating, cooling and lighting.	Multi-objective optimization	EnergyPlus, NSGA-II.	Minimize the energy need for heating, cooling and lighting.
Fang et al. [13]	Building depth, roof ridge location, skylight width, skylight length, skylight location, south window width, louver length, north window width, skylight orientation.	EUI, UDI	Multi-objective optimization	Ladybug tools, EnergyPlus, Radiance, Octopus.	Minimize the energy consumption, maximize the visual performance.
Lee et al. [18]	U-value, SHGC, Tvis, WWR, window orientations.	Annual heating, cooling, and lighting energy consumption.	Regression analysis	Commercial Fenestration/Façade Design Tool, EnergyPlus.	Investigate the optimal window performance properties in Asian regions.
Pilechiha et al. [21]	Window width and height, window sill and head height, distance of window edges from facade edges.	QV, EUI, sDA, ASE.	Multi-objective optimization	Rhinoceros-Grasshopper. Ladybug tools, OpenStudio, EnergyPlus, Octopus.	Quantify quality of view for office buildings and balance with energy performance and daylighting.
Zhu et al. [29]	Shape-related variables, WWR-related variables.	EUI, sDA, PPD.	Multi-objective optimization	Rhino-Grasshopper, Ladybug tools, OpenStudio, EnergyPlus, Octopus.	Improve the energy, indoor daylighting, and the thermal comfort performance.
Zhang et al. [30]	Orientation, depth of classroom, depth of corridor, glazing ratio of the interface, glazing material, shading type.	Energy demand, summer discomfort time, UDI.	Multi-objective optimization	Rhino-Grasshopper, Ladybug tools, Radiance, EnergyPlus, Octopus.	Minimize energy use while maximizing thermal and visual comfort.
Nasrollahzadeh [31]	Building wall, building roof, roof insulation, wall insulation, WWR, skylight, veranda, shading, glass type.	EUI, UDI, PPD.	Multi-objective optimization	Rhino-Grasshopper, Ladybug tools, Radiance, OpenStudio, EnergyPlus, Octopus.	Clarify the relationships between the objectives and the parameters.
Aksin et al. [33]	Width, depth, and height of the module, orientation, WWR, depth, count, angle, and direction of shading, wall insulation thickness, glazing type, cooling, and heating setpoints.	EUI, UDI, PPD.	Multi-objective optimization	Rhino-Grasshopper, Ladybug tools, Radiance, EnergyPlus, Octopus.	Optimize daylight, energy, and thermal performance of office buildings in different climates.
This study	South openable window area ratio (OWRs), north openable window area ratio (OWRn), south window-to-wall ratio (WWRs), north window-to-wall ratio (WWRn), solar heat gain coefficient (SHGC), louver depth, and wall thickness.	UDI, EUI, Thermal Discomfort Percentage (TDP)	Multi-objective optimization	Rhino-Grasshopper, Ladybug tools, Radiance, EnergyPlus, Octopus.	Optimize daylight, energy, and thermal performance of office buildings in the HSCW climate.

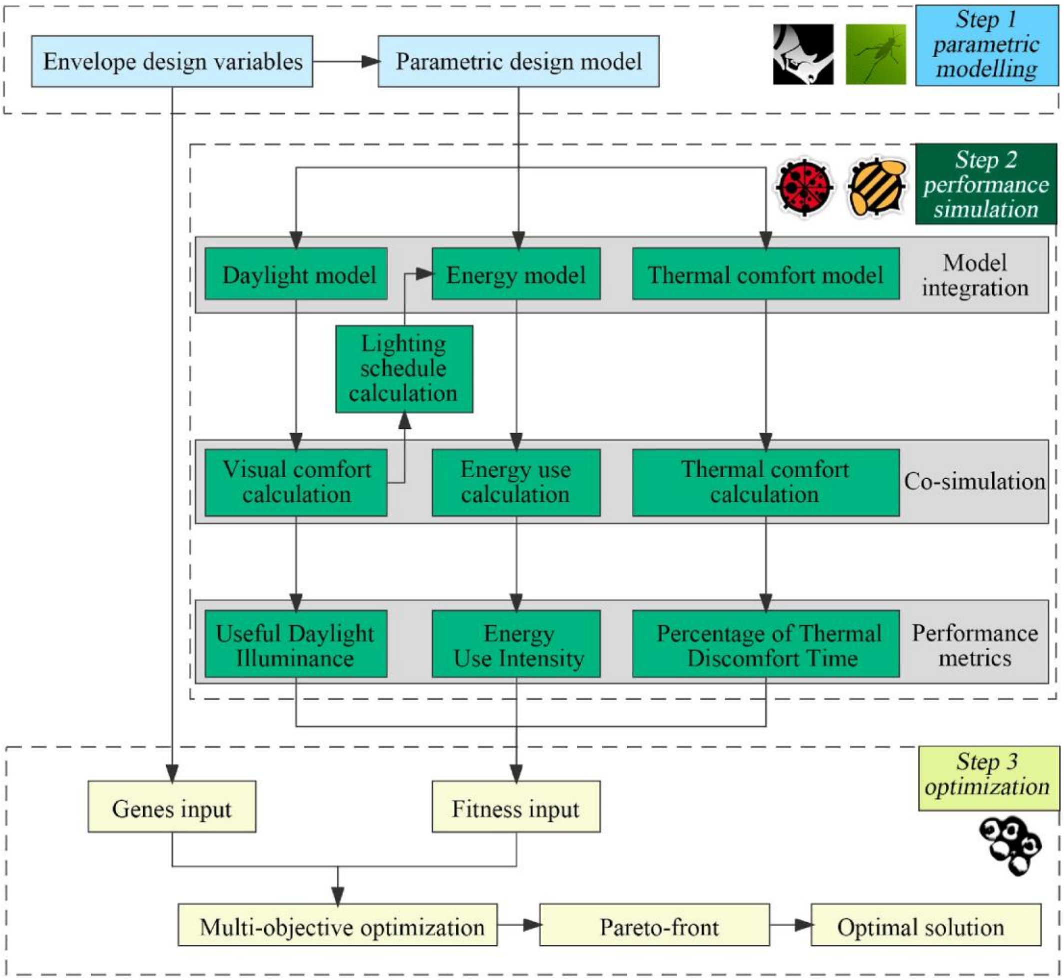
space-time daylight autonomy (sDA), as well as anticipated dissatisfaction percentage (PPD). In order to maximise UDI while minimising energy usage and summer discomfort time, Zhang et al. [30] redesigned school buildings in China's cold climatic zone. They evaluated the summer thermal discomfort time using the adaptive thermal comfort model in ASHRAE55-2010, and they reduced it by 9-23%. In order to shed light on the interrelationships between the goals and the parameters, Nasrollahzadeh [31] performed a multi-objective optimisation study that assessed EUI, UDI, and PPD using a variety of envelope parameters. Concerns

ISSN (print): 0034-3617 ISSN (online): 1873-1694

about building costs and carbon dioxide emissions have been voiced with the aforementioned three objectives [32]. While most of the aforementioned research has focused on either the winter or summer months to gauge thermal comfort, the optimisation of building envelopes has neglected to look at how natural ventilation might boost thermal comfort during the transitional seasons. Table 1 provides a summary of the factors, goals, and methodologies employed in recent focused design studies, as summarised in this short literature review. It is challenging to incorporate all design variables and performance metrics into a single study because of their diversity and complexity. Moreover, there is still a lot of unanswered questions in this field, and they fall into two main categories: first, there is a lack of guidance for design practices in existing single-objective optimisation studies because they don't account for the trade-off between multiple environmental performance; second, in existing multi-objective optimisation studies, the focused envelope design variables don't take into consideration the effect of shape variables related to natural ventilation on diffe

In order to optimise the envelope variables settings while balancing visual, energy, and thermal performance, this research developed a comprehensive paradigm for building envelope design. The goals of Useful Daylight Illumination (UDI), Energy Use Intensity (EUI) (kWh/m2/y), and Thermal Comfort Percentage (TDP) are subsequently computed. Many factors can affect the final design, such as the openable window area ratio in the south, the openable window area ratio in the north, the solar heat gain coefficient, the depth of the louvres, and the thickness of the walls. The discussion of the interacting effects of different factors and goals follows the optimisation process. Afterwards, the trade-off solution and several optimum solutions are used to summarise the suggested values of the design variables.

