A case study of the multi-objectives optimisation of an office energy retrofit in Indonesia's hot-humid climate

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ABSTRACT: It has been estimated that buildings account for more than 40% of global energy consumption, and this demand will continue to grow in line with increasing population and urbanisation. Therefore, there is a growing demand to develop retrofit systems in existing buildings to improve their energy performance, especially in developing countries such as Indonesia. The aims of this research were to use a multi-objective optimisation framework to investigate the most optimum solutions for the energy retrofit of an actual office building located in a hot-humid climate based on environmental criteria (minimise cooling energy) and social criteria (reduce discomfort hours) and to provide recommendations for energy retrofit projects for similar office buildings in Indonesia. The variables used in this optimisation were window-to-wall ratio, glazing type, window blind type, and shading type.

KEYWORDS: Multi-objective optimisation, Optimum solution, Building retrofit, Energy efficiency

1. INTRODUCTION

Building retrofit refers to upgrading existing buildings to improve their energy efficiency, comfort, and overall performance. Retrofitting existing buildings reduces energy consumption and greenhouse gas emissions worldwide, enhances energy efficiency, boosts occupants' productivity, decreases maintenance costs, and contributes to better thermal comfort [1]. However, choosing an optimal retrofit strategy usually involves considering many different approaches. Attia et al. [2] concluded that multi-objective optimisation (MOO) is one of the most vigorous forms of optimisation because it generates sets of solutions from trade-offs between two or more conflicting design objectives. The MOO concept relies on identifying all feasible solutions (building design or retrofit options), which are Pareto-optimal or non-dominated. Being non-dominated implies that no solution within it can improve an objective without being disadvantageous to at least another one. Those solutions constitute the Pareto front, representing the optimal trade-off between the objectives considered in the analysis [3].

Several retrofit case studies using genetic algorithms through MOO have been investigated. An active archive non-dominated sorting genetic algorithm (NSGA-II) has been applied by Rosso et al. [4] to attain the optimum solution for retrofitting residential buildings in Rome, Italy. Their method reduced computational time and identified a MOO solution that decreased annual energy demand by 49.2%, yearly energy costs by 48.8%, and CO2 emissions by 45.2% while achieving 60% lower investment costs than other criterion-optimal solutions. Lu et al. [5] found that occupants-oriented retrofit options, such as utilising lighting sensors based on occupancy, setting higher temperature setpoints, and reducing plug loads, could significantly exceed technological retrofits like replacing chillers and installing a green roof. Seghier et al. [6] proposed an optimisation method for retrofitting building information modelling (RBIM) to find the building envelope for an office building in Malaysia with two objectives: minimising the overall thermal transfer value (OTTV) and minimising retrofit costs. The method utilised three different software: Autodesk Revit for BIM authoring tools, Dynamo for visual scripting, and MATLAB to customise (NSGA-II) optimisation.

A review study from Hashempour et al. [7] revealed that most MOO retrofit studies were from developed countries. There have been very few retrofit studies for buildings located in hot-humid climates. Tavakolan et al. [8] recommended future studies in a different type of building and a different climate, i.e. a hot-humid climate. Hence, this study aimed to investigate and test a multi-objective optimisation energy retrofit of an office building in a hot-humid climate using environmental and social criteria (reduce discomfort hours) to apply the most optimum retrofit strategies.

2. METHODOLOGY

2.1 Case study, digital twins, and validation

The selected case study areas were the 4th, 9th, and 17th floors of the Ministry of Public Works and Housing, Republic of Indonesia (Pekerjaan Umum dan Perumahan Rakyat - PUPR)'s Office Building, as seen in Figure 1. The building's form and orientation had been designed to prevent direct solar radiation and to enhance thermal comfort. The floors were chosen to demonstrate the performance of the building's lower, middle, and top floors. Three loggers were installed for a month's continuous monitoring of indoor air temperatures and relative humidity in three rooms on each designated floor in October 2022 (Figure 2). The 4th and 9th floors represent the typical office layout in the PUPR building, while the 17th floor consists of a hall and a large dining area for occasional events. Based on the as-built drawings and building surveys, the existing building was digitally modelled in the DesignBuilder (DB) dynamic thermal simulation software (https://designbuilder.co.uk/). Figures 3 and 4 show the typical floor plans of the PUPR building. The digital twins of the three different floors were developed in DesignBuilder (DB) in separate files to avoid complicated simulations and computer crashes.