The major contributions of this optimization study are as follows: (1) the openable window area ratio (OWR) is introduced in this



/ig. 1. Framework for building envelope performance evaluation and optimization.

study and integrated into parametric building performance analysis to explore its potential for natural ventilation to improve thermal comfort during transition seasons. (2) the interactive effect of design variables on building performance and the contradictory relationships between multiple objectives are discussed. This study can provide designers and researchers with more comprehensive and in-depth understanding of the environmental performance mechanism of building envelope.

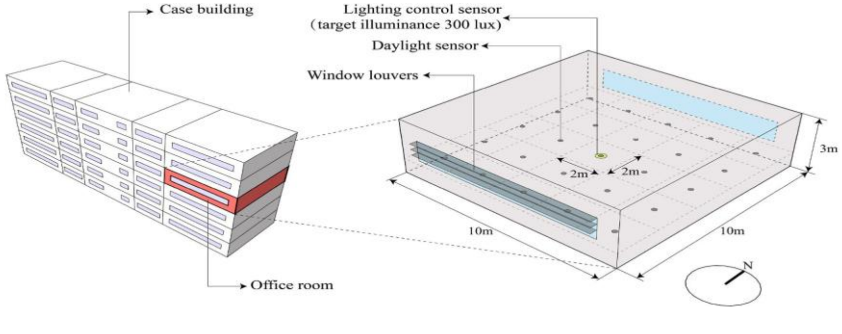
2. Methodology

2.1. Research framework

Figure 1 depicts the three-part structure for optimising and simulating building envelope performance. Creating a parametric model of the envelope's design requires first extracting its design variables. Environmental performance of the building, including thermal comfort, energy consumption, and daylighting, is modelled and calculated in the second step. Analysis of the data and the MOO procedure constitute the third stage. There are independent factors related to the envelope design and dependent variables pertaining to the building's physical environment performance measures. The collection of best solutions can be found eventually. For parametric modelling and parameter control, this research framework made use of the 3D graphics program Rhinoceros [34] and its plug-in Grasshopper [35]. In order to link the geometry to various established simulation engines, such as EnergyPlus [38] and Radiance [39], it utilised Ladybird tools [36,37] plug-ins. Octopus, an evolutionary MOO plug-in [40], is then employed to carry out the optimisation.

2.2. Constructing the case study

The five primary climate zones in China are defined by the Standard of Climatic Regionalisation for Architecture [41]. Some examples of these zones are the Mild Zone, the Hot Summer and Cold Winter Zone, the Severe Cold Zone, and the Cold Zone. The most difficult and contentious of them is the HSCW zone's climate-adaptive building design. There is a conflicting need for thermal-daylighting balance as well as a year-round equilibrium between insulation and openness in this zone. Moreover, building energy consumption will certainly rise [42] due to rising expectations of living standards, especially in regards to thermal comfort, which accompany economic growth in the HSCW Zone. Since our research aimed to simulate a typical Chinese metropolis in the HSCW zone, we used Nanjing (118.76E, 32.04 N) [43]. Nanjing has very cold winters and hot summers with temperatures close to 40 ◦C [43].
Various combinations of design variables are tested in an open office area with a flat roof (Fig. 2). Typical of office buildings in China's HSCW zone, the room is a north-south translucent area. The south façade has horizontal fixed sun louvres, while both the north and south facades have openable windows. Optimisation design can be more widely used if all of the design constraints are carefully considered [44]. While the variables pertaining to the building's shape and operation (heating and cooling setpoints) are left as fixed values, this research primarily examines those factors that are associated with the building's exterior. The performance of a building's envelope is greatly affected by factors like as the aperture opening and shading, as well as the kind of envelope material. The following eight variables can be derived from this: inlet-outlet ratio, south window-to-wall ratio (WWRs), north window-to-wall ratio (WWRn), solar heat gain coefficient (SHGC), louvre depth, and wall thickness, respectively, which are all part of the building envelope design. Room dimensions (10 m width, 10 m depth, 3 m height) and louvre count (3) are the constant characteristics. Tabulated in Table 2 are the design variables along with their descriptions, beginning values, and ranges. Using the formula (V1*V4)/(V2*V5), we can find the inlet-outlet ratio, which is the ratio of the south openable window area to the north openable window area. After optimisation, the inlet-outlet ratio was used as an auxiliary metric to explain the research questions in the data analysis, but it is not considered an independent variable in and of itself. It is derived from the arithmetic of other variables (V1, V2, V4, and V5). The importance of the building envelope parameters to environmental performance informed the selection of the design variables and constant parameters. The glazing g-value and window-to-wall ratio were determined to be the most important parameters for regulating



/ig. 2. Dimensions and daylighting sensor locations in the test building.

Table 2

Building envelope design variables.

Variables	Description	Initial value	Range
V1: OWRs	The openable window area ratio of the south window.	0.5	[0, 1]
V2: OWRn	The openable window area ratio of the north window.	0.5	[0, 1]
V3: Inlet-outlet ratio	The ratio of the area of the south openable window area to the north openable window area [(V1*V4)/(V2*V5)].	1	–
V4: WWRs	South window-to-wall ratio.	0.5	[0.1, 0.9]
V5: WWRn	North window-to-wall ratio.	0.5	[0.1, 0.9]
V6: SHGC	Solar heat gain coefficient of the south window.	0.35	[0.1, 0.6]
V7: Louver depth(m)	None.	0.5	[0, 1]
V8: Wall thickness (m)	The thickness of external walls.	0.3	[0.05, 0.55]

total energy demand in many different climates [45]. The other study demonstrated that a proper shading device can significantly increase the thermal and visual performance of a building [46]. Besides, the thermal property of an opaque envelope will affect indoor energy consumption and comfort. And the effective area of operable ventilation can affect the indoor/outdoor airflow, thereby affecting the indoor thermal comfort. For the above-mentioned reasons, several significant parameters were selected as design variables. Moreover, some constant form parameters eliminated the impact of building form on this study. To better understand the parametrical logic between envelope design parameters and performance metrics, this study does not use the material type as a variable but uses the real value to describe the building envelope. The variables range is set as large as possible to provide a large searching space for alternatives. The initial values of all variables are set to the middle value of the range.

2.2. Building performance simulation

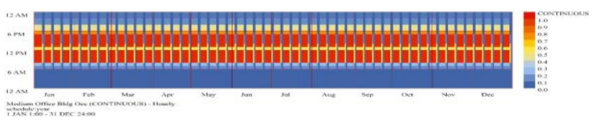
The daylighting and energy models used "Office:OpenOffice" program. The annual occupancy schdule is depicted in Fig. 3. Other details of the simulation settings are as follows:

2.2.1. Visual comfort simulation

Twenty daylighting test points, evenly distributed on a grid eight meters above ground level, make up the daylighting model. A 2 m x 2 m point grid is used. In the middle of the grid, as shown in Figure 2, is a lighting control sensor. The export was of the lighting schedule that was needed to reach the desired illumination level of 300 lux. Automatic dimming with an occupancy sensor that turns off the lights is the kind of electrical lighting control. By default, the lighting power is 250 W and the minimum electric dimming level is 20%. You may get a complete rundown of materials' optical characteristics in Table 3. Numerous studies use the Useful Daylight Illuminance (UDI) metric, which was developed by Mardaljevic and Nabil in 2005 [47], to assess the amount of daylighting that occurs inside a building. The proportion of time during active occupancy hours based on three lighting ranges—0-100 lux, 100-2,000 lux, and above 2,000 lux—is shown by this statistic. Despite heated controversy over whether 100 lux or 2,000 lux should be used as a threshold, avoiding indoor glare levels is possible by setting an upper illuminance bound. UDI100-2000 can show you the ideal level of light, which is somewhere in the middle. An overall value, AUDI100-2000, is obtained by calculating the average value of UDI100-2000 at all indoor test points. This metric is used to measure indoor daylighting levels in this study and is referred to as UDI in this paper. By doing so, we can better describe the lighting situation of the indoor space.

2.2.2. Modelling energy use

The details for the energy model of an open office space may be found in Table 4. The findings of the daylighting simulation will replace the lighting schedule in energy simulation, thus accounting for the decrease in building energy consumption due to the utilisation of natural lighting. This research used the optimal loads air system as the HVAC system [30]. No problems have been reported with this model's adherence to the secondary standard of the Chinese building code, which states that air conditioners should be set to relatively energy-efficient temperatures of 28C for cooling and 18C for heating. Energy savings ranging from 35 to 45 percent, depending on the climate zone, can be achieved by raising the cooling setpoint from 24 to 28 degrees Celsius, according to research by Hoyt et al. [49]. Places like Nanjing, which have a longer cooling phase, make this energy-saving potential more apparent. Earlier research has demonstrated that thermal comfort is unaffected by cooling setpoints above 28◦C [50,51]. Maximising the utilisation of natural ventilation is yet another advantage of raising the cooling setpoint. This energy model incorporates cross ventilation, which is powered by the pressure differential between windows on opposing sides of a structure. When all three of the conditions shown in Figure 4 are satisfied at the same time, natural ventilation will begin [52].



/ig. 3. The annual occupancy schedule in the open office room.

Table 3
The optical properties of building materials.

Building	Material type	Input value
Wall	Radiance opaque material	Reflectance: 0.84
Ceiling	Radiance opaque material	Reflectance: 0.84
Floor	Radiance opaque material	Reflectance: 0.2
louver	Radiance opaque material	Reflectance: 0.8
Window	Radiance glass material	Visible transmittance: 0.6

Table 4
Specifications for the open office room energy model.

Model	Type	Input value
Wall construction	Brick wall	Conductivity: 0.7195 W/m·K, Density: 1856 kg/m^3, Specific heat capacity: 839.4 J/kg·K, thickness (variable)
Ceiling construction	Adiabatic ceiling	–
Floor construction	Adiabatic floor	–
South glazing	5low-E+12Ar+5 (variable)	U-value: 1.8 W/m^2·K, SHGC (variable), Visible transmittance: 0.6
Nouth glazing	5low-E+12Ar+5	U-value: 1.8 W/m^2·K, SHGC 0.4, Visible transmittance: 0.6
Infiltration rate (per area of façade)	–	0.002 m^3/s·m^2
Lighting density (per area of floor)	–	11.84 W/m^2
People density (per area of floor at peak occupancy)	–	0.0565 ppl/m^2
Equipment load	–	Without consideration
Occupancy schedule	–	See Fig. 3
HVAC system	Ideal Air Loads system	
Heating setpoint		18°C (no setback)
Cooling setpoint		28°C (no setback)

Therefore, the natural ventilation will be turned on when:

$12 \le T_{a,out} \le 18°C$

$\& \ 23 \le T_{a,in} \le 28°C$

$\& \ T_{a,out} - T_{a,in} \ge 0.5°C$

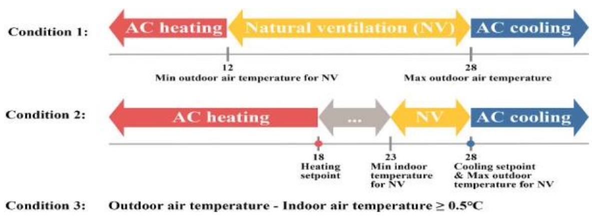
The benefits of this setting are: (1) natural ventilation can be fully utilized in the summer to save energy. (2) natural ventilation would not contradict with the air conditioning system.

The equipment load remains constant in all the building design variable combinations and so can be ignored in the optimization process. Energy use intensity (EUI) (kWh/m^2/y) is selected as the other optimizing metric in this study which is calculated by dividing the total annual energy load (the sum of heating, cooling, and electric lighting loads) by the building area.

2.2.2. Thermal comfort simulation

The purpose of energy conservation for buildings is to obtain maximum comfort by consuming as little energy as possible. With this understanding, in addition to energy use and visual comfort, thermal comfort should also be considered. For thermal comfort simulation, the adaptive comfort model is used to evaluate the predicted acceptability of thermal conditions in free-running naturally-ventilated space [53].

The basic assumption of the adaptive method refers to the principle of human adaptability: people have a natural tendency to keep comfortable by adapting to changing environments [54]. A survey of adaptive thermal comfort in the HSCW zone showed that people in this area have more robust climate adaptability [55]. So the larger comfort zones (24.8−29.2°C in summer and 11.8−16.8°C in



/ig. 4. The details of the annual HVAC setting.

(around winter) in this region enables individuals to engage in adaptive behaviours like opening windows and modifying their attire to be comfortable [55]. Based on ASHRAE Standard 55 [56], this study's adaptive thermal comfort model was developed. By plugging the average outside dry bulb temperature (Ta, out) into Eq. (1) [57], we can get the ideal temperature for interior comfort (Tcomf):
The thermal discomfort percentage (TDP) within a given time can be calculated by finding out if the hourly indoor operating temperature, with natural ventilation, is within the thermal comfort range where 90% of occupants feel comfortable. Only when the ambient temperature falls between the range of 10◦C to 33.5◦C may Eq. (1) be used. As a result, the TDP months of April–June and September–November are used as comfort metrics in this research. When the temperature within the building reaches 25C and the outside temperature is at least 0.5C lower, natural ventilation will be activated.

2.3. Model of optimal operation and fitness function

By using global search strategies, genetic algorithms have shown to be the most effective and efficient solution finding mechanism for the MOO issue [58,59]. In this research, we will address the MOO issue using Octopus, an optimisation tool for Grasshopper that is frequently utilised. Strength Pareto Evolutionary Algorithm-2 (SPEA-2) and Hypervolume Estimation (HypE) can both use it to produce the Pareto optimal solution [60]. Every generation's performance simulation happens in tandem with the optimisation process. Octopus is programmed with all factors of design as genes. Three goals—UDI, EUI, and TDP—are being evaluated. The intended goal to be maximised (UDI) is multiplied by —1 because Octopus employs SPEA-2 with Hyper-mutation to automatically control the design variables and continuously seek the minimum of the three objectives.
Using the Pareto front, this study finds trade-off solutions to a three-objective optimisation problem. In addition, the crossover rate is 0.8, the mutation rate is 0.9, the elitism probability is 0.5, and the mutation probability is 0.1. The optimisation process will end after 100 generations, and the population size is set to 50.
The trade-off solution that maximises UDI while minimising EUI and TDP is considered the best overall solution in this research. To rank all Pareto-optimal options and find the trade-off solution, the following fitness function (Eq. (2)) is utilised [20].

$$y = (UDI_i - UDI_{min})C_1 - (EUI_i - EUI_{min})C_2 - (TDP_i - TDP_{min})C_3$$

$$maximize\ (y) \qquad (2)$$

Where:

i = *result of iteration*

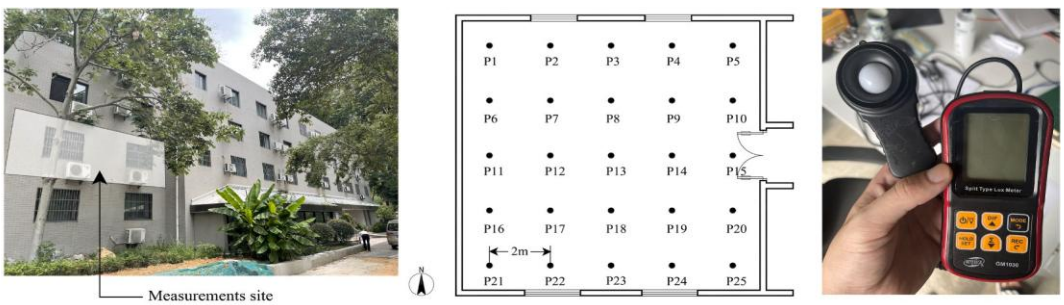
min = *minimum value in the optimization set*

max = *maximum value in the optimization set*

$$C_1 = \frac{100}{UDI_{max} - UDI_{min}}$$

$$C_2 = \frac{100}{EUI_{max} - EUI_{min}}$$

$$C_3 = \frac{100}{TDP_{max} - TDP_{min}}$$



/ig. 5. The location of the measurements site (a), the measure points in the office room (b), and the "Benetech" instrument for illumination and temperature measurements (c).