The building uses thermal-resistant glass for windows, a super silver dark blue 8 mm glass with a U-value of 5.739 W/m^{2}K. An opaque curtain wall consists of 8mm glass, plasterboard 12mm, glass wool 145mm, and plasterboard 12mm with a U-value of 0.225 W/m^{2}K. The cladding aluminium façade consists of 5mm thick metal aluminium, an air gap of 19mm, and cast concrete of 475mm, giving a U-value of 0.402 W/m^{2}K. The tiled wall at the front façade, from the ground floor until the 4th floor, consists of 15mm thick ceramic tiles, 10mm thick cement plaster, 100mm concrete block, and a 10mm thick cement plaster, with a U-value of 1.348 W/m^{2}K. The office spaces in the PUPR building utilise a central air conditioning system and a VAV dual duct water-cooled chiller with refrigerant R-134a. The seventeen-storey building also uses natural ventilation in its circulation areas, including corridors, lift lobbies, staircases, and toilets.

Figure 1: Pictures of the PUPR building and office interior

Figure 2: Loggers in 4th, 9th, and 17th floor

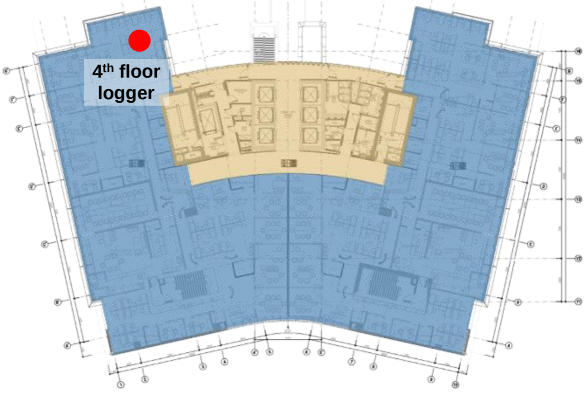

Figure 3: Typical 2nd, 3rd, 4th, 15th, 16th floor plans

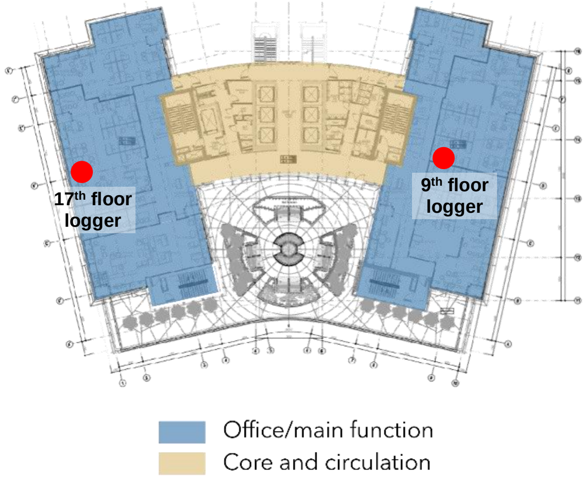

Figure 4:Typical 5th-14th & 17th floor plans

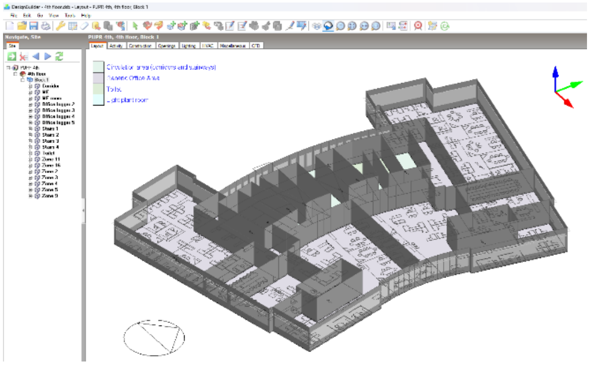

Figure 5: Digital twins of the 4th floor in DesignBuilder

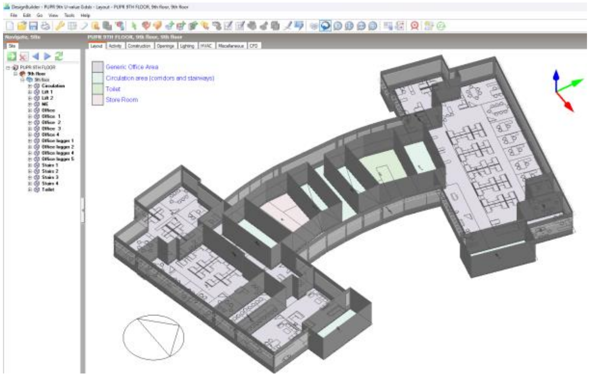

Figure 6: Digital twins of the 9th floor in DesignBuilder

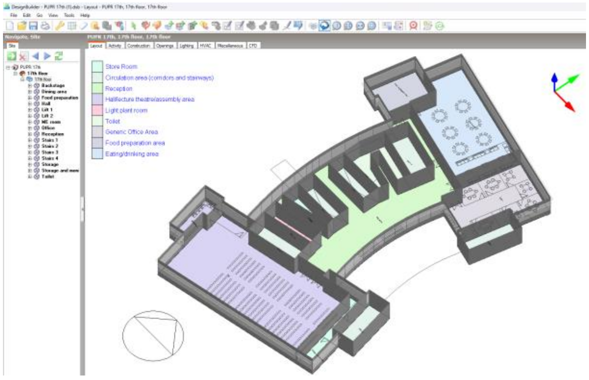

Figure 7: Digital twins of the 17th floor in DesignBuilder