3. Results

3.1. Model validation

In order to validate the simulation model, this study conducted field measurements. To ensure the model's accuracy, a real-life office building with a comparable envelope was used, as seen in Figure 2. This was done since the case building was derived from conventional office structures. The reference simulation model that was used for validation had its main characteristics set according to Table 4. As shown in Figure 5, 25 reference sites on the table surfaces (0.8 m) were used to quantify the illumination levels. The device used for measurement was the "BENETECH GM1030," which has a temperature precision of ±1◦C and an illuminance accuracy of ±3% when less than 100,000 lux. Two separate measurements of illumination were taken on July 6, 2022, at 9:00 a.m. and 15:00 p.m. From 8:00 a.m. to 17:00 p.m. on July 6, 2022, at 1-hour intervals, the room's temperature was recorded at the exact middle, one metre above floor level [56]. During the measurement, the heat and air conditioning were turned off, and the outside windows were left partially open.

The model's ability to provide realistic data is shown by the similarity in the distribution pattern of the observed and simulated illuminance data (Fig. 6). The brightness readings next to the window (>2000 lux) are noticeably higher than those in the room's middle (<600 lux). Despite this, the simulated illuminance value is consistently higher than the observed value at both times. Optimal solutions for future optimisation studies, such as reduced WWR, deeper louvres, and glass transmittance, will be more conservative as a result.
Following ASHRAE Guideline 14-2014 [61]: we computed the Mean Bias Error (MBE) and the Coefficient Variation of the Root Mean Square Error (CV (RMSE)) using Eq. (3) and Eq. (4), respectively, to measure the disparity:

$$MBE = \frac{\sum_{i=1}^{n}(Mi - Si)}{\sum_{i=1}^{n} Mi} \quad (3)$$

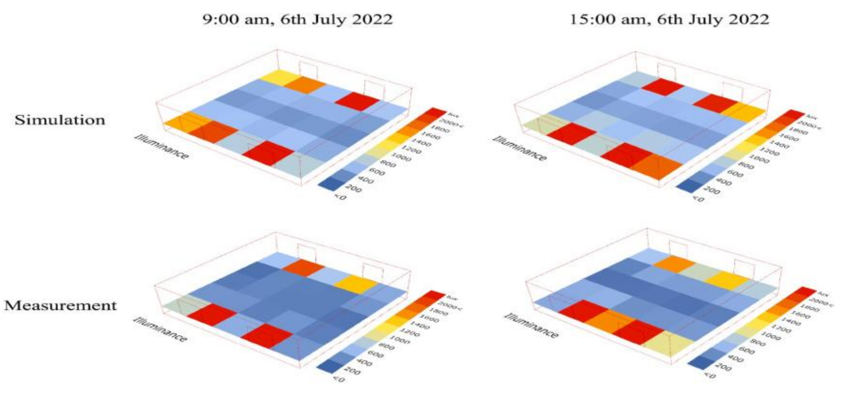
$$CV(RMSE) = \frac{1}{\overline{M}}\sqrt{\frac{\sum_{i=1}^{n}(Mi - Si)^2}{n}} \quad (4)$$

Where: Mi and Si are measured and simulated data at instance i, n is the total number of data values used for the calculation, $\overline{M}$ is the mean value of measured data.

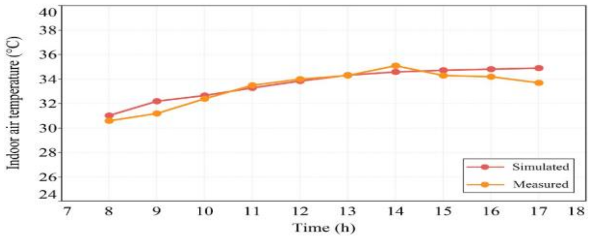
For the illuminance values in Fig. 6, MBE and CV(RMSE) are − 16.2% and 11.6%, respectively. As previous studies reported daylighting simulation errors of 20−30% have been considered acceptable [62,63], the distance between the measured and simulated data in this validation are within the acceptable limits.

Fig. 7 shows the comparison between measured and simulated indoor temperature during working hours (8:00 a.m. to 17:00 p.m.) with a interval of 1 h on the 6th July 2022. MBE and CV(RMSE) are − 0.93% and 0.57%, respectively. The ASHRAE Guideline 14 defines the acceptable limits for calibration of thermal models. When analysing hourly data, models are declared to be calibrated if they produce MBE within ±10% and CV(RMSE) within ±30%. Therefore, the thermal model is within the acceptable range.

Although the energy model has not been thoroughly validated in this study, the energy consumption is yield based on the daylighting model and the thermal model, which have been validated. In addition, since the purpose of this study is mainly to optimize the design solution of the envelope, the energy consumption results, as a relative indicator rather than an absolute value, can be used to



/ig. 6. Visualization of simulated and measured illuminance on the table surfaces (0.8 m) in the office room.



/ig. 7. Comparison between measured and simulated indoor temperatures during 8:00 a.m. to 17:00 p.m. with a interval of 1 h on the 6th July 2022.

compare different optimal solutions and determine the final trade-off solution. In conclusion, the model in this study could produce reliable results of thermal and daylighting simulation, and provide useful relative energy consumption values in the optimization process.

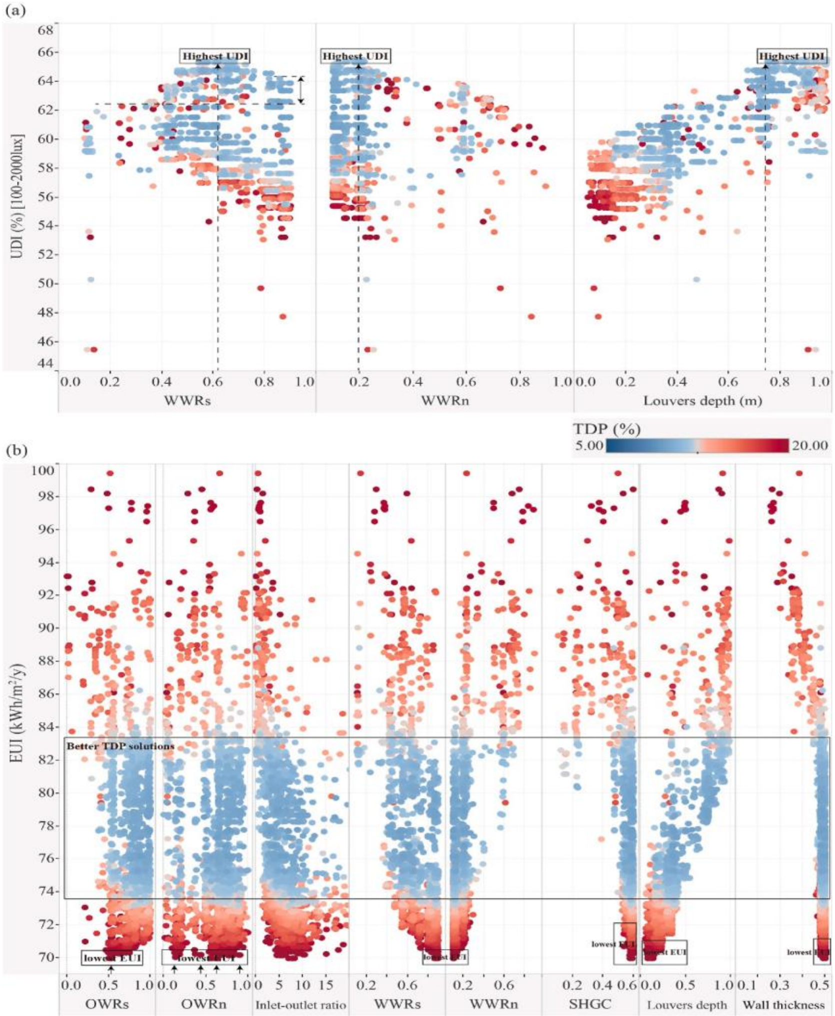
3.2. Analysis of objectives against design variables

Based on the The scatter plots show the correlational link between design factors and goals, based on data from over 5,000 simulations. These diagrams show potential solutions for building envelope design at each of the points. Figure 8(a) shows the connection between UDI, Louvre depths, WWRs, and WWRn. The mutual influence relationship between variables can be seen in a scatter plot with a clear trend, but in the absence of such a trend, no trend is visible. Furthermore, the scatter plot has the ability to display the distribution area of the best-performing design factors. When WWRs is approximately 0.6, the maximum UDI value is attained, as shown in Fig. 8(a). A proper daylight distribution is not achieved when there is either an excess of natural light or an inadequate amount of it, as UDI is the percentage of time when the illuminance level is between 100 and 2,000 lux. Reducing WWRs from 0.6 to 1.0 will lower UDI more effectively than raising them from 0.6 to 1.0, due to the fact that south louvres may filter the extra daylight created by the high WWRs. It is not necessary for a room to have north or south windows for there to be beneficial daylight distribution; in fact, when WWRn is around 0.2, UDI may go beyond 65%. Louvres with a depth greater than 0.75 m provide the maximum UDI for building shading designs. Reason being, louvres are crucial in reducing the impact of glare and maximising the dispersion of natural light in the area immediately around a window. When plotted against each design variable, the EUI and TDP results are shown in Fig. 8(b). Assuming an OWRs of around 0.5, the EUI is at its lowest (less than 70).You may get the lowest EUI when OWRn is within its complete range, therefore it's hard to tell how Rn affects energy usage compared to OWRs. The lower EUI seems to have a small north window and a big south window in the fourth and fifth graphs in Fig. 8(b), which might be a reflection of the optimisation process due to the changing trend of the point density. Reason being, in the winter, more radiant heat can be let in through large south windows, reducing the need for heating, and in the summer, extra radiant heat can be kept out of the room by utilising exterior louvres. Consequently, buildings in the HSCW zone that rely heavily on solar radiant heat have thick walls, thin louvres (about 0.1 m), and a high SHGC (approaching 0.6). As for the second goal, TDP, a more pleasant interior climate during transition seasons is shown by a shorter uncomfortable thermal duration and a bluer point in Figure 8 (b). While there is no discernible pattern to TDP in Fig. 8 (a), it is seen in Fig. 8 (b) that more effective TDP solutions often exhibit a modest EUI. It is important to carefully consider different building performance metrics and find the best design variables to reduce energy use, as cutting back without thinking will lead to more thermal discomfort during transition seasons.

3.3: Pareto front analysis

The optimal locations are the points at the bottom right of EUI-UDI and TDP-UDI, as well as the bottom left of EUI-TDP, in Figure 9, since maximising UDI and minimising EUI and TDP are the overall goals. The red dots show a Pareto-optimal solution, where improving one goal will always lead to deteriorating another. As can be seen in Fig. 9, every Pareto-optimal solution forms a Pareto-front.

In Figure 9, we can see the Pareto front of EUI and UDI, and what we see is that EUI grows as UDI does. What this implies is that more energy is needed to provide higher visual comfort inside. This is due to the fact that great visual performance solutions have relatively big WWRs and louvre depth. Window thermal insulation is much worse than wall thermal insulation, leading to higher energy bills. Heating costs go up in the winter because the deeper louvres don't let in as much solar radiation. Therefore, there was a negative correlation between energy performance and visual performance. Because more bigger windows significantly raise cooling and heating energy consumption compared to less lighting energy consumption as a result of more natural light, these two measures couldn't be more at odds with one another. The thermal comfort is subpar in every TDP-UDI scenario, regardless of the UDI value. For optimal thermal comfort, keep UDI at a moderate range. The depth of the louvres and the WWRs may interact in such a way that this happens. On the other hand, when UDI grows, TDP rises according to the Pareto borders of the two variables. This indicates that there is a negative correlation between thermal performance and visual performance as well.



/ig. 8. The 2D scatter plots of design variables against objectives: (a) scatter plots of WWRs, WWRn, and Louver depths against UDI; (b) scatter plots of all design variables against EUI and TDP.

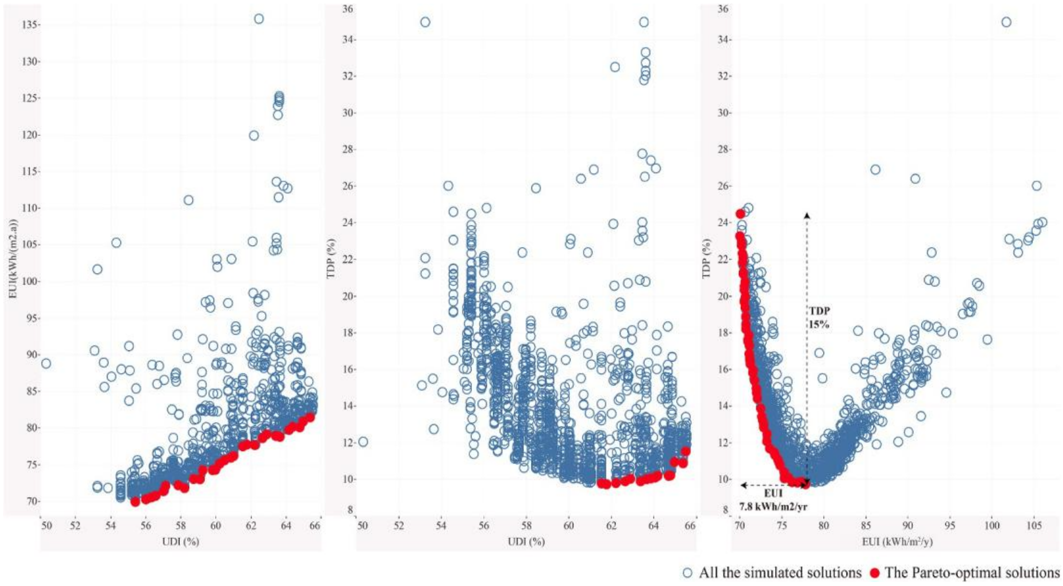
The Pareto front of TDP and EUI shows that TDP decreases with increasing EUI. A mere increase of 7.8 kWh/m^2/yr of EUI can reduce TDP by 15%. This means that the comfort time during the six months of the transition seasons will increase by 23 days. Consequently, thermal mass contributes to keeping the indoor temperature unaffected by outdoor temperature fluctuations. Thus, design options located at the bottom of EUI-TDP simultaneously get good thermal and energy performance.

3.3. The optimal solutions

The Pareto front and the UDI, EUI, and TDP scatter plots in the last generation are shown in Fig. 10. Architects can choose the optimal solution according to design requirements. On the one hand, the architect can determine the optimal solution according to the score of the fitness function (Eq. (2)). On the other hand, it can be observed that the points near the center of the right graph in Fig. 10 are better than other options. Their UDI, EUI, and TDP are about 60%, 75 kWh/m^2/y, and 11%.

Fig. 11 shows the value distribution of the building envelope design variables in the Pareto-optimal solutions. Since the optimizer can select any value within the given variable range, the x-axis indicates a more precise range in which the variable is located. The y-

ISSN (print): 0034-3617 ISSN (online): 1873-1694



/ig. 9. The Pareto front graph of all solutions in the multi-objective optimization process [MOO].