The baseline models were built in DB by importing the DXF files of each floor. Thermal properties and construction materials in all zones were customised according to the on-site measurements and data provided by the building manager. Figures 5, 6, and 7 show the digital twins on the 4th, 9th, and 17th floors of the PUPR building, respectively.

Weather data used in Design Builder were derived from the commercial software Meteonorm (https://meteonorm.com/en/), which calculates hourly values of weather parameters (station, interpolated, or imported data) using a stochastic model. Thus, the weather data of the office's location could be generated as EPW files and utilised in DesignBuilder. The outdoor temperature data from Meteonorm were then compared to the measured outdoor temperature and validated using the ASHRAE procedure [9]. Figure 8 reveals the comparison of outdoor temperature between the measured and Meteonorm data. The outdoor logger for measurement was located on an outdoor terrace shaded by the overhang on the ground floor. From this chart, the Meteonorm weather data shows more extreme lows and highs because of the average temperature from nearby weather stations.

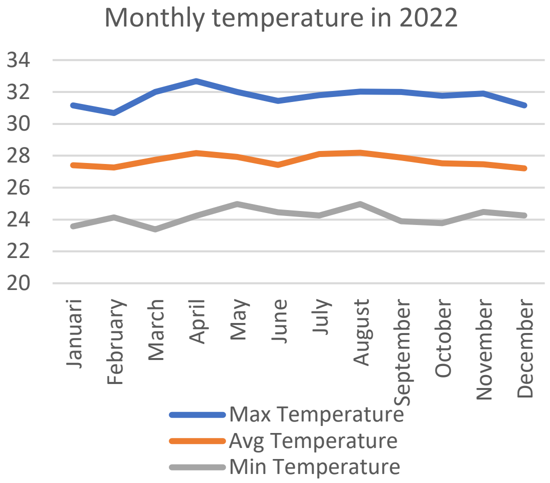

Figure 9: Average monthly air temperatures from Jakarta International Airport (CGK)

Figure 9 shows the monthly temperature of Jakarta city measured at the Jakarta International Airport in 2022. The average monthly air temperatures are very similar throughout the year due to Jakarta's location near to the Equator and its hot humid climate or tropical climate. This is in contrast to the monthly average air temperatures in subtropical climates, which have four seasons with marked temperature differences between summer and winter.