On one side of the graph you can see how often each variable appears in the set of Pareto-optimal solutions. Figure 11 shows that the WWRs and louvres of the Pareto-optimal solutions are often bigger (>0.5) and narrower (0.2-0.3 m), with WWRn values ranging from 0.1 to 0.2. Values between 0.9 and 1.0 for OWRs, 0.7 and 0.8 for OWRn, and 4-6 for the Inlet-outlet ratio occur most often. Furthermore, all Pareto-optimal solutions tend toward larger SHGC and wall thickness because SHGC is beneficial for winter solar heat gain and wall thickness is beneficial for improving thermostability.

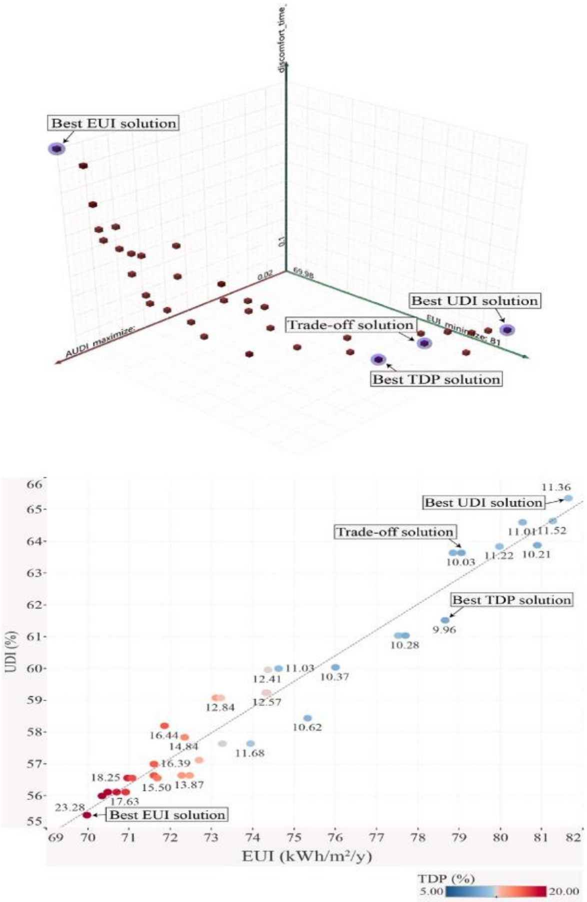
Using the final generation's Pareto front graph, we can find the best UDI, EUI, and TDP solutions. Equation (2) shows how to use the fitness function to get the trade-off solution out of all the possible solutions. Research on building optimisation does not provide a standard reference solution, however. When comparing the optimisation outcomes to the average first-generation simulation result [13] or a solution from a real-world building [31], there are a few options. Due to its applicability to the majority of preexisting structures, the study's reference solution is the initial one in which all design variables are set to mid-range values. In Figure 12, we can see the UDI distribution and the solutions' geometries. In Table 5 you can see the specifics of these answers.

It is possible to identify the improvement made by optimisation by comparing the reference solution with the four best options. The optimal EUI solution has a minimum energy demand of 69.98 kWh/m2/y, which is 26.4 kWh/m2/y lower than the reference solution. However, your thermal and visual comfort will suffer as a result. This best option in particular has a thermal disc omfort time that is almost double that of the others. A large window-to-wall ratio (0.9) and small louvres (0.14 m) are the defining features of an optimal EUI system, which may increase solar heat gain and decrease heating energy requirements during the winter. Beca use the cooling setpoint in this research is 28◦C, which is reasonably energy-efficient, the cooling energy demand during summer is pretty low. In order to achieve a balance between energy consumption, thermal comfort, and aesthetics, the building envelope must be designed to allow for both heat gain in the winter and heat insulation in the summer. It is also demonstrated by the resul t that a space-and time-adaptive dynamic envelope is required.

The best TDP solution has a TDP of only 9.99%, which is 9.45% lower than the reference case's 19.44% value and reduces the thermal discomfort time of the transition seasons. More oversized openable windows (0.98 and 0.79 of OWRs and OWRn) and deeper louvres (0.71 m) are the most noticeable differences between the best TDP and EUI solutions. Among the top solutions, the Inlet-outlet ratio (11.06) stands out as the greatest. It proves that natural ventilation is crucial for lowering the operating tem perature within a building.

The UDI only improves indoor visual comfort by 3.27%. This is due to the fact that the HSCW zone places a premium on heat-to-light balance, not because the design choices used for this study are only focused on enhancing UDI. So, this is a compromise that MOO search engines make in order to achieve energy, visual, and thermal performance all at once. Table 5 shows that the refer ence solution is inferior to the best UDI solution, but the other two metrics are clearly superior. A 15.3% drop in the EUI and a 41.6% drop in TDP were recorded. A high window-to-wall ratio, a sizable openable window area, and deep louvres are all characteristics of the optimal UDI and TDP designs. Furthermore, all optimal systems have substantial walls and a big SHGC.

While one measure in the trade-off solution is poorer than the other three ideal ones, it outperforms the reference solution overall (y value = —0.81), which reduced EUI and TDP by 18.4% and raised UDI by 2.5%, respectively. The trade-off solution has bigger values for all design variables except WWRn, which is less than the reference solution. For a well-rounded building performance, a wide south window with deep louvres, a high SHGC, and a large openable area ratio is ideal. The ideal solution that takes int o account all three goals is known as the trade-off solution.



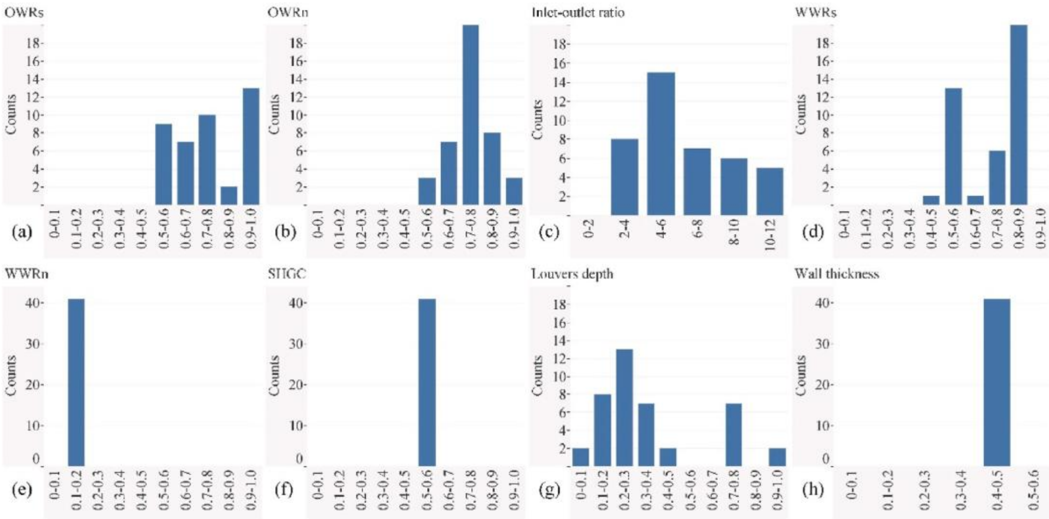
/ig. 10. The Pareto front graph (top) and the scatter plot (bottom) of the last generation (n.b. the number next to every point in the scatter plot represents TDP).