Energy simulations were then performed to calculate current energy performance during October 2022. The air temperatures in the selected zones (DB models) where the loggers were installed were then compared and validated against the measured data using the procedure given by ASHRAE using the formulae for Mean Bias Error (MBE) and Coefficient of the Variation of the Root Mean Square Error (CVRMSE). According to ASHRAE 14 (Section 6.3.3.4.2.2) [9], if using hourly data, the validation accuracy of the model should be +/- 10% for MBE and

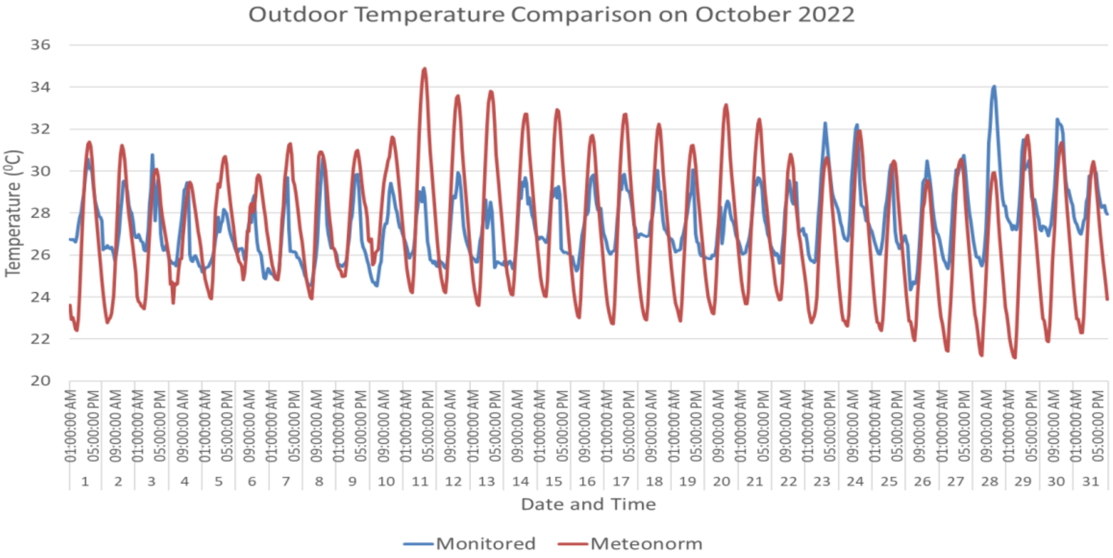

Figure 8: Measured and Meteonorm outdoor temperature comparison

<30% for CV(RMSE). The validation result for all three model floors and the outdoor temperature can be seen in Table 1. The results indicate that all models were within the ASHRAE standard and could be used for the next step, i.e. optimisation.

Table 1: Model validation result

Validation Result (Hourly Data)				
Model	MBE (%)	N_MBE (%)	RMSE (%)	CV(RMSE) (%)
4th floor	0.16	0.66	1.80	7.28
9th floor	-0.73	-3.02	2.11	8.71
17th floor	0.04	0.14	2.77	10.46
Outdoor temperature	-0.28	-1.03	2.40	8.75

2.2 Optimisation process

Table 2. Objectives and variables for the optimisation

Objectives		Variables				
1	2	Glazing type	Cooling setpoint temperature (°C)	Window Wall Ratio (WWR)	Window blind type	Local shading type
Discomfort (All Clothing) (hr)	Cooling energy (kWh)	Double Clear 6mm/13mm Air (U-value=2.665 W/m^{2}K)	Min 22, Max 28 Step (parametric) 2, Step (optimisation) 0.2	Min 20, Max 80 Step (parametric) 20, Step (optimisation) 2	none	0.5m projection Louvre
		Double Clear 6mm/13mm Argon (U-value=2.511 W/m^{2}K)			Blind with high reflectivity slats	1.0m projection Louvre
		Double LoE (e2=.1) Clear 6mm/13mm Air (U-value=1.761 W/m^{2}K)			Blind with low reflectivity slats	1.5m projection Louvre
		Double LoE (e2=.1) Clear 6mm/13mm Argon (U-value=1.493 W/m^{2}K)			Blind with medium reflectivity slats	0.5m Overhang
		Double LoE (e2=.1) Clear 6mm/6mm Air (U-value=2.429 W/m^{2}K)			Micro Louvre	1.0m Overhang
		Double LoE (e2=.2) Clear 6mm/6mm Air (U-value=2.552 W/m^{2}K)			Mid-pane blind with medium reflectivity slats	1.5m Overhang
		Project BIPV Window (U-value=1.960 W/m^{2}K)			Venetian blinds – light	2.0m Overhang
		Single LoE (e2=.2) Clear 6mm (U-value=3.779 W/m^{2}K)			Venetian blinds - medium	No Shading

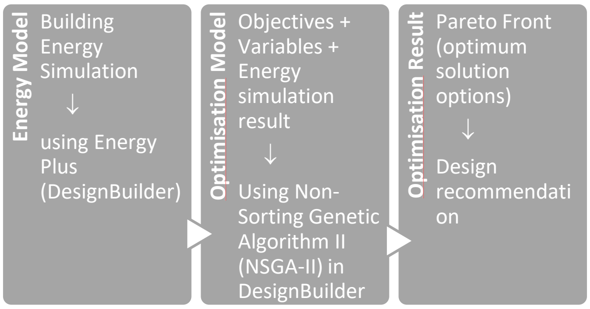

Figure 10: Multi-objective optimisation process

This study's optimisation objectives were to increase thermal comfort (minimise discomfort hours) and minimise the cooling energy. Additionally, six variables were added to the optimisation: glazing type, cooling set point temperature (°C), local shading type, window wall ratio (WWR), and window blind type. Table 2 shows the selected objectives and variables chosen as the parameters for the optimum retrofit strategies. After developing and simulating the energy model in DesignBuilder, as well as validating it, the next step was to create the multi-objective optimisation using Non-Sorting Genetic Algorithm II (NSGA-II) directly in DesignBuilder to get the optimum solutions (Pareto Front) for retrofit recommendation (Figure 10).

3. RESULT AND DISCUSSION

From the energy simulation in DesignBuilder, the total site energy usage during October 2022 for the 4th, 9th, and 17th floors were 55078.07 kWh, 39887.86kWh, and 40851.67kWh, respectively (Table 3). The 4th floor consumed more energy than the other floors, which might be due to the geometry and building area being larger than the other floors. Table 3 also shows that the district cooling intensity on each floor was more than 85% of the total site energy demand. This result confirmed that air conditioning took up most of the energy consumption of the PUPR building.

Table 3: Current energy performance of DB models

Model	**Total Site Energy (kWh)**	**District Cooling (kWh)**	**Energy Per Total Building Area [kWh/m^2]**	**District Cooling Intensity [kWh/m^2]**
4th floor	55078.07	47790.17	32.50	28.20
9th floor	39887.86	34235.64	32.62	28.00
17th floor	40851.67	37599.33	31.39	28.89

After obtaining the energy simulation results, an optimisation to generate retrofit solutions in each floor model was simulated directly in DesignBuilder using the selected objectives and variables shown in Table 2. The optimisation options or settings are a maximum generation of 200, a generation for convergence, and an initial population of 20 each.

The results of the simulations and optimisations in DesignBuilder showed that there were 35 sets of optimal retrofit design solutions for the 4th floor (Figure 12—top), 14 sets for the 9th floor (Figure 12—middle), and 55 sets for the 17th floor (Figure 12—bottom). Table 4 recommends configurations with the most optimum solution based on the Pareto front result for all three models.