4. Discussion

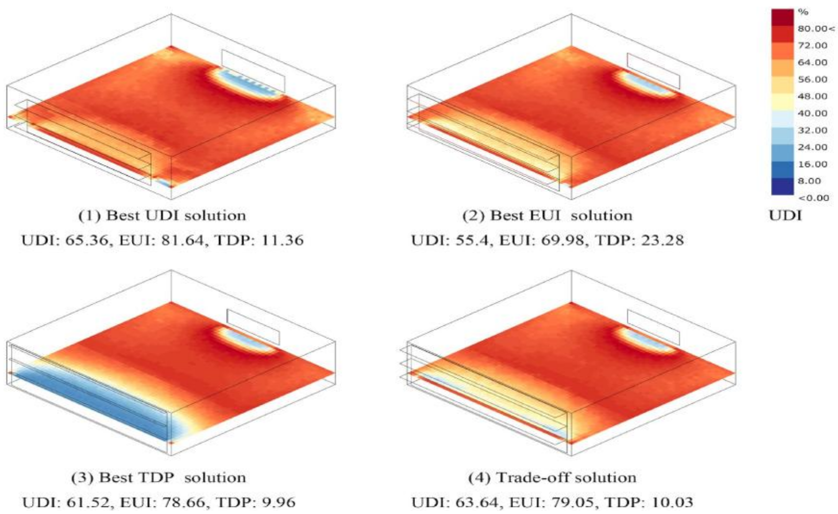
4.1. The interactive effect between the variables and the objectives

As discussed in the introduction, various building envelope design variables interact to affect environmental performance. Changing one variable while leaving other variables unchanged may cover up the facts. However, the optimization results show the MOO method helps to identify this interactive effect. Different variable combinations achieve different performances. Improving one performance always comes at the cost of reducing other performance metrics. As shown in Fig. 10, there is a strong linear relationship between the UDI and EUI for the set of optimal Pareto solutions in the final generation. With the increase of UDI and EUI, TDP shows a trend of first decreasing and then increasing. This not only indicates the contradiction between daylighting distribution, energy consumption, and thermal comfort but also proves that the envelope has great potential in the environmental control of buildi ngs.

In this study, from the results in Table 5, OWRs in the trade-off solution and the best TDP solution are relatively high; this suggests that good natural ventilation is indispensable in improving indoor thermal comfort. A large south window combined with deep louvers is the best choice to balance the visual, thermal, and energy performance in the HSCW zone. Future research can accurately adjust the value range of these variables based on this study, or directly use these values when it is necessary to set some parameters to be



/ig. 11. The value distribution of the building envelope design variables in the Pareto-optimal solutions (sub-figures: (a) OWRs, (b) OWRn, (c) Inlet-outlets ratio, (d) WWRs, (e) WWRn, (f) SHGC, (g) Louver depth, (h) Wall thickness) (n.b. OWRs is south openable window area ratio, OWRn is north openable window area ratio, WWRs is south window-to-wall ratio, WWRn is north window-to-wall ratio, SHGC is solar heat gain coefficient of the south window).



/ig. 12. Results for the best and trade-off design solutions (n.b. UDI: average Useful Daylight Illuminance, EUI: Energy Use Intensity, TDP: Thermal Discomfort time Percentage).

constant in other variable-optimization studies. Besides, Fig. 12 illustrates the UDI value at each sensor location of the four best solutions. It is apparent that deep louvers can weaken the adverse effect of large WWRs on indoor visual comfort, especially for improving the UDI near the south window. For the EUI, reduction of openable window area ratio from 0.9 to 0.5 is beneficial to reduce energy comsumption at the cost of visual and thermal comfort.

WWRn, SHGC, and wall thickness are similar in all the best solutions. The best UDI solution, the best TDP solution, and the trade-off solution have similar variable characteristics. In addition to the similarities embodied by these optimal solutions, as shown in Fig. 8, there are many alternatives with similar UDI and EUI that yield positive thermal performance. The multi-objective optimization method provides building envelope designers with more choices enabling them to find what they want according to actual needs.

Table 5
Design variable values and performance metrics of the best and trade-off design solutions.

		Reference solution	Best UDI solution	Best EUI solution	Best TDP solution	Trade-off solution
Design variables	V1: OWRs	0.5	0.7	0.5	0.98	0.98
	V2: OWRn	0.5	0.78	0.57	0.79	0.79
	V3: Inlet-outlet ratio	1	3.49	7.77	11.06	8.7
	V4: WWRs	0.5	0.57	0.9	0.9	0.73
	V5: WWRn	0.5	0.15	0.1	0.1	0.1
	V6: SHGC	0.35	0.59	0.59	0.6	0.59
	V7: Louvers depth(m)	0.5	0.76	0.14	0.71	0.71
	V8: Wall thickness(m)	0.275	0.5	0.5	0.49	0.5
Performance metrics	UDI (%)	62.09	**65.36**	55.4	61.52	**63.64**
	EUI (KWh/m^2/y)	96.38	81.64	**69.98**	78.66	**79.05**
	TDP (%)	19.44	11.36	23.28	**9.96**	**10.03**
y value		-	−0.96	−1.86	−0.99	**¡0.81**

4.2. Recommended values of the design variables

Based on Fig. 11 and Table 5, the recommended value ranges of design variables are summarized as follows: (1) for the openable window area ratio, it is wise to set the OWRs between 0.5 and 1.0 and the OWRn between 0.7 and 0.8, respectively; (2) for the window-to-wall ratio, a large WWRs (0.5−0.9) and a small WWRn (0.1−0.2) are beneficial; (3) for the south exterior louvers, the 0.7−0.8 m deep louvers are beneficial to blance the three performance; (4) for the other variables, having a higher SHGC (0.6) and heavier walls has a positive effect on heating energy saving.

Large south-facing windows combined with deep shading can provide even natural lighting in the room, while the main roles of small north-facing windows are to (1) supplement the natural lighting in the room, especially near the north windows; (2) promote convective ventilation in the room; and most importantly (3) reduce heat loss in the room during the cold winter. Therefore, small north windows are beneficial to improve the indoor daylighting, energy consumption and thermal comfort performance. This is consistent with the conclusion of Ref. [30] on the optimal WWRn (0.16) for Model B in cold winter regions. Besides, it should be noted that the reason why the conclusion of the SHGC value is different from previous studies [17] is that the energy model in this study has a higher cooling setpoint (28 °C), so the heating energy consumption occupies a more dominant than the cooling energy consumption. In addition, these recommended ranges are only trade-offs for environmental performance, cost and realistic operability also have an important impact on the variable values, but are not considered in this study.

4.3. Comparisons with previous building optimization designs studies

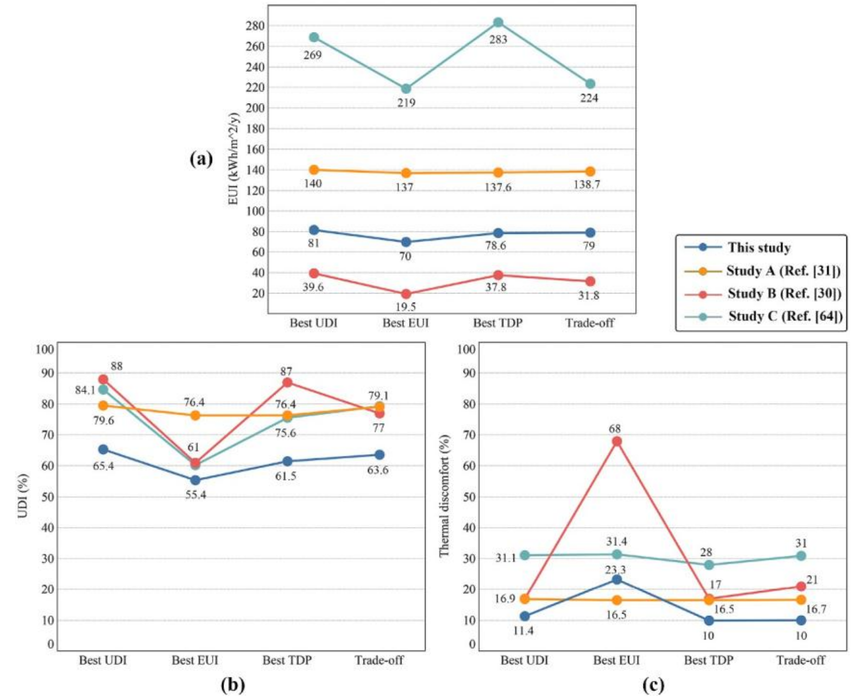
To further evaluate the strengths of this study in exploring various optimal solutions, the four optimal solutions of this study are compared with the results of the other three studies (Ref. [30,31,63]) that used the same objective function. The controdictory relationship between the performance of the four optimal solutions of these study is shown in Fig. 13. For example, the reduction of energy consumption in the best EUI solution will inevitably lead to the reduction of lighting performance and thermal comfort performance. Although the magnitude of change is significantly different from one study to another, a similar trend is seen in other studies (study A, B, and C). This is mainly due to the different climatic zones, building characteristics and simulation settings. The similar trends indicates the reliability of this study.