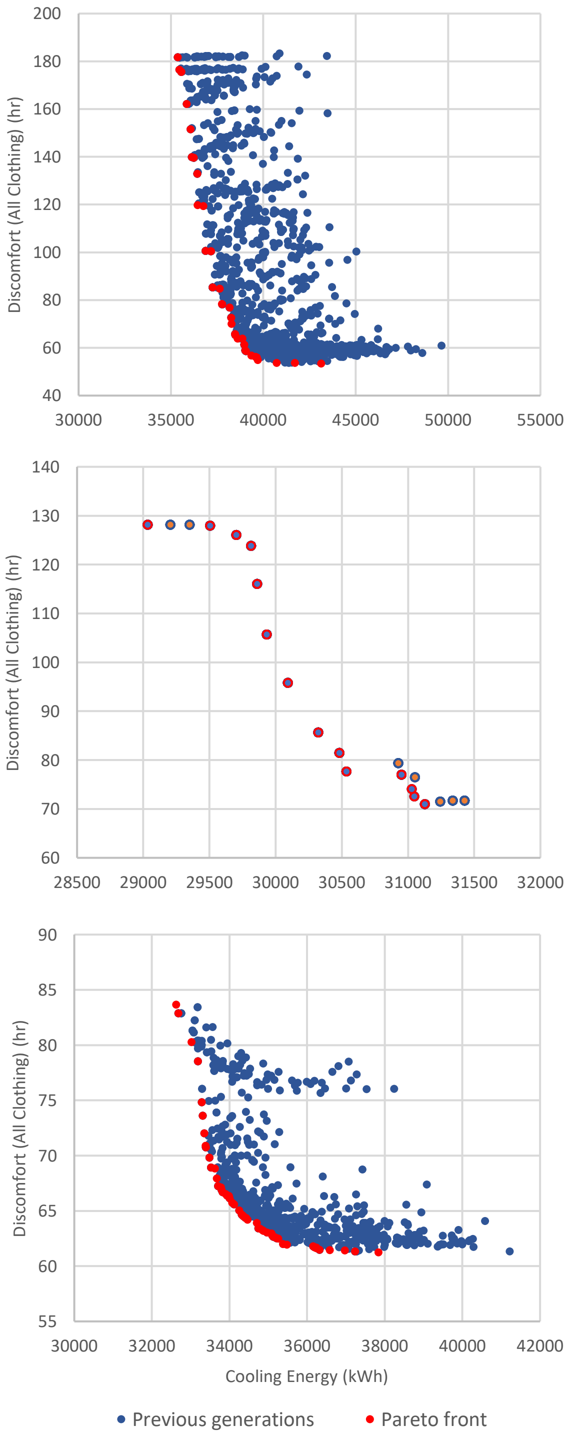

Figure 11: Optimisation results (discomfort hours v cooling energy) of the 4^{th} floor (top), 9^{th} floor (middle), and 17^{th} floor (bottom)

The optimum option for the 4th-floor model, which would have a cooling energy demand of 37,785.30 kWh and 78.17 discomfort hours, using double LoE clear glass 6mm/13mm with air cavity (e2=1) + 1.5 m projection louvre + Venetian blinds light + cooling setpoint temperature of 24.6 + 50% WWR. This option will reduce the cooling energy demand by 25.94% compared to the current building performance. The most optimum option for the 9th-floor model would have a cooling energy demand of 30,323.58 kWh and 85.6 discomfort hours using double clear 6mm/13mm with air cavity + 1.5m overhang blind with low reflectivity slats + cooling setpoint temperature of 26^{0}C + 64% WWR. This option can reduce the cooling energy on the 9th floor by 11.42%. The most optimum option for the 17th-floor model would have a cooling energy demand of 34,368.4 kWh using BIPV (Building Integrated Photovoltaic) + 1.5m projection louvre + blind with high reflectivity slats + cooling setpoint temperature of 23.4^{0}C + 46% WWR. This option will decrease the cooling energy on the 17th floor by 8.59%.

Based on all Pareto front solutions for the three models, the glazing type of double LoE clear glass 6mm/13mm with argon cavity (e2=1) and Double LoE clear glass 6mm/6mm with air cavity (e2=1) appeared the most beneficial compared to the other selected glazings in the optimisation. A 1.5 m projection louvre and a 2 m overhang occurred most frequently in the optimisation results for local shading type. Lastly, for the window blind type, light-diffusing Venetian blinds were shown to be the most optimum options.

4. CONCLUSION

This study applied MOO to retrofit an office building in the hot-humid climate of Indonesia. Three validated Design Builder digital twins of the office building were developed for the MOO analysis. The optimal trade-offs between the objectives considered in the study to minimise cooling load and minimise discomfort hours were also identified.

Based on the Pareto Front result in the optimisation calculations in Design Builder, the recommendation for the most optimum retrofit strategies is using:

(1) Double LoE clear glass 6mm/13mm with air cavity (e2=1) + 1.5 m projection louvre + Venetian blinds light + cooling setpoint temperature of 24.6 ^{0}C + 50% WWR,

(2) Double clear glass 6mm/13mm with air cavity + 1.5m overhang + blinds with low reflectivity slats + cooling setpoint temperature of 24.2^{0}C + 60% WWR, or

(3) Project BIPV (Building Integrated Photovoltaic) Window + 1.5 projection louvre + blinds with high reflectivity slats + cooling setpoint temperature of 23.4^{0}C + 46% WWR.

Table 4: Recommendation of optimum sets of solutions

Floors	Objective		Variable				
	Cooling energy (kWh)	Discomfort (All Clothing) (hr)	Cooling setpoint temperature (°C)	Window to Wall %	Glazing type	Local shading type	Window blind type
4th	35389.75	181.59	26	34	Dbl LoE (e2=.1) Clr 6mm/13mm Air	1.5 m projection Louvre	Venetian blinds - light (modelled as diffusing)
	37785.3	78.17	24.6	50	Dbl LoE (e2=.1) Clr 6mm/13mm Air	1.5 m projection Louvre	Venetian blinds - light (modelled as diffusing)
	43138.76	53.25	22	64	Dbl Clr 6mm/13mm Air	1.5m Overhang	<None>
9th	29035.21	128.1325	26	64	Dbl LoE (e2=.2) Clr 6mm/6mm Air	1.0m Overhang	Blind with medium reflectivity slats
	30323.58	85.60543	24.2	60	Dbl Clr 6mm/13mm Air	1.5m Overhang	Blind with low reflectivity slats
	29035.21	128.13	26	64	Dbl LoE (e2=.2) Clr 6mm/6mm Air	1.0m Overhang	Blind with medium reflectivity slats
17th	32630.07	83.64	26	74	Dbl LoE (e2=.1) Clr 6mm/13mm Arg	1.5 m projection Louvre	<None>
	34368.4	64.45	23.4	46	Project BIPV Window	1.5 m projection Louvre	Blind with high reflectivity slats
	37846.89	61.22	22.4	30	Dbl Clr 6mm/13mm Arg	1.0m Overhang	Blind with low reflectivity slats

However, detailed information on the building's materials' thermal properties was limited, so default materials similar to the current building were applied in the DesignBuilder models. The occupancy schedules were also not available. Hence, in DesignBuilder, the general office schedule from 9.00 to 17.00 was chosen for weekday activity.

For future studies, investigating the impact of the geometry of the building on the optimisation results and the cost-benefit analysis would be important. Furthermore, utilising multi-criteria decision-making could be beneficial for selecting the most optimum solution to retrofit the building in a hot-humid climate. This approach could ask the stakeholders, such as building users, architects, engineers, and academics, to be involved in analysing retrofit recommendations. Then, further research will apply the exact solutions to different types of buildings in hot-humid climates.

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