This study is effective in balancing energy, daylighting, and thermal performance in the HSCW zone. In terms of the optimal energy solution (the best EUI), study B and study C caused more loss of daylighting or thermal performance than this study. In Fig. 13, the best EUI solution in Study C has a 2.2% lower EUI (219 kWh/m^2/y) compared to the trade-off solution (224 kWh/m^2/y), while the UDI decreases by 24%. In contrast, the best EUI solution in this study had an EUI (70 kWh/m^2/y) 11.4% lower than the trade-off solution (79 kWh/m^2/y), while the UDI decreased by only 1.72%. In study B, the best EUI solution causes a significant increase (21%−68%) in thermal discomfort time percentage (see Fig. 13 (c)), but the increased TDP (6.6%) in the best EUI solution of this study is still acceptable. Besides, there are optimization studies such as study A that have very similar performance in various optimal solutions. This negligible difference weakens the flexibility of the optimization results when dealing with different design requirements. Therefore, the application of this objective function to different climatic zones produces different optimization effects, for example, it has a more limited effect in the Mediterranean climate (study A), but it has a significant effect in the HSCW regions of this study, which also shows the more practical significance of this study.

What is different from previous studies can be summarized as follows: (1) this study increases the diversity of variable types to some extent. The openable area ratio of both south and north windows is one of the variables in this study, while previous studies have often used this as a constant value; (2) the visual, energy and thermal performance are taken into account simultaneously, and the adaptive comfort model is used to evaluate the thermal comfort in the transition seasons. The interactive effect of design variables on these performance and the contradictory relationships between multiple objectives are discussed. The results of this study will provide references and insight for future design and decision-making for building envelopes in the HSCW zone.

5. Conclusions

This study proposed an overall framework of building envelope design to optimize the envelope variables settings and balance energy, thermal, and visual performance, based on the Pareto approach and a fitness function. The interactive effects between various



/ig. 13. Comparison of the optimization results (EUI (a), UDI (b), and thermal discomfort (c)) of this study with other studies (Ref. [30,31,63]). (the x-axis represents various optimal solutions, including the best UDI solution, the best EUI solution, the best TDP solution, and the trade-off solution).

References

[1] This sentence paraphrases two sources: the first is K. Moe's Insulating Modernism: Isolated and Non-isolated Thermodynamics in Architecture (DE GRUYTER, 2014), and the second is James Erickson's Envelope as Climate Negotiator: Evaluating the Capacity of Adaptive Building Envelope to Moderate Indoor Climate and Energy (Diss. Arizona State University, 2013). According to a study published in Indoor Built Environment, T. Zhang, W. Zhong, and C.W. Yu propose an energy agenda for architectural creation as a means to advance a sustainable built environment. The effect of passive measures on thermal comfort and energy conservation was studied by R. Yao, V. Costanzo, X. Li, Q. Zhang, and B. Li. [4] C. Mitterer, H.M. Künzel, S. Herkel, and A. Holm in Optimising energy efficiency and occupant comfort with climate specific design of the building (2012) 229-235. (https://doi.org/10.1177/1420326X211030786). In the Yangtze River region, there is a hot summer and cold winter climate. A case study of this phenomenon was published in the Journal of Building Engineering in 2018. The article can be found at https://doi.org/ 10.1016/j.jobe.2017.11.012. [6] In the book Automation and Control Trends, edited by P. Ponce, A.M. Gutierrez, and L.M. Ibarra, M. Koısir discusses adaptive building envelopes as a way to control the indoor environment in buildings. The article can be found at https://doi.org/10.5772/ The article "Towards the next generation of green building for urban heat island mitigation: zero UHI impact building" was published in the journal Sustain and can be accessed online at https://doi.org/10.1016/j.scs.2019.101782. Green glass space based design for the creation of sustainable cities: a case study, Sustain, by C. Xi, J. Ding, C. Ren, J. Wang, Z. Feng, and S.-J. Cao, Cities Society, 50 (2019), 101647, https://doi.org/10.1016/j.scs.2019.101647. Cities Soc. 80 (2022), 103809, https://doi.org/10.1016/j.scs.2022. 103809. [10] R. Yao, A. Short, Energy efficient building design, in: R. Yao (Ed.), Design and Management of Sustainable Built Environments, Springer London, London, 2013, pp. 179–202, https://doi.org/10.1007/978-1-4471-4781-7_10. [11] Y. Zhai, Y. Wang, Y. Huang, X. Meng, A multi-objective optimisation methodology for window design considering energy consumption, thermal environment and visual performance, Renew. Energy 134 (2019) 1190–1199, https://doi.org/10.1016/j.renene.2018.09.024. [12] T. Me´ndez Echenagucia, A. Capozzoli, Y. Cascone, M. Sassone, The early design stage of a building envelope: multi-objective search through heating, cooling and lighting energy performance analysis, Appl. Energy 154 (2015) 577–591, https://doi.org/10.1016/j.apenergy.2015.04.090. [13] Y. Fang, S. Cho, Design optimisation of building geometry and fenestration for daylighting and energy performance, Sol. Energy 191 (Keep going. Energy Review, Volume 31, Issue 1, Pages 101–112, 2014, doi:10.1016/j.rser.2013.11.036. [15] In Energy Build, Volume 57, Issue 3, Pages 6–13, 2013, doi:10.1016/j.enbuild.2012.10.035. [16] In Energy Rev., Volume 31, Issue 1, Pages 101–112, 2014, Susorova, Tabibzadeh, Rahman, Clack, and Elnimeiri examined the impact of geometrical factors on the energy performance and savings of fenestration in office buildings.M. Thalfeldt, E. Pikas, J. Kurnitski, H. Voll, Facade design principles for nearly zero energy buildings in a cold climate, Energy Build. 67 (2013) 309–321, https://doi.org/10.1016/j.enbuild.2013.08.027. [17] S. Zhou, J. Zhao, Optimum combinations of building envelop energy-saving technologies for office buildings in different climatic regions of China, Energy Build. 57 (2013) 103–109, https://doi.org/10.1016/j.enbuild.2012.11.019. [18] J.W. Lee, H.J. Jung, J.Y. Park, J.B. Lee, Y. Yoon, Optim In Energy 50 (2013) 522-531, the authors J. Gagne and M. Andersen discuss a generative facade design technique that takes daylighting performance objectives into account. The article is published in the Journal of Building Performance Simulation 5 (2012) 141-154 and can be accessed online at https://doi.org/10.1080/19401493.2010.549572.K. Konis, A. Gamas, K. Kensek, Passive performance and building form: an optimisation framework for early-stage design support, Sol. Energy 125 (2016) 161–179, https://doi.org/10.1016/j.solener.2015.12.020. [21] P. Pilechiha, M. Mahdavinejad, F. Pour Rahimian, P. Carnemolla, S. Seyedzadeh, Multi-objective optimisation framework for designing office windows: quality of view, daylight and energy efficiency, Appl. Energy 261 (2020), 114356, https://doi.org/10.1016/j.apenergy.2019.114356. [22] R. Energy 34 (2009) 2697-2705, https://doi.org/10.1016/j.renene.2009.05.015. [23] H.K. Abdullah, H.Z. Alibaba, Window design of naturally ventilated offices in the Mediterranean climate in terms of CO2 and thermal comfort performance, Sustainability 12 (2020) 473, https://doi.org/10.3390/su12020473. [24] R. Elghamry, H. Hassan, Impact of window parameters on the building envelope on thermal comfort, energy consumption, cost, and the environment, Int. J. Vent. 19 (2020) 233-259, https://doi.org/10.1C. Marino, A. Nucara, and M. Pietrafesa, "Does window-to-wall ratio significantly affect buildings' energy consumption?" A parametric analysis in the context of the Italian climate, published in the Journal of Building Engineering in 2017, pages 169–183, with the DOI 10.1016/j.jobe.2017.08.001.